CHAPTER 2

LITERATURE REVIEW

2.1 General

Liquefaction, in general, is the phenomenon of transformation of any substance into fluid phase. Dash (2010) defines liquefaction as the phenomenon marked by the significant reduction in strength and stiffness of the soil due to rapid cyclic loading. The loss of strength of granular cohesionless saturated soils (gravel, sand, and low plasticity silt) is for a short period of time, but sufficient enough to yield substantial failures. The impacts of liquefaction are frequently visible on the ground surface in the form of sand boils, major deformation or fractures, etc. (Lentini and Castelli (2019); Huang et al. 2013). During seismic shaking, the saturated sand deposits experience rapid development of pore water pressure while its dissipation is much slower. It may decrease effective stress to near zero value, eventually leading to transformation of soil solid to viscous fluid mass.

Over the past few decades, there has been considerable advances in both understanding and practice in context with the liquefaction manifestations and engineering approach in mitigating soil liquefaction. Rather seismic soil liquefaction has evolved into a topic of mainstream issue which has been addressed in most of the building codes and also in many of the studies. Despite of the fact that the rate of advancement in this field has been praiseworthy, there is still much that has to be done. Earlier the research was confined to the assessment of the likelihood of triggering liquefaction but with the time observations and experiences, researchers have now become aware of additional potential problems such as assessment of post-liquefaction strength, development of reliable countermeasures to inhibit future liquefaction and so on. Before developing the necessary engineered methods and tools for mitigation, it is mandatory to anticipate the potential risks and consequences of the liquefaction

2.2 Liquefaction Susceptibility

Past studies suggest that liquefaction susceptibility of soils is primarily a function of its grain size distribution and Atterberg's limits. Considering those parameters, a soil can be undertaken for preliminary assessment for liquefaction prior to extensive experimental investigations. Tuschida (1970) considered soil gradation curve as an indicative parameter to anticipate the potential of a soil towards liquefaction as shown in Fig 2.1. These curves clearly demonstrate that sands possess highest potential to liquefy when subjected to dynamic loads.

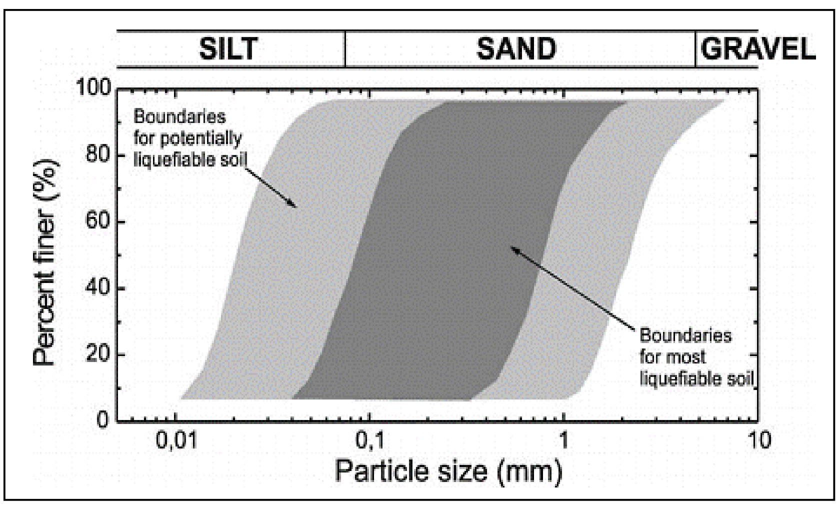


Fig. 2.1 Grain size distribution curve for liquefiable soils as proposed by Tsuchida (1970) (redrawn after Marto and Tan 2012)

Additionally, Wang (1979) followed by Seed and Idriss (1971) has given a Chinese criterion as shown in Fig 2.2. In order to be liquefiable a soil should meet the criteria of having clay fraction less than 15%, liquid limit (LL) less than 35% and water content higher than 90% LL. However, this criterion was found to be too conservative and therefore Andrew and Martin (2000) categorized the empirical data and developed a modified Chinese criterion. As per the criteria, the soils having clay content less than 10% and LL < 32% are prone to liquefaction. Further, for clay content greater than or equal to 10% and LL≥32% are not prone to liquefaction. For other cases, further studies are required.

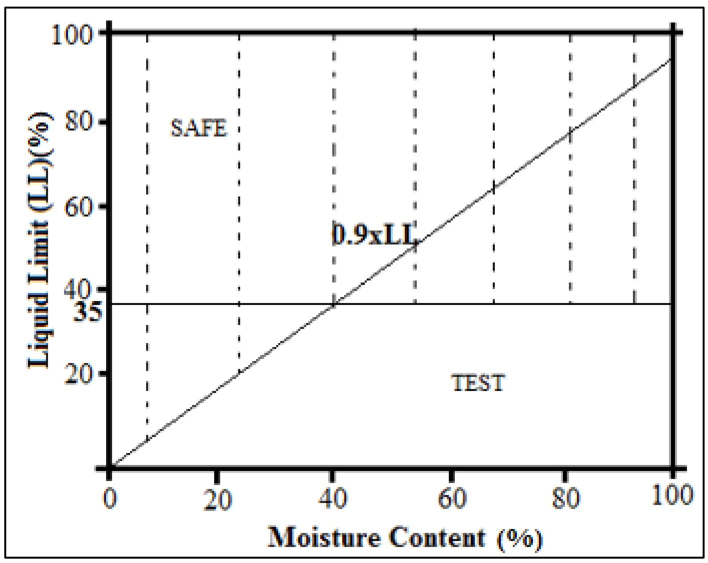


Fig. 2.2 Chinese criteria for liquefaction susceptibility (after Seed and Idriss 1982)

As reported in the literature, some of the studies have also considered Plasticity Index (PI) of the soil as a parameter to identify liquefaction susceptibility (Guo and Prakash 2000; Seed et al. 2001; Gratchev et al. 2006). Seed et al. (2003) has given an assessment chart to further improvise Modified Chinese criterion by incorporating the effect of plasticity index. It incorporates the major liquefaction susceptibility findings and has been shown in Fig. 2.3. Zone A depicts the soils which are most prone to liquefaction while those lying in Zone B are potentially susceptible to liquefaction under some specific conditions. The soils which do not lie in either of the two zones are considered as non-liquefiable.

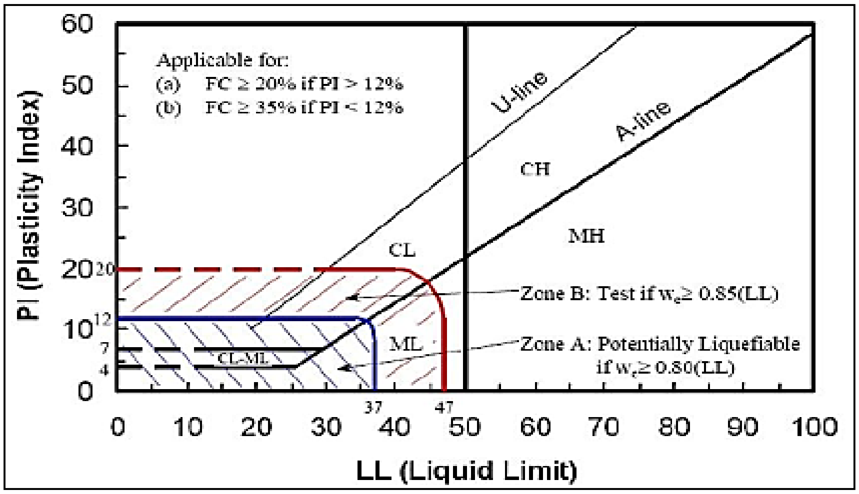


Fig. 2.3 Modified chinese criteria for liquefaction susceptibility (after Seed and Idriss 1982)

Sabbar et al. 2017 performed artificial neural networking and genetic programming to assess the liquefaction susceptibility of sands based on the ratio of minimum deviatoric stress and peak deviatoric stress (q_{min}/q_{peak}) which is considered as static liquefaction criterion.

2.3 Liquefaction Studies

Advancement of liquefaction assessment started with Seed and Idriss (1971) who developed a methodology based on empirical work termed as "simplified procedure" which was later improved and modified (Seed 1979; Seed et al. 1985; Youd 1997; Youd et al. 2001). Soon after the Niigata earthquake, various laboratory and field-based studies were conducted among various international geotechnical research groups to have a clear understanding of the liquefaction triggering mechanisms.

2.3.1 Laboratory Investigations

The geotechnical applications especially those subjected to earthquake, wave, wind or traffic loading requires a systematic understanding of the dynamic cyclic behavior of the soils. In order to aid the flow of the thesis, the next few subsections provide a brief review of the laboratory methods to evaluate liquefaction resistance.

2.3.1.1 Studies on Cyclic Triaxial Test

In the present practice, cyclic triaxial testing follows two approaches: (1) stress-based approach and (2) strain-based approach. In a stress-controlled test, a waveform of uniform cyclic stress amplitude and considerable frequency is applied on the soil specimens and the response in terms of excess pore pressure buildup and induced shear strain is recorded **(**Seed et al. 1960). Alternatively, in cyclic strain approach, a waveform of uniform cyclic strain amplitude is applied and the pore pressure response is monitored (Silver and Park 1976; Dobry et al. 1982; Dobry and Abdoun 2015). Extensive research has been carried out to study the liquefaction manifestations in sandy soils as well as mixed soils. Besides that, the cyclic response of several other geomaterials such as pond ash, coal ash, mine tailings etc. were also investigated. Apart from the conventional sands or sand-silt mixtures, the discussion in this thesis will also cover the cyclic behavior of other alternative geomaterials.

The liquefaction characteristics of saturated sandy soil subjected to both random and regular excitations were studied by Ishihara and Yasuda (1972, 1975). The maximum shear stress in case of regular cyclic loading is 47-60% of that in irregular cyclic loading for 20 loading cycles. Researchers have also performed triaxial testing using real-time earthquake time histories and found that the maximal shear strain (γ_{max}) required to induce liquefaction is close to 3.75 percent (Ishihara 1996; Tsukamoto et al. 2004). It was also reported that the threshold volumetric shear starin (γ_t), required to initiate cyclic settlement lied in the range of 0.01%-0.02% (Hsu and Vucetic, 2004). This threshold value denotes that level of volumetric shear strain below which the generation of excess pore water pressure is negligible and is unaffected by initial density (Ladd et al. 1989). Similar values of threshold volumetric shear strain were proposed by Kumar et al. (2015) based on the strain-controlled cyclic tests on saturated sandy soil. In case of unsaturated or partially saturated sandy soils, a correlation has been proposed between cyclic shear strain (γ_c) and volumetric strain (Sawada et al. 2006) where γ_c required to initiate the liquefaction was found to lie in the range of 0.4-3% (Dobry et al. 2015; Dobry and Abdoun, 2015).

Typical stress-strain behavior of the Nevada sand with the time history of pore pressure obtained from stress-controlled cyclic triaxial test in undrained condition reported by Yang et al. (2013) is shown in Fig. 2.4. Liquefaction was evitable from pore pressure time history when excess pore pressure reached the value of 150 kPa. The stress-strain behavior shows accumulation of deformation with each loading cycle.

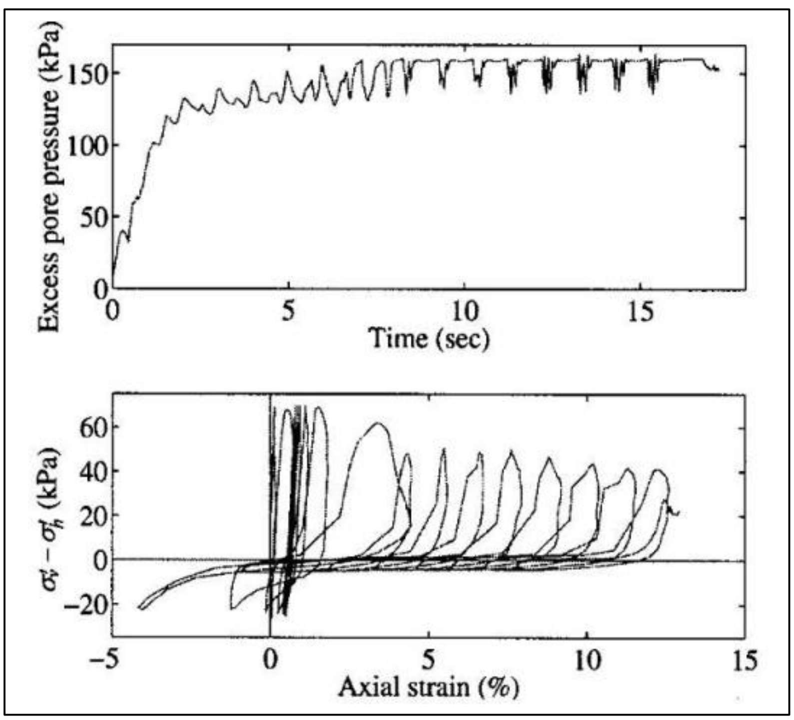


Fig. 2.4 Excess pore pressure-time history and typical stress strain curve for Nevada sand at D_r = 40% (redrawn after Yang et al. 2003)

Table 2.1 lists the recent cyclic shear tests performed on different types of geomaterials under different conditions using cyclic triaxial test along with their primary findings.

Table 2.1 Summary of some significant laboratory investigations over the past decade

S.No.	Researcher(s)	Type of soil specimen	Primary objective	Technique followed	Major Findings
1.	Jakka et al.(2010)	Loose and compacted pond ash	Response of pond ash under cyclic loading	Cyclic triaxial test	Samples collected from the inflow point exhibit higher cyclic strength.
2.	Mohanty and Patra (2014)	Pond ash	Cyclic response of pond ash at different degrees of relative compaction	Cyclic triaxial tests	All reconstituted pond ash samples exhibited Low potential to liquefy. Increasing compactness increases cyclic resistance.
3.	Lombardi et al. (2014)	Redhill 110 sand Toyoura sand	Cyclic and post-cyclic response of two types of silica sand	Multi-stage triaxial tests	A bilinear stress-strain model was formulated in terms of take-off shear strain, initial (low strain) shear modulus and high strain shear modulus.
4.	Ye et al. (2015)	Fujian sand	Role of pre-shear on the liquefaction response	Hollow cylinder torsional shear test	A small amount of pre-shear strain (upto 5%) causes sand to be more susceptible to liquefaction.
5.	Ochoa-Cornejo et al. (2016)	Ottawa sand	Efficacy of laponite in arresting liquefaction	Cyclic triaxial test	Laponite causes reduced mobility of the sand particles under cyclic loading thereby reducing liquefaction potential.
6.	Zhang et al. (2016)	Toyoura sand Nevada sand	Effect of degree of saturation, relative density and effective confining pressure on the liquefaction.	Cyclic Triaxial Test	Liquefaction resistance of sands increases with decreasing degree of saturation and increasing relative density and effective confining pressure.
7.	Bousmaha et al. (2016)	Sand-silt mixtures	Variation of critical shear strength of low plastic silty sand based on different parameters	Undrained triaxial tests	Equivalent void ratio proved to be a vital parameter to define the liquefaction proneness of low plastic silty sands.
8.	El Takch et al. (2016)	Non-plastic silt Sandy silt	Variation of critical shear strength of low plastic silty sand based on different parameters	Constant volume cyclic ring shear tests	CRR–V_{s1} relationships has little effect of fine content when it is greater than 50%.
9.	Sassa and Yamazaki (2017)	Medium silica sand	Effect of waveform irregularities and loading duration on the cyclic behavior of sands.	Undrained cyclic torsional shear tests Constant volume cyclic simple shear tests	Waveform correction coefficient was introduced which relates effective number of waves with normalized liquefaction resistance.

Table 2.1 Continued

S.No.	Researcher(s)	Type of soil specimen	Primary objective	Technique followed	Major Findings
10.	Chattaraj and Sengupta (2017)	Fly ash	Effect of confining pressure and void ratio on dynamic damping	Resonant column Cyclic triaxial	Samples collected from the inflow point exhibited higher cyclic strength.
11.	Do et al. (2017)	Gravels	Effect of density and confining pressure on the post-liquefaction performance of gravel soils.	Resonant column Cyclic triaxial	Given positive state parameter, increase in gravel content causes decrease in liquefaction resistance while the behavior gets reversed when the state parameter is positive.
12.	Kumar et al.(2018)	Cohesive soil	Dynamic properties under staged cyclic loading with different test conditions	Static undrained triaxial tests	While shear modulus degradation curve and damping ratio were significantly affected by change in confining pressure, they were unaffected by change in water content and dry density.
13.	Xu et al. (2019)	Sand Gravel Mixture (SGM)	Effect of gravel content on cyclic and post-cyclic behavior of SGM	Cyclic Triaxial Test	Both volumetric strain and damping ration decreased with increase in gravel content. A relation was proposed between the gravel content and normalized secant modulus and damping ratio.
14.	Lentini and Castelli (2019)	Sandy Soil	Liquefaction resistance of sandy soils from undrained cyclic triaxial tests	large scale cyclic simple shear	Cyclic resistance increase with the decrease in the initial confining stress and decreases as the silt content increases.
15.	Kumar et al. (2020)	Brahmaputra Sand	Liquefaction potential based on regular and irregular excitations	Stress-controlled cyclic triaxial test	The criterion for liquefaction initiation as per shear strain, peak ground acceleration and cyclic stress ratio are provided
16.	Liu (2020)	Medium Montery No. 0/30	Influence of fine content on liquefaction resistance	Cyclic Triaxial test	The criterion for liquefaction initiation as per shear strain, peak ground acceleration and cyclic stress ratio are provided.
17.	Zhu et al. (2021)	Dense and medium dense sands	Effect of loading frequency on liquefaction behavior	Cyclic triaxial test	No clear effect of loading frequency was observed.

2.3.1.2 Studies on Shake Table Tests

The use of shake table experiments in liquefaction studies provides a great advantage in simulating complex systems in a regulated laboratory environment and perhaps a chance to gain insight into the fundamental mechanisms governing the behavior of such systems (Banerjee et al. 2017). Various researchers have demonstrated the liquefaction phenomenon on reduced scale models under 1-g environment (Ye et al. 2013; Ha et al. 2011). Mohajeri and Towhata (2003) and Towhata et al. (2006) studied the rate dependent behavior of liquefied soils. The simplified procedure proposed by Seed and Idriss (1971) was modified by Youd et al. (2001) and Idriss and Boulanger (2008) which quantifies the cyclic stress ratio as per equation (2.1) below

$$CSR = 0.65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right)r_d \tag{2.1}$$

where, a_{max} = peak horizontal ground acceleration

g = acceleration due to gravity

σ_{vo} and σ'_{vo} are total and effective overburden stress respectively

r_d is the shear stress reduction factor

Pathak et al. (2010) investigated the effect of relative density on the earthquake induced liquefaction in sands using shake table tests. The obtained results were in close argument with the actual field data. Furthermore, the obtained results from shake table tests were compared with the other laboratory tests conducted on the similar soil by other researchers which have been shown in Fig. 2.5.

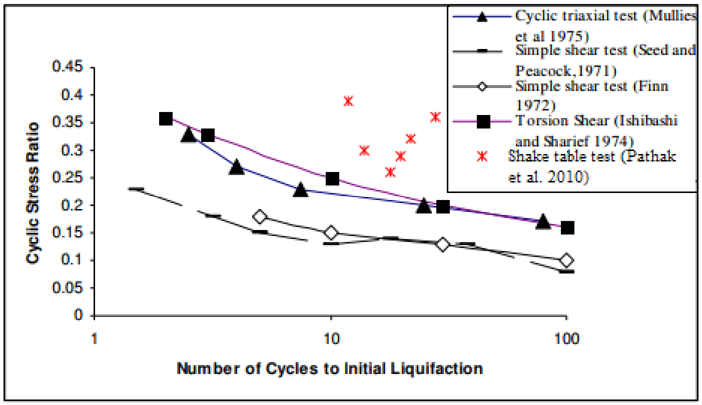


Fig. 2.5 Comparison of cyclic stress ratio versus number of cycles to liquefaction (Pathak et al. 2010)

Fig. 2.5 indicates that the values recorded during shake table test were on higher side as compared to the other test results. Likewise, a parametric evaluation was carried out by Varghese and Latha (2014) to study the effects of relative density, frequency and acceleration amplitude on the liquefaction behavior of sands. The evidence of substantial improvement in the liquefaction resistance with increase in the relative density implies that soil densification can be a reliable technique for liquefaction (Fig. 2.6 & Fig. 2.7). A threshold frequency was also proposed which is required to achieve initial flow liquefaction at a given PGA. As the frequency increases, liquefaction potential increases (Fig. 2.8)

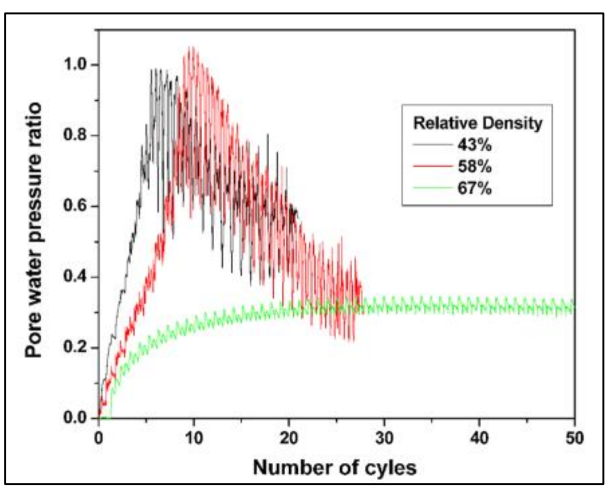


Fig. 2.6 Effect of relative density on PWP ratio (Varghese and Latha 2014)

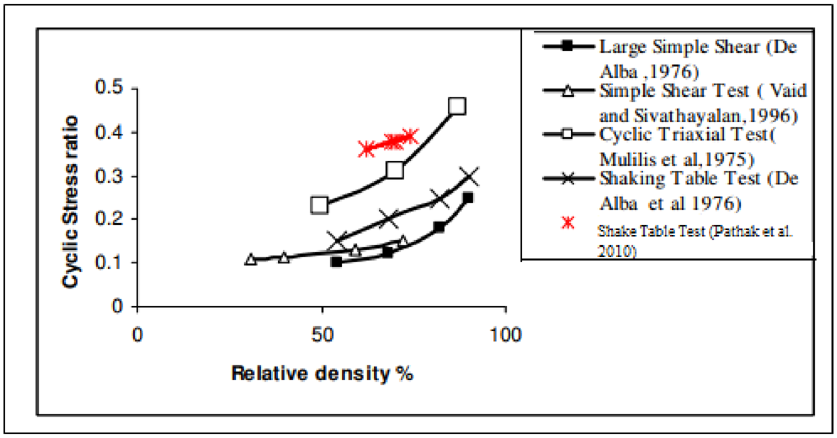


Fig. 2.7 Comparison of cyclic stress ratio versus relative density (Pathak et al. 2010)

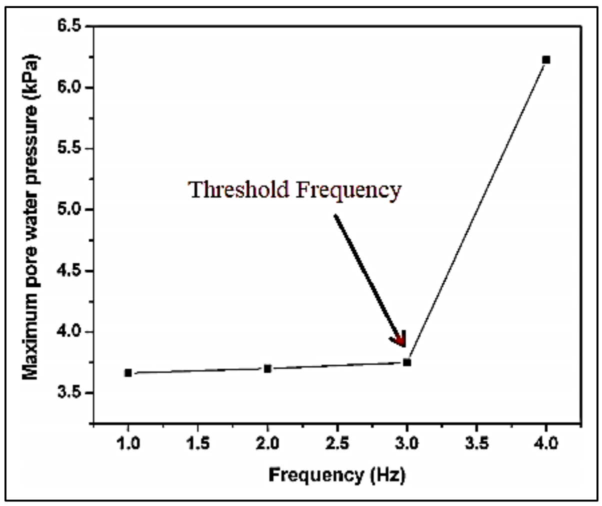


Fig. 2.8 Threshold frequency proposed by Varghese and Latha (2014)

Ueng and Lee (2015) studied the difference in the liquefaction behavior of saturated sands under one dimensional and two dimensional shaking. The liquefaction resistance of sand subjected to 2D shaking was found to be 0.75-0.85 times of that under 1D shaking.

Laboratories studies have also shown that the previous strain history has a significant impact on the liquefaction resistance of soils (Finn et al. 1970; Heidari and Andrus (2010); Dobry et al. 2015). Shaking of the geologically aged soil fabric reduced its re-liquefaction resistance (Ha et al. 2011). Heidari and Andrus (2012) observed that achieving full liquefaction state may completely eradicate the favorable effects of the geologic aging. The pre-shaking effects on the liquefaction resistance of the silty sand was also studied by El-Sekelly et al. (2016a) using centrifuge testing which suggested that the increasing number of pre shaking events tends to increase the resistance of the tested soil. Similar implications were given by Wang et al. (2019) where the past history of weak shaking events tends to increase the resistance while the strong shaking events tends to destroy the fabric structure and reduce the liquefaction resistance (Fig. 2.9).

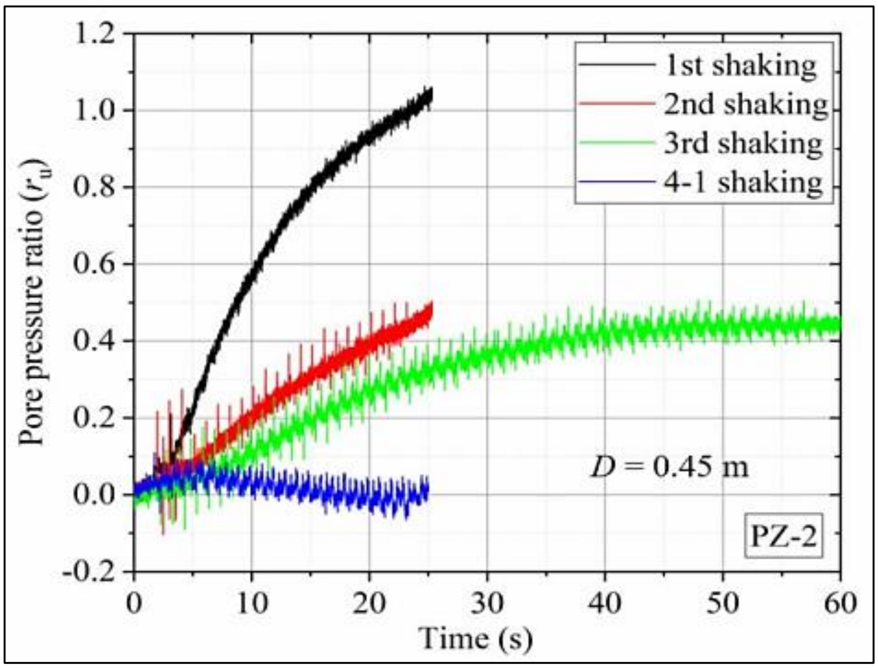


Fig. 2.9 Effect of shaking history on the pore pressure ratio (Wang et al. 2019)

Besides, several other studies have also focused on the liquefaction behavior of multilayered sands (Kokusho 1999; Kokusho and Kojima 2002; Brennan and Madabhushi 2005). Investigation of pore pressure dynamics in sand-silt layering deposits at different relative densities subjected to different input excitations was carried by Özener et al. (2009). These studies demonstrated that the presence of a less permeable silt interlayer inside the sand deposit, as well as the presence of a loose sand layer underneath dense sand deposits, can have a major impact on the pore water pressure generating mechanism.

All of these studies are mainly focused on the clean sands or silty sands. Indeed, in the author's knowledge, no work till now has been conducted to employ shake table model study in understanding the pore pressure behavior of hydrocarbon contaminated sands.

2.3.1.3 Studies on shear wave velocity based assessment

Shear wave velocity is a fundamental mechanical parameter of soil materials that can be measured easily on laboratory samples, allowing for direct comparisons between field and laboratory performance.

Shear wave velocity is a basic mechanical property of soil materials and measurements can easily be performed on laboratory samples, allowing direct comparisons between laboratory and field behavior. This benefit of shear wave velocity measurements can obviate the requirement for complex and expensive in situ measurements. Because equivalent shear wave velocity measurements may be conducted on reconstituted materials in the laboratory, it may reduce the necessity for the costly collection of undisturbed samples. Furthermore, because there aren't enough in situ databases for liquefaction resistance of soils, controlled laboratory testing employing shear wave velocity measurements is critical for building a bigger liquefaction resistance database (Zhou and Chen 2007). De Alba et al. (1984) performed the first laboratory study to investigate the relationship between shear wave velocity and the cyclic resistance of sand, followed by Tokimatsu et al. (1986), Tokimatsu and Uchida (1990), Huang et al. (2004), Zhou et al. (2005), Wang et al. (2006), Zhou and Chen (2008) and Baxter et al. (2008). Laboratory measurement of shear wave velocity can be done either through bender element tests or resonant column test. Yang and Liu (2016) studied the role of non-plastic fines on the shear wave velocity of sand using both bender element and resonant column test. Results revealed a decrease in V_s with increase in fine content. It was also seen that the values obtained from both the tests did not differ much as shown in Fig. 2.10.

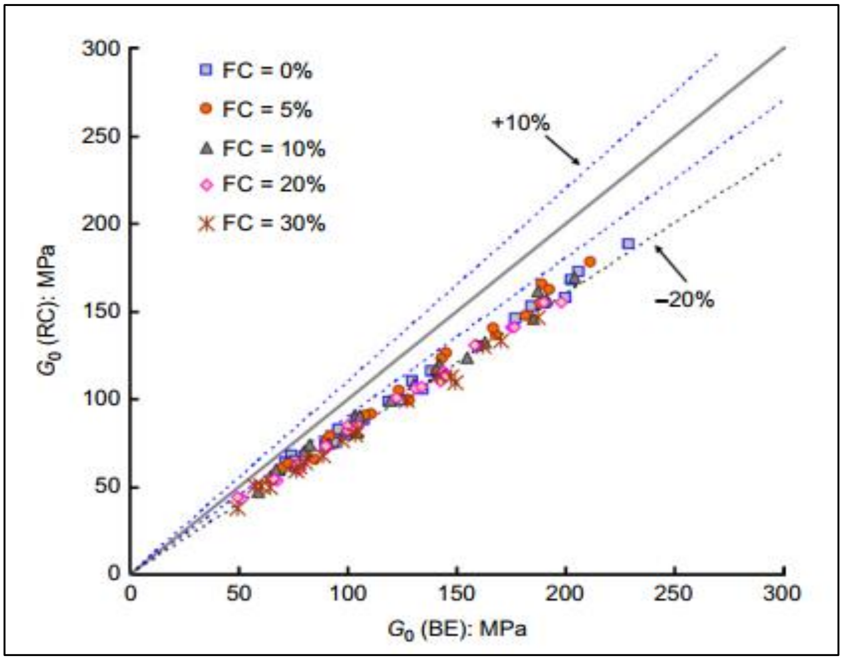


Fig. 2.10 Comparison of shear modulus measurements from resonant column and bender element test (Yang and Liu, 2016)

However, the use of bender element test for measurement of shear wave velocity in laboratory is more common. Shear wave observations made in the laboratory with bender elements were compared to shear wave measurements done in the field using seismic cone equipment by Robertson et al. (1995) and Chillarige (1977). They demonstrated that the findings are consistent after proper correction factors are applied. (Baxter et al. 2008). The study also involves a comparison between undisturbed block samples and reconstituted samples. The reconstituted samples prepared to a saturation of 55% demonstrated very good agreement with the block sample correlation as shown in Fig. 2.11.

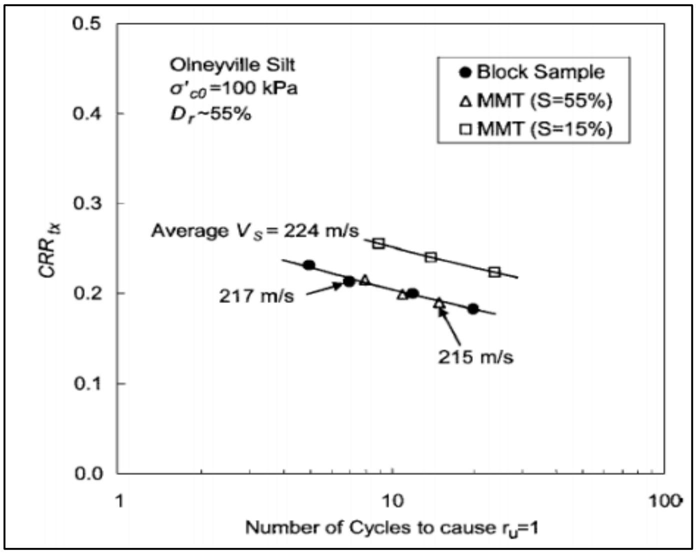


Fig. 2.11 Comparison of cyclic resistance of undisturbed block sample to reconstituted samples (Baxter et al. 2008)

Baxter et al. (2008) also compared the CSR_{tx} -V_s relationship for Niigata sand and Olyneyville silt using different sample preparation procedures. The CRR_{tx} –V_s correlations are independent of stress history and sample preparation methods (Fig. 2.12), but strongly dependent on soil types, according to their findings, which are consistent with previous laboratory investigations (Tokimatsu et al.1986).

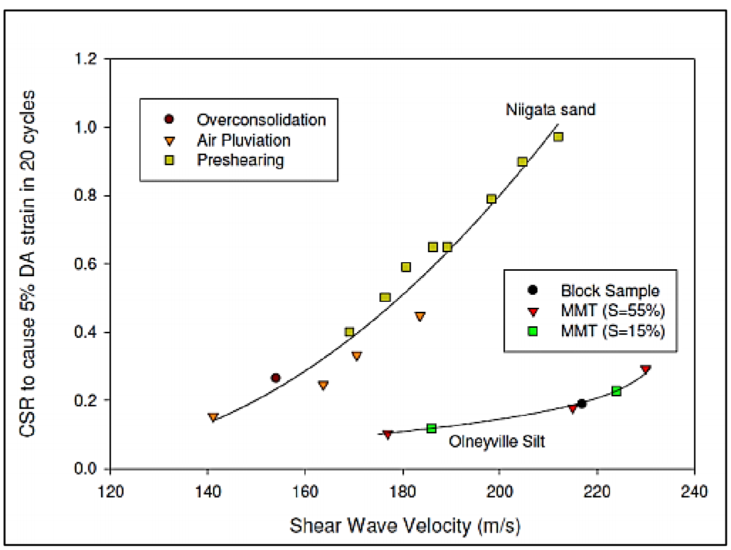


Fig. 2.12 Soil specific CSR – V_S relationship independent of sample preparation methods (Baxter et al. 2008)

The shear wave velocity is also used to evaluate the small strain stiffness of the soils as per the following equation (2.2).

$$G = \rho V_S^2 \tag{2.2}$$

where G is the small strain shear modulus

ρ is the density of the soil.

Therefore, bender element test can also be extended to determine the small strain shear modulus of the soil (Cabalar et al. 2019; Khosravi et al. 2016). Payan and Chenari (2019) evaluated the small strain modulus of the anisotropically loaded sands. The effect of matric suction on small strain shear modulus was investigated by Yang and Lin (2009) whose results revealed a limited reduction in V_s with increase in degree of saturation.

Shear wave velocity based assessment of liquefaction potential can be done by properly simulating the field seismic conditions in the laboratory or applying the suitable correction factors for field conditions. Rauch et al. (2000) and Simatupang et al. (2018) demonstrated the validity of laboratory based method for assessment of liquefaction potential and their close agreement with field studies.

2.3.2 Field Observed Phenomenon and In-situ Investigations

Huang and Jiang (2010) investigated the field phenomenon that had occurred during Wenchuan earthquake in China. A typical phenomenon of earthquake subsidence was observed in the soft ground which paved the way to investigate the possible types and distribution of soils that can experience liquefaction. Several earthquakes induced damages involving liquefaction as its root cause were observed, some of which has been listed in Table 2.2.

Table 2.2 Earthquake-induced damage observed from field investigations

Researcher(s)	Year	Site	Damage Type
Huang and Jiang (2010)	2010	Wenchuan, China	• Sand Boiling • Land Subsidence • Differential settlement • Ground Collapse • Ground cracks
Bhattacharya et al. (2011)	2011	Tokyo Bay Area	• Buckled Pavements • Sand Boils • Settlement
Yamaguchi et al. (2012)	2012	Tohuku, Japan	• Sand Boils
Lombardi and Bhattacharya (2014)	2014	Emila-Romagna, Italy	• Sand Boils • Sand Ejecta • Post-liquefaction reconsolidation settlement • Lateral Spreading
Sana and Nath (2016)	2016	Kashmir Valley, India	• Sand Boils

However, in many of the cases, the feasibility of conducting laboratory experiments for evaluating the soils tendency to liquefy is questionable. In such cases, several invasive and non-invasive in-situ techniques like Cone Penetration Test (CPT), Standard Penetration Test (SPT) or spectral analysis of surface waves (shear wave velocity based methods) can provide a sound technique for assessing the seismic stability of the soil deposits (Matasovic et al. 2016; Chang et al. 2011; Ku et al. 2012; Mohanty and Patra 2015; Saftner et al. 2015). Accounting these parameters, correlations have been proposed to evaluate in-situ liquefaction characteristics of the soil deposits. Andrus and Stokoe (1997, 2000) established a liquefaction resistance criteria based on the field measurements of shear wave velocity, V_s

and anticipated a relationship between cyclic Resistance Ratio (CRR) and corrected shear wave velocity (V_{s1}) for earthquakes of magnitude 7.5 (Fig. 2.13).

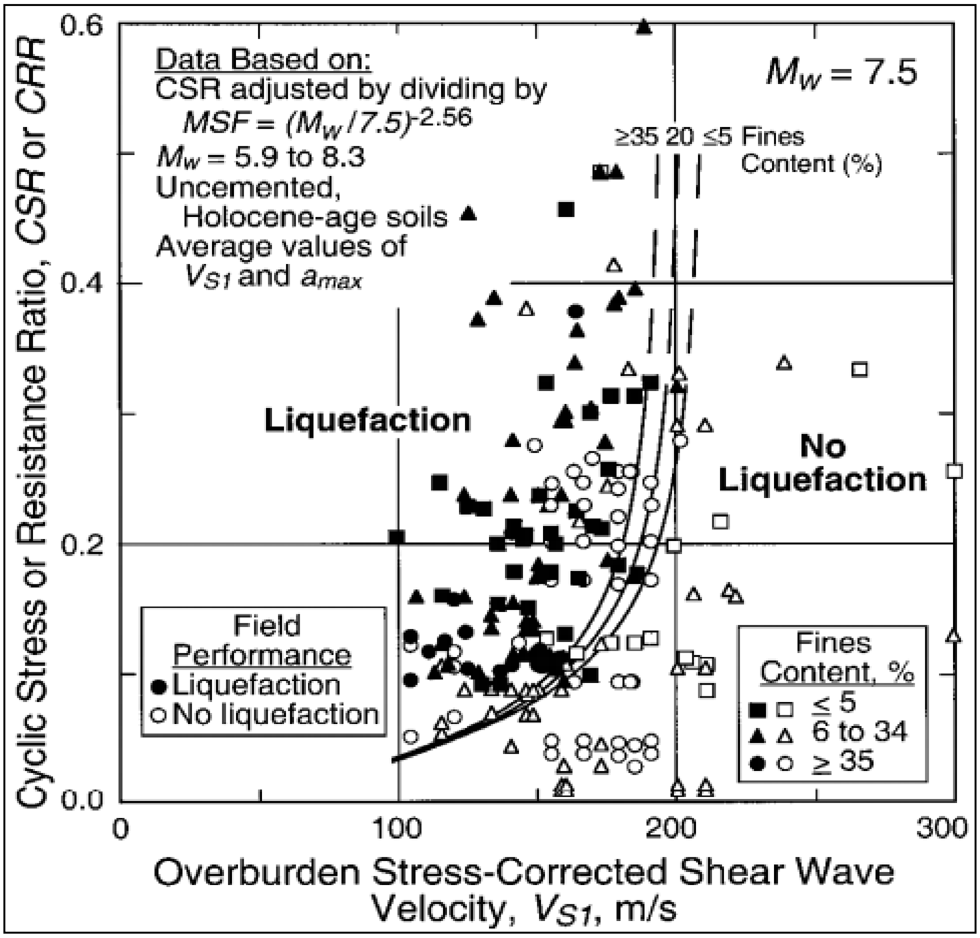


Fig. 2.13 Liquefaction criterion proposed for clean, uncemented soils from compiled case histories (Reproduced from Andrus and Stokoe 2000)

Kayen et al. (2004) compiled a database of in situ shear wave velocity measurements which were made by employing surface wave techniques at over 300 liquefaction and non-liquefaction sites around the world. Later, Kayen et al. (2013) updated this global database to include 422 cases of Vs liquefaction performance shown in Fig. 2.14. This enhanced database assists engineers in estimating the likelihood for liquefaction in specific sites, but it still needs to be expanded to encompass more soil types and sites

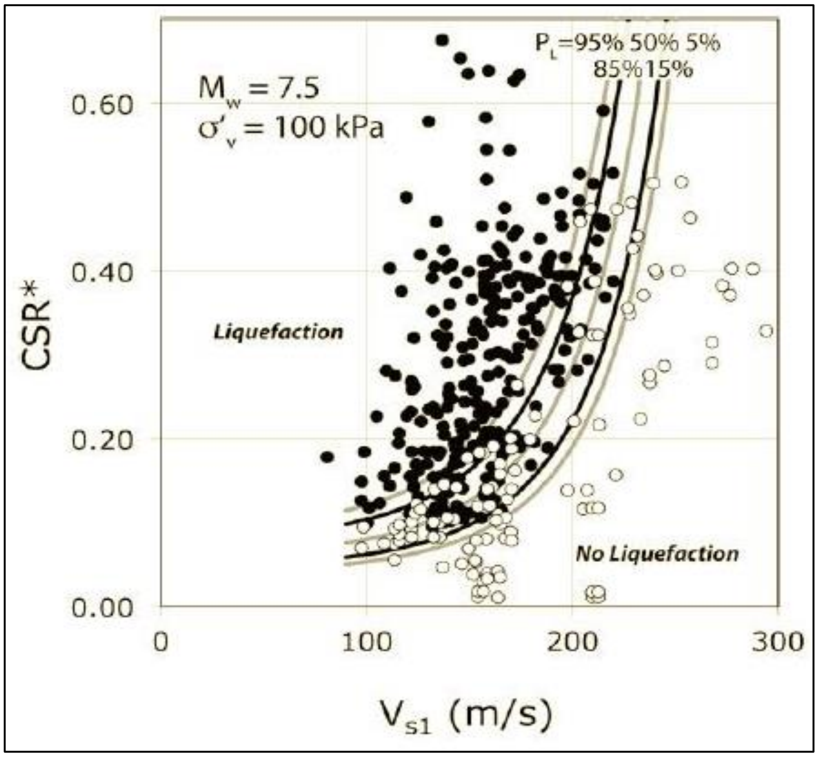


Fig. 2.14 Plot showing means of field case histories of liquefaction (solid circles) and non-liquefaction (open circles) and new probabilistic curves (Kayen et al. 2013)

. Heidari and Andrus (2011) and Maurer et al. (2013) developed liquefaction probability curves using a parameter called Liquefaction Potential Index which could anticipate the liquefaction occurrence under given conditions. However, the efficacy of this method was useful in predicting moderate-to-severe liquefaction manifestations, but the method was not much efficient for less severe liquefaction manifestations. Although, the existing correlations are limited to the natural deposits and its applicability for artificial fills can be too conservative. Wichtmann et al. (2019) developed a correlation between the liquefaction resistance of sands in spreader dumps of an opencast mines with CPT tip resistance and shear wave velocity shown in Fig 2.15.

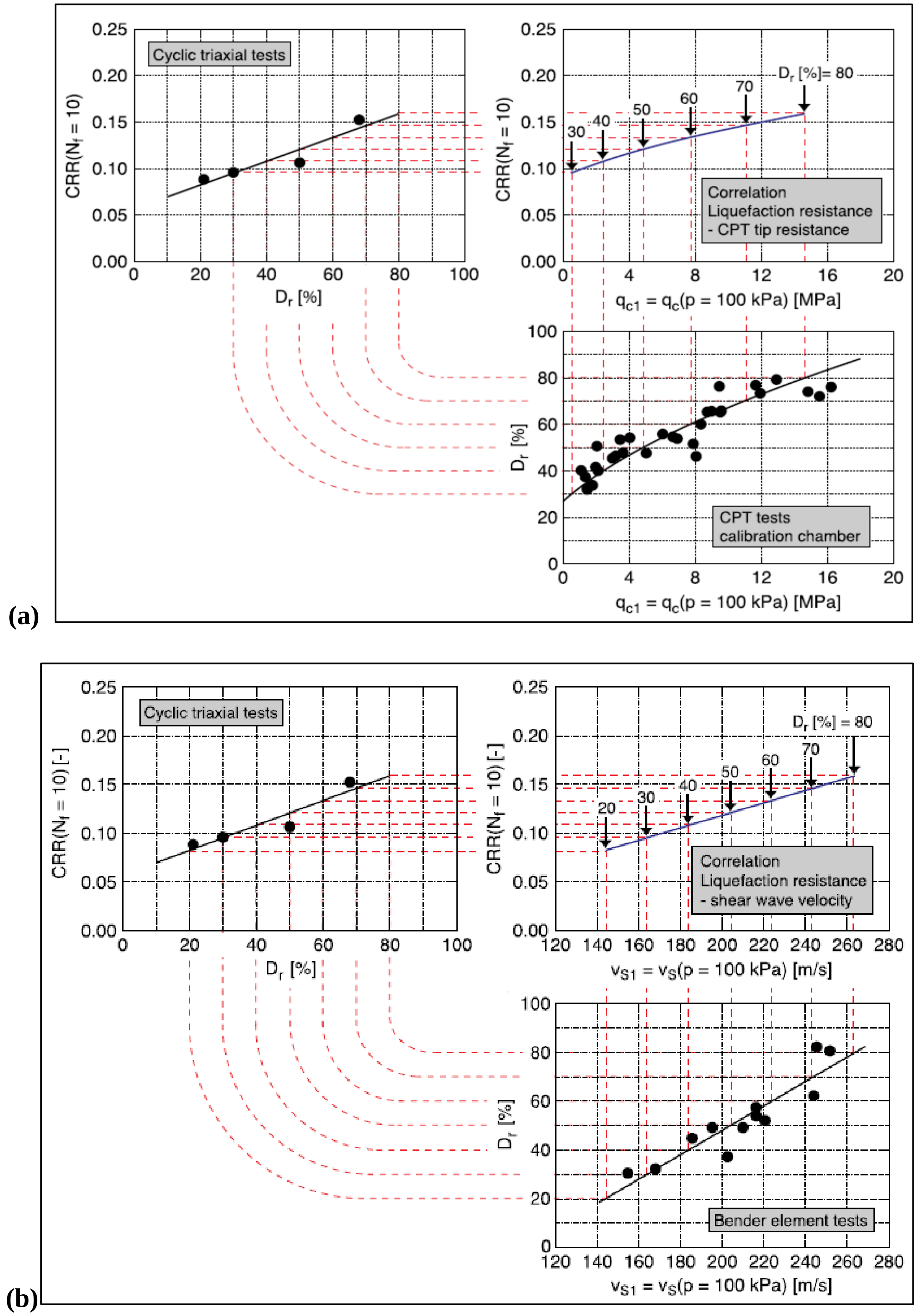


Fig. 2.15 Development of correlation between (a) CPT tip resistance and (b)shear wave velocity and liquefaction resistance of artificial sand fill (Wichtmann et al. 2019).

2.4 Dynamic Response of Hydrocarbon Contaminated Sands

Though numerous studies have been reported on liquefaction studies on various geomaterials as mentioned in table 2.1, limited number of studies reported the liquefaction mechanism and its mitigation in hydrocarbon contaminated soils. In practical scenario, where soil contamination has become a major issue of concern, it is mandatory to emerge out with techniques to remediate such contaminated sites and at the same time ensuring its environmental friendliness and sustainability.

From the literature available (Ho et al. 2011; Naeni and Shojaeddin 2014), it was seen that the presence of crude oil in the pore spaces have caused reduction in liquefaction potential initially but further increase in oil content drastically increased the liquefaction problems by increasing the mobility of the soil grains (Fig. 2.16).

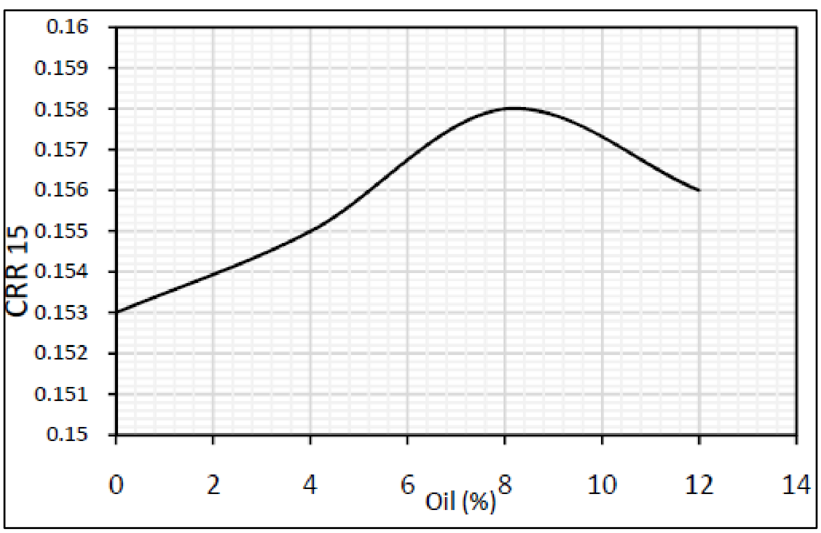


Fig. 2.16 Effect of oil content on cyclic resistance of sandy soil (after Naeni and Shojaedin. 2014)

It was also reported that huge damage was experienced during earthquakes experienced in Kettleman North Coalinga (1983) and Dome Oil Field, California (1985) and recently in

Bushehr, Iran (2014). Ho et al. (2011) compared the liquefaction potential of crude oil contaminated Li-Kang sand and sodium carboxymethyl cellulose (CMC) stabilized sand and reported a significant improvement in the cyclic resistance. Investigation of the effect of silt content on the liquefaction potential of oil contaminated Firouzkooh sand done by Naeni et al. (2019) reported a threshold silt content of 35 % upto which the liquefaction potential increases with increase in silt content while the trend gets reversed when silt content exceeds the threshold content. Pre and post cyclic behaviour of clayey soil contaminated with crude oil was studied by Hosseini et al. (2018) which revealed that the deformation modulus reduction was considerably more than reduction of shear strength due to oil contamination. Further, Hoesseni et al. (2019) also analyzed the elasto-plastic characteristics of gasoil containing clayey soil using cyclic triaxial apparatus. The study revealed that while gasoil contamination reduces the elastic properties of clayey soil, plastic strains on the other hand increases. This change in behavior implies quick failure of such soils under repeated loadings.

Hydrocarbon contamination may also induce microstructural changes in soil which may directly affect its response at the macroscale. One such response is propagation of shear waves through the soil matrix. The experimental endeavours conducted by Rajabi and Sharifipour (2017a) and Rajabi and Sharifipour (2017b) aimed to assess the effect of hydrocarbon on the shear wave velocity and maximum shear modulus of Firoozkooh sand (Fig. 2.17). Two critical oil contents were established. Upto first critical content there is a moderate increase in V_s. Beyond this amount, adding further crude oil upto second critical content decreases V_s and soon after exceeding the second critical content, the change becomes insignificant

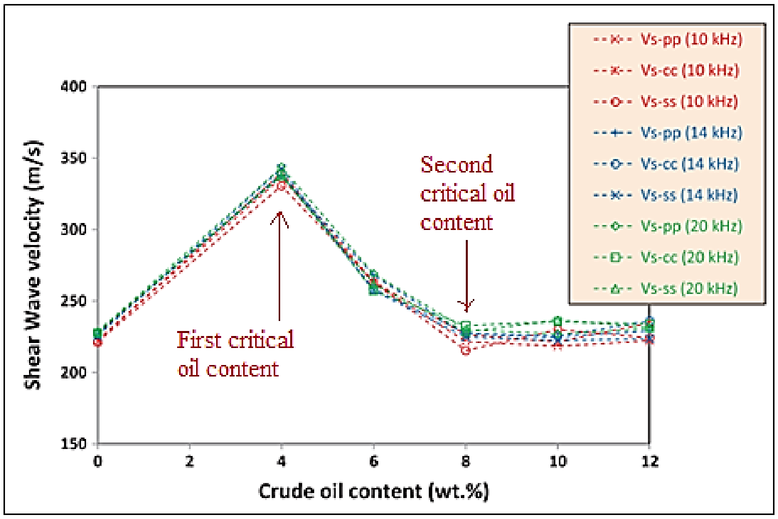


Fig. 2.17 Shear wave velocity (m/s) of clean and crude oil contaminated firoozkooh sand (Rajabi and Sahrifipour 2017b)

2.5 Liquefaction Mitigation Strategies

With the evolution in science and technology, new methods to mitigate liquefaction have been developed. It is required to review the recent developments in the liquefaction countermeasures to offer a quick reference for researchers and engineers as they encounter new engineering problems quite often. In general, liquefaction can be inhibited either by slowing down the rate of development of positive pore pressure or by increasing the rate of dissipation of pore pressure. Based on these two criteria, liquefaction mitigation techniques can be segregated into five categories namely (i) Soil densification (Compaction pile, Dynamic Compaction etc.), (ii) Soil replacement (Vibro-replacement, replacement of poor soil with more competent material, etc.) (iii) Soil Stabilization (permeation grouting, jet grouting, biocementation, etc.) (iv) Desaturation and (v) Drainage enhancement (PV Drains).

2.5.1 Densification

The efficacy of dynamic compaction in inhibiting the liquefaction manifestations has been well documented by several researchers (Kumar and Puri 2001; Zou et al. 2005; Feng et al.

2013; Brik and Robertson 2018). Simpson and Ronan (2008) showed that the Rapid impact compaction treatment was efficient in reducing the likelihood of liquefaction of the granular fill beneath the groundwater table by improving its tip resistance which was measured through CPT. Likewise, Shen et al. (2018) evaluated liquefaction probability considering the two aspects: the increase in the soil strength due to dynamic compaction and minimizing the variation in the soil strength. However, the use of stone columns has been the most widely accepted technique against liquefaction. It was initially started by Seed and Booker (1977) followed by number of researchers (Ishihara and Yamazaki 1980; Boulanger 1998; Adalier and Elgamal 2004). Krishna (2011) did extensive research on the various design concepts and the installation methods on the granular piles and assessed their respective efficiency in mitigating liquefaction hazards. Dense granular columns lead to a significant reduction in cyclic stress ratio as reported by Rayamajhi et al. (2016).

Shake table test conducted by Huang et al. (2016) revealed that among the three factors i.e. densification of nearby soils, drainage around the stone column and reduction in total cyclic shear stress, on which the efficacy of stone columns for mitigating liquefaction depends, the first factor i.e. densification seemed to be the most prominent one. In order to enhance the stiffness, drainage and to control lateral deformations geosynthetic encased stone columns were introduced (Tang et al. 2015; Geng et al. 2016; Vytiniotis et al. 2017). Prediction of the response of soil using finite element approach (Selcuk and Kayabali 2015; Tang et al. 2016; Rayamajhi et al. 2013) showed that the pore pressure ratio within the influence area of stone columns gets reduced due to densification effect (Fig. 2.18).

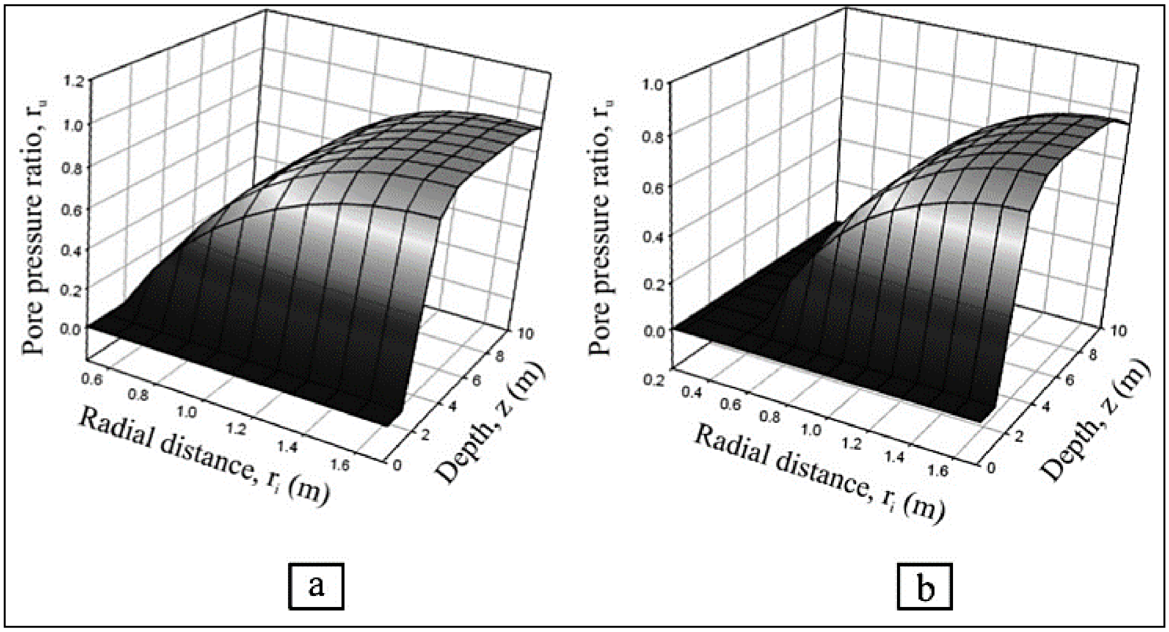


Fig 2.18 Effect of soil densification on pore pressure distribution(a) No densification effect (b) Densification effect included (after Selcuk and Kayabali 2015)

Likewise, Bahmanpour et al. (2019) investigated the effect of deep mixed columns on the liquefaction response of soil in shaking table experiment. It was indicated that deep mixed columns can considerably decrease the extent of liquefaction.

2.5.2 Soil Reinforcement

Reinforcement to the soil as a countermeasure against liquefaction can be imparted in the form of natural or synthetic fibers or through geosynthetics. Inclusion of fiber/mesh elements improves the cyclic strength of geomaterials significantly and arrests liquefaction manifestations even in loose samples with low confining pressures (Boominathan and Hari 2002). A similar type of work has been reported by several other researchers also (Liu et al. 2011; Noorzad and Amini 2014; Chegenizadeh et al. 2018). Alternatively, a number of studies (Table 2.3) have been performed on geosynthetic reinforced soils and it has shown promising results in arresting liquefaction.

Table 2.3. Overview of past studies with geosynthetics as a liquefaction countermeasure

Author(s)	Soil Type	Reinforcement Technique	Testing Method	Laboratory Findings
Altun et al. (2008)	Toyoura sand	Woven and non-woven geotextile	Cyclic torsional shear tests	Geotextile reinforcement significantly improves the cyclic resistance of sand
Hataf et al. (2010)	Sand	Geogrid and Grid Anchor	Model study with a hydraulic actuator giving cyclic loads	Geogrid and grid-anchor reduces the amount of permanent settlement as well as the number of cycles required to reach it.
Maheshwari et al. (2012)	Solani sand	Geosynthetic fiber, geogrid sheet, and natural coir fiber	Shake table tests	The reinforcements were very efficient in enhancing cyclic resistance of sand.
Indraratna et al. (2013)	Coal fouled ballast	Geogrid	Track process simulation apparatus	Geogrid provides additional internal confinement and particle interlocking at the interface between ballast and sub-ballast layer, which reduces deformation.
Mittal and Chauhan (2013)	Solani Sand	Uniaxial geogrid	Shake table test	Geogrid reinforced sand did not liquefy under seismic loading.
Latha and Varman (2016)	Fine Sand	Woven geotextile	Large scale triaxial apparatus	Compared to the unreinforced sand, reinforced samples exhibited substantially higher dynamic moduli.
Vijayasri et al.(2016)	Pond Ash	Woven geotextiles	Strain-controlled cyclic triaxial tests	Geotextile reinforcement in pond ash samples results in improved friction angle, drainage properties, and liquefaction resistance.
Khosravi et al. (2016)	Soft Clay	Soil-cement grids	Centrifuge test	The dynamic performance of soil-cement grids gets improved significantly due to internal interactions between the grids and enclosed soils.

2.5.3 Mixing of Fines

2.5.3.1 Non-plastic fines

Since fine-grained soils are resistant towards developing high pore water pressure, hence it can be expected that mixing of fines may reduce the liquefaction potential of host sands (Chang et al. 1982; Troncoso 1990; Koester 1993; Vaid 1994; Singh 1996; Thevanayagam et al. 2000). For sand-silt mixtures, comparison of liquefaction behavior of clean sand and silty sand based on global void ratio was found to be inappropriate as at the same global void ratio, they do not necessarily have the similar intergrain contact density. As such, the concept of equivalent inter-granular void ratio was suggested by Thevanayagam et al. (2016). Void ratio indices equivalent to the contact density (e_c) have been expressed in equation (2.3) and equation (2.4) depending on the silt content (f_c) of the soil relative to a threshold value (FC_{th}) (Thevanayagam and Martin 2002).

$$(e_c)_{eq} = \frac{[e+(1-b)f_c]}{[1-(1-b)f_c]} \qquad [f_c < FC_{th}] \tag{2.3}$$

$$(e_c)_{eq} = \frac{e}{[f_c+(1-f_c)R_d^m]} \qquad [f_c > FC_{th}] \tag{2.4}$$

where f_c is the fine content by weight, R_d is the ratio of the D_{50}'s of the host sand and silt in the soil mix; b and m are soil parameters (Kanagalingam and Thevanayagam 2006) which are a function of the grain size characteristics of the soils.

The liquefaction resistance of sands after mixing it with different amount of non-plastic fines was evaluated by Xenaki and Athanasopoulos (2003) through conducting a series of cyclic triaxial tests. The evaluation was done with respect to the global void ratio and also with respect to the intergranular and the interfine void ratios. Karim and Alam (2014) defined a limiting silt content up to which the liquefaction potential was reduced with an increase in silt content and a reverse behavior was observed when silt content exceeded the limiting value. (Fig. 2.19).

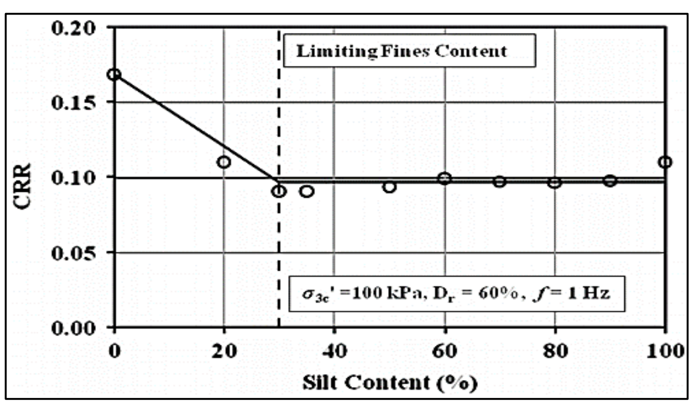


Fig 2.19 Variation of cyclic resistant ratio (CRR) with silt content (after Karim and Alam 2014)

2.5.3.2 Plastic fines

Apart from fine content, undrained behavior of sands mixed with plastic fines is also a function of several other parameters like plasticity of fines, clay mineralogy, pore water chemistry, etc. (Prakash and Sandoval 1992; Georgiannou et al. 1991; Gratchev et al. 2007). Clay-sized (0.002 mm) plastic fines can significantly improve the cyclic resistance of cohesionless soil (Dimitrova and Yanful 2012; Ku and Juang 2012; Kumar et al. 2013). Abedi and Yasrobi (2010) determined a threshold value of 10% clay content below which the liquefaction resistance reduces with increasing clay content, while an opposite trend was observed beyond this value as shown in Fig. 2.20.

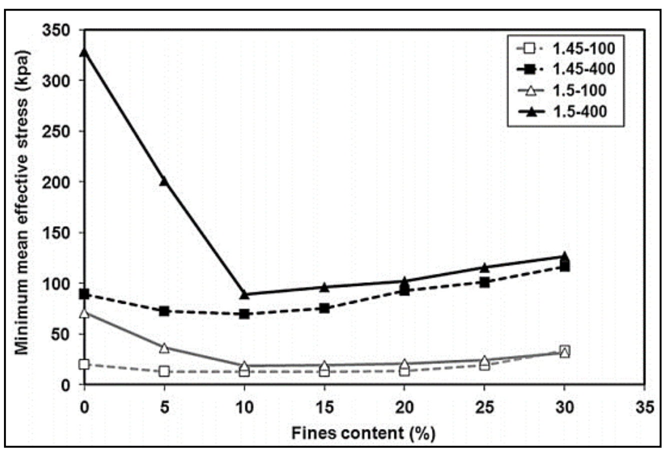


Fig. 2.20 Effect of fine content on the minimum mean effective stress of the specimens (after Abedi and Yasrobi 2010)

Studies conducted on cyclic behavior of cement treated soil (Abu-Farsakh et al. 2015; Suazo et al. 2016) revealed that higher levels of cementation increased the shear strength as well as liquefaction resistance of the soil. Different γ–N paths were obtained for different cement content and curing period (Fig. 2.21).

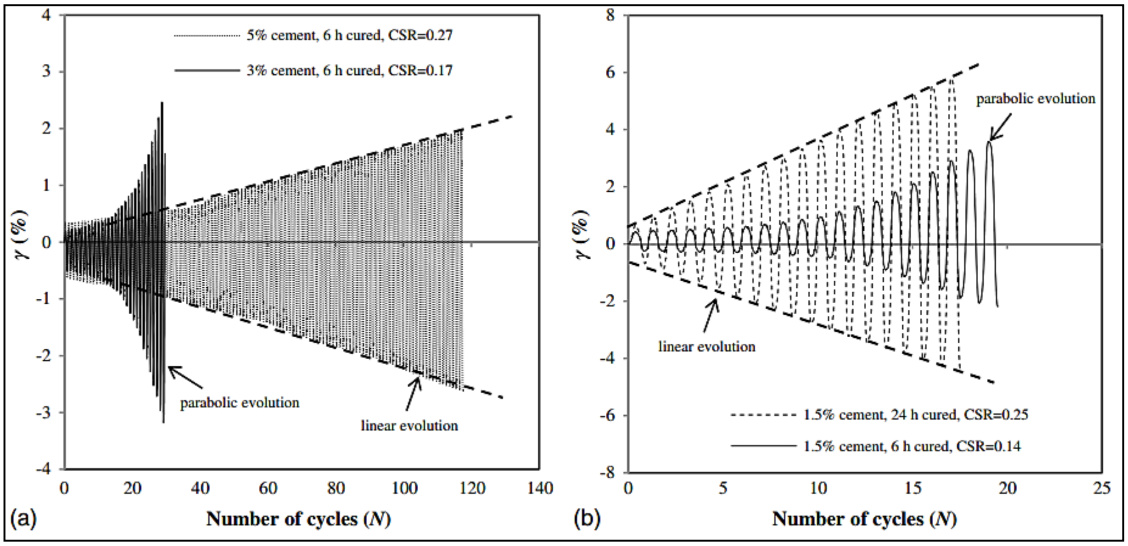


Fig. 2.21 Shear strain (γ) versus number of cycles (N) evolution of samples prepared at (a) different cement contents; (b) different curing ages (after Suaozo et al. 2016)

2.5.4 Application of waste materials

The likelihood of providing a more sustainable solution in the field of liquefaction mitigation studies increases with the amalgamation of multidisciplinary efforts and new environmental friendly technologies. As such, the potential of new and recycled materials have begun to be studied as a potential alternative to mitigate liquefaction. An alternate environmental friendly soil stabilizer lignosulfonate (LS), a by-product from timber industry, was efficient for treating fine sandy silt (Chen et al. 2014) and in comparison to traditional chemical admixtures it is cost-effective, environmental-friendly and does not appreciably change the pH level of soil after treatment. Fig. 2.22 shows the positive effect of lignosulfonate on the developed plastic axial strain and excess pore water pressure.

Among recycled materials, tire chips and biochar are good alternatives that help to manage waste. Tire chips have been used as a means of damping (Kaneko et al. 2013) and drainage (Edil et al. 2004; Hazarika et al. 2008; Hazarika et al. 2010). Results from cyclic undrained tests performed by Towhata (2008) on a mixture of tire chips and sand showed that the liquefaction resistance of sand was improved by the inclusion of tire chips. Yasuhara et al. (2010) compared three testing conditions namely pure sand, sand with gravel drain, and sand with tire chips drain. It was evident that tire chip drain accelerates the rate of dissipation of excess pore pressure, thereby enhancing the liquefaction resistance.

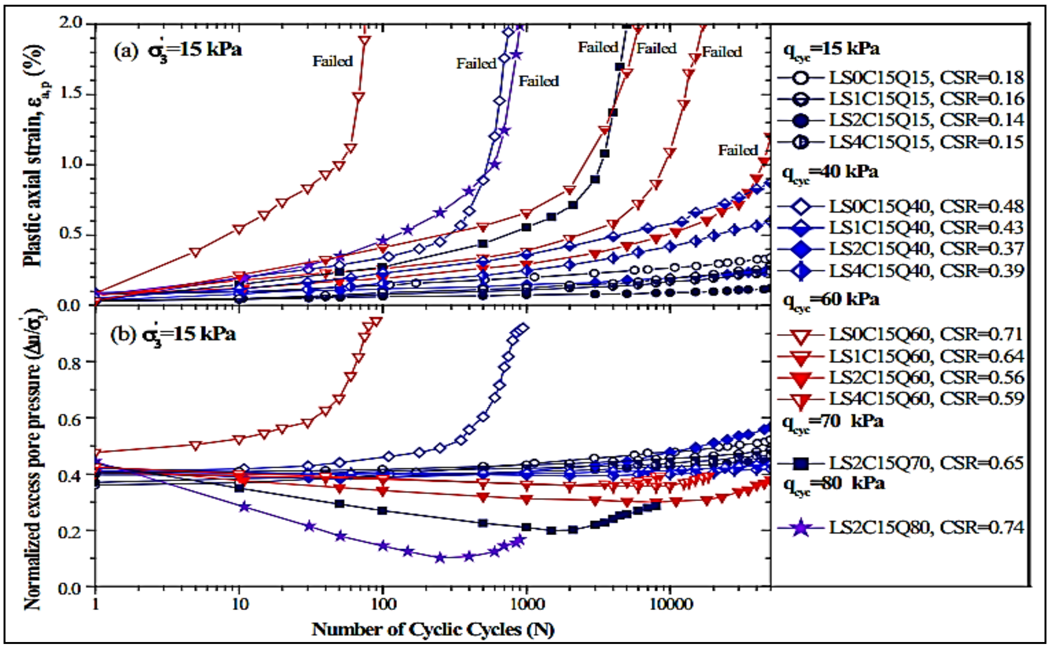


Fig. 2.22 Effect of LS content on the undrained behavior of sandy silt under various loading conditions as a function of the number of cycles when σ_3 ' = 15 kPa; (a) plastic axial strain; (b) normalized excess pore pressure (after Chen et al. 2014).

Fuchiyama and Konja (2016) examined the effect of tire chips mixed with pure sands in undrained cyclic triaxial conditions. Results demonstrated that there was hardly any development of pore water pressure resulting into a non-liquefaction condition. Pardo and Orense (2016) tested pure sand and dry sand mixed with 0%, 3.0% and 5.0% biochar by weight under monotonic loading followed by undrained cyclic shearing by a simple shear test apparatus and indicated that biochar improved the cyclic resistance.

2.5.5 Bio-cementation

Bio-cementation is a trending technique which utilizes microbially (denitrifying bacteria) induced formation of carbonate precipitation (MICP) (DeJong et al. 2006; Al-Thawadi 2008). The method involves chemical reactions between the injected nutrients along with $CaCl_2$ and urea in the presence of denitrifying bacteria. The reaction occurs as per equation (2.5) and (2.6) Ng et al. (2012).

$$CO(NH_2)_2 + 2H_2O \longrightarrow 2NH_4^{+} + CO_3^{2-} \quad (2.5)$$

$$Ca^{2+} + CO_3^{2-} \longrightarrow CaCO_3(s) \quad (2.6)$$

Similar types of results were quoted by Cheng et al. (2014) in which microbial grouting efficiently increased liquefaction resistance. The degree of mitigation achieved was found to be dependent on the yield of calcium carbonate. Higher yield of calcite crystals causes blocking of the pores thereby densifying the soil matrix. Gomez et al. (2014) presented a field scale application of MICP technique to improve soil characteristics. However, culture of urease active bacteria requires a highly controlled environment to achieve higher yield. Therefore, it may be possible to use enzymatic (urease) induced calcite bio-mineralization process (Carmona et al. 2016; Zhao et al. 2016).

Fig. 2.23 shows the generation of excess pore water pressure versus loading cycles in MICP treated sand with varying percentages of cementation solution (CS) presented by Xiao et al. (2018). For each case N_L denotes the number of cycles to liquefy. It can be clearly observed that the bio-cementation reduces the generation of excess pore water pressure as well as the number of loading cycles required for sand to liquefy.

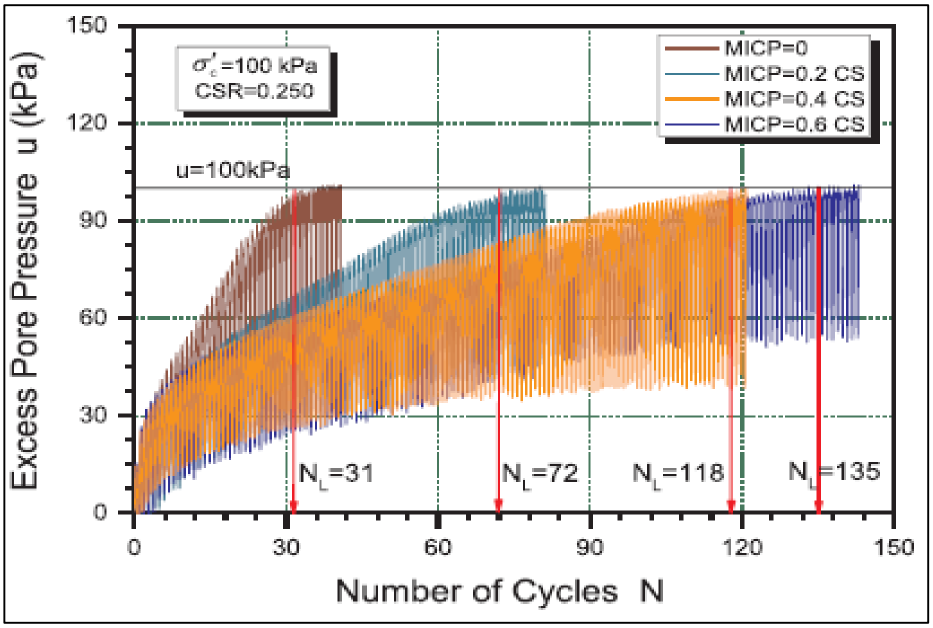


Fig. 2.23 Effect of bio-cementation on the development on excess pore water pressure under constant confining stress and cyclic stress ratio (after Xiao et al. 2018)

2.5.6 Induced Desaturation

Mitigation mechanism through this technique involves arresting the development of pore pressure by reducing the degree of saturation of soil mass. This reduction can be achieved by air injection, water electrolysis, microbial desaturation or any other chemical methods.

Yegian et al. (2007) induced partial saturation in various soil specimens using electrolysis process. Results from the simple cyclic shear tests performed by Eseller-Bayat et al. (2013) showed that a small amount of desaturation leads to a significant increase in liquefaction resistance. Wu and Sun (2013) gave an S-shaped graph showing critical condition for liquefaction for silts at varying degree of saturation. Silts below 60% saturation level did not liquefy at all. Likewise, Gao et al. (2013) carried out numerical simulation based on the Biot consolidation theory to evaluate liquefaction potential of soils at varying levels of saturation. Microbial desaturation was yet another technique whose performance was evaluated by He et al. (2013) using shaking table model tests. It was observed that a slight reduction in degree of saturation led to a considerable reduction in the generation of excess pore water pressure (Fig. 2.24).

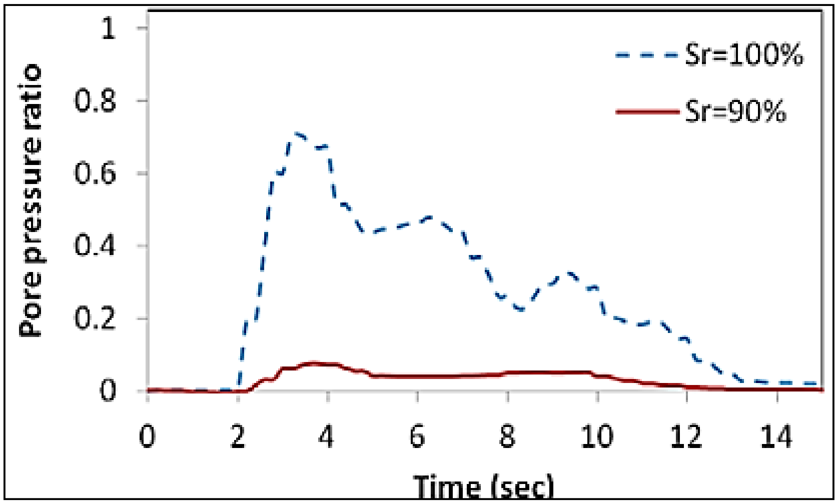


Fig. 2.24 Seismic response of saturated and desaturated sands under a_{max}= 1.5 m/s (after He et al. 2013)

2.5.7 Passive Site Remediation

Traditional densification methods to mitigate liquefaction problems involve high energy consumption, high costs and challenging to implement at already developed sites. To overcome such problems Gallagher (2000) introduced the concept of passive site remediation for treating liquefaction prone grounds with minimal disturbance to the existing structures.

2.5.7.1 Colloidal Silica Grouting

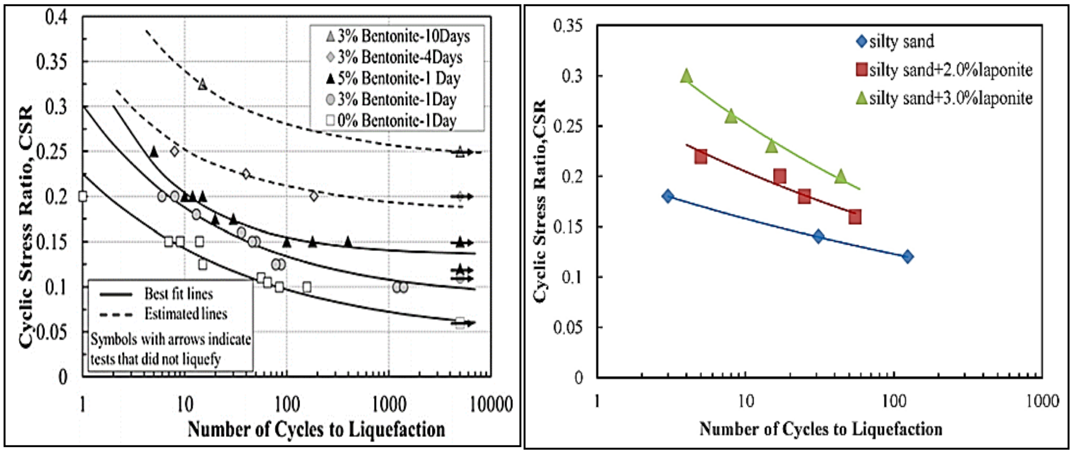
Gallagher and Mitchell (2002) applied the method of injecting a colloidal silica grout of low viscosity into the liquefiable ground which later on transforms into thick viscous cement-like material, thus strengthens the bond between the soil grains. Also, the viscosity of grout reduces the hydraulic conductivity and thereby contributes to mitigation process (Rodríguez et al. 2008; Conlee et al. 2012; Hamder et al. 2014). The gelation time of the silica grout can be altered by adjusting the pH of the colloidal solution (Rasouli et al. 2016). Gallagher et al.

(2007) gave a detailed mechanism of the liquefaction mitigation phenomenon using colloidal silica grouting.

2.5.7.2 Grouting using Nanomaterials

Despite of improving the soil liquefaction resistance significantly, colloidal silica grouts have limited applicability. It cannot penetrate deep into the soil at low pressures and is also not suitable for fine soils. Bentonite suspension grouting can be used instead whose principle is similar to that of colloidal silica grouting (Rugg et al. 2011). However, it is worth noticing that the principle behind the mitigation using fine grains and bentonite suspension grouting are not the same. In case of bentonite suspension grouting, an elastic restraint is provided to the sand grains which allows the formation of excess pore water pressure only above an elastic threshold (El Mohtar et al. 2008). El Mohtar et al. (2012) studied the effect of bentonite concentration and curing period on the generation of excess pore water pressure in silty sand (Fig. 2.25(a)). It was seen that the effect of permeation pressure on the cyclic behavior of sand was not significant. On the other hand, the amount of fine grains has a considerable effect on the liquefaction mitigation beyond a threshold value (Bayat et al. 2014).

Laponite is yet another alternative whose particle size is almost $1/10^{th}$ of that of bentonite. Howayek et al. (2014) provided SEM imagery of sand-laponite suspensions which highlights their long elongated column-like structure shown in Fig. 2.26(a). This type of structure helps in bridging the voids between the individual grains as shown in Fig. 2.26(b). Their high permeating power is a major advantage for almost all kinds of soils. Moreover, its high environmental friendliness and low cost/performance ratio make it an overall versatile stabilizer.



(a) **(b)**

Fig. 2.25 Cyclic response of (a) bentonite treated soil (after El Mohtar 2012) (b) Laponite treated soil (after Huang and Wang 2016)

Despite of having such major advantages over traditional grouts, only a handful of work has been conducted on studying its cyclic characteristics. Huang and Wang (2016) studied the role of laponite in mitigating the liquefaction phenomenon in silty sands by means of cyclic triaxial apparatus. As can be seen from Fig. 2.25(b), a little amount of laponite may increase the CSR to a great extent.

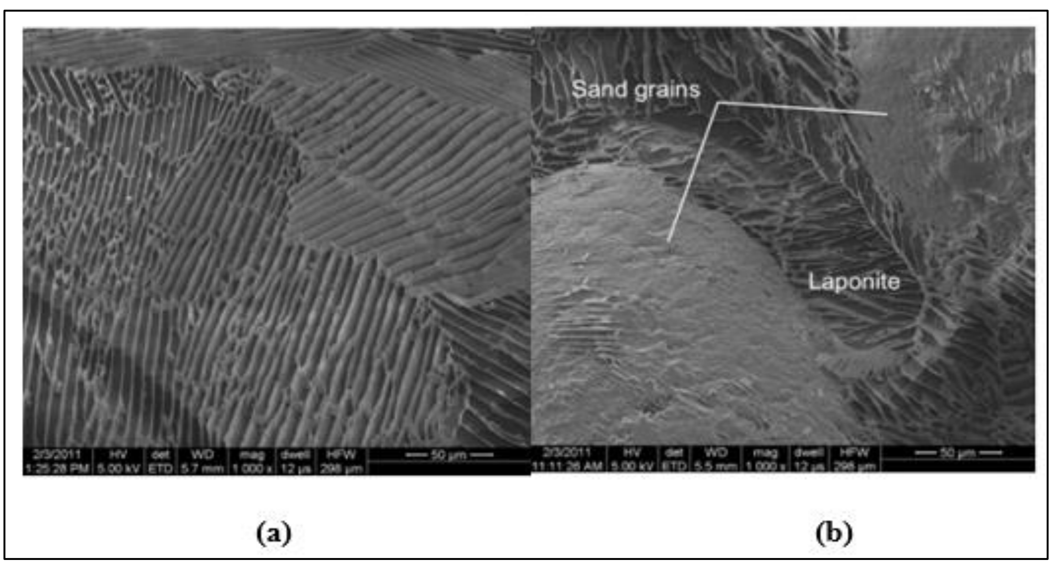


Fig. 2.26(a) Microstructure of Sand-Laponite suspensions (b) 3% laponite permeated specimen at 1000x magnification (after Howayek et al. 2014).

Taking into account several liquefaction mitigation techniques that has been recapitulated, table 2.4 shows their evolution over the past decade.

Table 2.4 Evolution of liquefaction mitigation techniques in recent years

S.No.	Reference(s)	Type of Soil	Technique Employed
1.	Shen et al. (2019)	Sand deposits	Dynamic Compaction
2.	George et al. (2019)	Fine sand strata	Sand Columns
3.	Zhao et al. (2016)	Fine grained silica sand	Hydrogel-EICP composite
4.	Pardo and Orense (2016)	Waikato river sand	Stabilization using biochar
5.	Carmona et al. (2016)	Poorly graded sand	EICP
6.	Thevanayagam et al. (2016)	Silty sand	Dynamic Compaction and Stone Columns
7.	Traylen et al. (2016)	Silty sand	Polyurethane grout injection
8.	Huang and Wang (2016)	Silty sand	Dry mixing of laponite as well as injecting laponite suspension
9.	Shifan Wu (2015)	Sand	Combined bio desaturation and bio clogging
10.	Hong et al. (2015)	Clean sand F_c< 6%	Stabilization using tire chips
11.	Khosravi et al. (2016)	Soft clay	Reinforcement using soil-cement grids
12.	Suazo et al. (2016)	Fine-grained tailings	Cemented paste backfill
13.	Vijayasri et al. (2016)	Pond ash	Geotextile reinforcement
14.	Rasouli et al. (2016)	Alluvial sandy soil	Permeation grouting of silica using controlled curved drilling technique
15.	Latha and Varman (2016)	Fine sand	Geotextile reinforcement
16.	Liu and Jeng (2015)	Marine sediments (Clayey sand)	Mixing with clay content
17.	Chen and Indraratna (2014)	Sandy silt	Stabilization with Lignosufonate
18.	Noorzad and Amini (2014)	Babolsar sand	Inclusion of Fiber
19.	El Mohtar et al. (2013)	Ottawa sand	Bentonite Suspensions with Sodium Pyrophosphate

Table 2.4 Continued

S.No.	Reference(s)	Type of Soil	Technique Employed
20.	Wang et al. (2012)	Expansive soil	Lime treatment
21.	Conlee et al. (2012)	Loose sand	Colloidal silica stabilizer
22.	Hataf et al. (2010)	Sand	Grid anchor and geogrid reinforcement
23.	Abedi and Yasrobi (2010)	Poorly graded sand	Mixture of bentonite and natural fines in varying proportions
24.	Ho et al. (2011)	Crude oil contaminated sand	Stabilization with carboxymethyl Cellulose (CMC)
25.	Thawadi (2008)	Sand	Microbially Induced Calcite Precipitate (MICP)
26.	Yegian et al. (2007)	Loose sand	Induced Partial Saturation

2.6 Summary

The chapter has outlined the major developments in the field of liquefaction studies and its mitigation techniques. Although the researchers have witnessed a great advancement in this particular filed, there are still some lacunae which needs to be addressed further. Extensive research has been conducted on evaluating the potential of sands to liquefy but it is worth noticing that the susceptibility to liquefaction has not just been confined to sands. There are numerous other materials such as flyash, pond ash, mine tailings, clays etc. that may also experience liquefaction under certain specific conditions when used as geomaterials. The basic mechanism involved behind the liquefaction manifestations is that the rate of generation of excess pore water pressure should be significantly greater than the rate of dissipation of excess pore water pressure.

Various mitigation techniques that are in practice have also been taken up for a detailed discussion. Many of the methods mentioned above are currently at the experimental stage. Dynamic compaction, vibro-floatation, stone columns, etc. have been popular and extensively employed techniques. However, these techniques are not suitable for already developed sites as they cause excessive disturbance to the existing structures. With rapidly developing infrastructures, it is rarely possible to get a bare site for new constructions. In such scenarios, passive site remediation can be considered as an all safe solution. The performance of a grout is judged by considering its, (1) ability to penetrate into the soils, (2) environmental friendliness and (3) Cost/Performance ratio. Traditional grouts usually involve heavy machinery and energy-intensive processes which may result in excessive carbon footprints. Also, they are not able to penetrate deeper into the soils due to their size constraints. Many researchers have brought nanoparticles into practice like laponite, owing to their extremely small size and hence their versatility to treat almost all types of soils. Bio-cementation and desaturation techniques still require further work and evaluation. It is expected that the bio-cementation technique has a great potential to be an environmental-friendly and a sustainable technique to counter the liquefaction phenomenon in the field. Additionally, there have been several severe oil spills around the globe which have contaminated the land resources and posed a threat of unsafe construction practices. The average numbers of pipeline spills are increasing significantly. Apart from this, other sources like oil-based drilling muds, industrial effluents etc. also add on to this problem and has jeopardized the quality of a vast amount of land area globally. Despite 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. Moreover, many of these contaminated sites lie in the high-risk seismic zones which attenuate the complexities in the existing problems. Only a handful of research has been taken up in this concern and it leaves a vast scope of further investigating these materials. Fig. 2.27 presents a research framework linking the existing research topics to the recommended future research directions.

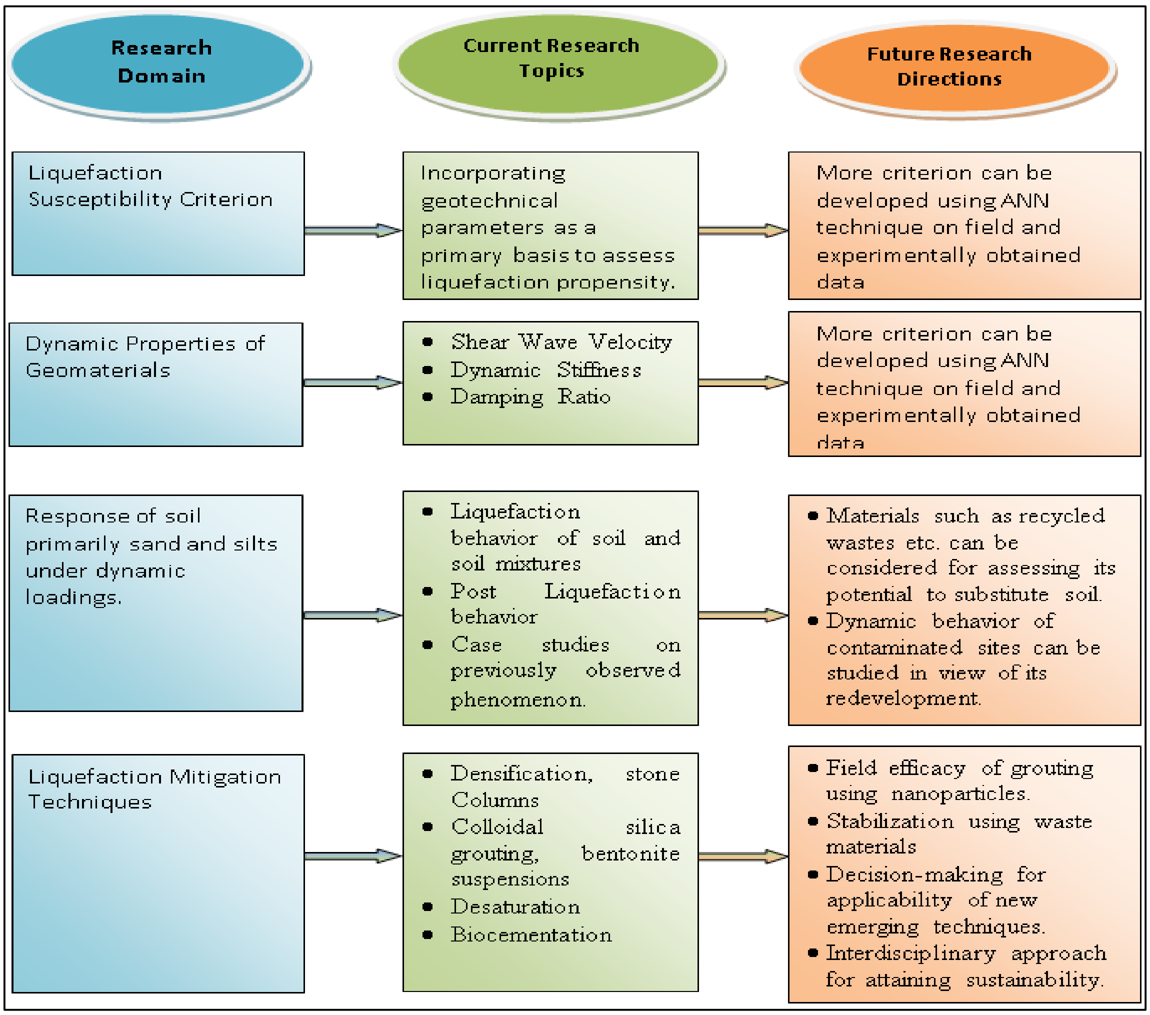


Fig. 2.27 Research framework linking existing research topics in liquefaction to future research directions