

Approaches to the Estimation of Soil Liquefaction Potential in South and Southeast Asian Countries: A Review

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ABSTRACT: Liquefaction is a natural phenomenon that occurs during an earthquake when there is excessive pressure of pore water and a drop in effective stress. Granular soils undergo liquefaction, transforming from a solid to a liquid state, and this is one of the main hazards to constructed infrastructures. The main causative parameters controlling the potential to liquefy of the ground are the geotechnical characteristics of the soil layers. Therefore, it is crucial to evaluate the liquefaction potentials in areas where granular soil is prone to liquefaction. The liquefaction potentials can be calculated through both experimental and numerical methods. In the experimental technique, laboratory tests, including cyclic simple shear, cyclic triaxial, and cyclic torsional shear, as well as field techniques such as the Standard Penetration Test (SPT), Cone Penetration Test (CPT), and Shear Wave Velocity (V_s), are utilized. In this study, we reviewed and analyzed the evaluation of the liquefaction potential of the experimental findings using field methods and some laboratory methods, along with software used for modeling, from South Asian nations like Bangladesh, India, Pakistan, Indonesia, Vietnam, and Thailand. Firstly, we described different approaches to evaluate liquefaction potentials; secondly, we discussed the uses of different techniques in various regions of different countries. Lastly, we provided a comprehensive review comparing the techniques utilized by different countries.

KEYWORDS: Liquefaction, Liquefaction Potential Index, Standard Penetration Test, and Cone Penetration Test.

1. INTRODUCTION

An earthquake is a form of natural calamity that happens yearly all over the world. As a result of the rapid transition of sand from a solid to a viscous fluid state, the ground becomes unsafe in this instance. Because of this, the liquefaction of saturated sand has become a crucial topic in soil dynamics (Finn, 1991).

The complex interactions among several large and small plates have given Asia its characteristic tectonic structure. To provide a better understanding of tectonic settings across Asia, this discussion includes data from recent research on seismic ground response, attenuation, liquefaction susceptibility, and site characterization from various regions. Northern Thailand lies in the region covered by the Indo-Australian and Eurasian Plates, which causes frequent earthquakes. For instance, the papers by Mase et al. (2018, 2020) reveal the susceptibility of the region to ground shaking and liquefaction. The research papers by Tanapalungkorn et al. (2020) and Mase et al. (2021) contain valuable information to improve seismic hazard assessment. The location of Bangkok in relation to the Three Pagodas Fault influences the level of seismic effects. The authors (Qodri et al., 2021) demonstrate how fault movement affects the site response. There is a cross-border effect in the two countries' border area between Thailand and Myanmar, as evidenced in the paper of Mase et al. (2022). This research shows that earthquakes in this transboundary zone cause a high level of soil liquefaction; therefore, there is a need for transboundary seismological studies and cooperation. Comparative concepts of liquefaction and ground response are presented by Japan (Osaka), as shown in the research papers by Mase et al. (2022, 2023).

The incorporation of these findings broadens our comprehension of local tectonic environments and improves seismic risk evaluation and mitigation tactics throughout Asia.

When liquefaction-induced damage results from a seismic event, the liquefaction potential index (LPI) is frequently employed to

determine and/or quantify the damage (Karim et al., 2019). According to Luna and Frost (1998), the liquefaction potential index (LPI) assesses the degree of liquefaction and forecasts surface manifestations of liquefaction, liquefaction impairment, or catastrophic risk at a liquefaction-prone location. LPI estimates the likelihood that liquefaction would cause damage at the surface level at the site of interest by combining the depth, thickness, and factor of safety against liquefaction (FS) of soil layers.

According to Iwasaki et al. (1982), liquefaction consequences are notable for $LPI > 15$ and mild for $5 < LPI < 15$. As stated by Toprak and Holzer (2003), $LPI \geq 5$ leads to sand boils, while $LPI \geq 12$ occurs in lateral spreads. Juang et al. (2005) investigated how ground surface damage caused by liquefaction influenced foundations. According to several studies (Iwasaki et al., 1982; Toprak & Holzer, 2003; Holzer et al., 2006), LPI provides an accurate depiction of liquefaction intensity during seismic tremors, and $LPI \geq 5$ is commonly regarded as the threshold for the surface manifestation of liquefaction. Sites with $LPI = 0$ have been deemed by Sonmez (2003) as not likely to liquefy, whereas sites with $0 < LPI < 2$, $2 < LPI < 5$, $5 < LPI < 15$, and $LPI > 15$ were described as having low, moderate, high, or severe liquefaction susceptibility, respectively.

There are two strategies, notably deterministic and probabilistic ones, to estimate the liquefaction potential of sand (Goharzay et al., 2017). The deterministic technique, often known as the stress method, was created by Seed and Idriss (1971) and has since undergone numerous revisions. Cone Penetrometer Test (CPT) and Standard Penetration Test (SPT) liquefaction resistances were correlated, and the factors needed to determine soil liquefaction resistance were identified by Seed and Alba (1985). The CPT, SPT, shear-wave velocity (V_s) measurements, and the Backer Penetration Test (BPT) for gravelly locations are the four field tests that Youd et al. (2001) recommended to measure liquefaction resistance. Three metrics, including the Liquefaction Evaluation Procedure (LEP) (Boulanger

& Idriss, 2014; Polus et al., 1985), the Liquefaction Potential Index (LPI) (Iwasaki et al., 1982; Sonmez, 2003), and the Liquefaction Severity Number (LSN) (Youd et al., 2001), can be used to determine the liquefaction potential of soils.

Through the Factor of Safety against Liquefaction (FSL), LEP can be utilized for forecasting soil liquefaction potential. One of the key benefits of FSL is that it can be used to categorize soils, with soils liquefying if the FSL value is less than 1.0 (Boulanger & Idriss, 2014). Conversely, the drawback of FSL is that it cannot certify that soil is free from liquefaction if the liquefaction potential is greater than 1 (Jha & Suzuki, 2009). The benefit of LPI is that it assigns a single value to the entire soil column as opposed to a number of safety parameters across various layers, and it employs SPT data to categorize the liquefaction potential of geological units (Sonmez, 2003; Sonmez & Gokceoglu, 2005). The more detrimental consequences of shallow liquefaction on dwellings and foundations were represented in LSN (Tonkin & Taylor, 2013). Additionally, LSN employed the volumetric densification strain within the layers of soil as an indicator for how much disruption from liquefaction is anticipated to have occurred at the ground surface (Nu et al., 2020).

Currently, the liquefaction potential of a soil is assessed using various semi-empirical methods that express its liquefaction tendency (Latifi et al., 2023). The loss of life, loss of livelihood, loss of energy, instability of the financial system, and decreased transit connections will all be affected by liquefaction in infrastructure buildings (Kongar et al., 2017). The city of Wajima in Ishikawa Prefecture has been severely affected by liquefaction following the January 1, 2024, M7.6 earthquake in Japan. The terrain has undergone significant alterations due to liquefaction, including warped roadways, slanted or partially buried homes, and bulging manholes (watchers.news, 2024). As a result, it is important to evaluate how field and laboratory findings were interpreted in order to ascertain the likelihood of liquefaction at some Asian nations.

The objective of this article is to review various liquefaction potential computation methods, evaluate the methods used by various nations, compare the results, and give a wide overview. The majority of countries in South Asia employed laboratory testing and SPT-based procedures, but only a small number also added CPT, citing it as more reliable than SPT. The majority of studies used Seed et al. (1971, 1979, 1982, 1983) as a reference for SPT computation. For CPT, the source is Robertson et al. (1988, 2009). To calculate LPI, Iwasaki et al. (1982) was consulted. Out of the 0.15g, 0.28g, 0.16g, 0.18g, and 0.3g, the maximum ground acceleration employed was 0.2g. The magnitude range was 5.5 to 7.5. For liquefaction potential, only three nations used software models, such as PLAXIS and LIQUITER, both 1D and 3D. However, there has been little discussion of potential methods for improving soil quality.

2. APPROACHES FOR COMPUTING LIQUEFACTION POTENTIAL

Liquefaction potential reflects the capacity of soil to withstand seismic stress and is primarily influenced by soil type, particle shape (granulometry), relative density, saturation level, and earthquake magnitude. The findings of in-situ experiments and the monitoring of earthquake history have helped to build semi-empirical methodologies (Latifi et al., 2023). These approaches could be split into three categories as a result:

- 1) Cyclic stress approach;
- 2) Cyclic deformation approach;
- 3) Energy approach

In order to study how soil responds to earthquakes, the assessment of the liquefaction potential was conducted mostly through laboratory studies. As a result, the most popular method for determining the likelihood of liquefaction is in-situ testing. The liquefaction resistance forecast developed by Seed and Idris (1971) is known as the "Simplified Procedure" and is employed worldwide. The process was originally created for the SPT and has undergone many modifications. Two additional techniques have been developed and are currently being used to assess liquefaction resistance, in

addition to the SPT. These tests are the shear wave velocity (V_s) test and the cone penetration test (CPT). The SPT and CPT are the most popular approaches (Youd et al., 2001), and extensive research has been conducted using these tests. Table 1 lists the benefits and drawbacks of each test procedure.

Table 1 Liquefaction analysis in situ test methods (modified from Youd et al. (2001))

Feature	SPT	CPT	V_s
Past measurements at liquefaction sites	Abundant	Abundant	Limited
Type of stress-strain behavior influencing test	Large strain, partially drained	Large strain, drained	Small strain, no excess pore water pressure
Quality control and repeatability	Poor to good	Very good	Good
Detection of variability of soil deposits	Good for closely spaced tests	Very good	Fair
Soil types in which test is recommended	Non gravel	Non gravel	All
Soil sample retrieved	Yes	No	No
Test measures index or engineering property	Index	Index	Engineering

In reality, not only do the static penetrometer test (CPT) and the dynamic penetrometer test (SPT) enable them to collect undamaged specimens, but they also provide information about the mechanical properties of the soil. By measuring the safety factor (F_s), which can be expressed as the ratio of the cyclic resistance CRR to the cyclic stress CSR (Equation 1), they intend to concentrate on the cyclic stress strategy, which depicts the soil response to seismic stimuli (Hossain et al., 2022; Seed & Idris, 1971):

$$F_s = CRR/CSR \quad (1)$$

2.1 Assessing Cyclic Resistance (CRR)

2.1.1 Robertson Approach

The formulation that follows can be utilized for determining the cyclic strength ratio according to Robertson and Wride (1998) (Robertson & Wride, 1998; Latifi et al., 2023) methodology:

$$S_i \ 50 \leq (q_{c1N}) < 160: \ CRR = 93 [(q_{c1N})_{cs}/1000]^3 + 0.08 \quad (2)$$

$$S_i \ (q_{c1Ncs}) < 50: \ CRR = 0.833 [(q_{c1N})_{cs}/1000]^3 + 0.05 \quad (3)$$

With $(1N)_{cs}$ the clean sand equivalent standardized penetration resistance in the following way:

$$(q_{c1N})_{cs} = k_c q_{c1N} \quad (4)$$

Here,

q_{c1N} stands for normalized penetration resistance, which is calculated using the cone's penetration resistance and adjusted for the effective stress;

k_c is a correction factor that is contingent upon the features of the soil grains, which will be specified later;

I_c stands for the soil activity type index;

σ_v and σ_v' are both total and effective stresses;

P_a is a pressure reference, has the same units as ($P_a = 100$ kPa if σ_v' expressed in kPa);

P_{a2} is a reference pressure and has the same units as q_c and σ_v ($P_{a2} = 0.1$ MPa if q_c and σ_v are in MPa).

2.1.2 Idriss and Boulanger Method with Other Authors

The corrected SPT blow numbers $N_{1(60)}$ are utilized to determine the cyclic resistance ratio (CRR) based on an article by Idriss and Boulanger (2010). The correlation is outlined by the authors as follows: $N_{1(60)}$ for various levels of fines content (FC). To synthesize case-history data and analyze their distributions across various situations, the CRR formulation for the SPT process was developed.

$$CRR_{M=7.5} = \exp \left\{ \frac{N_{1(60)CS}}{14.1} + \left[\frac{N_{1(60)CS}}{126} \right]^2 - \left[\frac{N_{1(60)CS}}{23.6} \right]^3 + \left[\frac{N_{1(60)CS}}{25.4} \right]^4 - 2.8 \right\} \quad (5)$$

Idriss and Boulanger (2010) described the approach that Skempton (1986) used to establish the SPT test for 30 cm penetration blow counts in order to calculate $N_{1(60)}$ (corrected SPT blow numbers) in their work. At a geostatic pressure of 1 bar, the overburden coefficient corresponds to the normalized value using several in situ test corrections. It is stated as:

$$N_{1(60)} = N_{spt} \times C_E \times C_N \times C_R \times C_B \times C_S \quad (6)$$

Here, C_N is the overburden correction factor, C_E is the energy correction factor, C_R is the correction factor for rod length, C_B is the correction factor for borehole diameter, and C_S is the correction factor for liner.

Using an equation created by Liao and Whitman (1986), the C_N correction factor is derived as follows:

$$C_N = \left(\frac{P_a}{\sigma_{vo}'} \right)^2 \quad (7)$$

Liao and Whitman (1986) stated that the recommended C_N correction factor ought to fall within the range of 0.5 and 2.0. Only the relative density and the shear resistance angle can be established via the C_N correction; undrained parameters are not eligible.

Idriss and Boulanger (2010) contend that the liquefaction case histories indicate that the liquefaction starting correlations shift toward less suspected as the fines content (F.C.) increases, as demonstrated by current SPT-based correlations. The clean sand equivalent $N_{1(60)CS}$ must be created by applying a fineness modification to the equivalent $N_{1(60)}$, from which the SPT blow number of the sand can be computed. In the literature, several formulae have been proposed for the clean-sand correction. As a result, it is represented as follows when empirically determined utilizing data from historical cases of liquefaction and taking into account the effects of fines content to the CRR (Idriss & Boulanger, 2010):

$$N_{1(60)CS} = N_{1(60)} + \Delta N_{1(60)} \quad (8)$$

$$\Delta N_{1(60)} = \exp \left[1.63 + \frac{9.7}{FC + 0.01} - \left(\frac{15.7}{FC + 0.01} \right)^2 \right] \quad (9)$$

Youd et al. (2001) suggest that the CRR for a 7.5 magnitude (M_w) earthquake ($CRR_{7.5}$) is calculated from the corresponding clean sand's overburden stress-corrected SPT resistance (Ansary et al., 2018).

2.2 Analyzing Cyclic Stress Ratio (CSR)

The cyclic stress ratio (CSR) is a measure of the cyclic behavior of soil. On a flat soil layer, it calculates the seismic demand (Ansary et al., 2018). It is the ratio of the average cyclic shear stress (τ_{av}) formed

on the horizontal surface of soils owing to cyclic or earthquake loading to the initial vertical effective stress (σ_o') occurring on the soil layer prior the cyclic stresses are applied to the (Robertson & Campanella, 1985). The thickness of the soil layer involved, the depth of the groundwater, and the intensity of other cyclic loading events, such as seismic shaking, are all taken into consideration by this parameter (Seed et al., 1983). The Simplified Procedure of Seed and Idriss (1971) states that the CSR formed in the field as a result of an earthquake loading at a depth of z from the ground surface can be determined by applying the equation below:

$$CSR = \frac{\tau_{avg}}{\sigma_o'} = 0.65 \times \frac{a_{max}}{g} \times \frac{\sigma_o}{\sigma_o'} \times r_d \quad (10)$$

Where a_{max} is the maximum horizontal acceleration caused by an earthquake that occurs at the surface of the ground, g is the acceleration of gravity, σ_o and σ_o' are the total and effective vertical overburden stresses at depth z , respectively, and r_d is the stress reduction coefficient that takes the flexibility of the soil column into account. In order to translate the peak cyclic shear stress ratio into a cyclic stress ratio that will accurately represent the majority of cycles across the whole loading period, Idriss and Boulanger (2004) advocated a factor of 0.65. The calculation of r_d can be performed as per Liao and Whitman (1986) using the following equations (Latifi et al., 2023).

$$\begin{aligned} r_d &= 1 - 0.00765 & \text{Si : } z \leq 9.15 \text{ m} & (24) \\ r_d &= 1 - 0.00765 z & \text{Si : } 9.15 \text{ m} < z \leq 23 \text{ m} \\ r_d &= 0.744 - 0.008 z & \text{Si : } 23 \text{ m} < z \leq 30 \text{ m} \\ r_d &= 0.5 & \text{Si : } z > 30 \text{ m} \end{aligned} \quad (11)$$

2.3 Assessment of the Safety Factor (FL)

The cyclic stress ratio (CSR) is contrasted to the liquefaction-resistance of the soil represented by the cyclic resistance ratio (CRR) for $M_w = 7.5$ earthquake (i.e., $CRR_{7.5}$) in accordance with the Simplified Procedure of Liquefaction Resistance Estimation put forth by Seed and Idriss (1971). Using a magnitude scaling factor (MSF), the CRR for earthquakes of different magnitudes is calculated using $CRR_{7.5}$. This is how the CRR, CSR, and MSF are used to figure out the factor of safety (FL) against liquefaction. Equation 1 can be written as follows:

$$F_L = (CRR_{7.5} / CSR) MSF \quad (12)$$

2.4 Liquefaction Potential Index (LPI)

Iwasaki et al. (1982) considered that the following factors are proportional to the degree of liquefaction in their proposed LPI value: the thickness of the liquid layer, its distance from the ground, and the degree to which the factor of safety (FL) is less than 1.0. The LPI is computed using the subsequent equations.

$$LPI = \int_0^{20} F(z) W(z) dz \quad (13)$$

$$F(z) = 1 - F_L \text{ for } F_L < 1.0 \quad (14a)$$

$$F(z) = 0 \text{ for } F_L \geq 1.0 \quad (14b)$$

$$W(z) = 10 - 0.5z \text{ for } z < 20 \text{ m} \quad (14c)$$

$$W(z) = 0 \text{ for } z > 20 \text{ m} \quad (14d)$$

where z is the depth from the ground surface in meters.

The probable outcome of liquefaction can be rated and examined based on Table 2 through the application of the PL probability index.

Table 2 Liquefaction occurrence based on probability index (Chen & Juang, 2000)

Probability Index	Class	Liquefaction probability
$P_L \geq 0.85$	5	Liquefaction almost certain
$0.65 \leq P_L < 0.85$	4	Liquefaction very likely
$0.35 \leq P_L < 0.65$	3	Liquefaction and non-liquefaction are possible
$0.15 \leq P_L < 0.35$	2	Liquefaction unlikely
$P_L < 0.15$	1	Liquefaction almost impossible

3. SEISMICITY OF SOUTH AND SOUTH EAST ASIA AND SELECTION OF COUNTRIES FOR EVALUATION

The degree of earthquake-related destruction of infrastructure is significantly influenced by the local soil qualities. Among the most spectacular causes of structural destruction during a seismic event is liquefaction. The Factor of Safety against Liquefaction is a relatively straightforward method that determines whether the soil is liquefiable. As a result, FOS only provides qualitative data and treats the site as reflected in the minimum value, regardless of the thickness of the relevant layers. But in order to create liquefaction susceptibility maps and make judgments about the liquefaction impact at a site, this information will not be sufficient. Iwasaki (1982) introduced the Liquefaction Index (LPI) scale, a measure of the aggregate liquefaction potential of soil to a depth of 20 m that accounts for subsoil information. According to Iwasaki (1982), the losses will be greater if the liquefiable layer is both thick and shallow with $FOS < 1$ (Anbazhagan, 2009). Figure 1 shows the world map of the countries investigated in this review paper. Because of tectonic plate movement, the Earth is constantly moving. The majority of the seven continents and the Pacific Ocean are made up of seven main plates.

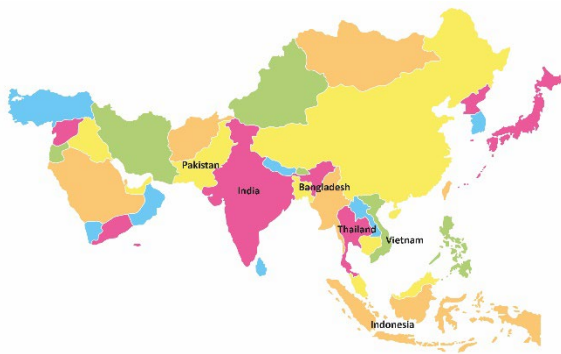


Figure 1 Asian map indicating the countries which are investigated in this study

Soil liquefaction in specific locations in some Asian countries is discussed in this chapter, along with various treatments / soil improvement techniques used to enhance soil properties. For accurate seismic response analysis, the distribution and quantity of measurement points are critical. The journal paper by Likitlersuang et al. (2020) suggests using grid patterns or random sampling to effectively cover varying ground conditions. The research paper (Mase et al., 2022) highlights the use of ambient noise measurements to identify variability and guide the placement of measurement points in areas with significant differences. The article by Nguyen et al. (2023) states that to ensure accurate data, there should be a statistically significant number of points. To provide thorough coverage, the quantity should be determined by considering the area size and desired data resolution, as stated in Mase et al. (2024).

By positioning and scaling measurement locations appropriately, using these methodologies contributes to the assurance of a strong and representative seismic analysis.

There are some suggestions for the Distribution of Measurement Points: Authors should think about combining focused observations in high variability areas with regular grid patterns to achieve thorough coverage. Based on statistical requirements to capture representative samples and reduce uncertainty, the number of measurement points should be determined. Measurements of ambient noise and geophysical properties can shed more light on the best locations and number of measurement points.

4. ESTIMATION OF SOIL LIQUEFACTION POTENTIALS IN DIFFERENT COUNTRIES

4.1 Liquefaction characteristics of Bangladesh

More than 80% of the Bangladesh landmass is composed of loose and mushy Quaternary sediments. Following the 1885 Bengal Earthquake, 1897 Great Indian Earthquake, and 1918 Srimangal Earthquake, massive liquefaction occurrences were seen in the alluvial formations of Bangladesh. Bangladesh is encircled by the Indo-Burma Folded Belt in the east, the Dauki Fault, and the Himalayan Syntaxis in the north, all of which are known to have historically experienced large earthquakes ($M_w > 7$). The liquefaction potential for Dhaka city ranged from exceptionally low to exceptionally high. In accordance with the average distribution of frequency of LPI for each zone, the geological units of Dhaka City are classified into three liquefaction hazardous zones, such as Zone 1, Zone 2, and Zone 3 (Ansary et al., 2018). The northeastern zone was thus designated as an earthquake-prone area. The Sherpur-Maulivibazar region was discovered to be susceptible to liquefaction. Through the use of cone penetration testing, it has been discovered that certain areas of Chittagong City are liquefiable up to filling level (Mahmud, 2015). By adopting ground improvement techniques or processes, the threat of liquefaction may be reduced. Prefabricated vertical drains (PVD) are a quick way to increase drainage capacity, and compaction is a quick way to increase soil density. Deep mixing method (DMM) or grouting can both be used to stabilize soft ground (Mahabub et al., 2020).

The urban population of Dhaka city has grown rapidly over the last 30 to 40 years, leading the government and commercial sectors in and around the city to reclaim additional territory. The standard procedure for creating these new regions is to simply fill lowlands between three and twelve meters deep with dredged silty sand. This results in liquefaction vulnerability in those regions. According to the flawless record, the banks of the Jamuna River migrated on both sides due to erosion of previously deposited loose, unconsolidated alluvial sediments. Thus, there is a possibility of hazards to a variety of engineering infrastructure, such as bridges, rail lines, roads, spurs, buildings, and covered or unsecured embankments along riverbanks. For these reasons, Dhaka and areas near the Jamuna River are studied here.

4.1.1 Ten Reclaimed areas of Dhaka City in Bangladesh

The goal of the article "CPT & SPT Tests in Assessing Liquefaction Potential" studied by Hore et al (2020) is to determine the potential for liquefaction caused by earthquakes in a few reclaimed areas of Dhaka city using both cone penetration testing (CPT) and standard penetration testing (SPT). Ten (10) specifically chosen reclaimed areas of the greater Dhaka city have been the source of CPT and SPT data collection. From the current ground level (EGL), the filling depth of the reclaimed areas ranges from 1.5 to 13.5 m. For the liquefaction analyses, the magnitude (M) and the maximal ground acceleration (a_{max}) have been set at 7.5 and 0.15g, respectively. In the ten (10) sites in Dhaka city that were chosen, the range of SPT-N, Cone tip resistance (MPa), local friction (kPa), and friction ratio varied between 1~42, 0.17~18.58, 0~273.2, and 0~9.34, respectively. It has been recognized that there is a considerable likelihood of liquefaction in the reclaimed regions of Dhaka city, particularly in

locations where soil was excavated to a depth of 1.5 to 4.5 m. The majority of the time, two separate depth zones have been the locations of the CPT liquefaction zone.

Based on CPT (Robertson, 2009) and SPT (Seed et al., 1983) data, the potential for liquefaction has been assessed, and laboratory tests have also been conducted to determine soil characteristics. A liquefiable zone is one where $FS < 1$, whereas a non-liquefiable zone is one where $FS > 1$. Table 3 displays the outcomes of the liquefaction analyses performed at the ten various locations previously mentioned.

Table 3 Liquefaction obtained based on two methods (Hore et al., 2020)

Sl. No	Location	CPT Based Liquefied Depth (m)	SPT Based Liquefied Depth (m)
1)	Bramangaon	a) 1.5 -10	a) 1.5~4.5
2)	Ashian City	a) 1.8 -3.9 b) 12.9 -14.4	a) 1.5~3
3)	Badda	a) 4.5 – 5.5 b) 8 – 9.5	a) 1.5~4.5
4)	Banasree	a) 0.7 – 4.8 b) 14.4 – 15.3	a) 1.5~4.5
6)	Gabtolli	a) 0.6 – 5.4	a) 1.5~4.5
6)	Kawran Bazar	a) 11.4 – 12.3	a) 1.5~6
7)	Purbachal	a) 1.5 – 5.0, b) 15 – 15.6	a) 1.5~3
8)	United City	a) 3.0 – 4.5, b) 10.5 – 12.0	a) 1.5~4.5
9)	Uttara	a) 2.7 – 4.8, b) 8.7 – 12.3	a) 1.5~7.5
10)	Kamrangirchar	a) 1.5 – 6, b) 7.5~12	a) 10.5~11.5

The CPT (Figure2) and SPT (Figure 3) data-based liquefaction potential index maps are similar in that low liquefaction zones have been identified in the center of the research area and are spread out in a north-south direction. The two methods yield slightly different liquefaction potential results. This difference could have several causes, including the data collection process. At 1.5 m intervals, the SPT N value has been recorded. The CPT value, on the other hand, was recorded at 0.01 m intervals.

Compared with SPT, this produces more consistent and trustworthy CPT data. The findings of the CPT test have revealed a specific zone of liquefaction that cannot be distinguished by SPT. However, just one zone has shown signs of SPT liquefaction. The highest Liquefaction Potential Index (LPI) values for CPT and SPT are 21 (Bramangaon) and 28 (Purbachal), respectively. Regarding CPT and SPT, the smallest results of the liquefaction potential index are 3, and 1, respectively, in Kawran Bazar. Dhaka City's center and north-south alignment have been identified as having minimal liquefaction potential zones. Bramangaon, Ashian City, Badda, Banasree, Gabtoli, Kawran Bazar, Purbachal, United City, Uttara, and Kamrangirchar are among the reclaimed regions.

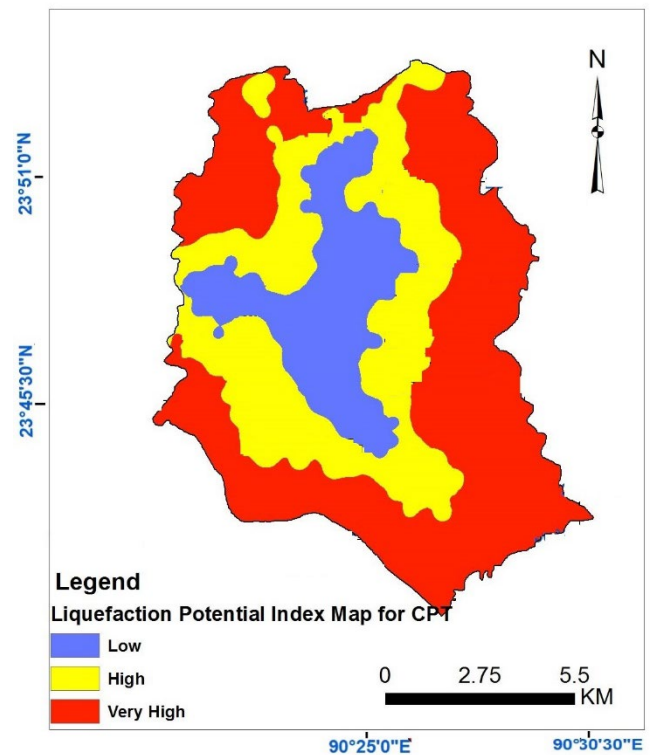


Figure 2 Liquefaction potential index Map based on CPT data (Hore et al., 2020)

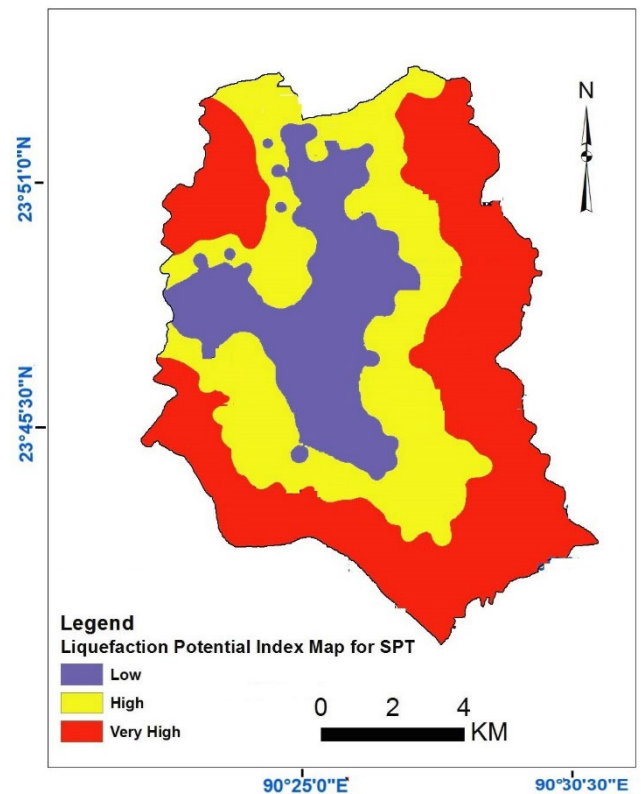


Figure 3 Liquefaction potential index Map based on SPT data (Hore et al., 2020)

4.1.2 Soil Liquefaction Potential from Sirajganj to Kurigram Area in Bangladesh

The standard penetration test (SPT) methodology was employed in the current research, "Assessment of Liquefaction Potential from Sirajganj to Kurigram Area, Bangladesh," by Mahabub et al. (2020), to analyze the liquefaction potential along the Jamuna River, a distance of about 140 kilometers, from Sirajganj to Kurigram. For the chosen peak ground acceleration value (0.28), liquefaction potential analyses were carried out at earthquake magnitudes 5.5 and 7.5 using LiquefyPro version 5 (2005) software. By evaluating the features of soil attributes, such as grain size, relative density, the thickness of sandy soils, the factor of safety, ground damage, and settlement, a liquefaction potential zone is generated. At earthquake magnitudes of 5.5 or greater, the soils in these areas are vulnerable to liquefaction. Sirajganj, Bogura, Gaibandha, and Kurigram experienced liquefaction to depths of up to 10 m during an earthquake with a lower magnitude ($M = 5.5$). In contrast, liquefaction occurred throughout the entire study area at a greater magnitude ($M = 7.5$), up to a depth of 15 to 20 m. According to the research, soils are dense to extremely dense and non-liquefiable at depths greater than 15–20 m. Based on the safety factor and other examined soil properties, a risk zonation map was created. The map was beneficial to the planning, mitigating, and sustainable development of the studied areas since it depicted the liquefaction potential zone. Figure 4 depicts an average river cut soil sequence.



Figure 4 A typical stratigraphic succession of observed sediments in the study area (Mahabub et al., 2020)

The acquired factor of safety values is used to determine the liquefaction potential against a certain depth. The majority of the liquefiable and moderately liquefiable soils are located in the depth range of 0.0 to 10 m for low earthquake magnitudes ($M = 5.5$). Similarly, soils with high earthquake magnitude ($M=7.5$) are moderately liquefiable in a wide range of 15–20 m depth (apart from a few boreholes). When ground damage from liquefaction is visible, the "Boundary Curves" method is applied (Ishihara, 1985), as shown in Fig.5. Considering soils from the research locations, Liquefy Pro, Version 5 (2011) software examined their propensity for liquefaction using SPT data. Because of the liquefiable soil layer, settlement amounts reduced with increasing depth and matched ground damage. Liquefaction is caused by unconsolidated, extremely loose to medium dense, consistently graded soils with significant thickness and fine content, a shallow groundwater table, ground manifestation, and soil settlement. As a result of higher SPT values (>30), it is determined that soils at greater depths (>15 –20 m) are dense to extremely dense and therefore termed non-liquefiable. The potential for liquefaction causes the engineering structure built at this depth (< 20 m) to collapse.

The results of this study can serve as an overall framework for ground failure susceptibility, land use planning, and mitigating earthquake-induced river erosional hazards. Additionally, the planning of the study area's mitigation and sustainable development is essential.

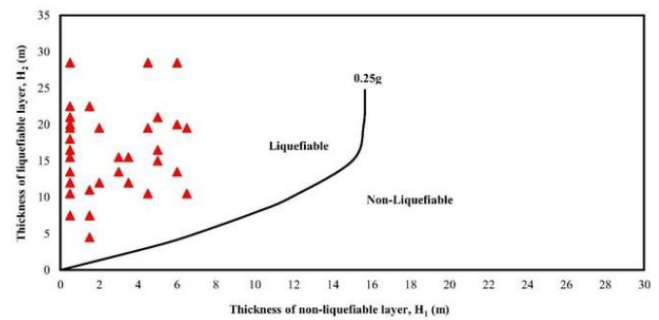


Figure 5 Evolution of ground damage due to liquefaction at the investigated area by "Boundary Curves," according to Ishihara (1985). (Mahabub et al., 2020)

4.2 Soil Liquefaction in India

With respect to population, Vijayawada city ranks 34th in India and ranks third in Andhra Pradesh. The city is expected to experience minor to medium-sized earthquakes annually, according to geological research and environmental instabilities and abnormalities (for example, the Richter scale earthquake in the Andaman Islands, which had a magnitude of 7.6) (Manee et al., 2011).

Ahmedabad, the capital of Gujarat state in western India, is a major industrial hub home to numerous large petrochemical complexes as well as academic institutions and organizations. Because of its growing population and industrialization, the city is seeing a significant surge in construction activity and the expansion of its settlement area. Given the foregoing, it becomes imperative to look into the liquefaction hazard, one of the main after effects of an earthquake.

4.2.1 Soil liquefaction potential of Vijayawada Region (CRDA) in India

The authors of the research "Probability-based Assessment of Soil Liquefaction Potential in Vijayawada Region (CRDA)", Donavalli et al. (2023), highlighted how saturated cohesionless soils with limited plasticity and density provide liquefaction challenges. Understanding the liquefaction potential in the CRDA region is crucial because capital-intensive structures are being built there, and a rise in population is anticipated due to AP growth. Liquefaction causes catastrophic damage to structures and poses a risk of losing lifelines. Each bore log in the experiment was examined for soil resistance to liquefaction, taking into account key soil variables, including grain size, fines content, unit weight, saturation percentage, SPT N value, and soil origin. To evaluate the liquefaction safety factor, the method proposed by Seed and Idriss was adopted. For greater reliability, the results from the semi-empirical computations are further contrasted to those from the software.

Data from 50 boreholes have been collected, covering soil density, water table, liquid limit, and SPT N-value. Liquefaction potential of soils can be assessed using software from Geo Stru called LIQUITER. Standard Penetration Test (SPT), Tests to determine the shear wave velocities (V_s), Cone Penetration Test (CPT), Cone Penetration Test Electric (CPTE), Cone Penetration Test Piezocone (CPTU), and Grading Curve are all field test methods supported by Liquiter that can be utilized for assessing liquefaction.

According to the seismic zone categorization, the Vijayawada CRDA Region is in Zone 3, with an earthquake intensity range of 6.5–7.0 and a PGA of 0.16g. In this study, the liquefaction potential was assessed for each location at two distinct magnitudes, 6.5 and 7. Figures 6 and 7 show the outcomes for one such location, demonstrating that the first layer is liquefiable at magnitude 7 but not at magnitude 6.5.

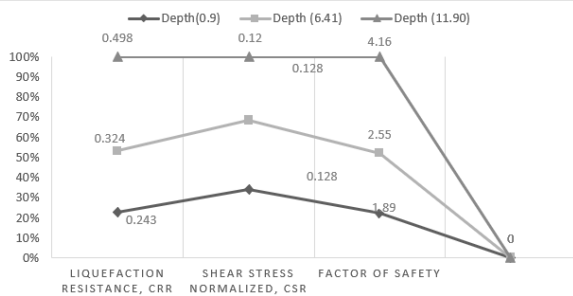


Figure 6 LPI of soil for magnitude of 6.5 and PGA of 0.16 g

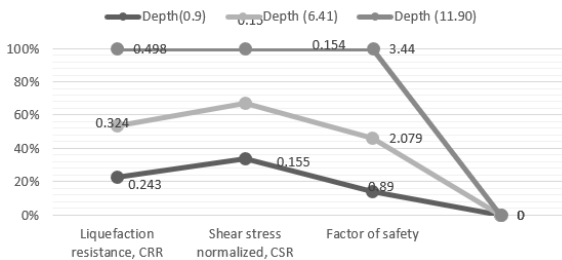


Figure 7 LPI of soil for magnitude of 7 and PGA of 0.16 g

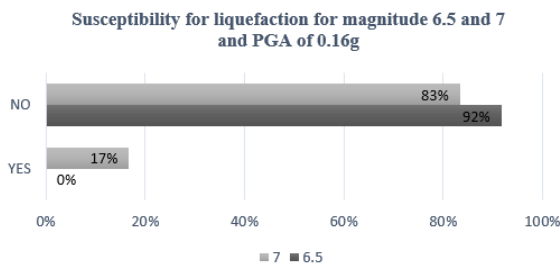


Figure 8 Susceptibility for liquefaction for magnitude 6.5 and 7 and PGA of 0.16 g

According to this research, out of the 50 areas considered for determining liquefaction potential, those for magnitudes 6.5 and 7 and a PGA of 0.16g are shown in Figure 9 (a and b). Analyses between the outcomes of empirical procedures and those produced by using software (Liquiter) are made. The most precise outcomes have been achieved through software analysis.

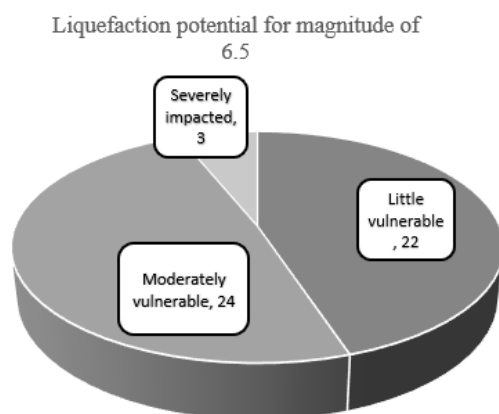


Figure 9(a) Liquefaction potential for magnitude 6.5

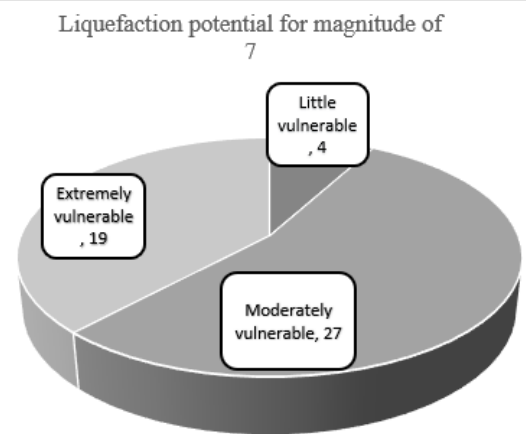


Figure 9(b) Liquefaction potential for magnitude 7

4.2.2 Ahmedabad Region, Western India

Dwivedi et al. (2017) examined the liquefaction potential of soil in the Ahmedabad city region, which predominantly comprises sandy to silty sediments and has seen major development activity recently. Information from 23 boreholes' Standard Penetration Tests (SPT) was gathered for the study.

To estimate CRR, the SPT N-values were adjusted. The findings of the study suggest that the liquefaction potential is quite low because the soil in the Ahmedabad city region is extremely compact, the water table is considerably smaller, and the SPT-N values are significant.

23 boreholes in all, 11 of which were 80 m deep, six of which were 40 m deep, and five of which were 35 m deep, were dug at various places to explore the subsurface lithological properties of the area.

Because the Clayey Sand (SC) strata contain sandy soil, liquefaction could take place in these layers. In addition, the water table is generally low, with the exception of boreholes BH08, BH07, and BH20, where the levels are, respectively, 3.5 m, 5.2 m, and 6 m. It has been noted that the liquefiable layers are primarily restricted to the center of the city. Due to compaction and fine materials, liquefaction is not apparent below 10 m, with the exception of BH-11, where it is seen at depths of 12 m for PGA 0.2 g and 12 and 15 m for PGA 0.3 g.

Eight layers in total were found to be liquefiable at five separate boreholes, six of which are the top layers (down to a depth of 10 m). It may be inferred that the research region is slightly liquefiable at six layers in two boreholes in the western portion, two in the eastern part, and one in the central section. Figures 10 and 11 show the estimated factor of safety for PGA 0.2 g and 0.3 g. As an outcome, it can be stated that construction operations are acceptable in the investigated region. High-rise buildings and large engineering structures, however, call for in-depth site-specific geotechnical assessments.

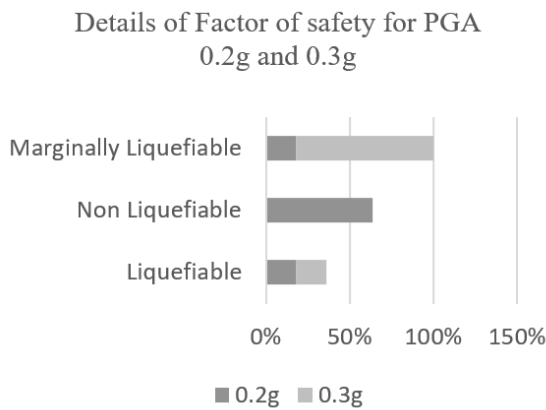


Figure 10 Estimated factor of safety for PGA 0.2 g and 0.3 g at different boreholes

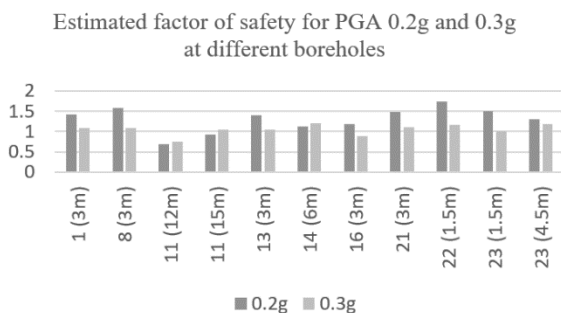


Figure 11 Details of Factor of safety for PGA 0.2 g and 0.3 g

4.3 Liquefaction Characteristics of Pakistan

Due to the significance of the region, the authors Khan et al. (2017) evaluated the geotechnical condition of the soil in the DHA area in the publication "Assessment of Soil Liquefaction Potential in Defence Housing Authority, Karachi, Pakistan." Buildings and infrastructure may sustain destruction from liquefaction as a result of the abrupt rise in pore pressure in the loose layers of saturated sand that results in a decrease in bearing capacity and shear strength. Incorporated by the Pakistani Army in the coastal region of Karachi is the Defense Housing Authority (DHA), a thoughtfully designed housing development. The soil in DHA is fine-grained, poorly graded, and composed primarily of recent-age sandy silt and silty sand. The water table is also found at relatively shallow depths in this area. Because the majority of high-rise buildings and massive civil constructions are being built in the DHA region, it is crucial to evaluate the geotechnical behavior of the soil there. The factor of safety (FS) was applied in the current research to analyze seismic soil liquefaction at 15 sites (30 boreholes) in the DHA. Using data from the Standard Penetration Test (SPT), the Relative Density (RD) was calculated. On every borehole specimen, a grain size analysis was also performed. According to the findings, the DHA region in Karachi is susceptible to liquefaction following major earthquakes of magnitudes between 6.5 and 7.5. In this research region, non-plastic soil occurs naturally.

Grain Size Analysis, Factor of Safety (FS), and Relative Density were among the metrics employed in this study to analyze the ability of the soil to liquefy in the DHA area. Using a simplified empirical technique based on SPT, liquefaction potential has been assessed in terms of the Factor of Safety (FS), as initially described by Seed and Idriss (1971).

Table 4 Calculation for FS of a representative site. (modified from Khan et al. (2017))

Site	Borehole	Layer Thickness (ft)	CSR	NSPT	CRR	FS		
						Mw = 6.5	Mw = 7	Mw = 7.5
1	1	6	0.19	9.00	0.10	0.81	0.63	0.53
		10	0.19	13.00	0.10	0.78	0.60	0.51
				14.00	0.06			
		5	0.21	14.00	0.10	0.73	0.56	0.47
GWT (m) 2.286	2	17	0.20	22.00	0.06	0.75	0.58	0.49
				24.00	0.06			
		6	0.20	5.00	0.10	0.75	0.58	0.49
		4	0.20	7.00	0.10	0.74	0.57	0.48
		5	0.21	8.00	0.10	0.72	0.56	0.47
		10	0.21	19.00	0.10	0.71	0.55	0.46
				21.00	0.06			

At 15 locations (30 boreholes), spanning the DHA region, the potential for soil liquefaction was assessed for earthquakes of magnitudes Mw=6.5, Mw=7, and Mw=7.5 with a maximum ground acceleration of 0.2g. According to the factor of safety (FS) against earthquakes with magnitudes Mw=6.5, Mw=7, and Mw=7.5, all 15 sites have FS < 1, making them all susceptible to liquefaction because liquefiable layers have FS < 1. A few layers show the critical point (FS=1) and the secure range (FS > 1), respectively. These layers are, however, comparatively slender. Table 4 presents the calculations for FS (Mw = 6.5, 7, 7.5). The research area is shown to be extremely sensitive to liquefaction, based on FS calculations from 15 DHA locations. A factor of safety (FS) calculation was made for earthquakes with magnitudes of 6.5, 7, and 7.5.

The presence of a groundwater table and non-cohesive soils (silt and sand) increased the likelihood that liquefaction might occur in the DHA during any significant seismic event. As a result, high-rise structures in the moderate seismic zone of Karachi are required to be prepared in accordance with Uniform Building Code clause 2B.

4.4 Liquefaction Characteristics of Indonesia

Yogyakarta International Airport, an international airport in Indonesia, along with its environs, constitutes an extremely significant building. Liquefaction studies are recommended in this area. The Yogyakarta International Airport is expected to boost the country's economy and enhance the well-being of the populace, particularly in the Yogyakarta region and throughout Indonesia, according to Transportation Minister Budi Karya Sumadi.

Mataram City is situated on the western shore of Lombok Island. It is the center and the backbone of the local economy. People's quality of life is severely impacted by earthquakes, as the 2018 M7.0 earthquake made abundantly clear. Knowing that subsoil liquefaction could occur is crucial to helping the government and residents in the potentially affected area implement the necessary mitigation measures.

4.4.1 Yogyakarta International Airport – Indonesia

The authors Ismaili and Asyifa of the paper "Analysis of Liquefaction Potential Based on SPT and CPT Data in the Yogyakarta International Airport Area" claimed that the frequency of earthquakes will harm both infrastructure and soil components. Based on SPT and CPT data, a simple analysis method for probable liquefaction was used. Cyclic stress ratio (CSR), cyclic resistance ratio (CRR), and security factors were determined from the data.

Regarding the possibility of liquefaction, a number of experiments and field investigations have been conducted (Isiwanto et al., 2017). Employing field test information from the Cone Penetration Test (CPT), Standard Penetration Test (SPT), and boring test, for instance, illustrates how this approach to analysis may be used in practice. The Cyclic Resistance Ratio (CRR), which

quantifies the capacity of the cyclic load induced by a seismic event, is compared with the Cyclic Stress Ratio (CSR) and Safety Factor values to determine the Safety Factor, which is used to assess the potential for liquefaction. The technique was developed by Youd et al. in 2001. Verify if the safety factor amount is greater than 1, which implies it is safe from liquefaction, or less than 1, which suggests that liquefaction may occur.

In accordance with analytical results, all soil sections at the sampling locations of the soil with a tremor magnitude (M_w) of 7.5 possess the potential of exhibiting liquefaction. For instance, the SF value of 0.17 is derived for the site of CPT1 with $M_w=7.5$ at a depth of 2 m. A low QC value may contribute to the low SF value. According to Iswanto et al. (2017), a low q_c value indicates that the soil is loose, which is one of the root causes of liquefaction.

The SF value can be used to determine whether a research area has the potential to liquefy. The locale or region of Yogyakarta International Airport is at risk of liquefaction, according to the two statistics used, namely SPT and CPT. To reduce the likelihood or consequences of liquefaction, proper abatement and management techniques are required.

4.4.2 Mataram City – Indonesia

Intan Puspitaningrum (2021) describes one of the causes of subsoil liquefaction in her article, "Analysis of subsoil liquefaction potential in the region of Mataram city in Indonesia," namely cyclic loads induced by earthquakes. On the west coast of Lombok Island is Mataram City. It serves as the region's capital and economic engine. The 2018 M7.0 earthquake served as a stark reminder of how detrimental earthquakes are to people's quality of life. The subsoil of Mataram city is susceptible to liquefaction, with the west coast of the city being the most severely affected and the eastern section of the city being the least likely, according to the examination of soil data collected from 9 SPT sites and 22 CPT sites. From the CPT-21 location, a maximum settlement of 0.458 m is anticipated.

The objective of this study is to evaluate the subsoil liquefaction potential of Mataram city in Lombok utilizing soil data collected using SPT and CPT in various areas. The factor of safety (FS) is then calculated using soil data to get the cyclic resistance ratio (CRR) and stress ratio (CSR). To derive vertical (S) and lateral displacement (LD) for the further analysis, they solely employed the FS value from the CPT result. Due to its higher consistency and uninterrupted profile opposed to other field tests, CPT has grown to be quite effective for site characterization (Zhang et al., 2002). Developing an almost consistent profile of resistance to penetration for stratigraphic explanation is one of the main benefits of employing CPT. In comparison to SPT, the outcome is typically more reliable. CPT is particularly effective for evaluating liquefaction resistance profile because of its stratigraphic abilities.

As shown in Table 5, several parameters for scaling have been offered by studies. For the sake of engineering practice, it is advised that the revised MSF suggested by Idriss in column 3 of Table 5 serve as the lower bound for the acceptable range for magnitudes 7.5.

Table 5 MSF value defined by various investigators (Intan Puspitaningrum, 2021)

Magnitude (1)	Seed and Idriss (2)	Idriss (3)	Andrus and Stokoe (4)
5.5	1.43	2.20	2.8
6.0	1.32	1.76	2.1
6.5	1.19	1.44	1.6
7	1.08	1.19	1.25
7.5	1.00	1.00	1.00
8.0	0.94	0.84	0.8
8.5	0.89	0.72	0.65

Figures 12 to 13 show the conclusions of the factor of safety obtained from the CPT and CPT data calculations according to the depth of observation.

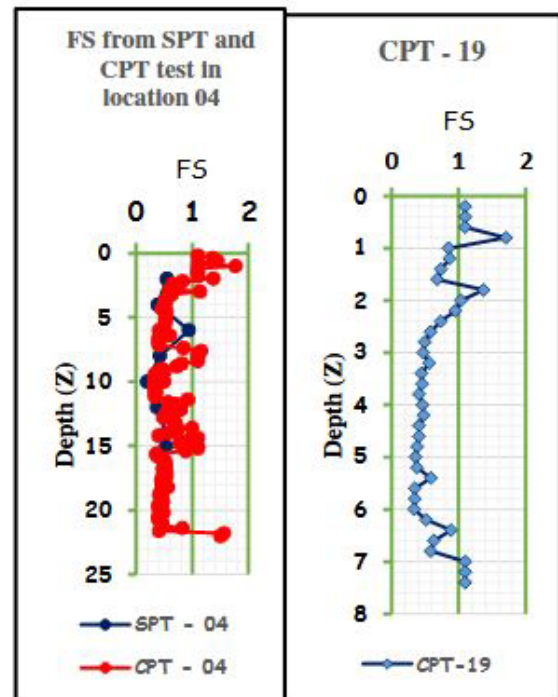


Figure 12 SF on location 04 and 19 (downtown and west coast) (Intan Puspitaningrum, 2021)

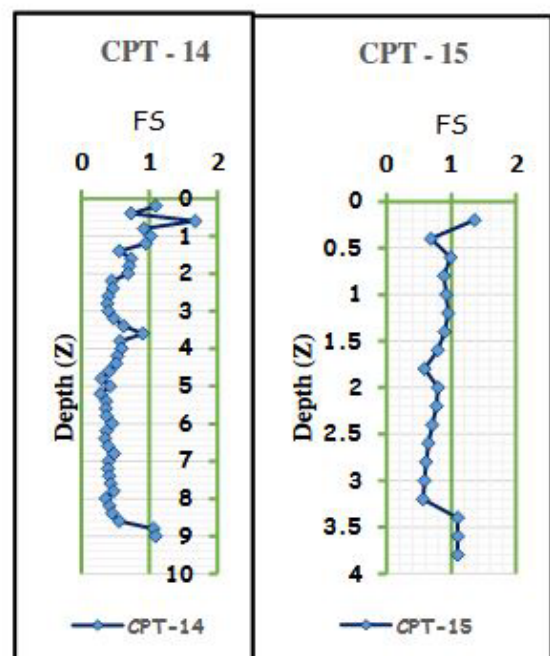


Figure 13 SF on location 14 and 15 (north area and eastern area) (Intan Puspitaningrum, 2021)

4.5 North Central Coast - Vietnam

Nu et al. (2021) stated in their study "Assessment of Soil Liquefaction Potential Based on SPT Values at Some Ground Profiles in the North Central Coast of Vietnam" that the North Central Coast of Vietnam has a broad range of loose sand that is frequently found on the surface. Due to its loose nature, this sand can become vulnerable to dynamic loads such as those caused by tremors, heavy traffic, or machine

foundation and may liquefy, possibly destroying the ground and the structures on it. In order to assess the liquefaction potential of sand utilizing the SPT and using a total of three factors, including the Factor of Safety against Liquefaction (FS_{LIQ}), Liquefaction Potential Index (LPI), and Liquefaction Severity Number (LSN), this paper conveys some ground descriptions from various locations along the North Central Coast of Vietnam.

The findings of the study indicate that the FS_{LIQ} , LPI, and LSN values are influenced by the SPT readings and the depth of sand specimens. According to this research, sand that is spread between 2.0 and 18.0 m and has a $(N1)_{60cs}$ value below 20 has a significant liquefaction potential with an $FS_{LIQ} < 1$, an LPI that is frequently exceeding 0.73, and an LSN that is frequently greater than 10. For construction projects in this area, these outcomes should be taken into account.

SPT readings and borehole specimens were collected to assess the liquefaction potential of sand on the North Central Coast of Vietnam. To evaluate particle size and categorize the soil, soil samples were employed. The SPT was carried out in the boreholes at 1.5–2 m depth intervals.

In this investigation, the factor of safety against liquefaction (FS_{LIQ}) will be evaluated using the SPT-based LEP described in Boulanger & Idriss (2014). The LPI will then be calculated, with modifications according to Iwasaki et al. (1982) and Sonmez (2003), as shown in Table 6. Last but not least, the LSN was computed in accordance with Tonkin and Taylor (2013), as shown in Table 7.

Table 6 Liquefaction Potential Classification based on LPI (Iwasaki et al. 1982) (Nu et al., 2021)

LPI	Liquefaction Potential
0	Non-liquefied
$0 < LPI \leq 2$	Low
$2 < LPI \leq 5$	Moderate
$5 < LPI \leq 15$	High
$LPI > 15$	Very high

Table 7 Liquefaction Potential Classification based on LSN (Tonkin & Taylor, 2013) (Nu et al., 2021)

LSN	Liquefaction Potential
0–10	Little to no expression of liquefaction, minor effects
10–20	Minor expression of liquefaction, some sand boils
20–30	Moderate expression of liquefaction, with sand boils and some structural damage
30–40	Moderate to severe expression of liquefaction, settlement can cause structural damage
40–50	A major expression of liquefaction, undulation and damage to the ground surface, severe total and differential settlement of structures
>50	Severe damage, extreme evidence of liquefaction at surface, severe total and differential settlements affecting structures, damage to services.

Figures 14, 15, and 16 show the outcomes of calculating the possibility for soil liquefaction along the North Central Coast of Vietnam. There are certain inferences that can be made based on the study's findings. The sand layer of the North Central Coast of Vietnam ranges in thickness from a few meters to greater than 10 meters, and it is frequently visible on the surface. The range of SPT scores is 1 to 38, with an average value of 9. A shift from 0.3% to 45.3% is seen in the fine contents (< 0.075 mm).

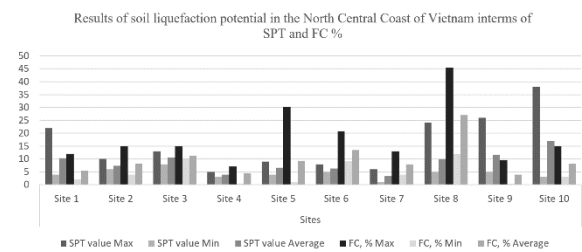


Figure 14 Results of soil liquefaction potential in the North Central Coast of Vietnam in terms of SPT and FC %

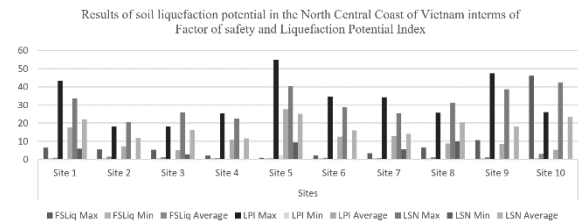


Figure 15 Results of soil liquefaction potential in the North Central Coast of Vietnam in terms of Factor of safety and Liquefaction Potential Index

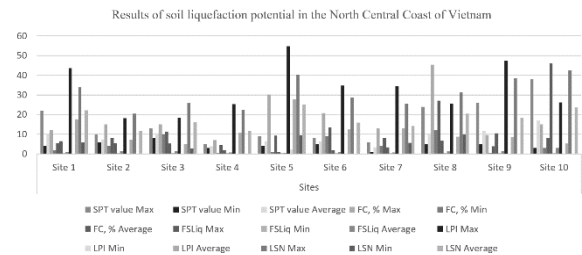


Figure 16 Results of soil liquefaction potential in the North Central Coast of Vietnam

The SPT values and the distribution of depth affect the likelihood of liquefaction in the sand layers in this area. Liquefaction potential varies among sandy soils. Site 5 has the greatest likelihood of liquefaction, whereas Site 10 has the least likelihood. The $(N1)_{60cs}$ value below 20 for sand dispersed between 2.0 and 18.0 m has a liquefaction potential of $FS_{LIQ} < 1$, LPI that is frequently greater than 0.73, and LSN that is frequently more than 10. The outcomes of this research can be utilized for forecasting the ability of the soil to liquefy when utilized for constructing structures along north central coast of Vietnam.

4.6 Chiang Rai – Northern Thailand

The study "Liquefaction analysis of sandy soil during strong earthquake in Northern Thailand" by Sukkarak et al., (2021), said that throughout the course of the previous few decades, Northern Thailand endured a number of quakes which triggered soil liquefaction. In order to assess the potential for liquefaction of Mae Lao Sand in the Chiang Rai area of northern Thailand, this study combined experimental findings with numerical techniques. A 1D site response model evaluation of the Mae Lao site was compared with SPT and downhole seismic test data collected during a field investigation. On Mae Lao Sand samples with various initial void ratios and confining pressures, a number of undrained monotonic and cyclic triaxial tests were performed. Liquefaction resistance curves were generated from cyclic triaxial test results at various deviator stress amplitudes. The stress-strain-pore water pressure response of Mae Lao Sand was studied using the findings of a numerical model of sand liquefaction. A 1D site response assessment identified tremor reactions under various groundwater and geological circumstances. The results collectively demonstrated that in-situ conditions and groundwater

depths have a significant impact on the liquefaction potential of sand layers, and that pore water pressure ratio drops as sand stiffness increases. They also demonstrated that the liquefaction potential of soil layers is substantially raised by soil thickness.

Multiple powerful tremors have occurred in Northern Thailand. Up to a depth of 32 m, SPT and downhole experiments were conducted. The SPT results revealed that $(N1)_{60}$ did not change significantly with depth. At the time of the observation, the groundwater level was approximately 1 m below the surface. The majority of the Mae Lao site consisted of sandy and clayey soils. Simulations were run using various sample void ratios and confining pressures ranging from 50 to 200 kPa. To assess liquefaction resistance, they calculated the CSR, defined as the ratio of cyclic shear stress to initial vertical stress (Youd et al., 2001). This value was derived using the method given by Seed and Idriss (1979). The CSR values exceeded 0.1 for all states and stresses tested and progressively decreased with increasing loading cycles. The CSR value declined below 0.1 after 100 loading cycles only when the condition was loose and $\sigma_0 = 100$ kPa. After 100 cycles, the CSR values in the dense phase were consistently greater than 0.15. Using the model and PLAXIS 2D V19, 1D site response investigation was conducted.

It came to the conclusion that an increase in confining pressure and sample void ratio makes soil liquefaction a higher probability, considering laboratory and 1D site response studies. Dense specimens exhibit greater softening under higher confinement pressures in undrained monotonic testing. The undrained shear strength and fluctuation of the effective mean stress rise when the void ratio decreases in the specimens. The two loose and dense specimens of Mae Lao Sand showed liquefaction sensitivity during

cyclic triaxial tests. The liquefaction resistance of the Mae Lao sand characteristics is remarkably variable, varying significantly based on the starting sand density and stress situation, compared to trials done on other kinds of sands and soils, yet they lie in a similar range.

5. COMPARISON OF SOIL LIQUEFACTION IN SOME ASIAN NATIONS

When studying soil liquefaction, a total of six Asian nations were considered. Comparing the procedures and requirements for soil liquefaction in six Asian nations is displayed in Table 8 below.

Table 8 makes clear which field methods are used: SPT and CPT, with SPT alone considered in most countries. Some nations asserted that the CPT results are more trustworthy than those from the SPT. Settlements from only two countries were computed. Software models were utilized in just a few nations for the analysis. The majority used the Iwasaki et al., 1982 reference for the LPI computation. The majority utilized Seed et al. (1971, 1979, 1982, 1983) as a reference for the SPT computation.

There are some limitations in some countries research papers. The data gathering techniques led to varied liquefaction potential findings between SPT and CPT methods in Bangladesh. The low liquefaction potential in Ahmedabad is attributed to compact soil, shallow water table, and high SPT-N values. SPT readings and sand depth influence FSLIQ, LPI, and LSN values. Certain soil profiles exhibit a notable liquefaction risk. Mataram city faces a significant liquefaction risk, warranting preventive measures.

Table 8 Comparison of soil liquefaction of Asian countries

Features	Bangladesh		India		Pakistan	Thailand	Vietnam	Indonesia	
Area	Ten reclaimed areas of Dhaka	Sirajganj To Kurigram	Vijayawada Region (CRDA)	Ahmedabad Region	Defence Housing Authority, Karachi	Chiang Rai	North Central Coast	Mataram City	Yogyakarta International Airport
Consulting Year	2020	2021	2022	2017	2017	2021	2021	2021	2022
Types of Method	Field and Laboratory	Field and Laboratory	Field and Laboratory	Field and Laboratory	Field	Field and Laboratory	Field	Field	Field & laboratory
Name of the method	SPT & CPT, Grain size analysis	SPT, Grain size analysis, Triaxial tests	SPT, Triaxial tests	SPT, Grain size analysis, Liquid limits	SPT	SPT, Down hole seismic tests, Cyclic Triaxial tests, undrained monotonic tests Initial void ratio.	SPT	SPT & CPT	SPT, CPT & boring test, grain analysis
Reference Method	CPT - Robertson, 2010 SPT - Seed et al., 1983	SPT - Seed et al., 1971 & 1982; Youd et al., 1997 & 2001; Martin et al., 1999.	SPT - Seed et al., 1971	SPT - Seed et al., 1971, Idriss et al., 2006	SPT - Seed et al., 1971	SPT - Seed et al., 1979	SPT - Youd et al., 2001;		SPT - Youd et al., 2001 CPT - Robertson et al., 1988
River of Study area	-	Jamuna	Krishna	Sabarmati	Coastal belt of Karachi			west coast of Lombok Island	
Number of locations/ boreholes	10 sites	51 bore holes	50 bore holes	23 boreholes	15 sites (30 boreholes)	3 locations, (TP1, TP2 and TP3)	10 sites	SPT- 9 sites CPT-22 sites	3 locations

Features	Bangladesh		India		Pakistan	Thailand	Vietnam	Indonesia	
Seismic Zone & Code	Zone II (BNBC-1993)	Zone III (BNBC-2015)	Zone III (IS-1893-Part I, 2002)	Zone III (IS-1893-Part I, 2002) (BIS 2000)	Moderate seismic zone provision 2B (Uniform Building Code)				
Settlement Calculation	-	Little and some cases extended up to 10 – 20m	-	-	-	-	-	0.46 m on CPT-21 0.05 m at CPT-22 site	
CSR	Seed et al., 1971	Seed et al., 1971	Seed et al., 1971	Seed et al., 1971 & 1982;	SPT-Seed et al., 1971	Seed et al., 1979		Seed et al., 1971	
CRR	Youd et al., 2001	Youd et al., 2001	Youd et al., 2001	Idriss et al., 2006	Idriss et al., 2006	Idriss et al., 2014	Idriss et al., 2014	Robertson et al., 1998	Idriss et al. 2008
FS		FS < 1 Liquefiable		FS < 1 Liquefiable					
	FS < 1 Liquefiable	1 < FS < 1.2 Marginally Liquefiable	FS < 1 Liquefiable	1 < FS < 1.2 Marginally Liquefiable	FS < 1 Liquefiable				
	FS > 1 Non-Liquefiable	FS > 1.2 Non-Liquefiable	FS > 1 Non-Liquefiable	FS > 1.2 Non-Liquefiable	FS > 1 Non-Liquefiable (Seed and Idriss, 1971).	FS < 1 Liquefiable (Idriss et al., 2006)	Boulanger & Idriss (2014).		
	(Iwasaki et al., 1978, 1982)	(Seed et al., 1971 and 1982; Ulusay et al., 2004;)	(Iwasaki et al., 1978, 1982)	(Seed et al., 1971 and 1982; Ulusay et al., 2004;)					
LPI Calculation	Iwasaki et al. (1982)	Seed et al., 1971 & 1982;	Iwasaki et al. (1978, 1982)	Seed et al., 1971 & 1982;	-	-	Iwasaki et al. (1982) Tonkin et al. (2013)		
Magnitude	7.5	5.5 & 7.5	6.5 & 7		6.5, 7 & 7.5	Tarlay earthquake	7	7	7.5
Maximum ground acceleration	0.15 g	0.28 g	0.16 g	0.2 g & 0.3 g	0.2 g	0.2 g	0.180 g		
Software used	-	Liquefy pro, Version 5 (2011)	LIQUITER	-	-	PLAXIS 2D V19		-	-
Method of Ground damage due to liquefaction	-	Boundary curves by (Ishihara, 1985)	-	-	-	-		-	

A low liquefaction zone was identified in the central research region, extending north-south, with outer areas ranging to highly liquefiable zones. Soils with SPT values >30 at depths >15–20 m are considered stable. Structures buried <20 m faced liquefaction damage. Ground improvement methods can reduce liquefaction risk: compaction densifies soil, PVD aids drainage, and DMM and grouting stabilize soft ground. Some sites show sensitivity to liquefaction, with varying degrees of vulnerability. The research region is moderately liquefiable at six strata. Geotechnical studies are vital for large structures. The DHA region of Karachi is at risk of liquefaction post-6.5 to 7.5 magnitude earthquakes. Liquefaction susceptibility increases with void ratio and confining pressure. SPT values and depth influence liquefaction potential. Site 5 is most likely to liquefy, while Site 10 is least likely. The research aids in forecasting soil liquefaction for the north-central coast of Vietnam. The west coast poses high liquefaction risk, with potential settlement up to 0.46m. The southern city portion has moderate liquefaction potential. The Yogyakarta airport region may experience liquefaction and requires mitigation measures.

6. CONCLUSION

This research underlines the urgent need to evaluate and mitigate soil failure caused by liquefaction in many Asian countries. Liquefaction may compromise not only the structural integrity of buildings but also that of underlying soils, thereby seriously endangering life, property, and infrastructure, as emphasized by Kongar et al. (2017). It was also noted that in-situ tests, such as the Standard Penetration Test (SPT), are the most widely used in the six Asian countries, but some countries have also adopted the Cone Penetration Test (CPT) because it is more reliable. Laboratory tests had also provided additional information on the liquefaction criteria regarding Seed et al. 1971, 1979, 1982, 1983 for SPT and Robertson et al. 1988, 2010 for CPT. Calculations of the LPI followed Iwasaki et al. (1982). Maximum ground accelerations used ranged from 0.15 g to 0.3 g. The typical range for earthquake magnitudes of 5.5 to 7.5 was used. Software for liquefaction analysis, like PLAXIS and LIQUITER, was used in only two countries.

Recommendations

- Implement SPT and CPT Together: Use both tests together as the first step for more realistic liquefaction assessments.
- Increase Laboratory Testing: Include advanced tests of soil properties in order to enhance the criteria.
- Utilize Techniques for Soil Improvement: Soil improvement techniques, including soil densification and grouting, should be applied to mitigate risks.
- Wider Application of Software: Software for advanced liquefaction analysis needs broader adoption.
- Develop Standard Guidelines: Development of standard guidelines, keeping local conditions in view for better preparedness, would be required.

The paper provides a good overview of the current state of liquefaction potential analysis in many Asian countries and identifies two key features of liquefaction: comprehensive testing and sophisticated analysis. However, major limitations are the variation in quality and in the protocols followed for testing in different countries, which introduces variability in the results. Further studies should focus on using standardized approaches and developing local guidelines for practical risk management. Improved testing, better soil analyses, and methods to stabilize soils are all necessary for mitigating liquefaction risks. Standardization of guidelines, along with wider adoption of more capable software, will lead to improved safety and resilience in the infrastructure.

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