Methods of Liquefaction Potential Evaluation– A Review

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A B S T R A C T

Liquefaction induced movements and leftover shear strength of the soil, which is very critical for analysis. Seismic occasions have an effect on floor conditions. This phenomenon of soil reasons instability in different type of structures. This occurs as a result of numerous instances of structural breakdown. The tensions of the load from the foundations cannot be preserved by the liquefied floor. Foundations that dip into the sand deposit cause the building to sag and eventually collapse. Regions with saturated soils are best suited for soil liquefaction.

So many various approaches to assessing soil liquefaction have been developed during the previous few decades for soil liquefaction assessment. Most of them use in open ground results like dynamic penetration test (SPT & CPT), paleo-seismic analysis and Shear Wave analysis & Velocity with site stratigraphy to assess the likelihood of soil strata liquefying. This article develops a more overview element based on available literature. A suggested method detailed in this review is used to identify the important soil compressibility parameters for the CPT-SPT correlations. This method helps to increase the consistency of the CPT-SPT correlations and offers a consistent pattern for crushable and non-crushable sands. Numerous empirical correlations have been proposed in siliceous soils to connect static cone tip resistance to SPT N-value.

Keywords: -Liquefaction, Soil, SPT, CPT, CRR, CSR, LiqiT and $V_{S.}$

1. Introduction

In a system known as liquefaction, the soil exhibits unsteady behavior, and seismic shaking weakens the soil's rigidity and strength. Liquefaction and associated phenomenon were liable for exquisite quantities of bad effects in historic seismic incidents worldwide. After analysis of the liquefaction of different regions with different specifications, reported by the many researchers, the soil layers have a SPT blow count where it defines that less than 14 blow count results of soil behave as liquefied soil and also defines soil layers having a accurate SPT blow count which is more than 20 are resistant to liquefaction. Concerning liquefaction, LiqiT soil software is also used to analyze soil response based on Cyclic Stress Ratio, Cyclic Resistance Ratio methods calculated by using Magnitude Scaling Factor, and Factor of Safety (Prasad et al., 2019).

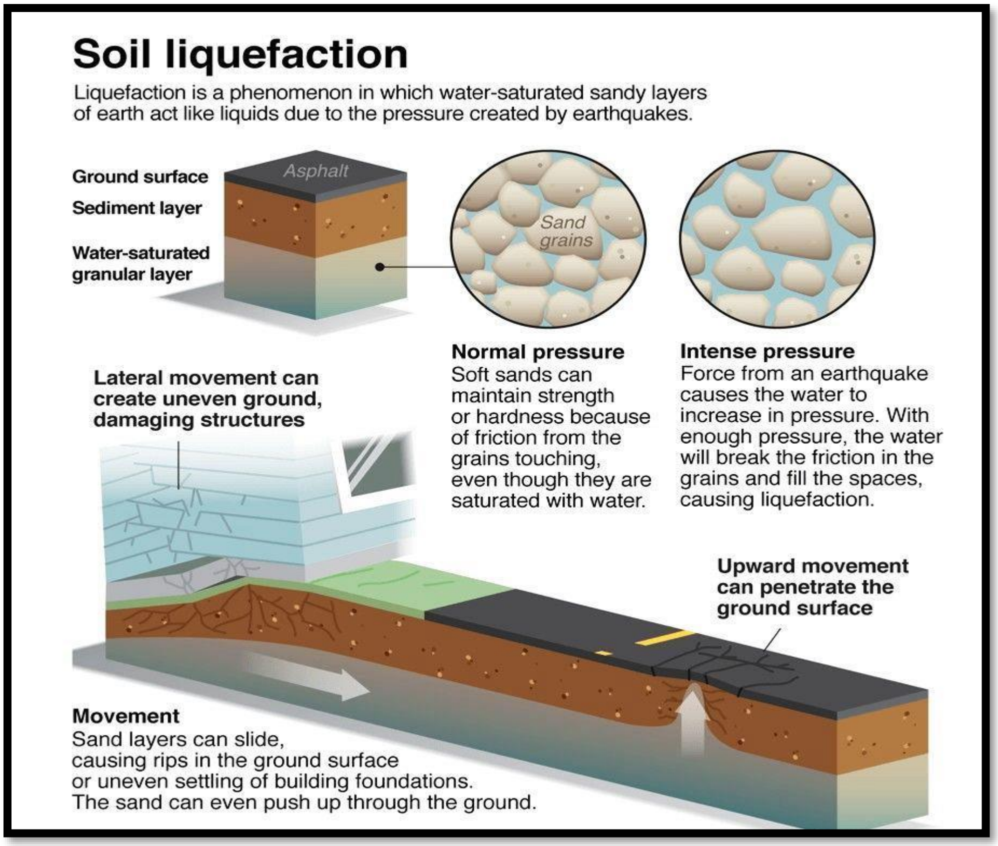


Figure: 1.1- Movement in Soil during Earthquake (Liquefaction), California Geological Survey By COREY G. JOHNSON

Empirical evidence has been used to support the development of analytical methods for determining liquefaction triggering by demonstrating the relationship between liquefaction resistance and various in-situ tests. The important country parameter and factors were utilized to determine many soil properties for tri-axial and plane stress cyclic loads (Nor Sand version) to evaluate the response of soil during seismic waves (Baki et al., 2012). For evaluation of the liquefaction problem, some data taken from the Semani site, located in Albania, established specific values for the evaluation of liquefaction and ground deformations brought on by liquefaction, such as lateral displacement and post-un solidification reconsolidation settlement (Boulanger and Idriss, 2008). In general, hazard analysis can be classified into two categories (Huang and Miao, 2017), liquefaction potential evaluation and liquefaction damage evaluation. This review introduces the assessment of the comprehensive behavior of soil liquefaction by mainly In-situ tests, dynamic laboratory tests, and dynamic model tests.

Summaries of the commonly used liquefaction methods like dynamic penetration test (SPT & CPT) and Shear Wave analysis have been given by Kuribayasi and Tatsiyoka (1975), Ishihara (1976), Chopra (2012), Chang et al.,(2014), Robertson (2015), Adhikari and D'Ayala (2019), Wang and Manga (2009), Zhu et al. (2021), Amantaand Dasaka (2021).

Table 1: Overview of the Reviewed Literatures

S. No.	Author	liquefaction methods	Soil Profile	Justification
1	Kuribayasi and Tatsiyoka	Re- liquefaction observation and case study of many Regions.	Alluvial soil and Sandy soil	To correlate the actual liquefaction phenomena and site conditions, this survey is about liquefaction process during different earthquake in Different area of Japan.
2	Ishihara et al.	Cyclic Tri-axial Shear Test.	Saturated sandy soil	To adopt this methodology for numerical computation of pore water pressure and to introduce a few additional assumptions and modifications.
3	Chopra et al.	Peak ground acceleration (PGA) and Modified Mercalli Intensity (MMI).	Clay loam type	In Kachchh region the unstable hazard is most in eastern components, moderate in central components and minimum in western components. These acceleration and MMI method is used to analyze maximum displacement per unit area.
4	Chang et al.	SPT tests down to a depth of 11 m & MAM & MASW.	Saturated sandy soil	This analysis adopt to outlined that SPT & CPT technique is not that much easy and correct because the instruments in MAM or MASW surveys are normal geophones used to analyze vibration.
5	P. K. Robertson	Comparing dynamic penetration test (CPT) based and shear wave based Methods.	Sandy soil (High fines)	To evaluate the differences between the VS-based and CPT-based liquefaction triggering methodologies in order to evaluate the corresponding CPT-based adjustments.
6	Adhikari and D'Ayala.	PRE & POST-SMM typology, seismic analysis by modeling of SMM building, analysis of Uniaxial, Lateral- shear	Clay loam, Sandy loam and Silty loam soils	The seismic capabilities of the PRE-SMM classification is very poor in all major directions, with the shorter direction being the weakest, making it impossible to determine the seismic

		and bending compression behavior.		vibration effects inside which direction.
7	Wang C.Y. and Manga M.	Field tests of earth's hydrologic system	Tanana earth (poorly drained soil)	Although well-graded gravel has increasingly been observed to liquefy during earthquakes and isn't just the product of entrainment by liquefied sand, liquefied sediments are typically sand or silty sand in most situations. It is difficult to explain how pore pressure may accumulate in stony soils and be kept at a level high enough to trigger liquefaction.
8	Zhu et al.	Depositional Methods (between Dry Funnel and Water Sedimentation), Tri-axial test.	Loose silty sand	Two phenomena are compared using the triaxial test: the collapsibility of loose sand samples reconstituted in an overly dry state was very low; and (ii) the rise in fines fraction may, to some extent, increase the collapsibility potential.
9	Amantaand Dasaka	Cyclic Tri-axial Shear Test.	Saturated granular soil	The volume of water that entered the sample as a result of air injection was collected and continuously quantified during the de-saturation procedure in order to introduce the change in volume following state change. Additionally, the specimen's volume change was correctly tracked during the de-saturation process.

Ibrahim (2014) proposed a method for liquefaction analysis of the Bedsa soil profile using SPT, CPT, and VS methodologies, which explain liquefaction due to the existence of loose sandy silt layers that lie near sandy profile areas. On the basis of this theory, a comparison was made based on CPT triggering method and V_S based procedure (Wride and Robertson, 1998). This comparison describes two V_S coefficients and the correlations predict an average V_S result for both calcium and silica based soils, the above-mentioned analysis demonstrates a consistent CPT–SPT relationship.

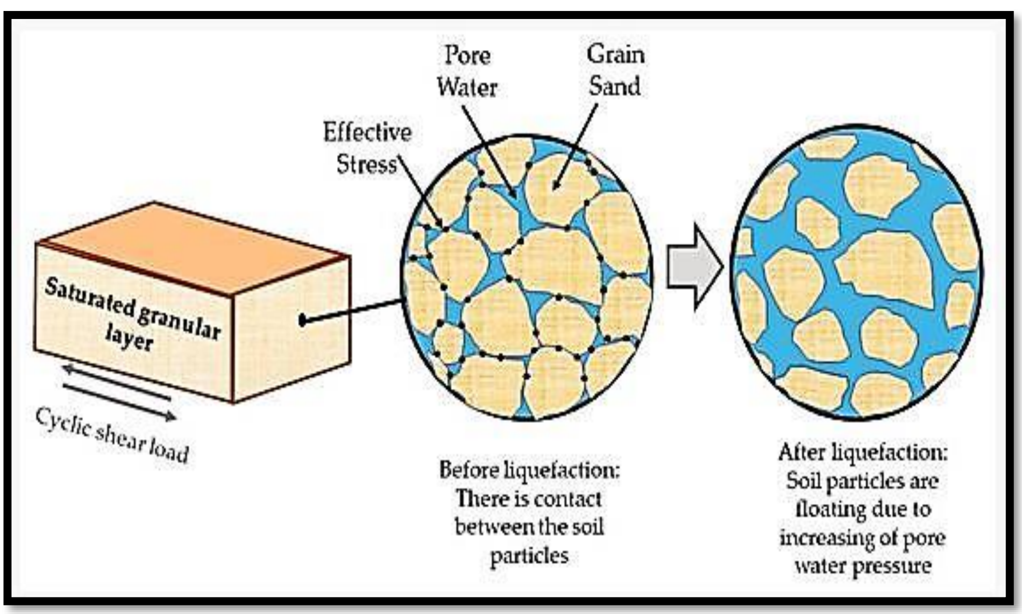
Various liquefaction methods comprise that SPT and CPT method is not very much simple and accurate as the instruments in MAM (Micro tremor Analysis Method) or MASW (Multichannel

Analysis of Surface Waves). In this surveys standard geophones used to analyze vibration (Shelley et al., 2014).

In the cyclic load method analysis, the cyclic pair passes a high-risk zone just after it triggers cyclic instability, as established by a corresponding monotonic loading test. It has been found that developed terrain with thick layers of soft soil and low groundwater levels is more prone to liquefaction. The results of cyclic un-drained experiments on loose soils clearly demonstrate that partially saturated soils exhibit enhanced resistance at saturation levels that are only a small percentage below 100 (Pietruszczak et al., 2003). The fixed-base and free-top resonant column tests produced specimens with dimensions resembling those of the tri-axial tests, which demonstrated the formation of liquefaction pore pressure at low strains. The effective stress ratios that cause instability were presented with a range to show the degree of uncertainty surrounding that respective area (Fatahi et al., 2014).

2. Positioning of studies in terms of theory

In saturated and cohesion-free soils, liquefaction refers to the loss of strength brought on by rising pore water pressures and decreasing effective stresses brought on by dynamic loading. It is a process in which the shear strength and stiffness of soil are decreased as a result of rapid loading or earthquake shaking (seismic effect). Post state change yield acceleration exploitation may be used to determine the soil's residual shear strength, which corresponds to the minimal strength that the lateral spreading is mobilized. The displacement of lateral spreading will be estimated using a new mark sliding block approach because lateral spreading is the horizontal displacement of soil underlain by liquefied soil once the phase transition is triggered (Yang et al., 2020).



<u>Figure: 2.1- Movement in Soil before and after Liquefaction, Department of Structural and Geotechnical Engineering, Santiago</u>

In order to recognize phase transition, it is necessary to understand the conditions that exist before an earthquake in a particular soil deposit. The majority of soil is made up of various types of soil particles that are constantly in contact with other nearby soil particles. The weight of the overlying particles creates contact forces that hold each soil particle firmly in place and give the soil its strength.

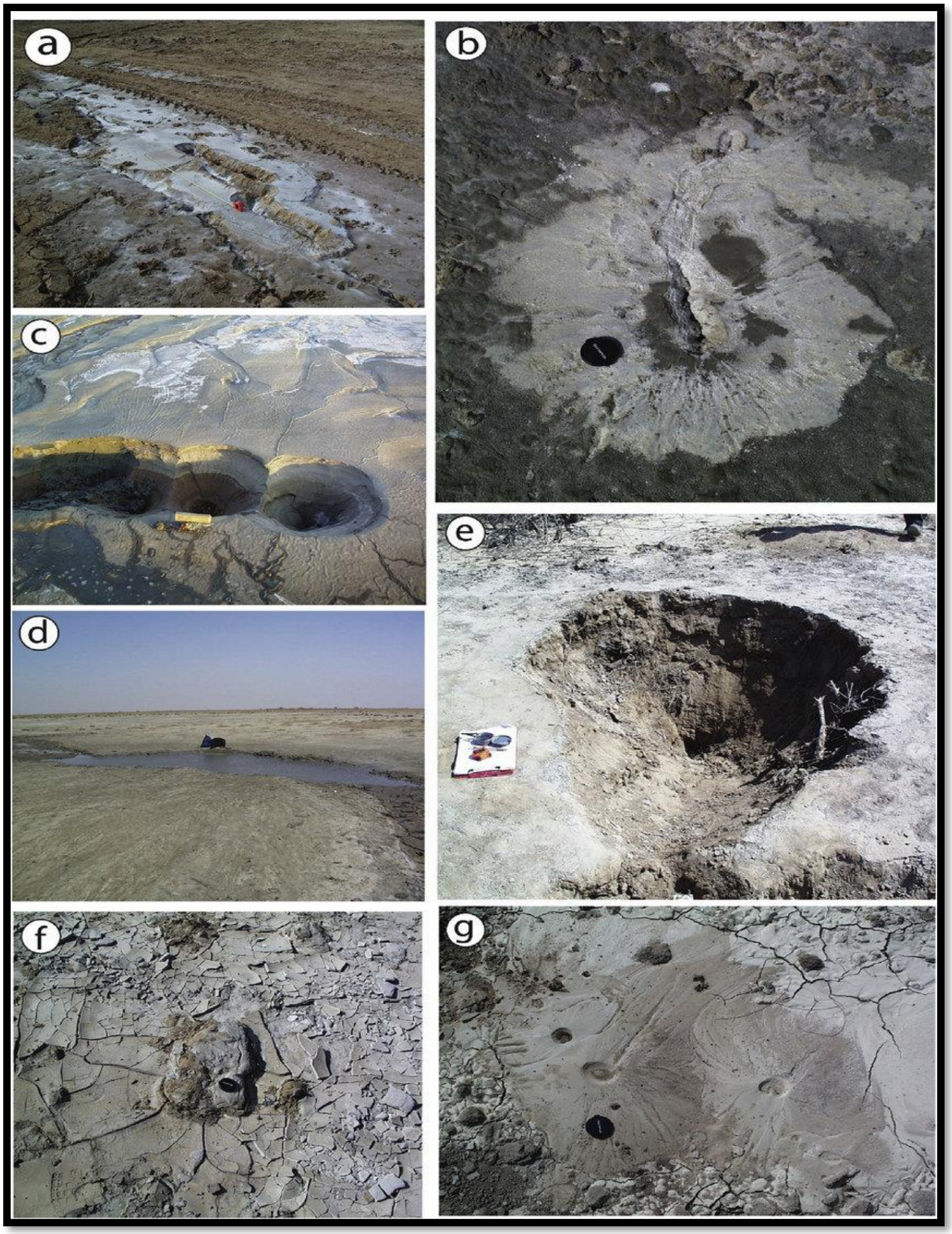


Figure: 2.2- Photos taken on the ground document the liquefaction caused by the 2001 Bhuj earthquake at (a) Chaubari; (b) Baneeari; (c) Kandala port; (d) Umeedpur; (e) dry crater at Umeedpur; (f) mudejecta from crater at Umedpur; (g) sand blow at Budhamora.

2.1 Past records of liquefaction

Since many years ago, liquefaction has been noted in association with earthquakes. In fact, written documents dating back hundreds of years contain reports of earthquake impacts that are now understood to be related to liquefaction. On the other hand, liquefaction has been so pervasive in recent earthquakes that it is frequently linked to them. Some of such incidents are significant.

Table 2: Past records of liquefaction

S. No.	Date	Place	Magnitude (Richter Scale)	Seismic Zone	Areas affected	Scale of Damage
1	20 Nov. 2021	Barranca Peru	7.5	II & V	Peru, Ecuador	A total of 4189 individuals became homeless once the quake broken several homes. 70% of homes were broken, together with 1976 completely destroyed. A second fatality was reported on twenty nine November. The three-year-old kid was killed by falling wood in Bongara Province. AN older person is additionally missing.
2	25 April 2015	Kathmandu , Nepal	7.8	V	Kathmandu, Central and Southern area of Nepal	The Kathmandu Valley experienced extensive soil liquefaction following the 2015 Gorkha Earthquake (Mw7.8). In order to ensure the safety liquefaction assessed by Standard Penetration Test. A comparison of the assessment results with 3 location observed during the 2015 Gorkha Earthquake validates the results. Based on back analysis, target SPT-N values (improved) are determined to ensure no liquefaction occurs.
3	18 Sept. 2011	Sikkim, India	6.9	IV	India, Bangladesh, Nepal, Bhutan, and	In North Sikkim's Pegoung regions, two of the Indo-Tibeetan Border Police's buildings collapsed. Several government facilities, including hospitals, were closed in Gangtok. The

					China	settlements of Lingzya, Sakyong, Pentoung, Bay, and Tholoung were completely destroyed by the considerable shaking. When a wall structure at the land Embassy collapsed, 3 people died.
4	08 Oct. 2005	Kashmir, India	7.6	Himalaya seismic zone.	Pakistan, India	Muzaffarabaad, the capital of the region ruled by Pakistan, was the heaviest hit in terms of casualties and destruction out of the three main districts in Kashmir. 85,900–87350 people are dead, 68,997–75,264 are hurt, and 2.8 million are displaced.
5	26 Jan. 2001	Bhuj, Gujrat	7.5	IV	Pakistan, India	Within the Kutch region, the cost was 12,297. Bhuj, which was only twenty kilometer from the epicenter of earthquake, was completely destroyed. The historic Swami Narayan Mandir, Praag Mahal, and Aaina Mahal and forts, as well as four hundredths of residences, eight colleges, two hospitals, and four kilometers of roads in Bhuj, were all badly destroyed by the earthquake.
6	21 Sept 1999	Chi-Chi, Taiwan	7.6	IV	Taiwan	51709 structures were destroyed, 2415 were murdered, 29 were missing, 11305 were hurt, and 53768 were damaged. Various damages has been generates in Central Taiwan, Northern Taiwan and Economic damage has been very broad.
7	28 Mar 1999	Chamoli, Rudrapr-ayag, India	6.6	IV	India	The price was 103. Many hundred people were scraped and just about 50,000 homes were broken. Over 2,000 villages were stricken by the earthquake.

3. Methodology

Semi-empirical methods were employed retest and improve the evaluation of the potential for liquefaction of saturated cohesion-less soils during earthquakes for usage in the field (Idriss and Boulanger,2008). Modified relationships were presented for a number of parameters, including the various factors like stress reduction (rd), seismic intensity scaling index for cyclic stress ratios (MSF), adjustment factor for cyclic stress ratios (K), and the overburden consolidation factor for penetration resistance values (CN). The case history databases of SPT and CPT were re-evaluated using these changed relations. It was advised to employ these reevaluations in practice and to make changes to the SPT and correlations for liquefaction utilizing CPT. Additionally, procedures based on the speed of the shear wave and techniques for evaluating the cyclic loading behavior of plastic fine-grained soils were addressed.

3.1 Semi-Empirical Procedures for Evaluating Liquefaction Potential

Typically, semi-empirical field-based methods for determining the likelihood of liquefaction during earthquakes involve two steps:

a) Developing an analytical framework to classify previous case study experiences; And
b) The creation of a suitable in-situ index to represent soil liquefaction configuration (Ahmad et al., 2014)

The original simple method (Idriss and Seed, 1971) for computing cyclic shear stresses brought up by seismic events remains a crucial part of this analysis sequence, even though the individual components have been reevaluated. Their research improves semi-empirical field-based methods for estimating the probability that non-cohesive soils would liquefy during earthquakes.

The stress reduction (rd), seismic intensity scaling index for cyclic stress ratios (MSF), adjustment factor for cyclic stress ratios (K), and the overburden consolidation factor for penetration resistance values (CN) are all recommended relations in this update.

3.2 CPT, SPT and Shear Wave Test

In the 1964 Nigata seismic event in Japan (Ishihara, 1977), semi-empirical methodologies for liquefaction potential analysis were found and applied using the SPT for distinguishing liquefiable circumstances and non-liquefiable conditions. A empirical method to distinguish between situations that are liquefiable and those that are not for many SPT data from big seismic events discussed like earthquakes in 1999: the Chi-Chi earthquake in Taiwan (mag. Mw=7.6) and Bhuj earthquake (mag. Mw=7.5),(Lin et al.,2021).

According to Raghukanth and Iyengar, (2007), where liquefaction was analyzed in Mumbai city, significant fault lines under Thane, Panvel, and Dhaaramtar creeks are located all around Mumbai. To assess the liquefaction potential in accordance with their recommendations using the SPT simplified procedure. The element of safety for typical values is shown against liquefaction for magnitudes to compare the two factors. Liquefaction capability has been shown in the form of contour lines following evaluation using the SPT method. As an outcome, the contour maps with a high degree of phase transition failures may be introduced at various locations around the town during powerful seismic waves.

Table 3: Comparison between SPT, CPT, Shear Wave analysis and Paleo-Seismic

Methodology	Sampler Type	Penetration Technique	Types of Soil	Limitation	Determination	Result	Process of Data collection
Standard Penetration Test (SPT)	Split Spoon	Seating Drive with Depth (driven by no. of blows)	Fine Grained Sands	Can be perform in any type of soil	Soil behavior, Pore pressure & Relative density	Inconsistent	Continuous
Cone Penetration Test (CPT)	Cone	20mm/s Speed with Target Depth (driven by tip of the cone)	Sand and Clay	Cannot be perform in any type of soil	Soil behavior, Pore pressure, sleeve friction & Shear wave velocity	Consistent	Intermittent
Shear Wave (V_s)	Using Surface Wave	Multichannel Analysis of Surface Wave (MASW) **or** Micro tremor Analysis Method (MAM)	Cohesion less and Cohesive soil	Can be perform in any type of soil	Shear wave velocity in different depth	Consistent	Continuous
Paleo-Seismic	Seismic wave	moment magnitude or surface wave magnitude	Sands and granular material	Loose soil	Sediment deformation, shear wave velocity and pore pressure	Inconsistent	Intermittent

3.3 LiqiT Software

This software is used for liquefaction of saturated cohesion less soil under the effect of seismic or strong motion; this is used for evaluation of the potential for liquefaction based on CPT, SPT, and V_s state methods (Prasad et al., 2019). It provides vertical settlements and lateral displacements due to liquefaction with accuracy.

3.3.1 General Parameters

There are parameters for the Cyclic Stress Ratio calculation under the section titled "General Parameters" (CSR). The following formula, which was first presented by Seed and Idriss (1971), is used to calculate CSR.

$$CSR= \tau_{(av)}/\sigma'_v = 0.65(\sigma_v/\sigma'_v)(a_{(max)}/g)\, r_d$$

Where:

- 0.65 : reduction factor transforming the "equivalent uniform shear stress" from the single or one-time peak cyclic stress.
- a_{max}: the maximum ground acceleration, measured in g.
- r_d : Stress reduction coefficient that takes the soil profile's flexibility into consideration.
- σ_v : total vertical stress from overburden.
- σ'_v : an efficient vertical overburden stress.

3.3.2 Data Input

Figure 3.1 shows input data sheet used in LiqiT software to enter SPT values accordingly. Where:

- Depth: Depth at which the field tests was performed.
- q_c and f_s: The load applied at different blow count (for a penetration depth of 30 cm or 1 ft).
- Gamma: The unit mass of soil at the test depth. If no value is entered, the software considers it equal to the value entered in the previous cell, if no value is entered in the previous cell, 19 kN/m³ is assumed.
- Fines: Percentage of fines in the soil in which the test was performed. If no value is entered, the software assumes granularity equal to the value entered in the previous cell, or 0.00% if no value is entered in the previous cell.

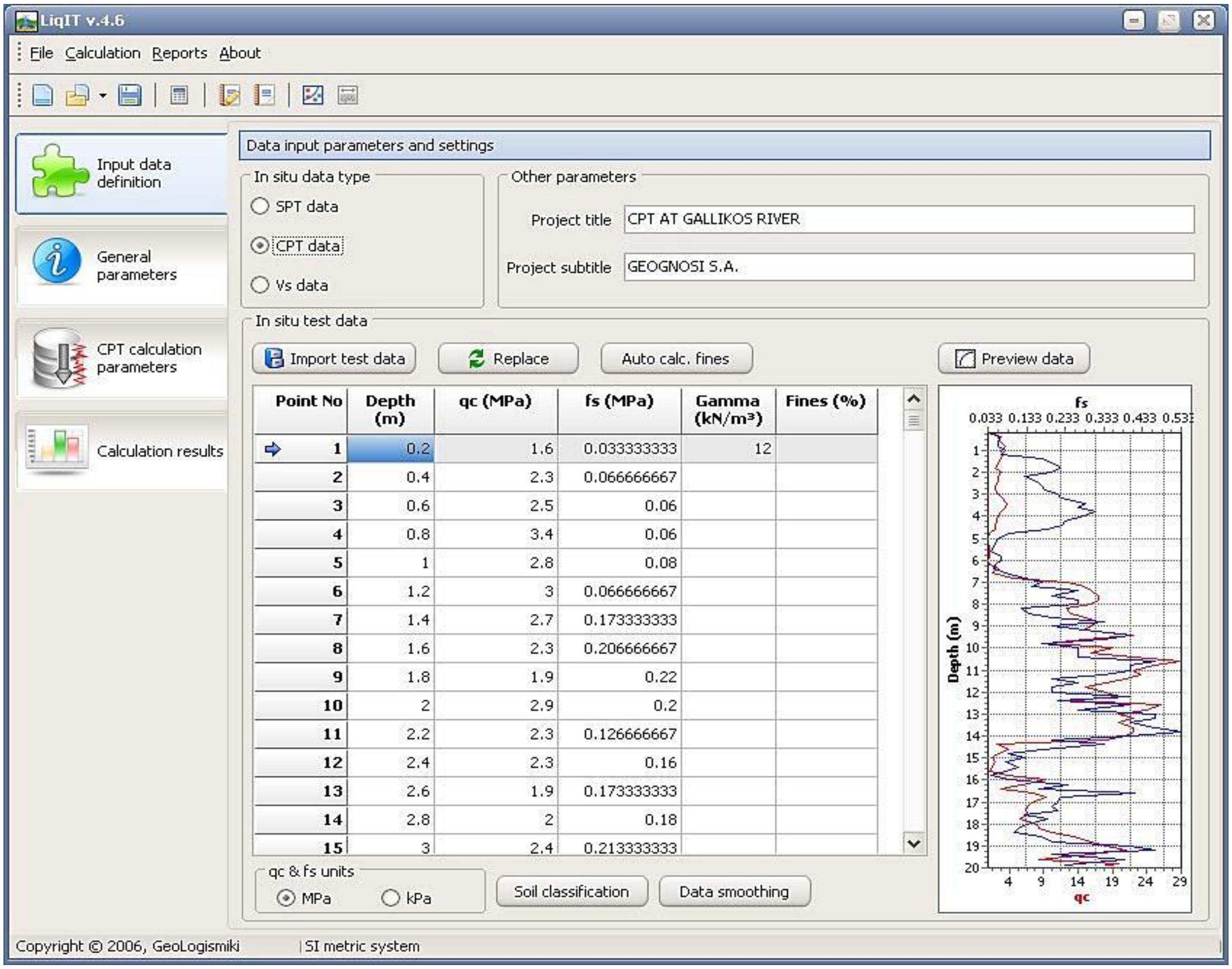


Figure: 3.1 - LiqIT main window, SPT and Wave Shear field data, LiqIT-v-4-7 Liquefaction analysis software by Geologismiki

3.3.3 Calculation and Result

Once all the required data has been entered, the liquefaction potential assessment is calculated by clicking the icon in the toolbar or by clicking on the icon located on the toolbar or on the menu Calculation then Run calculation. This also applies if input data, general parameters and/or calculation parameters are changed.

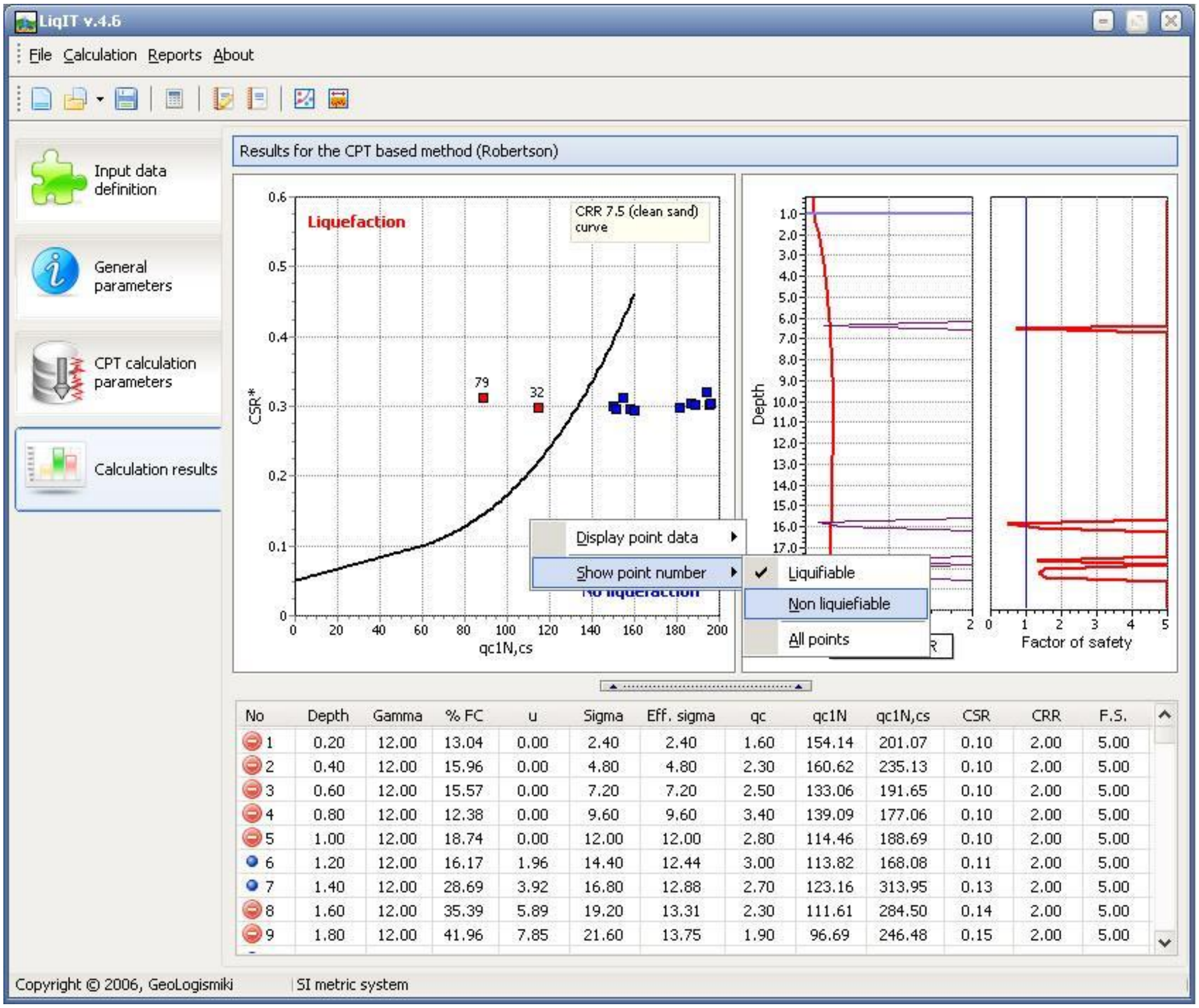


Figure: 3.2 – Result of Liquefaction of cohesion less soils, LiqIT-v-4-7-Liquefaction analysis software by Geologismiki

LiqIT generates graphs (accor-d-ing to the in-situ data type selected) and a table with the analysis basic results (figure-3.2), as well as a report with the analysis analytical results (figure-3.2).

4. Conclusion and Discussion

In this conclusion and in step with the studies of the many literatures, it's helpful to develop the correlation between CPT and SPT, as a result of once correlating we will get plentiful data supported SPT. We would like to underline the importance of the correlation between the two ways, SPT and CPT. We summarized conclusions in following points:

- Most of the researchers firstly select a specific location and Identify problems generates related to the soil of that location's surface. So because of the different soil profiles, the soil's shear strength is somewhat decreased as a result of liquefaction. The degree of the shear strength loss will have a significant impact on how the liquefaction behaves, whether it be substantial or minor.

- According to the historical data analysis, the mean energy quantitative relation was not recorded once the SPT was performed even supposing the quality donut-type hammer with 2 turning ropes around the cathead was used. Therefore, we tend to not recognize the energy applied during this space which could also be the rationale why the historical information worth and a new gained value are a small amount totally different.

- The SPT method's assessment states that soil liquefaction can occur as deep as 20 meters, and this test demonstrated that medium-density sand layers as deep as 30 meters could liquefy. This method was also investigated by technical demand parameters and with help of the soil model and its parameters also used the CPT method for correlation between SPT & CPT.

- On the other hand, the Cone Penetration Test (CPT) method is one of the most common methods, which are mostly used to identify the response of cohesive soils during liquefaction. It is not that suitable for any type of soil applications like discipline explorations, layout parameters, and first-rate control assessments.

- On the basis of their analysis, they adopted mostly CPT, SPT & Shear wave methods to analyze the different factors of this problem to resolve or decrease the effect of the hazard and protect soil from liquefaction. Many researchers used this method because of its accuracy and a real problem and data outcomes.

- LiqiT Software is an application based on SPT & CPT parameters and it gives the same result. Advantages of this application reduce the time for assessment, the best result, applies to any type of soil and it provides various factors according to cohesive or non-cohesive soil.

- Reviewing papers and analyzing various approaches identified about the behavior of soil during high vibrations:

    a) The direction of the lateral spread's extension is fixed.
    b) In areas with sand or muddy clay where the flow of water is mostly parallel.

- Finally, it is concluded that all the methods used by the various researchers are good to acknowledge the behavior of soil and ground surface response during earthquakes but they are not capable to protect soil from liquefaction, we should identify the precautions or provide protection to the soil, especially in important sectors from before and after earthquake hazards.

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