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Assessment Probability of Soil Liquefaction Potential Based on SPT Data with NovoLIQ Application

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ABSTRACT

Liquefaction is a geological phenomenon that occurs when soil loses its strength due to a shock, such as an earthquake, and becomes semi-liquid. Liquefaction usually occurs in water-saturated sandy soils that are subjected to seismic stress. During an earthquake, the pore water pressure in the soil increases, causing the soil grains to lose contact with each other and resulting in the soil becoming unstable and behaving like a liquid. This process can have serious impacts on building structures and the infrastructure above them, such as foundation shifts, building tilting, and structural collapse. Kulonprogo area is one of the areas that has a variety of soil types ranging from silt to sandy with a shallow groundwater table and is one of areas that according to BMKG, Kulonprogo area is included in the area that has the potential to be affected by megathrust. Seeing from this, the Kulonprogo area has a high liquefaction potential. Based on this, this research will calculate the liquefaction potential in the Kulonprogo area using Standart Penetration Test data. SPT testing is carried out to a depth of 30 meters to evaluate the characteristics of soil layers and obtain N-SPT values that reflect the density and strength of the soil in each layer. the soil data will be processed using Novoliq software to determine the liquefaction potential analysis. The calculation is carried out by determining the CRR and Safety Factor and then calculating the percentage probability of occurrence. The results of SPT testing at depths of up to 30 meters show a variety of soil types ranging from low plasticity silt in the upper layers to sand. The data was carried out with NovoLIQ Application to assessment probability of soil liquefaction. The results obtained obtained the CRR value on average at each depth is between 0.32-0.4 with SF between 1.04-1.73 which has a Liquefaction potential according to Youd and Nobel's theory of 26,6%-44,6% and according to Centin's theory of 65,1%-100%. According to SF calculations using the Boulanger and Idris theory, Vancouver Task Force, and Japanese Highway Bridge Code, soil with liquefaction potential begins at a depth of 7 ft with an SF of less than 1. This makes the Kulonprogo area have a high potential for Liquefaction, especially if a megathrust earthquake occurs.

1. Introduction

Indonesia is one of the countries located in an earthquake-prone area because it is located at the confluence of three active tectonic plates, namely the Eurasian Plate, the Indo-Australian Plate, and the Pacific Plate. This tectonic activity causes Indonesia to be frequently hit by earthquakes with moderate to high intensity [1]. One of the serious impacts of earthquakes is liquefaction, a geological phenomenon in which soil loses its strength and stiffness, turning semi-liquid due to increased pore water pressure during seismic events [2], [3].

Liquefaction occurs due to excess pore water pressure arising from sudden and rapid loading in undrained conditions. This loading can be in the form of earthquake tremors in the form of cyclic shear stresses [4]. Liquefaction usually occurs in water-saturated sandy soils, especially in areas with a shallow groundwater table, where the water table affects the safety factor value against liquefaction [5]. When an earthquake occurs, the shaking causes the pore water pressure to increase suddenly, which makes the soil grains lose contact with each other [3], [6]. s a result, the soil becomes unstable and unable to withstand the load on it. The impacts of liquefaction are devastating, including shifting of building foundations, tilting of structures, and even complete collapse. Liquefaction can also occur not only due to vibration but also liquefaction in the subsoil. This event is often called sandboil. Sandboil happens when the sand layer at a certain depth liquefies and affects the stability of the structure above it. In this event, the pore pressure in

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the sand layer increases due to the loading above, this excess pore pressure causes water to rise upwards, and if the hydraulic gradient is high, the sand grains also rise upwards [7].

Liquefaction is influenced by several factors, including earthquake shaking in the form of earthquake intensity and duration [8], [9], [10], [11]. The intensity of the earthquake is influenced by the magnitude and distance of the earthquake source; the greater the magnitude and the closer the location to the epicentral, the greater the intensity of the earthquake that occurs, and the magnitude of this earthquake will cause overburden pressure [12]. This results in the magnitude of the shear strain caused by the earthquake on soil compaction, which increases soil pore pressure. Generally, liquefaction occurs at a large earthquake intensity with a long duration [13].

In addition to earthquakes, other factors are soil conditions in the form of soil density, soil grain shape, soil grain gradation, soil saturation degree, and soil layer thickness [14], [15], [16], [17]. Liquefaction occurs in fine to medium sand soils. Soil density itself plays a major role in liquefaction. Loose sand with Dr <50% has a large liquefaction potential, while sand with densities ranging from 75% tends not to liquefy easily [2]. Soils with uniform grains and not plastic tend to be more prone to liquefaction [18]. Other factors that determine liquefaction are the condition of the water table and drainage [19]. Liquefaction occurs in saturated soils, so a shallow water table leads to greater liquefaction potential [9].

One of the areas in Indonesia that has a high potential for liquefaction is Kulonprogo Regency, which is located in the western part of the Special Region of Yogyakarta. Based on data from the Meteorology, Climatology, and Geophysics Agency (BMKG), this region is included in the zone potentially affected by earthquakes from the southern Java subduction zone [20]. Geologically, Kulonprogo has a complex variety of soil types, ranging from silt to sand [21], as well as a relatively shallow water table - two major factors that are indicators of susceptibility to liquefaction. Looking back at the rumors about the potential megathrust, Kulonprogo is one of the affected areas. Considering these conditions, it is very important to study the liquefaction potential in this region as an initial step in disaster mitigation. This research aims to calculate the liquefaction potential in the Kulonprogo region using the Cone Penetration Test (CPT) testing method. CPT testing provides information on soil technical characteristics [22], [23], such as density, shear strength, and soil type in each layer, and is used to obtain Standard Penetration Test (N-SPT) values, which are the basis for calculating liquefaction parameters [24], [25]. Later, this study is expected to provide accurate technical information about liquefaction potential in the Kulonprogo area and become an important reference in infrastructure development planning and geotechnical disaster risk mitigation strategies in the future.

Assessing soil liquefaction potential is a crucial aspect of geotechnical risk planning and mitigation, especially in earthquake-prone areas. As the need for quick, accurate, and field-data-based analysis grows, various empirical and semi-empirical methods have been developed to evaluate the Cyclic Stress Ratio (CSR) and Cyclic Resistance Ratio (CRR), two key parameters in liquefaction analysis. Among the available software options, NovoLIQ stands out as an application that integrates the latest theories with a practical and user-friendly interface.

The NovoLIQ application is developed based on a semi-empirical approach that references various cutting-edge theories, such as the Boulanger & Idriss (2014) method for N-SPT and CPT approaches, and allows for parameter adjustments according to local conditions and soil types. Additionally, this tool accommodates approaches from previous studies such as Youd et al. (2001), Seed & Idriss (1971), and modern probabilistic approaches like Cetin et al. (2004). This development demonstrates the integration of classical and contemporary theories within a simplified digital analysis system.

One of the main advantages of NovoLIQ lies in the ease of data input and the intuitive display of analysis results. Users only need to enter soil parameters from SPT/CPT tests, groundwater conditions, and earthquake parameters, and the application automatically calculates CSR, CRR, and the safety factor (Factor of Safety) against liquefaction. Additionally, the visualization of results in graphical and tabular formats facilitates the interpretation of soil layers prone to liquefaction, thereby greatly aiding in technical decision-making.

In terms of calculation accuracy, NovoLIQ has proven to deliver reliable results comparable to manual methods and more complex software. Validation against field data shows that the calculation results for the safety factor against liquefaction using NovoLIQ have a small deviation, provided that the input data used has been corrected and calibrated according to standards. Thus, the use of NovoLIQ can improve time efficiency, reduce the potential for human error in manual calculations, and provide a reliable platform for feasibility studies and geotechnical design.

The purpose of this research is to analyzed soil characteristics in the Kulonprogo region based on the results of the Standard Penetration Test (SPT). Besides that, the data will be processed and analyzed to obtain the Standard Penetration Test (N-SPT), Cyclic Resistance Ratio (CRR), and Safety Factor (SF) values as indicators of liquefaction potential in each soil layer. With that, it can later determine the level of liquefaction potential in the Kulonprogo area.

2. Methods

Evaluation of liquefaction potential was conducted in Kulonprogo, Yogyakarta; Data were collected in Sidatan Village, Kalidengen, Temon, Kulonprogo, Yogyakarta. at coordinates E S; 110°05'22.4”. Data was collected using the Standard Penetration Test (SPT) by obtaining N-SPT at each depth of the soil layer. In addition, other soil characteristics testing was also carried out to determine the type of soil and soil strength. The tests are moisture content, specific gravity, liquid limit, plastic limit, plastic index, void ratio, cohesion, friction angle, and coefficient of permeability.

Furthermore, the soil data will be processed using Novoliq software to determine the liquefaction potential analysis. The calculation is carried out by determining the CRR and Safety Factor and then calculating the percentage probability of occurrence. Earthquake data input refers to the magnitude of the megathrust earthquake with magnitude 8 and shallow depth [26], [27]. The depth of groundwater is obtained through the Boring and SPT data obtained.

2.1 Data Processing using NovoLIQ

Data processing was performed using NovoLIQ, geotechnical software used to assess soil liquefaction potential based on a semi-empirical approach. This method involves comparing the Cyclic Stress Ratio (CSR), which represents seismic loading, with the Cyclic Resistance Ratio (CRR), which represents soil resistance to liquefaction. The steps involved in data processing using NovoLIQ are as follows:

Data Preparation

The required field and laboratory data include Standard Penetration Test (SPT) results at various depths, soil specific gravity (γ), water content, and soil classification, groundwater table (GWT) depth, and earthquake parameters such as maximum ground acceleration (PGA) and earthquake magnitude.

Data Input into NovoLIQ

Data is entered into the NovoLIQ interface, including soil profiles based on depth (layers), adjusted N-SPT values (adjusted for energy ratio, overburden pressure, etc.), earthquake and groundwater information, and soil density (both dry and wet) for each layer.

CSR and CRR calculations

NovoLIQ automatically calculates CSR based on the equation by Seed & Idriss (1971) and CRR using corrected SPT values, following the empirical graph proposed by Youd et al. (2001) or Idriss & Boulanger (2008).

Liquefaction Potential Evaluation (Safety Factor)

The Safety Factor (SF) against liquefaction is calculated using the equation:

$$FS = \frac{CRR}{CSR} \quad (1)$$

f SF < 1, the soil layer at that depth is considered susceptible to liquefaction.

Interpretation of Results

The output includes graphical representations of CSR and CRR based on depth, as well as FS values for each soil layer. These results are used to identify depths with liquefaction potential and as a basis for designing mitigation measures.

Validation and Review

The analysis results are reviewed to ensure consistency with local geological conditions and the reliability of field data.

2.2 Liquefaction Analysis

Liquefaction analysis was conducted using several formulas to obtain the Cyclic Resistance Ratio (CRR) and Cyclic Stress Ratio (CSR) values. CRR itself is the liquefaction resistance of soil obtained from soil index parameters obtained by geotechnical tests such as SPT testing [22]. The liquefaction potential analysis is based on the safety factor value calculated by the ratio between CRR and CSR [28]. The procedure for calculating CRR, CSR, and safety factor values is based on the research of Seed and Indriss 1982, Youd et al. 2001, and Cetlin et al. 2018 [28], [29], [30].

3. Result and Discussion

3.1 Physical Properties of Soil

The physical and mechanical properties of the soil strongly influence liquefaction potential. Loose, water-saturated, sandy soils with uniform grain distribution and low density are most susceptible to liquefaction. Therefore, understanding soil properties is essential in planning building structures and disaster mitigation in earthquake-prone areas.

Table 1. Physical properties of soil

No	Physical Properties	Deep (7-13 ft)	Deep (20-98 ft)	Unit
1	Moisture Content	57.88	24.7	%
2	Specific Gravity	2.59	2.78	-
3	Liquid Limit	66.31	Non Plastic	%
4	Plastic Limit	43.16		%
5	Plasticity Index	23.15		%
6	Liquidity Index	2.20		%
7	Void Ratio	4.09	0.97	e
8	Finer #200	69.68	0.53	%
9	Cohesion	0.03	0.01	Kg/cm^2
10	Friction angle	4.7	29.86	^{o}

Table 1 shows the results of soil properties. When viewed from the USCS classification, the soil is included in the MH soil classification for depths of 2-4 meter and SP at depths of 4-30 meter. In the USCS (Unified Soil Classification System) classification, MH and SP soils exhibit different physical and mechanical characteristics, which significantly impact liquefaction potential, especially in earthquake-prone areas.

MH soils are inorganic silts with high plasticity, characterized by fine grain size and plastic behavior when wet. Although they have low bearing capacity and high compressibility, internal cohesion due to their plastic properties makes MH soils generally less susceptible to liquefaction. However, under saturated and disturbed conditions, some MH soils still tend to decrease in shear strength due to increased pore pressure, although not as intensely as non-cohesive soils.

In contrast, SP soils, which are classified as poorly graded sands, show a much higher liquefaction potential. Sands with a uniform grain size distribution, such as SP, tend to have a loose and less stable structure, especially under water-saturated conditions. When dynamic loads such as earthquakes occur, the contact between sand grains is drastically reduced due to increased pore water pressure, causing a sudden loss of shear strength. Therefore, SP soils, especially in loose and saturated conditions, are considered one of the most susceptible soil types to liquefaction [5]. In loose materials, the softening is also accompanied by a loss of shear strength that may lead to large shear deformations. Liquefaction in moderately dense to dense materials leads to transient softening and increased cyclic shear strains. However, a tendency to dilate during shear inhibits major strength loss and large ground deformations [29].

3.2 Standard Penetration Test (SPT) Results

Standard Penetration Test (SPT) is a commonly used method in soil investigation to evaluate liquefaction potential in earthquake-prone areas. Several important parameters obtained or calculated from SPT test results, such as overburden pressure, fines content, and relative density, directly influence the susceptibility of a soil layer to liquefaction. Overburden pressure, or the vertical effective pressure acting at a depth, plays a role in controlling the shear strength of the soil. The greater the overburden pressure, the higher the effective shear strength of the soil, so the liquefaction potential tends to decrease [31], [32], [33]. Therefore, soil layers with low overburden pressure at shallower depths are generally more susceptible to liquefaction than deeper layers.

Another parameter that plays an important role is fines content. The fine content affects the response of the soil to vibration [3]. Coarse-grained soils such as sand with low fine content (generally <15%) have a higher liquefaction potential due to their loose grain structure and good drainage ability, which allows pore pressure to increase rapidly during an earthquake [3]. In addition, coarse-grained soils with low relative density (loose) have a greater tendency to experience sudden compaction and increased pore pressure when shaken.

On the other hand, high relative density soils are more stable and resistant to liquefaction. In empirical analysis, SPT N values corrected for overburden pressure (N_{160}) are often used to assess these relative density conditions. Low N values, especially below 15, are usually associated with high liquefaction potential, especially in water-saturated sand layers [34]. The results of the SPT test are shown in Table 2 and Figure 1. In Table 2, the soil conditions at depths >20 ft have a very small fine content with NI60 values below 15 with low overburden pressure, so the soil at depths >20 ft has a high liquefaction tendency.

In analyzing liquefaction potential using the NovoLIQ application, the representation of soil properties based on depth is a fundamental aspect that determines the accuracy of the evaluation results. This application works with a layer-by-layer approach, where each soil layer is analyzed individually against relevant geotechnical parameters. The main input data includes layer depth, standard penetration test (N-SPT) values or CPT tip resistance values, soil bulk density (both dry and wet), soil type classification, and groundwater table position. The N-SPT values entered are typically corrected for energy, overburden pressure, and fines content to enhance alignment with actual field conditions. Soil unit weight is used in calculating total stress and effective stress, which influence the Cyclic Stress Ratio (CSR) value, while soil classification is used to adjust correction values in determining the Cyclic Resistance Ratio (CRR). The graphical visualization of layer-by-layer soil can be seen in Figure 2**.**

Figure 2 shows the results of data processing visualization using NovoLIQ, which shows the soil layers and soil types. Classification is based on N-SPT values at each soil depth, which aligns with the soil classification results from the borehole tests conducted and analyzed in the discussion of Soil Physical Properties. From the NovoLIQ data processing and borehole test data analysis, it was found that the soil has silt characteristics at a depth of 2–4 meters and sandy soil at a depth of 4–30 meters. With shallow groundwater and the possibility of high-intensity earthquakes, the soil in this area is susceptible to liquefaction. Liquefaction potential analysis was then conducted by calculating the CSR and CRR values using the Novoliq application, which will also yield the FS values for each soil layer.

Figure 1. Standard penetration test result

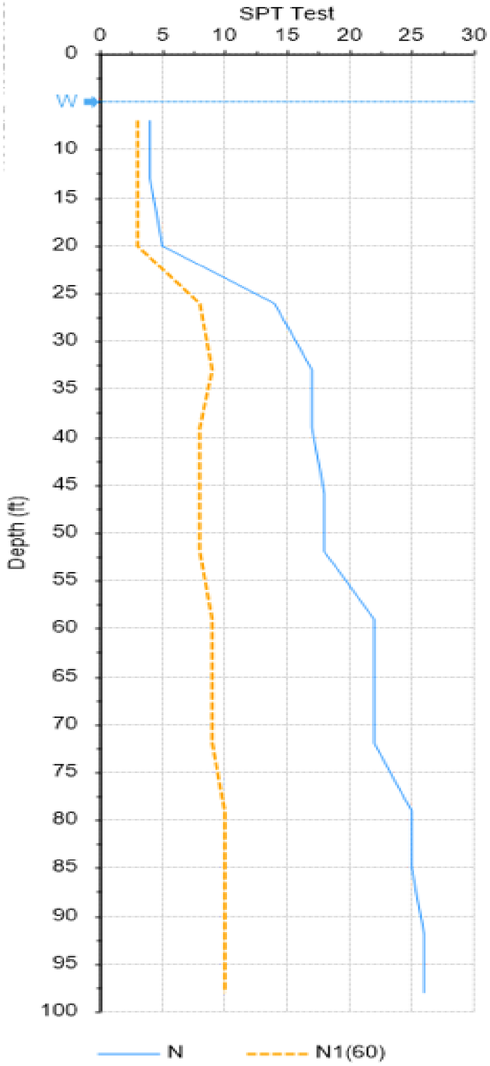
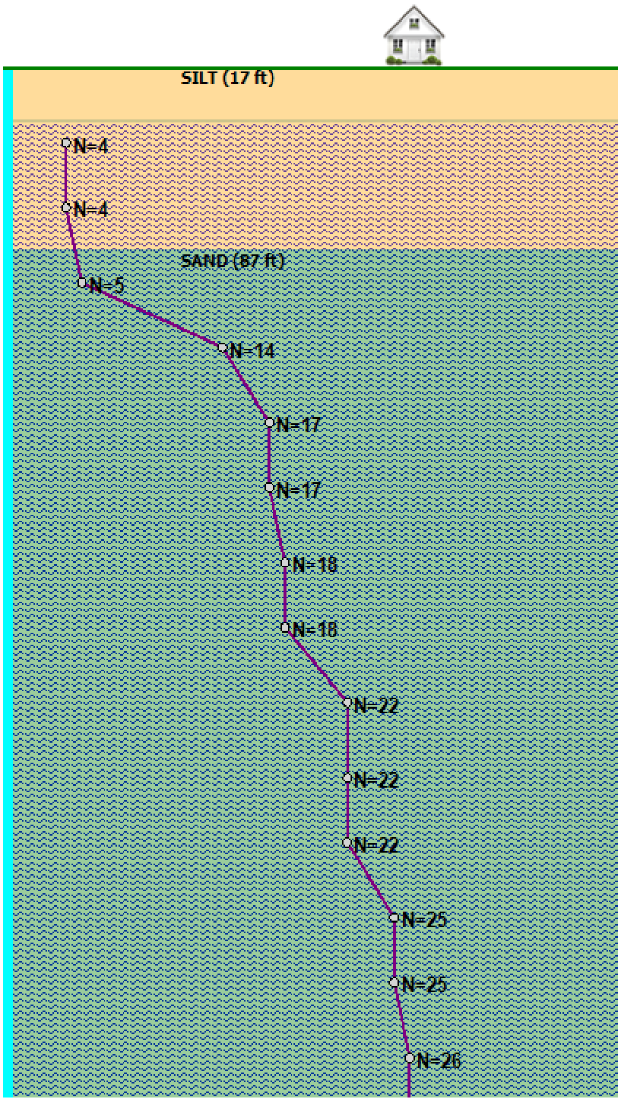


Table 2. Standard penetration test result

Depth (m)	Overburden Stress (ksf)		Fines Content (%)	SPT Test		Relative Density Dr (%)
	Total	Effective		N	N1(60)	
0-2	1.85	1.72	69.7	4	3	44
2-4	3.43	2.94	69.7	4	3	42.9
4-6	5.34	4.41	0.5	5	3	26.2
6-8	7.04	5.73	0.5	14	8	41.8
8-10	9.03	7.28	0.5	17	9	43.7
10-12	10.73	8.61	0.5	17	8	42.1
12-14	12.72	10.16	0.5	18	8	41.7
14-16	14.42	11.48	0.5	18	8	40.6
16-18	16.4	13.03	0.5	22	9	43.7
18-20	18.39	14.58	0.5	22	9	43.7
20-22	20.09	15.91	0.5	22	9	43.8
22-24	22.08	17.46	0.5	25	10	46.7
24-26	23.78	18.78	0.5	25	10	46.7
26-28	25.76	20.33	0.5	26	10	47.7
28-30	27.46	21.66	0.5	26	10	47.7

Figure 2. Visualization of layer-by-layer soil classification



3.3 Liquefaction Hazard Potential

Quantitative evaluation of liquefaction potential is generally done by comparing the cyclic stress with the soil resistance to liquefaction. In this case, the key parameters used are Cyclic Stress Ratio (CSR) and Cyclic Resistance Ratio (CRR) [30], [34]. The CSR value represents the earthquake-induced cyclic dynamic stress acting at a certain depth, while the CRR indicates the ability of the soil to withstand this stress without liquefaction. CSR is calculated using the empirical formula of Seed and Idriss (1971) by considering the soil's total stress and effective stress factors. As for CRR, several calculations were made, as seen in Table 3. Table 3 shows that the soil CSR values were obtained in the range of 0.237-0.3, while from several formulas, the average CRR values were obtained between 0.32-0.4. These CSR and CRR values provide a strong quantitative framework for determining the stability of the soil to earthquake loads. A factor of safety against liquefaction was then sought, the results of which can be seen in Table 4. In Table 4, the soil has an SF < 3, which reflects the level of susceptibility of a soil layer to liquefaction. The SF value should be ≥1.2 to be considered safe. In the Cetin et al. 2004 approach, the soil has liquefaction potential starting from a depth of 4 meter.

This study assessed the potential for soil liquefaction by analyzing the relationship between the Cyclic Stress Ratio (CSR) and the Cyclic Resistance Ratio (CRR), where CSR quantifies the cyclic load imparted by seismic shaking, and CRR denotes the inherent resistance of the soil to withstand that loading. The evaluation was conducted across several depth intervals using field data primarily derived from Standard Penetration Test (SPT) results to identify stratigraphic zones most susceptible to seismic-induced liquefaction.

The results presented in Table 3 indicate that CSR values are generally higher in shallower soil layers. This is primarily attributed to lower effective overburden stress in these upper zones, which results in a relatively greater influence of cyclic shear stresses generated by seismic ground motion. In essence, shallow soils experience higher stress demand due to their limited confining pressure, exacerbating their susceptibility to pore pressure buildup and subsequent strength loss.

Conversely, CRR values exhibit more variability across depths, largely governed by soil-specific parameters such as corrected SPT blow count (N_{160}), fine-grained content, and relative density. Soils characterized by low SPT values—indicative of loose packing—and a fine content below approximately 15% demonstrate reduced cyclic resistance. Such conditions are typically associated with clean to silty sands, which lack sufficient cohesion or interparticle contact to dissipate seismic energy effectively. These strata, therefore, exhibit lower CRR values, making them particularly vulnerable when subjected to earthquake-induced loading.

The interplay between high CSR and low CRR—especially in loose sandy layers with poor compaction and minimal fines—creates an unfavorable balance that significantly heightens the risk of liquefaction. This aligns with established empirical findings, where soils with low density, high permeability, and minimal cohesion are consistently identified as the most critical liquefaction hazard. Therefore, a detailed assessment of these parameters at varying depths is essential in quantifying the risk and designing appropriate mitigation measures.

The evaluation of liquefaction potential was conducted by comparing the Cyclic Stress Ratio (CSR) and the Cyclic

Resistance Ratio (CRR), from which the Factor of Safety (FS) against liquefaction was determined at multiple depths, particularly for soil layers located beyond 4 meters below the ground surface. The FS is defined as the ratio of a soil's capacity to resist cyclic loading (CRR) to the cyclic stress induced by earthquake shaking (CSR), expressed as FS = CRR / CSR. When FS is less than 1.0, it indicates a high likelihood of liquefaction under seismic loading; FS values between 1.0 and 1.2 fall into a transitional range where liquefaction is still considered possible and potentially critical, depending on design standards. In this study, Table 4 shows that the FS values fall consistently below 1.2 across multiple evaluation methods, including Boulanger & Idriss (2014), the Vancouver Task Force (2007), and the Japanese Highway Bridge Code. Each of these methodologies recognizes FS < 1.2 as a condition requiring attention in engineering design, particularly in seismic regions.

This conclusion is further supported by the Cetin et al. (2004) probabilistic method, which yielded a 100% probability of liquefaction (PL = 1.0) for the same layers, confirming the soil's vulnerability. These results are consistent with the site's geotechnical properties, such as low corrected SPT-N_{160} values, a shallow groundwater table, and loose to medium-dense silty sands, all known indicators of liquefaction susceptibility. The alignment between deterministic and probabilistic evaluations strongly indicates that the subsurface conditions present a significant risk of seismic-induced liquefaction, warranting ground improvement or mitigation strategies in future foundation or infrastructure development.

Table 3. Cyclic Resistance Ratio (CRR) dan Cyclic Stress Ratio (CSR) results

Depth (ft)	User Cyclic Stress Ratio	Cyclic Resistance Ratio 7.5							Cyclic Resistance Ratio 7.5 (average)
		Boulanger & Idriss (2014)	Vancouver Task Force (2007)	Cetin et al. (2004)	Japanese Highway Bridge Code	Tokimatsu and Yoshimi (1983)	Shibata (1981)	Kokusho et al. (1983)	
0-2	0.276	0.11	0.1	1.08	0.39	0.17	0.21	0.18	0.32
2-4	0.335	0.11	0.09	1.84	0.36	0.16	0.21	0.17	0.42
4-6	0.358	0.07	0.06	1.92	0.09	0.13	0.21	0.15	0.37
6-8	0.369	0.1	0.09	1.92	0.12	0.16	0.21	0.17	0.4
	0.372	0.1	0.1	1.92	0.12	0.16	0.21	0.18	0.4
8-10	0.353	0.1	0.09	1.92	0.1	0.16	0.21	0.17	0.39
10-12	0.321	0.1	0.09	1.92	0.1	0.16	0.21	0.17	0.39
12-14	0.3	0.09	0.08	1.92	0.09	0.16	0.21	0.17	0.39
14-16	0.282	0.1	0.1	1.92	0.09	0.16	0.21	0.18	0.39
16-18	0.268	0.1	0.1	1.92	0.09	0.16	0.21	0.18	0.39
18-20	0.258	0.1	0.1	1.92	0.08	0.16	0.21	0.18	0.39
20-22	0.252	0.11	0.11	1.92	0.08	0.17	0.22	0.18	0.4
22-24	0.247	0.1	0.11	1.92	0.08	0.17	0.22	0.18	0.4
24-26	0.241	0.11	0.11	1.92	0.08	0.18	0.22	0.19	0.4
26-28	0.237	0.11	0.11	1.92	0.08	0.18	0.22	0.19	0.4

Table 4. Safety factor and probability of liquefaction

Depth (ft)	Safety Factor							Safety Factor	Probability of Liquefaction PL (%)	
	Boulanger & Idriss (2014)	Vancouver Task Force (2007)	Cetin et al. (2004)	Japanese Highway Bridge Code	Tokimatsu and Yoshimi (1983)	Shibata (1981)	Kokusho et al. (1983)		Youd & Noble	Cetin et al. 2004
0-2	0.9	0.77	3	3	1.32	1.72	1.42	1.73	26.6	65.1
2-4	0.7	0.61	3	2.38	1.07	1.41	1.15	1.47	48.3	99.9
4-6	0.45	0.35	3	0.53	0.78	1.29	0.9	1.04	71.3	100
6-8	0.59	0.53	3	0.74	0.95	1.27	1.03	1.16	45.9	100
	0.61	0.57	3	0.69	0.98	1.27	1.05	1.17	41.5	100
8-10	0.61	0.57	3	0.66	1	1.33	1.08	1.18	44.6	100
10-12	0.66	0.61	3	0.67	1.09	1.46	1.18	1.24	45.2	100
12-14	0.68	0.62	3	0.65	1.14	1.56	1.24	1.27	47.4	100
14-16	0.78	0.76	3	0.71	1.29	1.68	1.38	1.37	40.7	100
16-18	0.81	0.8	3	0.71	1.36	1.77	1.45	1.41	40.5	100

Depth (ft)	Safety Factor							Safety Factor	Probability of Liquefaction PL (%)	
	Boulanger & Idriss (2014)	Vancouver Task Force (2007)	Cetin et al. (2004)	Japanese Highway Bridge Code	Tokimatsu and Yoshimi (1983)	Shibata (1981)	Kokusho et al. (1983)		Youd & Noble	Cetin et al. 2004
18-20	0.84	0.83	3	0.71	1.41	1.84	1.51	1.45	40.3	100
20-22	0.92	0.96	3	0.74	1.52	1.91	1.62	1.53	34.1	100
22-24	0.94	0.97	3	0.73	1.55	1.95	1.65	1.54	34	100
24-26	0.98	1.04	3	0.74	1.62	2.02	1.72	1.59	32	100
26-28	0.99	1.06	3	0.73	1.65	2.05	1.75	1.6	31.9	100

In evaluating the potential for soil liquefaction, the comparison between the Cyclic Stress Ratio (CSR) and the Cyclic Resistance Ratio (CRR) plays a very important role, with several theories offering different methods for their calculation. The widely used formulation by Boulanger and Idriss (2014) improves upon the classical approach of Seed and Idriss (1971) by introducing updated correction factors, including adjustments for fine particle content and magnitude scaling factors, resulting in conservative CRR values, particularly for clayey sands. On the other hand, the probabilistic framework introduced by Cetin et al. (2004) incorporates statistical confidence levels and site variability, often yielding less conservative CRR values in denser soils due to performance-based calibration. Region-specific approaches, such as those developed by the Vancouver Liquefaction Task Force (2007), adjust CSR and CRR estimates to local geological conditions, often resulting in higher CRR values for dense urban soils compared to generic methods. Similarly, the Japanese Highway Bridge Code adopts a conservative empirical formula specifically designed for critical infrastructure, emphasizing safety in bridge foundation design. Tokimatsu and Yoshimi (1983) and Shibata (1981) pioneered CPT-based liquefaction assessment methods, with the former offering moderate CRR estimates suitable for sandy soils and the latter occasionally overestimating resistance in clayey soil conditions due to limited fine particle corrections. Meanwhile, Kokusho et al. (1983) proposed a laboratory-calibrated energy-based approach, which better captures soil behavior under cyclic loading, particularly for saturated loose sands. These methodological differences highlight the influence of theoretical assumptions, soil type, and regional calibration in determining CRR and CSR values. Therefore, cross-comparison of methods is recommended in practice to ensure more reliable and location-specific liquefaction assessments.

4. Conclusion

The soil investigation results show a variation in soil classification based on the USCS system, with MH soils identified at depths of 7–13 ft and SP soils at 20–98 ft. MH soils are inorganic silts with high plasticity, generally less susceptible to liquefaction due to their cohesive nature, although saturated and disturbed conditions can still reduce their shear strength. In contrast, SP soils are poorly graded sands with a loose structure. They are highly prone to liquefaction, especially when saturated, as the pore water pressure can rise rapidly under seismic loading. The Standard Penetration Test (SPT) results indicate that soil layers below 20 ft have low fines content (<15%), low corrected SPT values ($N_{160} < 15$), and low overburden pressure, all of which suggest high liquefaction potential. A quantitative assessment was conducted comparing CSR (Cyclic Stress Ratio) and CRR (Cyclic Resistance Ratio). CSR values are higher in shallow layers due to low effective stress, while CRR values vary based on soil properties. The resulting factor of safety (FS) values are less than 1.2, indicating liquefaction potential. This finding is further supported by the Cetin et al. (2004) method, which showed a 100% probability of liquefaction, aligning with soil classification and SPT-based evaluations.

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