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Liquefaction Potential Based on Cone Penetration Test (CPT) : Case Study in Institut Teknologi Sumatera, Lampung

A Yudi¹, N B Wirawan¹, S A Fauzan¹, R Nadeak¹

¹Civil Engineering Department, Institut Teknologi Sumatera, Lampung Selatan, Lampung

Abstract. Institut Teknologi Sumatera (ITERA) is the only state institute in Sumatera, specifically located in South Lampung region, which is a coastal area with dominant sandy soil type. It soil type can allow liquefaction. The purpose of the research is to analyze the mitigation potential of liquefaction with the deterministic method. It is expected that the research result could be used as a reference in planning of the ITERA future development. This analysis takes into account deterministic data that compares Cyclic Resistance Ratio of the soil (CRR) with Cyclic Stress Ratio (CSR) caused by an earthquake. CSR depends on the depth of soil layer, total vertical pressure, effective vertical pressure, earthquake magnitude and maximum acceleration in each layer of soil. CRR is obtained from the empirical correlation with the Cone Penetration Test (CPT) results. Judging from the results of the CPT test, the soil type in ITERA is loose sand and clay. Based on earthquake parameters and CPT test data at 12 points, ITERA is in the category of medium liquefaction potential with a safety factor value of less than 2.

Keywords: Liquefaction, CPT (Sondir), Cyclic Stress Ratio (CSR), Cyclic Resistance Ratio (CRR), Safety Factor.

1. Introduction

Indonesia is located at the confluence of three major tectonic plates, namely the Indo-Australian Plate, Eurasian Plate, and Pacific Plate, as well as one micro tectonic plate, the Philippine Micro Plate. This condition has consequences for earthquake-prone natural disasters and all the effects that will accompany each earthquake event (Soebowo et al., 2009).

One of the phenomena that can accompany the earthquake event is liquefaction. Liquefaction is an event where the soil changes from the solid phase to the liquid phase due to increased pore water pressure in the soil cavity. This event is mainly related to saturated sand soil conditions that have loose or moderate density. The impact of increasing the soil pore pressure is that the soil loses its shear strength drastically due to the decrease in the effective stress of the soil along with the increase in pore water stress. The loss of ground shear strength will cause severe damage to the structure or infrastructure above it. The most prominent damage is usually located in coastal areas or ports (Idriss and Boulanger, 2008).

According to Soebowo, et al. (2009), liquefaction events can cause collapse, collapse, soil cracks, slides and others. From the liquefaction research that has been done, it is known that liquefaction events generally only occur in areas formed by granular sedimentary layers which saturate water with a low density.



Institut Teknologi Sumatera (ITERA) is the only state institute in Sumatera, specifically located in South Lampung region, which is a coastal area with dominant sandy soil type. Its soil type can allow liquefaction. Therefore, it is necessary to analyze mitigation of liquefaction potential in the ITERA region which aims to prevent liquefaction which is illustrated by the security factor variable.

In this study, it was devoted to the area of Institut Teknologi Sumatera, and is expected to be used as a basis for planning for further development. Area's ITERA is expected to provide novelty and gap from previously study.

2. Basic Theory

2.1. Earthquakes

An earthquake is an event of energy release which causes a sudden dislocation (shift) on the inside of the earth. The occurrence of an earthquake is caused by the release of forces from within the earth, namely the original jolt sourced from within the earth propagates through the surface and breaks through the surface of the earth's skin because of its disturbed balance. The earth's crust becomes shifted until the balance returns. Earthquakes occurs every day on earth, but most are small and do not cause damage. Small earthquakes will also accompany large earthquakes and can occur before or after a large earthquake occurs which is called aftershocks (Soebowo et al., 2009).

2.2. Soil

The soil is generally understood as material consisting of solid aggregates that are not cemented to each other and from decaying organic materials accompanied by liquid and gases which fill the empty space between the particles (soil pores). Solid granules on the soil are the result of weathering of rocks both physically and chemically (Yulman, 2010).

The properties of soil can be divided as follows (Yulman, 2010):

1. Clay

Clay is a mineral particle soil with a silicate base frame less than 4 micrometers in diameter. Clay contains fine fused silica and aluminum. Elements of silicon, oxygen, and aluminum are the elements that make up the most of the earth's crust. Clay is formed from the process of weathering silica rocks by carbonic acid and partly produced from geothermal activity.

2. Sand

Sand is an example of granular mineral material. Sand grains are generally between 0.0625 to 2 millimeters. Sand-forming material is silicon dioxide, but on some tropical and subtropical beaches it is generally formed from limestone. Sand is technically two properties, namely loose sand (low density) and solid sand (high density). In general liquefaction occurs on loose sand (low density).

3. Lanau

Lanau has a particle size in the range of 0.074 mm down to 0.001 mm which is formed due to weathering of rocks. They may be organic if they are contaminated with organic material or can be inorganic. Most silt layers are contaminated by clay minerals so they are cohesive. 5-8% of the clay content can make the silt layer have cohesion, depending on the particle size and type of clay minerals. At a high percentage of clay, or depending on the visual effect, the silt layer can be freely called "clay".

2.3. Liquefaction

The term liquefaction was first created by Mogami and Kubo in 1953 which has historically been used to name the occurrence of various phenomena involving soil deformation due to monotonous, transient, or repeated disturbances in saturated cohesionless soils which are under undrained conditions. As has been known, dry cohesionless soils tend to condense under conditions of static and cyclic loads. When saturated non-cohesive soil receives a fast load under undrained conditions, the soil will tend to condense which causes pore water pressure to increase and effective soil pressure to decrease (Yulman, 2010).

Liquefaction occurs only on saturated soils, so the depth of the ground water level affects the vulnerability of liquefaction. Vulnerability to liquefaction will decrease with the depth of the water

table. The effects of liquefaction are generally seen in locations where the ground water level is only a few meters from the ground. In locations where the surface level of the groundwater is fluctuating, liquefaction may also fluctuate (Soebowo et al., 2009). One of the liquefaction events that caused structural damage was during the Niigata earthquake in 1964, as in Figure 1.

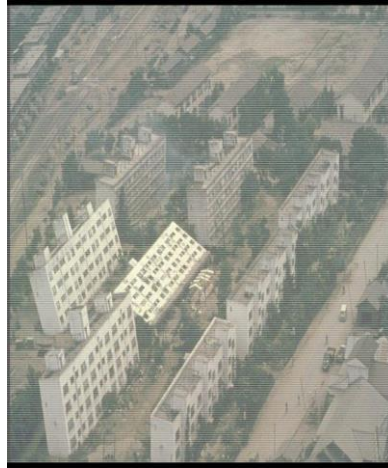


Figure 1 Effects of Liquefaction on the Niigata, Japan Earthquake in 1964 (Idriss and Boulanger, 2008)

2.4. Correlation Analysis Framework to Know the Potential of Liquefaction

Several approaches have been proposed in the past 45 years to analyze the potential for liquefaction. The widely used approach is a pressure-based approach that compares cyclic pressures induced by earthquakes with cyclic resistances from the soil. Cyclic pressure induced by earthquakes below the ground surface is mainly due to the effects of horizontal shocks. Figure 2 schematically illustrates the pressure and pore water pressure acting on soil elements below the soil surface before and during the horizontal shock of an earthquake. Vertical shocks from this profile will produce temporary additional changes in total vertical pressure, horizontal total pressure and pore water pressure, but vertical and horizontal effective pressures are not affected. This causes vertical shock not mentioned in the analysis.

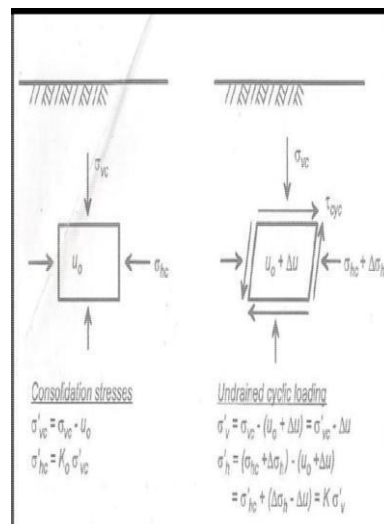


Figure 2 Cyclic Pressure on Soil Elements Under Soil Surface When Horizontal Shocks Occur (Idriss and Boulanger, 2008)

2.5. Calculation of Cyclic Pressure Induced by Earthquakes

Shear stress induced at all depths of the soil layer when an earthquake occurs is caused primarily by vertical propagation of the horizontal shear wave. This pressure analysis procedure can be calculated if the soil rubber and the movement input are known. One-dimensional dynamic analysis has been developed to make it easier to get r_d . This analysis has shown that r_d characterize of earthquake

movements (intensity and frequency), wave velocity profiles at a location, and nonlinear dynamics of soil properties (Idriss and Boulanger, 2008). Response analysis on hundreds of parameters that get the r_d parameter as a function of depth (z) and earthquake magnitude (M) (Idriss and Boulanger, 2008).

With the following equation:

$$r_d = \exp(\alpha(z) + \beta(z)M)$$

$$\alpha(z) = -1,012 - 1,126 \sin\left(\frac{z}{11,73} + 5,133\right)$$

$$\beta(z) = 0,106 + 0,118 \sin\left(\frac{z}{11,28} + 5,142\right)$$

Where :

z = depth in meters.

M = moment magnitude.

Sinus value in radians.

The above equation can only be mathematically applied to $z < 34$ m. However, the uncertainty of the increase in r_d with the increase in depth, so that the above equation can actually only be done at a depth of less than 20 m.

Cyclic pressure induced by earthquakes where this pressure affects liquefaction potential is 65% of the peak cyclic pressure (Idriss and Boulanger, 2008). This is what is called the Cyclic Stress Ratio (CSR) which is formulated as follows:

$$CSR = 0,65 \frac{\tau_{max}}{\sigma'_{vc}} = 0,65 \frac{\sigma_{vc}}{\sigma'_{vc}} \frac{\alpha_{max}}{g} r_d$$

Where

α_{max} = Maximum earthquake acceleration on the surface

σ_{vc} = Total vertical pressure (kN/m²)

σ'_{vc} = Effective vertical pressure (kN/m²)

g = gravity (m/s²)

r_d = Shear pressure coefficient

2.6. Field Investigation to Evaluate Liquidity Potential

The results of field investigations such as sondir can be used to find cyclic prisoners from the land called the Cyclic Resistance Ratio (CRR). After that, we compare the CRR with CSR, where the comparison between CRR and CSR is a factor of security whether liquefaction occurs or not (Yulman, 2010). For this reason, it is necessary to know the correlation between the results of the field tests to obtain the CRR.

Data from field tests in the form of CPT or sondir can be used to evaluate the potential for liquefaction. CPT has a conical penetrometer with a diameter of 35.7 mm which will push into the ground at a rate of 20 cm / sec. When it happened, the transducer on the CPT or sondir tool will record the force on the conus, the resistance force on the skin which is behind the conus. The tip force divided by the cross-sectional area of the penetrometer is the resistance of the tip of the q_c and the resistance of the skin force divided by the skin area is friction (f_s). The main advantage of sondir is that it provides continuous data recording from penetration prisoners. The disadvantage is that it is very difficult to penetrate layers that have large particles such as rocks.

The empirical correlation between soil types and various measurements of sondir has been developed, as shown in Figure 3 which shows an empirical chart which categorizes the soil into five different soil properties with the basis of the value of the conus end (q_c), friction ratio (FR).

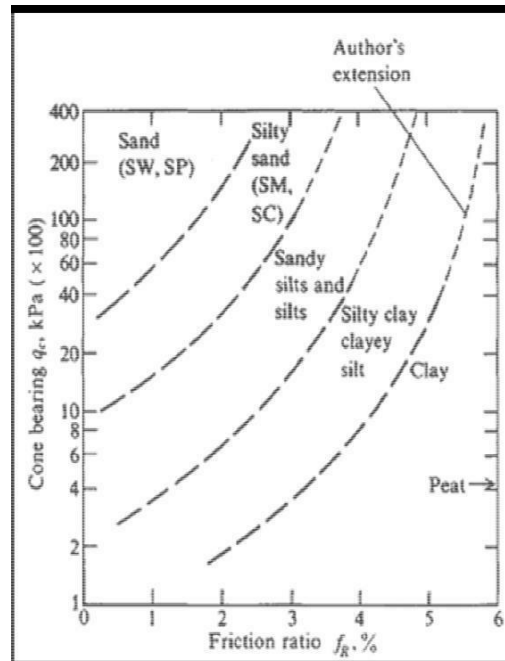


Figure 3 Graph of the Nature of Soil with Normalized CPT Proposed by Robertson and Campanella 1983 (Yulman, 2010)

2.7. Overburden Correction in Field Tests

CPT penetration resistance in sand increases with increasing stress confining, where the q_c value of the depth and location that is located cannot be directly compared to each other. The correction factor of the CPT value is C_N , then the following equation is obtained:

$$q_{ci} = C_N q_c$$

The C_N value is obtained by the formula proposed by Idriss and Boulanger (2008), namely:

$$C_N = \left(\frac{P_a}{\sigma'_{vc}} \right)^{1,338 - 0,249 (q_c)^{0,264}} \leq 1,7$$

Where,

- C_N = Correction factor of CPT value
- σ'_{vc} = Effective vertical pressure (kN/m²)
- P_a = Pressure 1 atm (100 kPa)
- q_c = End resistance (kN/m²)

If the C_N value is more than 1.7, then the C_N value = 1.7.

2.8. Magnitude Scaling Factor (MSF)

Magnitude scaling factor (MSF) is used to determine CSR and CRR that use the usual M value (conventionally taken $M = 7.5$), because the CRR depends on the number of cyclic loads that correlate with M (Idriss and Boulanger, 2008). The basic definitions of MSF are:

$$MSF = \frac{CRR_M}{CRR_{M=7,5}}$$

MSF values on different M values can be calculated using the approach used by Idriss and Boulanger (2008) as follows:

$$MSF = 6,9 \exp\left(\frac{-M}{4}\right) - 0,058 \leq 1,8$$

If the MSF value is more than 1.8, then the MSF value = 1.8.

2.9. Overburden Correction Factor (K_σ)

The overburden correction factor (K_σ) is used to determine CSR and CRR against the value of normal effective stress overburden, because CRR in sand depends on effective overburden stress (Idriss and Boulanger, 2008). K_σ value can be obtained from:

$$K_\sigma = 1 - C_\sigma \ln\left(\frac{\sigma'_{vc}}{P_a}\right) \leq 1,1$$

If the K_σ value is more than 1.1, then the value of $K_\sigma = 1.1$ is used.

Where the C_σ coefficient is obtained from the correlation with the penetration resistance overburden proposed by Idris and Bulanger (2004) as follows:

$$C_\sigma = \frac{1}{37,3 - 8,27 (q_{c1})^{0,264}} \leq 0,3$$

The C_σ coefficient is limited to a maximum of 0.3. If the C_σ value is more than 0.3, then the value of $C_\sigma = 0.3$ is used. The value of q_{c1} also has a limit that is $q_{c1} < 211$.

2.10. Correlation of CPT with CRR in Sand Soil

As we know the strength and stiffness of the soil based on the field test is obtained from the SPT and CPT values. This power will produce the value of Cyclic Resistene Ratio (CRR) which will be compared with Cyclic Stress Ratio (CSR) which comes from the dynamic movement of the soil due to the earthquake. The correlation between CRR and CPT proposed by Boulanger (2004) based on the results of his study are as follows:

$$CRR_{M=7,5;\sigma'_{vc}=1} = \exp\left\{\frac{q_{c1cs}}{540} + \left(\frac{q_{c1cs}}{67}\right)^2 - \left(\frac{q_{c1cs}}{80}\right)^3 + \left(\frac{q_{c1cs}}{114}\right)^4 - 3\right\}$$

$$CRR_{M,\sigma'_{vc}} = CRR_{M=7,5;\sigma'_{vc}=1atm} \cdot MSF \cdot K_\sigma$$

The safety factor for triggering liquefaction as previously mentioned is the CRR value compared to CSR as the following formula:

$$FK = \frac{CRR_{M;\sigma'_{vc}}}{CSR_{M;\sigma'_{vc}}}$$

2.11. Earthquake Wave propagation from basic to surface rocks

In this study the correlation between CPT (Sondir) and Vs proposed by Robetson and Cabal (2009) is used based on the results of the 100 CPT profile investigation data in California combined with some published data the result is normalized shear velocity V_{s1} (m/s).

$$V_{s1} = V_s \cdot \left(\frac{P_a}{\sigma'_{vc}}\right)^{0,25}$$

$$V_s = \sqrt{\alpha_s \left(\frac{q_c - \sigma_{vc}}{P_a}\right)}$$

$$\alpha_s = 10^{(0,55.I_c + 1,68)}$$

2.12. Amplification Factors

The amplification factor that can be used in the analysis of the maximum earthquake acceleration on the surface is the amplification factor developed by Stewart et al. 2003 (Misliniyati, 2010). In addition, the amplification factor of the American Society of Civil Engineers (ASCE) 2010 can also be used in the analysis by first knowing the classification of soil types on the soil profile reviewed.

Table 1. Site Classification Based on Correlation of Field Land Investigations and Laboratories

Site Classification		V, (m/s)	N	Su (kPa)
A	Hard rock	$V \geq 1500$	N/A	N/A
B	Rock	$750 < V \leq 1500$	N/A	N/A
C	Very Dense Soil and Soft Rock	$350 < V \leq 750$	$N > 50$	$Su \geq 100$
D	Medium Soil	$175 < V \leq 350$	$15 \leq N \leq 50$	$50 \leq Su \leq 100$
E	Soft Soil	$V < 175$	$N < 15$	$Su \leq 50$

Source: 2010 Indonesia Earthquake Hazard Map (Ministry of Public Works, 2010)

Table 2. Amplification Factors

Site Classification	S _{PGA}				
	PGA≤0,1	PGA=0,2	PGA=0,3	PGA=0,4	PGA≥0,5
Hard rock (S _A)	0,8	0,8	0,8	0,8	0,8
Rock (S _B)	1,0	1,0	1,0	1,0	1,0
Very Dense Soil and Soft Rock (S _C)	1,2	1,2	1,1	1,0	1,0
Medium Soil (S _D)	1,6	1,4	1,2	1,1	1,0
Soft Soil (S _E)	2,5	1,7	1,2	0,9	0,9

Source: 2010 Indonesia Earthquake Hazard Map (Ministry of Public Works, 2010)

3. Research Methods

3.1. General Description of Research

Not all soil are susceptible to liquefaction hazards. The first step to analyzing the potential hazards of Liquefaction is to conduct a vulnerability analysis or potential Liquefaction. If the soil conditions in a location are not potentially liquefied then the liquefaction hazard will not occur. Criteria for analysis of potential liquefaction at a location determined from the type of soil. So that in this study an analysis of potential liquefaction with deterministic methods based on sondir data on each type of soil layer was carried out.

The analysis uses deterministic method, by comparing the value of Cyclic Resistance Ratio (CRR) which describes the resistance or strength of the ground against the Cyclic Stress Ratio (CSR) which describes the earthquake load that occurred. The comparison above will produce a number of security factors that indicate the potential danger of Liquefaction. The value of a safety factor against liquefaction is 1.2. If it is small from the value, the location being reviewed has a high risk of liquefaction.

3.2. Research Location

In this study, researchers took data at ITERA, as in Figure 4.

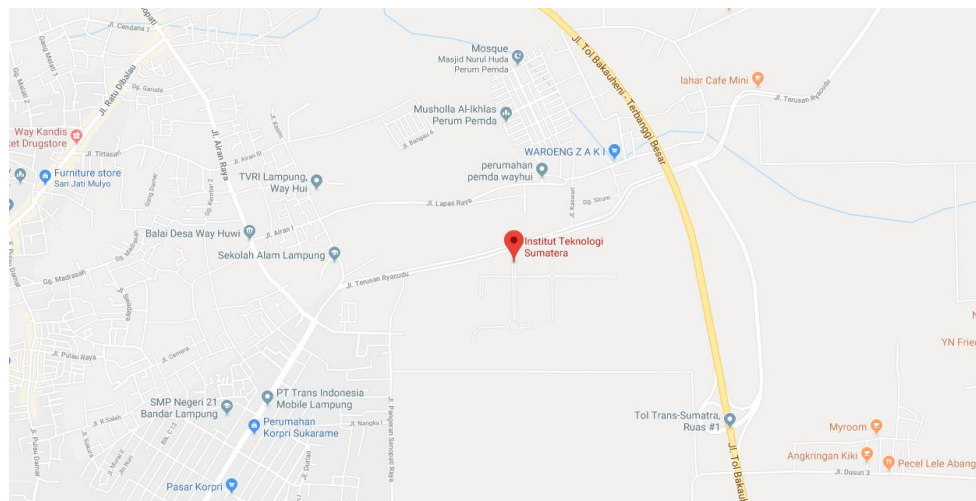


Figure 4 Research sites in Institut Teknologi Sumatera (Source : Google maps)

3.3. Data Collection Methods

Primary data is obtained by conducting a CPT test (sondir) at the research location. Indonesia's 2012 earthquake zoning map and literature study on several studies relating to the evaluation of liquefaction potential.

3.4. Data Processing Analysis

In this research, analysis of liquefaction potential is conducted by deterministic methods published by Idriss and Boulanger (2008). This method uses a comparison of Cyclic Resistance Ratio (CRR) which describes the ground resistance to Cyclic Stress Ratio (CSR) which describes the earthquake load that occurred. The stages and methods that will be carried out in this analysis are as follows:

1. Determination of Soil Types in each Layer.
2. Calculating the Value of Cyclic Stress Ratio (CSR) for each Soil Layer.
3. Calculating the value of Cyclic Resistance Ratio (CRR) for each subsoil.
4. Calculation of Factors of Safety from the CPT Test.

4. Results

4.1. General

In the evaluation of liquefaction potential with the deterministic method obtained in the form of parameters of the value of the security factor. The value of the security factor is obtained from the comparison of the value of Cyclic Resistance Ratio (CRR) with Cyclic Stress Ratio (CSR). The variables that influence CSR values are maximum earthquake acceleration on the surface, shear pressure reduction coefficient, and total vertical pressure and effective vertical vertical pressure. The CRR value is obtained from the empirical correlation with the CPT test results at 12 points scattered in ITERA.

CPT data collection is carried out to a limit of 10 meters. But sondir only reaches a depth of 1.4 - 8.4 meters. This is because the conus penetration has not been able to penetrate the deeper layers of soil.

4.2. CPT Field Test Data

The results of the CPT field test were conducted at 12 points spread in ITERA. Field tests on 12 points were obtained different results and different depths. This is because the ability of the sondir device is limited.

Table 3. CPT Test Results at 12 points ITERA location

Location	Tahanan Ujung (qc) (kg/cm ²)	friction ratio (FR) (%)	Depth (m)
Point 1	220	1	3,6
Point 2	200	3	3,0
Point 3	225	1	2,0
Point 4	230	1	1,4
Point 5	200	3	8,4
Point 6	220	1	4,0
Point 7	230	1	2,2
Point 8	230	1	1,8
Point 9	230	1	3,0
Point 10	200	3	4,2
Point 11	200	0,25	1,6
Point 12	200	0,25	2,2

4.3. Safety Factor Calculation Results from the CPT Test

Liquefaction potential at ITERA falls within the category of safe from liquefaction as seen in the value of the security factor ranging from 1.4 - 2.

5. Conclusion

The conclusions obtained from the research results of liquefaction potential in ITERA with deterministic methods are as follows:

1. The value of ground end resistance in ITERA consistency ranges from 200 kg/cm² - 230 kg/cm².
2. The danger of liquefaction potential at ITERA falls within the category of regions with a potential level of safe liquefaction, seen in the value of the security factor ranging from 1.4-2.
3. ITERA liquefaction with CPT test data at 12 points shows that the entire ITERA region is in a safe condition against liquefaction hazards when an earthquake occurs with a magnitude > 7.9 and 0.4g earthquake acceleration on the bedrock.

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