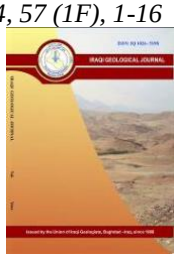
Iraqi Geological Journal

Journal homepage: https://www.igj-iraq.org



Cone Penetration Test-based Analysis for Shallow Liquefaction Potential Evaluation Due to Maximum Credible Earthquakes of Cimandiri Fault in Sukabumi, West Java, Indonesia

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Received:
27 September 2023
Accepted:
21 March 2024
Published:
30 June 2024

Abstract

The West Java region in Indonesia is prone to seismic activity due to its location near several tectonic plate boundaries. Every year a significant earthquake occurred in West Java, resulting in widespread damage and loss of life, one of which resulted from active fault activity, namely the Cimandiri fault. One of the primary hazards associated with seismic events is soil liquefaction, which can occur during seismic events. This research journal presents a detailed investigation into the shallow liquefaction potential evaluation in the affected region using the Cone Penetration Test. The investigation involved extensive fieldwork, including CPT measurements and soil sampling at various locations within the research area. The CPT data were utilized to determine the soil properties and estimate the liquefaction potential using established empirical correlations. The results of the analysis revealed significant variations in the liquefaction potential across the research area. The liquefaction values indicate low to high vulnerability to liquefaction considering the Liquefaction Potential Index (LPI). During an earthquake, vertical settlement values are estimated from 20 mm to 60 mm. Furthermore, horizontal displacement values are 10-70 cm. The findings from this study contribute to the understanding of shallow liquefaction potential in Sukabumi, West Java, Indonesia. The CPT-based analysis provides a reliable and efficient method for assessing liquefaction susceptibility, offering valuable information for urban planning, infrastructure design, and seismic hazard mitigation strategies.

Keywords: Liquefaction; Maximum Credible Earthquakes; Cimandiri Fault; Seismic hazard

1. Introduction

Natural disasters often occur in Indonesia, such as earthquakes, due to its location on the world's ring of fire. The earthquakes are triggered by subduction activity, in the south of Java Island. West Java itself is categorized as an area that has a high potential level of earthquake. On the other hand, several active faults are known in West Java namely Cimandiri Fault, Lembang Fault, Baribis Fault, Garsela Fault, Cipamingkis Fault, and Citari Fault (Supendi et al., 2018). One of the impacts that often occurs due to earthquakes is liquefaction in the ground, which can cause damage to infrastructure such as buildings, bridges, highways, etc. Liquefaction can lead to various geotechnical problems, such as

DOI: 10.46717/igj.57.1F.1ms-2024-6-10

ground settlement, lateral spreading, and structural failure (Mian et al., 2013; Mase et al., 2021). It occurs when the cyclic loading induced by the occurrence of an earthquake induces a rise in the pore water pressure inside the soil, thereby diminishing its effective stress, and resulting in a loss of shear strength (Mase et al., 2022). The liquefaction susceptibility depends on several factors, including soil type, saturation level, and earthquake characteristics (Xu et al., 2020).

The research was conducted in Sukabumi, West Java, Indonesia. There are three sites The study was carried out in Sukabumi, a region located in West Java, Indonesia. This research includes three site investigations, as depicted in Fig. 1. The designated points for site inspection are denoted as V1 through V3. The scope of the study is limited to a 10 km radius surrounding the Cimandiri Fault. Cone Penetration Test (CPT) investigations are done within the study area. According to Robertson (2015), the CPT testing method is presently the predominant approach employed for in-situ testing in the context of liquefaction analysis. The CPT test yields three primary areas of information. Three categories of information are typically included in test results: parameters that are directly measured during the test, parameters that are calculated or adjusted from the original parameters, and supplementary information. The characteristics that are directly monitored, such as cone resistance, sleeve friction, and pore pressure, can be organised in a tabular format and graphically represent the corresponding depth (Eslami and Fellenius, 2004; Stegman et al., 2006).

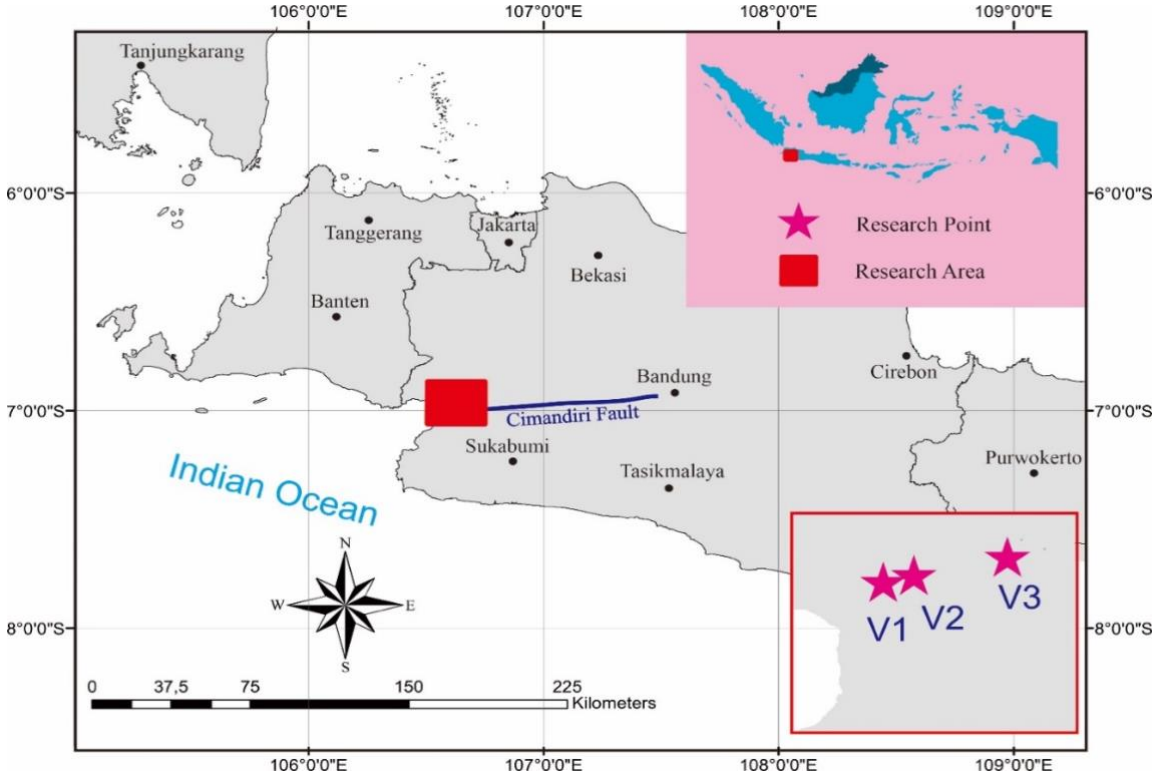


Fig. 1. Research area

The CPT is employed as a reliable and widely used method for assessing soil liquefaction potential (Johari and Khodaparast, 2014). The CPT involves driving a cone-shaped penetrometer into the ground and measuring the resistance encountered during penetration (Eslami et al., 2019). The obtained data provides valuable information about the soil properties and its liquefaction susceptibility. By conducting CPT-based analysis, this research aims to provide a comprehensive understanding of the shallow liquefaction potential in Sukabumi. The outcomes of this study will contribute to the seismic hazard assessment and geotechnical design considerations for infrastructure development in the region. It will aid engineers, urban planners, and policymakers in making informed decisions to mitigate the risks

associated with liquefaction. Furthermore, this study will enhance the existing knowledge base on liquefaction potential evaluation in Indonesia, particularly in regions with similar geological and seismic characteristics. The findings can be incorporated into future geotechnical guidelines and codes of practice, facilitating safer and more sustainable construction practices.

1.1. Seismic and Geological Condition

The Cimandiri fault that is concerned in this study, is situated along the Cimandiri River, which runs roughly SW to NE. It extends from the Pelabuhan Ratu Gulf through the populated cities of Pelabuhan Ratu, Sukabumi, and Cianjur to the Bandung region of West Java, Indonesia. According to Marliyani et al. (2018), the Cimandiri fault zone spans roughly 100 kilometres in length and is predominantly characterised by the presence of recent volcanic deposits. The Cimandiri fault is linked to the probable occurrence of significant earthquake disasters that the nation is expected to confront in the future. It is advisable to adopt a probabilistic approach, specifically considering a 2% likelihood of exceedance within a 50-year timeframe. According to Febriani (2016) and Cipta et al. (2018), the maximum credible earthquakes (MCE) have a magnitude of approximately 7.2 Mw. Additionally, the Cimandiri fault zone exhibits slip-rate of fault ranging from 0.5 to 4 cm each year as shown in Fig. 2. (Irsyam et al., 2013).

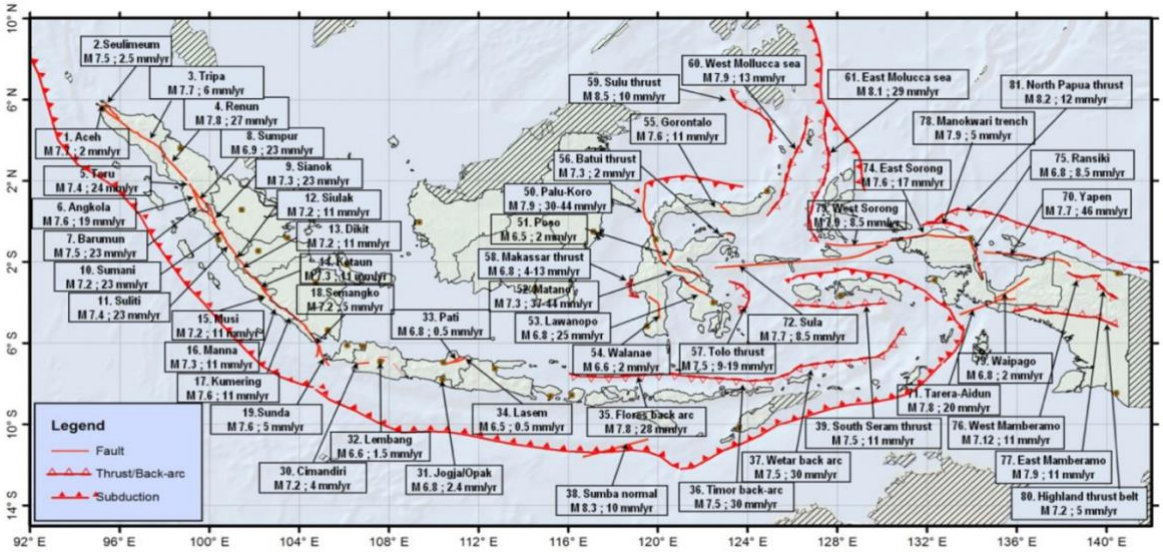


Fig. 2. Maximum magnitudes and slip-rate of fault sources in Indonesia (Irsyam et al., 2013)

The concept of maximum credible earthquakes pertains to the seismic events of the highest magnitude that may be produced by a particular fault, as determined through geological and seismological investigations (Petricca et al., 2022). The occurrence of these earthquakes is believed to have taken place in previous times and holds the possibility of recurring in the future, albeit with undetermined timing. A multitude of faults and folds can be found near the Cimandiri fault zone. According to Febriani et al. (2018), the Cimandiri fault zone exhibits a geological strike orientation of roughly N70°-80° E. The topography observed at the study location predominantly consists of undulating plains and undulating to steep hills, situated in the western region of Mount Gede. The region under consideration is predominantly characterised by Quaternary sediments, specifically consisting of recent volcanic materials such as volcanic breccias, lava, and tuff (Rizal et al., 2020). The Quaternary deposits exhibit characteristics of softness, looseness, and lack of consolidation, rendering them susceptible to seismic activity and amplifying the impact of earthquakes.

2. Methods

2.1. Cone Penetration Test Investigation

The utilization of the Cone Penetration Test (CPT) can be used to evaluate simplified liquefaction and presents more notable benefits when compared to alternative in-situ test indices (Boulanger and Idriss, 2016). The measurements obtained from the CPT yield three primary components, namely cone resistance (qc), sleeve friction (fs), and the friction ratio (Rf), as depicted in Fig. 3.

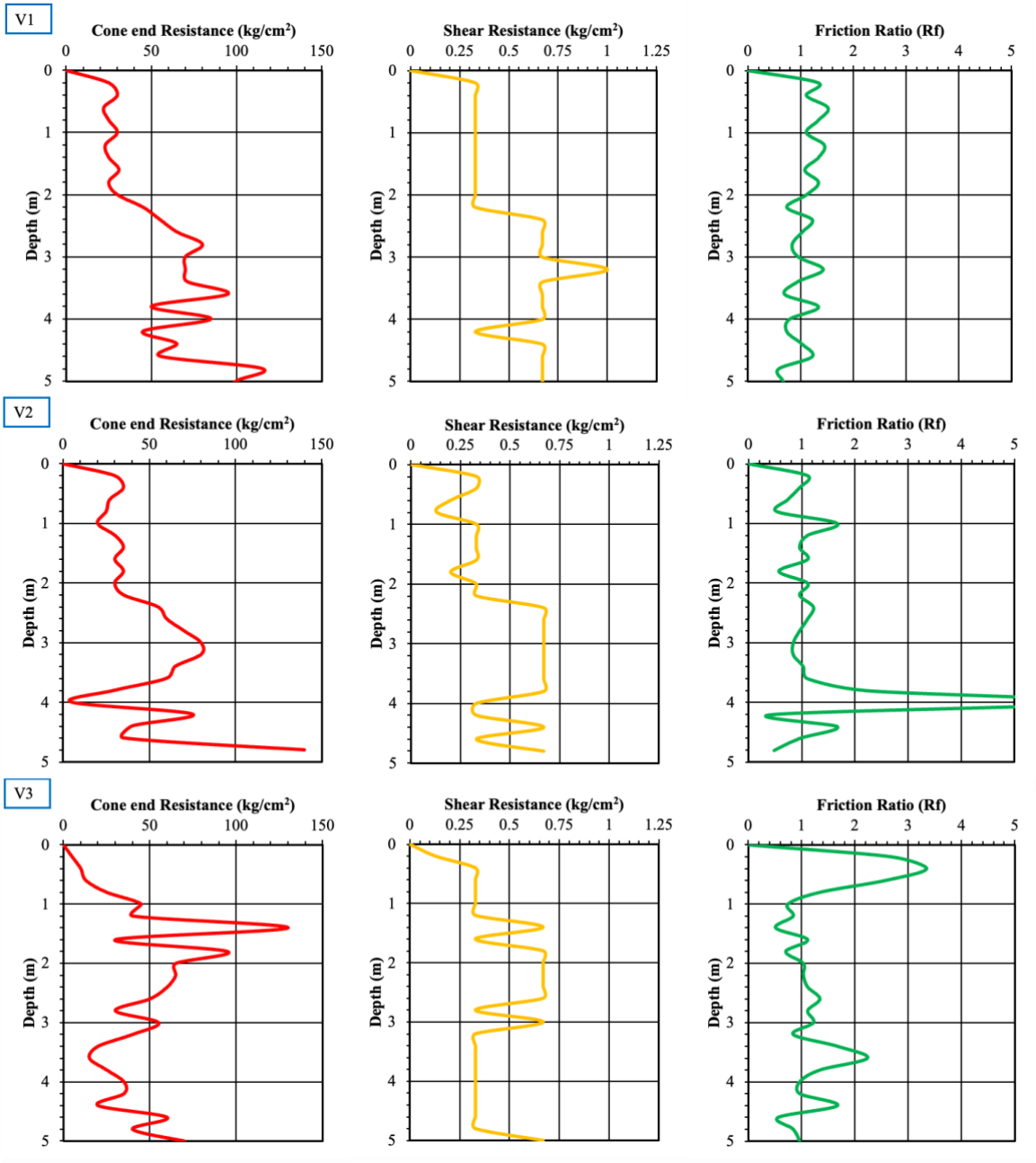


Fig 3. Cone Penetration Test (CPT) measurement results in the research area

On the contrary, it is imperative to consider the geological history of the research area as it plays a crucial role in determining the in-situ effective stress, which in turn greatly influences both the cone resistance and the friction sleeve stress (Boulanger and Idriss, 2016). Nevertheless, it is imperative to note that these deductions about soil classification do not yield a specific soil type, but rather a classification based on soil behaviour. Typically, undrained CPT testing is conducted on fine-grained

soils, while drained testing is performed on coarse-grained soils. Pore pressures are generated under undrained conditions, and their measurement provides significant benefits to both the cone resistance and the sleeve friction. Under conditions of drainage, pore pressures are absent, thereby allowing for the measurement of in-situ static pore pressure. The purpose of CPT-based liquefaction procedures is to assess the likelihood of soil liquefaction in soils that are prone to this phenomenon. It is not recommended to utilize these methods for high plasticity, fine-grained, "non-liquefiable" soils, as this may lead to less precise evaluations of liquefaction hazards (Maurer et al., 2015). Instead, there are other more suitable approaches available for high plasticity soil to forecast cyclic behaviour in such soils proposed by Boulanger and Idriss (2016)

The data acquired from a CPT assessment can be categorized into three main classifications: The parameters assessed during the test can be categorized into three groups: directly measured parameters, parameters that have been generated or changed using the original data, and supplemental information (Duan et al., 2021). The characteristics of cone resistance and sleeve friction, which are acquired through direct measurement, can be systematically arranged in a tabular format and visually depicted in conjunction with the relevant depth. The inclusion of the friction ratio, cone resistance and sleeve friction adjusted for pore pressure in a single table has also been described by Chow et al. (2014). When plotting these parameters on a graph, it is recommended to use the y-axis to indicate the depth below the surface. The values on the y-axis should decrease as they move downwards. The x-axis should be used to show the parameter count, with values progressing in ascending order from the left side to the right side. The analysis of CPT (cone penetration test) data can be impacted by multiple factors, highlighting the importance of recognising and dealing with these factors wherever possible, such as considering the estimation of pore water pressure. In their study, Lunne et al. (2002) recognised three fundamental elements of cone design that can influence the process of interpretation.

2.2. Seismic Hazard and Ground Motion

This study employs ground motion attenuation relationships to estimate the maximum surface acceleration (a_{max}) caused by seismic activity resulting from the Cimandiri active fault. The peak ground acceleration (PGA) is employed for the assessment of cyclic shearing magnitudes (Badreldin et al., 2022). Before conducting a liquefaction analysis, it is imperative to assess the factors associated with seismic ground motion, such as acceleration and magnitude. The selection of the earthquake setting is predicated upon the determination of the highest credible magnitude of an earthquake that has the potential to occur within the designated study region (Syukri et al., 2021). Based on the findings of Irsyam et al. (2013) and Marliani et al. (2016), it has been determined that the Cimandiri Fault possesses the potential to induce seismic events of magnitudes reaching up to Mw 7.2. The potential for significant destruction exists within a 10-kilometer radius of the study region as a result of the presence of earthquakes with magnitudes ranging from Mw 6 to Mw 7. The estimated spatial separation between the sites under investigation and the location of the Cimandiri Fault rupture.

In line with the mechanism of seismic source, several widely recognized attenuation functions, such as the Next Generation Attenuation (NGA), were chosen. The estimation of spectral acceleration at sites under inquiry for geotechnical analysis involves the use of Next Generation Attenuation West 2 (NGA-West 2) models. These models are utilized to characterize earthquakes. The study conducted by Abrahamson et al. (2014) is utilized to estimate spectral acceleration at soil sites (Qodri et al., 2021, Qodri et al., 2022). The NGA-West 2 model is obtained by calculating the weighted average of many NGA-West 2 models. The objective of this implementation is to minimise the influence of unpredictability on the variability of ground motion.

Given the absence of documented strong motion data about previous earthquakes induced by the Cimandiri Fault, the Mw 6.9 Loma Prieta earthquake, sourced from the PEER database, has been

selected as the most suitable input motion for the examined sites, as per Ancheta (2022). The input motion is subsequently derived from the spectral matching acceleration earthquake. The spectral acceleration for sites under examination can be acquired by an analysis conducted according to the NGA-West2 methodology. Subsequently, motion input is generated for each site under investigation. The spectrum matching method proposed by Abrahamson et al. (2014) was implemented in this investigation, as depicted in Fig. 3.

The spectral matching approach is of great importance due to its ability to generate ground acceleration by utilising the matched spectral acceleration. The method iteratively determines the ideal spectral match that is by the target spectrum. The determination of the target spectrum is contingent upon the features of the site and the mechanics of the earthquake. The spectral acceleration that has been matched is then subjected to reverse analysis to ascertain the ground motion at the spot. With artificial earthquake scenario by spectral matching approach, seismicity in the research area is assumed to be the peak acceleration value at the surface (PGA) about 0.2 g and consistent with the PGA value by Mase et al. (2023). The maximum groundwater level is assumed to reach the ground surface as a result of earthquake vibrations, and the distance to the earthquake source is estimated to be around 10 km from the research area.

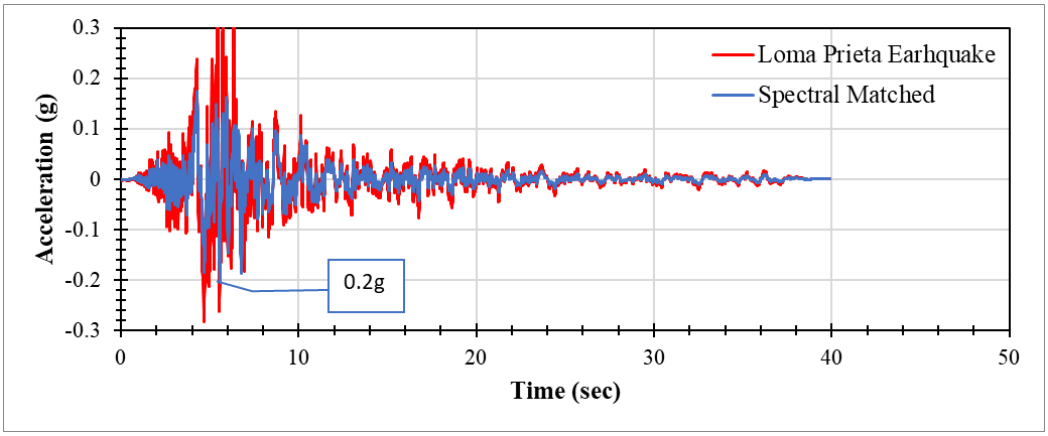


Fig 3. Spectral matched for the input motion

2.3. Liquefaction Potential Evaluation

The liquefaction assessment in this study involves the interpretation of cone penetration testing data using the CLiq software. CLiq a CLiq is a computer software program that specialises in soil engineering applications developed by Geologismiki (Geologismiki Geotechnical Software, 2006). Its purpose is to facilitate the evaluation of soil liquefaction through the utilization of Cone Penetration Testing. CLiq is a software tool that has been developed with the primary purpose of conducting liquefaction analysis by utilizing CPT data (Rupesh et al., 2022) It offers various graphical representations and outcomes for fundamental CPT interpretation, such as cone resistance and friction ratio. Furthermore, it offers outcomes about the examination of liquefaction, encompassing the element of safety, classification of soil behaviour, susceptibility to liquefaction, vertical settlement, and lateral displacement. CLiq utilises empirical correlations to estimate geotechnical parameters for the goal of interpreting individual data fundamentally. The assessment parameter constants have the potential to be adjusted for individual CPT files, hence improving accuracy by specific contextual factors. The alterations in question can yield varying degrees of impact on the outcomes of liquefaction analysis, ranging from minor to significant. Consequently, it is imperative to exercise caution when dealing with these modifications. This study presents cyclic liquefaction plots, factors of safety, liquefaction potential index, and vertical and lateral displacements. The plots also incorporate the classification of soil behaviour type.

The classification of the primary soil behaviour types in the study area was based on the CPT data, namely the CPT resistance (qc). The soil behaviour type charts incorporating the normalisation of cone resistance and friction ratio corrected for pore pressure (qt) were created by Robertson and Wride in 1998. The determination of a soil's behaviour type is presently accomplished by employing the CPT to derive the soil behaviour type index, Ic. This index is defined as follows:

$$I_c = \sqrt{[3.47 - log_{10}\ Q)^2 + (1.22 + log_{10}\ Q)^2} \quad (1)$$

In this context, Q represents the normalised CPT penetration resistance, expressed as a dimensionless quantity. Similarly, F is the normalised friction ratio, measured in percentage. The normalised soil behaviour type according to the CPT is depicted in Fig. 4; Table 1 below displays the boundaries of each soil behaviour type as indicated by the index, Ic.

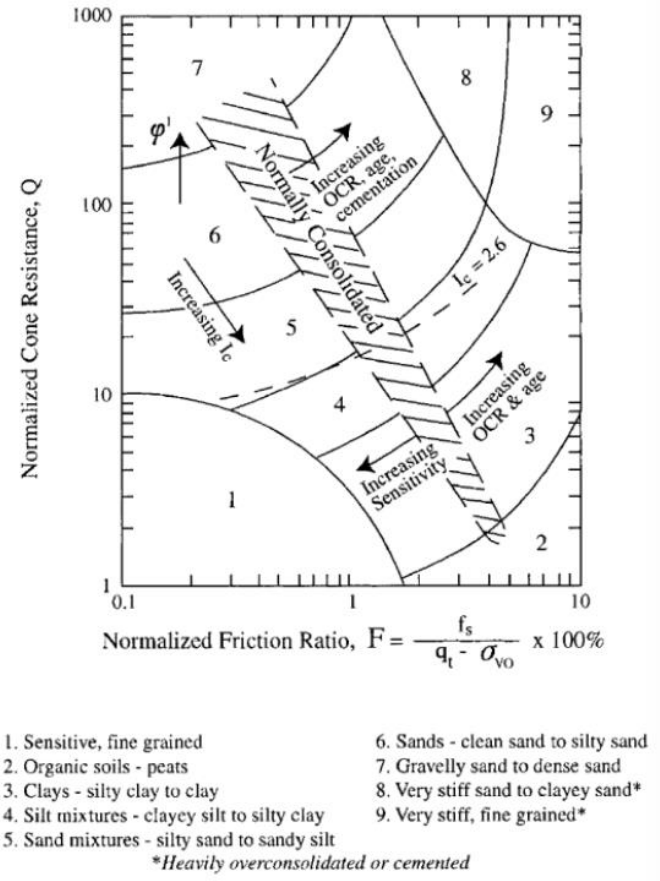


Fig. 4. CPT-based Soil Behavior Type chart (Robertson, 1990).

Table 1. Soil Behaviour Type (SBT) classification (Robertson, 1990).

Zone	Soil Behaviour Type (SBT)
1	Sensitive fine-grained
2	Clay - organic soil
3	Clays: clay to silty clay
4	Silt mixtures: clayey silt & silty clay
5	Sand mixtures: silty sand to sandy silt
6	Sands: clean sands to silty sands
7	Dense sand to gravelly sand
8	Stiff sand to clayey sand*
9	Stiff fine-grained*

Liquefaction is a phenomenon that takes place when the application of rapid loading results in the build-up of excessive porewater pressure inside saturated granular soils, frequently in association with seismic events. The correlation between soil strength and effective vertical stress (σvo') is such that a decrease in effective stress resulting from an increase in pore pressures (u) will result in a decrease in soil strength. In the study conducted, as stated by Seed and Lee (1966), soil liquefaction is a phenomenon characterised by a quick decrease in both strength and stiffness. It commonly arises due to a sudden loading event or the application of stress, such as seismic activity. Liquefaction transpires when the soil's shear strength is fully depleted or when the effective stress of the soil has practically diminished to zero. The global significance of soil liquefaction, which impacts sandy and silty soils, extends beyond the localised setting of Sukabumi, making it an issue of utmost importance for structural integrity worldwide. The precision and reliability of liquefaction analyses have experienced notable enhancements due to extensive research conducted over the past few decades, which has been helped by the development of the CPT.

The formulation of the Cyclic Stress Ratio (CSR) and the Cyclic Resistance Ratio (CRR) was first introduced by Seed and Idriss (1971) to provide a quantitative measure of a soil's ability to resist liquefaction triggered by seismic events. The term CSR pertains to the seismic loading imposed on a soil stratum by a particular earthquake occurrence. Conversely, the CRR refers to the soil's capacity to endure and oppose liquefaction. The determination of the factor of safety is based on the ratio between the CRR and the CSR. The evaluation of the CRR can be conducted via laboratory testing, particularly by employing high-quality, undisturbed samples. However, due to the probable difficulties and expenses involved in obtaining it, there has been a significant increase in the usage of the CPT. Seed and Idriss (1971) devised a simplified method to estimate the CSR based on the CPT, utilising the highest ground acceleration (a_{max}) recorded at a particular site. This approach involves the process of conceptualising CSR as:

$$\boldsymbol{CSR} = \frac{\tau_{av}}{\sigma'_{vo}} = 0.65 \left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right) \boldsymbol{r_d} \quad (2)$$

$$rd = 1.0 - 0.00765z \text{ for } z \leq 9.15\ m \quad (3a)$$

$$rd = 1.0 - 0.00765z \text{ for } 9.15\ m < z \leq 23\ m \quad (3b)$$

Where: τav is the average cyclic shear stress, a_{max} is the highest horizontal acceleration experienced at the earth's surface, g = 9.81m/s^2 is the acceleration due to gravity, σ_{vo} and σ'_{vo} are the total and effective vertical overburden stresses, respectively, and r_d is a stress reduction factor, dependent on depth. CSR is influenced by seismic movements, whereas the CRR quantifies the resistance of the soil deposit against liquefaction. The databases obtained from field investigations conducted after an earthquake have been employed to produce demarcation curves that establish a correlation between a stress-normalized resistance parameter derived from an in-situ test and the soil's resistance to cyclic loading induced by a seismic event of magnitude 7.5 (CRR7.5) is being examined. Field performance data collected from seismic events with magnitudes differing from 7.5 are modified to correspond to commensurate values of CSR7.5.

$$\text{CSR7.5} = \frac{CSR}{MSF} \quad (4)$$

The magnitude of an earthquake has a direct impact on the duration of shaking, hence increasing the number of severe stress cycles. The soil's resistance to liquefaction will decrease as the number of significant stress cycles at a constant stress ratio increases. The cyclic stress ratio does not account for the influence of earthquake magnitude; hence, magnitude scaling factors (MSF) were devised. The designated magnitude for conducting cyclic stress-based analysis is 7.5.

$$MSF = 31.9\ (Mw) - 1.72 \quad (5)$$

The estimation of the CRR is typically derived from the corrected CPT measurement. In their study, Robertson and Wride (1998) constructed a graphical representation that illustrates a comparative analysis of three distinct approaches for estimating the CRR. According to Robertson and Wride (1998), a simplified equation is proposed to estimate the CRR using the normalised penetration resistance (qc1n)cs of clean sand. This estimation is based on various grain characteristic parameters, including the soil behaviour type index. The subsequent parts will go into this topic. The equation proposed by Robertson and Wrides is presented as follows:

$$If\ 50 \leq (qc1n)cs < 160, CRR = 93[(qc1n)cs1000]3 + 0.08$$
$$fIf\ (qc1n)cs < 50, CRR = 0.833[(qc1n)cs1000]3 + 0.05 \quad (6)$$

Where: $(qc1n)cs$ is dependent on both the measured penetration resistance (qc1n) and the grain properties of the soil.

$$(qc1n) = CQ(qc/Pa) \quad (7)$$

Factor of Safety (FS), can be calculated after measuring CSR and CRR. This can be done using the following equation:

$$FS = \frac{CRR}{CSR} \quad (8)$$

Liquefaction will occur if FS is less than 1. Conversely, if FS is greater than 1, liquefaction will not occur. In this research, shear strain (γ) will be used to measure whether liquefaction occurs somewhere. The FS against liquefaction were computed using the CPT-based liquefaction evaluation procedure proposed by Robertson and Wride (1998). The FS cannot specifically measure the extent of foundation damage caused by soil liquefaction, and this depends in turn on the severity of the liquefaction. Instead, it is determined by using the Liquefaction Potential Index (LPI) as a method that utilises the CPT to assess a soil's ability to resist liquefaction during seismic events and to determine the magnitude of liquefaction. The LPI was proposed by Iwasaki et al. (1982) and Sonmez (2003) and defined as:

$$LPI = \int_0^{Zcrit} F(z).w(z).dz \quad (9)$$

Where, F =1- FS for FS ≤ 1.0 and F = 0 for FS > 1.0; z is the depth below the ground surface (in meters) and W(z) = a depth weighting factor equal to 10-0.5z, and dz is the differential increment of depth. Z is indicated with script as the maximum depth to which liquefied layers produce effects on the surface. Traditionally, the critical depth is assumed to be 20 m, but recently Ozocak and Sert (2010), based on experimental evidence successive to earthquakes in Adapazari (Turkey) in 1999 and based on the limit curves for manifestations of surface liquefaction in Ishihara et al. (1985), have proposed to take for earthquakes of "usual" magnitude the critical depth of 10 m. The classes of liquefaction potential by several researchers are presented in Table 2 below.

Table 2. Liquefaction Potential Index Classifications

Liquefaction potential	LPI (Iwasaki et al., 1982)	LPI (Sonmez, 2003)	LPI (Maurer et al., 2014)
Non-liquefiable	0	0	0<LPI≤4
Low	0<LPI≤5	0<LPI≤2	4<LPI≤8
Moderate	5<LPI≤51	2<LPI≤5	8<LPI≤15
High	15<LPI≤100	5<LPI≤15	LPI>15
Very high	-	LPI>15	

3. Results

The investigation carried out on CLiq provides a brief overview of the results obtained from the analysis carried out, with special emphasis on the variables relevant to the scope of this research, namely

changes in the soil behaviour type, vertical settlement, lateral displacement, FS and LPI. The locations are designated as V1 to V3.

3.1. Soil Behavior Type

The soil behaviour types in this research, defined by Robertson and Wride (1998), are displayed in Fig. 5. According to the findings of the site investigation, silty sand soils dominate research areas, and the groundwater level is relatively close to the surface around 1.5 m. At shallow depths (0 to 1.5 m), silt (ML) and silty sand (SM) layers are present. Silty sand (SM) layers are typically found at depths of 0.5 to 5 m. The CPT resistance is about 30 to >100 kg/cm^2.

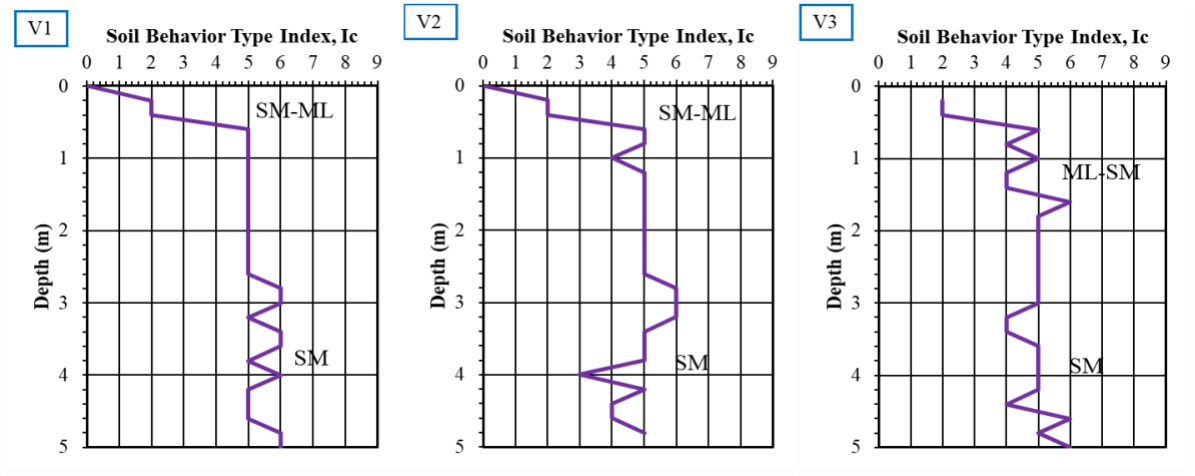


Fig. 5. Soil behaviour type index in the research area

The Cone Resistance Ratio (CSR) was calculated for each soil profile as the ratio of the corrected CPT resistance (qc) to the effective vertical stress (σvo'). CSR values were used to assess the liquefaction potential, with higher CSR values indicating lower liquefaction susceptibility. The results of CSR in the research area are averaging 0.2 to 0.4 considered as silty sand soil. On the other hand, The Cyclic Resistance (CRR 7.5) was determined through numerical modelling from the CPT data obtained from the research area. CRR 7.5 values represent the soil's ability to resist cyclic loading during an earthquake. The results of CSR and CRR are presented in Fig. 6 below.

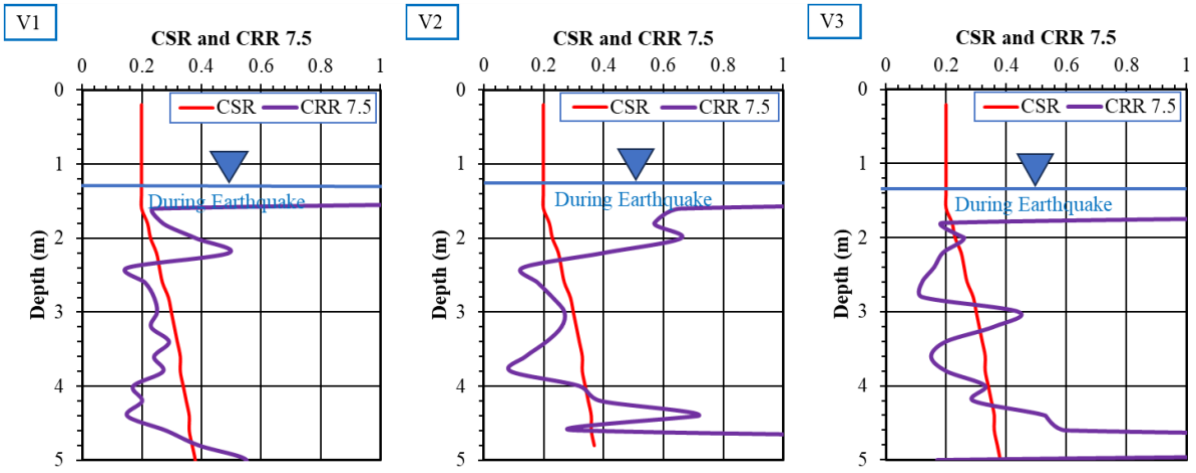


Fig. 6. Soil behaviour type index in the research area

3.2. Vertical Settlement and Horizontal Displacement

The potential vertical settlement during a seismic event was estimated for different depths as shown in Fig. 7. Settlement values are estimated from 20 mm to 60 mm. Furthermore, Horizontal displacement during an earthquake was also evaluated with displacement values around 10-70 cm as presented in Fig. 8. These settlements and displacement are critical considerations for engineering design and infrastructure resilience in the study area.

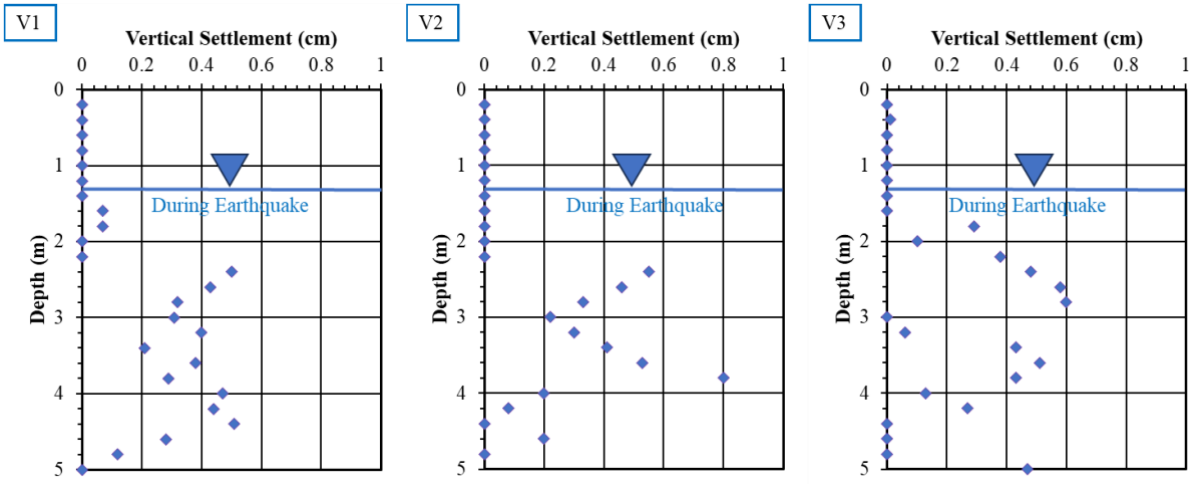


Fig. 7. Vertical settlement in the research area

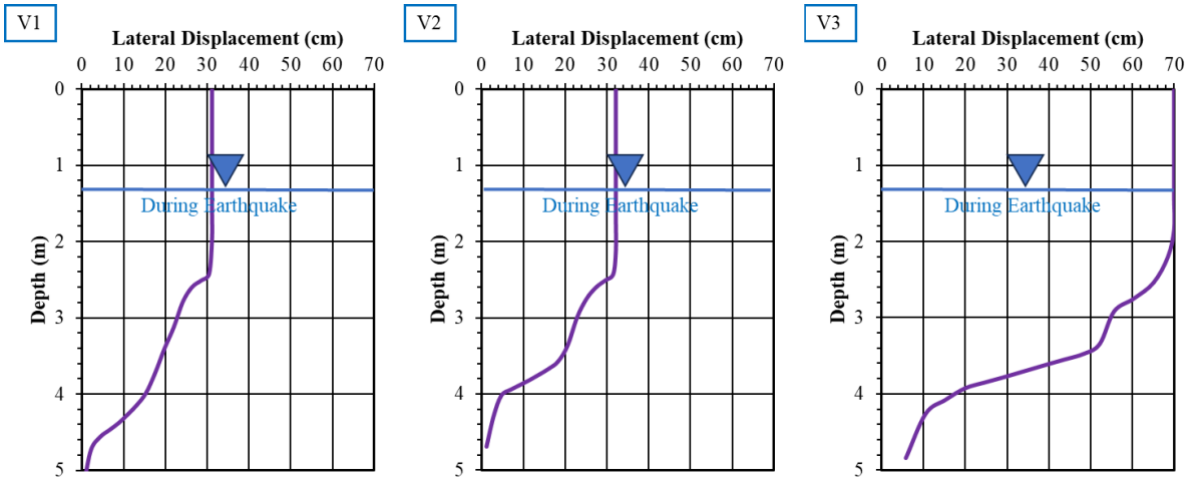


Fig. 8. Lateral displacement in the research area

3.3. Liquefaction Potential

According to liquefaction analysis using CPT data by Robertson & Wride (1997) and Boulanger and Idriss (2004) method using maximum credible earthquake of Cimandiri Fault (Mw 7.2), the layer that is prone to liquefaction and non-liquefaction were identified as demonstrated in Fig. 9**.**

Considering the Factor of Safety (FS) of liquefaction potential with depth as shown in Fig. 10, several depths in V1 to V3 in Sukabumi, West Java were found to have a factor of safety (FS) less than 1, indicating their susceptibility to liquefaction during a significant seismic event. The liquefaction tends to occur between a depth of 2.00 m and 5.00 m where the qc cone resistance value is less than 100 kg/cm^2 (Robertson and Campanella, 1985). Furthermore, the data obtained from the site investigation

revealed that the soil layers were predominantly composed of silty sand (SM), indicating a relatively high liquefaction susceptibility.

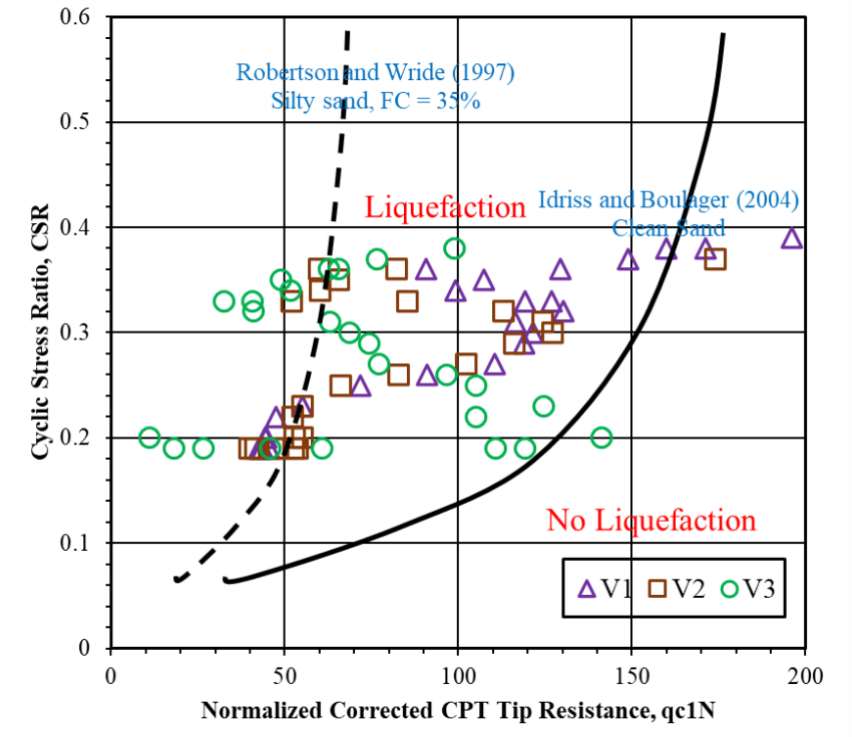


Fig. 9. Liquefaction Potential Analysis

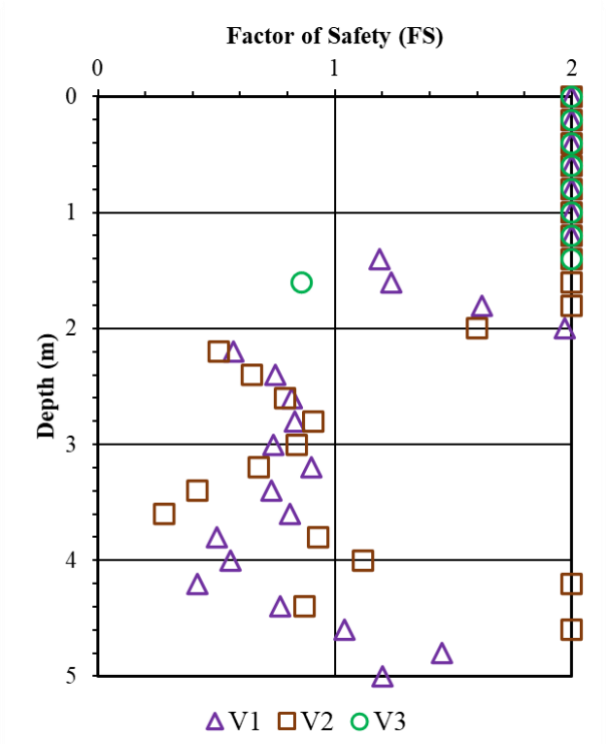


Fig. 10. Factor of safety in the research area

Fig. 11 displays the LPI values acquired through the analysis of weighting factors, with V1 to V3 being classified as having a level of vulnerability ranging from low to high for liquefaction. as reported by Iwasaki et al. (1982) and Maurer et al. (2014). Sonmez (2003) categorizes that research area as having low to high vulnerability.

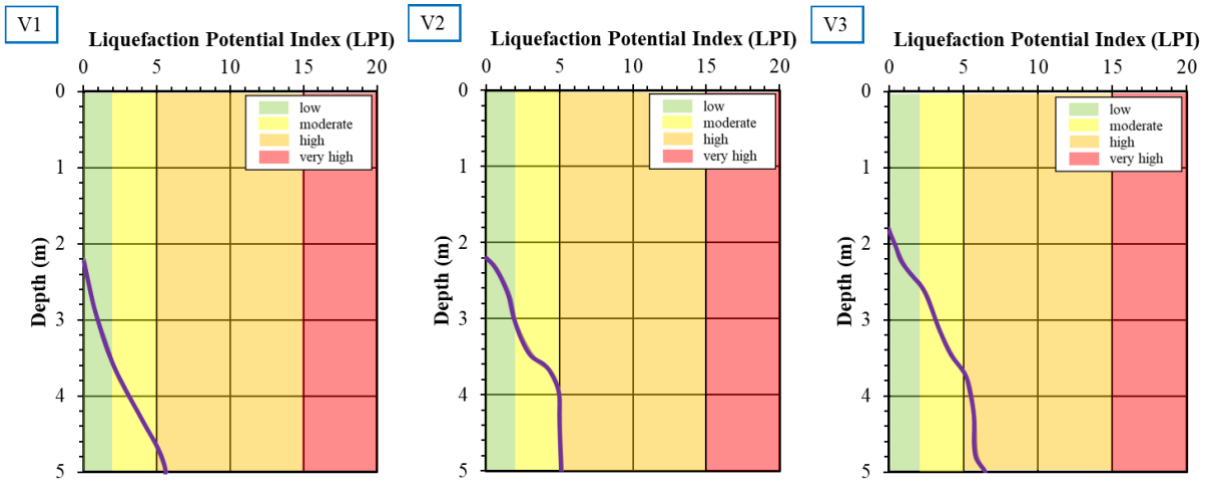


Fig. 11. Liquefaction Potential Index (LPI) values in the research Area

4. Discussion

The research areas are found to be predominantly characterized by sedimentary materials, specifically silt and sand particles (silty sands) according to the results of CPT soil behaviour type analysis. This observation suggests the presence of increased soil resistance, which enables the management of cyclic mobility generated during seismic events (Kennedy and Mahmood, 2023). The vertical settlement and lateral displacement are indicative of the potential vertical and lateral displacement of the ground surface, which is calculated by integrating the highest shear strains over the depth.

The investigations conducted by Cliq analysis involved the computation of probable maximum shear strains, utilising the relationship established by Ishihara and Yoshimine (1992). From a factor of safety (FS) standpoint, critical depth refers to the depth at which the liquefiable layer is most vulnerable and where liquefaction is initially induced when seismic forces surpass the soil's resistance (Dimitriadi et al., 2018). In theory, the detection process should involve the simultaneous consideration of tip resistance and friction ratio, supplemented by the inclusion of a boring log for soil categorization. The utilisation of the estimated CRR profile facilitates the determination of the layer's minimal resistance threshold and its related critical depth. In general, The LPI values indicate that the research area has a low to moderate liquefaction potential Index, primarily due to its shallow groundwater table and low CPT resistance.

5. Conclusions

The evaluation of the liquefaction potential exhibited divergent outcomes at different depths within the research area. The seismic parameters of the Cimandiri Fault's Maximum Credible Earthquake, which had a magnitude of 7.2, were employed in this study to evaluate the possibility of liquefaction. The evaluation of liquefaction susceptibility requires the comparison of cyclic shear stresses (CSR), which are expressed as normalised cyclic stress, and cyclic resistance ratios (CRR). This research paper provides an examination of the likelihood of shallow liquefaction resulting from the most severe earthquakes that can occur on the Cimandiri Fault in Sukabumi, West Java, Indonesia. The analysis is

conducted with the Cone Penetration Test. The employed approach was effectively utilised to evaluate the degree of liquefaction vulnerability. According to the factor of safety, the liquefiable layer is 2.00 to 5.00 m and the liquefaction values indicate low to high vulnerability to liquefaction considering the Liquefaction Potential Index (LPI). During an earthquake, vertical settlement values are estimated from 20 mm to 60 mm. Furthermore, Horizontal displacement values are 10-70 cm. Furthermore, the research indicates that engineers operating at the regional level should duly consider the potential ramifications of liquefaction within the specified study region, particularly while strategizing for the development of forthcoming infrastructures. The authors additionally suggested the utilisation of the methodology employed in this study to investigate liquefaction events in diverse geographical areas.

Acknowledgement This study was supported by Institut Teknologi Nasional Yogyakarta (ITNY) Research Fund. The authors are grateful to the Department of Civil Engineering and Department of Geological Engineering, Institut Teknologi Nasional Yogyakarta and the Department of Civil Engineering, University of Bengkulu, Indonesia.

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