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ASSESSING LIQUEFACTION RISK AT LHOKSEUMAWE BEACH: IMPACT OF THE 2004 ANDAMAN AND 2016 PIDIE JAYA EARTHQUAKES

*Abdul Jalil[1], Lindung Zalbuin Mase[2] and Yovi Chandra[1]

[1]Department of Civil Engineering, Faculty of Engineering, Universitas Malikussaleh, Aceh, Indonesia
[2]Department of Civil Engineering, Faculty of Engineering, University of Bengkulu, Bengkulu, Indonesia

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ABSTRACT: This paper presents a study of liquefaction in Lhokseumawe, Indonesia, a topic of urgent importance due to the 2004 Andaman Earthquake (Mw 9.2) and the 2016 Pidie Jaya Earthquake (M_w 6.5). Evaluations of liquefaction potential were conducted in conjunction with particle size distribution analyses and data collected from three Cone Penetration Test (CPT) and three Standard Penetration Test (SPT) locations, which assessed the engineering characteristics and geological conditions of the area. Latitude and longitude coordinates from the sites of the hand-bore, SPT, and CPT tests were utilised to determine the peak ground acceleration (PGA) values associated with these two significant earthquakes. The analysis of liquefaction potential in Lhokseumawe, employing SPT and CPT data, utilised semi-empirical methods. The distribution of soil particle sizes played a crucial role in determining the liquefaction potential. The findings indicate that the study area is primarily composed of poorly graded sand (SP) and well-graded sand (SW). Potential liquefaction sites were generally observed at a depth of 1 meter; however, significant liquefaction potential was also identified at depths of 15 and 18 meters below the surface. Overall, the results of this study emphasise the crucial importance of conducting preliminary investigations into soil liquefaction before commencing construction activities.

Keywords: Liquefaction, Earthquake, Geological Conditions, Peak Ground Acceleration (PGA), *Construction Activities*

1. INTRODUCTION

Liquefaction is a critical geotechnical hazard that occurs when saturated, unconsolidated soils temporarily lose strength and stiffness in response to seismic shaking, resulting in significant ground deformation [1,2]. This phenomenon poses serious threats to infrastructure and human safety, particularly in seismically active regions with loose sandy soils and shallow groundwater tables. The 2004 Andaman earthquake, with a magnitude of M_w 9.2 [3]. The 2016 Pidie Jaya earthquake, with a magnitude of M_w 6.5, is a significant seismic event that has had a profound impact on the region and is crucial in understanding the liquefaction potential in Lhokseumawe. The 2016 Pidie Jaya earthquake has underscored the vulnerability of various areas in Aceh Province, Indonesia, to earthquake-induced hazards, including liquefaction [4].

Liquefaction vulnerability in Pidie Jaya was highlighted by [5], with evidence of lateral spreading and associated damage to infrastructure, particularly road embankments. The 2004 Great Sumatra–Andaman earthquake was one of the most powerful earthquakes in recorded history and profoundly impacted Banda Aceh City and the surrounding coastal zones [2].

Lhokseumawe, a coastal city located in the northern part of Aceh Province, is situated within a geologically complex region characterised by recent alluvial and volcanic deposits. The area is located between two major tectonic features: the Sunda megathrust and the Sumatran fault system. These tectonic boundaries are known to generate significant seismic activity, raising concerns about liquefaction during future earthquakes.

Recent studies have increasingly emphasised the application of engineering field tests to improve the reliability of liquefaction potential assessment. [6]conducted an in-situ investigation using penetration-based field tests to evaluate liquefaction susceptibility in shallow subsurface layers. Aini et al. (2024) [7,8] conducted comprehensive field-based geotechnical investigations, combining in-situ penetration testing and groundwater observations, to assess liquefaction potential in infrastructure development areas. Liquefaction susceptibility in fine-grained soils has also been examined through engineering field investigations. Hakam et al. (2021) [9] conducted a comprehensive liquefaction assessment for toll road construction sites founded on fine-grained soils using field-based geotechnical testing, including in situ penetration tests and groundwater level measurements. The study revealed that soil plasticity characteristics, groundwater conditions, and cyclic loading effects significantly influenced liquefaction behaviour in fine-grained deposits. By relying on field test data rather than laboratory testing alone, this research provided direct evidence that liquefaction is not exclusively associated with sandy soils. Consequently, the findings underscore the need to incorporate fine-grained soil deposits into liquefaction evaluation and infrastructure design practices, particularly for large-scale transportation projects. The study by Mase et al. (2025) [10](10) highlights that strong ground motion characteristics, particularly vertical acceleration and long-duration shaking, play a critical role in triggering deep liquefaction during the 2018 Palu earthquake. The results show that strong ground motion plays a key role in causing severe soil damage.

Although several studies have examined regional seismic hazards in Aceh [(11)]. Considering the city's economic and strategic significance, a site-specific liquefaction analysis is not only necessary but could also significantly impact disaster preparedness and informed urban development. This study could provide crucial insights for disaster management professionals and urban planners.

The use of site investigation data is crucial for supporting liquefaction analysis. This is because soil resistance can significantly enhance liquefaction resistance. Otherwise, the cyclic stress from the earthquake could degrade the liquefaction resistance. Therefore, the site investigation data must be known before conducting the liquefaction potential analysis.

This study aims to assess the liquefaction potential in Lhokseumawe through a combination of field and analytical approaches. The primary methods employed include Standard Penetration Test (SPT)-based analysis, utilising the simplified procedure developed by Seed et al. in 1985, which estimates the cyclic resistance ratio (CRR) from SPT data and updated correlations from the Idriss and Boulanger method in 2008. The Cone Penetration Test (CPT)-based analysis employs the Robertson and Wride method of 1998 to assess soil behaviour type and liquefaction potential from CPT data.

Evaluation of the cyclic stress ratio (CSR) from site-specific seismic loading parameters, including peak ground acceleration (PGA) and earthquake magnitude—calculation of the factor of safety (FS) against liquefaction by comparing CSR and CRR. The in situ CRR was determined from SPT and CPT field tests. Data for this study were collected from subsurface investigations, borehole logs, and geotechnical reports, as well as regional seismic hazard data from the Meteorology, Climatology, and Geophysics Agency of Indonesia or BMKG.

2. RESEARCH SIGNIFICANCE

The significance of the study lies in the need to assess liquefaction potential in the Lhokseumawe area beach. The area is characterised by a well-defined spatial arrangement, with industrial buildings clustered in designated zones, a centrally located government activity centre, and surrounding areas supporting diverse economic activities. The findings of this study could significantly impact the safety and resilience of these structures and activities.

3. GEOLOGY SETTING AND SEISMICITY

Lhokseumawe City is located on the northeastern coast of Aceh Province, northern Sumatra, Indonesia, facing the Malacca Strait. Geologically, the area lies within the North Sumatra sedimentary basin, characterised by extensive Quaternary deposits derived from fluvial, deltaic, and marine sedimentation processes. The regional geology is strongly influenced by both tectonic activities associated with the Sunda subduction system and sedimentary processes along the coastal plain.

The surface geology of Lhokseumawe is dominated by Quaternary alluvial and coastal deposits, consisting primarily of loose to medium-dense sands, silty sands, sandy silts, and clayey layers. These deposits were formed by river systems draining from the Bukit Barisan Mountain Range toward the coastal lowlands, resulting in thick accumulations of unconsolidated sediments. In coastal and low-lying areas, marine and estuarine deposits are commonly interbedded with fluvial sediments, creating highly heterogeneous subsurface conditions.

From a tectonic perspective, northern Sumatra is one of the most seismically active regions in Indonesia. The area lies within the Sumatra–Andaman subduction zone, where the Indo-Australian Plate subducts beneath the Eurasian Plate, generating large megathrust earthquakes such as the 2004 M_w 9.2 Sumatra–Andaman event. In addition to subduction-related seismicity, inland crustal earthquakes are associated with the Sumatran Fault System, a major right-lateral strike-slip fault extending along the length of Sumatra. Although the main trace of the Sumatran Fault is located west of Lhokseumawe, its segmented structure contributes to regional seismic hazard.

Hydrogeologically, the Lhokseumawe area is characterised by a shallow groundwater table, particularly in coastal and deltaic zones. Groundwater levels are commonly found at depths of less than 5 m below ground surface, especially during the rainy season. The combination of shallow groundwater conditions and loose granular soils significantly increases the area's susceptibility to earthquake-induced liquefaction.

Overall, the geological setting of Lhokseumawe—characterised by young unconsolidated sediments, shallow groundwater, and high seismicity—creates favourable conditions for liquefaction occurrence during strong ground shaking. These geological and tectonic conditions underline the importance of detailed site-specific geotechnical investigations and liquefaction hazard assessments for infrastructure development in the region.

Seismic activity in the Lhokseumawe area has been influenced by major tectonic events, notably the 2004 Andaman earthquake and the 2016 Pidie Jaya earthquake. The impact of the 2004 Andaman earthquake was documented by [12], while the effects of the 2016 Pidie Jaya earthquake were reported by [13]. The epicentres of these earthquakes are plotted in Fig. 1. Lhokseumawe is located between the Sunda megathrust and the Sumatran fault system, within a basin composed of recent alluvial and volcanic deposits [14].

The surface and subsurface geology in the area is classified mainly as silty sand, clayey sand, clay and sand deposits. The deposits were found in the Lhokseumawe City area and along the coastline.

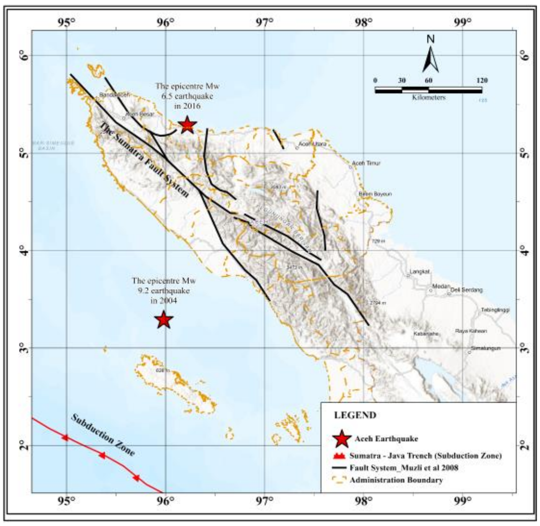

Fig 1. Seismicity in the Lhokseumawe area

Lhokseumawe is situated in a graben area (Fig. 2) composed of the Seureula Formation (T_{ps}), Julurayeu Formation (Q_{Tjr}), IDI Formation (Q_{pi}), and Young Alluvium Deposits (Q_h) [15]. According to [15] the geology of Lhokseumawe primarily consists of layered sedimentary deposits, including gravel, sand, silt, and fluvial deposits, found along the active Sumatran Trench.

The subsurface stratigraphy at the three borehole locations is summarised in Table 1. The soil profile generally consists of silty sand and poorly graded sand layers underlain by clayey deposits, indicating heterogeneous alluvial sedimentation. The soil profile was classified using the USCS system and is presented as stratigraphy, with the corresponding lithology illustrated in the borehole columns BH-1, BH-2, and BH-3 in Fig. 3. Figure 3 illustrates the soil stratigraphy profile, showing that silty sand (SM) extends from the ground surface to a depth of approximately 4 m at location BH-1 and continues toward BH-2 with a similar depth variation. A low-plasticity (CL) clay layer is observed at BH-3. Subsequently, a poorly graded sand (SP) layer is encountered at BH-1, BH-2, and BH-3, with varying thicknesses. Lenses of silty sand (SM) are present at BH-1 and BH-3, becoming slightly thicker at BH-2.

At depths ranging from 8 m to 16 m, a silty sand–poorly graded sand mixture (SP-SM) is identified at BH-1 and BH-2, while only a lens of this layer appears at BH-3. Between depths of 16 m and 30 m, a low-plasticity clay (CL) layer is found at BH-1, whereas interbedded silty sand (SM) layers occur between 24 m and 34 m, extending from BH-2 to BH-3.

At greater depths, from 34 m to 42 m at BH-2, a clayey sand (SC) layer is encountered, followed by a silty sand (SM) layer extending from 42 m to 50 m.

Table 1: Summary of subsurface stratigraphy at borehole locations (BH-1, BH-2, and BH-3)

Bore hole	Depth (m)	Soil Classification	Description
BH-1	0-3	SM	Silty sand, loose to medium dense
	3-6	SP	Poorly graded sand
	6-12	SP-SM	Sand with silt
	12-30	CL	Lean clay, medium plasticity
BH-2	0-2	SM	Silty sand
	2-6	SP	Poorly graded sand
	6-10	SM	Silty sand
	10-15	OL	Organic silt/clay
	15-25	SP-SM	Sand with silt
	25-30	SM	Silty sand
BH-3	0-4	CL	Lean clay
	4-18	SP	Poorly graded sand
	18-28	SP-SM	Sand with silt

4. METHODS AND THEORY

This research was conducted along the coastal area of Lhokseumawe City, Aceh Province. Soil resistance tests were conducted at six locations using the Standard Penetration Test (SPT) and Cone Penetration Test (CPT) methods. The assessment of liquefaction potential in the Lhokseumawe area was carried out using a deterministic approach based on N-SPT and CPT data, following the methodology proposed by Idriss and Boulanger in 2008. This method involves comparing the Cyclic Resistance Ratio (CRR), which represents the soil's resistance to liquefaction, with the Cyclic Stress Ratio (CSR), which reflects the seismic loading induced by an earthquake.

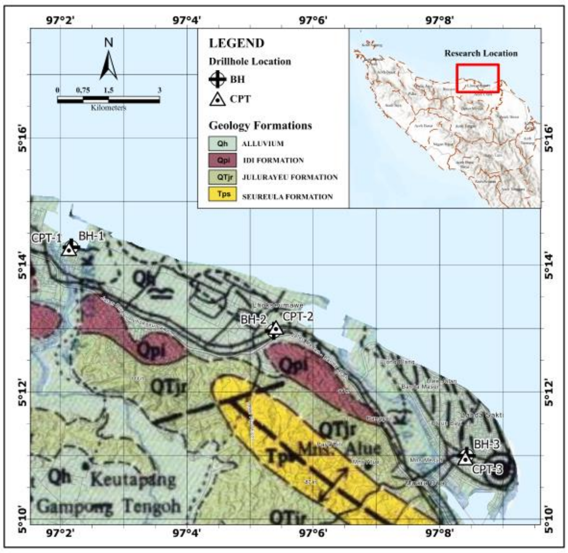

Fig 2. Geological map of the Lhokseumawe area

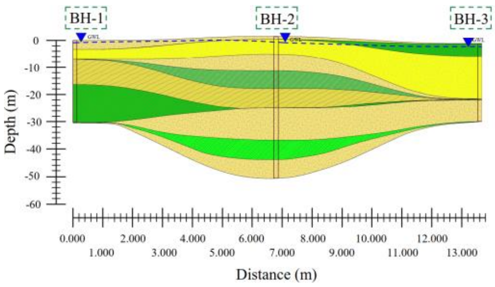

Fig 3. The soil profile along the beach area study

4.1 Soil Classification for Each Subsurface Layer

The identification and classification of soil types for each soil layer were conducted based on laboratory test results from undisturbed soil samples collected from that layer. The soil types were classified according to the Unified Soil Classification System (USCS). Additionally, the site classification was conducted in accordance with the Building Code of the Indonesian National Standard for Seismic Resistance Design [16], which provides guidelines for seismic design based on local soil conditions. The potential for liquefaction and loss of soil strength was evaluated using site-specific peak ground acceleration (PGA), earthquake magnitude, and source characteristics consistent with the Maximum Considered Earthquake Ground Motion (MCE_G). The MCE_G is the maximum ground motion expected at a site for a specified earthquake. Peak Ground Acceleration (*PGA*) is calculated using Equation 1, which provides a quantitative basis for evaluating seismic loading at the site.

$$PGA_M = F_{PGA} \times PGA \quad (1)$$

Where PGA_M is the peak ground acceleration for the Maximum Considered Earthquake Ground Motion (MCE_G) adjusted for site class effects, *PGA* is the value obtained from the seismic hazard map based on the Indonesian Earthquake Map regulations (accessible via the Puskim application), and F_{PGA} is the site amplification factor corresponding to the site classification.

The Cyclic Resistance Ratio (*CRR*) represents the capacity of soil to resist liquefaction under cyclic loading induced by earthquakes. It is defined as the ratio of the cyclic shear stress required to cause liquefaction to the effective overburden stress, normalised to a reference earthquake magnitude (commonly $M_w = 7.5$). Liquefaction is considered to occur when the cyclic demand imposed by an earthquake exceeds the soil resistance, i.e., $FS_{liq} < 1$.

The most widely used approach for estimating *CRR* is the simplified procedure originally proposed by Seed and Idriss (1971) and later refined by Idriss and Boulanger (2008). *CRR* determination using the SPT-based method.

$$CRR = exp\left(\frac{(N_1)_{60cs}}{14,1} + \left(\frac{(N_1)_{60cs}}{126}\right)^2 - \left(\frac{(N_1)_{60cs}}{23,6}\right)^3 + \left(\frac{(N_1)_{60cs}}{25,4}\right)^4 - 2,8\right) \quad (2)$$

CRR determination using *the CPT-based* method.

$$CRR = exp\left(\frac{q_{c1Ncs}}{540} + \left(\frac{q_{c1Ncs}}{67}\right)^2 - \left(\frac{q_{c1Ncs}}{80}\right)^3 + \left(\frac{q_{c1Ncs}}{114}\right)^4 - 3\right) \quad (3)$$

Earthquakes induce cyclic stress and contribute to the potential for liquefaction. Approximately 65% of the peak cyclic stress is considered in evaluating this potential, which is defined as the Cyclic Stress Ratio (CSR). The CSR can be calculated using Eq. 4.

$$CSR = 0.65 \times \left(\frac{\sigma_{vc}}{\sigma'_{vc}}\right) \times PGA_M \times r_d \quad (4)$$

where σ'_{vc} is the effective (16) vertical stress and σ_{vc} is the total vertical stress at depth *z*. The parameter r_d is the shear stress reduction factor. Soil strength and stiffness were obtained from field tests using the

Standard Penetration Test (SPT) and Cone Penetration Test (CPT). These strength parameters are used to determine the Cyclic Resistance Ratio (CRR) [17]. The factor of safety against liquefaction potential can be calculated as the ratio of the Cyclic Resistance Ratio (CRR) to the Cyclic Stress Ratio (CSR) induced by an earthquake. The factor of safety against liquefaction triggering can be expressed by Eq. (3).

$$FS_{liq} = \frac{CRR_{M,\sigma' vc}}{CSR_{M,\sigma' vc}} \quad (5)$$

Where FS_{liq} is the factor of safety against liquefaction. If FS_{liq} is less than 1.0, the soil is considered susceptible to liquefaction. Conversely, if FS_{liq} is greater than 1.0, the soil is considered safe with respect to liquefaction potential.

5. RESULTS AND DISCUSSION

The Peak Ground Acceleration (PGA) values were obtained from the latest Indonesian earthquake map, which was analysed using probabilistic seismic hazard analysis. The information is available on the website https://rsa.ciptakarya.pu.go.id/2021 by entering the coordinates of locations BH-1, BH-2, and BH-3. Standard Penetration Test (N-SPT) data were used to determine the soil site class in the Lhokseumawe area, in accordance with SNI-1726-2019, and the soil was classified as Medium (*SD*). By entering the geographic coordinates of the N-SPT test locations into the Indonesian seismic map, the *PGA* values for each site were found to be 0.41g, 0.45*g*, and 0.48*g*, respectively.

The calculated factor of safety against liquefaction (FS_{liq}) will be illustrated using liquefaction potential curves, providing a visual representation of the soil's susceptibility to liquefaction with depth.

The soil parameters presented in Table 1 were used for the liquefaction potential analysis, employing the simplified procedure proposed by Idriss and Boulanger (2008) [17].

5.1 Liquefaction Potential Based on SPT Data

Figure 4 shows that the depth of the drill hole is 30.45 meters below the ground surface. Liquefaction potential was identified at depths ranging from 3 meters to 15 meters under the earthquake scenario of M_w 9.2. The analysis at BH-1 indicates the presence of deep liquefaction. Similar cases of deep liquefaction were reported by [18] following the 2011 Canterbury Earthquake, where firm ground shaking was found to trigger widespread liquefaction significantly [19]. The depth of ground below 5 meters is shallow, with a water table that can affect the liquefaction trigger.

Table 1. Soil parameter

Items	Ground water level (m)	γ (kN/m³)	γ_{sat} (kN/m³)
BH-1	0.80	17.0	19.5
BH-2	1.85	17.0	19.5
BH-3	2.00	16.5	18.8
CPT-1	0.8	17.0	19.5
CPT-2	1.85	17.0	19.5
CPT-3	2.00	16.5	18.8

Deep soil liquefaction was confirmed at a depth of 3–15 meters using the Tsuchida (1970) method (Figure 5). This was correlated with Standard Penetration Test (N-SPT) data to confirm that the deep, medium- to loose-density saturated sand layer was susceptible to liquefaction, an area identified by a high groundwater table. Liquefaction potential occurs at shallow groundwater depths and is accompanied by large earthquake shocks. The manifestation of liquefaction can be correlated with the results of the safety factor analysis <1, indicating a high possibility of collapse of saturated sandy soil losing its strength and behaving like a liquid [20].

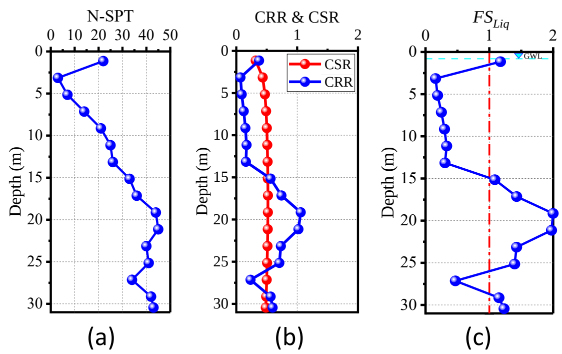

Fig. 4. Liquefaction Potential Curves at BH-1 for Mw 9.2: (a) N-SPT Data, (b) *CRR* and *CSR* curves, (c) Factor of safety against liquefaction.

The SPT data were used to analyse the liquefaction potential for a scenario with Mw 9.2 at BH-2 (Fig. 5) and BH-3 (Fig. 6). Figure 5 shows that liquefaction potential was observed at depths between 3 and 12 meters. A non-liquefying layer was identified at depths of 12 to 17 meters. The liquefaction potential was analysed for an M_w 6.5 scenario at BH-1, BH-2, and BH-3 (Figure 7). The depths at which liquefaction was observed were similar to those in the M_w 9.2 scenario, with a slightly reduced severity.

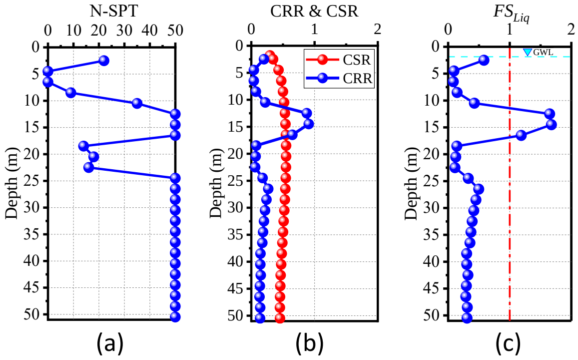

Fig.5 Liquefaction potential curves at BH-2 for M_w 9.2: (a) N-SPT data, (b) *CRR* and *CSR* curves, (c) Factor of safety against liquefaction.

The parameter r_d can be adequately expressed as a function of depth and earthquake magnitude (M_w). In this study, the r_d values were calculated using earthquake scenarios with M_w values of 6.5 and 9.2 for BH-1, BH-2, and BH-3. For the Mw 9.2 scenario, the calculated rd values ranged from 1.01 to 0.30 for BH-1, 1.01 to 0.79 for BH-2, and 1.00 to 0.94 for BH-3. Meanwhile, for the M_w 6.5 scenario, the r_d values ranged from 0.99 to 0.51 for BH-1, 0.98 to 0.50 for BH-2, and 1.00 to 0.51 for BH-3.

The results indicate that the r_d values decrease significantly with increasing depth, particularly up to approximately 34 m below the ground surface, consistent with the findings of Idriss (2008) (17). In addition, the uncertainty of r_d increases with depth, and the relationship is considered applicable only for depths of $z \leq 34$ m. Furthermore, according to Cetin et al. (2004) [21]. The r_d values are influenced by several factors, including depth, earthquake magnitude, shaking intensity, and the average shear-wave velocity within the upper 12 m of the site.

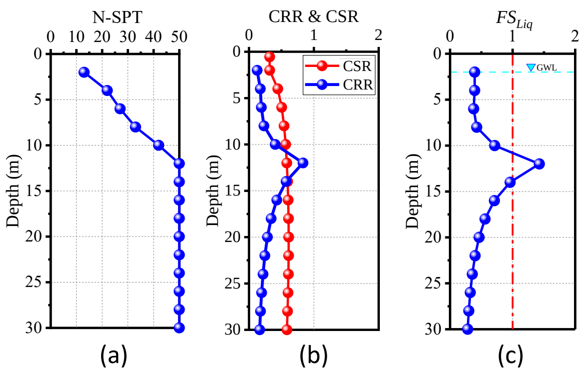

Fig.6 Liquefaction potential curves at BH-3 for M_w 9.2: (a) N-SPT data, (b) *CRR* and *CSR* curves, (c) Factor of safety against liquefaction

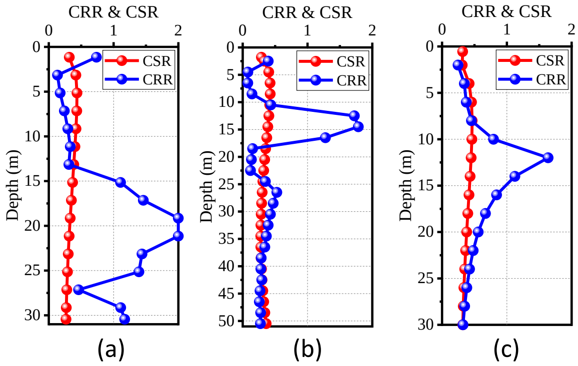

Fig.7 Liquefaction potential curves at BH-1, BH-2, and BH-3 for M_w 6.5: (a) *CSR* and *CRR* curves at BH-1, (b) *CSR* and *CRR* curves at BH-2, (c) *CSR* and *CRR* curves at BH-3

The grain size analysis based on the Tsuchida curve indicates that the soil samples from BH-1 are susceptible to liquefaction. Most of the grains from BH-1 fall within the potentially liquefiable range, with the highest liquefaction potential identified at a depth of 25.45 meters below the ground surface, indicating deep liquefaction potential. The grain gradation analysis for BH-1 is presented in Fig. 8, while the liquefaction potential determined from the grain size analysis according to the Tsuchida criteria is shown in Fig. 8.

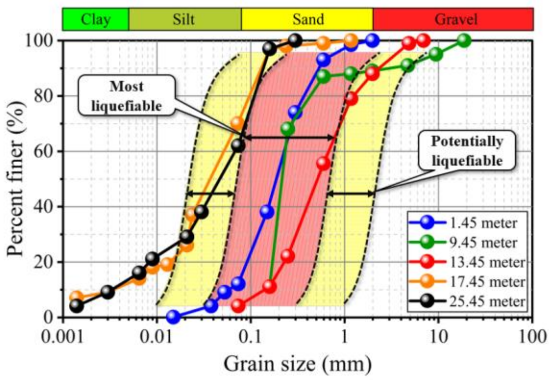

Fig.8 Liquefaction soil curves for BH 1, modified from [22]

The grain size analysis based on the Tsuchida curve indicates that the soil samples from BH-2 are susceptible to liquefaction. Most of the grains from BH-2 fall within the highly liquefiable range, with the greatest liquefaction potential occurring at depths between 8.45 m and 50 m below the ground surface, indicating deep liquefaction potential. The grain gradation analysis for BH-2 is presented in Fig. 9, while the liquefaction potential determined from the grain size analysis according to the Tsuchida criteria is shown in Fig. 9.

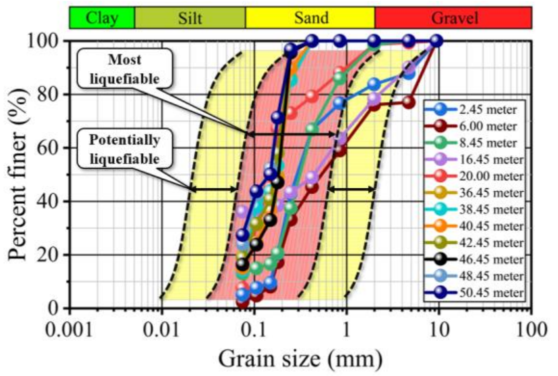

Fig.9 Liquefaction potential curves BH 2, modified from [22]

5.2 Liquefaction Potential Based on CPT Data

The CPT data were used to analyse the triggering of liquefaction potential, following the simplified procedure proposed by Idriss and Boulanger (2008). The liquefaction assessment was conducted under the assumption of level ground conditions for a moment magnitude (M_w) 6.5 earthquake, with Peak Ground Acceleration (PGA) values of 0.41*g*, 0.45*g*, and 0.48*g*. These PGA values represent the geometric mean of ground shaking observed during the 2016 Pidie Jaya earthquake.

In addition to the M_w 6.5 scenario, the CPT data were also used to evaluate liquefaction potential under a M_w 9.2 earthquake scenario, following the 2004 Andaman earthquake [23]. Liquefaction potential was identified at depths ranging from 2 to 8 meters below the ground surface (Figs. 10-11). The analysis used Peak Ground Acceleration (PGA) values of 0.41*g*, 0.*45g*, and 0.48*g*, which represent the geometric mean of ground shaking based on the Indonesian National Standard.

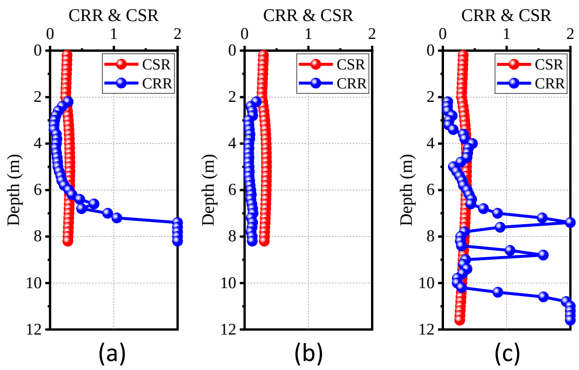

Fig.10 Liquefaction potential curves at CPT-1, CPT-2, and CPT-3 for M_w 6.5: (a) *CSR* and *CRR* curves at BH-1, (b) *CSR* and *CRR* curves at BH-2, (c) *CSR* and *CRR* curves at BH-3

6. CONCLUSION

The liquefaction potential analysis was carried out using both N-SPT and CPT data. Liquefaction potential was identified at depths ranging from 2 to 11 meters below the ground surface. Two earthquake scenarios, based on the Pidie Jaya and Andaman earthquakes, revealed the possibility of deep liquefaction. The effects of such liquefaction could cause significant damage to infrastructure facilities.

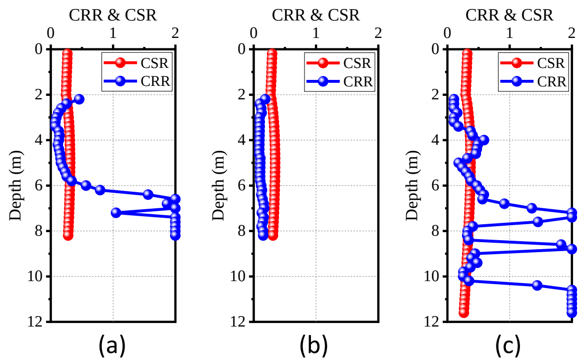

Fig.11 Liquefaction potential curves at CPT-1, CPT-2, and CPT-3 for M_w 9.2: (a) *CSR* and *CRR* curves at BH-1, (b) *CSR* and *CRR* curves at BH-2, (c) *CSR* and *CRR* curves at BH-3

7. ACKNOWLEDGEMENTS

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