SEISMIC GROUND RESPONSE ANALYSIS FOR LIQUEFACTION ASSESSMENT IN BUNAKEN, NORTH SULAWESI, INDONESIA

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ABSTRACT

Bunaken Island is a quaternary deposit of Holocene age. Dominating sand layers, shallow groundwater table, and near active fault locations make the area highly susceptible to liquefaction. This study aims to determine the minimum ground acceleration that can potentially trigger liquefaction in the area. In this study, earthquakes originating in the North Sulawesi Thrust were modelled with various magnitudes. PGA was calculated using the attenuation function from : Liu and Tsai (2005), Abrahamson et al. (2016), Atkinson and Boore (2003), and Zhao et al. (2006). Each earthquake parameter was analyzed for its liquefaction potential using the simplified procedure by Idriss and Boulanger (2008), and then the minimum earthquake parameter value that can cause liquefaction was determined. The analyses show that the study site has the potential for liquefaction if more than Mw 5.8 earthquake occurs with a PGA value of above 0.17g. The BKN-BH02 borehole is the most critical point of the four boreholes made at the study site.

Keywords: seismic, ground response, liquefaction

1. INTRODUCTION

Indonesia is an archipelagic state located in the Ring of Fire, where earthquakes occur most frequently. Predominant loose sand deposits and the shallow water table in some areas are prone to liquefaction. In 2017, massive liquefaction occurred due to the earthquake that hit Palu City, Central Sulawesi, which claimed many lives. In addition to the central part of the island, the northern side of Sulawesi, namely the Sulutgo area, is also prone to earthquakes. The seismically active North Sulawesi Thrust holds potential hazard of imminent earthquake. However, studies on the seismicity of the northern side of Sulawesi Island are still scarce. Therefore, this study was carried out on Bunaken Island, an island located in the north of Sulawesi Island, which is part of Bunaken National Marine Park, a famous tourist attraction crowded with domestic and foreign tourists. The study site is shown in Figure 1.

This study aims to determine the most minor earthquake parameters (PGA and magnitude) that can trigger liquefaction in Bunaken, North Sulawesi. Several prior studies on liquefaction potential have been carried out in Soekarno Bridge [1] and Port of Bitung [2]. Kramer and Day as cited in Mase [3] stated that the smallest amax that can trigger liquefaction is 0.1. However, amax is not the only factor that causes liquefaction, soil strength is also considered a quite significant factor. The authors have conducted a study on liquefaction potential in Bunaken Island, but have not determined the smallest earthquake parameters that can trigger liquefaction potential.

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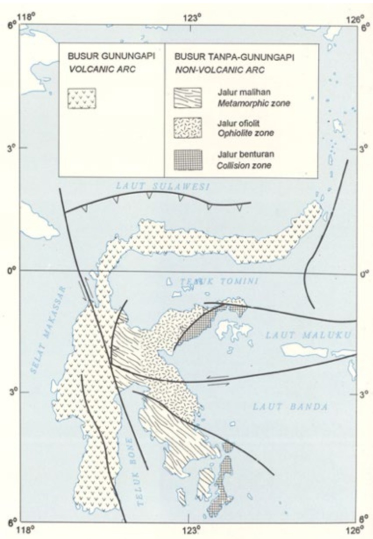
Figure 1 Study site modified from [4]



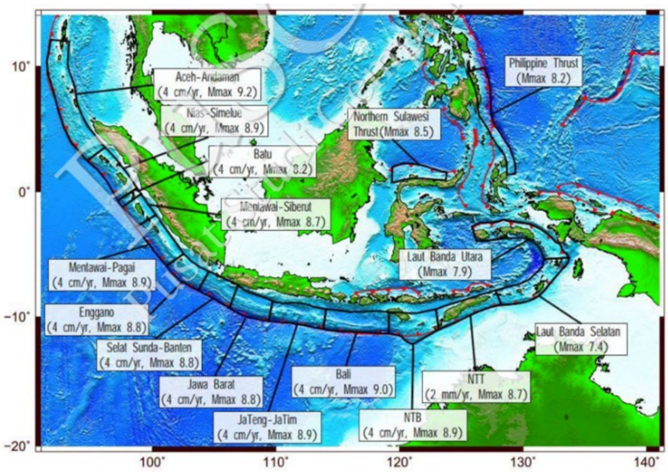


Figure 1 Regional Geology Setting in Sulawesi Island [5]

Figure 2 Subduction Map in Indonesia [5]

1.1. Geology and Seismicity

The stratigraphy of Bunaken Island are quaternary deposits of holocene age, with the constituent materials being pebbles, gravels, sand, silt clay, and locally a thin layer of plant remains, including river, beach, and lake deposits [6]. Geological conditions on Sulawesi Island is a complex tectonic setting [7]. Existing geological structures are still actively moving and have the potential to cause earthquakes. The northern side, namely the Sulutgo area, is still heavily affected by the movement of geological structures. In this area, the North Sulawesi Thrust is actively moving with a geodetic acceleration of 42-50 mm/year [8]. Meanwhile, on the western side, there is the Gorontalo Fault which is also actively moving, whereas the Sorong Fault moves westwards from eastern Indonesia. Figure 1 and Figure 2 show the earthquake sources on Sulawesi Island.

Sulawesi is located in the triple junction, a zone where three plates meet [5]. As a result, a deformation pattern occurs in the form of a strike-slip fault and a thrust fault. The seismicity in the northern part of Sulawesi Island is related to subduction in the north, as well as Palukoro and Matano faults in the middle. The subduction in the north, namely the North Sulawesi Thrust, can cause earthquakes of up to M_w 8.5 [5]. There have been several earthquakes in the northern and eastern waters of Sulawesi Island. The earthquake's magnitude varied from M_w 4 until 7.8. From these earthquake histories, it is known that the PGA generated is relatively very small; it is in line with the condition that liquefaction never occurred in Bunaken Island.

An earthquake is a disaster that comes suddenly and can cause huge losses. Therefore, seismic hazard analysis is needed to study the effect of historical earthquakes on the above-ground infrastructure. Seismic hazard analysis is divided into two: Deterministic Seismic Hazard Analysis and Probabilistic Hazard Analysis. Deterministic Seismic Hazard Analysis is based on an earthquake parameter that may occur in a location, while Probabilistic Hazard Analysis takes into account the magnitude and time of past earthquakes and then combines them with probabilistic methods. Seismic hazard analysis is carried out to determine the PGA value of an area against possible earthquakes that may occur in the future.

1.2. Liquefaction Hazard

Liquefaction is a change in the condition of the sandy soil from solid to liquid-like due to the increase in pore water pressure caused by dynamic loads. Types of soil susceptible to liquefaction are saturated loose sand [9]. The loose sand layer deforms when an earthquake occurs, causing the pore water pressure to rise. If the pore water pressure increases to be equal to the total stress, the soil will lose its ability to withstand the load; thus, liquefaction occurs.

In 2019, the Geological Agency of Indonesia compiled a map of the liquefaction susceptibility zone by correlating seismic data with geological data. On this map, the Geological Agency of Indonesia uses an acceleration value of more than 0.1g [10] on a 500-year return period (10% in 50 years). Figure 4**Kesalahan! Sumber referensi tidak ditemukan.** displays the liquefaction susceptibility zone in North Sulawesi Province. As seen there, the study site is in the zone of high liquefaction susceptibility.

2. MATERIALS AND METHOD

The initial stage of this study was the determination of several earthquake simulations originating from the North Sulawesi Thrust with various magnitudes. Then, the PGA value was determined by using the attenuation equation and referring to the previously simulated earthquake data. After that, secondary data sourced from earthquake maps, as a comparison of PGA values obtained from empirical calculations, was collected. The earthquake parameters (magnitude and PGA) were used to determine the liquefaction potential at four boreholes, i.e., BKN-BH01, BKN-BH02, BKN-BH03, and BKN-BH04 [11]. The location of each borehole is presented in Figure 1. Furthermore, the analysis of the obtained liquefaction potential was discussed to determine the smallest earthquake parameter that can trigger liquefaction

2.1. Determination of PGA Value

PGA (Peak Ground Acceleration) is the impact caused by an earthquake at a specific location. It is determined by calculating the attenuation of earthquake vibration. There are various equations to determine the value of PGA. The appropriate GMPE (Ground Motion Prediction Equation) is selected by looking for similarities between the study site and the conditions when determining the equation. These similarities can be in the form of similarity of earthquake sources, depth, soil conditions/types, and geological conditions. In this study, the authors choose the GMPE method, which uses an earthquake model originating from subduction as the earthquake source at the study site. Therefore, the authors employed the equations as follows: Liu and Tsai (2005) method, Abrahamson et al. (2016) method, Atkinson and Boore (2003) method, and Zhao et al. (2006) method.

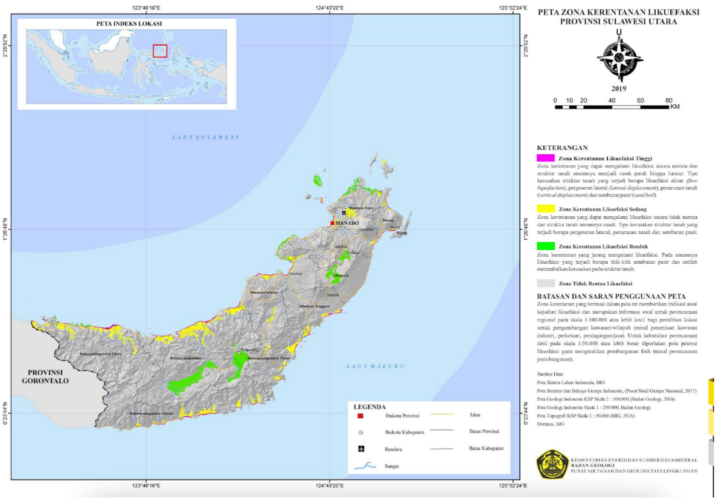


Figure 4 Map of North Sulawesi Liquefaction Susceptibility Zone modified from [12]

The Liu and Tsai method [13] was carried out by determining the minimum and maximum PGA values, then taking the average value as the PGA value for further analysis. The PGA value is determined by Equation (1).

$$ln\ ln\ (PGA_h) = -0,852\ ln\ ln\ (L_{hp} + 1.24) - 0,0071L_{hp} + 1.027\ M_w + 1.062 \pm 0.719 \quad (1)$$

where:

PGA_h = peak ground acceleration
L_{hp} = hypocenter distance
M_w = magnitude of the earthquake

The Abrahamson et al. [14] method uses global subduction as the basis for its assumptions. Abrahamson et al. (2016) conducted an analysis with earthquake models in Japan, Cascadia, and Taiwan. This method employs several coefficients such as coefficient of magnitude, depth, and soil layer. The PGA value is determined according to Equation (2).

$$lnS_a = 4.2203 + 0.9\Delta C_1 + [-1.350 + 0.1(M - 7.8)]\ ln\{R_{rup} + 10exp[0.4\ (M - 6)]\} + (-0.0012)R_{rup} + f_{mag} + f_{FABA} + f_{site} \quad (2)$$

where:

S_a = peak ground acceleration
$\otimes C_1$ = correction factor
M = magnitude of the earthquake
R_{rup} = depth of earthquake source
f_{mag} = earthquake magnitude coefficient
f_{FABA} = depth coefficient
f_{site} = soil layer coefficient

As with the previous method, the Atkinson and Boore [15] method use global subduction as the basis for its assumptions. This method employs the site coefficient at the study site as a correction factor. The PGA value is determined according to Equations (3), (4), and (5).

$$log\, log\, Y = 2.991 + 0.03525M + 0.00759h + (-0.00206)R - g\, log\, log\, R + 0.19slS_D + 0.29S_E \quad (3)$$

$$R = \sqrt{D_{fault}{}^2 + \Delta^2} \quad (4)$$

$$\Delta = 0.00724\ 10^{0.507M} \quad (5)$$

$$g = 10^{1.2-0.18M} \quad (6)$$

where:

Y = peak ground acceleration
M = magnitude of the earthquake
h = depth of earthquake source
S_l, S_D, S_E = site coefficient

Lastly, the Zhao et al. [16] method uses subduction earthquake sources in Japan, Iran, and the Western United States for its assumptions. This method considers the Vs of the soil in the study area. Several correction factors such as depth, earthquake source, and site are also considered. The PGA value is determined according to Equations (7) and (8).

$$\boldsymbol{Y = 1.101M_w + (-0.00564)x - (r) + 0.01412\,(h - h_c)\delta_h + F_R + S_1 + S_s + S_{SL}(x) + C_k} \quad (7)$$

$$r = x + c\, exp\, exp\, (dM_w) \quad (8)$$

where:

Y = peak ground acceleration
Mw = magnitude of the earthquake
x = epicenter distance
h, hc = depth of earthquake source
δ_h = depth correction factor
FR = earthquake source correction factor
S_I, S_S, S_{SL}, C_k = site correction factor

After obtaining the PGA value, the corrected PGA value at ground level (PGA_M) was then calculated based on SNI 1726:2019 by first determining the soil classification as there are different coefficient factors for each type of soil (hard, medium, and soft soil).

2.2. Liquefaction Potential Analysis

The liquefaction potential can be determined by various methods, either empirically, physically [17], or numerical modeling. The employed soil data varies, ranging from SPT, CPT, and vs30. The data owned by the authors is SPT data; thereby, a simplified procedure developed by Idriss and Boulanger (2008) was applied in this study. This refers to a previous study conducted by Mase [18], who stated that this method was the most appropriate method to analyze the liquefaction that occurred in Padang (2007).

It is necessary to know the value of CSR (Cyclic Stress Ratio), which is the stress generated by the earthquake compared to the effective stress of the soil to determine the liquefaction potential. The following equation can calculate CSR value by Seed and Idriss (1971):

$$CSR = 0.65 \times \frac{a_{max}}{g} \times \frac{\sigma_v}{\sigma'_v} \times r_d \quad (9)$$

with,
a_{max} = maximum ground acceleration
g = acceleration due to gravity
σ_v = vertical total stress
σ'_v = effective vertical stress
r_d = stress reduction coefficient
Then, the calculation of the cyclic resistance ratio (CRR) value, namely the strength of the soil to withstand sudden dynamic loads, is also needed. In this study, CRR value is calculated based on the SPT value as the following equation by Idriss and Boulanger [19]:

$$\boldsymbol{CRR} = \left[\boldsymbol{exp\ exp}\left(\frac{(N_1)_{60cs}}{14{,}1} + \frac{(N_1)_{60cs}}{126}\right)^2 - \left(\frac{(N_1)_{60cs}}{23{,}6}\right)^3 + \left(\frac{(N_1)_{60cs}}{25{,}4}\right)^4 - 2{,}8\right] \times \boldsymbol{MSF} \quad (9)$$

with,
CRR = Cyclic Resistance Ratio value
(N1)60cs = $(N_1)_{60}$ value corrected for fine grain content
MSF = earthquake magnitude correction factor
After determining the CSR and CRR values, both values were then compared to get the Factor of Safety (FS) value. FS is a parameter to determine the liquefaction potential. If the FS value is less than 1, the soil layer has the potential to liquefy. Conversely, if the FS value is more than 1, the soil layer has no potential for liquefaction.

3. RESULT AND DISCUSSION

On-site soil testing was carried out at four boreholes, as described in the previous chapter. Table 1 shows the coordinates, and the depth of drilling carried out in the field. The type of soil at the drilling sites is sandy soil, comprising sand and gravel up to a depth of 45m. At several boreholes, corals were found at the bottom. The type of soil on Bunaken Beach is loose sand. So, at the time of drilling, undisturbed samples (UDS) of the soil could not be taken. Several parameters related to laboratory testing were determined by the correlation of SPT data.
The results of the analysis of BKN-BH02 indicated that the soil at this borehole was soft soil with $\underline{N}$= 12, whereas the other three boreholes were classified as sites of medium soil with $\underline{N}$ of 20–50. BKN-BH04 was the borehole with the highest value of $\underline{N}$, which is 35. Meanwhile, BKN-BH01 and BKN-BH03 had $\underline{N}$ 24 and 26 respectively. This classification determines the value of the PGA multiplier F_{PGA}. In addition to soil classification, the magnitude of the PGA value also affects the value of F_{PGA}. This value is needed to correlate the PGA values to determine the PGA value at ground level (PGA_M).
The results of the sieve analysis on the Disturb Sample (DS) showed that the soil at the study site was classified as coarse-grained soil, with soil passing sieve No. 200 being less than 50%. BKN-BH02 had fine grain content of 6% at a depth of 3m and 23% at a depth of 13m, whereas the other three boreholes had fine grain content ranging from 11-19%.
The four boreholes analyzed in this study are located in areas affected by tides. All of them are in a saturated condition, thus all the volume weight used is in a saturated condition (γ_{sat}). Since the soil was very loose and could not be sampled, the

determination of the $©_{sat}$ value was approximated by the correlation by William T, Whitman, and Robert V [20].

Table 1 Drilling Data

BOREHOLE NAME	COORDINATE		OCEAN DEPTH		CASE LENGTH (M)	DRILLING DEPTH (M)	NUMBER OF SPT TESTS
	EASTING	NORTHING	HIGH TIDE	LOW TIDE			
BKN-BH01	698,224.23	176,462.40	1.70	0.30	33.00	35.00	18
BKN-BH02	698,240.42	176,528.03	1.40	0.00	43.00	45.12	23
BKN-BH03	698,405.25	176,524.78	3.50	1.80	37.00	39.42	20

In Indonesia, there are several sources that can be used as references for seismic planning. From the existing references, the authors obtained the PGA value based on several sources, namely:

1. PGA of the peak acceleration in bedrock (S_B) map due to subduction earthquake source with 84-percentile (150% median) [5] is 0.2g – 0.25g
2. PGA of the peak acceleration in bedrock (SB) map for probability of exceeding 5% in 10 years, referring to the liquefaction susceptibility map by the Geological Agency of Indonesia [12] is 0.2g – 0.25g
3. PGA of the peak acceleration in bedrock (SB) map for a probability of exceeding 2% in 50 years, referring to SNI 1726:2019 [21] is 0.4g – 0.5g
4. PGA from the Indonesian Design Response Spectrum Application (RSA PU) [22] used as a reference at design was 0.47g

With reference to the possibility of earthquakes in the future, the authors simulated the liquefaction potential for various earthquake models. The earthquake was assumed to originate from the North Sulawesi Thrust, which is 97 km from the study site. The magnitudes of the earthquake were assumed to range from M_w 8.5, which is the maximum magnitude of earthquake according to PusGen [5], to M_w 5.8. The attenuation function of the earthquake model was then calculated using: Liu and Tsai (2005) method, Abrahamson et al. (2016) method, Atkinson and Boore (2003) method, and Zhao et al. (2006) method. The calculated PGA values are as shown in Table 2.

Table 1 Earthquake Modeling for Liquefaction Potential Analysis

EARTHQUAKE MODEL	EARTHQUAKE DATA		DISTANCE TO SITE		PGA WITH DSHA METHOD			
	D	Mw	Epicenter	Hypocenter	Liu and Tsai, 2005	Abrahamson et al (2016)	Atkinson and Boore (2003)	Zhao et al. (2006)
Mw 8.5	20.0	8.5	97.19	99.23	0.23	0.28	0.24	0.19
Mw 8.4	20.0	8.4	97.19	99.23	0.20	0.24	0.23	0.18
Mw 8.3	20.0	8.3	97.19	99.23	0.18	0.23	0.23	0.16
Mw 8.2	20.0	8.2	97.19	99.23	0.17	0.22	0.22	0.15
Mw 8.1	20.0	8.1	97.19	99.23	0.15	0.21	0.21	0.14
Mw 8.0	20.0	8.0	97.19	99.23	0.13	0.20	0.20	0.13
Mw 7.9	20.0	7.9	97.19	99.23	0.12	0.19	0.18	0.12
Mw 7.8	20.0	7.8	97.19	99.23	0.11	0.18	0.17	0.11
Mw 7.7	20.0	7.7	97.19	99.23	0.10	0.18	0.15	0.10
Mw 7.6	20.0	7.6	97.19	99.23	0.09	0.17	0.14	0.09
Mw 7.5	20.0	7.5	97.19	99.23	0.08	0.16	0.12	0.08
Mw 7.4	20.0	7.4	97.19	99.23	0.07	0.15	0.11	0.07
Mw 7.3	20.0	7.3	97.19	99.23	0.07	0.15	0.10	0.07
Mw 7.2	20.0	7.2	97.19	99.23	0.06	0.14	0.08	0.06
Mw 7.1	20.0	7.1	97.19	99.23	0.05	0.13	0.07	0.06
Mw 7.0	20.0	7.0	97.19	99.23	0.05	0.13	0.06	0.05
Mw 6.9	20.0	6.9	97.19	99.23	0.04	0.12	0.05	0.05
Mw 6.8	20.0	6.8	97.19	99.23	0.04	0.12	0.04	0.04
Mw 6.7	20.0	6.7	97.19	99.23	0.04	0.11	0.04	0.04
Mw 6.6	20.0	6.6	97.19	99.23	0.03	0.10	0.03	0.03
Mw 6.5	20.0	6.5	97.19	99.23	0.03	0.10	0.02	0.03
Mw 6.4	20.0	6.4	97.21	99.24	0.03	0.09	0.02	0.03
Mw 6.3	20.0	6.3	97.21	99.24	0.02	0.09	0.02	0.02
Mw 6.2	20.0	6.2	97.21	99.24	0.02	0.09	0.01	0.02
Mw 6.1	20.0	6.1	97.21	99.24	0.02	0.08	0.01	0.02
Mw 6.0	20.0	6.0	97.21	99.24	0.02	0.08	0.01	0.02
Mw 5.9	20.0	5.9	97.21	99.24	0.02	0.07	0.01	0.02
Mw 5.8	20.0	5.8	97.21	99.24	0.01	0.07	0.00	0.01

In condition M_{max} 8.5, PGA value from empirical method (attenuation function) show the value approach PGA of the peak acceleration in bedrock (S_B) map due to subduction earthquake source with 84-percentile (150% median) and PGA of the peak acceleration in bedrock (S_B) map for probability of exceeding 5% in 10 years. It's quite far with PGA of the peak acceleration in bedrock (S_B) map for a probability of exceeding 2% in 50 years and PGA from the Indonesian Design Response Spectrum Application (RSA PU).

In the M_w 8.5 earthquakes, the four boreholes showed liquefaction potential in several soil layers. Accumulatively, all boreholes had very high liquefaction potential. The analysis of the liquefaction potential was carried out on other earthquake parameters using the PGA value obtained from each attenuation function. The results of the analyses can be seen in Table 1. Based on the result, in BKN-BH01 borehole, liquefaction occurred due to the M_w 7.7 earthquake with a PGA value of 0.16g in Liu and Tsai (2005) method and Zhao et al. (2006) method, the M_w 7.4 earthquake with a PGA value of 0.18g in Atkinson and Boore (2003) method, and the M_w 6.8 earthquake with a PGA value of 0.20g in Abrahamson et al. (2016) method. In BKN-BH02 borehole liquefaction occurred due to the M_w 6.9 earthquake with a PGA value of 0.11g in Liu and Tsai (2005) method and Zhao et al. (2006) method, the M_w 6.8 earthquake with a PGA value of 0.11g in Atkinson and Boore (2003) method, and the M_w 5.6 earthquake with a PGA value of 0.16g in Abrahamson et al. (2016) method. In BKN-BH03 borehole liquefaction occurred due to the M_w 7.8 earthquake with a PGA value of 0.18g in Liu and Tsai (2005) method and Zhao et al. (2006) method, the M_w 7.4 earthquake with a PGA value of 0.18g in Atkinson and Boore (2003) method, and the M_w 7.1 earthquake with a PGA value of 0.20g in Abrahamson et al. (2016) method. In BKN-BH04 borehole liquefaction occurred due to the M_w 7.9 earthquake with a PGA value of 0.19g in Liu and Tsai (2005) method and Zhao et al. (2006) method, the M_w 7.3 earthquake with a PGA value of 0.22g in Atkinson and Boore (2003) method, and the M_w 7.3 earthquake with a PGA value of 0.22g in Abrahamson et al. (2016) method.

Each attenuation equation produces different earthquake parameter values. Liu and Tsai (2005) method and Zhao et al. (2006) method obtained relatively the same value, whereas Abrahamson et al. (2016) method and Atkinson and Boore (2003) method showed quite different values. This is because each equation used different subduction references and geological conditions so that when applied to North Sulawesi Thrust, they got different values. Based on the results, BKN-BH04 has the lowest level of susceptibility to liquefaction, followed by BKN-BH3 then BKN-BH01. And the last one, BKN-BH02 has the highest level of susceptibility to liquefaction. As shown in Table 2, at BKN-BH01 and BKN-BH02, the most critical depth for liquefaction to occur is 21m. According to Iwasaki [23], if liquefaction occurs at a depth of more than 20m, the effect will not reach the ground surface. Meanwhile, the above-ground buildings at the study site are supported by spun piles with a diameter of 50cm and a depth of 16m. Disturbances in the soil up to 4D under the tip of the pile can disrupt the stability of the foundation. However, if it occurs below that level, it is relatively not disturbing the stability of the foundation. For BKN-BH01 and BKN-BH02, it is necessary to calculate the smallest earthquake parameters that can cause liquefaction at a depth of <18m (16m + 4D).

Table 4 shows the minimum earthquake parameters that trigger liquefaction potential along the pile (<18m). From Table 4, it can be seen that the critical depth that triggers liquefaction and disturbs above-ground buildings is 11m for BKN-BH01 and 7m for BKN-BH02. Based on Table 4, in BKN-BH01 borehole, the liquefaction occurred that can be disturb the stability foundation are due to the Mw 8.0 earthquake with a PGA value of 0.21g in Liu and Tsai (2005) method, the Mw 8.1 earthquake with a PGA value of 0.22g in Zhao et al. (2006) method, the Mw 7.7 earthquake with a PGA value of 0.24g in Atkinson and Boore (2003) method, and the Mw 7.3 earthquake with a PGA value of 0.26g in Abrahamson et al. (2016) method. Beside that, In BKN-BH02 borehole, the liquefaction occurred that can be disturb the stability foundation are due to the Mw 7.1 earthquake with a PGA value of 0.13g in Liu and Tsai (2005) method, the Mw 7.0 earthquake with a PGA value of 0.13g in Zhao et al. (2006) method, the Mw 6.9 earthquake with a PGA value of 0.13g in Atkinson and Boore (2003) method, and the Mw 5.8 earthquake with a PGA value of 0.17g in Abrahamson et al. (2016) method. Based on the calculations, BKN-BH02 is found to be the most critical point for liquefaction. The potential for liquefaction can occur during an earthquake originating from the North Sulawesi Thrust with a magnitude of Mw 5.8 and a PGA value of 0.17g according to Abrahamson et al. (2016) method.

Table 3 Table of The Smallest Earthquakes Triggering Liquefaction

BOREHOLE	LIU AND TSAI (2005)			ABRAHAMSON ET AL (2016)			ATKINSON AND BOORE (2003)			ZHAO ET AL (2006)		
	Mw	PGA_M	$D_{CRITICAL}$	*Mw*	PGA_M	$D_{CRITICAL}$	*Mw*	PGA_M	$D_{CRITICAL}$	*Mw*	PGA_M	$D_{CRITICAL}$
BKN-BH-01	7.7	0.16	21	6.8	0.20	21	7.4	0.18	21	7.7	0.16	21
BKN-BH-02	6.9	0.11	21	5.6	0.16	21	6.8	0.11	21	6.9	0.11	21
BKN-BH-03	7.8	0.18	1	7.1	0.20	1	7.4	0.18	1	7.8	0.17	1
BKN-BH-04	7.9	0.19	1	7.3	0.22	1	7.6	0.22	1	7.9	0.19	1

Table 4 Table of The Smallest Earthquakes Triggering Liquefaction in <18m Soil Layers

BOREHOLE	LIU AND TSAI (2005)			ABRAHAMSON ET AL (2016)			ATKINSON AND BOORE (2003)			ZHAO ET AL (2006)		
	Mw	*PGA$_M$*	*D$_{CRITICAL}$*	*Mw*	*PGA$_M$*	*D$_{CRITICAL}$*	*Mw*	*PGA$_M$*	*D$_{CRITICAL}$*	*Mw*	*PGA$_M$*	*D$_{CRITICAL}$*
BKN-BH-01												
H critical along borehole	7.7	0.16	21	6.8	0.2	21	7.4	0.18	21	7.7	0.16	21
H critical length of drill pile (<18m)	8.0	0.21	11	7.3	0.26	11	7.7	0.24	11	8.1	0.22	11
BKN-BH-02												
H critical along borehole	6,9	0.11	21	5,6	0,16	21	6,8	0,11	21	6,9	0,11	21
H critical length of drill pile (<18m)	7,1	0,13	7	5,8	0,17	7	6,9	0,13	7	7,0	0,13	7

4. CONCLUSION

Based on the analysis of the four existing boreholes, it can be concluded that the study site has the potential for liquefaction triggered by earthquakes of certain magnitudes. The minimum earthquake parameter that can cause liquefaction at this point is Mw 5.8 with a PGA value of 0.17g using the Abrahamson et al. (2016) method; Mw 6.9 with a PGA value of 0.13g by the Atkinson and Boore (2003) method; Mw 7.0 with a PGA value of 0.13g in Zhao et al. (2006) method; and Mw 7.1 with a PGA value of 0.13g with Liu and Tsai (2005) method. BKN-BH02 is proven to be the most critical point for liquefaction to occur.

For future studies, it is necessary to evaluate the foundations of vital buildings in areas that have the potential for liquefaction. In the development of such area, the stability of the building structure when liquefaction occurs is extremely needed to be taken into consideration.

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