Groundwater level influence on liquefaction potential at Pombewe housing site, Sigi regency, Central Sulawesi.

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Abstract. The September 28, 2018, earthquake in Palu, Central Sulawesi, caused liquefaction and destroyed at least 3,720 houses. Therefore, it is necessary to consider the potential of liquefaction in choosing a residential location, especially in liquefaction-prone zones. The parameters of soil type, seismicity, and the groundwater table as a determinant of the saturation level determine liquefaction potential. The research aims to see the influence of groundwater level parameters in increasing the liquefaction potential when other parameters are met. The study was conducted at the Pombewe permanent housing site, Sigi Regency, Central Sulawesi. This shelter is an official relocation area for victims of the 2018 earthquake. Preliminary data stated that the location is safe from liquefaction potential because it has a deep groundwater table. The study used the CPT-based liquefaction triggering procedure method by Boulanger and Idriss and assumed that the groundwater table at the site was shallow. The Liquefaction Potential Index determines the potential liquefaction level. The results show that the area under review will only experience liquefaction if the groundwater table is above 1.0-11.6 meters (LPI>0). If the water table rises above that depth, the LPI value increases to $1.6x10^{-9}$ – 0.44. Thus, the water table is a determining parameter in analyzing the liquefaction potential of an area.

1 Introduction

Sulawesi is one of Indonesia's seismically active islands due to its position on top of the interconnection between the Indian-Australian, Eurasian, Pacific, and Philippine Sea plates [1]. One of the latest and most significant earthquakes produced by this interconnection derived from the slip-strike movement of the Palukoro fault for about 150 km from north to south of Palu City[2], [3]. This 7.5 M_w 2018 Palu earthquake not only directly impacted building structures with the cyclic loading but also affected the soil and triggered flow liquefaction in several areas, including Balaroa, Jono Oge, Petobo, Lolu, and Sibalaya. The damage of both disasters was recorded to be at least 115.103 houses destroyed, and 3720 of them were caused by liquefaction [4]. This is by far the most devastating damage in the

Indonesian history of liquefaction that caused thousands of fatalities, which then makes Palu City, Sigi Regency, and the surrounding area categorized as a high liquefaction-prone zone according to the Indonesian Liquefaction Vulnerability Zone Atlas of 2019 [5].

Based on the severity of the risk posed by liquefaction, soil susceptibility to liquefaction should be one of the parameters in choosing a housing area, especially for the relocation of liquefaction survivors. Central Sulawesi Provincial government planned the relocation areas in 2019 for the Palu 2018 earthquake and liquefaction survivors. These areas were endeavoured to be close to affected areas to ease the adaptation process for affected communities. One of them was the Pombewe permanent housing site [4].

Pombewe permanent housing in Sigi Regency, Central Sulawesi, is located approximately 1 km from the liquefaction-affected area of Jono Oge (Figure 1(a)). The area with at least 104 ha with 1500 housing units has a higher ground level than Jono Oge and a 5.9%-degree slope steeper than Jono Oge. The whole area construction started in October 2020 and was finished by Mei in 2023. Before turning into a housing site, the area was owned by a local plantation company. It was one of the limited available areas that were sufficient to accommodate a significant number of survivors. Preliminary studies were conducted in deciding the area to be a relocation site. It was held by the JICA mission team in 2018. The assessment of the area concluded that it was safe from liquefaction due to the deep groundwater table [4].

Based on the preliminary research, the area would not be affected by the liquefaction due to the absence of a saturated soil layer. This study aims to examine the liquefaction potential if the hydrological condition of the site was altered due to land use conversion from plantation to estate area. The study will evaluate the soil behavior type of the area using Cone Penetration Test measurements taken on the site in January 2020 (A) and February 2022 (B) (Figure 1(b)). By altering groundwater levels in the CPT-based liquefaction triggering procedure, each borehole's Liquefaction Potential Index (LI) was kept in a zero range to see the maximum groundwater level allowed in the area.

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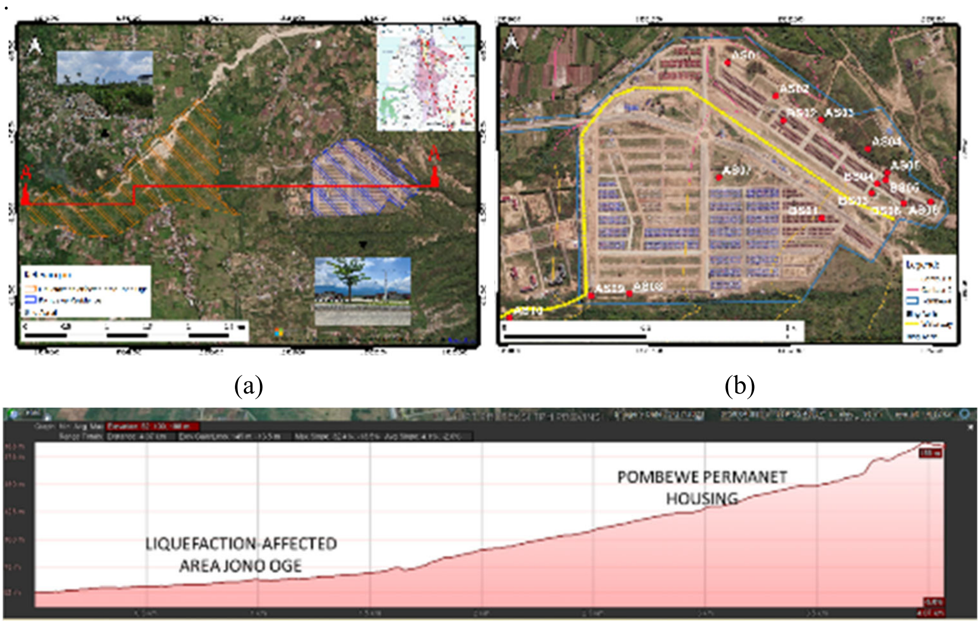


(a) (b)

(c)

FIGURE 1. (a) Pombewe permanent housing and liquefaction affected area 2018 Jono Oge, (b) CPT locations of Pombewe permanent housing-Bing Aerial Open-Source Map-

modified[6] (c) Elevation difference of Liquefaction Affected Area- Jono Oge towards Pombewe permanent housing (cross-section A'-A)[7].

2 Geological Conditions

The Pombewe permanent housing site is in the old alluvium fan deposit (Qf2)[8], no longer subject to periodic flooding events, and has become more stable than the younger alluvium fan deposit[9]. Furthermore, the area contains weakly hardened sediments that consist of conglomerates, sandstone, mudstone, coral limestone, and marl, which are included in the Celebes Molasse of Sarasin and Sarasin (1901) (QTms) formation[10]. The existence of sandstone and coral limestone in the sediments produced the sandy texture of the soil [9], which allows it to store water between the particles, become saturated, and more vulnerable to liquefaction caused by cyclic loading from the earthquake [11].

Compared to other earthquake sources around Pombewe permanent housing, the Palukoro fault has become the most influential factor in the site's seismicity level due to its less than 10km distance [12]. The short distance reduces the damping ratio of the cyclic loading from the source to the site[13]. The Palukoro fault also has a 58mm/year slip rate movement but a 130-year earthquake cycle. This means that the accumulation of the fault's rapid movement would only be released once every 130 years and would likely create a massive earthquake that increases the chance of liquefaction to happen [14].

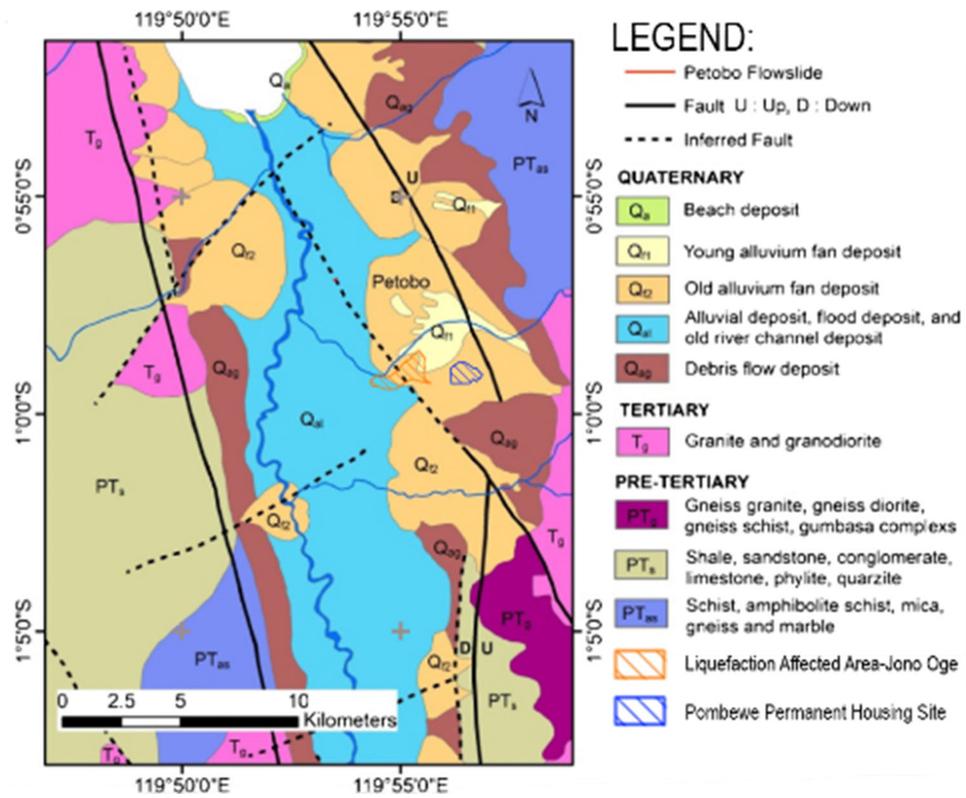


FIGURE 2 Geological map of Palu and surroundings. The study area comprises alluvial, flood, and river channel deposits [6].

3 Geological Conditions

3.1 The Determination of Peak Ground Acceleration (PGA)

The PGA bedrock determination in this paper used the ground motion prediction equations proposed by several researchers and used in the Indonesian Earthquake Hazard Deaggregation Map Book for Earthquake Resistant Infrastructure Planning and Evaluation [12]. Those were proposed by Boore-Stewart-Seyhan-Atkinson (2014); Campbell- Borzogna (2014); and Chiou-Youngs (2014) for shallow crustal slip-strike earthquakes[1]. This calculation was simplified by Emel Seyhan, PhD (2015) by using the NGA-WEST application. The site classification of Pombewe permanent housing was surveyed by the Meteorological, Climatological, and Geophysical Agency of Palu Regional in 2019 using the Vs30 value of the area. The housing is in an area with a Vs30 value range from 350-360, classified as very dense soil and soft rock (C) (Figure 3). The value was then used as input value in the NGA-WEST application to calculate the PGA of the area. The parameter utilized for the location near the fault was the average deviation of the PGA value. Subsequently, the PGA outcome necessitates amplification by a rupture directivity coefficient of 1.1. [12]. The result of the PGA calculation is presented in Table 1 with a value of 0.590 g.

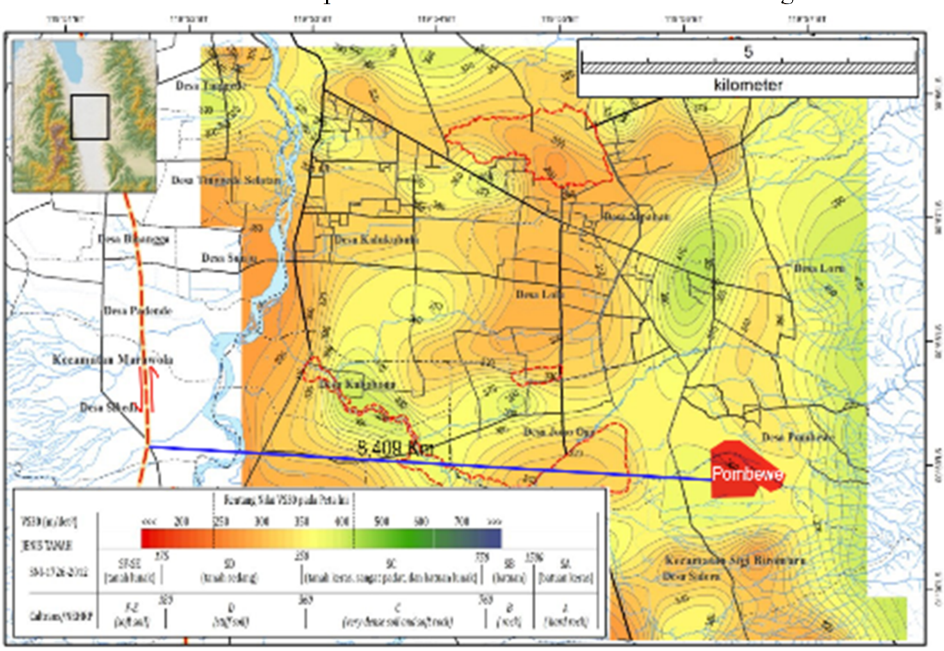
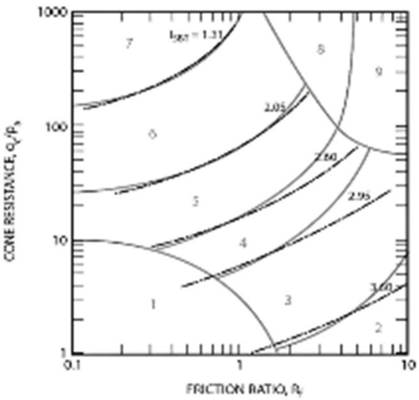


FIGURE 3. Soil Classification of Sigi Regency Area 2019 by Meteorological, Climatological, and Geophysical Agency of Palu Regional-Modified[15]

Methods	Determined PGA
Boore-Stewart-Seyhan-Atkinson (2014)	0.605
Campbell- Borzogna (2014)	0.479
Chiou-Youngs (2014)	0.526
Average x 1.1	**0.590**

Table 1 The surface PGA,g calculations result.

3.2 Soil Stratigraphy



(a)

I_{SBT}	Zone	Soil Behaviour Type (SBT)
	1	*Sentitive fine-grained*
Ic > 3.60	2	*Clay-organic soil*
2.95 < Ic < 3.60	3	*Clays: clay to silty clay*
2.60 < Ic < 2.95	4	*Silt mixtures: clayey silt & silty clay*
2.05 < Ic < 2.60	5	*Sands mixtures: silty sand to sandy silt*
1.31 < Ic < 2.05	6	*Sands: clean sands to silty sands*
Ic < 1.31	7	*Dense sand to graverly sand*
	8	*Stiff sand to clayey sand**
	9	*Stiff fine-grained**

**Overconsolidated or cemented*

(b)

FIGURE 4. (a) Non-normalized ISBT chart updated version, (b) Soil Type Behavior classification. [16], [17]

The soil stratigraphy will be developed using the soil behavior type (SBT) method proposed by Robertson 1986 based on cone resistance (qc) and friction ratio (Rf). Soil behavior type could determine whether the soil layers are vulnerable to liquefaction, with the sand (clean sands) type being the most vulnerable [11]. This method's chart was updated in 1990 and 2010 and could directly use CPT measurement results by using the equation below[16]:

$$I_{SBT} = [\left(3.47 - log\left(\frac{q_c}{p_a}\right)\right)^2 + (logR_f + 1.22)^2]^{0.5} \quad (1)$$

3.3 Cone Penetration Test (CPT) Based Liquefaction Trggering Procedure

To determine the maximum level of groundwater allowed in the Pombewe permanent housing site before and after the land improvement, this research used CPT-based liquefaction triggering procedure. This semi-empirical procedure was proposed by Boulanger and Idriss (2014) and was an update of the 2004 and 2008 procedures with more recent historical data on CPT-based liquefaction ever happened. This method compared the cyclic resistance ratio (CRR) of the soil with the cyclic stress ratio from the earthquake (CSR) [11], [18], [19]. The soil layer is considered liquefied if the comparison results or safety factor is ≤ 1.2 [20].

$$SF = \frac{CRR}{CSR} \quad (2)$$

The CSR value was alternated from the initial method proposed by Seed and Idriss (1967). This method was then developed by Idriss and Boulanger 2008 by considering the magnitude scaling factor (MSF) and overburden correction factor (Kσ), which express as the equation below[11], [19]:

$$CSR_{M=7.5,\sigma'_v=1} = 0.65\frac{a_{max}}{g}\frac{\sigma_v}{\sigma'_v}r_d\frac{1}{MSF}\frac{1}{K_\sigma} \quad (3)$$

The soil total stress (σ'v) was derived from the CPT measurements, while the shear stress reduction factor (rd) that accounts for the dynamic response of the soil profile and is influenced by the depth of the layer was calculated using the equation 5 to 7 [19]:

$$r_d = \exp\left[\alpha(z) + \beta(z).M\right] \quad (4)$$

$$\alpha(z) = -1.012 - 1.126\sin\left(\frac{z}{11.73} + 5.133\right) \quad (5)$$

$$\beta(z) = 0.106 + 0.118\sin\left(\frac{z}{11.28} + 5.142\right) \quad (6)$$

The MSF is used to account for the influence of cyclic loading duration on the liquefied layer and expressed as the equation below:

$$MSF = 1 + (MSF_{max} - 1)\left(8.64\exp\left(\frac{-M}{4}\right) - 1.325\right) \quad (7)$$

$$MSF_{max} = 1.09 + \left(\frac{q_{c1Ncs}}{180}\right)^3 \leq 2.2 \quad (8)$$

The Kσ accounts for the influence of overburden and has maximum of 1.1 value for the very low total stress. This was calculated using the equation below:

$$K_\sigma = 1 - C_\sigma \ln\left(\frac{\sigma'_v}{P_a}\right) \leq 1.1 \quad (9)$$

$$C_\sigma = \frac{1}{37.3 - 8.27(q_{c1Ncs})^{0.264}} \leq 0.3 \quad (10)$$

The determination of CRR value used several steps that convert the cone resistance (qc) value from the CPT measurements into cone resistance with correction for overburden stress effect (equation 12-14), the equivalent adjustment for fines content (FC) to clean sand (q_{c1Ncs}) (equation 13)

$$q_{c1N} = C_N \frac{q_c}{P_a} \quad (11)$$

$$C_N = \left(\frac{P_a}{\sigma'_v}\right)^m \quad (12)$$

$$m = 1.338 - 0.249(q_{c1Ncs})^{0.264} \quad (13)$$

CN = overburden correction factor, Pa = atmospheric pressure, and qc1N is the resistance to penetration obtained in the same sediment at an overburden pressure of 1 atm if all other characteristics remain constant. Since all the values of the equation are interconnected, iteration is required to determine each of them.

$$q_{c1Ncs} = q_{c1N} + \Delta q_{c1N} \quad (14)$$

$$\Delta q_{c1N} = \left(11.9 + \frac{q_{c1N}}{14.6}\right)\exp\left(1.63 - \frac{9.7}{FC+2} - \left(\frac{15.7}{FC+2}\right)^2\right) \quad (15)$$

The CRR value for the earthquake magnitude of 7.5 and effective overburden stress at 1 atm would be calculated using the equation below:

$$CRR_{M=7.5,\sigma'_v,1atm} \quad (16)$$

$$= exp(\frac{q_{c1Ncs}}{113} + \left(\frac{q_{c1Ncs}}{1000}\right)^2 - \left(\frac{q_{c1Ncs}}{140}\right)^3 + \left(\frac{q_{c1Ncs}}{137}\right)^2 - 2.80)$$

3.4 Liquefaction Potential Index (L_I)

The Liquefaction Potential Index (L_I) method that was used in this paper was proposed by Iwasaki (1984) to evaluate the impact of soil liquefaction on the structure above it; the impact was influenced by the depth and thickness of the liquefied layer [21]. This method was then modified by Sonmez (2003) to accommodate the non-liquefied and moderate susceptibility layer, as shown in Table 1[20]. The L_I for the discretized layer with a depth of less than 20m Luna and David (1998) proposed the equation below[22]:

$$L_I = \sum_{i=1}^{n} w_i S_i H_i \quad (17)$$

$$w_i(z) = 10 - 0.5z$$
$$S_i = 0 \; for \; SF \; \geq 1{,}2$$
$$S_i = 1 - SF < 0.95$$
$$0.95 < \; S_i < 1.2 = 2 \times \; 10^6 e^{-18.427FL}$$

Where w_i = weight function for layer i; S_i = degree of severity for layer i; H_i = thickness of discretised layer and n = number of discretised layers.

Liquefaction Index (L_I)	Liquefaction Potential
0	Non- Liquefied (for FS ≥ 1.2)
0<LPI≤2	Low
2<LPI≤5	Moderate
5<LPI≤15	High
>15	Very High

Table 2 Liquefaction Potential Categories by Sonmes 2003

4 Result and Discussion

Soil stratigraphy of Pombewe permanent housing area was established using soil behavior type method by Robertson (2010). This method was applied to the available CPT data with maximum depth of each borehole differ based on qc value up to 250, which is minimum value in considering under structure for housing area. The depth was range from 2-12.4 meters below the surface. The stratigraphy revealed that the area consists primarily of sand and sand mixtures of varying thickness, depending on the soil's topography. Figure 5(a,b) depicts a sand layer that is typically thinner in the hillside area than in the area near the natural waterway (Figure 5(c,d)), which also has a layer of dense to gravelly sand. In this case, the area near the waterway with the thicker sand layer was more susceptible to liquefaction. The presence of silt mixture as the topsoil was consistent with the previous land use of the area as a plantation site.

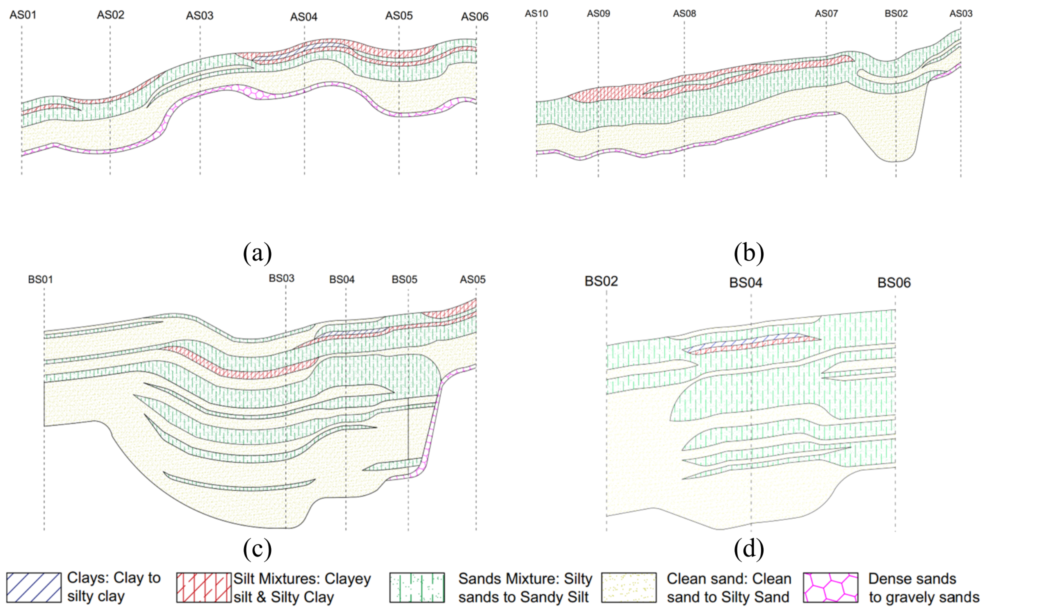


FIGURE 5. (a)-(d) Stratigraphy from CPT locations of Pombewe permanent housing area grouped based on linear CPT points position.

Table 3 Ground water level alteration effect on the change of L_I to indicate the permitted maximum water level.

CPT	Max Depth*		GWL Alteration From Max Depth (m)								Max GWL (m)
			+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	+0.2	
AS01	2.60	L_I Value	0	0	0	0	0	0	$4.7 \cdot 10^{-9}$		1.6
AS02	2.80		0	0	0	0	0	0	0	$4.7 \cdot 10^{-9}$	1.6
AS03	2.00		0	0	0	0	$1.0 \cdot 10^{-9}$				1.0
AS04	2.40		0	0	0	0	0	0	0.28		1.4
AS05	3.40		0	0	0	0	0	0	0.18		2.4
AS06	3.20		0	0	0	0	0	$8.6 \cdot 10^{-9}$			2.4
AS07	3.60		0	0	0	0	0	0	0.19		2.6
AS08	4.40		0	0	0	0	0	$9.3 \cdot 10^{-9}$			3.6
AS09	4.00		0	0	0	0	0	0	$5.8 \cdot 10^{-9}$		3.0
AS10	3.20		0	0	0	0	0	0	$1.0 \cdot 10^{-8}$		2.2
BS01	5.40		0	0	0.62						5.0
BS02	8.40		0	0	$4.3 \cdot 10^{-9}$						8.2
BS03	12.40		0	0	0	0	0	0.32			11.6
BS04	11.60		0	0	0	0	0.34				11.0
BS05	10.40		0	0	0	0.27					10.0
BS06	6.60		0	0.44							6.6

The maximum ground water level (GWL) of each borehole was decided using the liquefaction analysis method and the calculation of liquefaction potential index (L_I). The change of L_I value indicates the availability of liquefied layer due to ground water level alteration. The liquefaction analysis was using earthquake magnitude of the latest 7.5 Mw in Palu 2018. The PGA was determined using the method in previous chapter with the value of 0.543g. Table 3 illustrates the changed L_I value due to the alteration of ground water level on each borehole. This change indicates that the addition of GWL for every 0.2 m from the maximum depth of the boreholes affected the layer liquefaction potential. When the change happened, means that the exact layer would liquefy if it was induced with water or saturated and the GWL must be kept below this layer to prevent the liquefaction. Thus, we decided maximum GWL that were allowed from each borehole.

Figure 6 shows the estimated maximum GWL for the Pombewe permanent housing area. The area on the west side elongated to north which has the highest ground elevation, and a steep hillside topography has the maximum permitted GWL range from 1.0-2.4. While the area at the north side of the waterway was estimated to have lower GWL with the value of 6.6-11.6 m and considered as the most vulnerable zone of all. The south side of waterway on the other hand has the maximum allowed GWL from 2.2 to 5 m.

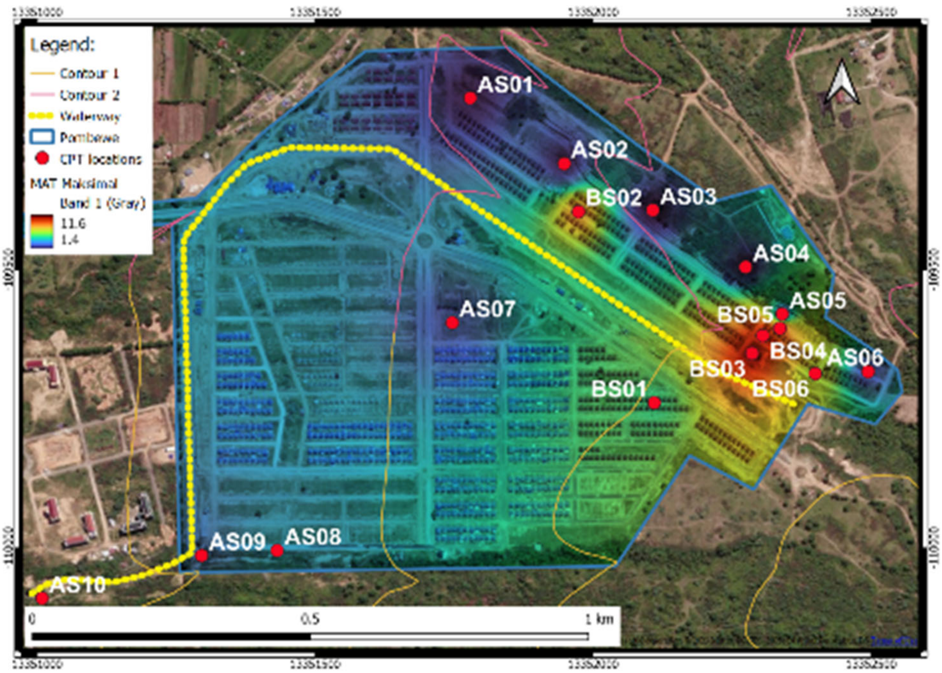


FIGURE 6. Permitted GWL of each boreholes-Bing aerial open-source map[6], RBI Palu City and Sigi Regency contour map-modified[23].

5 Conclusion

The geological features of the site exhibited the vulnerability to liquefaction, which is the sandy soil due to its position on Celebes Molasse of Sarasin and Sarasin (1901) (QTms) sediment formation that contains sandstone and coral limestone. The presence of Palukoro fault, which is only under 10km of distance from the site, also incorporates its liquefaction susceptibility. Furthermore, the soil investigation using the SBT method was conducted. The stratigraphy showed that the area mainly consisted of sands and mixtures susceptible to liquefaction.

The liquefaction potential analysis using a CPT-based liquefaction triggering procedure and LI has been conducted in the Pombewe permanent housing to find the maximum GWL allowed in the area. The changed LI value was monitored while adding up GWL every 0.2m from the maximum depth of each borehole to the liquefaction procedure calculation. The change indicates if the liquefaction would happen if the layer was saturated, and the GWL needs to be kept below this exact layer to prevent the liquefaction. The analysis estimated varying GWL for each borehole depends on the area topography range from 1.0-11.6m. This value could be used to find the proper liquefaction mitigation proposed for the housing site.

The north-to-west steep hillside area with a maximum GWL of 1.2-2.4m could be controlled with a natural retaining wall using specific plants that could both retain the soil and allow the groundwater discharge. The housing area on the south of the waterway could be treated with land improvement by compacting processes to prevent the water from above the ground from infiltrating and saturating the land. The dense soil in this area was expected to hold the water to resurface from below the layer. On the other hand, the area on the north of the waterway, which appears to be the most vulnerable to liquefaction and the GWL, also needs to be kept as low as 6.6-11.6 meters below the ground needs more investigation and data to decide the suitable liquefaction mitigation.

6 Acknowledgments

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