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Analysis of Vulnerability to Liquefaction Based On N-SPT in the Petobo Area of PALU City

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Abstract
The earthquake that occurred in Palu in September 2018 was one of the large-scale earthquakes with a magnitude of 7.4, which was then followed by a tsunami and the emergence of the phenomenon of liquefaction. Tsunami and liquefaction in several locations in Palu City, Sigi Regency and Donggala Regency caused severe damage and killed thousands of people. The research location focused on the liquefied Petobo area and its surroundings. This study aims to determine the vulnerability to liquefaction based on the bearing capacity of the soil in the study area. This research was conducted using N-SPT test, followed by data analysis using Cyclic Stress Ratio (CSR) and Cyclic Resistance Ratio (CRR) values, and factor of safety (FS). The research was conducted at 6 N-SPT testing points with the depth of the groundwater table in the liquefaction-affected area less than 10 meters and even artesian water at some points. Based on the results of the liquefaction potential evaluation method based on the FS value, it is known that the liquefaction zone that occurs at the testing points from point LP-1 to point LP-4 with a factor of safety (FS) value equal to one occurs at shallow soil depths, which are less than 10 m. At point LP-5, the liquefaction potential is less than 10 m. At point LP-5, liquefaction potential occurs at depths of 9-10 and 13 m, but the upper layers do not have liquefaction potential. Point LP-6 has a safety factor value of more than one so it does not have the potential for liquefaction. The value of settlement from LP-1 - LP-6 shows a value of 0 - 29.86 cm.

Keywords: Liquefaction, Petobo, N-SPT

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I. INTRODUCTION

Palu City and its surroundings within a century (1905-2005) based on records have been hit by earthquakes with magnitude > 4.5 SR more than 10 (ten) events, based on topographic, geological, and seismological conditions, the Palu City area has the potential to experience earthquake damage including secondary disasters (tsunamis, liquefaction, and cliff avalanches) as happened on May 20, 1938, an earthquake with a magnitude of 7.6 SR whose vibrations were felt throughout the island of Sulawesi. **[5]**

lndonesia is one of the earthquake-prone countries that is also prone to liquefaction events. Therefore, before constructing a structure or other civil building, a soil investigation should be conducted, one of which is an evaluation of liquefaction potential, so that structures that are resistant to liquefaction events in particular and earthquakes in general can be planned. The results of this research can be used as input to the central government and local governments as a policy consideration in evaluating future regional spatial planning.

1.1 Definition of Liquefaction

Liquefaction is a process of changing the condition of water-saturated sandy soil to liquid, due to the increase in pore water stress whose value equals the total stress due to dynamic loads so that the effective stress of the soil decreases to near zero.**[6]**

1.2 Determining the Factor of Safety (FS) Value Based on CSR (Cyclic Stress Ratio) and CRR (Cyclic Resistance Ratio) Values

1.2.1 Determine the Cyclic Stress Ratio (CSR) Value

The Cyclic Stress Ratio (CSR) value is the ratio between the cyclic stress caused by the earthquake and the effective vertical stress of the soil. In determining the value of the Cyclic Stress Ratio (CSR), the equation written by Youd and Idriss (1997) is used, as follows.

$$\mathbf{CSR = 0,65.\frac{amax}{g}.\frac{\sigma v}{\sigma' v}.rd}$$

Description;
CSR = Cyclic Stress Ratio
αmax = Maximum horizontal acceleration due to earthquake at the earth's surface (m/s2)
g = Earth's gravitational acceleration (9.81 m/s2)
σv = Total vertical stress of soil at depth z (kN/m2)
σ'v = Effective vertical stress of soil at depth z (kN/m2)
rd = Stress reduction factor

As for the ratio between the total vertical stress of the soil and the effective vertical stress of the soil, it can be calculated using a simple equation found in the theory of Soil Mechanics **[1]**.

$\sigma v = \gamma . z$

$\sigma' v = (\gamma - \gamma w)\, z$

The reduction factor (rd) is a value that can affect the stress in the soil. The greater the soil depth, the smaller the reduction factor as shown in the following equation **[4]**.

rd = 1,00 − 0,00765z	for $z \leq 9{,}15$ m
rd = 1,174 − 0,0267z	for $9{,}15 \leq z \leq 23$m
rd = 0,744 − 0,008z	for $23 \leq z \leq 30$m
rd = 0,5z	for $z \geq 23$m

1.2.2. Determine the Cyclic Resistance Ratio (CRR) Value

Cyclic Resistance Ratio (CRR) is the amount of soil resistance to liquefaction hazards caused by cyclic stress. In determining the CRR value, it can be obtained by using field test data such as Standard Penetration Test (SPT).

a) Determine the Value (N)60

N60 is the N SPT value at 60% energy ratio which can be determined using the following formula **[2]**:

N60 = Nm. CE. CB. CR. CS
With,
Nm = N-SPT obtained from field tests;
CE = correction for energy hammer ratio (ER);
CB = correction for borehole diameter;
CR = correction factor for rod length;
CS = correction for sample.

b) Determine the Value (N1)60

The corrected overburden penetration resistance value, (N1)60, is calculated using the overburden correction factor, CN, as follows **[2]**:

(N1)60 = CN. N60

This equation only applies to non-cohesive soils. The CN value is expressed in the following equation **[4]**:

CN = (Pa/(σ’vc))0,5 ≤ 1,7
with,
Pa = pressure at 1 atm = 101 kN/m2.
The CN value must not exceed 1.7.

c) Determine the value of (N1)60cs

Determining the value of (N1)60CS can be determined using the following equation **[2]**:

(N1)60CS = (N1)60 + Δ(N1)60

Δ(N1)60 = exp+(1,63+9,7/(FC+0,01)–(〖15,7/(FC+0,01))〗^2)

Or use the following equation developed by L.M. Idriss with the help of R.B. Seed for the correction factor (N1)60 equalizing the clean sand value, (N1)60cs as follows:

(N1)60cs = α + β(N1)60

Where the values of α and β are coefficients determined from the following equation:

α = 0	for FC ≤ 5%
α = exp [1.76 − (190/FC2)]	for 5% < FC < 35%
α = 5.0	for FC ≥ 35 %
β = 1.0	for FC ≤ 5%
β = [0.99 (FC1.5/1.000)]	for 5% < FC < 35%
β = 1.2	for FC ≥ 35%

Or using the following equation (Liao and Due to the increase in N-SPT values with increasing effective overburden stress, the overburden stress correction factor using the equation proposed through (NCEER, 1997) can be seen in the equation as follows **[7]**

$C_N = 2{,}2 / (1{,}2 + \frac{\sigma' v}{Pa}) \leq 1{,}7$

Or using the following equation **[4]**:

$$CN = \left(\frac{pa}{\sigma'vc}\right)^{0,5} \leq 1,7$$

Description:

σ'vc = vertical effective stress of overburden (kPa)

Pa = pressure at 1 atm = 101 kN/m2

d) Determining the CRR Value

Determining the CRR value of the corrected earthquake magnitude (Mw) based on the value of (N1)60cs, Idriss and Boulanger (2006) cited in Tsai et al. (2009), provide an equation as shown in the equation below.

$$CRR^{7,5} = \exp \frac{(N1)60cs}{14,1} + (\frac{(N1)60cs}{126})^2 - (\frac{(N1)60cs}{23,6})^3 + (\frac{(N1)60cs}{25,4})^4 - 2,8$$

e) Magnitude Scaling Factors (MSF) Values

Magnitude Scaling Factors (MSF) values are used to equate CRR values to a common value of Moment Magnitude (Mw) = 7.5 where the CRR values obtained from this liquefaction potential evaluation are based on an earthquake of 7.5 Mw. Seed and Idriss (1982) cited in Youd and Idriss (2001), provide an equation for the MSF value for magnitudes greater than 7.5 Mw and smaller than 7.5 Mw. The equation can be shown in the following equation.

$$Mw < 7,5; \quad MSF = \frac{10^{2,24}}{Mw^{2,56}}$$

$$Mw > 7,5; \quad MSF = (\frac{Mw}{7.5})^{-2.56}$$

f) Determine the Overburden Stress Correction Factor Value (Kσ)

Seed (1983), introduced an overburden stress correction factor (Kσ). This overburden stress correction factor (Kσ) is taken into account because it is useful for adjusting CRR values to effective stress values. The equation for the overburden stress correction factor (Kσ) is given. **[9]**

$$K\sigma = (\frac{\sigma' vo}{pa})^{(f-1)}$$

To obtain the value of f (soil relative density), the following equation can be used.

$$f = 0,831 - \frac{N1(60)cs}{60}$$

with:

Kσ = Effective overburden stress correction factor

σ'vo = Effective overburden stress (kN/m2)

Pα = Pressure at 1 atm (101 kN/m2)

f = Relative density factor of soil

g) Determining the CRRMw Value

In determining CRR values with magnitudes different from 7.5 Mw, Magnitude Scaling Factors (MSF) are used as the correction factor as cited in Youd and Idriss (2001), with the equation shown below.

CRRMw = CRR7,5. MSF. Kσ

I.2.3 Determine the Factor of Safety (FS) Value

In evaluating soil resistance to liquefaction, a guideline is needed to determine the reference value or limit value whether the evaluated soil has the potential for liquefaction or not. The reference value is called the factor of safety (FS) value. The factor of safety (FS) value is the ratio between the CRR value (soil resistance to liquefaction) and the CSR value (cyclic stress that causes liquefaction). If the result of the factor of safety (FS) is less than one, it indicates that the evaluated soil has the potential for liquefaction. The complete equation for the factor of safety (FS) can be seen in the following figure.

$$\mathbf{FS} = \frac{CRRMw}{CSR}$$

Provided that:

If FS < 1 (Liquefaction occurs)

If FS = 1 (Critical condition)

If FS > 1 (No liquefaction occurs)

II. RESULT AND DISCUSSION

The research site is located in Petobo Village, South Palu Sub-district, Palu City, Central Sulawesi Province. The research location can be seen in Figure 1.

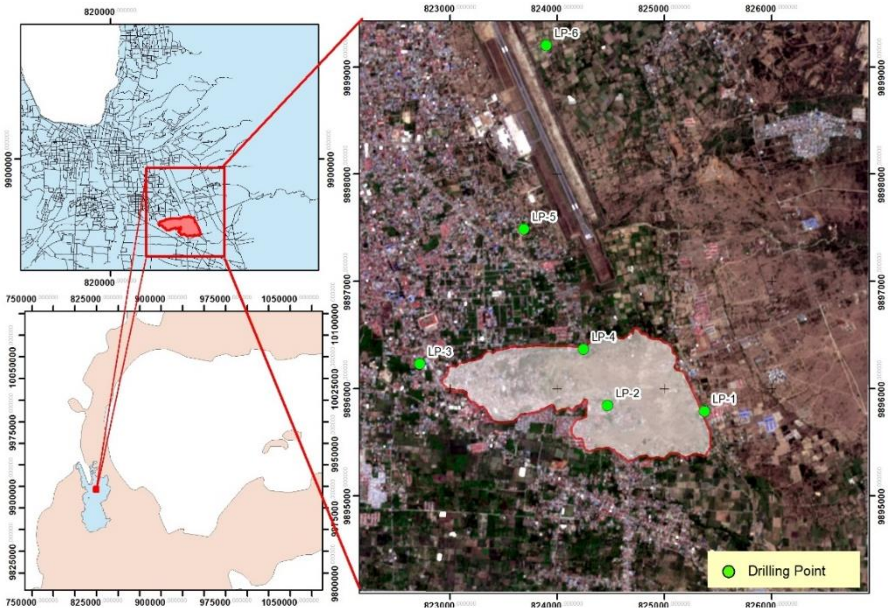

Figure 1: Research Location Map

Table 1: Borehole Coordinates (JICA Project Team, 2019 [3])

x (m E)	y (m S)	z	Name	Depth	Ground Water Table
825376	9895789	79	LP-1	35	11,22
824472	9895841	62	LP-2	32	2,6
822721	9896233	48	LP-3	30	0,13
824246	9896370	61	LP-4	30	0,8
823692	9897486	67	LP-5	30	5,59
823903	9899203	112	LP-6	27	20

The data used in this research are primary data sourced from JICA Team Project, 2019. Primary data are drill log data, N-SPT data, and groundwater level data with coordinate points in table 1.

Liquefaction potential analysis using LiqIT v.4.7.7.5 Soil Liquefaction Assessment Software. The analysis of liquefaction potential in this study uses the NCEER (National Center of Earthquake Engineering Research) method in 1998 with the Deterministic analysis type, fines Correction method using Idriss & Seed with the depth of the groundwater table according to each test point so as to obtain the safety factor (FS) value as found in table 3. If the value of FS<1 indicates that the area is prone to liquefaction, if the value of FS=1 indicates that the area is critical to liquefaction and if the value of FS>1 indicates that the area is not prone to liquefaction. The following are the results of data processing to find the FS value at each drill location. The results of data processing of LP-1 - LP-6 points using LiqIT Software to determine the Safety Factor (FS) value are shown in Figure 3 - Figure 8. The settlement value obtained for each point from the results of data processing using LiqIT v.4.7.7.5 Soil Liquefaction Assessment Software is shown in Table 2.

Table 2: Settlement values obtained for points LP-1 - LP- 6

Name	Settlements (cm)
LP-1	5,27
LP-2	29,86
LP-3	10,8
LP-4	22,94
LP-5	7,8
LP-6	0

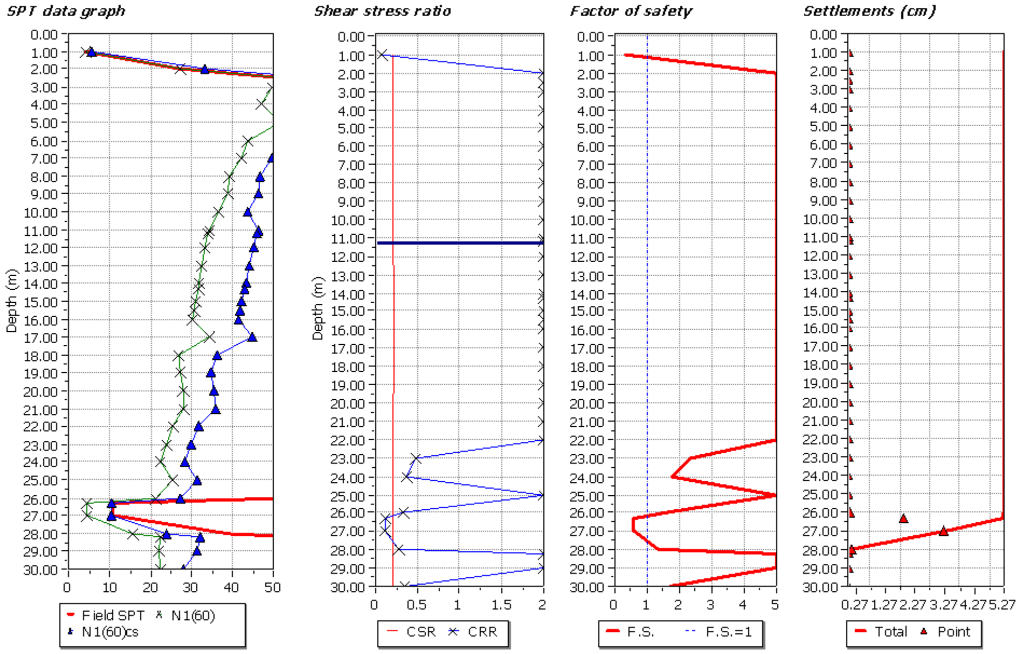

Figure 2: Graph of the relationship between SPT values, Shear Stress Ratio, Factor of Safety (FS), and Settlements against soil depth at point LP – 1

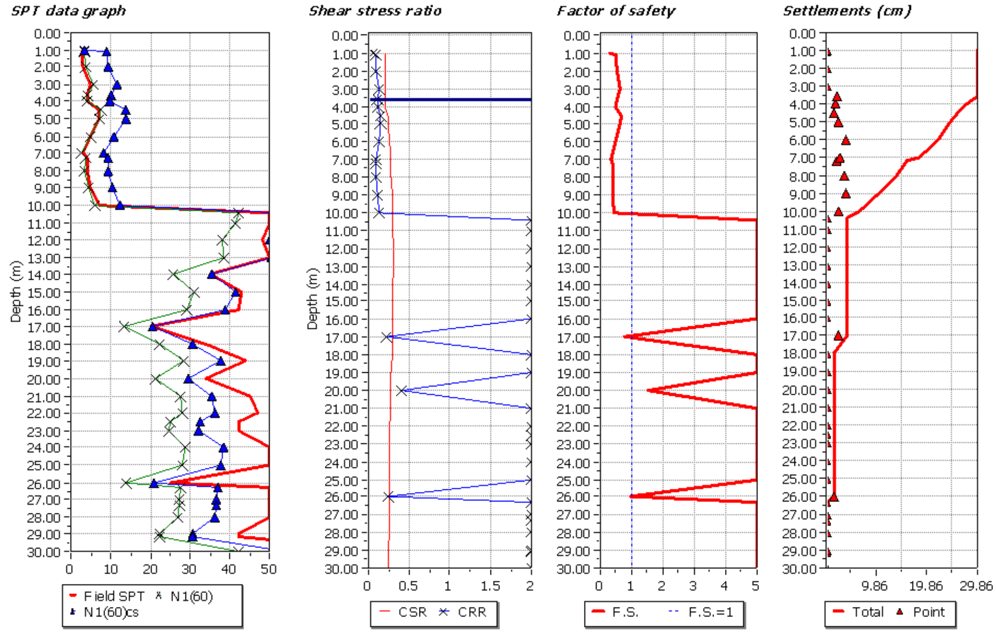

Figure 3: Graph of the relationship between SPT values, Shear Stress Ratio, Factor of Safety (FS), and Settlements against soil depth at point LP – 2

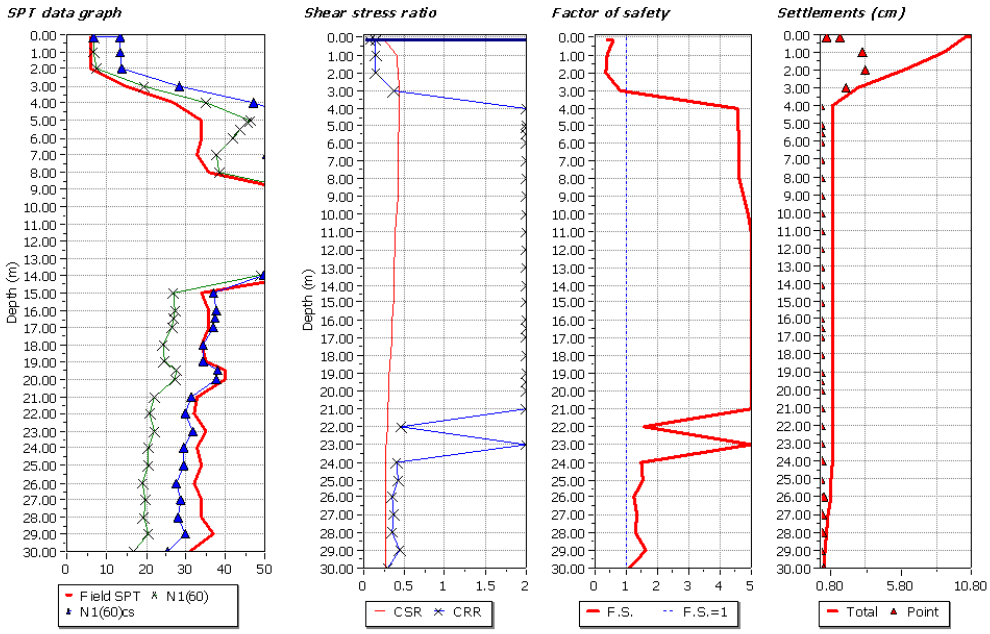

Figure 4: Graph of the relationship between SPT values, Shear Stress Ratio, Factor of Safety (FS), and Settlements against soil depth at point LP – 3

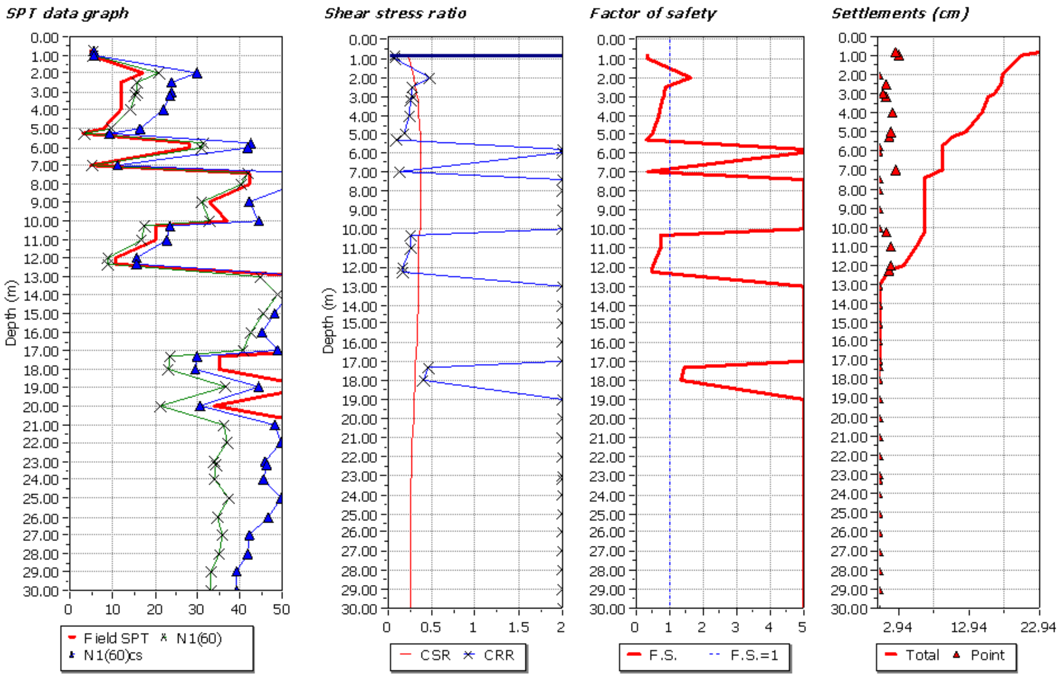

Figure 5: Graph of the relationship between SPT values, Shear Stress Ratio, Factor of Safety (FS), and Settlements against soil depth at point LP – 4

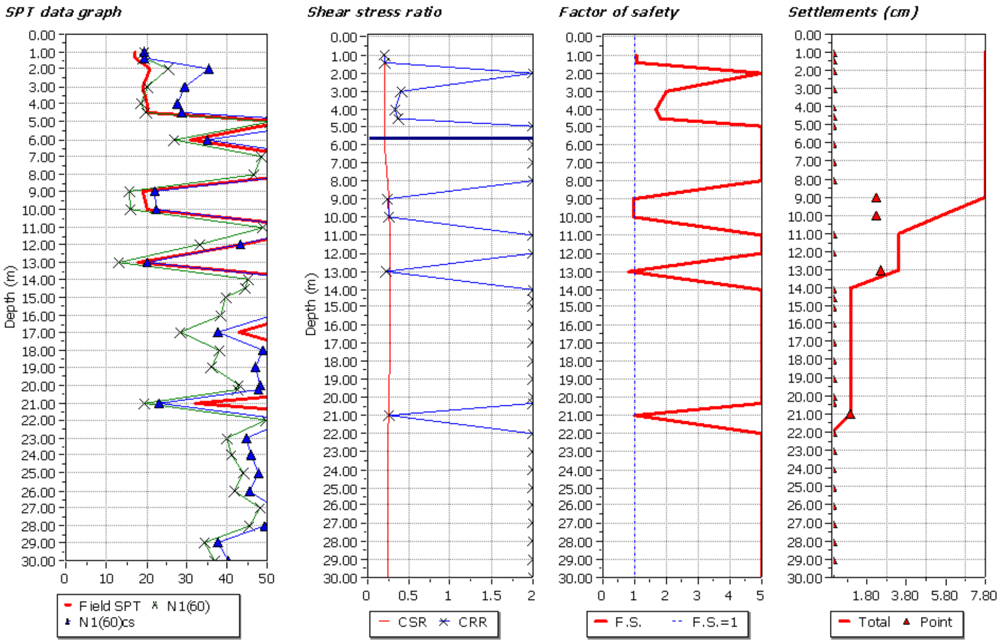

Figure 6: Graph of the relationship between SPT values, Shear Stress Ratio, Factor of Safety (FS), and Settlements against soil depth at point LP - 5

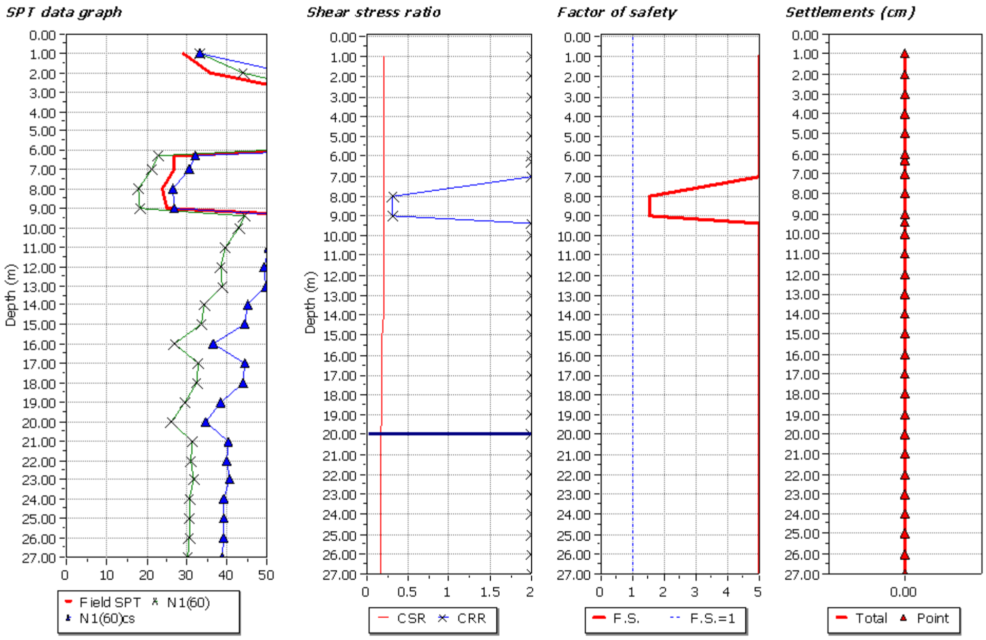

Figure 7: Graph of the relationship between SPT values, Shear Stress Ratio, Factor of Safety (FS), and Settlements against soil depth at point LP – 6

In order to obtain an overview of the arrangement of the subsurface layers from the calculation of the liquefaction potential of Points LP-1 - LP-6, it is illustrated in the form of a cross-sectional profile model of the layers. The vertical cross-sectional profile model is shown in Figure 9.

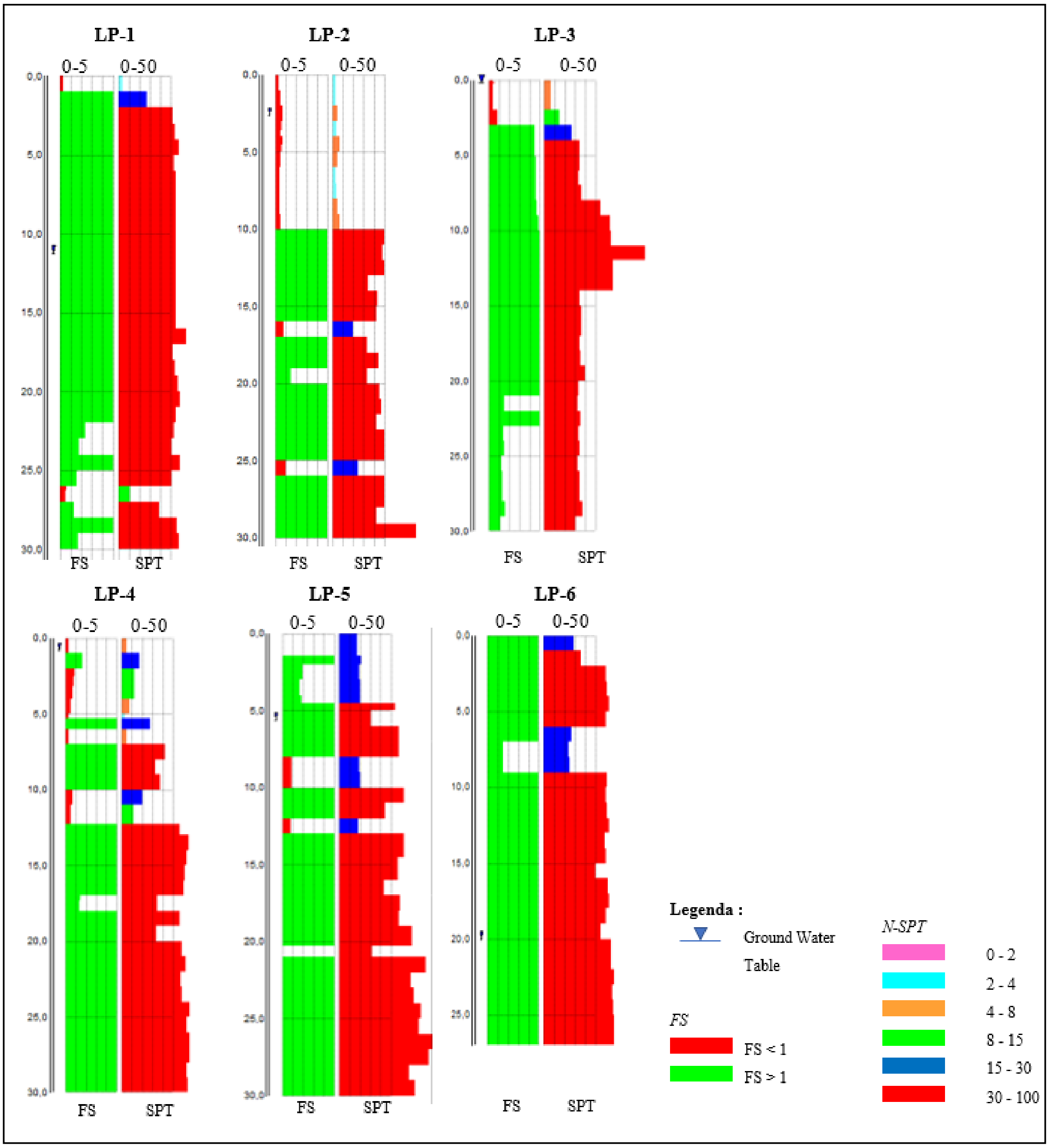

Figure 8: Cross section of the relationship between SPT value and Factor of Safety against soil depth at point LP-1 - LP-6

Table 3: Summary Results of Factor of Safety Values at Each Test Point

LP - 1		**LP - 2**		**LP - 3**		**LP - 4**		**LP - 5**		**LP - 6**	
D (m)	FS	D (m)	FS	D (m)	FS	D (m)	FS	D (m)	FS	D (m)	FS
1	0,34	1	0,28	0,13	0,39	0,8	0,34	1	1,03	1	5
2	5	1,1	0,49	0,2	0,56	1	0,31	1,4	1,03	2	5
2,5	5	2	0,51	1	0,36	2	1,62	2	5	3	5
3	5	3	0,63	2	0,35	2,5	0,85	3	1,98	4	5
4	5	3,6	0,54	3	0,83	3	0,8	4	1,66	5	5
5	5	4	0,5	4	4,56	3,2	0,78	4,5	1,83	6	5
6	5	4,5	0,67	5	4,55	4	0,69	5	5	6,3	5
7	5	5	0,62	5,1	4,56	5	0,5	6	5	7	5
8	5	6	0,46	5,5	4,61	5,3	0,28	7	5	8	1,5
9	5	7	0,34	6	4,61	5,8	5	8	5	9	1,54
10	5	7,2	0,38	7	4,62	6	5	9	0,94	9,4	5
11	5	8	0,36	8	4,64	7	0,33	10	0,93	10	5
11,2	5	9	0,38	9	4,74	7,4	5	11	5	11	5
12	5	10	0,44	10	4,9	8	5	12	5	12	5
13	5	10,4	5	11	5	9	5	13	0,79	13	5
14	5	11	5	12	5	10	5	14	5	14	5
14,3	5	12	5	13	5	10,3	0,73	14,5	5	15	5
15	5	13	5	14	5	11	0,71	15	5	16	5
15,5	5	14	5	15	5	12	0,49	16	5	17	5
16	5	15	5	16	5	12,3	0,49	17	5	18	5
17	5	16	5	16,5	5	13	5	18	5	19	5
18	5	17	0,76	17	5	14	5	19	5	20	5
19	5	18	5	18	5	15	5	20	5	21	5
20	5	19	5	19	5	16	5	20,3	5	22	5
21	5	20	1,5	19,5	5	17	5	21	1,02	23	5
22	5	21	5	20	5	17,3	1,44	22	5	24	5
23	2,35	22	5	21	5	18	1,33	23	5	25	5
24	1,78	22,5	5	22	1,55	19	5	24	5	26	5
25	5	23	5	23	5	20	5	25	5	27	5
26	1,62	24	5	24	1,46	21	5	26	5		
26,3	0,57	25	5	25	1,53	22	5	27	5		
27	0,56	26	0,93	26	1,23	23	5	28	5		
28	1,32	26,3	5	27	1,35	23,2	5	29	5		
28,2	5	27	5	28	1,3	24	5	30	5		
29	5	27,3	5	29	1,63	25	5				
30	1,71	28	5	30	1,1	26	5				
		29	5			27	5				
		29,1	5			28	5				
		30	5			29	5				
						30	5				

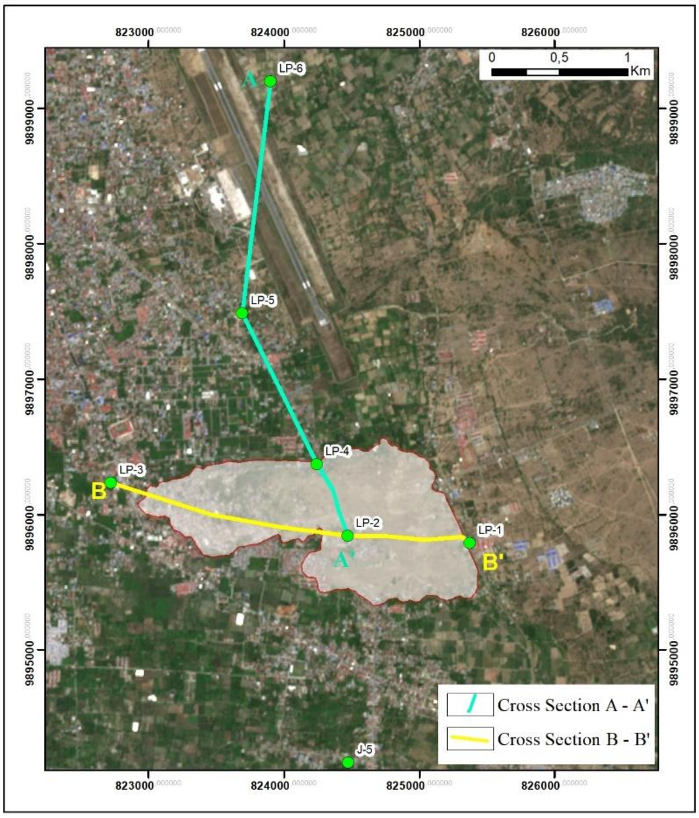

Figure 9: Point Map of Cross Section A-A' and Cross Section B-B'

Figure 10 shows the drawing of Cross-Section Lines A-A' and B-B' showing the correlation of potential liquefaction zones between drill points. Line A-A' shows the correlation between drill points at Points LP-6, LP-5, LP-4 and LP-2. Cross section B-B' shows the correlation between points at Points LP3, LP-2 and LP-1.

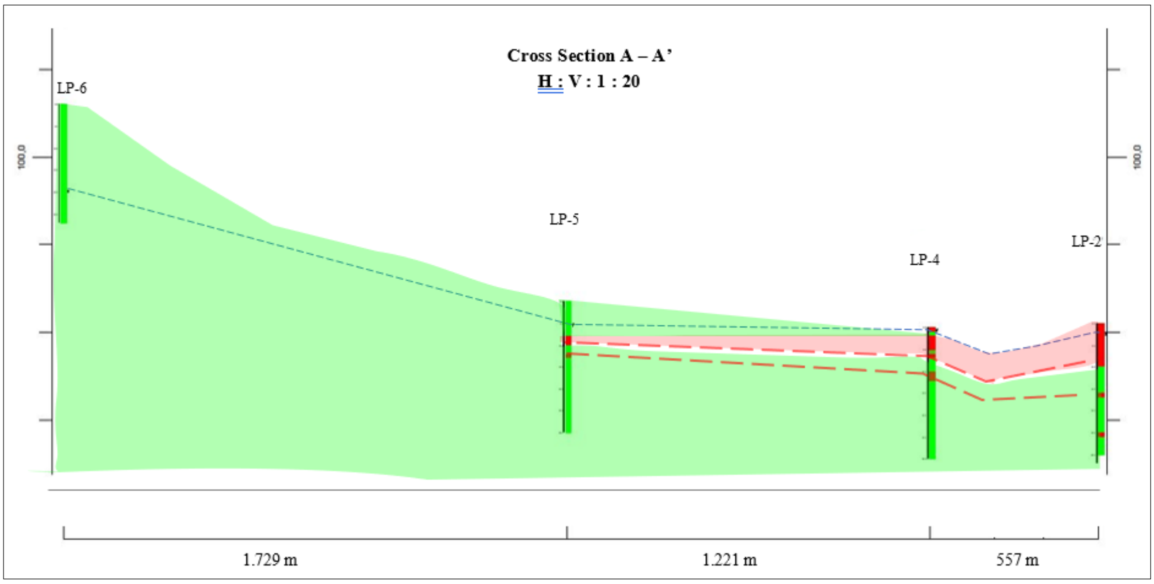

Figure 10: Liquefaction Zone at Points LP-6, LP-5, LP-4, and LP-2

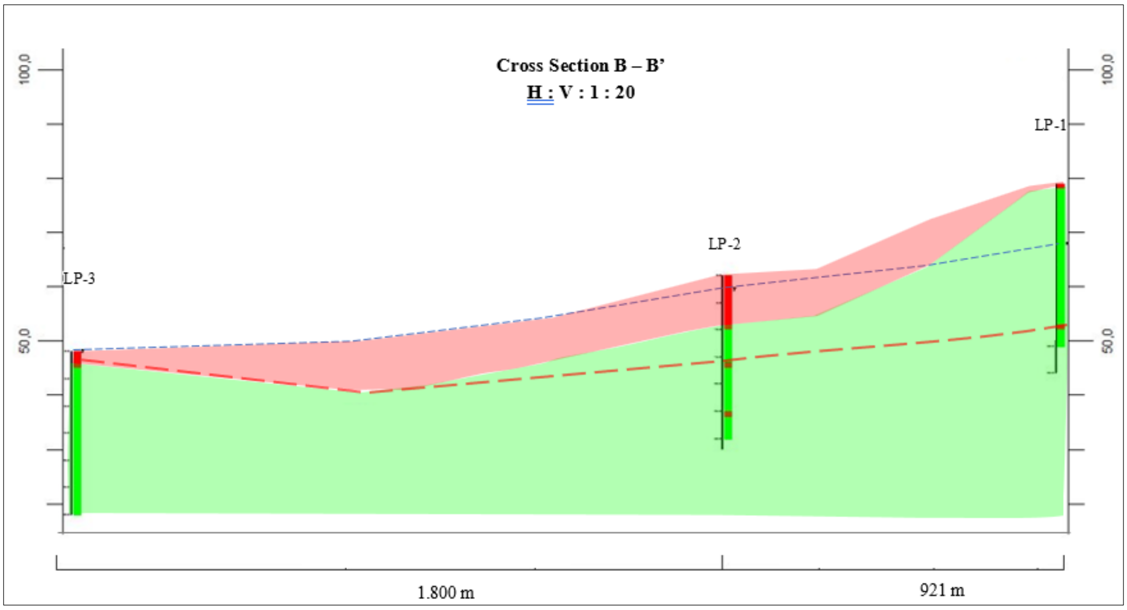

Figure 11: Liquefaction Zone at Points LP3, PS-4, LP-2, and LP-1

Liquefaction that occurs in a soil layer can not only occur due to cyclic loads, but also due to the presence of water-saturated soil layers. The presence of water-saturated soil layers is strongly influenced by the location of the groundwater table. The shallower the water table is from the surface, the more potential liquefaction will occur. Based on this, it can be concluded that the soil layer where liquefaction occurs is the soil layer that is partially above and below the location of the groundwater table to a depth of 10 m when it reaches a factor of safety (FS) value equal to one. Figure 11 to Figure 12 show the soil layers that have the potential for liquefaction. In the figure, it is known that the liquefaction zone that occurs at the test points from point LP-1 to point LP-4 with a factor of safety (FS) value equal to one occurs at a shallow soil depth, which is less than 10 m, so it can be concluded that the area has the potential for liquefaction. At point LP-5, the potential for liquefaction occurs at depths of 9-10 and 13 m, but the upper layers do not have the potential for liquefaction. Unlike the case with point LP-6, whose safety factor value is more than one so that it does not have the potential for liquefaction.

III. CONCLUSION

Based on the results of N-SPT data processing, it is known that the liquefaction zone that occurs at the testing points from point LP-1 to point LP-4 with a factor of safety (FS) value equal to one occurs at a shallow soil depth, which is less than 10 m, so it can be concluded that the area has the potential for liquefaction. At point LP-5, the potential for liquefaction occurs at depths of 9-10 and 13 m, but in the upper layers there is no potential for liquefaction. Point LP-6 has a safety factor value of more than one so it does not have the potential for liquefaction.

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