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Liquefaction Potential in Matano Sub-District, Bungku Tengah District, Morowali Regency Using Swedish Weight Sounding Test

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Abstract
Matano Sub-district is one of the sub-districts located in Bungku Tengah District, Morowali Regency, Central Sulawesi Province. The total area of Matano Sub-district is 57.7 hectares. Matano is strategically located with access to natural resources and has significant economic potential, particularly in the mining and fisheries sectors. It is also a tourism destination, with the Matano Beach Pier being a popular site frequently visited by the community. This study was conducted using the Swedish Weight Sounding (SWS) test and laboratory tests, including grain size analysis, Atterberg limits, and soil unit weight testing. The research stages included field data collection using the SWS equipment, which produced values of Nsw, N, qa, and qu. Subsequently, laboratory testing of the Atterberg limits and sieve analysis was performed, yielding results for grain gradation, liquid limit (LL), plastic limit (PL), and plasticity index (PI).
Based on results from all test points, the Factor of Safety (FS) values ranged from 0.28 to 1.13. The soil characteristics obtained from the SWS tests at ten test locations produced three main parameters: Nsw, qa, and qu. The Nsw values ranged from 0.00 to 357.14 n/m, qa ranged from 0.00 to 315.71 kN/m², and qu ranged from 2.25 to 312.86 kN/m². The testing was conducted at 10 locations, with the groundwater table depth measured at 0.50 meters. Liquefaction potential was evaluated using grain size distribution and Tsuchida's liquefaction potential curve, which showed that some samples fell within the red zone (indicating high liquefaction potential), while others fell within the black zone (indicating potential for liquefaction). Using the Modified Chinese Method, all test points were found to have liquefaction potential.
Based on the Swedish Weight Sounding results, most FS values were < 1, indicating that points P1 to P10 have liquefaction potential, as shown in the FS table. From the various methods used to analyze liquefaction potential, it can be concluded that all tested points are susceptible to liquefaction at depths less than 10 meters, with an earthquake acceleration (amax) of 0.15 g and an earthquake magnitude of 5 Mw.
Keywords: *Liquefaction Potential, Swedish Weight Sounding, Matano Sub-district, Morowali.*

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I. INTRODUCTION

Soil is composed of solid particles and pore spaces. When an earthquake occurs in soil that is saturated or located near a water source, these pore spaces become filled with water, reducing the overall volume of the soil. This process increases the pore water pressure between soil particles, causing the particles to move freely in the water and lose the inter-particle bonds that hold them together.

Substantially, this change reduces the soil's shear strength, causing the soil mass to behave like a liquid. In this liquefied state, the soil deforms easily, and heavy objects such as buildings constructed on it may suffer damage due to the loss of internal support. Liquefied soil can behave like quicksand, submerging structures or materials on the surface. Moreover, it can also trigger landslides.

If liquefaction occurs on a large scale, buildings can be pulled down into the ground. The soil may continue to sink along with the structures on top. The interface between the soil and the building's foundation can be severely damaged. Water from the ground can seep through cracks in the walls and floors, causing damage to equipment and electrical connections. Therefore, soil liquefaction poses a serious risk to human safety, especially when it occurs in residential areas (Tirton.Id, 2019).

Matano Sub-district is one of the administrative areas located in Bungku Tengah District, Morowali Regency, Central Sulawesi Province. The total area of Matano is 57.7 hectares. Strategically situated with access to natural resources, Matano has significant economic potential, particularly in the mining and fisheries sectors. It is also a popular tourism destination, with Matano Beach Pier being one of the frequently visited attractions by the local community.

Matano is considered one of the areas with high liquefaction potential. According to a report from the Regional Disaster Management Agency (BPBD) of Morowali Regency, this region has not yet experienced liquefaction despite several earthquakes occurring in recent years.

The objectives of this study are as follows:

1. To determine the soil characteristics and bearing capacity in Matano Sub-district, Bungku Tengah District, Morowali Regency.
2. To identify the liquefaction potential in Matano Sub-district, Bungku Tengah District, Morowali Regency

II. RESEARCH METHODOLOGY

2.1. RESEARCH LOCATION

The planned research location is situated in Matano Sub-district**,** Bungku Tengah District**,** Morowali Regency**.** The exact location of the research area can be seen in the figure below:

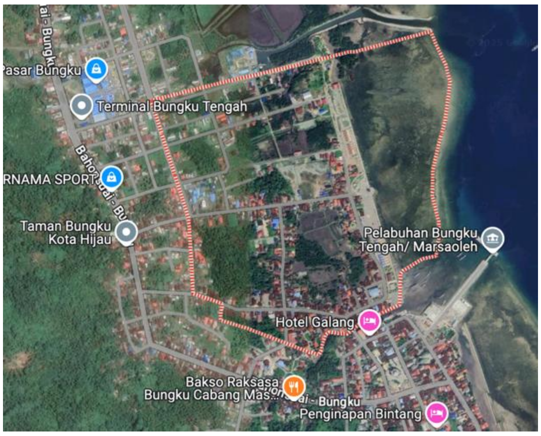

Figure 1. Research Location

2.2. FIELD TESTING

Field testing was carried out using the Swedish Weight Sounding (SWS) tool, with a total of nine (9) test points. The results obtained from the Swedish Weight Sounding test were used to evaluate the soil's resistance to liquefaction hazards.

The steps involved in using the Swedish Weight Sounding tool are explained as follows:

1. Equipment Preparation
2. After setting up the equipment, check whether the tip of the rod penetrates the ground. If it does, measure the depth from the reference surface to the next scale mark at the point where penetration stops, and record this as the penetration depth under 50 N load.
3. Next, add a 100 N load on top of the clamp and perform the same operation as in step 2.
4. Repeat step 3 while adding additional loads in increments. The load sequence is as follows**:** 50 N (clamp), 150 N, 250 N, 500 N, 750 N, and 1000 N**.**
5. When penetration ceases at the 1000 N load, measure the total depth of penetration. Then rotate the handle clockwise, with every 180° rotation counted as one turn**.** Record the number of turns for every 25 cm of penetration depth**.**
6. Measurement can be considered complete in the following cases: a. The number of turns reaches 50 turns without achieving 25 cm of penetration. b.The resistance on the handle increases significantly. c. The screw point contacts a rock or hard layer, indicated by a sudden lack of resistance while turning the handle.
7. Once measurement is completed, remove all the weights and withdraw all rods using a hydraulic bottle jack, or manually if possible.

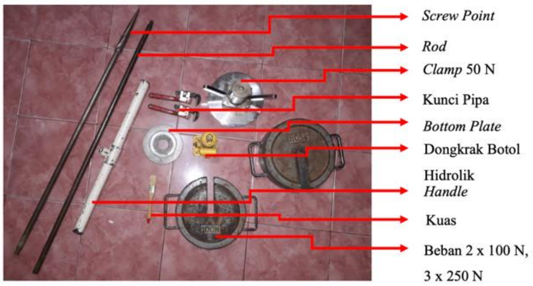

Figure 2. Components of the Swedish Weight Sounding Apparatus

2.3. LABORATORY TESTING

Laboratory testing consisted of the following three tests:

2.3.1. Sieve Analysis

This test aims to determine the grain size distribution of coarse and fine aggregates using a set of sieves with mesh sizes No. 4", 10", 20", 40", 60", 80", 100", and 200". The soil sample is oven-dried for 24 hours at a temperature of approximately ±110°C before sieving. The resulting grain size distribution (gradation) is used for soil classification and for evaluating the soil's resistance to liquefaction hazards.

2.3.2. Atterberg Limits

This test is performed on soil that passes through the No. 40 sieve. It aims to determine the soil consistency limits, including the Liquid Limit (LL)**,** Plastic Limit (PL)**,** and Plasticity Index (PI)**.**

2.3.3. Soil Unit Weight

This test determines the dry unit weight**,** wet unit weight**,** and moisture content of the soil sample. These parameters are used to evaluate the density level of the soil at the test points.

III. RESULTS AND DISCUSSION

The research was conducted in Matano Sub-district, Bungku Tengah District, Morowali Regency. The study area is located near the Bungku Tengah Public Health Center (Puskesmas). Swedish Weight Sounding (SWS) tests and soil sampling were carried out at 10 (ten) points. The depths obtained from the SWS tests ranged from 1.95 meters to 5.95 meters at points P1 through P10. Meanwhile, both disturbed and undisturbed soil samples were collected from a depth of 1 meter below the ground surface. These soil samples are expected to represent the soil structure at the research location.

Figure 3. Research Location

To determine the soil characteristics and liquefaction potential of the area, several laboratory tests were conducted, including sieve analysis, Atterberg limits, and soil unit weight tests.

Sieve Analysis

The soil samples were oven-dried for 24 hours at 110°C before the sieve analysis. The samples were weighed, then sieved using the following sieve sizes: 3/8, 8, 16, 20, 40, 60, 80, 100, and 200 mesh. The sieves were vibrated using a sieve shaker. To classify the soil type according to the Unified Soil Classification System (USCS), the results of the grain size distribution were combined with Atterberg limits test results. The grain size distribution curves for the 10 soil samples can be seen in Figure 4.

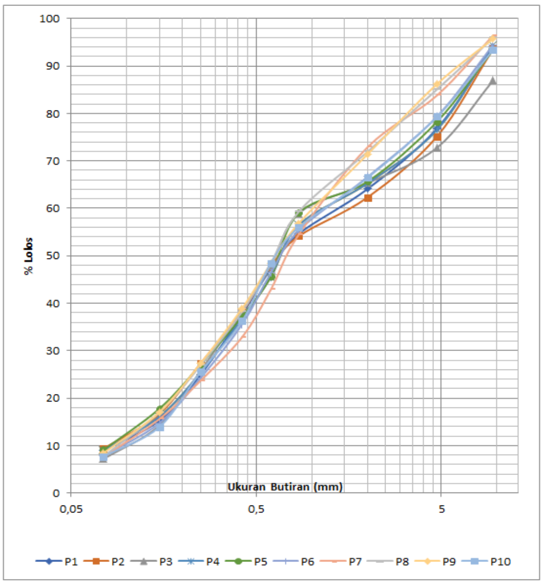

Figure 4. Grain Size Distribution for Each Soil Sample

Atterberg Limits

The Atterberg limits test was conducted on soil samples passing the No. 40 sieve. This test yielded values for the Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI). However, the Atterberg limits test could not be performed for samples P1 through P10 due to the absence of LL and PL values.

Based on Table 4.2, the percentage passing the No. 200 sieve is 8.31%, and the percentage passing No. 8 sieve averages 79.36%, classifying the soil as sand. The calculated coefficients of uniformity (Cu) and curvature (Cc) do not meet the criteria for well-graded sand (Sw: Cu > 6 and Cc = 1–3). Therefore, the soil is classified as SP (poorly graded sand). Given the percentage passing No. 200 is between 5% and 12%, the soil could be classified as SP-SM or SP-SC, where SM requires PI < 4 and SC requires PI > 7. Since PI = 0, the soil is classified as SP-SM.

Soil Unit Weight

Secondary data from a study by Ariflan (2023) in Morowali was used to determine soil unit weight. The field dry unit weight (γ) was 16.51 kN/m³, and the saturated unit weight (γ_{sat}) was 20.13 kN/m³. The saturated unit weight will be used to calculate the effective stress below the groundwater table.

Field testing was conducted at 10 points using the Swedish Weight Sounding (SWS) apparatus.

Swedish Weight Sounding (SWS)

The results of the SWS tests are presented in Tables 1, showing penetration depth, number of half-turns per meter (Nsw), allowable bearing capacity (qa), unconfined compressive strength (qu), and the N-SPT value converted from applied load (Wsw) and number of half-turns (Nsw)

Table 3. Results of Grain Size Analysis and Atterberg Limits

NO.	URAIAN PENGUJIAN	SAT.	SAMPEL										
			P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Rata-rata
I.	**Analisis Ukuran Butiran**												
1.	Tertahan #8	%	23,14	24,82	27,21	23,41	21,70	20,61	16,16	14,89	13,78	20,68	20,64
2.	Lolos #8	%	76,86	75,18	72,79	76,59	78,30	79,39	83,84	85,11	86,22	79,32	79,36
3.	Tertahan #200	%	91,02	90,59	92,77	91,04	90,89	92,18	92,34	92,22	91,53	92,28	91,69
4.	Lolos #200	%	8,98	9,41	7,23	8,96	9,11	7,82	7,66	7,78	8,47	7,72	8,31
5.	D60	mm	1,00	1,20	0,90	1,00	0,80	0,95	0,95	0,90	0,83	1,00	0,95
6.	D30	mm	0,22	0,20	0,20	0,22	0,20	0,22	0,23	0,20	0,20	0,22	0,21
7.	D10	mm	0,08	0,08	0,10	0,080	0,080	0,095	0,09	0,09	0,08	0,10	0,09
8.	Cu		12,50	15,00	9,00	12,50	10,00	10,00	10,56	10,00	10,38	10,00	10,99
9.	Cc		0,61	0,42	0,44	0,61	0,63	0,54	0,62	0,49	0,60	0,48	0,54
II.	**Batas-batas Atterberg**												
1.	Batas Cair (LL)	%	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2.	Batas Plastis (PL)	%	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
3.	Indeks Plastisitas (PI)	%	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	Jenis Tanah		**SP-SM**	**SP-SM**	**SP-SM**	**SP-SM**	**SP-SM**	**SP-SM**	**SP-SM**	**SP-SM**	**SP-SM**	**SP-SM**	

Nsw VALUES

The Nsw values obtained from the Swedish Weight Sounding (SWS) tests are summarized in Table 4, which presents the Nsw values at each test point, from P-1 to P-10. Based on the Nsw values divided by depth intervals per meter, as shown in Table 14 and Figure 5, the Nsw values at all test points within the depth range of 0 – 1 meter vary between 0.00 – 266.67 n/m. At the depth range of 1 – 2 meters, the Nsw values range from 0.00 – 250.00 n/m. For the depth interval of 2 – 3 meters, the Nsw values vary from 0.00 – 357.14 n/m. At depths between 3 – 4 meters, the values range from 0.00 – 294.12 n/m. For depths of 4 – 5 meters, Nsw values range from 0.00 – 294.12 n/m, and for the depth interval of 5 – 6 meters, they range between 0.00 – 250.00 n/m.

Table 4. Nsw Values at Points P-1 to P-10

NILAI NSW																			
P1		P2		P3		P4		P5		P6		P7		P8		P9		P10	
D (m)	Nsw (n/m)	D (m)	Nsw (n/m)	D (m)	Nsw (n/m)	D (m)	Nsw (n/m)	D (m)	Nsw (n/m)	D (m)	Nsw (n/m)	D (m)	Nsw (n/m)	D (m)	Nsw (n/m)	D (m)	Nsw (n/m)	D (m)	Nsw (n/m)
0,05		0,07		0,08		0,06		0,06		0,08		0,08		0,09		0,07		0,07	
0,10		0,10		0,10		0,09		0,08		0,11		0,11		0,13		0,10		0,11	
0,12		0,13		0,16		0,11		0,14		0,13		0,17		0,15		0,14		0,13	
0,16		0,16		0,20		0,18		0,17		0,17		0,18		0,20		0,18		0,20	
0,20		0,21		0,27		0,21		0,21		0,22		0,22		0,23		0,20		0,71	
0,24		0,28		0,33		0,26		0,28		0,25		0,27		0,25		0,27		0,89	
0,25	100,00	0,39	72,73	0,41	37,50	0,32	92,31	0,32	88,89	0,28	0,00	0,31	133,33	0,31	0,00	0,48	4,76	1,00	18,18
0,50	68,00	0,50	118,18	0,50	88,89	0,50	72,22	0,50	50,00	0,50	0,00	0,50	57,89	0,50	63,16	0,50	0,00	1,25	0,00
0,75	96,00	0,75	88,00	0,75	48,00	0,75	84,00	0,75	12,00	0,75	24,00	0,75	0,00	0,75	28,00	0,75	0,00	1,50	0,00
1,00	76,00	1,00	76,00	1,00	92,00	1,00	44,00	1,00	0,00	1,00	64,00	1,00	0,00	1,00	0,00	1,00	12,00	1,75	0,00
1,25	116,00	1,25	112,00	1,25	72,00	1,25	0,00	1,25	0,00	1,25	36,00	1,25	0,00	1,25	0,00	1,25	0,00	2,00	0,00
1,50	144,00	1,50	128,00	1,50	68,00	1,50	0,00	1,50	0,00	1,50	0,00	1,50	0,00	1,50	24,00	1,50	0,00	2,25	0,00
1,75	172,00	1,75	148,00	1,75	112,00	1,75	0,00	1,75	0,00	1,75	0,00	1,75	12,00	1,75	52,00	1,75	52,00	2,50	0,00
1,95	250,00	2,00	172,00	2,00	124,00	2,00	20,00	2,00	16,00	2,00	0,00	2,00	68,00	2,00	36,00	2,00	44,00	2,75	16,00
		2,18	277,78	2,25	156,00	2,25	68,00	2,25	72,00	2,25	48,00	2,25	116,00	2,25	16,00	2,25	84,00	3,00	44,00
				2,50	172,00	2,50	76,00	2,50	60,00	2,50	40,00	2,50	120,00	2,50	0,00	2,50	72,00	3,25	24,00
				2,67	294,12	2,75	84,00	2,75	116,00	2,75	8,00	2,75	192,00	2,75	0,00	2,75	104,00	3,50	0,00
						3,00	108,00			3,00	16,00	2,89	357,14	3,00	0,00	3,00	124,00	3,75	0,00
						3,25	124,00			3,25	48,00			3,25	64,00	3,25	144,00	4,00	48,00
						3,42	294,12			3,50	84,00			3,50	76,00	3,47	227,27	4,25	60,00
										3,75	132,00			3,75	104,00			4,50	44,00
										3,92	294,12			4,00	132,00			4,75	92,00
														4,17	294,12			5,00	84,00
																		5,25	148,00
																		5,50	136,00
																		5,75	164,00
																		5,95	250,00

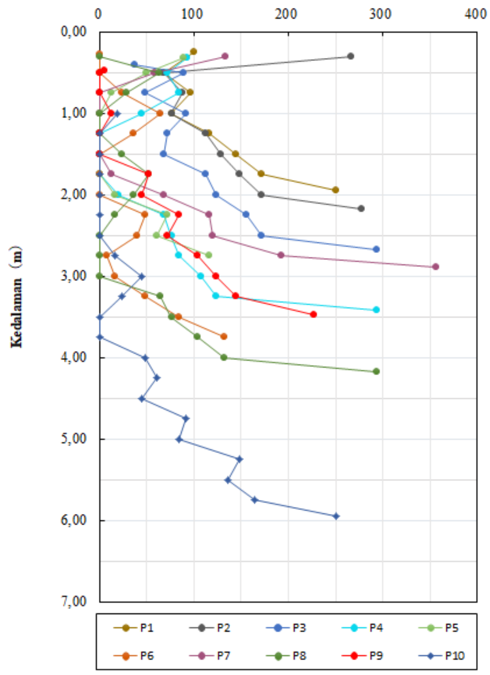

Figure 5. Relationship Between Nsw Values and Depth

ALLOWABLE BEARING CAPACITY VALUES (qa)

The allowable bearing capacity values (qa) obtained from the calculations based on the Swedish Weight Sounding test results are summarized in Table 5, which shows the summary of qa values at each test point, from P-1 to P-10.

Based on the qa values divided by depth intervals per meter, as shown in Table 5 and Figure 6, the qa values at all test points within the depth range of 0 – 1 meter vary between 0.00 – 243.33 kN/m². At the depth range of 1 – 2 meters, the qa values range from 30.00 – 230.00 kN/m². For the depth interval of 2 – 3 meters, the values range between 30.00 – 265.29 kN/m². At depths between 3 – 4 meters, the qa values vary from 30.00 – 265.29 kN/m². For depths of 4 – 5 meters, the values range from 65.00 – 265.29 kN/m², and for the depth interval of 5 – 6 meters, the qa values range between 138.80 – 230.00 kN/m².

Table 5. qa Values at Points P-1 to P-10

NILAI qa																			
P1		P2		P3		P4		P5		P6		P7		P8		P9		P10	
D (m)	qa (kN/m²)	D (m)	qa (kN/m²)	D (m)	qa (kN/m²)	D (m)	qa (kN/m²)	D (m)	qa (kN/m²)	D (m)	qa (kN/m²)	D (m)	qa (kN/m²)	D (m)	qa (kN/m²)	D (m)	qa (kN/m²)	D (m)	qa (kN/m²)
0,05	0,00	0,07	0,00	0,08	0,00	0,06	0,00	0,06	0,00	0,08	0,00	0,08	0,00	0,09	0,00	0,07	0,00	0,07	0,00
0,10	0,00	0,10	0,00	0,10	0,00	0,09	0,00	0,08	0,00	0,11	0,00	0,11	0,00	0,13	0,00	0,10	0,00	0,11	0,00
0,12	0,00	0,13	0,00	0,16	0,00	0,11	0,00	0,14	0,00	0,13	0,00	0,17	0,00	0,15	0,00	0,14	0,00	0,13	0,00
0,16	0,00	0,16	0,00	0,20	0,00	0,18	0,00	0,17	0,00	0,17	0,00	0,18	0,00	0,20	0,00	0,18	0,00	0,20	0,00
0,20	0,00	0,21	0,00	0,27	0,00	0,21	0,00	0,21	0,00	0,22	0,00	0,22	0,00	0,23	0,00	0,20	0,00	0,71	0,00
0,24	0,00	0,28	0,00	0,33	0,00	0,26	0,00	0,28	0,00	0,25	0,00	0,27	0,00	0,25	0,00	0,27	0,00	0,89	0,00
0,25	110,00	0,39	88,18	0,41	60,00	0,32	103,85	0,32	101,11	0,28	30,00	0,31	136,67	0,31	30,00	0,48	33,81	1,00	44,55
0,50	84,40	0,50	124,55	0,50	101,11	0,50	87,78	0,50	70,00	0,50	30,00	0,50	76,32	0,50	80,53	0,50	30,00	1,25	30,00
0,75	106,80	0,75	100,40	0,75	68,40	0,75	97,20	0,75	39,60	0,75	49,20	0,75	30,00	0,75	52,40	0,75	30,00	1,50	30,00
1,00	90,80	1,00	90,80	1,00	103,60	1,00	65,20	1,00	30,00	1,00	81,20	1,00	30,00	1,00	30,00	1,00	39,60	1,75	30,00
1,25	122,80	1,25	119,60	1,25	87,60	1,25	30,00	1,25	30,00	1,25	58,80	1,25	30,00	1,25	30,00	1,25	30,00	2,00	30,00
1,50	145,20	1,50	132,40	1,50	84,40	1,50	30,00	1,50	30,00	1,50	30,00	1,50	30,00	1,50	49,20	1,50	30,00	2,25	30,00
1,75	167,60	1,75	148,40	1,75	119,60	1,75	30,00	1,75	30,00	1,75	30,00	1,75	39,60	1,75	71,60	1,75	71,60	2,50	30,00
1,95	230,00	2,00	167,60	2,00	129,20	2,00	46,00	2,00	42,80	2,00	30,00	2,00	84,40	2,00	58,80	2,00	65,20	2,75	42,80
		2,18	252,22	2,25	154,80	2,25	84,40	2,25	87,60	2,25	68,40	2,25	122,80	2,25	42,80	2,25	97,20	3,00	65,20
				2,50	167,60	2,50	90,80	2,50	78,00	2,50	62,00	2,50	126,00	2,50	30,00	2,50	87,60	3,25	49,20
				2,67	265,29	2,75	97,20	2,75	122,80	2,75	36,40	2,75	183,60	2,75	30,00	2,75	113,20	3,50	30,00
						3,00	116,40			3,00	42,80	2,89	315,71	3,00	30,00	3,00	129,20	3,75	30,00
						3,25	129,20			3,25	68,40			3,25	81,20	3,25	145,20	4,00	68,40
						3,42	265,29			3,50	97,20			3,50	90,80	3,47	211,82	4,25	78,00
										3,92	265,29			3,75	113,20			4,50	65,20
														4,00	135,60			4,75	103,60
														4,17	265,29			5,00	97,20
																		5,25	148,40
																		5,50	138,80
																		5,75	161,20
																		5,95	230,00

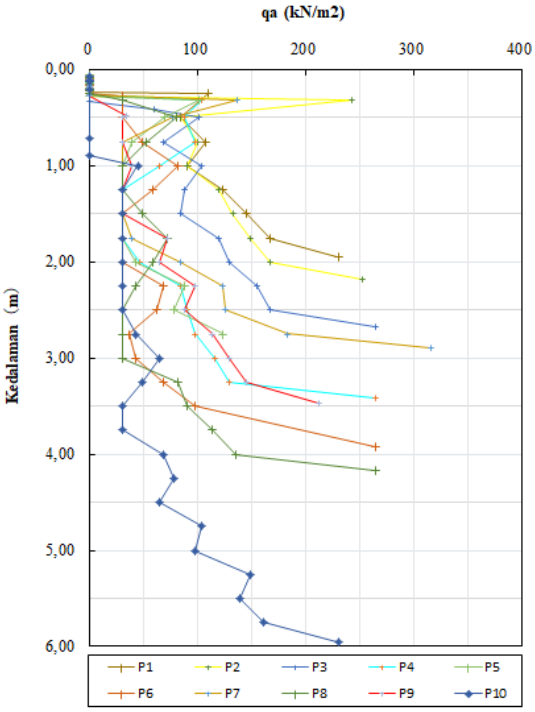

Figure 6. Relationship Between qa Value and Depth

6. UNCONFINED COMPRESSIVE STRENGTH VALUE (qu)

The unconfined compressive strength value (qu), obtained from the calculation of the Swedish Weight Sounding test results, is presented in Table 6. This table shows a summary of the qu values at each point, from Point P-1 to Point P-10.

Based on the qu values divided into depth intervals per meter, as shown in Table 6 and Figure 7, the qa values at all test points within the 0–1 meter depth range vary between 2.25 – 245.00 kN/m². In the 1–2 meter depth range, the Nsw values range from 45.00 – 232.50 kN/m². In the 2–3 meter depth range, values range from 45.00 – 312.86 kN/m². For the 3–4 meter range, values range from 45.00 – 295.00 kN/m².

Table 6. qu Values at Points P-1 to P-10

NILAI qu																			
P1		P2		P3		P4		P5		P6		P7		P8		P9		P10	
D (m)	qu (kN/m²)	D (m)	qu (kN/m²)	D (m)	qu (kN/m²)	D (m)	qu (kN/m²)	D (m)	qu (kN/m²)	D (m)	qu (kN/m²)	D (m)	qu (kN/m²)	D (m)	qu (kN/m²)	D (m)	qu (kN/m²)	D (m)	qu (kN/m²)
0,05	2,25	0,07	2,25	0,08	2,25	0,06	2,25	0,06	2,25	0,08	2,25	0,08	2,25	0,09	2,25	0,07	2,25	0,07	2,25
0,10	6,75	0,10	6,75	0,10	6,75	0,09	6,75	0,08	6,75	0,11	6,75	0,11	6,75	0,13	6,75	0,10	6,75	0,11	6,75
0,12	11,25	0,13	11,25	0,16	11,25	0,11	11,25	0,14	11,25	0,13	11,25	0,17	11,25	0,15	11,25	0,14	11,25	0,13	11,25
0,16	22,50	0,16	22,50	0,20	22,50	0,18	22,50	0,17	22,50	0,17	22,50	0,18	22,50	0,20	22,50	0,18	22,50	0,20	22,50
0,20	33,75	0,21	33,75	0,27	33,75	0,21	33,75	0,21	33,75	0,22	33,75	0,22	33,75	0,23	33,75	0,20	33,75	0,71	33,75
0,24	45,00	0,28	45,00	0,33	45,00	0,26	45,00	0,28	45,00	0,25	45,00	0,27	45,00	0,25	45,00	0,27	45,00	0,89	45,00
0,25	120,00	0,39	99,55	0,41	73,13	0,32	114,23	0,32	111,67	0,28	45,00	0,31	145,00	0,31	45,00	0,48	48,57	1,00	58,64
0,50	96,00	0,50	133,64	0,50	111,67	0,50	99,17	0,50	82,50	0,50	45,00	0,50	88,42	0,50	92,37	0,50	45,00	1,25	45,00
0,75	117,00	0,75	111,00	0,75	81,00	0,75	108,00	0,75	54,00	0,75	63,00	0,75	45,00	0,75	66,00	0,75	45,00	1,50	45,00
1,00	102,00	1,00	102,00	1,00	114,00	1,00	78,00	1,00	45,00	1,00	93,00	1,00	45,00	1,00	45,00	1,00	54,00	1,75	45,00
1,25	132,00	1,25	129,00	1,25	99,00	1,25	45,00	1,25	45,00	1,25	72,00	1,25	45,00	1,25	45,00	1,25	45,00	2,00	45,00
1,50	153,00	1,50	141,00	1,50	96,00	1,50	45,00	1,50	45,00	1,50	45,00	1,50	45,00	1,50	63,00	1,50	45,00	2,25	45,00
1,75	174,00	1,75	156,00	1,75	129,00	1,75	45,00	1,75	45,00	1,75	45,00	1,75	54,00	1,75	84,00	1,75	84,00	2,50	45,00
1,95	232,50	2,00	174,00	2,00	138,00	2,00	60,00	2,00	57,00	2,00	45,00	2,00	96,00	2,00	72,00	2,00	78,00	2,75	57,00
		2,18	253,33	2,25	162,00	2,25	96,00	2,25	99,00	2,25	81,00	2,25	132,00	2,25	57,00	2,25	108,00	3,00	78,00
				2,50	174,00	2,50	102,00	2,50	90,00	2,50	75,00	2,50	135,00	2,50	45,00	2,50	99,00	3,25	63,00
				2,67	265,59	2,75	108,00	2,75	132,00	2,75	51,00	2,75	189,00	2,75	45,00	2,75	123,00	3,50	45,00
						3,00	126,00	3,00	138,00	3,00	57,00	2,89	312,86	3,00	45,00	3,00	138,00	3,75	45,00
						3,25	138,00	3,25	174,00	3,25	81,00			3,25	93,00	3,25	153,00	4,00	81,00
						3,42	265,59	3,40	295,00	3,50	108,00			3,50	102,00	3,47	215,45	4,25	90,00
										3,75	144,00			3,75	123,00			4,50	78,00
										3,92	265,59			4,00	144,00			4,75	114,00
														4,17	265,59			5,00	108,00
																		5,25	156,00
																		5,50	147,00
																		5,75	168,00
																		5,95	232,50

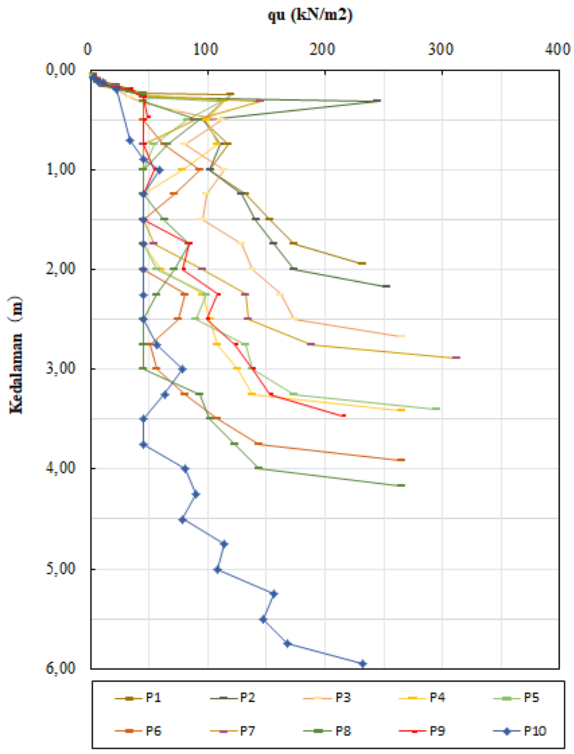

Figure 7. Relationship Between qu Value and Depth

LIQUEFACTION POTENTIAL EVALUATION METHOD

To obtain accurate analysis results, the researcher used three methods to evaluate the potential for soil liquefaction. These methods involve calculating the factor of safety (FS) based on the values of CSR and CRR.
Determining the Factor of Safety (FS) Based on CSR (Cyclic Stress Ratio) and CRR (Cyclic Resistance Ratio)
To calculate the factor of safety (FS), both CSR and CRR values are needed. These values are used in a ratio to serve as parameters for determining whether a soil is susceptible to liquefaction or not. In this evaluation, the N-SPT value is used, which is a converted result from the SWS (Swedish Weight Sounding) test.
1. Determining the Cyclic Stress Ratio (CSR)
To determine the CSR value, various parameters are required, one of which is the peak ground acceleration (PGA) at the bedrock. This acceleration value can be determined based on the peak ground acceleration map at bedrock for each seismic region in Indonesia, published by the National Earthquake Study Center (Pusat Studi Gempa Nasional) in 2017. The zonation map is shown in Figure 8.

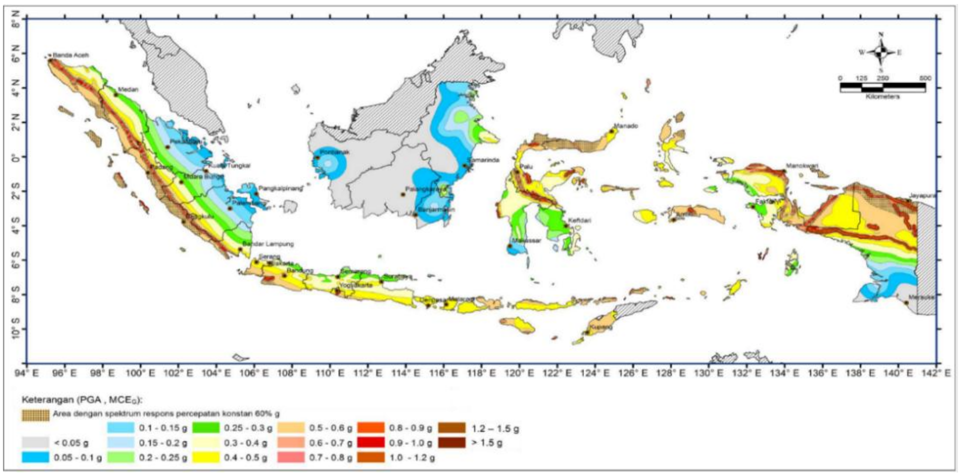

Figure 8. Earthquake Zonation Map of Indonesia – 2017

Based on the 2017 earthquake zonation map of Indonesia, and according to the Earthquake Study Report of the Palu Earthquake, Central Sulawesi Province, September 28, 2018 (Magnitude 7.4) conducted by the National Earthquake Study Center team, the obtained values were: Horizontal vector acceleration: 333 gal Vertical vector acceleration: 335 gal Note: 1 gal = 0.001 g, or 1 g = 981 gal Thus, after conversion: 0.34149 g
Based on the calculation above, the value of FS = 0.57 < 1, indicating that the soil is potentially susceptible to liquefaction.

The calculation results at Point P-2 at various depths can be seen in Table 20. Meanwhile, the calculation results from Point P-2 to Point P-10 at various depths are also presented.

Table 7. Results of FS (Factor of Safety) Calculation at Point P-2 with amax = 0.34 g and Earthquake Magnitude of 7.4 Mw

TITIK P2																					
Kedalaman D (m)	Berat Isi (kN/m³)	σv (kN/m²)	σ'v (kN/m²)	rd	Pa (kN/m²)	a max (g)	g (m/s²)	CSR	N-SPT	(N1)60	FC (%)	α	β	(N1)60 CS	CRR7.5	MSF	f	Kσ	CRRMw	FS	Keterangan
0,07	16,51	1,16	0,47	1,00	101	0,34	9,81	0,54	0	0	9,41	0,68	1,02	0,78	0,06	1,03	0,83	2,18	0,14	0,27	Berpotensi Likuefaksi
0,10	16,51	1,65	0,67	1,00	101	0,34	9,81	0,54	0	0	9,41	0,68	1,02	0,68	0,07	1,03	0,82	2,06	0,14	0,26	Berpotensi Likuefaksi
0,13	16,51	2,15	0,87	1,00	101	0,34	9,81	0,54	1	1	9,41	0,68	1,02	1,16	0,07	1,03	0,82	1,97	0,14	0,25	Berpotensi Likuefaksi
0,16	16,51	2,64	1,07	1,00	101	0,34	9,81	0,54	1	1	9,41	0,68	1,02	1,70	0,07	1,03	0,82	1,92	0,14	0,25	Berpotensi Likuefaksi
0,21	16,51	3,47	1,41	1,00	101	0,34	9,81	0,54	2	2	9,41	0,68	1,02	2,21	0,07	1,03	0,82	1,85	0,14	0,25	Berpotensi Likuefaksi
0,28	16,51	4,62	1,88	1,00	101	0,34	9,81	0,54	2	2	9,41	0,68	1,02	2,72	0,07	1,03	0,81	1,77	0,14	0,25	Berpotensi Likuefaksi
0,39	16,51	6,44	2,61	1,00	101	0,34	9,81	0,54	7	7	9,41	0,68	1,02	7,68	0,10	1,03	0,78	1,82	0,19	0,36	Berpotensi Likuefaksi
0,50	16,51	8,26	3,35	1,00	101	0,34	9,81	0,54	10	10	9,41	0,68	1,02	10,78	0,12	1,03	0,76	1,81	0,23	0,43	Berpotensi Likuefaksi
0,75	20,13	13,29	10,84	0,99	101	0,34	9,81	0,27	8	8	9,41	0,68	1,02	8,72	0,11	1,03	0,78	1,57	0,18	0,66	Berpotensi Likuefaksi
1,00	20,13	18,32	13,42	0,99	101	0,34	9,81	0,30	7	7	9,41	0,68	1,02	7,60	0,10	1,03	0,78	1,45	0,16	0,52	Berpotensi Likuefaksi
1,25	20,13	23,35	16,00	0,99	101	0,34	9,81	0,32	10	10	9,41	0,68	1,02	10,36	0,12	1,03	0,77	1,41	0,18	0,55	Berpotensi Likuefaksi
1,50	20,13	28,39	18,58	0,99	101	0,34	9,81	0,33	11	11	9,41	0,68	1,02	11,45	0,13	1,03	0,76	1,36	0,18	0,54	Berpotensi Likuefaksi
1,75	20,13	33,42	21,16	0,99	101	0,34	9,81	0,34	12	12	9,41	0,68	1,02	12,82	0,14	1,03	0,75	1,32	0,19	0,55	Berpotensi Likuefaksi
2,00	20,13	38,45	23,74	0,98	101	0,34	9,81	0,35	14	14	9,41	0,68	1,02	14,46	0,15	1,03	0,74	1,28	0,20	0,57	Berpotensi Likuefaksi
2,18	20,13	42,07	25,59	0,98	101	0,34	9,81	0,36	21	21	9,41	0,68	1,02	21,68	0,23	1,03	0,70	1,31	0,31	0,86	Berpotensi Likuefaksi

Note: The depth of 2.00 m is used as an example for the calculation.

PARTICLE SIZE ANALYSIS

The results of the laboratory tests in the form of particle size analysis provide an overview of the soil characteristics under investigation. These characteristics are useful in determining whether the soil has the potential for liquefaction or not.

Tsuchida (1970) provided criteria for soil characteristics that are susceptible to liquefaction through a grain size distribution curve. The test results obtained from the particle size analysis, when correlated with the grain size distribution curve according to Tsuchida (1970), are shown in Figure 9.
Let me know if you want the content formatted for a report or presentation, or if you want help translating Table 7, Table 10, or Figure 9 as well.

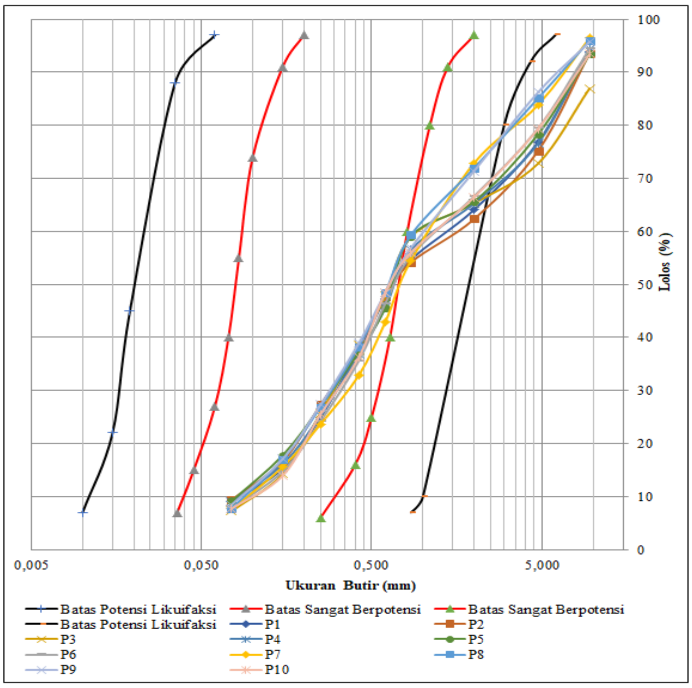

Figure 9. Grain Size Distribution Curve According to Tsuchida (1970)

Table 8. Liquefaction Potential at Points P1–P10 Based on the Tsuchida Method

Titik	Sangat Berpotensi Likuefaksi (%)	Berpotensi Likuefaksi (%)	D50 (mm)
P1	43,1	68,1	0,700
P2	58,5	65	0,700
P3	60,8	59,8	0,700
P4	46	69	0,750
P5	49	73	0,700
P6	45,1	74,1	0,700
P7	44,3	80,3	0,800
P8	50,2	81,2	0,650
P9	46,5	83,5	0,650
P10	47	75	0,650

Based on Figure 9. which shows the grain size distribution curve according to Tsuchida (1970), it was found that at points P-1 to P-10, most samples fall within the red boundary curve, which indicates a high potential for liquefaction. Some gradation curves fall within the black boundary, which still indicates potential for liquefaction.

To determine the characteristics of the soil, grain size analysis results are correlated with Atterberg limits. Based on the Unified Soil Classification System (USCS), all samples from the test points fall into the sand category, since all soils had less than 50% passing the No. 200 sieve. Therefore, the soil type at all points from P-1 to P-10 is sand.

ATTERBERG LIMITS

In addition to grain size analysis, Atterberg limits testing can also be used to determine the characteristics of the soil being studied and to identify soil criteria that are potentially susceptible to liquefaction. There are two methods commonly used to analyze liquefaction potential using Atterberg limits data.

However, since Atterberg limits testing could not be conducted on the samples from this site (i.e., no Liquid Limit (LL) or Plastic Limit (PL) values were obtained), then based on this method, points P-1 to P-10 are considered to fall within Zone A, by assuming LL = 0%, PL = 0%, and PI = 0%.

In addition to grain size analysis, Atterberg limit tests are used to evaluate the soil's characteristics and potential for liquefaction. Two methods are typically used in this analysis. However, in this case, Atterberg limits could not be obtained for the samples (no LL or PL values). Therefore, it is assumed that:

SWEDISH WEIGHT SOUNDING

Field tests using the Swedish Weight Sounding (SWS) method produced results. These tables provide the Nsw values (number of half-turns), with an average Nsw value of 79.46 n/m across all test points. In Table 9, the allowable bearing capacity (qa) was calculated, with an average of 62.56 kN/m². In Table 10, the unconfined compressive strength (qu) was calculated, with an average of 76.03 kN/m².

These averages indicate that if a soil layer has Nsw, qa, or qu values below the average, it is more likely to be susceptible to liquefaction, compared to layers with values above the average. The highest values of Nsw, qa, and qu for each test point were observed at the deepest penetration level, when the number of half-turns (Na) exceeded 50 rotations. These values increased significantly beyond the 50 Na threshold.

When penetration occurred at Na < 50, the Nsw, qa, and qu values were noticeably lower. If the depth at which Na = 50 is plotted across all points, the pattern is visualized in Figures 11 and 12.

Table 9. Liquefaction Potential Analysis Based on Na

Na	Parameter Rata-rata	Titik Pengujian									
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
< 50	Nsw (n/m)	110,29	132,39	97,04	9,39	54,68	33,33	63,57	37,20	49,29	43,91
	qa (KN/m²)	63,66	77,66	67,27	53,05	50,46	40,48	52,32	43,46	47,51	50,10
	qu (KN/m²)	78,12	91,13	81,21	67,68	65,25	55,79	67,11	58,54	62,48	64,62
> 50	Nsw (n/m)	172,00	277,78	294,12	294,12	333,33	294,12	357,14	294,12	227,27	250,00
	qa (KN/m²)	167,60	252,22	265,29	265,29	296,67	265,29	315,71	265,29	211,82	230,00
	qu (KN/m²)	174,00	253,33	265,59	265,59	295,00	265,59	312,86	265,59	215,45	232,50

This table presents the Nsw, qa, and qu values at each point, along with the average value at each test location. The threshold used is Na = 50 rotations. If the average values are below the threshold, liquefaction is more likely; If average values are above the threshold, the potential for liquefaction is lower.

LIQUEFACTION POTENTIAL ANALYSIS BASED ON FACTOR OF SAFETY (FS)

Based on the liquefaction potential calculations conducted using procedures agreed upon during the NCEER (National Center for Earthquake Engineering Research) workshops in 1996 and 1998, the Factor of Safety (FS) values were obtained. Table 20 presents a summary of the FS values at each test point, from Point P-1 to Point P-10, across various depths.

Meanwhile, Figure 10 shows the graphical relationship between FS values and soil depth at each test point.

Table 10. presents the summary of FS values for each point (P-1 to P-10) at all depths.

FS																			
P1		P2		P3		P4		P5		P6		P7		P8		P9		P10	
D (m)	FS	D (m)	FS	D (m)	FS	D (m)	FS	D (m)	FS	D (m)	FS	D (m)	FS	D (m)	FS	D (m)	FS	D (m)	FS
0,05	0,31	0,07	0,30	0,08	0,28	0,06	0,30	0,06	0,30	0,08	0,28	0,08	0,28	0,09	0,28	0,07	0,29	0,07	0,28
0,10	0,28	0,10	0,29	0,10	0,27	0,09	0,29	0,08	0,29	0,11	0,27	0,11	0,27	0,13	0,26	0,10	0,28	0,11	0,27
0,12	0,28	0,13	0,28	0,16	0,26	0,11	0,28	0,14	0,27	0,13	0,27	0,17	0,26	0,15	0,26	0,14	0,27	0,13	0,27
0,16	0,28	0,16	0,28	0,20	0,26	0,18	0,27	0,17	0,28	0,17	0,27	0,18	0,26	0,20	0,26	0,18	0,27	0,20	0,26
0,20	0,28	0,21	0,28	0,27	0,25	0,21	0,28	0,21	0,28	0,22	0,27	0,22	0,27	0,23	0,27	0,20	0,28	0,71	0,22
0,24	0,28	0,28	0,28	0,33	0,26	0,26	0,00	0,28	0,28	0,25	0,27	0,27	0,27	0,25	0,27	0,27	0,27	0,89	0,36
0,25	0,50	0,39	0,40	0,41	0,31	0,32	0,45	0,32	0,45	0,28	0,27	0,31	0,55	0,31	0,26	0,48	0,25	1,00	0,37
0,50	0,36	0,50	0,47	0,50	0,39	0,50	0,37	0,50	0,33	0,50	0,24	0,50	0,33	0,50	0,34	0,50	0,24	1,25	0,30
0,75	0,68	0,75	0,66	0,75	0,51	0,75	0,63	0,75	0,44	0,75	0,46	0,75	0,40	0,75	0,32	0,75	0,40	1,50	0,28
1,00	0,52	1,00	0,53	1,00	0,54	1,00	0,51	1,00	0,35	1,00	0,48	1,00	0,34	1,00	0,34	1,00	0,37	1,75	0,27
1,25	0,56	1,25	0,55	1,25	0,44	1,25	0,36	1,25	0,31	1,25	0,37	1,25	0,31	1,25	0,31	1,25	0,31	2,00	0,25
1,50	0,58	1,50	0,55	1,50	0,40	1,50	0,33	1,50	0,29	1,50	0,28	1,50	0,28	1,50	0,32	1,50	0,29	2,25	0,24
1,75	0,61	1,75	0,55	1,75	0,46	1,75	0,31	1,75	0,27	1,75	0,27	1,75	0,28	1,75	0,35	1,75	0,35	2,50	0,23
1,95	0,80	2,00	0,58	2,00	0,45	2,00	0,32	2,00	0,28	2,00	0,25	2,00	0,35	2,00	0,30	2,00	0,32	2,75	0,25
		2,18	0,87	2,25	0,49	2,25	0,39	2,25	0,35	2,25	0,31	2,25	0,42	2,25	0,26	2,25	0,37	3,00	0,28
				2,50	0,51	2,50	0,38	2,50	0,32	2,50	0,29	2,50	0,41	2,50	0,23	2,50	0,34	3,25	0,25
				2,67	0,82	2,75	0,38	2,75	0,40	2,75	0,24	2,75	0,53	2,75	0,23	2,75	0,38	3,50	0,21
						3,00	0,41	3,00	0,40	3,00	0,24	2,89	1,13	3,00	0,22	3,00	0,40	3,75	0,21
						3,25	0,43	3,25	0,48	3,25	0,28			3,25	0,30	3,25	0,42	4,00	0,26
						3,42	0,83	3,40	0,95	3,50	0,32			3,50	0,31	3,47	0,57	4,25	0,27
										3,75	0,38			3,75	0,34			4,50	0,25
										3,92	0,71			4,00	0,37			4,75	0,30
														4,17	0,69			5,00	0,29
																		5,25	0,36
																		5,50	0,34
																		5,75	0,38
																		5,95	0,51

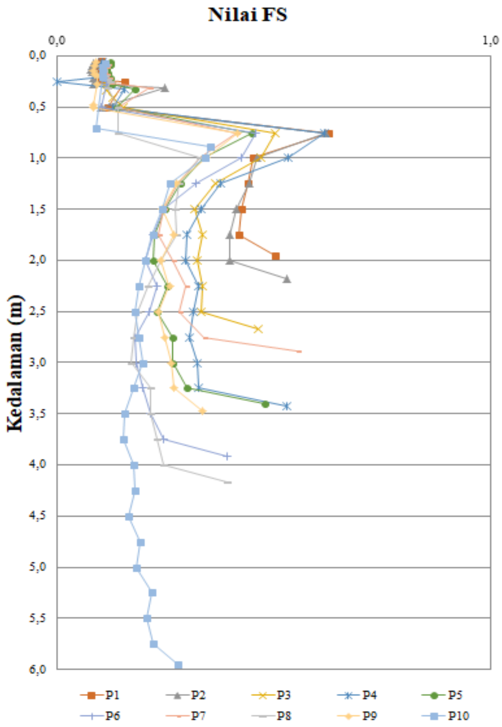

Figure 10. Relationship Between FS Values and Depth at Each Test Point with amax = 0.34 g and Earthquake Magnitude 7.4 Mw

Based on Table 20 and Figure 13, the results obtained at the final penetration depth for each point—P-1 through P-10—indicate a potential for liquefaction. This is because the FS values are below one, which means the soil is susceptible to liquefaction

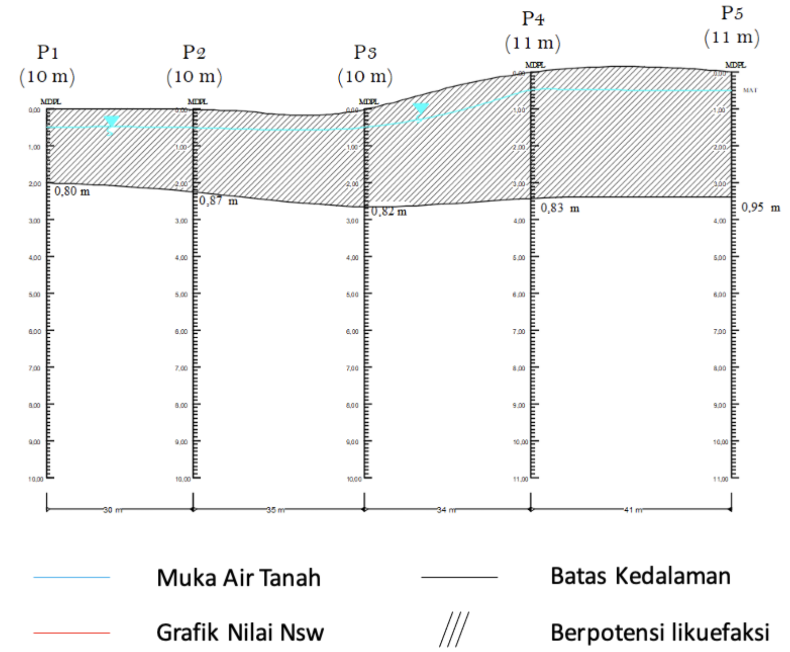

Figure 10. Liquefaction Zones at Points P-1 to P-5

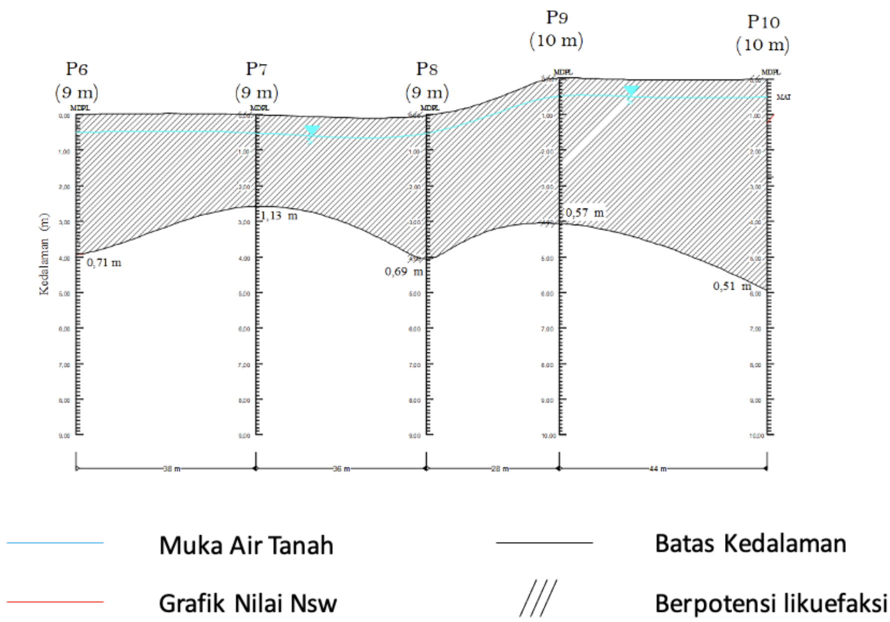

Figure 11. Liquefaction Zones at Points P-6 to P-10

IV. CONCLUSION

Based on the results of field and laboratory tests conducted at all test points in Matano Sub-district, the following conclusions can be drawn:

1. The soil characteristics obtained through Swedish Weight Sounding testing at ten test points produced three main parameters: Nsw, qa, and qu.
   Nsw values range from 0.00 to 294.12 n/m
   qa values range from 30.00 to 265.29 kN/m²
   qu values range from 2.25 to 295.00 kN/m²
   Based on the Unified Soil Classification System (USCS), the soil type at all test points (P1 to P10) is classified as sand.
2. From the Swedish Weight Sounding test results:

The average Nsw across all test points is 80.54 n/m
The average qa is 62.56 kN/m²
The average qu is 76.43 kN/m²
Soil layers with Nsw, qa, and qu values below the average are more susceptible to liquefaction compared to those with values above the average.

The liquefaction potential, based on grain size distribution curves using Tsuchida's liquefaction criteria, showed that: Some curves fall within the red zone, indicating very high liquefaction potential Others fall within the black zone, indicating potential for liquefaction Using the Modified Chinese Method, all test points were found to have liquefaction potential. Based on the Swedish Weight Sounding test results, in general, the Factor of Safety (FS) is less than 1, indicating that Points P1 to P10 are susceptible to liquefaction, as shown in the FS table. From the various methods used to analyze liquefaction potential, it can be concluded that all reviewed points are potentially susceptible to liquefaction at depths less than 10 meters, under a seismic acceleration (amax) of 0.15 g and earthquake magnitude of 5 Mw

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