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Spatially Distribution of Soil Ultimate Bearing Capacity at Singkil-Aceh Based on a Static Cone Penetration Test

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Abstract – The Singkil Sub-district of Aceh Singkil District comprises alluvium deposits with a relatively low ultimate bearing capacity. The ultimate bearing capacity of the soil is closely related to the safety of a building. The important thing related to estimating the ultimate bearing capacity of the soil is in-situ soil investigation. This study aims to estimate the spatial distribution of soil ultimate bearing capacity using field test data in the Singkil Sub-district. Estimating ultimate bearing capacity is useful to provide an initial picture for various planning and infrastructure development activities in the study area. Twenty CPT in-situ tests have been obtained from various field works in Aceh Singkil Regency. Field data analysis, based on empirical methods, was carried out to obtain the value of the ultimate bearing capacity of the soil at the test location. Then, the estimated distribution of the maximum bearing capacity obtained was carried out. The zoning map of the distribution of soil ultimate bearing capacity in the study was developed from this research. This map can be used as a form or effort of disaster mitigation by various stakeholders involved in planning and building various infrastructure facilities in the Singkil Sub-district.

Keywords: Ultimate Soil Bearing Capacity, Spatial Distribution, Singkil, In-Situ Test, Field Test.

Introduction

Morphologically, the area of Aceh Singkil Regency is in the coastal area, and the northern area is a plain area with a slope between 0% - and 8%. In areas away from the coast is a hilly area with a slope between 8% - and 30%. The condition of land elevation shows that Aceh Singkil Regency is between an altitude of 0-100 meters above sea level (masl). Most of the coastal areas are located at an altitude between 0-and 5 meters above sea level. Meanwhile, the conditions are relatively hilly in areas away from the coast, with an altitude between 5-100 meters above sea level.

Geomorphologically, the north-northeast part of Aceh Singkil Regency is an area with hilly physiography dominated by a hill system in folded hills. Between the hills, some rivers and tributaries flow to the Indonesian Ocean. The physiography consists of alluvial plains of rivers and sea sand deposits in the south-southwest, most of which are unique swamp ecosystems. In addition, there are also organic soils and peat. In the southern part, Aceh Singkil areas are generally dominated by limestone and sand deposits.

Consequently, the southern part of the Aceh Singkil District is an area with a carrying capacity that varies from medium to poor. In addition, the northern part adjacent to the river in the Aceh Singkil District area is an area that is prone to erosion because most of the soil-forming material consists of parent material in the form of clay, limestone, and quartz sand. Some regions of Aceh Singkil District are prone to tidal waves and coastal abrasion.

Based on the general geological map covering the study location is shown in Figure 1. Aceh Singkil Regency mainly comprises one formation and one rock unit, namely the Tutut Formation and the Quaternary Alluvium rock unit. The Tutut Formation consists of a conglomerate of sandstone, slightly siltstone, and mudstone (Cameron *et al.*, 1983). According to Wijaya & Hidayat (2007), the Tutut Formation is compact, easily destroyed. Alluvium units of Holocene age with constituents of coarse sand to clay and organic material.

As described above, the carrying capacity of the soil in Aceh Singkil Regency is estimated to be moderate to poor. Therefore, subsurface research on soil parameters in Singkil, Aceh Singkil Regency needs to be carried out. Investigation into subsurface conditions of a place is a prerequisite for planning building construction elements. This investigation is also necessary to obtain sufficient information about an economical design for a proposed project. Soil exploration aims to obtain sub-surface details about the planning of civil building foundations where exploration activities include soil drilling, soil sampling, field testing (Eslami *et al.*, 2011), laboratory testing, and groundwater observation. The objectives of conducting soil exploration are, among others: a). To determine the natural conditions and soil layers in the location under review; b). To obtain undisturbed and disturbed soil samples for visual identification of soils and conducting necessary laboratory tests; c). To determine the depth of hard soil, if possible, found to the maximum depth deemed necessary; d). To conduct field tests (in situ tests) such as static cone penetration test (known as sondir in Indonesia), seepage test, vane shear test, and standard penetration test; e). To observe water flow (soil) to subsurface and from the land location, and f). To study the possibility of specific problems of building behavior that already existed in the vicinity of the site.

A field investigation is essential to decide whether a proposed engineering work is feasible and economically sufficient to plan. Soil exploration is necessary to analyze the safety or collapse cases of existing works, select materials, and determine construction methods to be carried out.

Soil bearing capacity is the maximum strength of the soil to withstand pressure (due to building loads) properly without causing failure. Failure of soil is an excessive settlement or shear failure (inability) of the soil to resist shear forces. To carry the load onto the soil layer, the foundation is designed keeping in mind the limits of the strength of the soil supporting the building (Leshchinsky, 2015; Raj *et al.*, 2018; Castelli & Motta, 2010). If the load increases, the shear stress reaches the limit value where the soil mass will deform and fail (Chakraborty & Mahesh, 2016; Zhou *et al.*, 2018; Georgiadis, 2010; Cinicioglu & Erkli, 2018). The load that causes failure is called the failure load and the pressure that occurs is called the ultimate soil bearing capacity (Xiao *et al.,* 2018a; Xiao *et al.*, 2018b; Xiao *et al.*, 2019a; Xiao *et al.*, 2019b).

In other words, the bearing capacity of the soil is the ability of the soil to carry out the maximum pressure or load allowed to work on the foundation (Ansour *et al.*, 2016; Eslami *et al.*, 2011; Moshfeghi & Eslami, 2018). In the foundation design, the magnitude of the load is divided by the safety factor. The value obtained is called the allowable earth stress. For the safety requirements, it is recommended that the safety factor of collapse due to maximum load is equal to 3. For less important structures, the safety factor may be taken less than 3. Safety factor 3 is very important to overcome the uncertainty of the subgrade conditions.

Based on this background, it is possible to find several problems related to environmental conditions at the study site, including a). What is the value of the bearing capacity of the soil in the study location based on field tests? And b). What is the spatial distribution of soil bearing capacity of the Singkil area, Aceh Singkil district using field test data obtained from field tests?

This study aims to estimate the bearing capacity of the soil in the Singkil area, Aceh Singkil district using field test data. The results of this study will provide a better understanding of the subsurface conditions at the study site. In addition, the technique proposed in this research will enable soil engineers to plan the necessary actions in various disaster mitigation efforts. The results of this study can also be used for further analysis of earthquake micro zonation in the study area.

In principle, the urgency of this research is in planning and implementing infrastructure development in the Singkil area, Aceh Singkil district. The contribution to this research will be realized in the form of outputs, among others: a) becomes the basis of civil engineers in planning an appropriate and economic dimension and cross-section of the foundation for construction development in Singkil, Aceh Singkil Regency; b) application of the using field tests in conducting analysis of soil bearing capacity; and c) adding references to implementers in the field of construction projects and mitigation strategies for existing buildings at the study site.

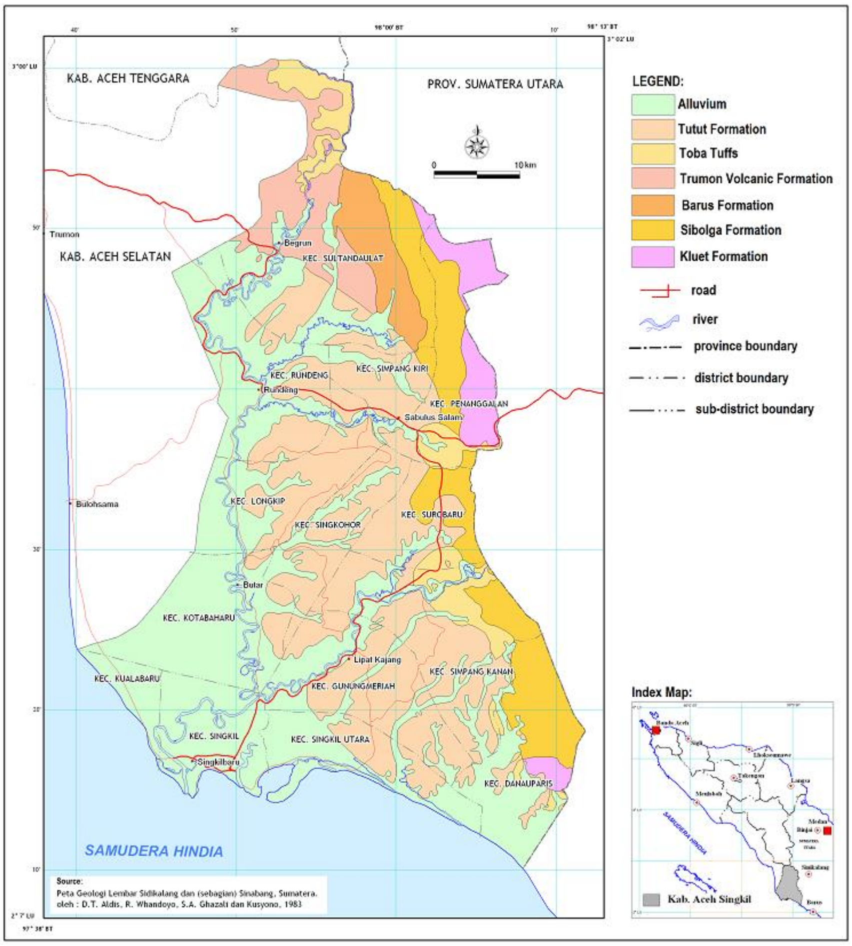

Figure 1. Geological regional of the study site

The research was designed according to the engineering principles contained in various references. The field test implementation method that will be used is a sondir test which refers to the method provided by the American Society for Testing Materials (ASTM D3441-75T) (Lunne *et al.*, 1997), "Tentative Method of Deep, Quasi-static, Cone and Friction-Cone Penetration Test of Soil." Sondir test was carried out to determine the cone resistance of the soil layer expressed in kg/cm^2 and the adhesive resistance expressed in kg/cm^2 (Yunita *et al.*, 2021).

The tool used in this static cone penetration test is a Dutch Penetrometer type instrument with a capacity of 2.5 tons which has a cone of 10 cm^2, a cone taper angle of 60^0 to measure the resistance of the tip, and is equipped with a sleeve with the same diameter as the cone with a blanket area of 100 cm^2 (Setiawan *et al.*, 2021). To measure the adhesive resistance of the soil layer in more detail, the equipment for this static cone penetration tester can be detailed as follows: a) Sondir tool 1 unit; b) Manometer scale 250 kg/cm2; c) Sondir iron pipe with a length of 1 meter complete with 20 rods; d) Biconus 1 piece; e) 4 ground fasteners, and e) Other equipment and materials.

The static cone penetration test implementation begins with cleaning around the test point carried out so that the static cone penetration device can be erected vertically. Then do the anchorage of the sondir tool so that the equipment during the test does not shake and remains upright. Static cone penetration testing work is carried out after the sondir rod pipe is connected to the bi-conus, and the test can only be started after the sondir tool is re-checked for perpendicularity and the gastrin oil is fully filled, and air bubbles from the hydraulics are removed. For collecting the data of cone resistance, local adhesive resistance, and total adhesive resistance, the pipe rod connected to the bice is mechanically pressed into the ground every 20 cm by rotating the handlebar of the sondir equipment with a standard speed of 20 mm/second and a maximum of 1 cm/second. These values are obtained from the readings of the static cone penetration manometer. Every 1-meter changes in depth, it is necessary to connect the pipe/rod sondir.

Materials and Methods

This research begins with the introduction and formulation of the problem, followed by a literature study. Additional data collection is carried out by contacting companies engaged in land investigation services. The data that has been collected is analyzed to provide useful results for solving research problems. The approach used in this research includes literature study and field testing. A literature study was conducted to gain a comprehensive initial understanding of the condition of the study area. In contrast, the field test was carried out to obtain primary data onto the field.

Desk study

Secondary data is collected at this stage. The licensing process is also carried out at this stage. All parameters used in the survey form were reviewed and studied. Existing data was also collected and further studied. After the parameters in the survey form are finalized, the recruitment process and debriefing training for surveyors in the field are also carried out at this initial stage. This briefing was carried out to obtain a common understanding of implementing survey forms in the field.

Data collection

The process of collecting field data is carried out in stages. Trained surveyors were mobilized in pairs. The collected field data will be directly checked by the researcher to be checked for completeness. If it is found that the value of the evaluation results by the surveyor is below the threshold, then the experts will check directly in the field. This follow-up evaluation will be used as additional data for the analysis of the bearing capacity of the soil. Complete data will be entered into the database simultaneously.

Data analysis

Data processing uses Microsoft-Excel software computing tools, and the results are displayed in the form of tables and graphs. A zoning map was created using AutoCAD software. The analysis carried out is the analysis of the carrying capacity of the soil at a depth of 1.4 meters and 2.4 meters. The purpose of the analysis is to determine the bearing capacity of the soil at a depth of 1.4 meters and 2.4 meters at the study site. Schmertmann (1977) proposed the bearing capacity of shallow foundation soils using s-CPT data, namely Meyerhof's (1956) formula, as follows:

$$\frac{q_a}{q_c} = \frac{B}{40}\left[\frac{1}{\frac{D}{B}}\right] \tag{1}$$

where q_a is the allowable bearing capacity (kg/cm^2), B is footing width (m); D is footing depth (m), and q_c is cone resistance (kg/cm^2). The calculation of bearing capacity analysis used in this study is a shallow square footing with a dimension of 1 x 1 meter. Two foundation depths of 1.40 mbgl and 2.40 mbgl are considered.

For shallow foundations (Hardiyatmo, 2002), the settlement estimation is based on the calculation of the distribution of stress due to loading with the 2V: 1H spread method (2 vertical units versus 1 horizontal unit), which can be illustrated in Figure 2 below.

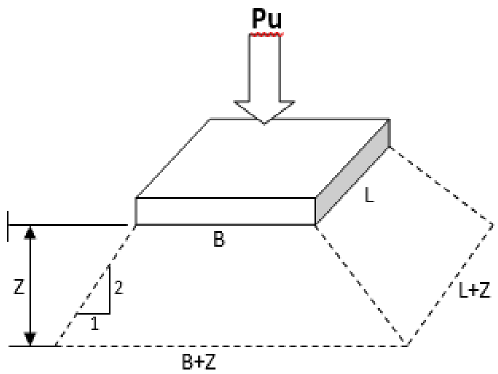

Figure 2. Illustration of stress distribution due to loading with 2V:1H distribution method (2 vertical units versus 1 horizontal unit)

The vertical stress increase at depth Z is:

$$\Delta P = \frac{P_u}{A_z} = \frac{P_u}{(B+Z)(L+Z)} \tag{2}$$

where: ΔP is the increase in vertical stress at depth Z (kg/cm²); P_u is working load (kg); A_z is the area at depth Z (cm2); B is footing width (cm); L is footing length (cm); dan Z is the depth of the point in terms of the base of the foundation tread (cm).

The magnitude of the decrease that occurs is calculated by the Sanglerat's equation (1972), namely:

$$S = \sum_i^n H_o \frac{\Delta P}{\alpha \overline{q}_c} \tag{3}$$

where: S is settlement total (cm); H_o is the thickness of the soil layer under consideration (cm); α is the compressibility coefficient of the soil layer where this value depends on the type of soil in the review layer, and q_c is the average cone tip resistance value in the soil layer under consideration (cm).

Table 1. Interpretation of soil relative density based on cone resistance for granular soil (Schmertmann, 1977)

No.	Cone resistance/CR (kg/cm²)	Relative density class
1	0 – 16	Very loose
2	16 – 40	Loose
3	40 – 120	Medium
4	120 – 200	Dense
5	>200	Very dense

Table 2. Interpretation of soil relative density based on cone resistance for low plastic cohesive soil (Olsen *et al.*, 1995; Robertson *et al.*, 1983; Shahri *et al.*, 2015)

No.	Net cone resistance (KPa)	Consistency
1	<275	Very soft
2	275 – 500	Soft
3	500 – 930	Medium stiff
4	930 – 1800	Stiff
5	>1800	Very stiff/hard

Calculation of stability against settlement is carried out for each layer of soil under the foundation footprint, where a review of the calculation of settlement is carried out in the middle of each soil layer. Based on the results of the cone penetration test, i.e., cone resistance data, the relative density/consistency of the soil layer can be interpreted. In the case of granular soil, the interpretation of the relative density can be from very loose to very dense, as shown in Table 1 (Schmertmann, 1977). For cohesive soil, the classification by Shahri *et al.*, 2015 can be applied. In the Indonesian common practice (Wesley, 1977), Standard Nasional Indonesia (SNI 2827:2008), the quasi-static CPT is terminated if three successive cone resistance readings reach 150 kg/cm². This 150kg/cm² cone resistance can be interpreted as a hard/dense layer (Schmertmann, 1977; Shahri *et al.*, 2015); Robertson *et al.*, 1983). Therefore, this 150 kg/cm² is adopted in this study to justify the depth of the hard/dense layer.

Results

The estimated depth of dense/hard layer

Data from the manometer reading on the CPT tool are cone resistance (CR) and total resistance (TR), which are expressed in units of kg/cm². From the two reading values, the sleeve friction (SF) is calculated. Using the hard/dense layer criteria, as mentioned above, the depth of the hard/dense level in each tested location is justified. The depth of stable soil at the study site varies from 6.2 meters to more than 13.2 meters below the existing ground level (mbgl), as shown in Table 3 and Figure 3.

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Table 3. Estimated dense/hard level in the study site

No.	Point	Location Coordinates		Depth of soil layer (m) with qc >150kg/cm2
		North	East	
1	MCPT#01	97.8174749	2.2695733	7.60
2	MCPT#02	97.8136852	2.2718631	8.60
3	MCPT#03	97.8152755	2.2733033	6.40
4	MCPT#04	97.8080117	2.2718505	11.60
5	MCPT#05	97.8107040	2.2819905	10.60
6	MCPT#06	97.8051052	2.2750283	10.60
7	MCPT#07	97.8091651	2.2756179	8.00
8	MCPT#08	97.8033145	2.2758776	10.20
9	MCPT#09	97.8071024	2.2786351	8.80
10	MCPT#10	97.8029752	2.2797124	8.20
11	MCPT#11	97.8046868	2.2835966	7.60
12	MCPT#12	97.8000901	2.2819744	7.80
13	MCPT#13	97.7957567	2.2825061	10.80
14	MCPT#14	97.7914812	2.2826937	10.40
15	MCPT#15	97.7907752	2.2845155	7.00
16	MCPT#16	97.7875812	2.2869981	7.60
17	MCPT#17	97.7840405	2.2857678	7.40
18	MCPT#18	97.7848220	2.2905724	7.00
19	MCPT#19	97.7768213	2.2853574	6.20
20	MCPT#20	97.7699904	2.2855554	13.20

Estimated ultimate bearing capacity

As aforementioned, soil ultimate bearing capacity analysis is based on the formula from Meyerhof (1956), as in Equation 1. In the following section, more emphasis is placed on the results of soil bearing capacity analysis of a 1 square meter foundation with a foundation depth of 1.40 mbgl and 2.40 mbgl.

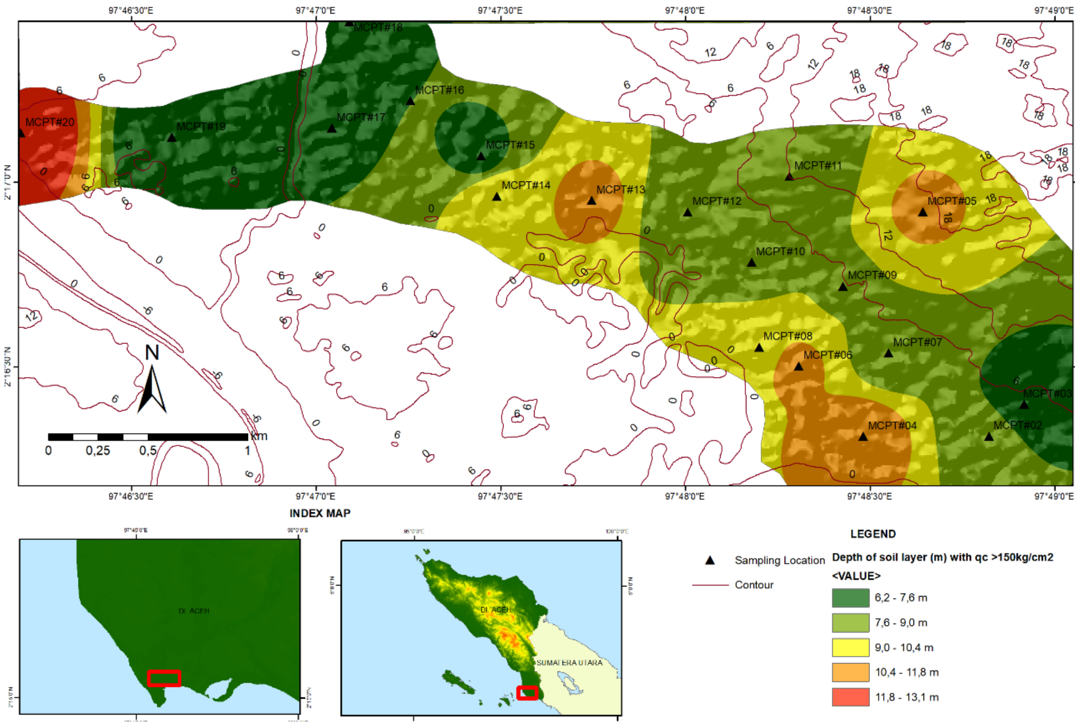

Figure 3. Estimated depth of dense/hard layer at the study site

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Table 4. Estimated ultimate bearing capacity and its total settlement at a depth of 1.2 mbgl.

No.	Point	Location Coordinates		At a depth of 1.2m below the ground surface	
		North	East	Estimated Ultimate bearing capacity (Ton)	Estimated total settlement (mm)
1	MCPT#01	97.8174749	2.2695733	9.17	7.99
2	MCPT#02	97.8136852	2.2718631	10.08	12.56
3	MCPT#03	97.8152755	2.2733033	7.33	7.37
4	MCPT#04	97.8080117	2.2718505	8.80	10.97
5	MCPT#05	97.8107040	2.2819905	2.20	6.99
6	MCPT#06	97.8051052	2.2750283	2.20	12.99
7	MCPT#07	97.8091651	2.2756179	7.33	14.94
8	MCPT#08	97.8033145	2.2758776	3.67	10.35
9	MCPT#09	97.8071024	2.2786351	5.50	7.26
10	MCPT#10	97.8029752	2.2797124	2.20	6.75
11	MCPT#11	97.8046868	2.2835966	1.10	8.41
12	MCPT#12	97.8000901	2.2819744	1.47	12.71
13	MCPT#13	97.7957567	2.2825061	11.00	17.11
14	MCPT#14	97.7914812	2.2826937	0.55	10.66
15	MCPT#15	97.7907752	2.2845155	1.47	8.19
16	MCPT#16	97.7875812	2.2869981	6.42	10.66
17	MCPT#17	97.7840405	2.2857678	8.25	12.14
18	MCPT#18	97.7848220	2.2905724	6.42	10.01
19	MCPT#19	97.7768213	2.2853574	3.30	10.39
20	MCPT#20	97.7699904	2.2855554	5.13	10.77

Estimated ultimate bearing capacity at 1.2 mbgl

The study area has a very variable ultimate bearing capacity at a depth of 1.4 mbgl. The study area is dominated by the ultimate bearing capacity of >7.5 ton/m^2. Detailed estimated ultimate bearing capacity at 1.2 mbgl at the study site is tabulated in Table 4. The area which has a bearing capacity of less than 7.5 tons/m^2 occupies the mid of the Singkil District, as presented in Figure 4.

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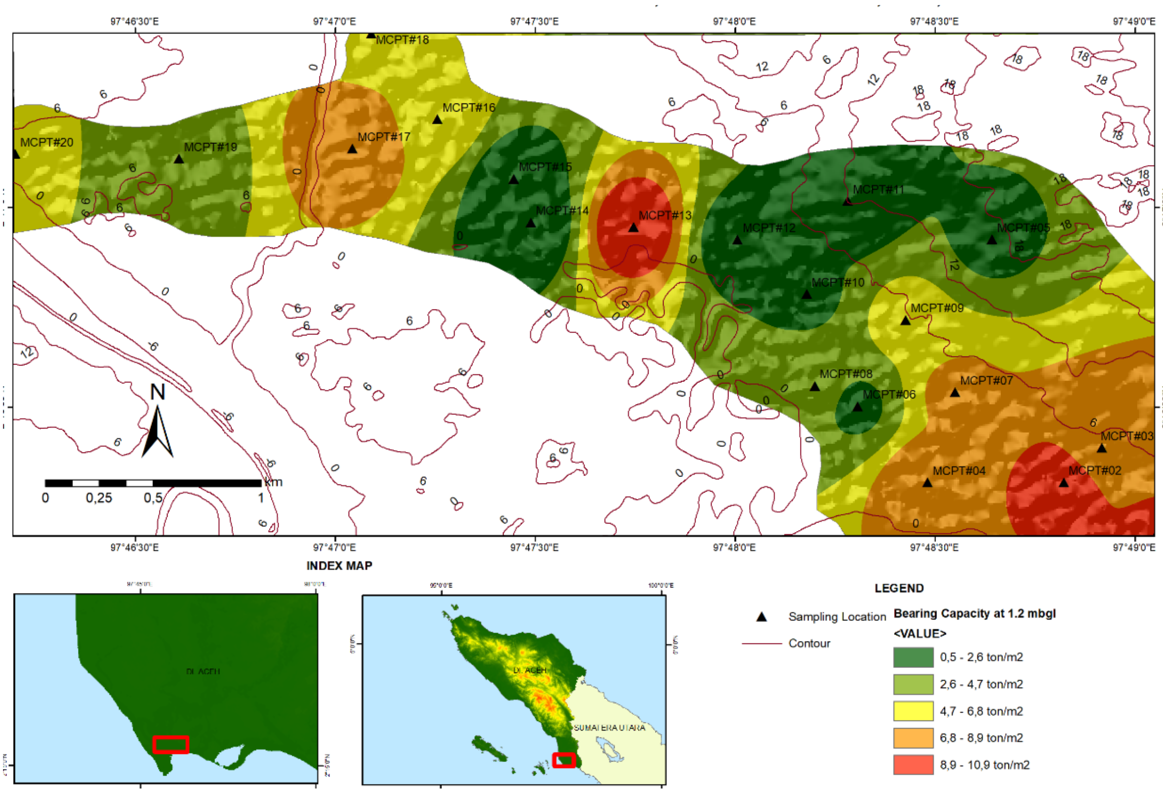

Figure 4. Estimated ultimate bearing capacity at 1.2 mbgl at the study site.

Estimated ultimate bearing capacity at 2.4 mbgl

The ultimate bearing capacity at the study site is dominated by less than 20 tons/m^2. Generally, a higher ultimate bearing capacity is suggested in the south area of the study site, as shown in Figure 5. Detailed estimated ultimate bearing capacity at 2.4 mbgl at the study site is presented in Table 5.

Table 5. Estimated ultimate bearing capacity and its total settlement at a depth of 2.4 mbgl.

No.	Point	Location Coordinates		At a depth of 2.4m below the ground surface	
		North	East	Estimated Ultimate bearing capacity (Ton)	Estimated total settlement (mm)
1	MCPT#01	97.8174749	2.2695733	36.83	17.98
2	MCPT#02	97.8136852	2.2718631	21.25	21.90
3	MCPT#03	97.8152755	2.2733033	29.75	16.48

Table 6. Depth of hard/dense layer of the present study.

No.	Depth of hard/dense layer of qc>150kg/cm^2 (m)	Frequency	Percentage
1	0.00 – 2.50	0	0.00
2	2.51 – 5.00	0	0.00
3	5.01 – 7.50	5	25.00
4	7.51 – 10.00	8	40.00
5	>10	7	35.00
	TOTAL	20	100

Table 7. Tabulation of ultimate bearing capacity of the present study.

No	Ultimate bearing capacity (ton/m²)	At 1.4 mbgl depth		At 2.4 mbgl depth	
		Frequency	**Percentage**	**Frequency**	**Percentage**
1	0.00 – 2.50	7	35.00	0	0.00
2	2.51 – 5.00	2	10.00	0	0.00
3	5.01 – 7.50	6	30.00	2	10.00
4	7.51 – 10.00	3	15.00	2	10.00
5	>10	2	10.00	16	80.00
	TOTAL	20	100	20	100

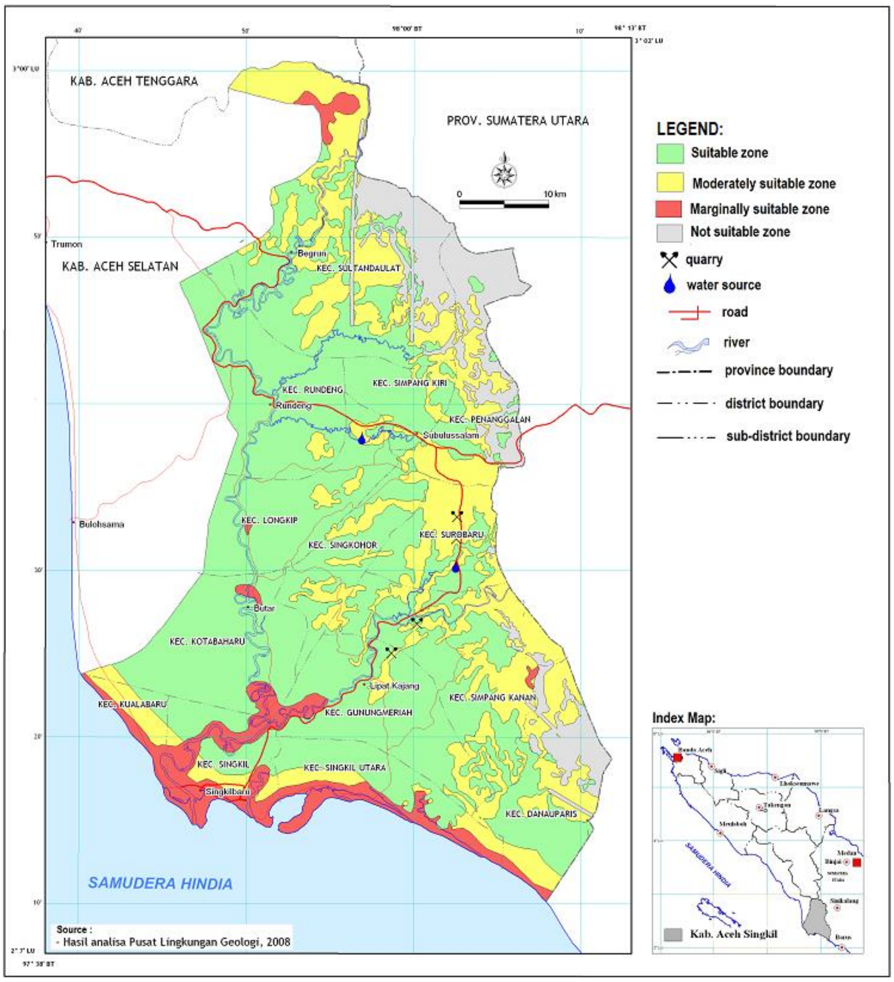

Figure 6. Land use recommendation at the study site.

Discussion

The depth of stable soil at the study site varies from 6.2 mbgl to 13.2 mbgl. Simple statistical analysis suggests that the majority depth of stable soil is > 7.50 meters below the existing ground level (mbgl) of 75.0%. At the study site, there is no stable soil layer found at depths of less than 5.0 mbgl. The depth of stable soil ranging from 5.0 to 7.5 mbgl has a percentage of 25% of the total 20 test points, while depths between 7.5 to 10.0 mbgl are 40.0%. The rest of 35% is found >10 mbgl. A detailed tabulation can be seen in Table 6 below.

In terms of ultimate bearing capacity, most of the areas in the study location have an ultimate bearing capacity of <2.5 tons/m² for a depth of 1.4 mbgl. The ultimate bearing capacity for the depth of 2.4 mbgl is mostly >10 tons/m². Detailed tabulation of the ultimate bearing capacity at the study site is presented in Table 7. A general land use recommendation for the study site was proposed by the Indonesian Environment Geology Office, as shown in Figure 6.

Conclusion

The spatial distribution of ultimate bearing capacity and the hard/dense layer depth at the Singkil (Indonesia) area has been estimated based on the 20 CPT data across the study site. Zoning for ultimate bearing capacity and the hard/dense layer depth at Singkil (Indonesia) has been carried out and presented. Generally, a higher ultimate bearing capacity is suggested at a depth of 2.4 mbgl. Due to soil variability, a factor of safety of 4.5 is recommended to calculate the allowable bearing capacity at the Singkil area. This study is still far from perfect, considering the very complex conditions of the underground surface at the study site, so a couple of suggestions are given: a) Adding more CPT testing points are suggested. These additional CPT tests will increase the resolution of the map. b). For more detailed results in future research, it is necessary to obtain soil samples through hand/machine drilling or other tools or other methods, i.e., passive seismic data analysis.

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