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Soft soils: A study on their electrical resistivity values and geotechnical properties (porosity, SPT and particle size distribution)

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Abstract: Soft soils pose abundant engineering issues due to its low bearing capacity and shear strength. Comprehensive study on soft soil's physical properties such as shear strength and ability to store water (porosity) could help in devising the optimum ground improvements and foundations techniques. Therefore, physical properties of soft marine clay in Nibong Tebal were thoroughly studied using 2-Dimensional Resistivity Imaging (2-DRI) method in conjunction with porosity measurements, standard penetration test values (SPT-n) and particle size distribution (PSD) analysis. The 2-DRI profile depicts three lithologies, which are unsaturated topsoil, saturated soft clayey soil and saturated sandy soil in the area. The soft soil extends up to 32 m in thickness where it overlies the sandy layer and could be correlated back to lithology profile from borehole record. Additionally, soil samples were collected at three locations along the survey line for porosity measurements via saturation porosimetry method. The samples demonstrate that the clay layer has a very large porosity range and signifies that the soil will compress tremendously under load. On the other hand, SPT-N values of the soft clay is also very low; thus, could be classed as very soft to soft cohesive soil with very low shear strength as compared to a higher range SPT-n values of the sandy layer. The PSD result also compliments the 2-DRI, porosity and SPT results to show distinct differences between topsoil and the soft clay layer in terms of the presence of fine grains. These results further indicate that the thick upper layer is not capable of bearing immense loads such as high-rise infrastructures due to the soil's high porosity and low shear strength. Hence, the area must undergo ground remediations prior to any infrastructure developments on the land.

Keywords: Soft soil, porosity, shear strength, excessive settlement, Nibong Tebal, SPT

INTRODUCTION

Soft soils are soils composed of fine clayey particles in conjunction with high water content in their pores; therefore, contributes to the soils' low shear strength and bearing capacity. In light of the extensive distribution of clay throughout the world, land instabilities are a common event especially in regions with high rainfall as the interaction between clay and water results in the disintegration of the clay (Diaz-Perez *et al.*, 2007; Tan, 2001). Soft soils cause many engineering problems due to excessive settlement of the soil during and after construction phases as soft soils have high compressibility and porosity (Mamat *et al.*, 2019).

For safety measures, porosity and permeability of soils are assessed prior to constructing infrastructures, slope protections, dams and bridges (Lambe & Whitman, 2008). Due to rapid urbanization in Malaysia, developers are beginning to utilise these problematic soft soils. This calls for a thorough understanding of soft soils' characteristics to assist researchers and practitioners in formulating optimum and cost-effective land remediations and foundation techniques prior to any construction process (Mamat *et al.*, 2019).

Therefore, this paper aims to characterize soft soil's physical properties such as electrical resistivity values, soil shear strength and ability to store water (porosity) using geophysical and geotechnical methods by conducting a study at Nibong Tebal.

STUDY AREA AND GEOLOGY

Nibong Tebal, Seberang Perai (Malaysia) is covered with soft marine clay deposits as a result from sea level transgression during Mid-Holocene (Hassan, 1990; Raj, 1992). This simultaneously hinders high rise infrastructure developments in the area.

The area sits on a relatively flat topography with less than 20 m height from sea level in a three-km radius. Submerged during Mid-Holocene high sea levels, the area has since become dry land after the retreat of the shoreline from its maximum inland position. The area is part of Parit Buntar Member (Gula Formation), which consists of soft-marine clay that could reach up to 15 m thickness deposited in marine and/or mangrove environment (Hassan, 1990; Raj, 1992). Figure 1 shows the geology of Nibong Tebal and its surroundings.

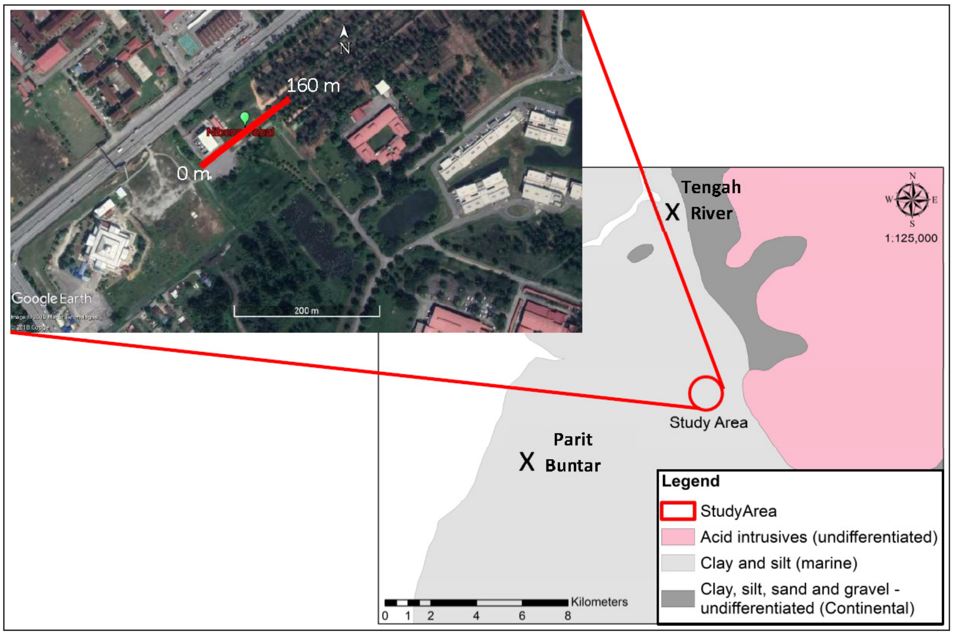

Figure 1: Orientation of resistivity line on site and the geology of its surrounding. (Department of Mineral and Geoscience Malaysia, 1985; Google Earth Pro, 2020).

METHODS AND MATERIALS

The geophysical survey was the primary method for this study where 2-Dimensional Resistivity Imaging (2-DRI) survey was chosen. The acquired 2-DRI data is supported by porosity data from hand auguring on site where porosity saturation technique was applied onto the soil samples. Standard penetrating test values (SPT-n) of the soil were also included.

Geophysical survey

Based on a simple four-electrode configuration, 2-DRI survey employed a multi-electrode resistivity meter system on 41 electrodes to increase the coverage area of the ground and the number of data acquired on site (Loke, 2004) such as illustrated in Figure 2. Using Schlumberger array configuration, a constant electrode spacing of 4 m was chosen to give a 160 m total length of the resistivity (Figure 3) where the line was designed to cut across an existing borehole. The measured 2-DRI data was then subjected to least-squares inversion in conjunction with a smooth constraint to obtain true resistivity values of the ground. From the 2-DRI profile, the extension of soft soil at Nibong Tebal site was distinguished prior to studying its physical characteristics from geotechnical methods.

Geotechnical methods

Geotechnical data executed in this study are porosity and SPT-n obtained from hand auguring and existing borehole record respectively in order to study the physical properties of soft soils. The borehole record was also used to verify the distribution of soft soil obtained from 2-DRI. Stainless Steel Soil Core Sampling Mini Kit, which consists of auger and soil core sampler, were used to collect undisturbed soil samples for porosity measurements via saturation porosimetry test for measured porosity, $\phi_{measured}$. This test is widely used by researchers including American Society for Testing and Materials (ASTM) Standard

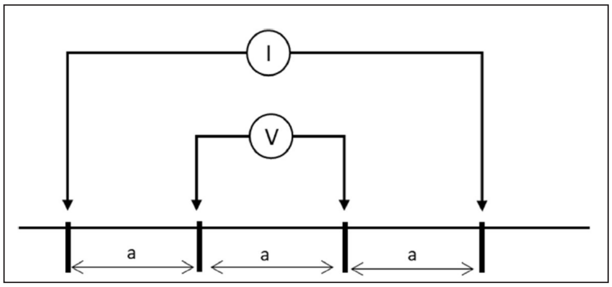

Figure 2: An electrical circuit based on four-electrode configuration used in the survey where *I* represents ammeter, *a* represents electrode spacing and *V* is the voltmeter (Loke, 2004).

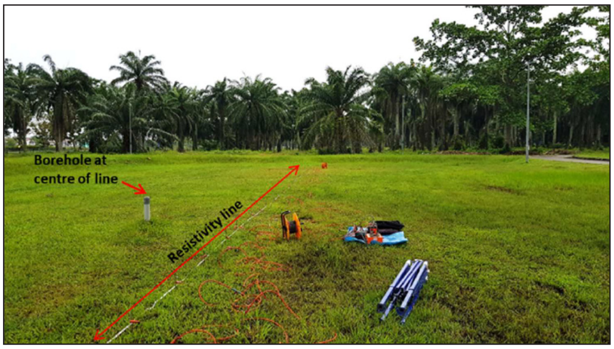

Figure 3: Resistivity survey conducted on site and the location of borehole relative to the line.

(2015), Kuila (2013) and International Society for Rock Mechanics (2007). As the samples are saturated, soil porosity was obtained based on the association between the saturated pores (void volume) and bulk volume of soil as shown in Eq. (1). By calculating the difference between the fully saturated and dehydrated (oven-dried), $\phi_{measured}$ was easily acquired.

$$\phi_{measured} = (\text{Void volume}(cm^3)) / (\text{Bulk volume}(cm^3)) \quad (1)$$

The samples were also subjected to particle size distribution (PSD) analysis, which consists of mechanical and wet sieving to determine the amount of fine grains in the soft soil. PSD analysis refers to the distribution of dry soil mass over a range of particle sizes based on Stokes' law where the produced PSD curve provides information on the percentage of fine grains (silt and clay) present in bulk of soil based on size classification. The preparation of samples for PSD analysis was conducted according to ASTM 2217 (1998) whereas hydrometer analysis and mechanical sieving follow ASTM D422-63 (2007). The combination of the two analyses produced a PSD curve where the distribution of grain sizes of soils was identified. The analysis was conducted only on samples that represent the saturated soil (depths 1.8 m, 2.8 m, and 3.8 m) to assess the presence of fine-grains in the saturated soil. Lastly, SPT-n of the soil were obtained from an existing borehole record where the bore hole is situated at the centre of the survey line.

RESULTS AND DISCUSSION

With RMS error of 5.7 %, the 2-DRI profile of the ground is considered accurate according to Oualid (2018) and Abdul-Nafiu *et al.* (2013). From the profile (Figure 4), the ground in this survey has low resistivity values ranging from nearly 0 – 1200 Ωm in the covered 32 m depth (Figure 4). The ground can be distinguished into three layers; unsaturated topsoil, saturated soft clayey soil and saturated sandy soil. The saturated soft soil was identified by its low resistivity values of ≤10 Ωm attributed to the high surface conductivity of the soil and its water-loving properties; therefore, causing the soil to be able to hold large amount of water in its pores.

The soft soil is situated beyond depths of 0.9 – 1.6 m from the ground surface with a thickness that reaches up to 32 m, varying along the survey line with unsaturated layer overlying this layer. Considering its thickness, the soft soil has high potential in causing engineering problems.

Three holes were augured along the 2-DRI survey line as illustrated in Figure 4. Undisturbed soil samples were first collected at 0.8 m depth while the subsequent sample collections were conducted at depth intervals of 1 m. The water table was at 1.15 m depth, which implies that all soft soil samples were in naturally saturated condition except for the soil samples at 0.8 m depth. The soil porosity, $\phi_{measured}$, results at Nibong Tebal were tabulated in Table 1. The results show that all soil samples at 0.8 m depth have distinctly different range of $\phi_{measured}$ values

Table 1: Porosity results depicting two soil types along the 3.8 m depth.

Distance of augured hole on line (m)	Depth of soil sample (m)	Porosity (%)	Average porosity of area (%)
61	0.8	40.3	38.0 (top soil) 66.9 (soft soil)
	1.8	58.4	
	2.8	70.1	
	3.8	69.6	
80	0.8	39.5	
	1.8	64.9	
	2.8	67.9	
	3.8	70.4	
89	0.8	34.1	
	1.8	55.4	
	2.8	73.3	
	3.8	71.9	

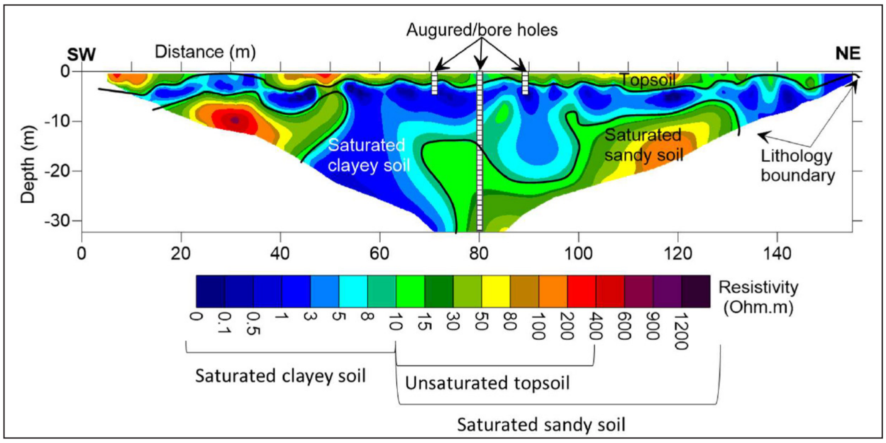

Figure 4: Identified soft soil distribution from 2-DRI result and the locations of augured and bore holes.

(34.05 – 40.29 %) as compared to those at deeper depths (55.4 – 73.3 %). Nearly twice larger in $\phi_{measured}$ values, this signifies that they are of different soil types, where the 0.8 m soil samples are the topsoil while the high porosity soil samples are the targeted soft clayey soil. This results strongly correlate with 2-DRI results in terms of soil profiling. Considering the immense porosity of the soft soil, this explains its low electrical resistivity property, which enables the soil to store immense pore water volume in its pores where the pore water occupies up to of the soft soil. The high conductivity of the pore water dramatically reduces the soft soil's resistivity readings.

Appearance-wise, the soft soil was easily differentiated from the topsoil in terms of colour and texture. Nibong Tebal's fine-textured soft soil is contributed by the high percentage of silt and clay. Its light grey colour with swampy smell also strongly suggests marine origin (Figure 5a). In contrast, the top soil is coarse-textured with reddish-brown colouring (Figure 5b). In addition, the whitish coloured particles in the topsoil sample are polystyrene; therefore, a proof of man-made soil for land stabilisation of the soft soil underneath.

The SPT-n result of the ground obtained from the borehole (Table 2) also agrees with 2-DRI and porosity results as three distinct soil layers having different soil stiffness could be identified; hence, validates each other.

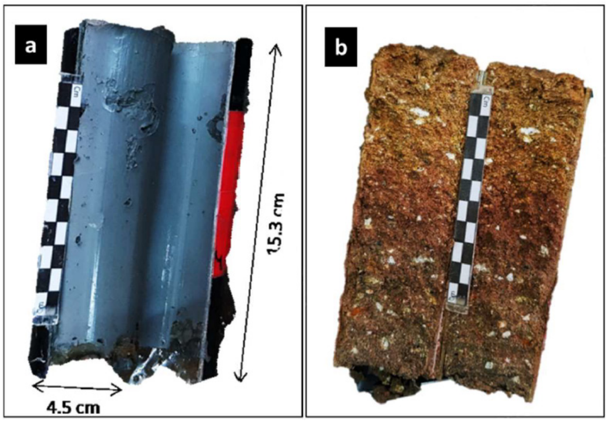

Figure 5: Undisturbed soil samples where a) shows smooth textured soft soil while b) have coarse-textured top soil layer with reddish-brown colouring.

With zero SPT-n value of the soft soil, this depicts its low bearing capacity to support immense load for building structures. Its inability to support buildings proves that optimum ground remediations and foundations are keys in development on soft soil lands.

Meanwhile, results on PSD analysis on the soil samples (Table 3) also supports the classification of the ground. Only the top most soil sample has fine grains of 42.3 % while deeper soil samples have significantly greater amount; 60.8 – 95.8 %. Making up almost the entire bulk of soil, the substantial amount of fine grains explains the high porosity values of the soft soil and the low SPT-n values.

Thick spatial distribution, high porosity and low bearing capacity of the soft soil are ingredients for soil failure. In its natural state, the soil holds a large amount of pore water in its pores. Stress introduced by load induces soil compression via soil rearrangement with pore water as a lubricant in this mechanism (Song *et al.*, 2017). The pore water is also simultaneously being expulsed out of the soil as porosity is reduced as illustrated in Figure 6. This results in land subsidence before finally causing building failure.

Table 2: SPT-n values of the subsurface showing soil strengths while verifying 2-DRI result of three-layer soils in Nibong Tebal.

Depth (m)	Type of soil	SPT-n
0 – 3	Medium stiff clay	6
3 – 15	Very soft clay	0
15 – 30	Medium dense sand	10 – 16

Table 3: PSD analysis results that shows distinct difference between top soil and soft soil in the terms of fine grains presence.

Depth (m)	Presence of particle size (%)	
	<75 µm (silt and clay)	≥75 µm (sand)
0.8	42.3	57.7
1.8	60.8	39.2
2.8	95.8	4.2
3.8	74.0	26.0

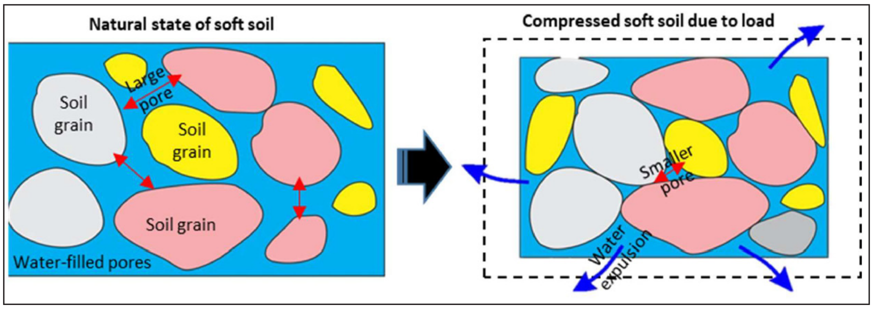

Figure 6: Effect of compression on soft soil where loss of soil volume occurs due to reduction of porosity and pore water.

CONCLUSION

At Nibong Tebal site, the saturated soft soil has very low electrical resistivity values (≤10 Ωm) as a result of large amount of pore water combined with its substantial amount of fine grains lowers the soil's resistivity values. The high porosity of the soil (55.4 – 73.3 %) provide space for pore water to occupy and lubricate soil rearrangement via compression when load is placed on top of the soil. This depicts that porosity plays a pivotal role on a material's bearing capacity.

Furthermore, zero SPT-n value and a thickness of up to 32 m, the soil's low bearing capacity cannot maintain its integrity after the structures are erected, especially high-rise buildings. This is attributed to the compaction of soils as they settle when immense load is introduced; therefore, inducing structural failures.

It is obvious that the area is covered with thick soft soil with high probability for excessive compression. Current soil remediations include soil chemical stabilizers or physically modify the soil via soft soil replacement, expedite pore water dissipation, insertions of prefabricated vertical drains and installation of stone column. However, better ground remediation techniques and foundation designs that are cost-efficient and reliable are still imperative in tackling soft soils. With these physical behaviours of soft soils, they could serve as a guide for researchers to formulate superior designs for soft soil developments to avoid structural damage and loss of lives.

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