CPTU Penetrations into the Marine Clays and Laterite Soils of Northwest Peninsular Malaysia

Mohamad R. Selamat, Dziaudin Z. Abidin, Muhammad Z. Yusoff, Ros N. Rosli, Muhd H. Ramli, Ashraf Q. Alkinani and Reda A. Abdelhalim

Abstract Site investigation penetrations by CPTU were carried out in Northwest Peninsular Malaysia to demonstrate the contrasting profiles between the marine clays of the coastal plains and the laterite soils of the inlands. From the findings, the trends of persistent low resistance with depth for the marine clays and fluctuating higher resistance with depth for the laterite soils were found quite consistent when evaluated in terms of either the cone resistance, sleeve friction, or standard penetration number. The CPTU interpreted behaviors for the various marine clays were clayey silt to silty clay, clay, sensitive fine grain, and silty clay to clay, to mention the most dominant ones, while for the underlying hard layer were sand and sand to silty sand. The CPTU interpreted behaviors for the laterite soils, among others, were silty clay to clay, clay, clayey silt to silty clay, silty sand to sandy silt, and sand to silty sand. In addition, the laboratory classification procedure, namely the Unified Soil Classification System, gave a different name for each of the CPTU interpreted behaviors, for the marine clays and for the laterite soils, which this paper shows and clarifies. The CPTU penetrations reaffirmed that the marine clays of the quaternary coastal plains are clayey and very soft while the laterite residual soils of the inlands are relatively more sandy and stronger.

Keywords Marine clays · Laterite soils · CPTU · Northwest Peninsular Malaysia · Coastal plains · Inlands

M. R. Selamat (✉) · D. Z. Abidin · M. Z. Yusoff · R. N. Rosli · M. H. Ramli · A. Q. Alkinani · R. A. Abdelhalim
School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Penang, Malaysia
e-mail: cemrs@usm.myz

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1 Introduction

Regional developments in Northwest Peninsular Malaysia which covers the states of Perlis, Kedah, Pulau Pinang, and Perak have been going over both, the coastal plains and the inlands. However, the coastal plains which occupy a third of the 32,000 km^2 total area are the more developed and crowded portion with the bigger cities of Penang, Butterworth, Alor Setar, Kangar, and Manjung located within. The inlands are relatively less developed but also consist of big cities such as Sungai Petani and Ipoh.

The coastal plains are underlain by various quaternary deposits which were formed under marine environments within the last 2.6 million years and unaffected by the plate tectonic movement [6]. The Gula formation which covers most of the plains consists mainly of the soft clays while the lesser Beruas and Simpang formations are made up mostly of peats, silts, sands, and gravels [6]. Tests carried out on soils on the ground of Engineering Campus, Universiti Sains Malaysia gave the general results of LL > 50% and PL < 50% which conform to results obtained by others such as Al-bared and Marto [1]. These high plasticity clays (CH) are comparatively very soft and are well known for being problematic as a foundation material.

As one travels to the interior, the plains gradually turn into the rainforest-clad inlands, the soils of which were formed by the various weathering processes, the main ones being the laterite soils. The abundant laterite soils of the inlands have become the choice fill material for projects on the coastal plains due to the favorable engineering properties.

A geological map showing the delineation between the coastal plains and the inlands is given in Fig. 1.

Development projects in the area have resulted in countless site investigation (SI) penetrations carried out either by the cone penetration with pore water pressure acquisition (CPTU) technology or the more traditional wash boring method. This paper attempts to generalize the results obtained from penetrating the marine clays on the coastal plains as compared to those obtained from penetrating the laterite soils on the inlands. The number of sites considered is numerous but the cases brought into discussion are limited to one representative from each ground, due to the limited space available for the discussion and presentation.

The discussion goes further by highlighting the discrepancies in interpreted soil names as produced by the CPTU system as compared to those resulted from classifying the soils based on the Unified Soil Classification Method (USCS). The study used results obtained mainly from running the CPTU however in the case where samples were said to have been extracted from the ground, this was only made possible from running the wash boring method.

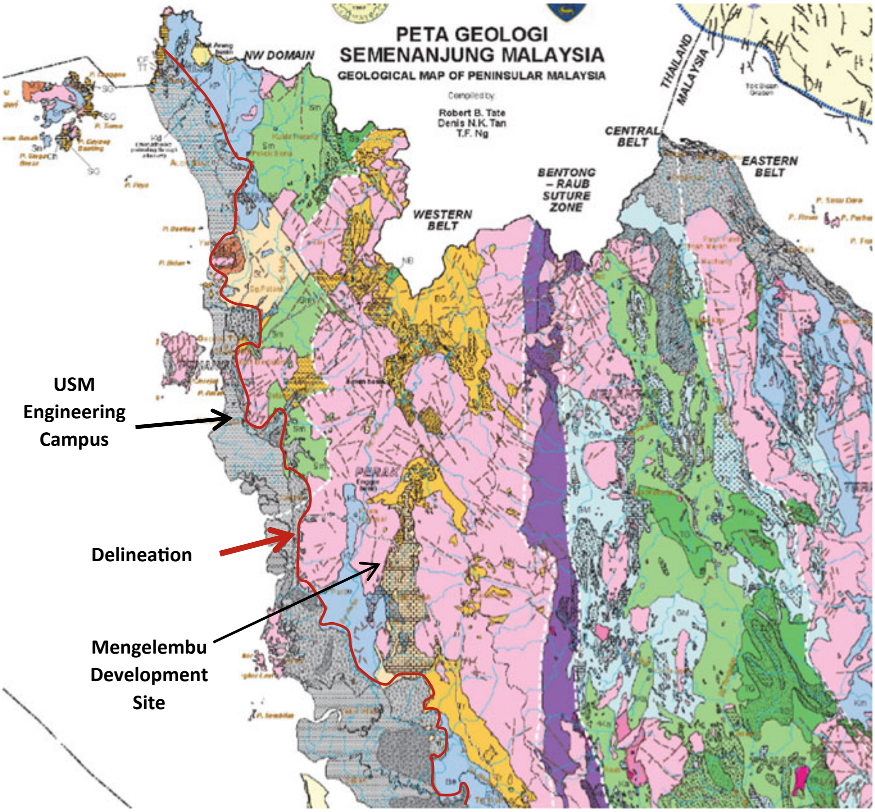

Fig. 1 A geological map showing the delineation marking the boundary of the quaternary coastal plains in Northwest Peninsular Malaysia

2 CPTU Versus Wash Boring

The CPTU has gained tremendous popularity due to its capability in providing results with greater details where soil type can be given for every cm of penetration however the wash boring is the more widely used method where samples can be retrieved and the personnel required to carry out the work can be the less trained ones. The CPTU and wash boring methods for SI have often been considered as options in a particular project; the fact is each one is better than the other in any particular work considered. In many projects, both procedures have been carried out together as complementary to each other.

In measuring the standard penetration number (SPT), the CPTU can be considered advantageous due to its electronic operation and as such the results are independent of the operator. On the other hand, in a wash boring procedure, the SPT measurement which involves counting hammer blows for each 30 cm penetration can be quite dependent on the operator which renders the repeatability and accuracy of the readings questionable.

The nature of a borehole washing in a wash boring procedure may also disturb and soften the bottom of a borehole therefore affecting the SPT count. When the ground is very soft, the veracity issue is manifest in the prolonged penetration of the SPT probe due to the inertia of the descending hammer. Such over measurement would interpret the soil to be even softer than it really is. The CPTU method would not be troubled by any induced softening by water because there is no washing involved. Instead, the CPTU provides a continuous and controlled penetration at a constant speed thus the probe does not penetrate by inertia or momentum.

The CPTU data can be said as intrinsically more legitimate for the theoretical interpretation, thus the better option, according to authors such as Kim et al. [3]. Having some advantageous said about the CPTU, the system however is not as robust as the wash boring especially in penetrating a deeper ground or a harder material. The CPTU furthermore is incapable of retrieving any sample from the depths which the wash boring method is designed for and so good at.

3 Methodology

USM's School of Civil Engineering operates a CPTU assembly in its commercial services. The main hydraulic penetration system is the crawler mounted Hyson 100 kN with F1L 208/210D diesel engine, provided by Apvandenberg, a Dutch firm. The data acquisition computer and program are the E4FCS, which together with the various CPTU cones were provided by Vertek-Hogentogler, a firm based in USA. The other parts include the depth counter and the diesel powered crawler. The complete assembly while in operation in the field is as shown in Fig. 2. The school also operates a wash boring machine by collaborating with local contractors.

For this study, the CPTU results for only one location on the coastal plains and another in the inlands were selected for analysis and presentation. The wash boring method was used to retrieve samples from one of the locations. It would not be convenient to involve a large number of sites despite the availability of penetration records as the evaluation of the results for each site was only possible to be carried out by manual observation. The two sites where the SI results were obtained from are given in Fig. 1—these are the USM Engineering Campus in Nibong Tebal and a proposed development site in Mengelembu, Perak. The location on the plains represents sites with marine clays while the location on the inlands represents sites with laterite soils. Furthermore, the profiles from both sites which were brought into discussion were equally cropped to consist of only the top 14 m to facilitate the comparative evaluation.

The characterizations of the penetration curves were entirely by description of the trends. The curves selected for the characterization were the cone resistance (q_t), the sleeve friction (f_s), and the interpreted Standard Penetration Number (SPTN). Parts of a cone that measure q_t and f_s are given in Fig. 3.

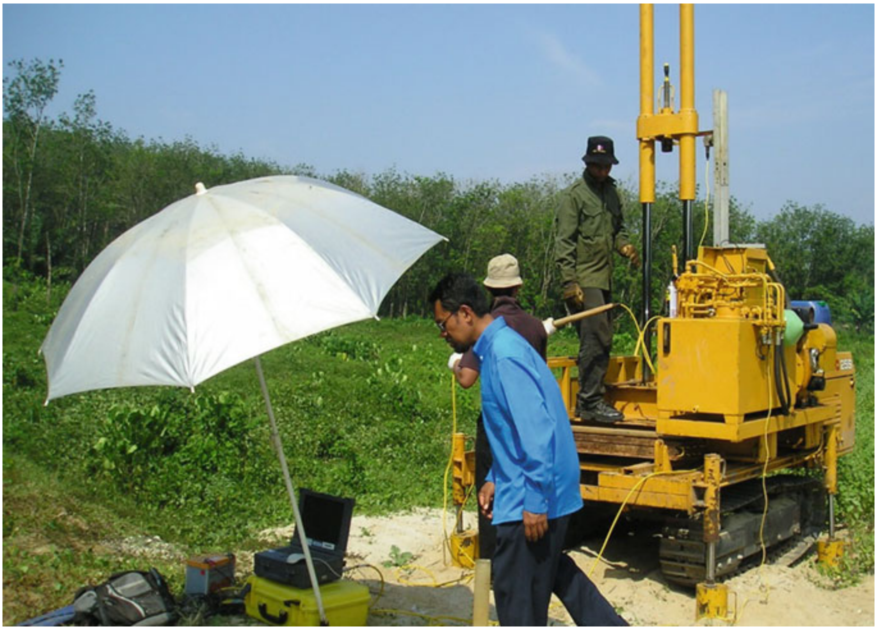

Fig. 2 CPTU assembly of the School of Civil Engineering, Universiti Sains Malaysia consisting of crawler mounted Hyson 100 kN penetration system and Vertek-Hogentogler data acquisition system

Note that q_t is the corrected version of q_c and still represents the cone resistance, however with a correction using Eq. (1):

$$q_t = q_c + u_2(1 - a) \tag{1}$$

where u_2 being the pore water pressure behind the cone and a being the cone area ratio, which amounts to 0.38 for the cone used in the study. Since the data coming from the CPTU method were acquired while advancing the cone, the depth difference between subsequent data acquisition is almost infinitesimal.

The characterization of the soils was by the mention of soil names as given by the CPTU system and as obtained from the lab soil classification procedure, based on the Unified Soil Classification System (USCS). In providing the latter, the tests carried out in the lab were mainly the sieve analysis and the Atterberg limits. The sieve and hydrometer analyses, Atterberg Limit test, specific gravity test, and moisture content test were carried out according to the British Standard - BS EN ISO 17892-12:2018 [2].

For the purpose of the paper, whenever marine clay is mentioned, it refers to the clayey portion of the quaternary deposits although generally the term is also used to include the sands as well. In providing soil names based on the USCS, for the

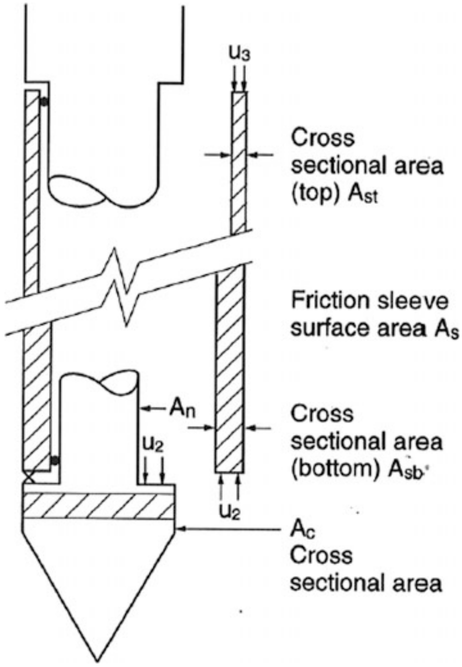

Fig. 3 Cone parts that measure q_c, f_s, and u_2 [5]

marine clays, split spoon samples were retrieved from a wash boring site not far from where the CPTU was carried out.

Whenever laterite soil is mentioned, it refers to the red residual soil, formed at site by the weathering process of the parent rock. In providing soil names based on the USCS, for the laterite soils, artificial samples with varying contents were produced by mixing with different amounts of sand in order to come up with soils of different names as would be identified either by the CPTU system or the lab soil classification procedure. The eventual names resulted from using the different methods for the same soils were then compared and the difference in each case was highlighted.

4 Results and Discussions

4.1 Soils Behaviour from CPTU

The cone resistance (q_t) for the marine clays and the laterite soils are respectively given in Fig. 4a, b. For the case, the marine clays are showing low and consistent cone resistance from 0.5 to 11.5 m deep. Over the top, the clays are overlain by a thin laterite fill which placement has become hardened. Down at the bottom, the clays are underlain by a strong sand layer which normally would provide a platform

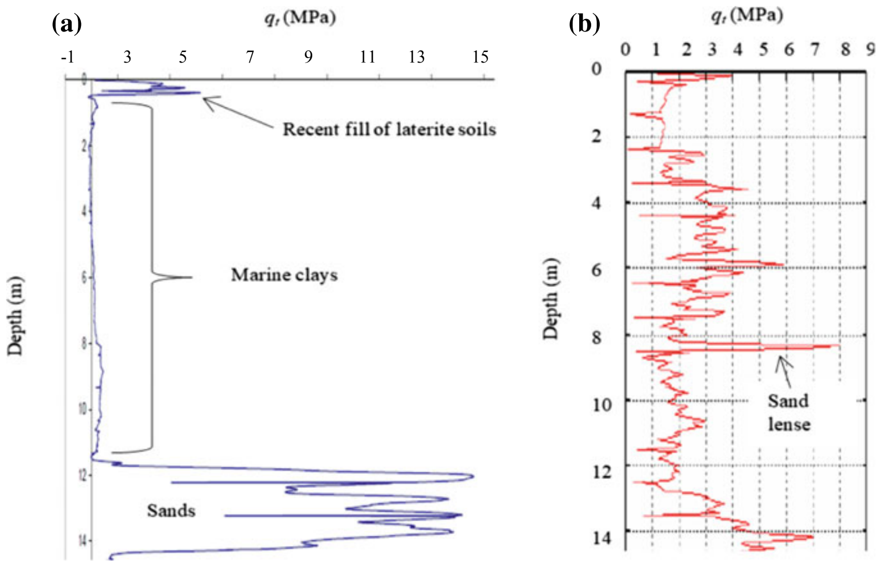

Fig. 4 CPTU result for q_t of the **a** quaternary deposit of USM Engineering Campus, **b** Mengelembu residual soil

for end bearing piles to rest upon if such foundation measures were employed. In the case of a Perforated Vertical Drainage (PVD) installation or fill or embankment placement over the top of the ground, the same sand layer provides the bottom drainage in the consolidation process of the marine clays. It is worth noting that in this case the cone penetration strengths amount to almost zero indicating the softness of the clays.

On the other hands, the laterite soils are showing higher and fluctuating penetration resistance for the entire 14 m depth. At 14 m, a relatively hard stratum was met by the penetration which could also provide a platform on which foundation piles can rest upon if such are used. In this case the cone penetration strengths amount to much higher average values in comparison to those of the clays, indicating the relative strength of the laterite soils.

The trends given by the sleeve friction (f_s) results are quite similar as those given by the q_t, for the clays and the laterite soils, as in Fig. 5a, b. A jump in the value of q_t is reflected by a similar jump in f_s, or vice versa. Thus the sleeve friction strength, like the cone resistance strength, is a function of the general soil strength. For the soft marine clays, the values given by q_t and f_s are quite consistent with depth; however, the situation is different with the laterite soils, where the trend is more erratic. This is probably due to the presence of coarser soil particles in the latter's case which led to the peak resistance.

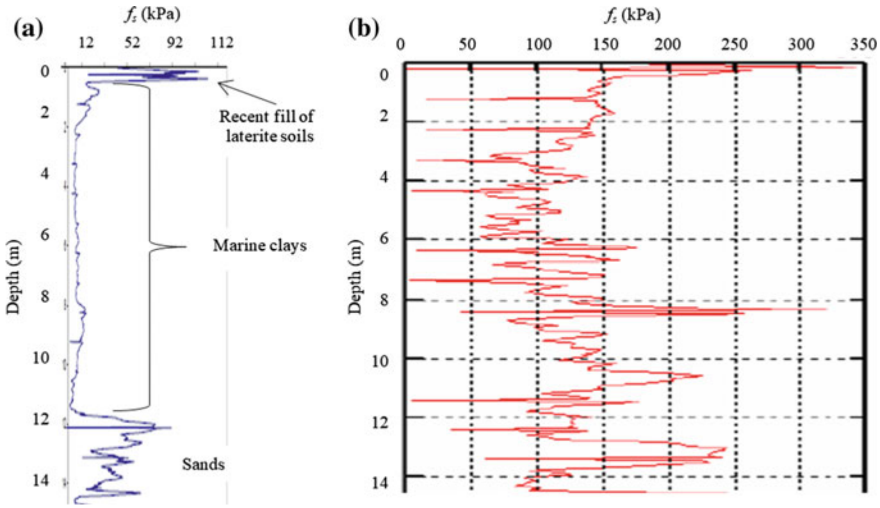

Fig. 5 CPTU result for f_s of the **a** quaternary deposit of USM Engineering Campus, **b** Mengelembu residual soil

4.2 SPTN Interpretation from CPTU Data

The interpreted standard penetration test number (SPTN) for the quaternary deposits and the laterite soils are respectively given in Fig. 6a, b. The SPTN is a measure of soil strength and the traditional means of measuring it is by penetration of the standard penetration test (SPT) rod, which is driven by the SPT hammer, in a test in the bore hole. The SPTN as interpreted by a CPTU test on the other hand is determined based on the empirical relationships developed from studies of the SPTN data produced by actual standard penetration tests.

Robertson et al. [5] for example, presented the relationship of Fig. 7 which relates SPTN from actual standard penetration tests to various parameter values of the CPTU tests where the spots represent the actual SPT results. In Fig. 7, the parameters q_c and p_a represent cone resistance and atmospheric pressure respectively while N_{60} represents the actual SPTN by assuming 60% hammer efficiency. The various soil types are arranged according to the mean particle size of the corresponding material. Thus the curve of Fig. 7 correlates a soil type to its respective q_c and p_a parameters and the expected SPTN value from a CPTU test, from which q_c, p_a, and soil type are obtained.

The particle size characteristics can also be estimated using soil behavior type (SBT) table, as given by the $(q_c/p_a)N_{60}$ ratios of Table 1. The zones of Table 1 in turn can be related to the friction ratio (F_r), one such example is given by Fig. 8 although with modified zone number, where there is a clear trend of increasing F_r with increasing fines content and decreasing grain size [4].

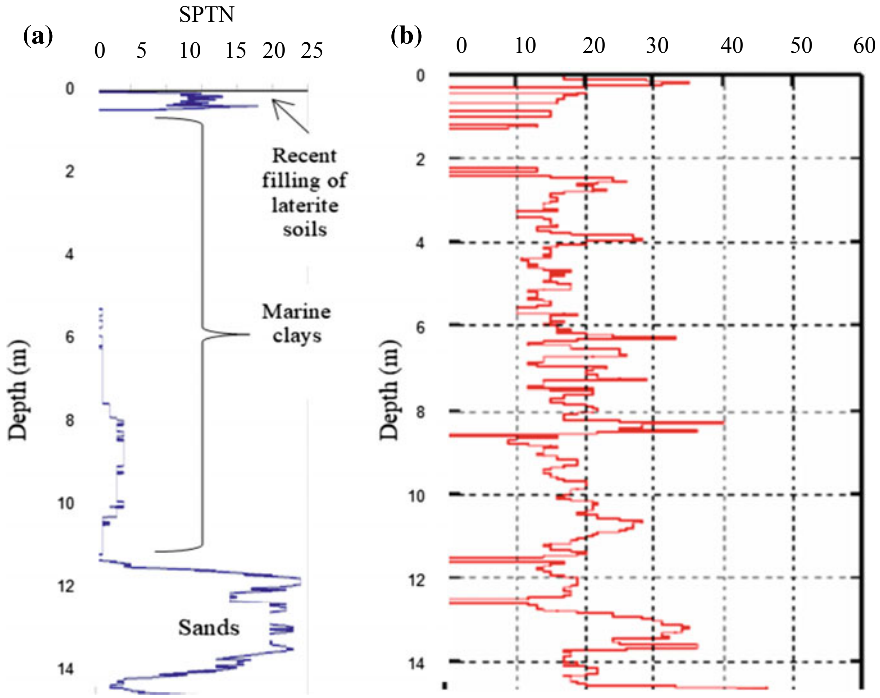

Fig. 6 SPTN by CPTU of the **a** quaternary deposit of USM Engineering Campus, **b** Mengelembu residual soil

Fig. 7 SPTN versus various CPTU parameters by Robertson et al. [5]. *Note* q_c is cone resistance; p_a is atmospheric pressure; SPTN of a test assumes 60% hammer efficiency, given here as N_{60}

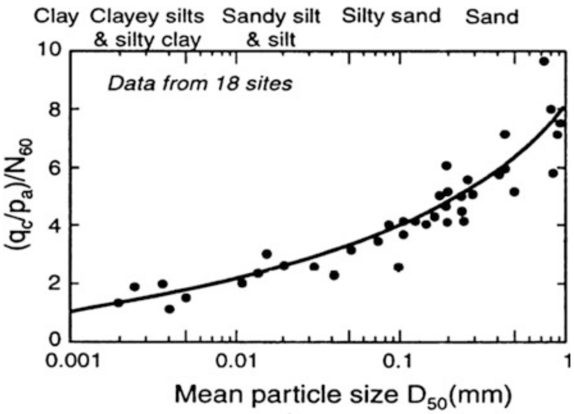

Figure 7a, b indicate that the SPTN for laterite soils are much higher than for the marine clays. Note that the interpreted SPTN is dependent on cone resistance but not on cone sleeve friction, thus the SPTN trends are closely related to the q_c trends of Fig. 4a, b. Note also that the interpreted SPTN from CPTU will not necessarily

Table 1 Suggested $(q_c/p_a)/N_{60}$ ratios

Zone	Soil behavior type	$(q_c/p_a)/N_{60}$
1	Sensitive fine grained	2.0
2	Organic soils—clay	1.0
3	Clays: clay to silty clay	1.5
4	Silt mix: clayey silt and silty clay	2.0
5	Sand mix: silty sand to sandy silt	3.0
6	Sands: clean sands to silty sands	5.0
7	Dense sand to gravelly sand	6.0
8	Very stiff sand to clayey sand	5.0
9	Very stiff fine-grained	1.0

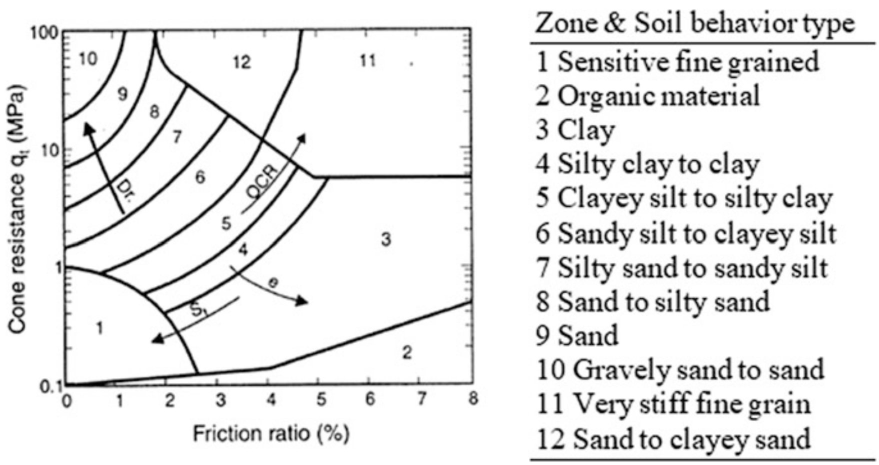

Fig. 8 Soil behavior types based on f_r and q_t

be verifiable by an actual SPTN; this can be deduced from Fig. 7 where the spots can veer away from the solid curve from which the CPTU interpretation is based upon.

4.3 Verification of CPTU Soil Behavior Types

The verification of the interpreted soil types followed. For the quaternary deposits, the soil types given by the CPTU are given in Table 2 next to the names obtained from soil classification works carried out in lab by following the USCS method. Clayey silt to silty clay as given by the CPTU system was instead the poorly graded sand or SP as given by the USCS soil classification procedure.

Table 2 Comparison between soil types as given by CPTU and lab classification according to the USCS for the quaternary deposit

Depth at site where soil was present (m)	CPTU Soil behavior type	USCS Soil classification
0.5	Clayey silt to silty clay	Poorly graded sand (SP)
1.5	Clay	Low plasticity clay (CL)
3.5	Sensitive fine grain	
8.5	Silty clay to clay	
9.0	Clayey silt to silty clay	
12.5	Sand to silty sand	Poorly graded sand (SP)

Clay, sensitive fine grain, silty clay to clay, and clayey silt to silty clay as given by the CPTU system were all identified as low plasticity clay or CL by the USCS soil classification procedure. Finally, the sand to silty sand given by the CPTU system was instead identified as the poorly graded sand or SP by the USCS. The names from the two methods of interpretation did not always match—at times they were completely mismatched.

For the laterite soils, the soil types given by the CPTU are given in Table 3 next to the names obtained from soil classification works carried out in lab following the USCS method. Unlike in the case of the quaternary deposits, the soils tested in the lab were not collected from test site, but were created by mixing laterite soils with sand. The sand mixes were tested using the CPTU systems and the resulting interpreted soil behavior in each case—in case there was a similar behavior observed in the field CPTU result—was compared to the outcome of naming the sample using the USCS, the resulting data of which are given in Table 3.

The silty clay to clay given by the CPTU was identified as clayey sand (SC) by the USCS. The clay from CPTU was given as silty, clayey sand (SM-SC) by the

Table 3 Comparison between soil types as given by CPTU and lab classification according to the USCS for laterite soil mixes

Depth at site where soil with same name was present (m)	CPTU name	Sample mix for test	USCS name
6.2	Silty clay to clay	100% laterite soil and 80% laterite soil + 20% sand	Clayey sand (SC)
9.6	Clay	60% laterite soil + 40% sand	Silty, clayey sand (SC-SM)
5.1	Clayey silt to silty clay	40% laterite soil + 60% sand	Silty sand (SM)
5.9	Silty sand to sandy silt	20% laterite soil + 80% sand, and	Poorly graded sand (SP)
None	Sand to silty sand	100% sand	

USCS. The clayey silt to silty clay from CPTU was given as silty sand (SM) by the USCS, while silty sand to sandy silt was translated as poorly graded sand (SP). Again, the names from the two methods of interpretation did not always match—at times they were completely mismatched.

5 Conclusions

This paper evaluates the results obtained from penetrating the marine clays on the coastal plains and the laterite soils on the inlands. The two CPTU site investigation files analysed in this paper were respectively considered representing the soils of coastal quaternary plains and the residual grounds of the surrounding inlands in Northwest Peninsular Malaysia. The plains' soils were mostly clays while the inlands' materials were mostly the laterite soils, which had more sands in comparison to the other soils had. The clays' thickness was about 12 m; the soils were soft, and had very low SPTN of 2 or less. The residual soils were about of the same thickness as the clays but were much stronger based on the higher SPTN values, which averaged in the 20 s. Needless to say, the actual thicknesses of both grounds vary with location.

For every site on the plains, the clays were underlain by a layer of sand, which is normally shallow enough to be reachable by foundation piles. In the inland, the bedrock was about as shallow as the sand stratum of the plains, or even shallower. The trends by which q_t, f_s, and SPTN changes with depth were similar, for the clays and the laterite soils. On the plains, the 3 given parameters were low in value for the clay but peaked upon reaching a sand stratum. In the inland, the values fluctuated with depth but like in the plains, they peaked upon nearing the bedrock.

The CPTU system identified the behaviour of a soil by way of its cone—how it sensed the soil using transducers. The clays of the plains had the following behaviour identifications, to cite the most observable ones: clayey silt to silty clay, clay, sensitive fine grain, and silty clay to clay; the underlying stratum was sand to silty sand. Meanwhile, the inlands' residual soils had the following identifications, among others: silty clay to clay, clay, clayey silt to silty clay, silty sand to sandy silt, and sand to silty sand. Thus the inlands' soils had a lot more sands in their midst although their clays are quite similarly described as the clays of the plains. For the same soil, the given soil names based on CPTU measurement and laboratory procedure are not necessarily similar to each other as the CPTU interprets a behaviour through the transducers attached to the cone while the laboratory procedure provides a name by physically measuring the grain sizes and plasticity of the soils. The general results of penetrating the marine clays and the laterite soils display the contrasting features of the two geotechnical materials in terms of strength and composition and of the two profiles in terms of various materials' presence in the field.

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