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Characterization and Geotechnical Properties of Penang Residual Soils with Emphasis on Landslides

[1]Fauziah Ahmad, [1]Ahmad Shukri Yahaya and [2]Mohd Ahmadullah Farooqi
[1]Associate professor, Universiti Sains Malaysia, Penang, 14300 Nibong Tebal, Penang, Malaysia
[2]PhD. Student Universiti Sains Malaysia, Penang, 14300 Nibong Tebal, Penang, Malaysia

Abstract: The predominantly hilly terrain of Penang Island combined with average maximum daily temperatures ranging between 27-35°C and peak rainfall as high as 647 cm makes the overall area potentially susceptible to landslips. Over the recent past construction industry has shown a rapid growth mainly due to increase in the inflow of international tourists and other economic reasons. Eventually, the magnitude of disaster associated with landslides has also increased and that is one of the major concerns of engineering geologists and geotechnical engineers. With this background this paper attempts to characterize the largely granitic residual soils of Penang Island by discussing the nature, structural features, engineering behavior and field properties of soil samples extracted from 8 sites. These sites are distinctly chosen from a database of 31 sites for they are located over different prime geological formations. The mean values of various design properties at different depths are calculated and plotted to identify the property trend with depth and important behavioral features relevant to landslides are discussed. Similarly, compression index values are plotted against initial void ratio and liquid limit separately and resulting correlations are compared with the established ones. Correlations given by Azzous are found to hold good. Lastly, in the light of the lessons learnt from the past landslides and the current characterization results some improvements regarding slope instability problem are discussed.

Keywords: Geotechnical properties, characterization, landslides, residual soils, Penang Island

INTRODUCTION

The in situ behavior of soils is complex because it is heavily dependent on numerous factors. To acquire appropriate understanding, it is necessary to analyze them not only through geotechnical engineering skills but also through other associated disciplines like geology, geomorphology, hydrogeology, climatology and other earth and atmosphere related sciences. However, it is known that the problems, even when tackled within the framework of geotechnical engineering, are huge and arduous. It is understood that geotechnical problems with socio-economic impacts like landslides can only be addressed within a framework that accounts for behavioral features in natural soils. Research is actively taking place in many countries, each focusing on natural deposits of local importance, and a unified framework that can account for all important effects is still being developed [1]. The development of this unified framework requires a huge and joint effort from as many sources as possible taking underway the best of their academic and technical skills and using best possible instruments. With this idea in the backdrop this paper attempts to summarize the index, strength, compressibility and field properties of tropical residual soils of Penang and discusses important correlations and facts that emerged thereof. Moreover, the authors have no hesitation in accepting that this work can only serve as a small entity in this whole enterprising task.

GEOGRAPHY AND GEOLOGY OF PENANG ISLAND

Penang is the second smallest and one of the 13 states of Peninsular Malaysia. It is situated at the north-eastern coast and constituted by two geographically different entities - an island (area: 293 km^2) called Penang Island (or "Pulau Pinang" in Malay Language) and a portion of mainland called Butterworth (area 738 km^2), connected, besides a regular ferry service, through a 13.5 km long Bridge. The island is located between latitudes 5° 8' N and 5° 35' N and longitudes 100° 8'E and 100° 32' E [2].

The climate is tropical with the average mean daily temperature of about 27°C and mean daily maximum and minimum temperature ranging between 31.4°C and 23.5°C respectively. However, the individual extremes are 35.7°C and 23.5°C respectively. The mean daily humidity varies between 60.9% and 96.8%. The average annual rainfall is about 267 cm and can be as high as 624 cm [2]. The two rainy seasons are south-west monsoons from April to October and north-east monsoons from October to February. The terrain

Corresponding Author: Fauziah Ahmad, School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia,14300 Nibong Tebal, Penang, Malaysia, Tel: 604-5996268, Fax: 604-5941009

consists of coastal plains, hills and mountains. The population is mainly concentrated on the eastern side of the Island, probably due to its close proximity with the mainland.

There are three main geological formations in Penang (Refer to Table 1) and their distribution is as given in Figure 1. Data obtained from different sites is so grouped that every site in one group is located over one formation. Wherever found necessary, the data collected from each group of sites is further divided into three subgroups each representing a distinct nature of soil (sandy, silty and clayey) found over that formation. The groups and their abbreviated codes are as shown in Table 1.

The major portion of Penang Island is underlain by igneous rocks. All igneous rocks are granites in terms of Streckeisen classification [3]. These granites can be classified on the basis of proportions of alkali feldspar to total feldspars. On this basis granites of Penang Island are further divided into two main groups: the North Penang Pluton, approximately north of latitude 5° 23' and the South Penang Pluton. In the northern part of the island, the alkali feldspars that generally do not exhibit distinct cross-hatched twining are orthoclase to intermediate microcline in composition. In the southern region, they generally exhibit well-developed cross-hatched twining and are believed to be microcline [2]. The North Penang Pluton is divided into Ferringhi Granite, Tanjung Bungah Granite and Muka Head micro granite. The South Penang Pluton is divided into Batu Maung Granite and Sungai Ara Granite.

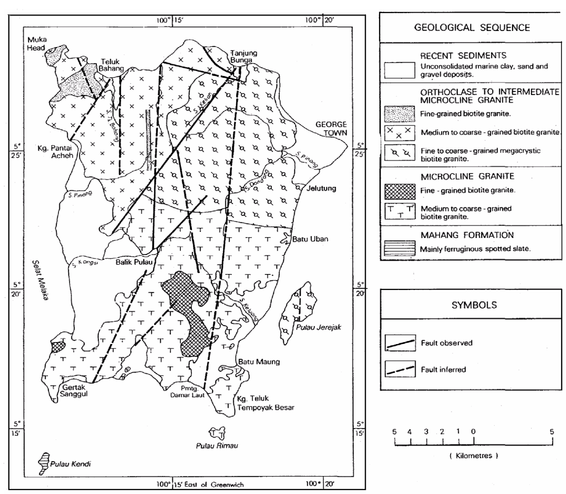

Fig. 1: Geological map of Penang Island

For explanation of these granite sub-classes any good publication can be referred. (See Reference [2])

GEOLOGY OF GROUPS

Tanjung Bungah: Tanjung Bungah is located on the northern coast of Penang Island over the north Penang Pluton (NPP) of late Carboniferous Age. This area is underlain by medium to coarse-grained biotite granite layer with predominant orthoclase and subordinate microcline. It has relatively plain topography.

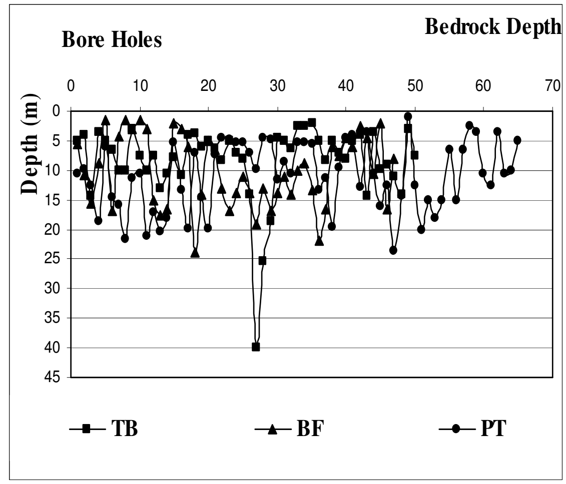

Fig. 2: Bedrock depth profiles

Paya Terubong: Paya Terubong is located on the south eastern half of the Penang Island over the south Penang Pluton (SPP) of late Carboniferous Age. The SPP is found to be composed of coarse-grained Prophyritic Muscovite-Biotite granite and medium-grained Prophyritic Muscovite-Biotite. Fig. 1 shows the geological map of Penang Island. The orientation of Paya Terubong valley is along north-south direction. The valley marks the position of the Central Penang Fault Zone.

Batu Ferringhi: Batu Ferringhi is located on the north western coast of Penang Island. This area is famous for its exotic beaches and a popular spot for national and international tourists. Geologically, this area is also underlain by medium to coarse-grained biotite granite

Table 1: Site groups representing each geological formation

Group Name	Code Used in This Paper	Formation	Age
Tanjung Bungah	TB	Fine to coarse grained biotite granite with orthoclase to intermediate microcline	Early Jurassic
Paya Terubong	PT	Medium to coarse grained biotite granite with microcline	Early Permian-Late Carboniferous
Batu Ferringhi	BF	Medium to Coarse grained biotite granite with orthoclase to intermediate microcline	Early Jurassic

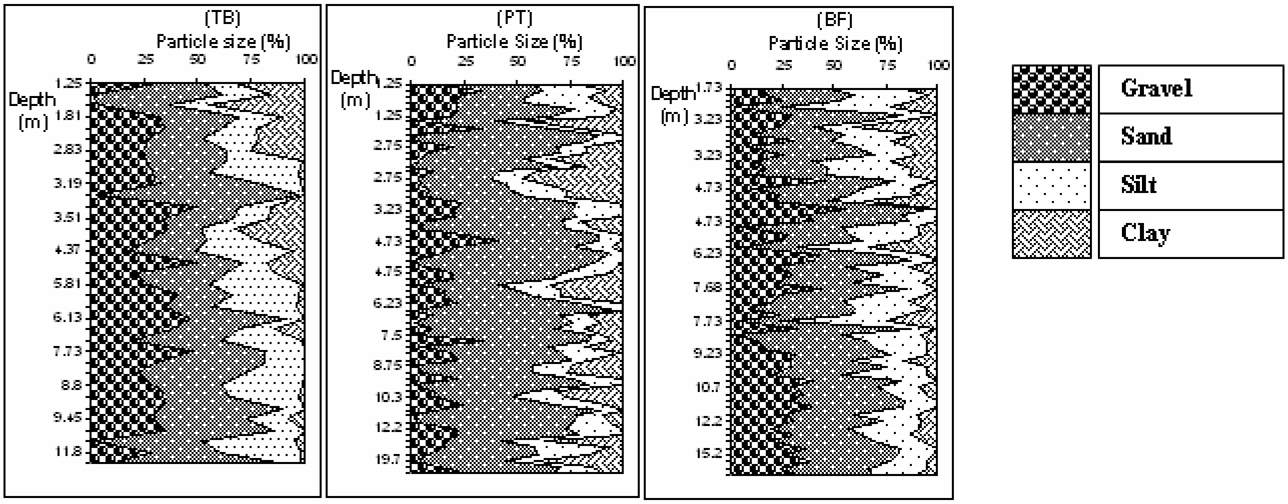

Fig. 3: Variation of particle size percentage with depth

layer with predominant orthoclase and subordinate microcline. The color of rock varies from light grey to dark grey according to the amount of biotite present. Occasionally, particularly in sheared rocks, the alkali feldspar may exhibit a pinkish tinge at crystal boundaries and along feldspar cleavages due to weathering. Tourmaline patches are common especially when in close contact with fine-grained biotite granite.

RESIDUAL SOILS

Ideally, there is no universally accepted definition of residual soils. Different researchers gave different definitions. However, the common phenomenon in all such definitions is that the residual soil is a material formed in situ by weathering of rocks and remained at the place where it was formed. For example, one such definition says “residual soils are those that form from rock or accumulation of organic material and remain at the place where they were formed” [4]. The Public Works Institute of Malaysia defined it as ‘a soil which has been formed in situ by decomposition of parent material and which has not been transported any significant distance’ and residual soil as “a soil formed in situ under tropical weathering conditions” [5]. The tropical residual soils are formed in tropical areas, physically defined as the zone contained between 20^o N (Tropic of Cancer) and 20^o S (Tropic of Capricorn) of the equator, which includes Malaysia. Table 2 gives the proposed classification of weathering profile over metamorphic rock (Clastic Metasediment) in Peninsular Malaysia [6].

THICKNESS OF RESIDUAL SOILS IN MALAYSIA

The thickness of residual soil layer varies from place to place depending upon the factors (Table 2) responsible for weathering like, rainfall, temperature chemicals present, compositions of parent rocks, etc. and the extent to which the weathering process has advanced [7].

Table 2: Weathering agencies and their description

Factors	Description
Climate	Refers to the effect on the surface by temperature and precipitation.
Geologic	Refers to the parent material (bedrock or loose rock fragments) that provide the bulk of most soils.
Geomorphic / Topographic	Refers to the configuration of the surface and is manifested primarily by aspects of slope and drainage.
Biotic	Consists of living plants and animals, as well as dead organic material incorporated into the soil.
Chronological	Refers to the length of time over which the other four factors interact in the formation of the particular soil.

Table 3: Classification of weathering profile over metamorphic rock (Clastic Metasediment) in Peninsular Malaysia[6]

Term	Zone	Description
Residual Soil	VI	All rock material is converted to soil. The mass structure and the material fabric (texture) are completely destroyed. The material is generally silty or clayey and shows homogenous color.
Completely Weathered	V	All material rock is decomposed to soil. Material partially preserved. The material is sandy and is friable if soaked in water or squeezed by hand.
Highly weathered	IV	The rock material is in the transitional stage to form soil. Material condition is either rock or soil. Material s completely discolored but the fabric is completely preserved. Mass structure partially present.
Moderately	III	The rock material shows

Weathered		partial discoloration. The mass structure and material structure is completely preserved. Discontinuity is commonly filled by iron-rich material. Material fragment or block corner can be chipped by hand.
Slightly Weathered	II	Discoloration along discontinuity and may be part of rock material texture are completely preserved. The material is generally weaker but fragment corners cannot be chipped by hand.
Fresh Rock	I	No visible sign of rock material weathering. Some discoloration on major discontinuity surfaces.

In Malaysia, tropical residual deposits are found in abundance and because the climate is hot and humid the formations are intense with a predominance of chemical weathering over other processes of weathering, thus resulting in deep weathering profiles and soil mantles often exceeding 30 m [8].

WEATHERING PROFILES

A typical weathering profile is a vertical section of the soil layers or soil horizons that reflects progressive stages of transformation from fresh bedrock through weathered material to ground surface. Weathering profiles have been studied by various researchers [9, 10, 11, 12, 13, 14, 15].

ENGINEERING PROPERTIES

Depth of Bedrock: The profiles of bed rock depth for the three areas are as shown in Fig. 2. The mean value and range remain almost the same but the range is quite high as shown in Table 4. In just one borehole the depth overwhelmingly reaches up to 40 m, which may apparently be attributed to operator error. Nevertheless, the minimum and maximum values are quite in agreement with the ranges given in literature [8].

Classification and Index properties: Laboratory tests were performed according to British Standards [16]. The percentages of gravel, sand, silt and clay particles in samples taken from the three areas are plotted against depth in Fig. 3. Note that the percentage of clay content is relatively less in the samples obtained from BF region, percentage and deep layer of clay which makes it more vulnerable to landslides. The natural moisture content, liquid limit, plastic limit and plasticity index are plotted along the depth in Fig. 4. Again, PT area shows high natural moisture content and high liquid limit. The trend of natural moisture content is increasing with depth which combined with deep clay layer makes it most susceptible area to landslides.

Specific gravity of soil solids is also plotted against the depth as shown in Fig. 4. The minimum, maximum and mean values of dry density of soils found in the three regions under study are as shown in Table 4. The mean values remain almost the same but the soil in the area of PT exhibits low values which may be attributed to higher clay content. The Plasticity Charts in Fig. 8, show that Soil at BF area is silty type while at PT and TB are clayey type.

Field Properties: With adequate selection of field test, proper control over the procedures adopted and careful extraction of undisturbed samples, the in situ tests can give better information about the behavior of the residual soils. They are considered to be a preferred means of strength characterization. In Malaysia Pressure Meter Test (PMT) and Cone Penetration Test (CPT) are generally used. However, Standard Penetration Test (SPT) and Macintosh Probe (MP) are extensively used.

The values of SPT N-Values are plotted against depth and are shown in Fig. 5. Note that the BF area shows high values in all the three soil types while the silts of both PT and TB areas show quite low values. TB clay also shows low N-values while the clays of both PT and BF show quite high N-values which may be attributed to the high gravel content (Fig. 3 and Table 4).

Strength Properties: The residual soils are generally found in unsaturated condition. The shear strength of unsaturated soils can be represented by the so-called extended Mohr-Coulomb criterion [17].

$$\tau_{ff} = c' + (\sigma - \mu_a)\tan\phi' + (u_a - u_w)\tan\phi^b \quad (1)$$

τ_{ff} = shear stress on the failure plane at failure; c' = effective cohesion; σ = normal stress; u_a = pore-air pressure; $(\sigma - u_a)$ = net normal stress; ϕ' = effective angle of shear resistance; u_w = pore-water pressure; $(u_a - u_w)$ = matric suction; and ϕ^b = angle indicating

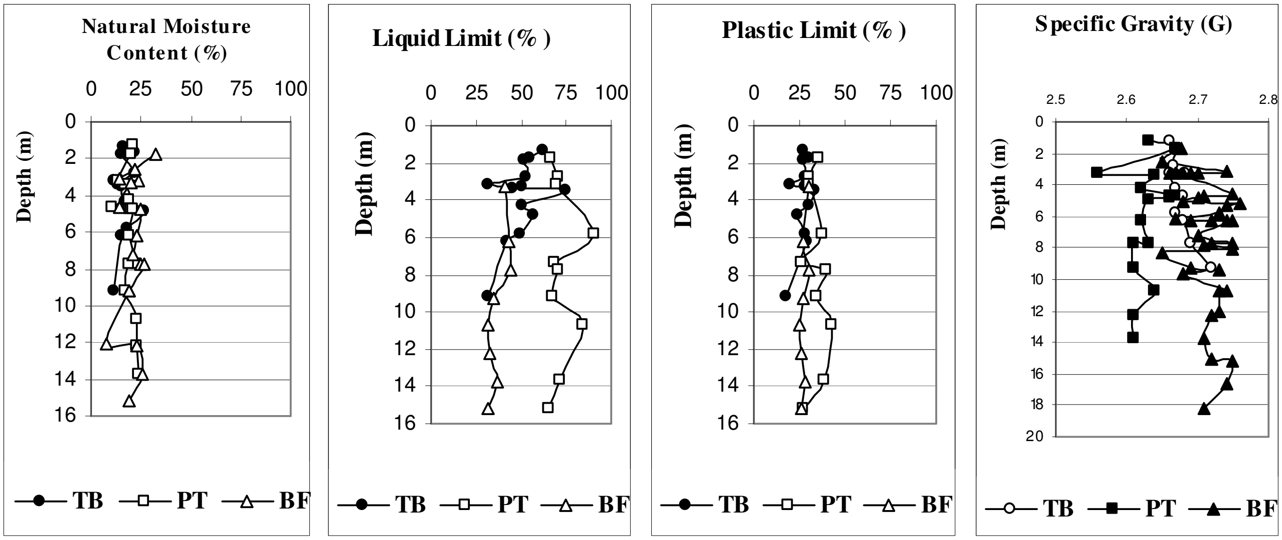

Fig. 4: Variation of liquid limit, plastic limit, natural moisture content and specific gravity with depth

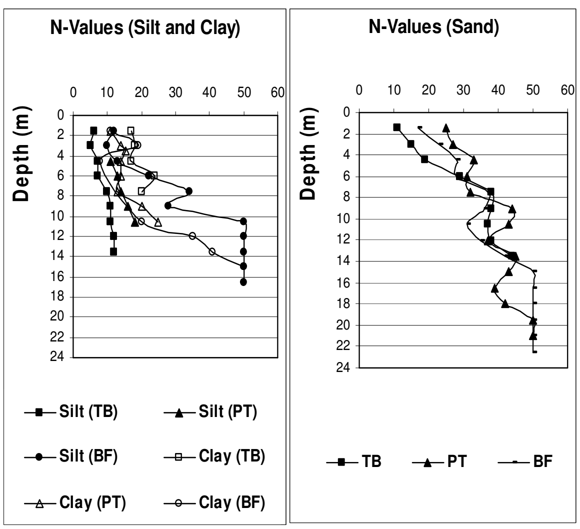

Fig. 5: Variation of SPT N-Values with depth

the rate of increase in shear strength relative to matric suction.

As the soil approaches saturation, the pore pressure, u_w, approaches the pore pressure, u_a and Equation (1) becomes:

$$\tau_{ff} = c' + (\sigma - \mu_w)\tan\phi' \qquad (2)$$

which is the Mohr-Coulomb strength criterion for saturated soils. In applying Equation (2) to unsaturated soils, the shear strength component due to matric suction, i. e. $(u_a - u_w)\tan\phi^b$, is masked as the cohesion intercept, c ($= c' + (u_a - u_w)\tan\phi^b$). Therefore, the cohesion intercept, c, in residual soils appear to vary widely [18].

In Fig. 6, effective cohesion, c′ and effective angle of internal friction, ϕ′ are plotted with depth for the samples taken from all the three groups. Note that the effective cohesion, for all the three cases, shows large variations as explained [18]. The variation in c′ and ϕ′ as shown in Fig. 6 also explains the variation of clay content shown above (Fig. 3). In Fig. 7, the angle of internal friction is plotted against clay content, the variation shows that ϕ′ decreases with increasing percentage of clay.

Stiffness and compressibility: The compressibility of tropical residual soils can be roughly determined by oedometer and triaxial compression tests. An undisturbed sample should be used to get more reliable results even though trimming of undisturbed residual soil samples is difficult because of gravel contents. About 2 - 8 tests should be conducted depending upon the complexity of the condition [19]. However, oedometer test is not suitable for measuring compressibility of coarse grained soils and hence not advisable for testing predominantly coarse grained residual soils. In that case triaxial test is more suitable. Geoguide 3 [5] suggests the use of Rowe Cell, which can accommodate larger samples and provide better drainage conditions. Compression tests normally take days to complete. Often the speed of site activity demands to get the results soon. In that case some empirical estimates are useful not to substitute the actual laboratory determined values but to restrict the number of tests. In Fig. 9 the compression index values are plotted against liquid limit values for all the three sites. The results were then compared with the correlations given by Azzous [20] and Terzaghi [21] and were found to show fairly strong correlation with the following relationship,

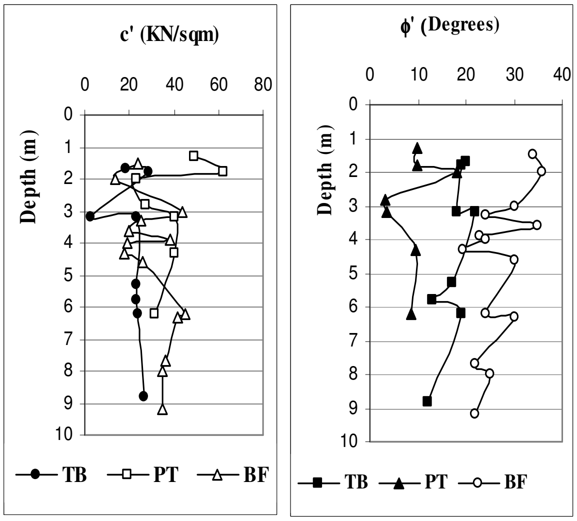

Fig. 6: Variation of shear parameters with depth

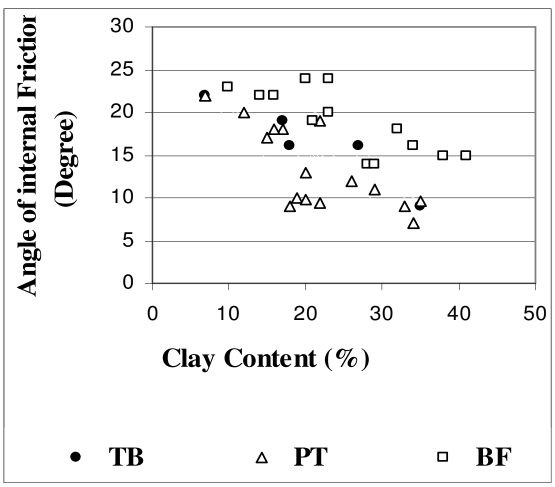

Fig. 7: Variation of angle of internal friction with clay content

suggested by Azzous et al.[20].

$$C_c = 0.007(LL - 7) \quad (3)$$

In Fig. 10 the values of C_c are plotted against initial void ratio. The results are again compared with the correlations suggested by Azzous et al.[20] and Poh [22]. Again the results showed stronger correlation with the following relationship, suggested by Azzous[20].

$$C_c = 0.3*(e_o - 0.27) \quad (4)$$

CONCLUSIONS

After analyzing the data obtained from different sites located in different parts of Penang Island the following conclusions can be drawn:

1. From the plasticity charts it is shown that soil at BF area is silty type while at PT and TB areas are clayey type.

Table 4: Summary of engineering properties

Property Name	Location					
	TB		PT		BF	
	Range	Mean	Range	Mean	Range	Mean
W_n (%)	9-38	23	15-30	23	11-41	24
LL (%)	32-75	51	65-90	73	32-44	37
PL (%)	24-43	32	17-34	25	22-33	28
G	2.66-3	2.68	2.56-3	2.63	2.65-3	2.71
PI (%)	12-42	24	30-53	38	6-14	10
Dry Density (KN/m^3)	1.41-2.31	1.68	1.13-1.93	1.60	1.45-2.01	1.70
Bedrock Depth (m)	2.1-40	8.4	0.9-23.55	10.9	1.5-24	10.2
Gravel (%)	2-50	28	1-34	14	2-45	27
Sand (%)	15-76	38	32-85	55	22-55	40
Silt (%)	11-43	23	4-28	18	15-54	26
Clay (%)	0-33	12	0-42	13	0-22	7
c' (KN/m^2)	2.5-29	21	23-62	39	14-45	30
ϕ' (Deg.)	12-22	17.5	3.3-9.8	8.9	22-36	27
C_c	0.12-0.24	0.197	0.12-0.39	0.25	0.2-0.25	0.22

2. From the plasticity charts it is shown that soil at BF area is silty type while at PT and TB areas are clayey type.
3. The value of effective cohesion shows a wide variation that is attributed to its unsaturated condition as the shear strength component due to matric suction, gets included in cohesion intercept.

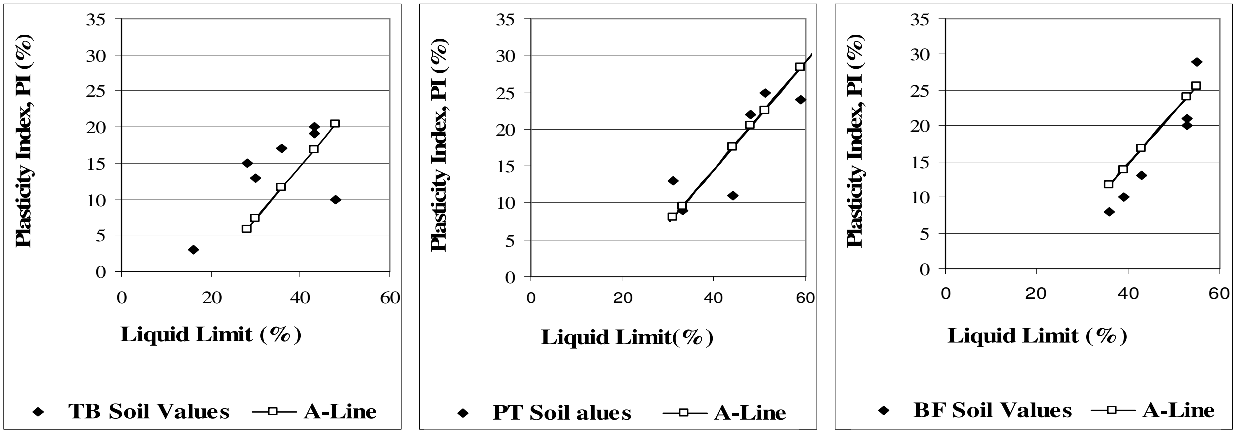

Fig. 8: Plasticity Charts

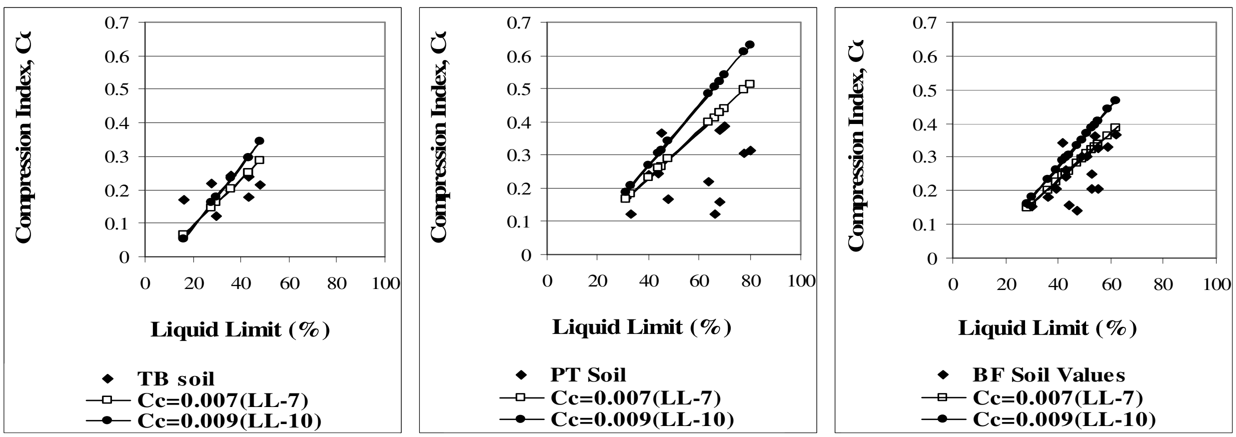

Fig. 9: Compression index versus liquid limit

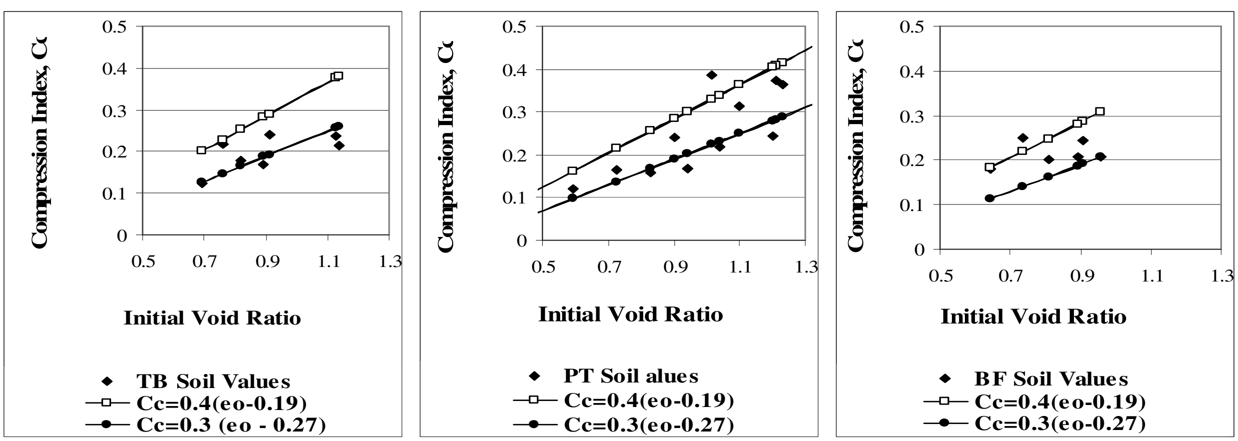

Fig. 10: Compression index versus initial void ratio

4. The soil at the PT area shows such characteristics that it is highly susceptible to deep landslides. The soils at TB area, despite showing high liquid limit values, are only susceptible to shallow landslides.

5. The engineering properties obtained from in situ and laboratory tests are as summarized in Table 4. Two empirical relationships [20] for coefficient of compression are found to show fairly strong correlation with granitic residual soils of Penang.

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