GEOSEA V Proceedings Vol. I, Geol. Soc. Malaysia, Bulletin 19, April 1986; pp. 453–468

Residual soil development on sedimentary rocks of the Jurong Formation in Singapore

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Abstract: The Jurong Formation constitutes a variable siliciclastic succession which produces residual soils of differing character. Details of the variability of particle size distribution and plasticity characteristics within the profiles of these residual soils are presented. This variability has considerable implications for strength, permeability and compressibility characteristics. Some results of *in situ* penetration tests confirm this variability with depth. Details are also provided of the properties of a thin zone apparently intermediate between completely weathered rock and residual soil. This zone is believed to be an important factor in slope instability in some areas.

INTRODUCTION

Residual soils result from the *in situ* weathering of rocks and subsequent modification by pedological processes. In humid tropical areas, the weathering is mainly by chemical decomposition with hydrolysis as the major process. This tends to result in significant changes in physical and chemical composition of the parent rock, and a secondary "layering" is commonly imparted onto the residual soil by the pedological processes.

Most of the work undertaken on weathered materials in humid tropical environments has been on those overlying igneous rock. This has concentrated for example on the gradation of the weathering product from the bedrock surface (e.g. Nossin & Levelt, 1967), or from the applied point of view, the variation in the amount and distribution of corestones with depth. On sedimentary materials, the problem of corestones does not appear to arise, probably because of the inherent primary porosity of the materials. There is however considerable variability in the profile as evidenced by the results from *in situ* penetration testing during site investigations and from recent investigations of slope failures (Pitts, 1983). This work is an attempt to describe and explain some of the causes of the heterogeneity of these residual soils.

Residual soils on sedimentary rocks in West Malaysia have been considered by West and Dumbleton (1970) and for Singapore by Alexander (1959) and Peaker and Morton (1969). The main emphasis in all cases was on chemical and mineralogical composition. It is the aim here to introduce a more systematic description of the physical variability within the profile.

NATURE OF THE PARENT MATERIAL

The sedimentary rocks under consideration belong to the Jurong Formation, and constitute a series of variable siliciclastics ranging from clay rich cleaved mudrocks

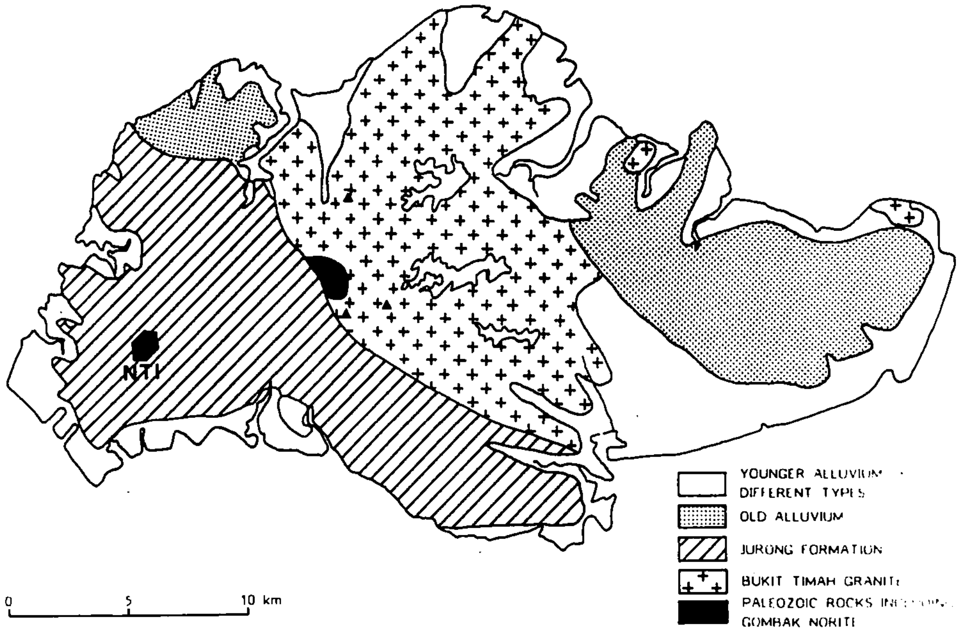

Fig. 1. Simplified geological map of Singapore island, showing the location of the NTI campus.

through to breccio-conglomerates. The sequence is Upper Triassic in age, although deposition may have continued into Jurassic times. Volcanic activity contemporaneous with the deposition of the sedimentary materials produced spilite, tuff, chert and dolerite within the Jurong Formation.

The Jurong Formation which covers in excess of one quarter of Singapore Island (Fig. 1) is strongly folded, with folds varying in their geometry from open to vertical isoclinal and isoclinal overfolds. Further parasitic folding on the limbs of some of the larger folds ensures that very rapid variation in strike and dip occurs. The beds generally strike NW (PWD 1976, Pitts, 1984), in the study area.

The residual soils under investigation are in the western part of Singapore, mainly on and around the campus of the Nanyang Technological Institute (Fig. 1) covering an approximate area of 200 hectares. It is not proposed to suggest in detail sources of variation within the soils due to the various environmental factors important in soil formation, but mainly to observe and account for recorded sources of heterogeneity within individual profiles.

IN-SITU TEST

The non-homogeneous nature of the residual soils in question became evident from the results of a series of *in situ* penetration tests through the materials. A number of field tests were conducted on the NTI campus using Swedish ram sounding and weight sounding tests. The blow counts from ram sounding tests (RST) correlate well with the SPT N Values, both being dynamic penetration tests. The weight sounding test results are related to the undrained shear strength of the soil.

1. **Ram Sounding Test**
   The ram sounding test consists of a 63.5 kg hammer dropped through a free fall of 500 mm by means of a hydraulic lift mechanism with automatic lift and drop. A 38 mm rod with a 15 sq. cm cone point is driven by the hammer and the number of blows required to drive the cone point 200 mm is recorded as the N value. The test is well controlled and there is little room for variability.

2. **Weight Sounding Test**
   In this test, a 200 mm long screw shaped cone point on a 22 mm diameter drill rod is driven by a 100 kg weight using constant rotation. The number of half turns required to drive the cone point 200 mm is recorded as the N value in this test.

A major advantage with both tests is that recordings are continuous over short intervals of measurement. Furthermore, they are quick, easy and inexpensive to carry out, neither one requiring a borehole in which to undertake the tests. Records of weight sounding and ram sounding values for tests carried out on level ground are illustrated in Fig. 2. The weight sounding results for tests on a gentle slope are shown in Fig. 3. In the case of Fig. 2 the junction of Grade V and Grade VI material is quite clear, at about 2 metres. Its position is more variable but no less clear beneath the slope surface.

THE NATURE OF THE RESIDUAL SOILS

The term "residual soils" as used by engineering geologists and civil engineers is somewhat at variance with pedological terms used by, e.g. Peaker and Morton (1969). Their terms "lateritic" and "non-lateritic" soils include not only Grade VI (Anon 1970) weathered material, but also some Grade V, as indicated by the description of their "LITHOMARGE" unit as retaining the original bedrock structure. For the most part, Grade VI materials only will be considered here.

Samples have been taken with two main aims in mind: firstly to observe the variation in the nature of the residual soils close to the contact with the underlying sedimentary rock; and secondly to observe variations in the characteristics of the residual soils within the profile. The dipping structure of the beds results in rapid variation in the succession along an outcrop. This permits any hypothesis based on variability with rock type to be tested relatively easily. The junction between Grade V and Grade VI materials is very abrupt in all cases so far observed and its shape does not seem to be influenced by the structure of the underlying rocks. A series of samples was taken within 100 mm of the junction over six different bedrock lithologies and a summary of grading and plasticity characteristics is shown in Table 1. Four examples are presented of profiles through residual soil successions overlying different types of bedrock (Table 2).

Soil classification tests were performed to determine the properties of the soils. They were carried out according to the specifications in BS 1377 (1975). In all cases, wet

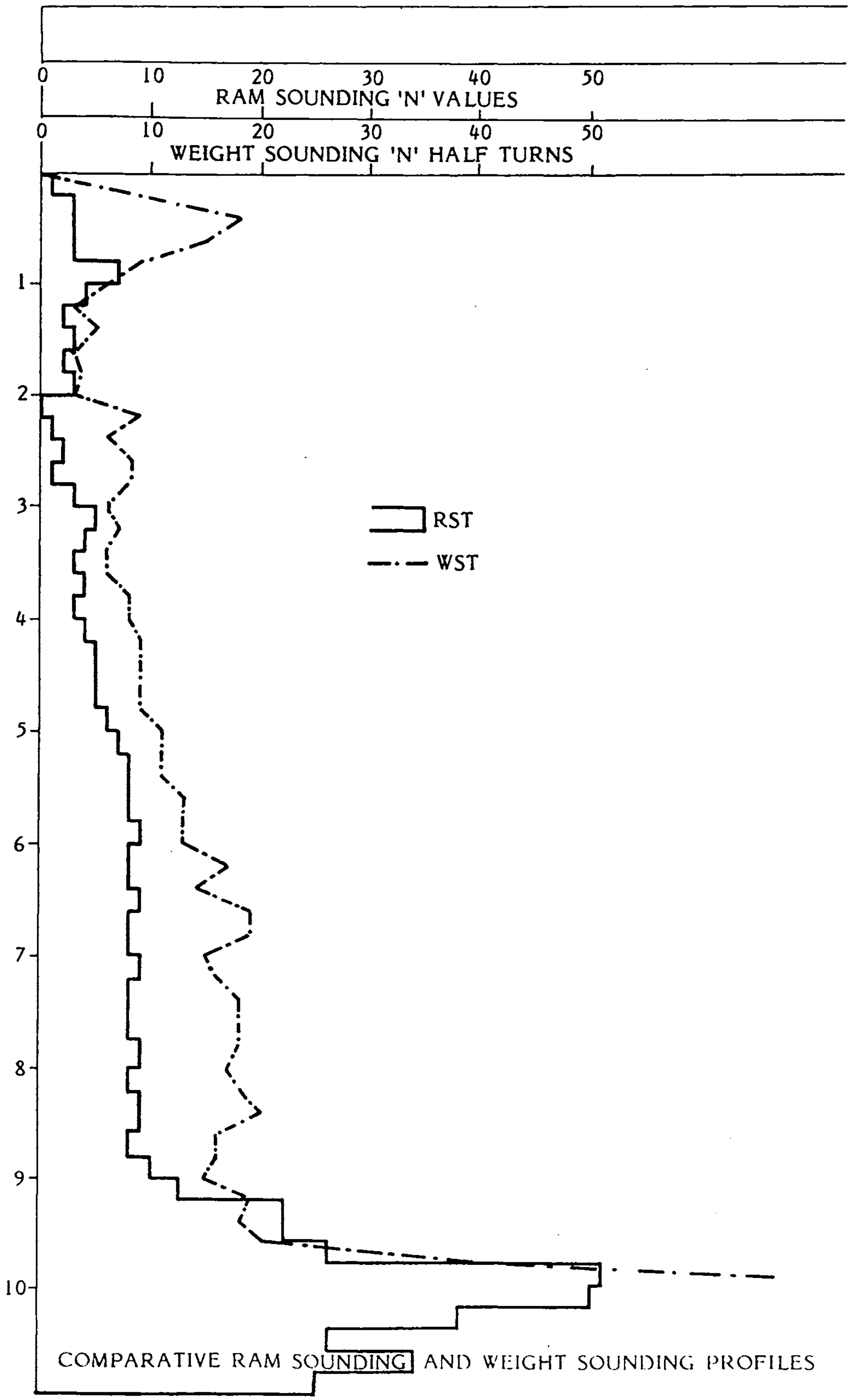

Fig. 2. Results of ram sounding and weight sounding tests through residual soils and weathered rocks of the Jurong Formation.

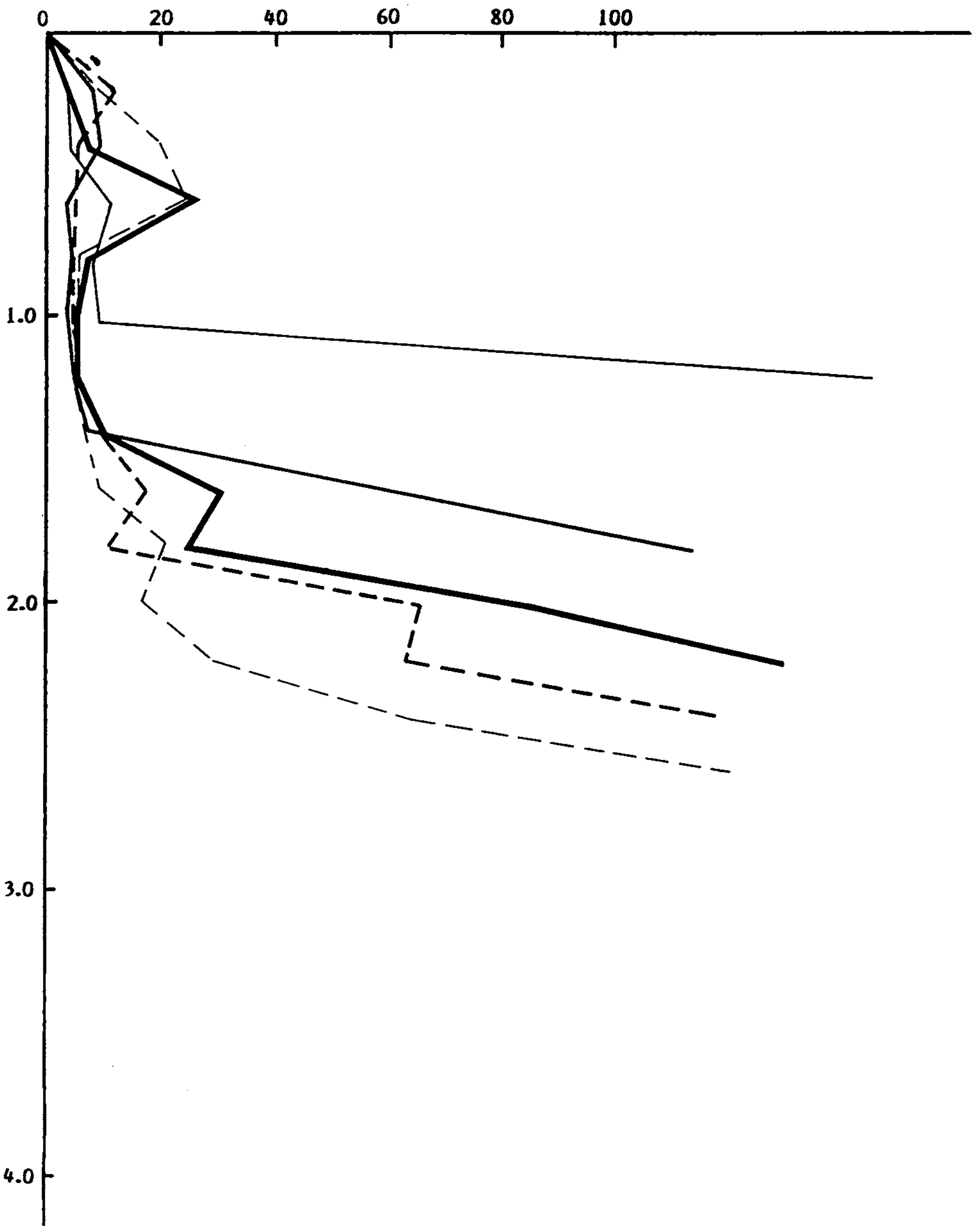

Fig. 3. Profiles of weight sounding tests on residual soils on a gentle slope.

TABLE 1

CHARACTERISTICS OF RESIDUAL SOILS NEAR TO THE BEDROCK CONTACT

Bedrock Type	Particle Size Distribution				Plasticity Characteristics		
	% Gravel	% Sand	% Silt	% Clay	W_L%	W_p%	PI%
A Cleaved dark red silty, slightly clayey MUDROCK	8	21	39	32	46	24	22
B White and red mottled silty CLAY	8	27	33	32	44	24	20
C Cream to pale brown silty CLAY	6	28	40	26	36	28	8
D Purple cemented silty clayey MUDROCK	3	22	46	29	42	18	24
E White and yellow mottled sandy, silty MUDROCK	3	19	43	35	44	23	21
F Brown sandy, clayey SILTSTONE	4	11	51	34	44	25	19

TABLE 2

RESIDUAL SOIL PROFILES

	Distance from contact (cm)	% Gravel	% Sand	% Silt	% Clay	W_L %	W_p %	PI %
F. Profile over brown sandy, clayey SILTSTONE								
1.	10	4	11	51	34	44	25	19
2.	20	7	20	41	32	39	20	19
3.	30	3	19	45	37	46	23	23
4.	40	3	24	43	30	41	21	20
G. Profile over pale brown sandy silty CLAY								
1.	40	0	22	35	43	52	27	25
2.	80	0	27	35	38	52	28	24
3.	120	0	17	40	43	52	29	23
4.	140	0	20	36	44	57	28	29
H. Profile over yellow with red mottling, fissured silty CLAY								
1.	20	0	13	13	74	67	36	31
2.	40	0	12	13	75	67	35	32
3.	60	0	10	15	75	67	33	34
4.	80	5	20	9	66	69	34	35
5.	100	14	21	5	60	70	35	35
6.	120	4	21	10	65	68	31	37
7.	140	10	25	7	58	64	23	41
8.	160	0	16	10	74	68	35	33
9.	180	0	15	10	75	69	35	34
J. Prolife over purplish-red slightly clayey silty fine and medium feldspathic sandstone								
1.	10	1	51	21	27	49	27	22
2.	20	5	44	17	34	57	33	24
3.	30	9	60	8	23	63	29	34
4.	40	20	54	6	20	56	26	30
5.	50	18	62	6	14	58	25	33

sieving and hydrometer analyses were undertaken to determine the particle size distribution, and Atterberg limit tests, to indicate plasticity characteristics. It is well known that different amounts of work imposed on liquid limit samples leads to variations in liquid limit values (Moh & Mazhar 1969). The normal trend is for additional work to break up soil aggregations, thereby increasing the effective area of clay platelets available to take on adsorbed water. This causes a gradual increase in the liquid limit with time. All liquid limit tests were undertaken to a strict timetable, equal time periods of mixing being carried out immediately prior to testing. Further remixing to different moisture contents was then kept to a minimum within the constraints of proper sample preparation. The mixing time chosen is based on the work of Gidigasu (1974) which indicates that further changes in liquid limit after one hour of mixing are relatively minor.

The results of the plasticity tests reveal quite a wide range of values. It is however fairly apparent from Fig. 4 that points are to some extent clustered for the individual

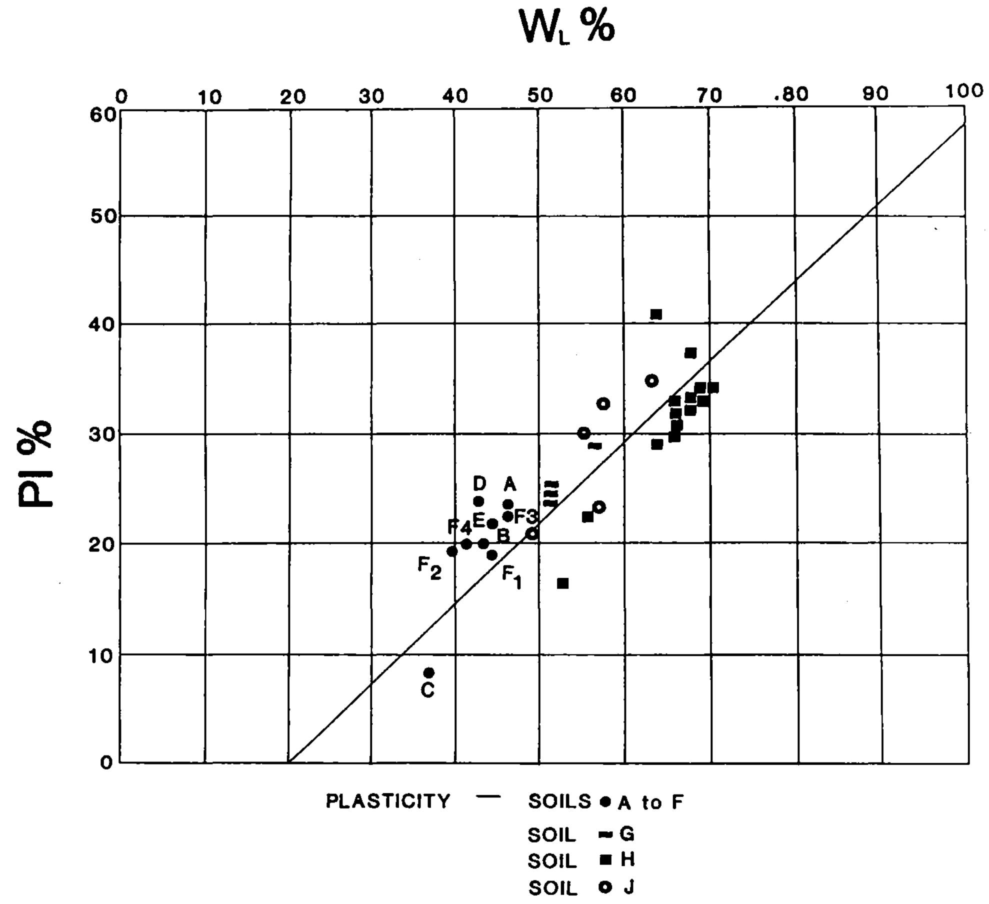

Fig. 4. Plasticity characteristics of residual soils overlying the Jurong Formation.

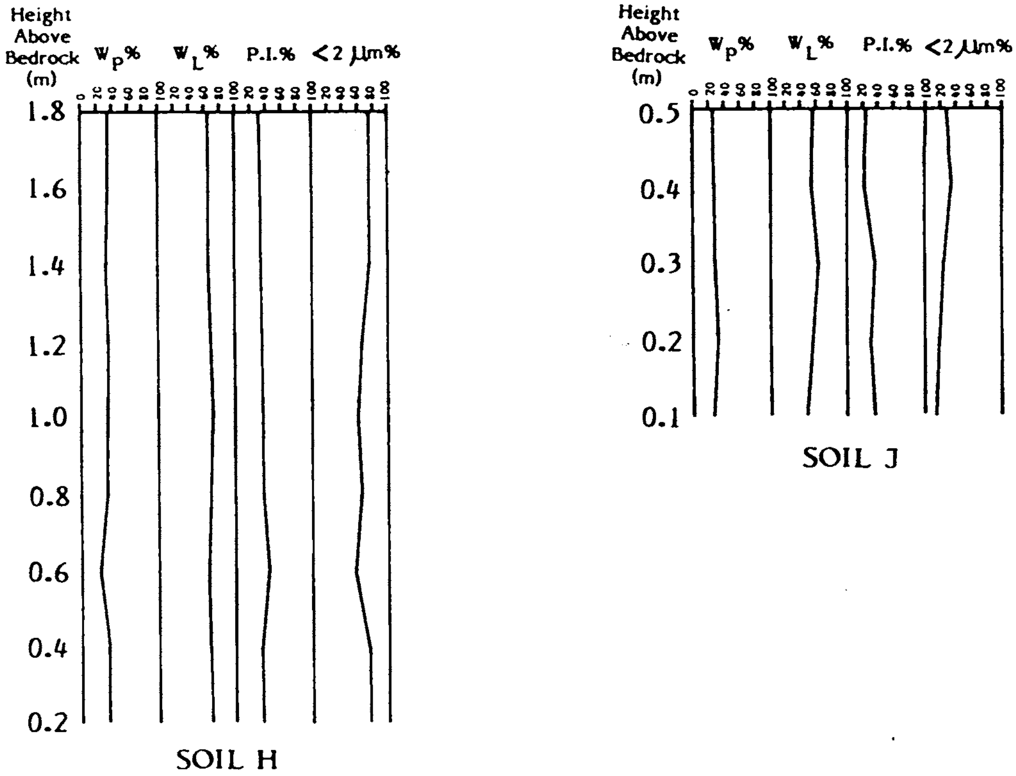

Fig. 5. Profiles of index properties through two residual soils overlying the Jurong Formation.

profiles measured. The points generally fall very close to the A line, with a majority plotting just above. Soil H which has by far the highest clay content of the profiles investigated predictably shows the highest plasticity. However, soil J which generally has a low clay content reveals a relatively high spread bridging the gap between the main cluster of points formed by soils A to F inclusive, and the more plastic soil H. This may indicate a possible discrepancy between particle size and plasticity results for soil J, perhaps indicating a more marked breaking down of aggregations during mixing for the plasticity tests which was not revealed during the sedimentation test. Profiles of plasticity characteristics for soils H and J are shown in Fig. 5.

The results of the classification tests further illustrate the non-homogeneous nature of these residual soils. Single values describing particle size or plasticity characteristics quoted in the literature (e.g. Nixon & Skipp, 1957; and Peaker & Morton, 1969) are not very meaningful. For soil H, the wide range of particle size distribution measured over a profile less than 2.0 metres deep is illustrated in Fig. 6. The range indicated is for one bedrock type only. One feature of particular interest is the indication that depletion of coarse and medium silt is occurring producing a gap graded soil. In the case of soil H, originally a compacted non-laminated silty clay

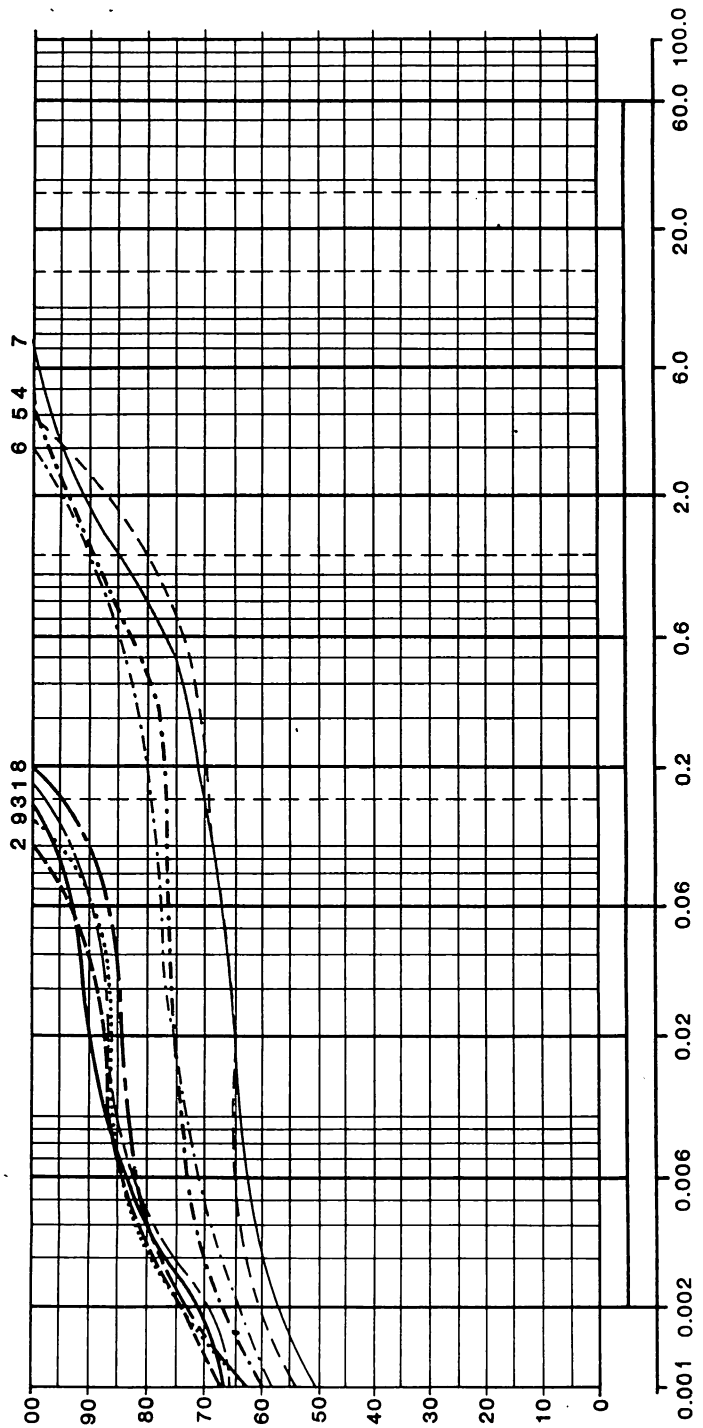

Fig. 6. Particle size distribution curves for samples taken at 200 mm intervals through a residual soil profile overlying Jurong Formation.

mudrock, the profile indicates a characteristically fine grained soil near to the contact with the Grade V material, followed by a coarsening in a zone of aggregated fines, cemented by re-deposited iron compounds, with further fine grained members close to the surface. This is presented as one example, not necessarily a typical one. This sample site was a cutting through fairly level ground. On slopes, the nature of the material on an identical bedrock was somewhat different, particularly from the aspect of the deposited iron compounds.

In Fig. 7, the range of particle sizes is indicated for the full suite of bedrock types so far investigated within the Jurong Formation. For comparitive purpose, particle size envelopes (Fig. 8) showing a more limited range are presented for Grade VI materials overlying igneous rocks in Singapore, (Nossin and Levelt, 1967) and a metamorphic rock from Sri Lanka (Sinclair, 1980). For individual, relatively uniform bedrock types, the variability is very much less although over the gabbro, with a large suite of minerals susceptible to alteration, the variability is large.

In the excavations for the new NTI campus, a range of bedrock types showed deposition of linear "veins" of ironstone throughout the Grade V weathered material. These were found to follow the bedding and master joint sets. In the Grade VI material, the ironstone was broken up into jumbled slabs. It is believed that this is the material described by Peaker and Morton (1969) as "Cuirasse de Fer" which refers to a different material than that usually called Cuirasse which is an ironstone caprock. This material has not been included in the main particle size distribution diagrams. In this particular case, the transition from Grade VI material is not as abrupt as generally encountered, and includes an "intermediate" zone. The characteristics of the material above, within and below the intermediate zone are shown in Table 3. In each case, all the material passed the 63 micron sieve. However, in terms of particle size distribution, the materials above and below the intermediate zone were much more similar to one another than to the material forming the intermediate zone. Visually, the intermediate zone resembled the Grade V material more closely than that of Grade VI. Two other features are of interest: firstly, the 'Cuirasse de Fer" was not obvious in the intermediate zone; and secondly, the zone contained a system of open vertical or sub-

TABLE 3

CHARACTERISTICS OF THE GRADE V—GRADE VI
BOUNDARY ON GENTLE SLOPES

	% Sand	% Silt	% Clay	W %	W_L %	W_P %	PI %	A
Intermediate Zone	10	50	40	33	52	30	22	.75
Above Intermediate Zone	15	38	57	34	57	31	26	.54
Below Intermediate Zone	4	42	54	30	51	28	23	.52

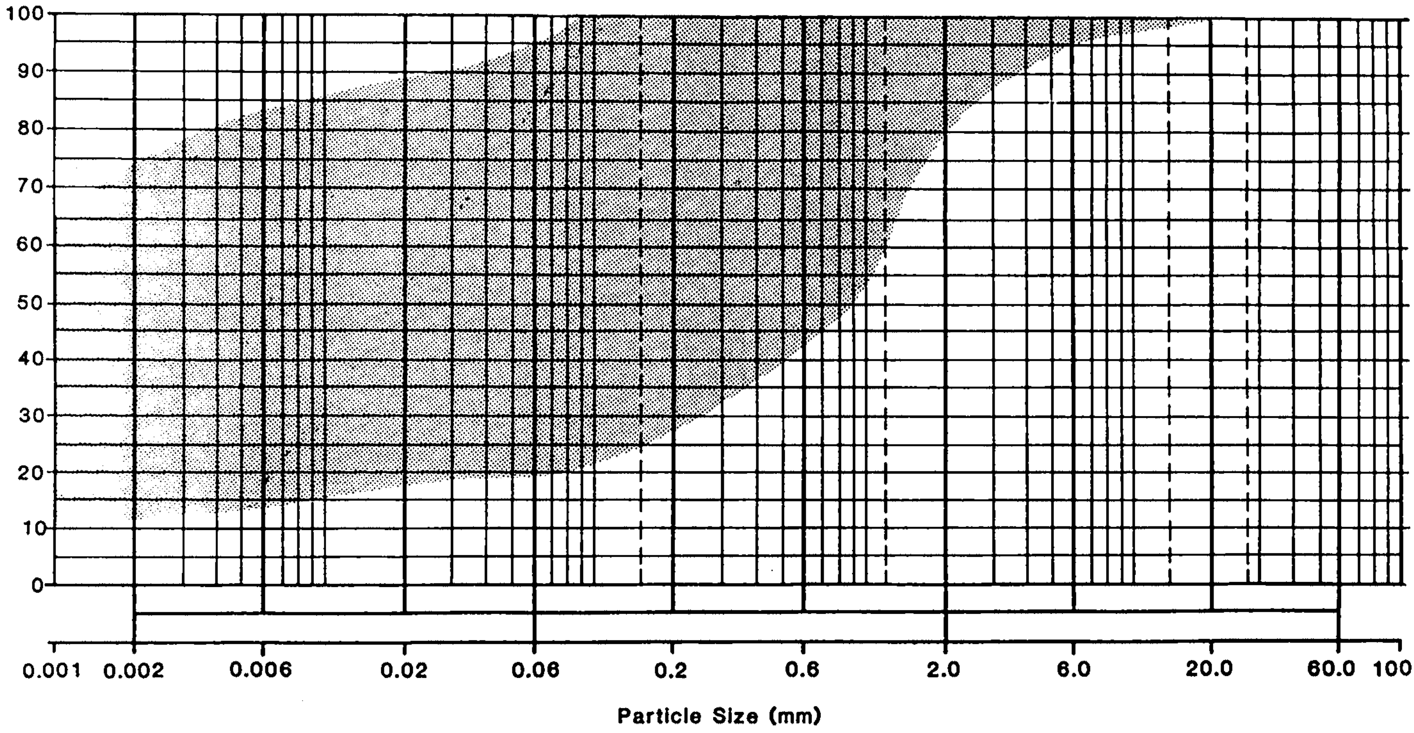

Fig. 7. The range of particle size distribution curves for the full suite of samples tested from residual soils overlying the Jurong Formation.

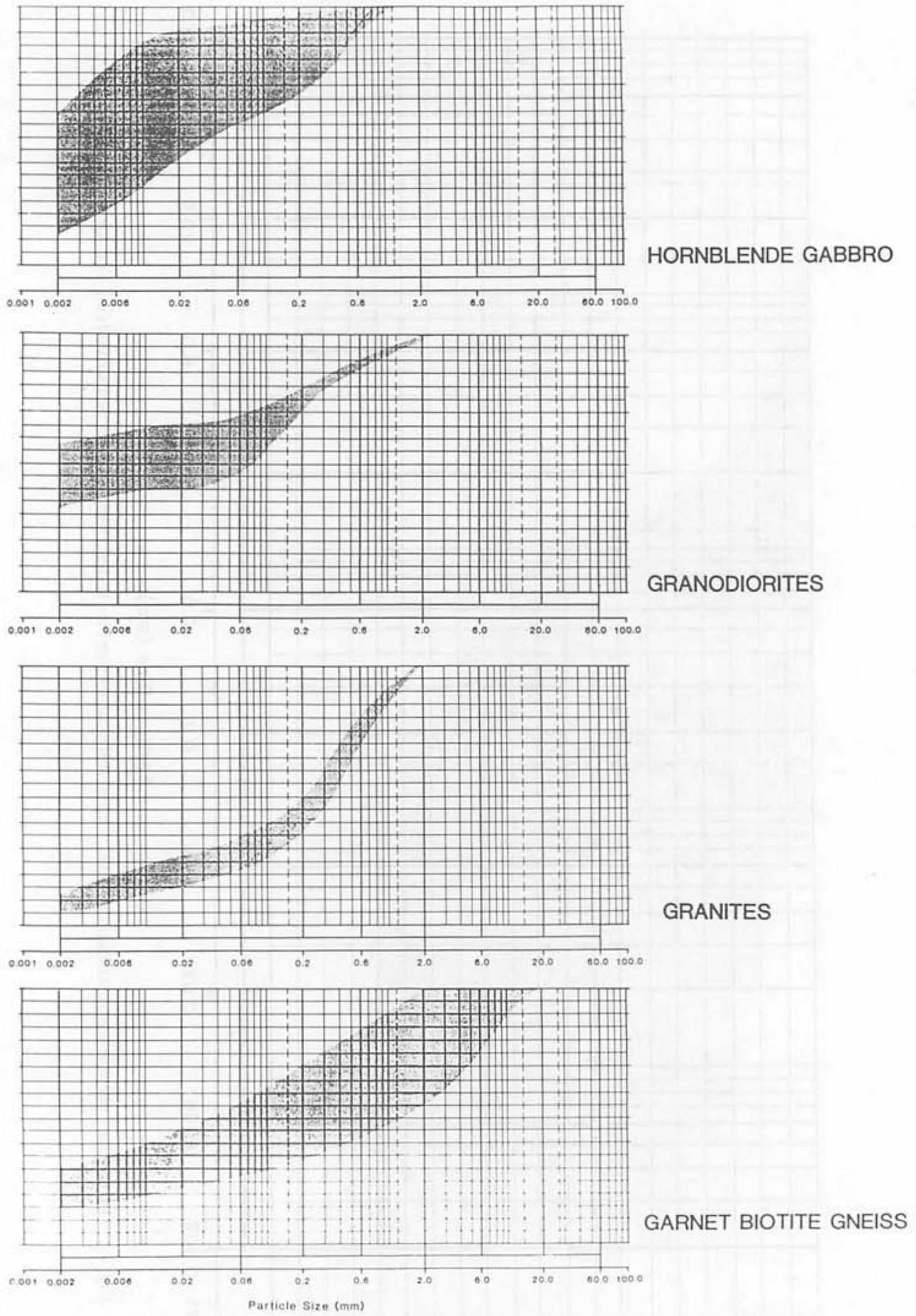

Fig. 8. Ranges of particle size distribution curves for residual soils overlying igneous rocks in Singapore, and a metamorphic rock from Sri Lanka.

vertical fissures. The precise status of the intermediate zone is not clear, and may result from weathering and pedological processes, or be a product of pedological processes following stress relief. It is believed to have a profound influence on slope stability in the area (Pitts 1983; 1986).

MINERALOGY

No X-Ray diffraction tests have been undertaken on the residual soils under review. However, some inferences as to the dominant minerals can be made. The parent materials are siliciclastics, and in the case of the coarser lithologies indicate a possible granitic provenance. Quartz is the dominant mineral forming the grains, but feldspar is also quite common within both arenaceous and to a lesser extent rudaceous members. Quartz in the form of fine and medium sand forms a significant proportion of most of the bedrock types, and appears to survive within the residual soils virtually intact throughout the profile. Alexander (1959) felt that even the coarse quartz was vulnerable to solution under humid tropical climates, and presents some test data to support this. No clasts of feldspar have been found during visual inspection of the soils even though they or their alteration forms are clearly present in Grade V arenaceous materials. The mudrocks are most likely to be illite rich in view of their age and appearance.

Activity values (Skempton 1953) are determined as the ratio of plasticity index to clay fraction. The range of values, between 0.31 and 0.71 is relatively small, and perhaps indicates that whilst kaolinite, the least active of the common clay minerals, is the most abundant clay mineral present, that others, possibly mainly illite, are also present to increase the activity value. Activity data in relation to specific mineralogy is shown in Fig. 9. Kaolinite is quoted as having activity values of between 0.33 and 0.46 (Skempton 1953) and illite, the next most active mineral, 0.90. The illite is probably derived from the parent mudrock, whereas the kaolinite is more likely to have resulted from alteration of illite during the weathering process. It should be noted that the clay fraction is expressed as a percentage of the whole soil, as recommended by Skempton (1953). West & Dumbleton (1970) have used a modified value based on the clay content expressed as a percentage of the $<$ 420 micron fraction. As a result, their published values are not directly comparable. However, on re-calculation using a comparable clay content value, the values of activity for their soils overlying sedimentary rocks range between 0.51 and 0.72.

DISCUSSION

Since very little work has been carried out previously on residual soils overlying sedimentary rocks there is little information with which to compare the results presented here. An additional difficulty concerns terminology. The use of "laterite" or "lateritic" does not necessarily refer to the same materials covered by weathering Grade VI used by engineering geologists. There is no doubt, however, that the results presented indicate the presence of soils of a non-homogeneous nature, crudely stratified by processes of leaching and redeposition. Zones of enhanced strength and permeability are formed within generally weak, clayey deposits of low strength and relatively high compressibility.

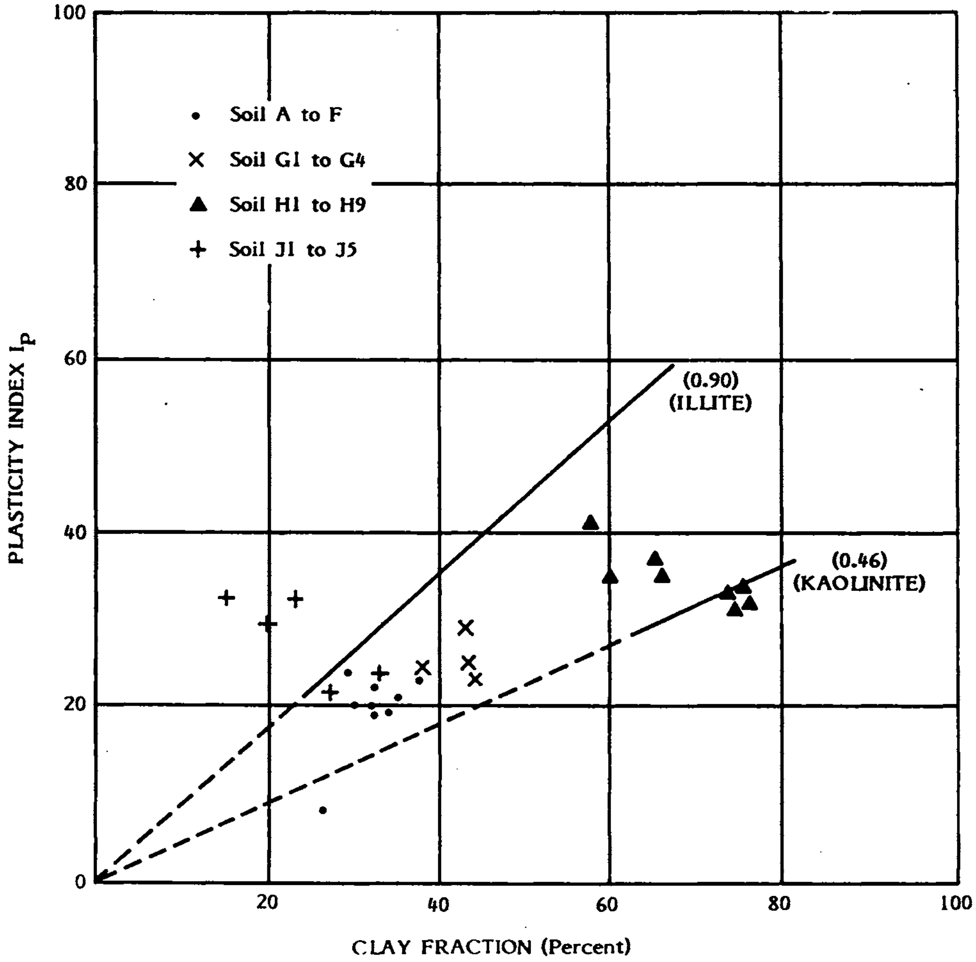

Fig. 9. Relationship between plasticity index and clay fraction (Activity) with activity values for illite and kaolinite.

Peaker and Morton (1969) present a diagram (Fig. 3 p. 127) explaining the formation of a "typical" profile, and include a relatively shallow water table with ironstone/bauxite caprock. No ironstone caprock, either continuous or otherwise, has been observed at any locality. In only two areas have lateritic gravels been recorded as discrete bands within the residual soil profile, once on the NTI campus, and in borehole samples at the site of Bukit Batok new town, very close to the contact with the Bukit Timah Granite. Elsewhere, however, their presence is indicated as a small gravel content on the particle size distribution curves.

The range of values of plasticity characteristics quoted by Peaker & Morton (1969) is far smaller than recorded during this work. The range of liquid limit values quoted is only 40% to 50%, and plastic limits of 16% and 18%. The range of these parameters have been found to extend well beyond these, especially on clay-rich bedrock. In addition, values for plasticity and particle size characteristics vary within any residual profile. This makes the choice of "typical" values difficult and the usefulness of average values dubious. Although only classification data are presented, the variation within the data have profound implications for other soil mechanics properties, especially shear strength, compressibility and permeability.

Peaker & Morton's (1969) first conclusion (p. 129), that the residual soils develop according to bedrock type, seems to be substantially true. However, within the generally varied group of mudrocks making up a large part of some facies (PWD 1976) of the Jurong Formation, most of the residual soils bear basic similarities not obviously shared by the parent materials. In the case of more arenaceous and rudaceous parent materials, the coarseness of the quartz grains resists solution and renders the residual soils over them generally sandier in character. More data are required on these coarser soils which overlie particularly the rocks of the Rimau Facies of the Jurong Formation. However, the conclusion by Peaker & Morton that the engineering properties of the "lateritic" and 'lithomargic" materials (most particularly relating to the finer grained bedrocks) are similar is not borne out by this work. Details of the lithormarge are not presented as this constitutes Grade V material. However, the results of the penetration testing usually indicate clearly the position of the Grade V—Grade VI junction, as the resistance to penetration shows a sudden increase. There is, furthermore, a marked decrease in permeability between the Grade VI and V materials, not only in magnitude but also in directional anisotropy.

The results of the classification tests quoted by West and Dumbleton (1970) for residual soils over sandstone-shale successions of a similar age in West Malaysia are more in keeping with those found in the present investigation. The results cover the more characteristic wider range, although other physical trends through a particular profile are not presented.

CONCLUSIONS

Residuals soils overlie sedimentary rocks over a large portion of Singapore. The basic engineering properties have been little studied as the tendency is to treat them as though they are of igneous origin. It is a common practice to pile through these materials and the less weathered material below. A better understanding of these materials may allow a more varied and economical foundation design to be presented. In addition, due to the increased construction activity and the resulting stress relief, landsliding has become an important problem in some parts of Singapore especially after the major storms during the wet seasons of 1982–83 and 1983–84. Failures on residual soils and weathered rocks of the Jurong Formation constitute a significant proportion of such failures. Only by understanding the characteristics of the materials can their behaviour in foundations or on slopes be appreciated.

This work, although at an early stage, has clearly indicated that residual soils are not homogeneous masses, but that they are layered, with profound changes in character and properties with depth. Original bedrock has some influence on the nature of the residual soils formed above. Generalisation is, however, difficult at this stage because of the highly varied nature of the Jurong Formation, and the, as yet, limited survey of the lithologies represented within it. It is clear though that in residual soils proper, pedological processes rather than merely weathering ones are of prime importance in producing a more open textured, strongly pedal soil with fines-enriched and fines-depleted layers and zones of mineralogical enrichment and depletion.

Singapore has developed to a major extent during the past two decades, during which time massive construction programmes have been undertaken. Even in the very early years of its foundation, however, reclamation projects constituted an important part of civil engineering activity. In the area of the central and southern Central Business District a range of hills was removed for this purpose leaving a new, graded landscape of fresh rocks. Modern construction projects have revealed that weathered bedrock now extends down to 5 m to 7 m in this area. More recent removal of hills has resulted in a similar effect of producing a surface in fresh rock. Under the humid tropical climate of Singapore, this is likely to change relatively rapidly, and foundation conditions may change considerably within the life of an engineering structure. It is of some importance then to ensure that the development of tropical soils is understood so that appropriate allowances may be made during design and construction.

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Manuscript received 17th July 1984.