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A review of geology and engineering geology in Singapore

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Summary

A mass rapid transit (MRT) railway system is soon to be constructed in Singapore. Attention is being paid to details of the engineering geology of the island, which are generally not well documented or understood. The main solid formations, both igneous and sedimentary, are deeply weathered, often with an abrupt boundary between completely weathered and slightly to moderately weathered rocks. They have a high degree of fracturing and the sedimentary Jurong Formation has a high but variable dip. They are overlain by Quaternary deposits, many of which have poor geotechnical properties. A soft marine clay and overlying peaty deposits present particular problems in excavations. Each has a low strength and high compressibility and water tables are close to the ground surface. Variations in the geotechnical characteristics of the marine clay are now being recognized. The soft deposits are mainly found in buried channels cut during lower stands of sea level in the recent geological past. The channels have steep sides, and at many sites geotechnical conditions change very rapidly.

Introduction

During the next decade a mass rapid transit (MRT) railway system, which is likely to demand a large geotechnics input, is to be constructed in Singapore. The purpose of this paper is to review the more important geological formations in Singapore and their engineering geological significance. Many civil engineering projects have been undertaken in Singapore during the past decade, the most important of which have been high rise buildings, reclamation projects and expansion of the port refineries. In general, most of the more recent sediments and weathered rocks are piled through, sometimes bypassing adequate foundation materials. On some occasions, construction runs into trouble or piling is found not to be viable. In such cases, the engineering geology is considered and alternative foundation designs presented.

The MRT project has forced local contractors to consider the engineering geology of Singapore in greater detail. The existing details are generally poorly documented. In the discussion of Nowson's (1954) paper on the foundations of the Asia Insurance Building, Little (1954) expressed surprise at the poor knowledge of the soil conditions in as large a city as Singapore. Only recently has any kind of systematic work commenced on gathering information on the various soils and rocks in Singapore (e.g. Ahmad & Peaker 1977; Ramaswamy 1975; Tan & Lee 1977). However, many of the commercial investigators are reluctant to release their findings and so detailed collating of conditions is difficult.

Regional setting

Singapore lies close to the southern extremity of a southerly projection of the Eurasian tectonic plate. It is just north of, but generally now away from the influence of, the Java Trench, which is part of the northerly termination of the Indian Plate. In the geological past, Singapore has come under the influence of the developing Indonesian Island Arc. The northerly-dipping subduction zone is migrating southwards, away from Singapore (Read & Watson 1975).

The generalized structural 'grain' of the region is southeast to south. This results from major phases of mainly fold deformation in the Middle to Upper Palaeozoic, and the late Triassic to Lower Jurassic, and from Tertiary faulting (Gobbett & Tjia 1973).

Pre-Pleistocene formations

The rocks of Singapore (Public Works Department (PWD) 1976) consist mainly of four solid series (Fig. 1):

Jurong Formation—Upper Triassic, Lower and Middle Jurassic
Gombak Norite—Upper Palaeozoic
Bukit Timah Granite—Lower and Middle Triassic
Sajahat Formation—Lower Palaeozoic

A more detailed succession with a brief listing of lithological characteristics is shown in Table 1.

Sajahat formation

Lower Palaeozoic sandstones and mudrocks of the Sajahat Formation crop out in one small area only and seem not to have been encountered during civil engineering activity. They are known to exist beneath younger deposits in the eastern part of Singapore island.

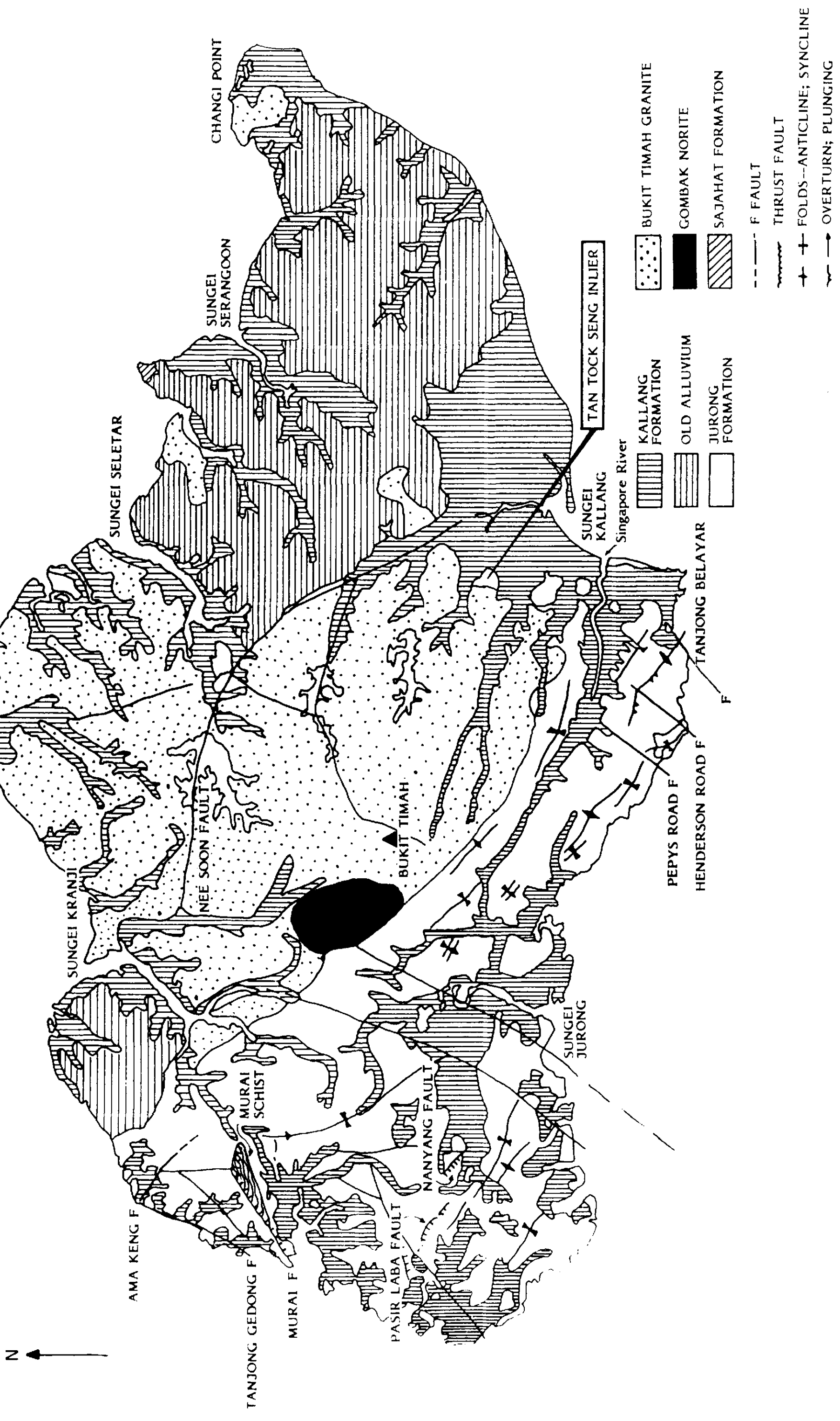

FIG. 1. Generalized geological map of Singapore Island.

TABLE 1. *Summary of the Geological succession in Singapore*

PALAEOZOIC		MESOZOIC				No local rocks of later Mesozoic and early and mid Cainozoic ages exist	CAINOZOIC				
		Triassic			Jurassic		Pleistocene		Holocene		
Lower	Upper	Lower	Middle	Upper	Lower		Early	Late	5000 BP	Present	
											KALLANG FORMATION
										X	Reef member: coral, unconsolidated calcareous sand, some quartz, iron-cemented sand
										X	Transitional member: unconsolidated dark mud, muddy sand or sand with peaty layers.
										X	Littoral member: well sorted unconsolidated beach quartz-sand with some laterite, shell and sandstone fragments. Iron-cemented beach rock also exists.
									XXX	XX	Alluvial member: alluvial pebble beds, sands, muddy sands clays and peat.
								X	XX	XXX	Marine member: mainly unconsolidated blue-grey clayey mud with peat and sand horizons.
									X		TEKONG FORMATION: unconsolidated sand with some cobbles.
							XX				HUAT CHOE FORMATION: white kaolinite-rich clay and occasional quartz gravel.
							XX				OLD ALLUVIUM: loose quartz-feldspar sand and gravel with occasional weak sandstone and conglomerate.
											JURONG FORMATION
				X							Murai Schist: mudrock cleaved and sheared by dynamic metamorphism on thrust faults.
				X	X						Tengah Facies: muddy sandstones with grits and conglomerates. Poorly cemented.
				X	X						St John Facies: muddy sandstones with carbonaceous laminations.
				X							Rimau Facies: well cemented quartz sandstone to quartz conglomerate.
				X	X						Ayer Chawan Facies: well bedded, mainly black sandstones and mudrocks; red conglomerates, basic lava, and volcanic ash are also included.
				X							JONG Facies: well cemented conglomerate and sandstones and occasional mudrocks and basic lavas.
				X	X						Queenstown Facies: red to purple mudrocks, sandstones and occasional conglomerates; some volcanic ash also occurs.
			X								DYKE ROCKS. Acid (older) and basic (younger) dykes intruded into all older rocks.
		X	X								BUKIT TIMAH GRANITE. Mainly acid igneous rocks, but with some less acid forms due to mixing of the granite and Gombak Intrusives e.g. a 'Hybrid' granodiorite is recognised.
	X										PALAEOZOIC VOLCANICS. Coarse and fine grained pyroclastic rocks. Mainly on offshore islands.
X											GOMBAK INTRUSIVES. Basic igneous rocks of mainly noritic and gabbroic composition. Now much altered by later intrusion.
X											SAJAHAT FORMATION. Hard quartzite, sandstone and mudrocks.

Intrusive igneous rocks

Intruded into the Sajahat Formation are gabbroic and noritic rocks of the Gombak group. Both of these series are intruded by a more acid sequence with rocks ranging from granodiorites, produced largely through hybridization, through adamellites to a variety of truly granitic rocks. The intrusion of the Bukit Timah Granite caused marked alteration of much of the suite of basic rocks. The plutonic rocks are intruded by small dykes of both doleritic and aplitic composition. Both of the major plutonic series are extensively quarried for aggregates, and the 'granitic' series in particular produces strong and durable materials of a high quality.

Until relatively recently (PWD 1976) all the accounts of the geology of Singapore had the Bukit Timah Granite intruded into the widespread sedimentary sequence of the Jurong Formation. This is now believed not to be the case, although no exposure or borehole of the contact of the 'granites' and Jurong Formation has been recorded. The widespread distribution of completely weathered granite found in boreholes which are close to the contact with the Jurong Formation strongly indicates that the junction between the two formations would be of little geotechnical significance if it was encountered.

The Jurong Formation

The Jurong Formation which is of late Triassic, and Lower to Middle Jurassic age consists of a wide variety of sedimentary rocks which may be divided up into six facies. It seems that similar environments of deposition occurred periodically during the time of deposition. However, there is clearly some confusion over the recognition of the various facies, a task made even more difficult by the effects of weathering which has produced a rather similar end product throughout. The Jurong Formation most probably originated at a continental margin, since the rock types, sedimentary structures, chemistry and fossils indicate environments which include alluvial, deltaic, estuarine, lagoonal, littoral and shallow shelf sea. The rock types include various types of conglomerate, sandstones, and mudrocks. Some of the mudrocks are organic-rich and have, through phases of intra-bed shearing, assumed the form of graphitic schists. The mudrocks in particular vary considerably even within a single site. Bedding contacts are often weak and ruptured and offer little resistance under lateral or vibratory loads. Compacted mudrocks often produce differential settlements and rebound, and frequently deteriorate rapidly during construction (Ramaswamy 1975). In the completely weathered state, *in situ* strengths of approximately 0.25 to 2.0 MN/m^2 are common.

Included within the Jurong Formation is a boulder bed which has caused considerable foundation problems in and around the Central Business District (CBD) of Singapore. It is not reported in any of the geological accounts of Singapore but has been described in papers on the foundations of certain structures, (e.g. Sehested 1960). In the early 1950s, it was first encountered during the construction of the Asia Insurance Building (Nowson 1954). The caissons of a development on the south side of the Singapore River have been excavated through the boulder bed where it is at least 135 m thick, and in the foundations for a major high rise development, just to the north of the river, 65 m are reported without coring through the base. The boulder bed is normally reported because it precludes the use of pile foundations, and several of the high rise developments in the CBD are built on the boulder deposit. The foundations utilized are usually either thick reinforced concrete rafts or caissons. The deposit consists of boulders of sandstone, up to the size of a double decker bus but normally up to 2 or 3 m^3. The spaces between the boulders are filled with a stiff, overconsolidated, silty clay. The proportion of clay to boulders varies considerably from place to place, but in general range from 40–50% at shallow depths, to 90% at lower levels (Sehested 1960). The clay has an *in situ* moisture content of 10% to 27% and a cohesion of 60 to 150 kN/m^2. The boulder bed forms a lozenge-shaped deposit from the northern part of the CBD northwards to the Cathay Building, Singapore's first high rise development. It thins quickly to the east and dies out just offshore in Marina Bay. No termination of the deposit has been found in the west. The boulders are generally quite fresh with only a thin patina of weathered material. The origin of the deposit is unknown: the most likely explanation is as a landslide deposit which occurred towards the end of the deposition of the Jurong Formation. A similar deposit is found in Macau (R. Davies, pers. comm.), although of much more recent age, where a major landslide in a granite mass came to rest on soft marine clays, the clay squeezing up between the granite boulders. The antiquity of the Singapore deposit, if of the same origin, would help to account for the stiffness of the clays between the boulders. It is definitely an intraformational deposit, since undisturbed beds of Jurong Formation sandstone overlie it (Nowson 1954).

To ensure good sampling of Jurong Formation material, triple tube core barrels are essential. Coring is not a common practice in Singapore and the results are sometimes disappointing. Significant RQD is rarely measured on Jurong Formation samples, and its strength range is normally weak to moderately weak. Some sandstone bands do show significantly greater strength when fresh and recent attempts to use percussion drilling progress as an indicator of *in situ* strength proved generally unsuccessful because of the extremely rapid wear on the bit.

Geological structure

The structure of the Jurong Formation mainly comprises a series of open folds, but also includes isoclinal folds and overfolds. Parasitic folds are found on the limbs of some larger folds and these result in rapid variation in strike and dip. The general strike is NW–SE, but the dips may vary over short distances from a few degrees to vertical or even overturned (Leow 1962). Some of the mudrocks have an axial planar cleavage, although the development of this is extremely variable. In the fine-grained red mudrocks of parts of western Singapore, the cleavage is slaty and well developed, whereas in the grey silty mudrocks, the sandstones, and conglomerates, the cleavage is usually less clear and appears to be fracture cleavage. In several of the dark grey and black carbonaceous mudrocks and in the coarse mudrock clasts of some conglomerates, internal shearing has obviously taken place producing slightly curved polished and finely slickensided surfaces.

Both the basic and more acid rocks are well jointed although the patterns of jointing are quite different. The basic rocks have strongly east–west and north–south striking sets, whereas the granitic rocks have relatively randomly oriented joints, almost always vertical or sub-vertical (Hutchison 1964).

Most of the faults which cut the Jurong Formation and the plutonic rocks trend between north and northeast with a minor northwesterly group. Three major thrust faults exist in the Jurong Formation and schistose rocks, the so-called Murai Schists, are associated with two of them (PWD 1976). Apart from these, most of the faults, although fairly numerous, are quite small in scale. They are mainly wrench faults with offsets of up to 5 or 6 m, and some small dip-slip faults with a few tens of cm of displacement. Nevertheless, despite their small size the faults are normally infilled with up to 100 mm of clay gouge, which when wet is extremely soft.

Quaternary deposits

Recent sediments found in Singapore cover a large proportion of the total surface area of the island, probably in excess of half, including virtually the whole of the eastern third of the island. The Old Alluvium and the Kallang Formation are the two main drift units in Singapore.

Old Alluvium

The oldest of the drift deposits is locally called the Old Alluvium. It is an extension of a deposit found in southern Johore and exists as an extensive sheet in the offshore zone to the east of Singapore. An area of about 12 km^2 of Old Alluvium exists in the northwestern part of Singapore, but the main area is in the east of the island, where it exists as a virtually uninterrupted sheet either at the surface or buried beneath younger deposits. The maximum recorded thickness of the Old Alluvium is 195 m, although it may be even thicker. It has been recorded at a depth of −150 m (PWD 1976). Its age is probably Plio-Pleistocene and its formation may be related to downfaulted areas (Burton 1964). Its form is strongly indicative of an old alluvial succession, possibly that of a major braided river system (Gupta *et al.* 1980). It consists mainly of medium dense to very dense, semi-indurated, clayey quartzo-feldspathic coarse sand and fine gravel with cross bedding, scour marks, coarser gravel stringers and lenses of silt and clay. Recent evidence from boreholes suggests that many more beds of finer grain occur at greater depth. Most of the feldspar is almost totally kaolinized down to depths of about 8 m. The succession is highly variable vertically and laterally and appears to consist of a variety of sub-units with fluviatile associations (Gupta *et al.* 1980). A review of some basic geotechnical properties of the Old Alluvium has recently been presented by Tan *et al.* (1980). Standard penetration test values are extensively used and correlated with other soil mechanics properties by these authors.

The Tekong Formation is a thin sequence of mainly sands and gravels of littoral and fluvial origins (PWD 1976). In the area of the Padang where the original coastline was prior to the reclamation projects, fluviatile sands of the Tekong Formation possess a uniform grain size and during recent sampling work displayed a tendency to run. It is not, however, altogether clear whether this is a completely natural tendency or is, at least in part, the result of the sampling process. In some places near the coast the Tekong Formation consists not of sands but of estuarine muds, very often peaty, and sometimes of pure peat.

The overlying Kallang Formation consists of late Pleistocene and Recent deposits which are of marine, alluvial, littoral and estuarine origin. These deposits cover much of the coastal plain, immediate offshore zone and the deeply incised river valleys which penetrate to the centre of Singapore Island. By far the most important unit of the Kallang Formation is the Marine Member locally called the 'marine clay'. It occurs over an area covering one quarter of Singapore Island, but no surface outcrops exist. Its thickness is extremely variable with a maximum recorded of 35 m. It comprises an upper and lower part, although in some areas only one part may exist. The marine clay is pale grey to dark blue in colour, soft, silty, kaolinite-rich and has shell fragments disseminated throughout. It contains intercalations of sand, silt, peat and shells. An activity value of 0.95 perhaps indicates a more complex mineralogy (Lim 1982), possibly the result of weathering of the original clay minerals. The maximum recorded elevation of the marine clay is +2 m above sea level (Tan & Lee 1977) and resulted from major changes of sea level, which occurred during late glacial and post-glacial times. When sea level dropped, valley floors were scoured to the new base level. As sea levels rose after the final glacial episode, the valleys were flooded and the lower member was deposited up to about 12,000 BP. When sea level dropped again, during the Younger Dryas, the top of the lower member became vegetated, weathered or covered with sandy, shallow-water deposits. As the sea level rose again, from about 10,000 BP, the upper member was deposited, reaching a level of +2 m during the post-glacial climatic optimum of 5000–6000 BP. The upper and lower members are separated by a weathered crust on top of the lower member, and the clay in this zone is much stiffer.

Geotechnically, the marine clay is problematical. The *in situ* moisture contents show levels at or close to the liquid limit, the settlements are very great and the cohesive strength low. The clay is normally consolidated and except for the desiccated layer produces a maximum *in situ* vane shear strength of about 36 kN/m^2 at 21 m, giving c/p ratios of 0.25. The effective strength parameters are approximately $c' = 0$, and $\phi' = 18°$ to 20°. A comparison of some properties of the Singapore marine clay with other marine clays from elsewhere in the world is summarized in Table 2.

The marine clay has a weakly flocculated structure with no large open areas. This results in a medium sensitivity of up to 8. The silt particles are subrounded, which further discourages an open structure (Barden 1972). The presence of a variety of microfossils confirms the marine origin of the clay. Layers a few cm thick and containing marine gasteropods and oyster-like bivalves also occasionally occur.

Unlike most of the post-glacial marine clays in the world, the Singapore clay does not become siltier with depth, retaining its essential characteristic of 65–70% clay throughout. However, contrary to most of the published reports, it is not as homogeneous as suggested. Lateral variation tends to occur where the marine clay abuts against hills which stood above sea level at the time of its deposition. The characteristics also tend to vary at different points around Singapore and, in some areas, sand seams, silt lenses or organic layers exist. Recent excavations for the basement of an hotel in the city centre revealed the presence of significant beds of red-brown sand and also occasional beds of virtually pure clay. This layered structure also appears to exist on part of the south coast of Singapore Island and supports the findings at the experimental dyke at the Pandan reservoir. Attempts to accelerate settlements (Table 3) by providing vertical sand drains proved unsuccessful, in that the sand drains were shown to serve little purpose (Harvey 1982). Drainage of excess pore pressures took place along the interbeds of coarser material within the marine clay. Each interbed reduced the length of the drainage path and thereby accelerated the settlement to virtually the same rate as that for the clay with vertical sand drains. These findings also show that the surprisingly high values of mass permeability reported (Ahmad & Peaker 1977) to be more realistic in some places. Those values, of 10^{-3} cm s^{-1} are very different from the laboratory tests which give results of 10^{-8}–10^{-10} cm sec^{-1}. The seams of sand and possibly the shelly layers may explain the disparity to some degree. However, no location for the permeability tests is cited and such non-homogeneity is not found in all locations.

Some experiences of strutted excavation in marine clay have been published by Tan (1972). Heave of the

TABLE 2. *Comparison of Singapore marine clay with other marine clays*

		Marine clay		
Properties	*Singapore Marine clay*	*James Bay Marine clay, Canada*	*Leda clay, Canada*	*Norwegian Marine Clay*
Cu (kN/m^2)	4–76	19–77	38–96	7–28
Sensitivity	8	2–12	7–32	42 (ave.)
Moisture content %	30–91	22–38	28–50	27–40
Liquid limit %	50–110	26–38	20–45	25–36
Plastic limit %	18–22	14–18	18–24	17–20
Plasticity index %	30–75	5–18	5–20	6–20
Bulk density (Mg/m^3)	1.3–2.0	1.8–2.0	1.7–2.0	1.6
c'	0	0	0	0
ϕ'	12–16°	30–32°	25–30°	26–30°

Modified after Ahmad & Peaker 1977.

TABLE 3. *Observations of settlement of a trial dyke for the Pandan reservoir built on marine clay*

Degree of consolidation	*Without vertical sand drains* (%)	*With vertical sand drains* (%)
Theoretical approach	10	50
From pore pressure cells	41	44
From settlement apparatus	55	58

After Harvey (1982).

base of excavations in marine clay is common. For an excavation with a critical depth of approximately 5 m, 75 mm of heave is commonly experienced. Beyond this, the heave becomes considerable, and heave of 0.6 m is reported in excavations of 6 m. The close proximity of other buildings necessitates, in strutted excavations, the installation of the first strut long before any critical depth is reached. Also, a large difference exists in the amount of damage at the edge of the excavation depending on whether the wale beams have wedges driven at their ends in contact with sheet piles. One example of a 15 m basement with wedges produced very little movement, whereas at an adjacent, much shallower (6 m) strutted excavation without wedges, the movement was much worse. At a construction site for an hotel in the city centre, the 18 m deep basement excavated in marine clay has retaining walls of 1.5 m diameter contiguous bored piles and 0.8 m thick slurry trench walls, each penetrating 4 m below formation. The groundwater table was 1.5 m below the surface. Lateral movements of the walls of only about 10 mm were recorded during excavation of the first two basements.

In addition to the natural landscape, Singapore is extending her boundaries with large reclamation projects. Most of these are areas of hydraulic fill, and the southern terminus of the north–south line of the MRT at Marina South will be on such a reclaimed area. A major reclamation project providing 650 hectares of land for the new international airport at Changi involved the use of such hydraulic fill. Soil improvement works are normally required for the fill and for the underlying material which is commonly marine or alluvial clay of the Kallang Formation (Choa 1980). Some areas of the CBD are on land reclaimed in the middle of the nineteenth century, where fill, old sea walls, and old foundations are frequently encountered to depths of 6–7 m. Beneath that is normally found about 3 m of sand which formed the old beach.

The influence of weathering

Weathering plays a major role in altering the fabric of the rocks in Singapore. The residual soils which are produced tend for the most part to vary between clayey sands and sandy clays. The igneous rocks have regoliths of up to 30 m thick, but on low-angled slopes there is little gradation of weathering grade and corestones are rare. Hence, in many areas, particularly low lying ones, a sudden change from Grade VI to Grade III or possibly Grade II is common (Komoo 1982). Occasionally, hard material is encountered within completely weathered granite; in general, these are not granite corestones but finer-grained aplite dykes. The use of Grade VI to cover the full thickness of residual soil is, however, misleading because pedological processes take over from those of weathering and a stratification of the residual soil ensues. This may take the form of redeposition of iron compounds as hard pans, zones of fines enrichment or fines depletion, and concentrated organic layers. The regolith also shows a steady but marked increase in clay content upwards from the main body of rock (Nossin & Levelt 1967). The major differences between regoliths on the basic igneous rocks and those of the 'granitic' suite is the sand content, and this simply reflects the general absence of significant quantities of quartz in the parent gabbroic material. The soils derived from the 'granitic' rocks in particular are generally strong and very stable in almost any depth of excavation. However, there are exceptions, and considerable instability has resulted at seepage points in hillsides from the top of thin seams of white clay (Sehested 1960). In some instances, it is difficult to differentiate some of the Quaternary deposits from weathered bedrock, particularly in the case of the white and grey sandy clays and clayey sands.

The residual soils on the Jurong Formation tend to form on mixed arenaceous–argillaceous successions. The soils generally contain between 35 and 50% of clay size material, with fine to medium sand making up most of the remainder. A very small silt content is present, producing uneven particle size distribution curves (Fig. 2).

The weathering can produce Grade V rock down to 45 m, and sometimes deeper. The high fracture frequency and inherent porosity of the sedimentary rocks renders corestone virtually unknown and, although the structure of the rock tends to be well preserved to great depth, the rock itself is often weak and friable. The weathering often masks the fact that not all of the

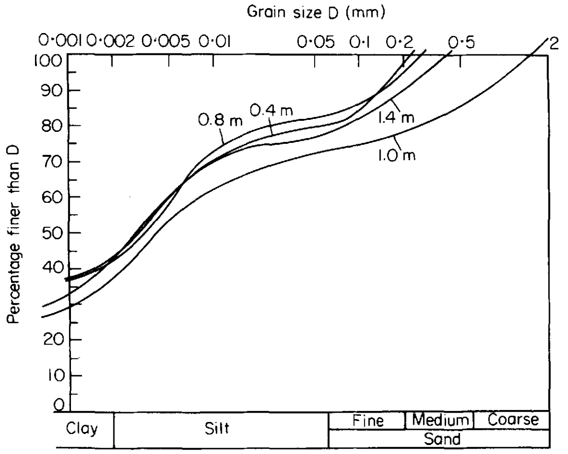

FIG. 2. Particle size distribution curves for some residual soils on a Jurong Formation sandstone-mudrock succession in western Singapore.

sandy clay soils are true residual soils, that is where transportation of material has been of a low order. Many slope wash deposits exist, and old vegetation layers and stratified residual soils buried beneath slope wash are occasionally found. Seepage from more permeable buried horizons has been the cause of several small-scale slope failures in western Singapore, (Pitts, 1983). The tendency to use piles so extensively has effectively ensured that there is little real understanding of the properties and behaviour of local residual soils. In view of the widespread distribution of these materials, it represents a serious gap in our knowledge and misses a possible opportunity to design a wider range of more economical foundations.

Buried channels

Variation in the thickness of soils is a very great problem and it is quite common in Singapore to see rows of piles protruding at the surface by different amounts. The lower and upper surfaces of the Old Alluvium are extremely undulating and the base of much of the Kallang Formation depends on the patterns of erosion generated by the varying sea levels in post-glacial times. The eroded channels which contain the marine clay are extremely steep-sided, and pile penetrations varying between 5 m and nearly 30 m in a distance of 1 m separation are reported (Sehested 1960).

Many of the major routeways in Singapore follow the path of infilled channels which were cut during glacial times. Many of the stations for the MRT are also to be sited along these routeways. The channels tend to be extremely steep sided, and dramatic changes in geotechnical conditions have been encountered in many parts of the city. The successions encountered within the buried channels are enormously variable, both vertically and laterally, but commonly consist of some configuration which includes fill, peat or peaty silts and clays, beach sand, marine clays, fluviatile sands and completely weathered bedrock. In some areas, fill has been deposited directly on to highly organic soils contained within a buried channel. Subsequent dewatering has caused large amounts of settlement and a circular depression of about 0.5 km diameter in an area west of the city centre contains several piled structures which have developed gaps between the pile cap and the ground surrounding it.

Groundwater

In many of the low areas of Singapore. the water table is within 1.5 m of the surface, and this causes particular problems in the areas of infilled buried channels. Construction excavations in the Recent deposits usually require considerable support and dewatering of the excavation. Sheet pile walls are utilized where depths are not great. In deeper basements, fully braced excavations, contiguous bored piles and diaphragm walls are all used.

In a recent project involving the excavation of deep caissons, relief wells were sunk to lower the groundwater pressures in steeply-dipping Jurong Formation rocks. A buried channel immediately adjacent to the site had piezometers installed within the infilling soft soils. Very little change in the piezometric head was recorded and it seems that a layer of clay at the base of the Recent succession has effectively isolated the Recent soils from the rocks as far as groundwater is concerned. The groundwater in the soils of the Recent succession is perched (R. Davies, pers. comm.).

In some locations, for example at the bottom of the Recent succession in the major buried channel trending northwards from the city centre, a thick wedge of fluviatile sand exists. High confined groundwater pressures may be expected at such locations, although significant artesian head is not often reported. In the northern part of the CBD, near to the Singapore River, groundwater levels are influenced to the extent of approximately 0.5 m by tidal action (R. Kannan, pers. comm.).

Only on the higher ground does the water table become much deeper, although how deep has not been widely determined. In the area of the Tan Tock Seng inlier, a hill less than 20 m high composed of Jurong Formation rocks, it is at about 10 m below the surface. These deeper groundwater levels have in turn led to some slope stability problems in certain areas. During heavy rains in late November 1982 a large number of slope failures occurred. Those recorded were on slopes in residual soils and highly to completely weathered Jurong Formation rocks in part of the west of Singapore Island (Pitts, 1983). The stability of the slopes where water tables are deep seems to depend on the level of the negative pore pressures maintained in the near surface layers. During periods of particularly intense rainfall, the negative pore pressures are in part destroyed by rapid percolation of water from the surface. On such occasions, the effective strength of the soil drops sufficiently for failure of the slopes to occur.

Conclusion

The geology of Singapore requires a great deal of further investigation. Furthermore, a more systematic approach to soil sampling and testing is urgently required. The forthcoming MRT construction is very likely to improve the situation and it is to be hoped that once started, thorough site investigation will be seen as an essential prerequisite to civil engineering construction in the future. The work of the PWD Special Services Department on the island-wide resources survey is also adding to the geological information. It is, however, most important that the existing information is collated and that some post-constructional monitoring of structures is encouraged to check design assumptions. In the last case, the reclamation projects undertaken around Singapore have been carried out as completely separate contracts with no continuity. It is, therefore, hardly surprising that contractors are reluctant to install expensive monitoring equipment which may ultimately be for the benefit of a competitor. It is essential, though, that experienced engineers should not have further cause to comment on the poor knowledge of the engineering geology of Singapore.

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