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Recent advances in the knowledge of geology, mineral and energy resources of Singapore since 1981

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INTRODUCTION

Singapore does not have a single agency investigating the various aspects of its geology. Various organizations investigate those aspects of geology that affect their activities. Since 1981 the developments in geology and related earth sciences came about as a result of either the continuing activities of relevant agencies, e.g. offshore geophysical surveys by the Port of Singapore Authority, or the problems and investigations ensuing from developments within the country, e.g. collection of geotechnical information by the Mass Rapid Transit Corporation. This paper will describe the developments in various aspects of geology and related earth sciences in Singapore since 1981. A summary of the activities of the various organizations and the information they collected since 1981 is first presented.

ORGANIZATIONS INVOLVED IN GEOLOGICAL INVESTIGATIONS IN SINGAPORE

Various government and private organizations that have been collecting or providing information about geology, energy and mineral resources of and in Singapore are listed in Table 1. Their major activities from 1981 to the present are also indicated; highlights of the activities of some of these organizations are summarized below.

Singapore joined the Committee for Co-ordination of Joint Prospecting for Mineral Resources in Asian Offshore Areas (CCOP) in the early 1970s and has since been represented by the Economic Development Board. Although there are no offshore petroleum exploration activities within the country to benefit fully from the CCOP programmes, some benefits have been provided by CCOP in recent years, e.g. seismic profiler surveys (Ringis, 1980), training courses and seminars for geoscientists. During its feasibility study for the establishment of a Regional Centre for Quaternary Geology in Southeast Asia, the fact-finding mission from CCOP visited the National University of Singapore (then University of Singapore), Public Utilities Board, Public Works Department and the Port of Singapore Authority and found enough interest and activity in Quaternary studies that would benefit from the establishment of such a centre (van de Meene *et al.*, 1980).

The Geological Unit of the Public Works Department, which was formed in 1972, has been maintaining its role to prepare and update continuously the geological maps of the republic, assess the engineering and geotechnical characteristics of the rock formations, study the sources of construction materials and other natural resources and provide expert and consultative advice on geological matters. The establishment of the MRT (Mass Rapid Transit) Laboratory and geotechnical investigation of subsurface material along the pro
 TABLE I

 MAJOR GEOLOGY-RELATED AGENCIES AND THEIR ACTIVITIES IN SINGAPORE, 1981-PRESENT

	NAME OF AGENCY	MAJOR ACTIVITIES IN GEOLOGY & RELATED SCIENCES		
I	INTERNATIONAL			
	Committee for Co-ordination of Joint Prospecting for Mineral Resources in Asian Offshore Areas (CCOP)	Provided assistance in conducting geophysical surveys off the east and southeast coast		
п	NATIONAL/GOVERNMENT	· · ·		
	1. Public Works Department (PWD) Geological Unit	 a. Reprinted the 1976 publication and geological maps b. Borehole data collected by PWD and others are now available to users c. Continue to give advice on geology, administer quarries and conduct geotechnical investigation d. Setting up the MPET to horartory. 		
	2. Port of Singapore Authority (PSA)	 a. Land reclamation b. Offshore surveys for reclamation and dredging c. Development and maintenance of beaches and harbours 		
	3. Housing and Development Board (HDB)	Land reclamation		
	 Resources Development Corporation (RDC) Mass Rapid Transit Corporation (MRTC) 	Quarrying for granitic rocks, sand and clays Geotechnical investigation related to construction of the MRT		
ш	TERTIARY INSTITUTIONS			
	 National University of Singapore (NUS) Geography Department Civil Engineering Department Nanyang Technological Institute (NTI) School of Civil and Structural Engineering 	Research projects on Old Alluvium, beaches, and surfacial materials Research projects on engineering properties of earth materials for various purposes Research on geotechnical properties of earth materials and slope stability		
IV	OTHERS	· · ·		
	 Southeast Asian Petroleum Exploration Society (SEAPEX) 	 a. Conducts regular seminars and biannual offshore conference on geology related to petroleum exploration in Southeast Asia b. Publishes and makes available information related to geology and tectonics of Southeast Asia and the Pacific 		
	2. Private organizations	· · · · · · ·		
	 Geotechnical consulting companies e.g. Dames & Moore 	Some useful geotechnical data collected but not really available to the general public		
	ii. Small companies servicing oil exploration in the region, e.g. Robertson Research	Data collected by them are not directly related to or about Singapore		

posed route of the MRT have also been its major activities during 1981-84. From late 1983 the Public Works Department makes available bore hole data to developers and other users.

The Geography Department of the National University of Singapore (NUS) continues to seek information on various aspects of geology and other related earth sciences on Singapore. Among the major projects that were completed after 1981 or currently in progress are 'Study of Old Alluvium' (Gupta *et al.*, 1980), 'Study of Beaches in the Eastern Part of Singapore' (Wong, 1981), 'Hydrological Properties of Surfacial Material' and 'Electrical Resistivity Surveys' (Devi, 1982). The Civil Engineering Department of the NUS has mainly been concerned with the geotechnical properties of near surface material for stability (Ramaswamy *et. al.*, 1982a) purposes or for constructional material (Ramaswamy & Aziz, 1982; Ramaswamy *et. al.*, 1982a). The ongoing projects in this department include 'Lime Stabilization of Singapore Peaty Soils', 'Selection of Singapore Rocks for Durable Concrete', and 'Prevention of Rain-induced Erosion and Earthslips in the Context of Highway Development' (Personal communication, M.A. Aziz).

The School of Civil and Structural Engineering of the Nanyang Technological Institute (NTI) offers courses in geology for civil engineers, engineering geology and soil and rock mechanics. A geology and rock mechanics laboratory has been established with a wide range of equipment for laboratory and field use including geophysical prospecting. A series of international seminars on an annual basis has also been established. The first one on 'Construction Problems in Soft Soils' was held in December 1983. The 1984 seminar is on 'Piling' and the 1985 one will be on 'Residual Soils and Weathered Rocks'. Several publications have resulted from the activities of the NTI School of Civil and Structural Engineering (Pitts, 1983a; 1983b; 1984a; 1984b; 1984c; Pitts & Kannan, 1984).

Most of the private geological organizations in Singapore are involved in petroleum related activities. The publications by and available through the Southeast Asian Petroleum Exploration Society (SEAPEX) form a significant geological information source in Singapore. Its *Membership Directory* (1984 edition, especially pp. 33-47) provides a list of organizations that are directly or indirectly related to petroleum activity in this region. The *Directory of Geoscientists in Southeast Asia* (1982) also provides an insight into the organizational expertise available in geosciences in the private sector in Singapore. With the approval of the MRT project in 1983 a number of highly specialized companies have moved into Singapore to offer their geotechnical services.

DEVELOPMENTS IN PURE GEOLOGY

To date the *Geology of the Republic of Singapore* with its 79 pages of text and 8 coloured geological maps at a scale of 1:25,000 published by the Public Works Department (1976) remains the most detailed account of Singapore's geology. No revisions or amendments have since been published. A summarized map and tables extracted from this publication are presented in Figure 1 and Table 11. Very few studies have been conducted in the past few years to expand the information on basic geology of Singapore.

The Geography Department of the NUS has a project which involves the detailed field and laboratory investigation of the Old Alluvium in the eastern part of Singapore Island. In the first report of this project Gupta, *et al.*, (1980) identified four major lithological units in the



Fig. 1 Simplified Geological Map of Singapore Extracted from *Geology of the Republic of Singapore* (1976). Source: Singapore '82, published by the Information Division, Ministry of Culture, p. 180.

Old Alluvium: coarse sand with fine pebbles, medium to coarse sand, silt-clay and pebble bed. The mapped areas of these units decreased in the same order and the deposit was found to be overwhelmingly sandy. Based on detailed observation of several sections where the sedimentary features were clearly marked, the authors attributed the possible genesis of the Old Alluvium to deposition by bedload channels, probably braided. No fossils were found in this study and they did not consider this deposit to be of marine origin.

In another study the CCOP Project Office assisted the Port of Singapore Authority to carry out a seismic profiler survey off the east coast of Singapore. This multipurpose survey aimed to delineate areas off the east coast of Singapore which may be underlain by sandy deposits suitable for reclamation purposes, try to determine the pattern of sediment movement in the area, with particular emphasis on the structure of the Johore Shoal and elucidate the history of deposition of sediments in the area. The results of this survey were reported in several of the CCOP publications, e.g. their *Newsletter* (vol. 7, no. 3, September 1980) or their *Proceedings* (Ringis, 1980).

A total of 172 line-km of seismic profiling in an area of over 100 km² with lines at 1 km intervals in an east-west direction and 1-2 km intervals in a north-south direction were completed. The results indicated a relatively complex pattern of sedimentation over the area. Old Alluvium was inferred to be occurring in most of the surveyed area and its surface was found to be incised by several channels having a depth of 35 m or more in the southwestern part and to about 90-95 m below sea level in the southeastern part. The deepest channel is interpreted to have been the previous channel of the Johore river, which was incised into the

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FORMATION	ROCK TYPE	GEOLOGICAL AGE	LOCATION
Kallang (youngest) Tekong Huat Choe	Alluvium of different types	Pleistocene to Holocene	In river valleys, along coasts, in isolated patches
Old Alluvium	Coarse semi-hardened sand with clay and pebbles	Early Pleistocene	East Singapore: Tampines, Changi Bedok, Siglap North Singapore: Buloh Besar area
Jurong	Sedimentary rocks — mainly shale, sand- stone and conglomerate	Late Triassic to Early Jurassic	South, southwest and west Singapore, nearby islands
Bukit Timah Granite	Igneous rocks: granite, granodiorite, and varieties thereof	Early Triassic	 (1) Central, northern and parts of northeastern Singapore (2) Changi and Pulau Ubin
Gombak Norite	Basic igneous rocks	Paleozoic	Central Singapore
Paleozoic Volcanics	Volcanics	Paleozoic	Pulau Tekong and nearby islands
Sajahat (oldest)	Metasediments	Paleozoic	Pulau Tekong and nearby islands, Punggol Point

TABLE II ROCKS OF SINGAPORE (IN ORDER OF THEIR AGE)

Source: Singapore '82, published by the Information Division, Ministry of Culture, p. 179.

surface of the Old Alluvium during one or more periods of lower sea level. Subsequent fluctuations of sea level resulted in a complex pattern of sedimentation (for example, clayey sand in the northwest or coarse sand in the southeast) covering the surface of the Old Alluvium with sediments that were probably derived through reworking of the Old Alluvium itself from adjacent areas.

The Johore Shoal was inferred to be a relict feature which was built as a spit during a past period of lower sea level. The major part of the survey area and especially the deeper central parts are inferred to be receiving only fine mud at present time, brought into the area in suspension by the Johore river and the smaller rivers flowing into it from the north and the northeast.

In the northern and northeastern part of the surveyed area the acoustic basement was inferred to 'consist mostly of metamorphic rocks, with some possible igneous basement in the northwestern section' (Ringis, 1980. p. 228).

The reports of the survey indicated the sites where sediments suitable for reclamation could be found. Dredging is in progress at some of these sites. For a better and more detailed

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interpretation of the seismic results, the reports also recommended the drilling of 18 boreholes to reach the bedrock or at least 30 m below sea level.

During a survey for the construction of the Changi International Airport, Choa *et al.* (1981) had also reported buried channels cut into the Old Alluvium; these were filled with marine clay which they considered belonging to the Kallang formation. Borehole data indicated that the marine clay exists in two distinct layers separated by a transition zone having organic matter and/or mottled reddish brown tissued clay. This was interpreted as desiccation due to sea level change.

Pitts (1983b) provided additional information and interpretation for the origin, nature and extent of recent deposits in Singapore. In addition to a survey of published information and field and laboratory investigation, he made use of unpublished information available through investigation for the MRT. He inferred that the Tekong Formation may have a much wider distribution at depth than its limited surface outcrop as it was encountered at several points during the site investigation for the MRT subway. He also found the littoral members of the Tekong Formation to be very similar to those of the Kallang Formation both lithologically and geotechnically. From these data longitudinal and transverse sections were constructed along the valley buried by these recent deposits. While the Alluvial Member was found to be mostly thin, rarely exceeding 8 m in thickness, the Transitional Member reached a thickness of up to 13 m in the Central Business District; the Marine Member, though having an extremely variable thickness, reached a maximum thickness of 35 m. Based on the more recent borehole data Pitts modified the isopachous (isopachyte) map presented by Lim (1982) for the Marine Member of the Kallang Formation in the Singapore city area. The Marine Member was also believed to be far less homogeneous than has been widely believed. The anisotropic and hetergeneous nature of this Marine Member would have significant geotechnical implications.

There are some unpublished reports providing information about the subsurface geology in Singapore. Devi (1982), for example, determined the electrical resistivity and selfpotential in the three most widely distributed rock groups in Singapore and interpreted the results to provide information on overburden thickness, approximate location of formation boundaries and depths to the water table at various sites.

DEVELOPMENTS IN GEOLOGICAL RESOURCES

Aside from some non-metallic earth materials used for construction purposes, Singapore does not have any economically exploitable energy or mineral resources. The exploitation of earth materials for construction purposes continued during the past three years. Due to its location and services available Singapore also continues to provide services and facilities for energy-related activities in the region. Some of the more important aspects are discussed below.

EARTH MATERIALS FOR CONSTRUCTION PURPOSES

These include (1) granites and other, mostly plutonic, igneous rocks, (2) sand and gravel, and (3) clays for brick-making and ceramics.

Granite and related rocks

The Geology of the Republic of Singapore reported nine quarries located in the Central Singapore Granite and three on Pulau Ubin. In 1983, sixteen quarries were in operation of which five were under the management of the Resources Development Corporatioh and the rest were privately owned. The total production was 12.1 million tonnes³ used mainly for construction and road making.

Some engineering properties of rocks used in road and pavement construction were studied by Ramaswamy and Aziz (1981; 1982). In the first study, various igneous and sedimentary rocks including 'granite, microgranite, granodiorite, dolerite, gabbro, andesite, sandstone, siltstone and shale' (Ramaswamy & Aziz, 1981, p. 463) collected in Singapore were tested in the laboratory for the 'polished stone coefficient' and other standard tests mainly to evaluate the 'skidding resistance'. Results seemed to indicate that the behaviour of the rocks followed the order as listed above, i.e. granite exhibiting the most desirable and shale the least desirable characteristics.

In the second study (Ramaswamy & Aziz, 1982), the influence of shape and gradation of coarse granitic aggregates was tested in the laboratory for the stability of bituminous mixes for use in surface wearing course of roads. In terms of the (Marshall) stability and (Tensile) strength, the performance of mixes decreased with the following shape of the aggregates : elongated > irregular > flaky.

Sand and Gravel

Old Alluvium remains the major source of sand and gravel on land. The number of sand quarries declined over the years as many of the smaller quarries exhausted their reserves. By 1983, of several quarries in existence, only three were in active production throughout the year; two were managed by the Resources Development Corporation and one was privately owned. The total production for 1983 was 2.6 million m³.

In addition to quarrying activities, coastal reclamation has also led to an increasing utilization of material from the land and sediments dredged from the sea during the past few years. For example, most of the fill material (over 110 million m³) for the East Coast Reclamation Scheme was provided from the neighbouring deposits of Old Alluvium on land. Fill material for the Changi Reclamation Scheme comprised of sediments from the adjoining seabed which was most probably an offshore extension of the Old Alluvium (Tham, 1984).

Aside from providing material for land reclamation, the sediments are also used for construction purposes including the making of concrete from washed sand. The suitability of sand dredged from the sea for concrete construction was studied by Ramaswamy *et al.* (1982c) who found it to be suitable in most cases. Use of sea sand for concrete construction would, according to the authors, increase the amount of this resource available in Singapore.

Clays

Any active construction industry of magnitude existing in Singapore would require numerous clay products such as bricks, sanitary wares, etc. W.N. Tan (1983) has reviewed the ceramic production in Singapore and described the location, historical development,

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activities and other aspects of the various ceramic industries in Singapore, in addition to identifying the sources of raw materials for these industries. Except for the kaolin-rich Huat Choe Formation, which has now more or less been exhausted, there are no extensive fine (pure) clay deposits in Singapore. Clay deposits are, nevertheless, found on the island especially in the Jurong Formation but these do not cover large volumes of uncontaminated clays. As a result, the local clays are suitable only for stoneware or earthware products and are thus used for manufacturing bricks and flowerpots. For high-value ceramic products such as porcelain and vitreous china the clays have to be imported.

Except for the decorative and studio potters, all the clay for industrial works are located in the western and southwestern parts of Singapore on the Jurong Formation, influenced by their proximity to the clay sources. Clay has also been supplied from excavations in other geologic formations but these comprise small amounts. According to Tan (1983) there is enough clayey material available, mainly in the Jurong Formation, for the local brickworks and other related industries. There are some unpublished reports on clay resources prepared and available for some brickworks.

ENERGY RESOURCES

Singapore is involved in various activities related to petroleum exploration, development and distribution. These activities depend on global and regional developments related to oil which during the past few years were not very favourable, e.g. depressed economies of the developed countries,oil producers setting up their own refineries. The response by Singapore to these new developments included the following: (1) formation of the Singapore National Oil Company (SNOC), (2) oil storage, (3) energy conservation, (4) study and development of alternate energy resources, (5) reduction in refining and increase in other activities. These are discussed briefly below.

Singapore National Oil Company (SNOC)

The government- owned SNOC, set up in August 1980, was authorized to undertake a wide range of activities under its articles of incorporation, such as refining, storage, supply and distribution of petroleum and petroleum products, and oil exploration (*Business Times*, April 29, 1983). Its major activities so far include stockpiling/storing of oil to meet Singapore's requirements, involvement in the project to pipe natural gas from Peninsular Malaysia and discussions with Petronas (Malaysian National Oil Company) on possible purchase of crude oil (*Straits Times*, October 4, 1983; *Business Times*, April 29, 1983).

Oil Storage

Soon after its formation, the SNOC started the stockpiling of 3.3 million barrels of crude oil in two VLCC's (very large crude carriers) anchored in Singapore's waters (*Business Times*, April 29, 1983). With the subsequent oil glut, Singapore scrapped the crude oil stockpile and is now moving towards product stockpiles by major consumers (*Straits Times*, October 4, 1983). Two major oil storage terminals are also being developed as a move to further develop the republic as a major oil trading centre. The first, which is a joint project of SNOC, Port of Singapore Authority, Jurong Town Corporation and a Dutch company, will be built on Pulau Busing with a storage capacity of 1 million m³ and it will be ready by 1987. The other, partially operational at Pulau Sebarok, will provide a capacity of 800,000 m³ (*Straits Times*, February 5, 1983).

Energy Conservation

The government continues to emphasize the need for energy conservation although this is not as pressing as was in 1979-81. For example, there is continuing crackdown on energy wasters through legislation and price structure, continuing public education on the need to conserve energy and adjustments of prices of petrol, gas and electricity according to the market price of oil (*Straits Times*, October 4, 1983).

Alternate Energy Sources

Alternate energy sources that have been considered or are being developed include natural gas, coal and nuclear energy.

Natural Gas. Both Malaysia and Indonesia want to develop their offshore gas fields for their own use. It is proposed to bring additional gas, through pipelines, to Singapore (*Straits Times*, October 4, 1983). From Indonesia the proposal recommends linking the Arun gas reserves in North Sumatra and the Natuna fields in the South China Sea to the Batam Islands and then connecting to Singapore. From Malaysia the natural gas from the offshore Trengganu field will be piped via Kerteh to Klang and then to Singapore. Greater progress in negotiation has been made with Malaysia and the pipeline is expected to reach Singapore by 1988 (*Straits Times*, October 4, 1983).

Coal. Several feasibility studies on coal-fired power stations were conducted prior to 1981. These earlier plans for three coal-fired stations have recently been shelved by the government for a number of reasons: coal was attractive during the oil crisis of the '70s but not so in this period of oil glut, its dubious environmental effects (pollution), uncertainty of supplies, large investment outlay required to build coal-fired stations, receiving depots, etc., Malaysian gas supply would be ten times cheaper than changing to coal (*Straits Times*, October 4, 1983).

Researchers on energy resources realize that the global coal supplies will well outlast the oil supplies and coal will come back as a major energy resource after oil has run out; therefore, the Singapore government has not entirely dismissed coal as an alternate energy source. As a result, Singapore has joined other ASEAN members to undertake a coal development study sponsored by the Economic and Social Commission for Asia and Pacific (ESCAP), United Nations Development Programme (UNDP) and Asian Development Bank (ADB). The study covers the feasibility of regional coal purchases, establishment of regional coal depots and other issues (*Straits Times*, October 4, 1983).

Nuclear Energy. Nuclear energy is attractive to Singapore for several reasons, e.g. nuclear power is cheaper, in view of limited water resources the cheaper power can be used to run desalination plants, etc. But mainly because of safety considerations the nuclear energy option is not actively pursued in Singapore.

Oil Refining and Other Activities

The future for Singapore's oil refining industry does not seem bright. According to reports in the local newspapers (*Straits Times*, October 4, 1983; *Business Times*, December 29, 1983) Singapore, currently the third largest refining centre in the world with a refining capacity of 1.1 million barrels, will utilize only half of this capacity by 1995. Several reasons have been cited for this drop in refining: new refineries to be constructed in Indonesia, Malaysia and the Middle East, global oil glut, substitution efforts, poor success in developing alternate business, e.g. with India, China, etc. Several recommendations have been proposed to combat this decline; these include consuming more fuel domestically, reversing the trend of substitution, cooperative multinational refining, changing the roles of oil industries (from refiners to traders), diversification, e.g. building petrochemical complex, etc. Fortunately, the forecasts have not yet come true due to several factors: the refineries in the neighbouring countries are not completed yet or are not operating without problems, traders are processing more oil with local refineries, spinoffs generated for Singapore by the Chinese offshore exploration programme.

Aside from refineries, Singapore also offers many services for oil and gas exploration in the region. Even though oil and gas exploration in Southeast Asia has been more active than anywhere else, business for Singapore's offshore support industry seems to be declining since the neighbouring countries are pushing for greater local involvement in services and operations at all levels (*Straits Times*, October 4, 1983). In view of these difficulties the local industry seems to be geared towards some of the above recommendations. Several companies, for example, are teaming up for operation in China. Refineries may also move into terminalling and it seems that Singapore's oil industry will be presenting itself as a fully integrated industry incorporating refining, terminalling, trading, offshore logistic support, etc (*Straits Times*, October 4, 1983; *Business Times*, March 10, 1983).

DEVELOPMENTS IN APPLIED GEOLOGY

Most of the geological investigations within Singapore are of applied nature related directly or indirectly to rapid urban development. These can be grouped under (1) land reclamation, (2) geotechnical studies including investigation for foundations and the MRT and slope stability, and (3) urban geomorphology, hydrology and soils including studies of beaches, sedimentation, floods and soil characteristics. The developments in these areas during the last three years are discussed below.

LAND RECLAMATION

Any study on the surfacial geology of Singapore would need to consider the reclaimed land as the land area is continually increased through land reclamation. Thus, three per cent more land area was added through reclamation since 1981 as shown in Table 111. Tham (1984) reviewed various aspects of reclamation in Singapore in order to determine the nearsurface hydrological properties of various types of reclaimed land. In terms of their location and/or major use the various reclamation projects can be categorized into seven schemes. A list of these schemes and some information about them is presented in Table IV.

In all major reclamation projects the fill materials were taken from nearby land or seabed for reasons of economy and environmental protection. The choice of material and the

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Year	Total Land Area (km ²)	% Increase since 1965 (Resulting from land reclamation)
1965	581.5	
1970	586.4	0.84
1975	598.8	2.63
1980	617.8	6.24
1981	617.9	6.26
1982	618.1	6.29
1983 (July)	636.0	9.37

TABLE III	
TOTAL LAND AREA OF SINGAPORE INCLUDING THE OFFSHORE ISLANDS.	1965-1983

Source: Tham (1984)

methods of reclamation and compaction depend mostly on location and intended use of the area. Thus, many of the East Coast and Jurong reclamation schemes, on which urban and industrial structures were to be built, comprised of heterogeneous sedimentary material and subjected to high values of compaction; some of the islands and coastal areas on which no large structures were to be erected were reclaimed by lightly compacted sand. Tham (1984) has provided further details on the methods of reclamation.

There have been several other unpublished reports and published papers describing the various technical, mainly engineering, aspects of reclamation in Singapore. These papers were presented at the Workshop on Coastal Geomorphology in Singapore in August/ September 1979, PORTECH 82: International Ports Technology Conference in Singapore in June 1982 (e.g. Rajendra et al., 1982) and the International Conference on Land Reclamation in England in April 1983 (e.g. Radhakrishnan et al., 1983; Wei & Lim, 1983). In addition to these, the annual reports of the various agencies involved in reclamation contain information about reclamation in Singapore. Most of these publications and reports were reviewed by Tham (1984) whose study is the first attempt at determining systematically the near-surface hydrological characteristics of the reclaimed land. Her results showed that the infiltration rates were affected by the type of fill material, vegetation, land use and the degree of disturbance after reclamation. The subsurface hydraulic conductivity also showed a wide range of values depending upon the type of fill material at various depths, inwashing of fine particles and varying degree of compaction of the fill material at various depths. One important and interesting finding of this study was that the conventional methods of flow measurements had to be modified for reclaimed land mainly due to the lack of lithification or cohension in the fill material.

GEOTECHNICAL STUDIES

Two aspects of geotechnical studies that have received significant attention in Singapore during the last three years are geotechnical properties of the near-surface material and slope stability. More information is being obtained for the first aspect as investigations for the MRT subway continue.

	MAJOR RECLAMATION SCHEME	PERIOD OF RECLAMATION	NO. OF PHASES	AREA RECLAIMED (HECTARES)	SOURCE OF FILL MATERIAL	AGENCIES INVOLVED
1.	EAST COAST RECLAMATION SCHEME (along southeastern coast)	1963 - present	7	1417.2	Old Alluvium for all except phase V (sand from seabed); 110+ million m ³	HDB
2.	CHANGI RECLAMATION (land for Changi Airport, recreation, future extension of airport)	1976 - 79	4	633	Sand from adjoining seabed	SPECS (Singapore Engineering and Consultancy Services Pte Ltd
		1 982 - 8 6		183		
3.	EAST COAST LAGOON CONTAINER COMPLEX RECLAMATION SCHEME (at southern tip of island)	I: ? - 1967 II: 1976 - III: ?	3	20(I) 23(III)	Sediments from seabed and weathered shales from nearby hills	PSA
4.	WEST COAST RECLAMATION (HDB's Clementi New Town, PSA's Pasir Panjang Port Complex, JTC)		·	89 (HDB) 66 (PSA)	Sedimentary material from nearby hills in Clementi, dredging from shoals & nearby seabed	HDB, PSA, JTC
5.	JURONG RECLAMATION (coastal area only, inland swamps excluded)	1973 - 78 ? - present	several	732 600 (estimated)	Sedimentary material from nearby hills in Jurong; 44.13 million m ³	Mainly JTC & PSA
6.	OFFSHORE ISLANDS RECLAMATION (for industry, recreation, navigation, etc)	1975 - present		400 (to date)	Mostly sand from seabed	Mainly PSA & JTC
7.	OTHER (MINOR) RECLAMATION SCHEMES (e.g. Kranji, Sembawang, Pasir Ris Park)			330+		

TABLE IV SUMMARY OF VARIOUS RECLAMATION SCHEMES IN SINGAPORE

Source: Tham, 1984, pp. 37-63

Geotechnical Properties of Earth Materials with Special Reference to Investigation for the MRT Subway

Recent and ongoing large scale projects of the government, e.g. public housing estates, MRT subway, and private enterprise, e.g. Raffles City, require detailed geotechnical investigations of subsurface material. These are conducted either by the government agencies or private consultants and contractors. Little, if any, of this information is systematically published except for occasional case studies. Information obtained through boreholes is now being collected by the Public Works Department and made available to concerned users. The following published and unpublished reports, produced during the past three years on geotechnical properties of earth materials in Singapore were reviewed for this report : Choa et al., (1981) on the mechanical properties of Changi Clay, Devi (1982) on electrical properties of three major rock groups in Singapore, Lim (1982) on geotechnical properties of Marine Clays, Pitts (1983b) on geotechnical properties of recent deposits, Pitts (1984a; 1984b) on engineering geology in Singapore, Rahman (1982) on physico-chemical properties of various soils and Ramaswamy et al. (1982a; 1982b) on soil stabilization. Among the numerous findings, the more noteworthy are the bimodal distribution of grain size (mainly sand and clay) for most soils in Singapore and the drastic (hundred to thousand fold) drop in flow rate from surface to subsurface as observed by Rahman (1982) and the considerable differences of the Marine Clay from post-glacial marine clays in other parts of the world as reported by Pitts (1983b). Pitts (1983b) found that the Marine Clay from Singapore was considerably more plastic and had lower shear strength and sensitivity values than Marine Clays from Canada and Norway.

A considerable part of the MRT track will be underground and even the sections above the ground will require information about the subsurface material for the foundation. An extensive programme of geotechnical investigation involving numerous bore holes and laboratory testing is envisaged. The Public Works Department as the material-testing consultant to the MRT Authority is setting up the MRT Engineering Laboratory at Kallang which will be ready by the end of this year (*Straits Times*, March 17, 1984). This will be basically a testing laboratory for soils, concrete, steel, etc. Data collected by the MRT Authority will be provided to the contractors involved in the construction (*Straits Times*, January 3, 1984). Until the MRT Laboratory is ready, testing will be done at the Special Services Testing Laboratory of the Public Works Department.

Slope Stability

After numerous landslides in Singapore following the big rainstorm in 1978, there was a spate of slope failures during the northeast monsoon season in 1982/83 and again in the 1983/ 84 season. These slope failures can be explained by the well recognized role of water tipping the balance of forces resisting or promoting slope failures. Even though Singapore is not a hilly country, slopes are continually being modified for construction of roads and/or buildings. With very limited land available, the slopes are often cut at rather steep angles. Under warm humid conditions the weathering of rocks is quite deep and the continuous input of water weakens the slopes. Following high intensity and long duration rainstorms during the wet season, many slope failures therefore occur throughout the island. The frequency of these failures seems to be increasing as more slopes are being modified. The Public Works Department attempts to prevent slopes in the urban areas from failing and correct the failed

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or damaged slopes by various measures such as terracing, vegetation, drainage, retaining walls, etc.

No comprehensive or systematic account of slope stability for Singapore has been published. Ramaswamy et al. (1981) reviewed the stabilization of some slopes carried out by the Public Works Department. Pitts (1983a; 1984b) presented the first systematic study on slope failure for an area in western Singapore. Over 47 slope failures ranging in volume from 2 m^3 to 500 m³, within an area of less than $1/2 \text{ km}^2$ (0.9 km x 0.5 km) were studied. While rotational slips mostly in residual soils were found to be the most widespread, other types of failure (e.g. rock slumps, translational slip, creep, etc.) in other materials (e.g. partly weathered rocks) were also encountered. Under relatively high flow rates the infiltration and percolation of rainwater was cited as a factor in causing long term deterioration of material shear strength. High intensity rainfall during an already wet period would further increase the pore pressure (decreasing shear strength) and increase the shear stress (by increasing the weight of the soil mass) to the point of triggering a series of slope failures. 'The actual cutting of the slopes and subsequent exposure to weathering' (Pitts, 1983a, p. 168) are thought to have initiated a gradual decrease in the shear strength of soils which was a contributory factor in causing the landslides.

Pitts has initiated a study of slope failures in Singapore to include the form of slope failures and their relationships to the local geological setting. His methodology includes installation of slope monitoring and piezometric equipment, soil testing and stability calculations.

GEOMORPHOLOGY, HYDROLOGY AND SOIL SCIENCES AS APPLIED TO URBAN ENVIRONMENT OF SINGAPORE

Geomorphology

Chua (1983) provided a survey of the alteration of the natural landscape in Singapore resulting from the spread of urbanization during the past two decades. Two other areas that have been systematically studied are the changes in the sediment load of the channels resulting from urban activities and the formation and subsequent changes of beaches between headland breakwaters.

Sedimentation Due to Construction Activities. Tang (1980) monitored three channels in drainage basins having two predominantly different land use patterns, one in an area under construction and the others in areas already built up and having various degress of vegetative cover. The marked increase in the sediment concentration in the runoff (streamflow) from the construction site was evident. Gupta (1982a; 1982b) showed that increasing discharge and sediment load in the channels have profound environmental effects based on examples of rapid landuse changes in Singapore and elsewhere. He not only emphasized the need, lack and applicability of such studies but also the ease and limited resources with which such very useful information could be collected. These papers highlight the study of problems arising from the hydrological, sedimentological and morphological transformations of drainage channels associated with urbanization. The results of such studies can be useful in planning a solution for these problems.

In a similar study Poon (1984) monitored twelve rainstorms from a construction site in western Singapore and extended the results to determine the sediment yield for larger units of time and space in other parts of the island having a similar geology.

Evolution of Beaches Between Headland Breakwaters. The southeastern coast of Singapore has been reclaimed in several phases to meet the needs of increasing urban activities. Breakwaters were emplaced to protect the reclaimed coast and some fifty such structures were used to protect eleven kilometres of the coast in 1980. Beaches formed between these structures were first described by Wong (1973) who has continuously monitored the evolution and changes of the beaches through systematic surveys (Wong, 1981). In general the beaches evolve through three phases and depending on the deployment of the breakwaters and the presence of drains acting as groins, four situations for beach evolution can be identified along the reclaimed coast. Empirical data indicate that the existence of a wide berm along each beach between a pair of breakwaters provides adequate protection from daily, fortnightly or seasonal variations and serves as a good indicator of beach equilibrium irrespective of beach shape.

Hydrology

One of the major hydrological problems due to rapid urbanization in Singapore is flooding. Aside from the major storms and consequent floodings such as those in 1954, 1969 and 1978, there had been numerous occasions since 1981 in which several parts of the island were flooded (e.g. Straits Times, March 16 & 19, 1984; Sunday Monitor, March 18, 1984). That urbanization increases runoff is well established and demonstrated for Singapore by Tang (1980) and Gupta (1982a; 1982b). The Drainage Department of the Ministry of the Environment which manages the urban stormwater runoff utilizes the Rational Formula for estimating the runoff for the design of the drains as there are very few gauged channels in Singapore. Alternate methods of runoff estimation for the Upper Bukit Timah Catchment were investigated by Kaur (1981) who found their applicability limited, due to significant space-time variability in precipitation magnitudes during local storms. Subsequently, Chia (1983) who had earlier developed a computer-based conceptual rainfall runoff model for the Upper Bukit Timah Catchment, proposed a quasi-linear instantaneous unit hydrograph approach for runoff estimation in the urban catchments of Singapore. Two other hydrological studies need to be mentioned. Lee (1982) studied the runoff process in a small drainage basin in Singapore and clearly indicated the problems of applying linear models for estimating runoff. M.S. Tan (1983) summarized the hydrological information that has been collected and is available in Singapore. The latter also has a very useful annotated bibliography on the subject.

Soil Sciences

Due to rapid urban development the geotechnical aspects of Singapore's soils have received most attention; these have already been discussed. Nevertheless, there are other aspects of soils, e.g. for agricultural purposes, for waste disposal, that are of importance and some of these have been studied during the past three years. For pedological purposes the soil map of Singapore produced by Ives (1977) remains the major document on this topic. No supplements or amendments have since been published but additional data on various characteristics of soils are continually made available. Rahman (1980, 1982) studied the

suitability of Singapore's soils as sites for waste-disposal. The various physical and chemical characteristics of the major soil series in Singapore were presented and their potential as sinks for waste disposal in terms of the various soil waste interactions was evaluated. While physically, these soils had favourable characteristics, their chemical characteristics were found to be very inadequate. Pitts and Kannan (1984) have studied the soils formed over the Jurong Formation.

CONCLUSION

Advances in the knowledge of geology and related earth sciences of Singapore since 1981 have been the result of the continuation of research as well as new developments, e.g. the establishment of the School of Civil and Structural Engineering in the Nanyang Technological Institute, MRT project. It is obvious that the need to meet the requirements of urban development will continue to be an important factor in determining the direction and character of the geological and related knowledge on Singapore. A fair amount of such knowledge remain unpublished in the form of reports in government agencies and private organizations; such information would contribute further to the understanding of the geological environment of Singapore if it is made available to others. The availability of borehole data from the Public Works Department and the Mass Rapid Transit Authority is therefore a commendable step in the direction of making more knowledge on the geology of Singapore available to others.

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