

Limestone Rocks of the Jurong Formation Engineering Experiences

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ABSTRACT: The presence of limestone rocks of the Jurong Formation remained undetected until recently mainly because of lack of surface exposures and mis-identification as siltstone or mudstone. Since 1987, limestone rocks have been positively identified in boreholes and construction works in the south west part of Singapore. A paper presented at the workshop on “Updating the Engineering Geology of Singapore” which formed part of Underground Singapore 2003 summarised the information available at the time on the limestone rocks encountered in Singapore. This paper addresses an area in the south west part of Singapore located along the coastline between the west bank of Sungei Pandan and eastern end of West Coast Highway where limestone rocks were met in boreholes and underground construction works. This area was largely reclaimed from the sea and the limestone rocks encountered at depth below the ground water table contain cavities and open water paths. These features combined with the relatively high strength of limestone rock and abrupt variations in rock head level give rise to challenging engineering and construction conditions. The paper gives a detailed description of the limestone rocks met in boreholes and excavations in the three zones of the stated area. It also makes reference to recent engineering experiences in Singapore limestone rocks which will be useful in the planning of future projects.

1 INTRODUCTION

The existence of Limestone rock was not detected or recorded during the publication of the “Geology of the Republic of Singapore” by PWD in 1976. This document however continues to be used widely by the local engineering community. Nowadays the presence of limestone rocks in Singapore is acknowledged and greater attention is being paid during site investigations to detect its presence. The properties of limestone rocks in Singapore and information required for design and construction in this formation are not very well established. The paper by Jeyatharan et al 2003, summarised the information available to that date on the limestone rock encountered in Singapore and made an attempt to define its extent, Figure 1. Since the publication of that paper underground construction projects have been located in the areas where limestone rock is present. One such area is located along the coast line between the eastern end of West Coast Highway and Jalan Buroh bridge encompassing West Coast Park and Pasir Panjang Container Terminals.

Within the stated area, three zones have been identified where substantial site investigations have been undertaken and underground construction works have been executed. The objective of this paper is to compare the information available from the three zones with a view to reaching generic conclusions regarding engineering aspects of the limestone rocks in Singapore.

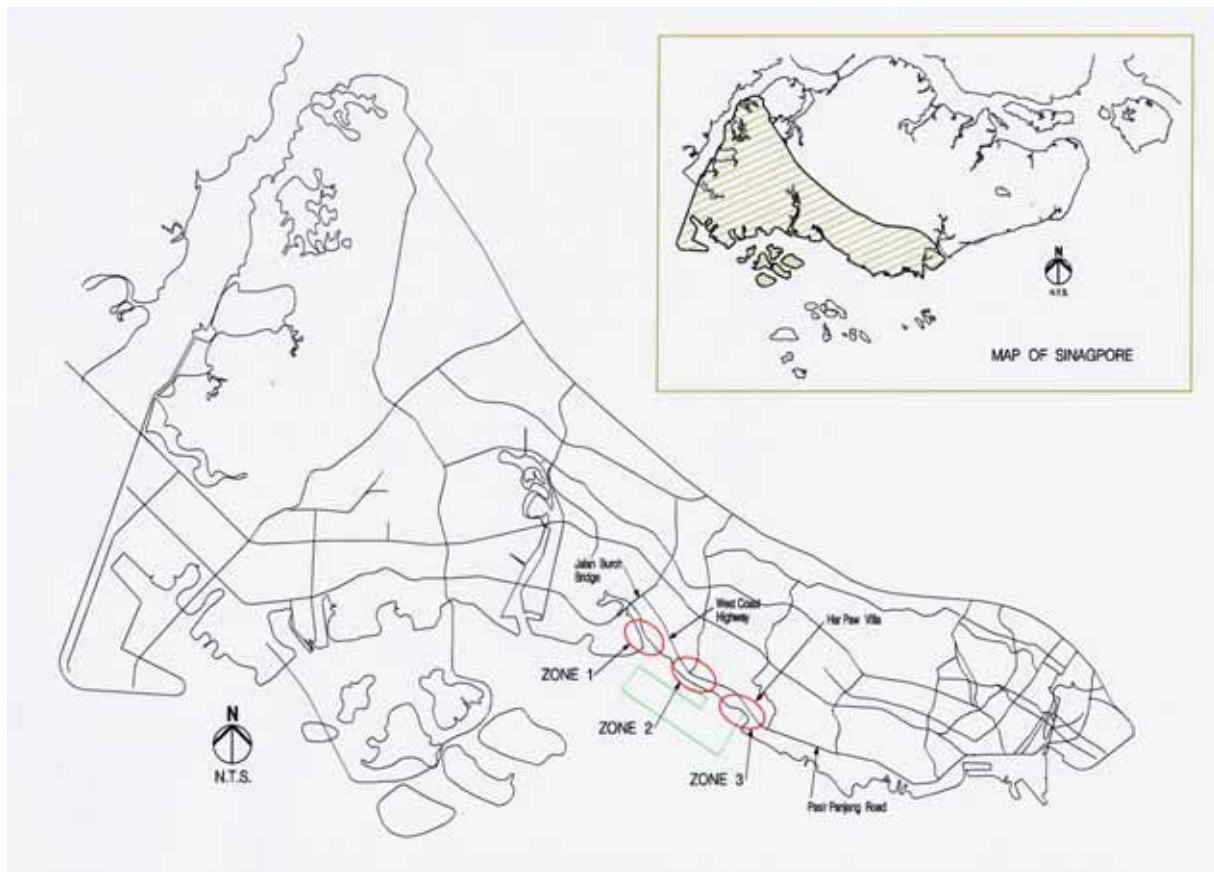


Figure. 1 Extent of area where limestone rocks are likely to be met in Singapore and locations of zones covered by this study

2 GEOLOGY

Limestone rocks are sedimentary rocks consisting of more than 50% carbonate and can include chemical, clastic and biological material. The formation of limestone is attributed to the first bacteria and one-celled plants that abstracted lime (CaCO_3) from early warm sea waters and deposited in jelly like masses. Later on early animals which were also sea creatures extracted lime from the sea waters to make protective coverings, shells and bones. Where these died their remains accumulated in thick masses at the sea floor to become limestone in time. At present an estimated 10% of the earth's land surface area is covered by limestone rocks.

The deposition of limestone rocks in the Singapore and Malayan Peninsula is believed to have occurred during the late Triassic to early Jurassic period. The deposition ceased when clastic materials of coarse sands and gravels become available as a result of an active uplift of the Malayan main Range Granite along the southern end basin. The shortening of the basin caused by the uplift gave rise to a compression of the region and created folds, faults and mild metamorphism of the Jurong Formation rocks including the limestone rocks.

There are a few other hypotheses available regarding the origins of the limestone rock in Singapore and its relationship with other members of the Jurong Formation. Since there is no surface outcrop and to date there is insufficient exposure at excavations, it has not been possible to confirm these theories. More detailed information has been obtained from recent site investigations for construction projects which can help to improve the present knowledge and understanding. From boreholes drilled down to depths ranging from 20m to 60m below ground level it is evident that limestone rock is in contact with other sedimentary rocks under reclaimed land. Limestone rock is also met in several boreholes drilled below the seabed but its seaward extent remains unknown.

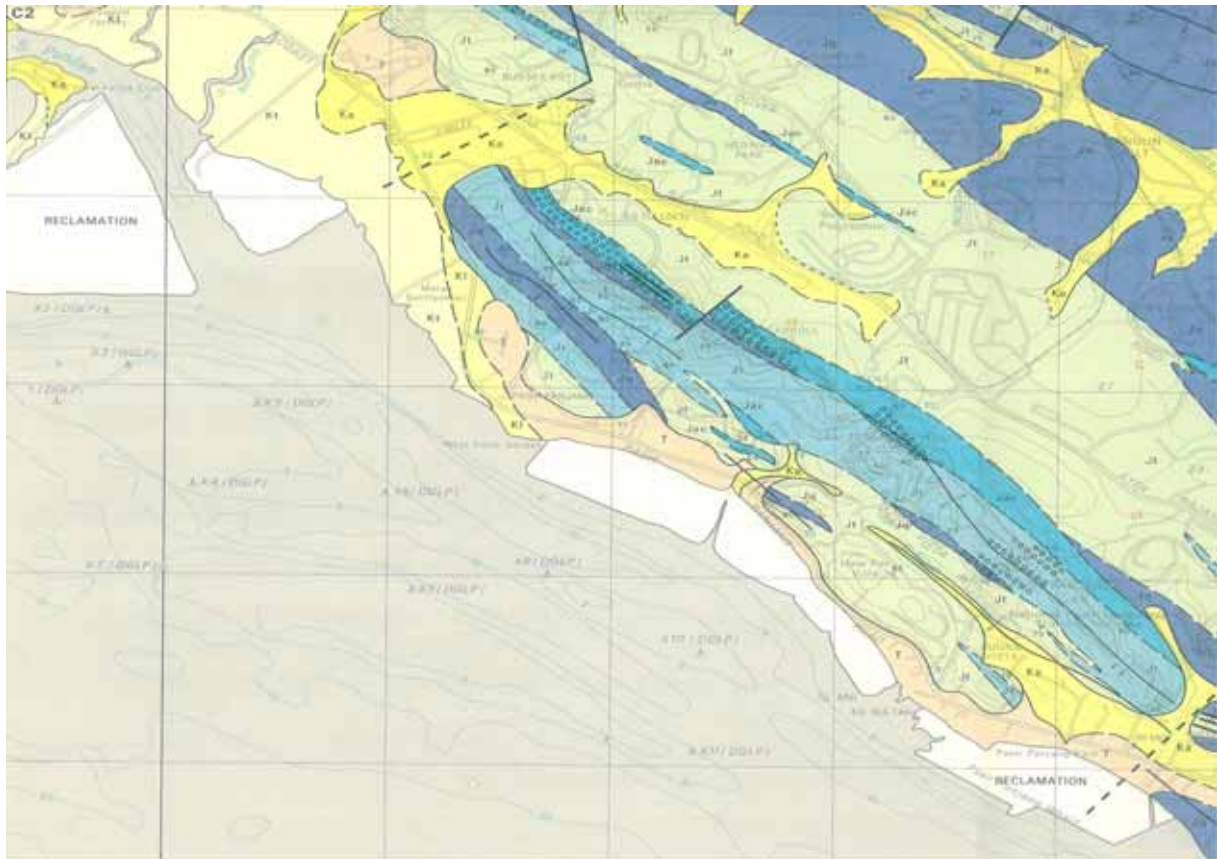


Figure 2. Geological map of area covered by the study (PWD 1976)

Note: presence of limestone was not shown in the map since it was undetected at the time

3 AREAS OF STUDY

In order to study the engineering properties of the limestone rocks site investigation data and construction information from three zones were collected and compared. The three zones included in the comparison study vary both in size and shape, Figure 1. These are described below:

- Zone 1 - Located around Sungei Pandan river and comprises of Pandan Road, Jalan Buroh bridge, western end of West Coast Highway and northern tip of West Coast Park. In this zone, information for the study was obtained from site investigations and building, bridge and tunnel construction projects.
- Zone 2 - Located along West Coast Park and Harbour Drive Road. In this zone, information for the study was gathered from site investigations and building (deep foundation) construction project.
- Zone 3 - Located near the eastern end of West Coast Highway. In this zone the information for the study was obtained from site investigations, building, MRT station and tunnel construction projects.

4 CHARACTERISTICS OF LIMESTONE ROCK

The main features of the limestone rock, and its top elevations with respect to Principal Datum are compared in Table 1.

Table 1. Properties of Limestone Rock

	Zone 1	Zone 2	Zone 3
Top level of rock (m RL)	72 to 87	60 to 85	65 to 84
Colour	Greenish grey, dark grey to black with many calcite veins	Light to dark grey with calcite veins	Light to dark grey with occasional calcite veins and iron oxide stains
Dip angle	Varies between 5° to 90°	Varies between 30° to 90°	Varies between 20° to 80°
Weathering	Slight to high (core surfaces show many micro cavity holes)	Slight to high	Slight to moderate
Fracturing	Closely spaced to massive RQD = 0 to 100%	Closely spaced to massive RQD = 0 to 100%	Closely spaced to massive RQD = 0 to 100%
Type	Not available	Siliceous; argillaceous; carbonaceous; styrolitic	Micritic; argillaceous; carbonaceous
Unconfined compressive strength (MPa)	16.8 to 182	13.4 to 56.3	18.5 to 89.3
Bulk Density (kg/m ³)	2280 to 2680	2400 to 2700	2350 to 2700

4.1 Upper Surface of Limestone Rock

Generally foundations are terminated on top of bedrock or at shallow depths immediately below. Since the surface of limestone rock is located at relatively shallow depth and its topography is highly variable, any tunnel, shaft, pile foundation or deep excavation is likely to encounter the upper layers of the rock. Therefore knowledge and understanding of the characteristics of the upper part of the limestone rock is essential. With this in mind an area in and around zone 1 was studied in detail making use of information available from 37 boreholes over a distance of approximately 1km.

This study indicates that there are several cavities situated very near the upper surface of the limestone rock (typically <3m depth). This leads to the inference that the upper surface could be in the form of a limestone pavement. The details of the cavities are described in Section 4.3.

Since the top of the limestone rock has withstood mechanical and chemical weathering processes, there is a possibility that the rock at this level may possess relatively high strength. However, out of a total of 6 boreholes considered, only one core from the first 1m depth was found suitable for testing. This recorded an unconfined compressive strength of 20MPa which is very low when compared with the average strength of 80MPa estimated for limestone rocks in Singapore.

One of the boreholes met an isolated core of limestone below which stiff silty clay was found for considerable depth. This block of limestone is believed to be a floater. A comparison of core recovery and Rock Quality Designation (RQD) obtained from all 37 boreholes is given in Figure 3. The averages of total core recovery (TCR), solid core recovery (SCR) and RQD are 77%, 39% and 32%, respectively, with a standard deviation of 34%. This confirms that the upper layer of limestone rock is not very strong and is closely jointed or fractured.

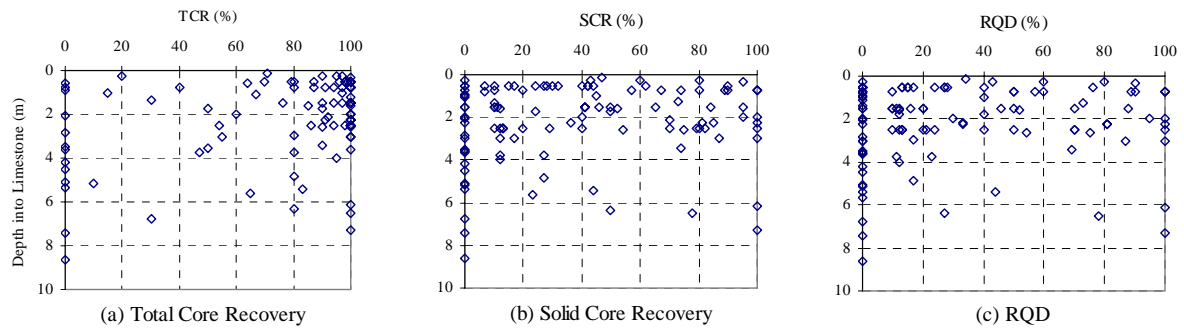


Figure 3. Comparison of core recovery and RQD at the upper layer of limestone rock

4.2 Locating the Upper Surface of Limestone Rock

The upper level of the limestone rock is highly variable even over short distances. Borehole investigations give most accurate results to locate the upper surface. However these are expensive and the results cannot be used to interpolate with sufficient confidence regardless of the proximity of the holes. Geophysical methods such as electrical resistivity and seismic surveys give a reasonably accurate indication of the top level of bedrock but were found to be not successful in detecting local features such as cavities or sink holes. A comparison of rock head levels obtained by geophysical surveys and boreholes show variations in the range of 0 to 5 m. The results from the geophysical methods predicted generally lower levels of limestone rock head. There was no significant difference noted in the bedrock levels indicated by resistivity survey and seismic survey.

Cone Penetration Testing (CPT) is an inexpensive as well as expedient method of sampling the top of limestone rock at closely spaced intervals. This method is particularly suitable for site investigations underwater. It is effective in most of the soil types and has proved to be practicable and reasonably accurate to depths sampled 15m below sea bed level. Information obtained from boreholes near the CPT sites show that hard residual soils (sand and stiff clays) and limestone fragments could over estimate the top of limestone by up to 4m.

4.3 Cavities, Sink Holes and Slump Zones

The karstic limestone contains, cavities, sink holes and slump zones. Since there is no documented evidence it is assumed that to date none of the construction projects in Singapore has exposed such features for manned inspection. There is however evidence in the form of sudden water loss or sinking of drill rods during site investigations, loss of concrete in pile foundations and escape of grouting fluids when back filling boreholes.

Cavities in boreholes can be recognized by observing the core surfaces for etching or pitting by solution processes. The distribution of size, shape and spacing of cavities in Singapore limestone rocks remains to be established. In zone 2 total length of cavities contributed to more than 30% of the cored length. The cavity infill materials are typically very soft silty CLAY and hard clayey SILT both with or without limestone fragments.

In zone 1, a liquid filled cavity was met between 17.5m and 21.0m depth below ground level. The drill rod suddenly dropped under its own weight after drilling through Kallang Formation clays with SPT "N" value of 10. The first metre of limestone rock met at the bottom of the cavity was highly weathered and brecciated. There was no loss of drilling water. The borehole was grouted with cement/bentonite at an initial 3 bar pressure. When the grout volume exceeded 5m³ it was decided to stop grouting further. Another borehole was drilled after 17 days within 1m of the first hole to check the extent of the cavity. In this hole, silty clay and gravelly sand with limestone fragments were found in the vicinity of the cavity but there was no evidence of the cement/bentonite grout pumped from the first hole. Similar experiences were recorded in zone 2 as well where two test boreholes drilled 0.75m and 1.0m either side of a grouted borehole cavity did not encounter any trace of grout or cavity. The conclusion that can be reached from these experiences is that the cavities encountered exhibit mild

form of karstic features and are most likely to be long and narrow slots. A comparison of the cavities met in the three zones is given in Table 2.

Table 2. Comparison of Cavities

Zone 1	Zone 2	Zone 3
8 boreholes out of 27 met cavities up to 1.7m in height. Two vertical open fractures 0.5m and 1.2m in height were also encountered.	21 boreholes out of 37 met cavities. In total 35 cavities of height 0.3m to 6.7m (generally 0.5m to 1.5m) were encountered. Of these 6 cavities were met at 0.5m to 0.8m depth below the top surface of limestone. These cavities were typically 0.5m to 3.5m in height.	3 boreholes out of 9 met cavities. Two of the boreholes required excessive amounts of grout during backfilling.
A cavity 1.7m in height was found in limestone fragments overlying limestone.	Sudden drop in limestone rock head to 60mRL was detected in one borehole which was surrounded by 5 other boreholes which showed bedrock to be at 84 to 83mRL. This is suspected to be a possible sink hole, open joint or similar karstic feature.	Another borehole drilled 23m into limestone rock met 9 cavities along its length.
Drilling rod sunk 3.5m under self weight in a cavity overlying limestone. This is suspected to be a slump zone.		

There is no clear indication of sink holes or slump zones in the three zones. This is partly because the surface topography in Singapore has been substantially changed by the built up environment. Nevertheless Admiralty charts indicate a number of localized depressions in the seabed some of which could well be formed by sink holes and slump zones.

4.4 Contact between Limestone and other Jurong Formation Rocks

Geologists are keen to establish the juxtaposition of the Singapore limestone rocks with respect to other Jurong Formation rocks. There are suggestions that the limestone rock should not be treated as part of the Jurong Formation rocks and should be separately categorised. There have been suggestions also to drill a 300m deep borehole into the limestone rock to identify the strata below. In this regard it is interesting as well as important to know what rocks are found at the contact locations.

In zone 1, limestone rock suddenly disappears at a faulted contact. At this interface carbonaceous mudstone which is highly to completely weathered, interbedded with fine and medium grained grey sandstone was found immediately below the limestone. There is evidence of fossils in the mudstones underlying the limestone rock at the interface of these two rocks. This was followed by greenish grey cataclastic rock (possibly Tuff or Mylonite) found approximately 50m below ground level. In the vicinity, another borehole met below limestone rock highly to completely weathered calcareous sandstone interbedded with mudstone approximately 50m below ground level.

On the south east end near Haw Par Villa (Tiger Balm Gardens), the limestone rock is in contact with deeply weathered muddy sandstone. The dip of the limestone and the depth of boreholes drilled are such that no rock to rock contact has been found on this side but steep variations in the limestone rock head level have been noted. Very strong sulphur rich joint infill material covered beneath muddy sandstone has been observed in close proximity to the perceived eastern boundary of the limestone rock in zone 3.

4.5 Permeability of Limestone Rock

The limestone rock in Singapore is situated well below the ground water table. The movement of water through this rock is controlled by both the joint system and the karstic features. Attempts have been made to estimate the rock mass permeability through in-situ falling head tests as well as packer tests. The falling head tests conducted in limestone rock yield coefficient of permeability 'k' value between 1.2E-05m/sec and 3.5E-09m/sec.

Packer tests were performed using a single packer in boreholes over a test length of approximately 5m. The results from 13 boreholes upto a depth of 57m below ground level in zone 1 are presented in Figure 4. The maximum lugeon value obtained was 39.5 at a depth of 47.5m in a land borehole.

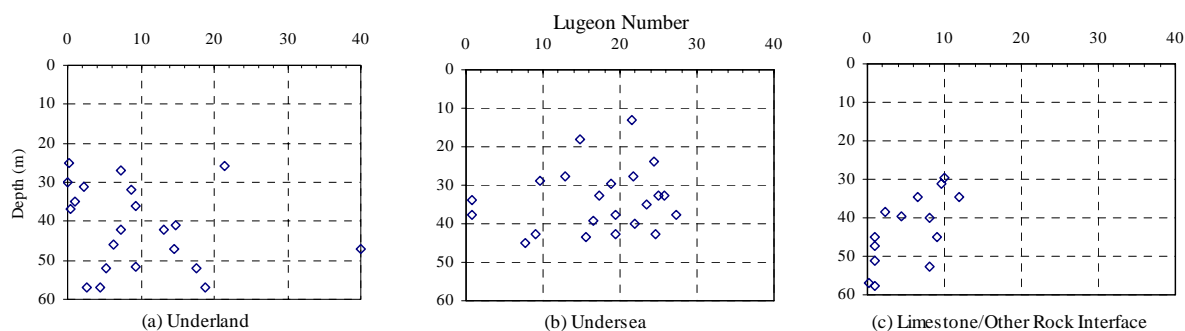


Figure 4. Packer Test Results

4.6 Abrasivity of Limestone Rock

Abrasivity is one of the properties of rock to assess its suitability for mechanical excavation. It is generally believed that since limestone is a carbonate rock it is not abrasive. However thin section petrographic analysis used to study the microscopic features of the rock suggests that quartz in small quantities is present as veins or joint infilling.

CERCHAR Abrasivity Index (CAI) is a tool to measure the abrasivity of rock in order to determine the cutting wear rate. The normal range of CAI for limestone rocks is 1.1 to 1.3. The abrasivity tests conducted on 22 samples from 7 boreholes in zone 1 however give an average CAI of 2.72 with a standard deviation of 0.85; the maximum value being 3.95 met at 55m depth below ground level. This would place the zone 1 limestone rock in the medium abrasive to very abrasive category based on the criteria for abrasiveness published by CERCHAR.

The high abrasivity encountered in cores from boreholes is surprising and could be attributed to the metamorphosed fine grained nature of the rock and the presence of quartz in the veins.

5 SOILS OVERLYING LIMESTONE ROCK

At all three zones described above, the Jurong Formation soils overlying limestone rock were initially classified as S4a and S4b in the borehole logs. However during excavation decomposed wood fragments, scoria and boulders of unweathered conglomerate rock were found suggesting that the overlying soils are not typical in-situ weathered Jurong Formation soils but colluvium which is a collective description of soils transported by various physical mechanisms. A brief summary of the different types of soils found to be overlying the limestone rock is given in Table 3.

Table 3. Description of soils and rock overlying limestone rock

Zone 1	Zone 2	Zone 3
Grey clayey SILT	Medium dense brown/grey clayey SILT	Medium dense reddish brown/grey to black clayey SILT
Grey clayey SAND (with decomposed wood and carbonaceous clay)	Stiff green/grey MARINE CLAY	Brown grey to black clayey SAND Brown to grey silty/coarse SAND to black silty CLAY
Brown/black silty CLAY	Dark grey to black silty SAND Brown silty CLAY Carbonaceous CLAY	
Limestone fragments Dark grey SILTSTONE (found at contact zone)	Limestone fragments	Limestone fragments Purple to reddish brown SANDSTONE Boulders of CONGLOMERATE

5.1 Shear Strength

The SPT “N” value gives a reasonable indication of the shear strength of soils. The shear strength of soils overlying limestone rock was found to be highly variable in plan as well as in elevation. The variation in “N” value with depth from boreholes in zone 1 drilled both under land and under sea is shown in Figure 5. One notable feature is that in some boreholes the shear strength initially increases with depth and then reduces rapidly near the top of the limestone. This feature is not characteristic of in-situ weathered Jurong Formation soils which demonstrate a general increase in shear strength with depth.

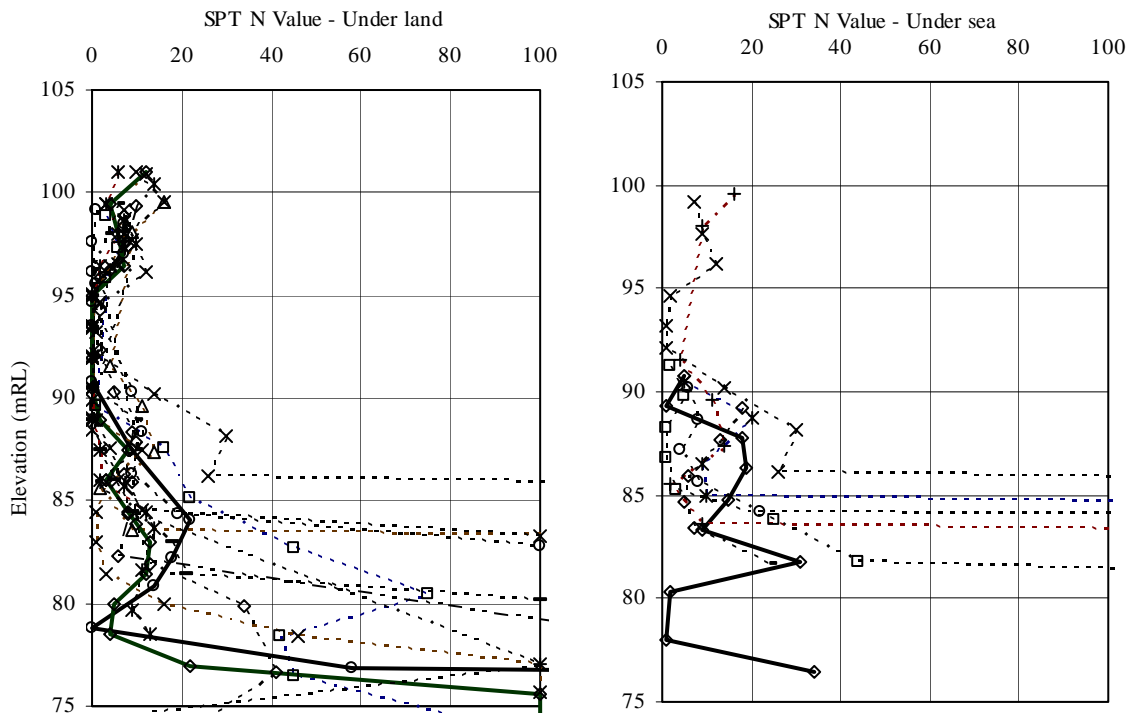


Figure 5. Variation of SPT “N” values with depth from boreholes under land and under sea
 Note: Solid lines illustrate an unusual reduction of soil strength above limestone

In zone 1, the soils overlying limestone are described as S4a or S4b in the boreholes. However these give the appearance of having been transported as fluvial muds and deposited in a shallow water environment. None of the samples of soil materials overlying limestone rock appear to contain marine fossils though organic materials and decomposed wood fragments were found down to 20m depth. In some areas the soils lying immediately above limestone rock were observed to be relatively weak, less dense and highly permeable.

5.2 Water Ingress

The nature of all the different types of soils and rocks overlying limestone in the three zones suggests that their deposition took place some time after the limestone rock was exposed as a surface outcrop, weathered and under went karstic processes. As a result, there are interconnecting fissures, joints and water paths in the limestone rock with possible direct connections to the sea. This makes excavations in soils overlying the limestone rock highly dangerous since as soon as a water path is established the whole excavation can become inundated rapidly and without warning. An indication of this possibility may be seen through loss of drilling water during site investigations. Table 4 compares the loss of drilling water during site investigations at the three zones.

Table 4. Loss of Drilling Water (Nos. boreholes with water loss/Total nos. of boreholes)

Zone 1	Zone 2	Zone 3
8/27	Not available	2/9

In order to prevent substantial water ingress into excavations located in or on top of limestone rocks some form of reliable water cut off measure is essential. Good quality jet grouting of the soils at the base of excavations located above the limestone rock has been carried out with success.

6 CONCLUSIONS

A study of engineering properties and experiences of limestone rocks from three zones in the south west coastline of Singapore where these rocks are encountered leads to the following conclusions.

The limestone rocks exhibit mild form of Karstic features. These are predominantly in the form of slot like cavities (narrow and long) in the two orthogonal directions. The percentage of cavities in terms of core length is significant and can be over 30%. The upper surface of the rock has a lower than average unconfined compressive strength and is closely fractured. Cavities have been found near the surface indicating the possibility that the rock may have been exposed at the land surface at a certain geological period in the form of limestone pavement. The karstic solution processes may have taken place at this time. The cavities are infilled with very weak, poorly consolidated, low density materials which are a mixture of sand, silt, clay and limestone fragments. The top of limestone rock is located at least 10m to 15m below ground or ground water level.

The soils overlying limestone rocks are generally colluvium that originate from the Jurong Formation rocks and give the false impression that these are in-situ weathered residual soils. There is significant variability in the engineering properties of soils overlying limestone rock, the most notable being the reduction in shear strength with depth in some areas. This could be the result of ancient landslides, variations in the nature of deposition or possible slump zones.

The in-situ permeability tests, namely falling head and packer tests indicate that the rock mass permeability is not vastly different to other Jurong Formation rocks and the 'k' values are generally below 1×10^{-5} m/s. However losses of drilling water and backfill grout have been experienced in boreholes and large inflows of water have been met in excavations confirming the possibility that there is interconnected water paths developed through an extensive solutioning system. The saline water met indicates that there can be direct connections to the sea.

The limestone rocks in the study areas do not give the appearance of being in the form of lenses or interbeds with other sedimentary rocks. Instead these appear to be a continuous body over the length of the study area but were observed to have a faulted contact with other rocks in both zones 1 and 3.

Contrary to popular belief, the limestone rocks studied exhibit medium to high abrasive properties. This is possibly because of the quartz content in the joint infilling and the metamorphosed fine grained nature of the rock.

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