

GEOTECHNICAL PROPERTIES OF WEATHERED SEDIMENTARY ROCKS

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SYNOPSIS

In the course of site investigation work for several large civil engineering projects in Singapore, laboratory tests such as unconfined compression test, point load test and slake durability test have been conducted on a large number of weathered sedimentary rock core samples. In addition, in-situ tests such as standard penetration test, pressuremeter test, plate load test and packer test were also performed at the sites. Based on this large data bank, a detailed study has been carried out to examine the geotechnical properties of highly to slightly weathered sedimentary rocks including sandstones, silts-tones and shaley mudstones. Correlation between standard penetration resistance, point load strength and unconfined compressive strength have been proposed. It is noted that pressuremeter modulus can be employed to estimate settlement of piles socketed in weathered rock. On the other hand, packer tests do not give an accurate permeability coefficient of the rock mass. It is also found that rocks of very low strength have low slaking durability and excavations in such rocks have high risk of failure when subjected to repeated wetting and drying process.

INTRODUCTION

Very deep weathering is a feature of the sedimentary rocks which underlie the southern and western parts of Singapore. The weathering can produce highly weathered rocks down to 50m, and sometimes deeper. Although the structure of the sedimentary rock tends to be well preserved, the rock material is often weak and friable. Due to large differences in rock weathering and fractures, there are wide variations in strength and compressibility characteristics with no clear trend to appreciable increase in rock quality over a great depth of 50m or more below rock head. Despite the fact that foundations of many highrise buildings are founded in such rock formations in Singapore, knowledge of the geotechnical properties of weathered sedimentary rocks is rather limited. Based on the findings of several extensive site investigations in weathered sedimentary rocks,

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the geotechnical properties of such rocks have been thoroughly investigated with a view to correlating various geotechnical parameters.

JURONG FORMATION

The sedimentary rock formation in Singapore is geologically termed the Jurong formation. It consists of stratified rocks of the late Triassic, and Lower to Middle Jurassic periods. The rocks include various types of mudstones, sandstones, shales and conglomerates. In and around the Central Business District of Singapore, boulders of less weathered sedimentary rock are occasionally found within the more highly weathered strata. The structure of the formation mainly comprises a series of open folds and faults. The general strike is NW-SE, but the dips may vary over a short distance from a few degrees to vertical, or even overturned. Pitts (1984) provided a concise account on the geology of the formation.

In the western part of Singapore, the rock is typically close to the ground surface with a subsurface profile consisting of several metres of completely weathered and decomposed rocks and residual soils, underlain by highly weathered and fractured rocks of undetermined thickness. A typical subsurface profile is shown in Fig.1. In the southern part of Singapore, the rock formation in usually overlain by deposits of soft marine clay of variable thickness ranging from 1m to 20m.

SITE INVESTIGATION

In the past decade, extensive site investigations have been conducted for several large civil engineering projects located within the Jurong formation area. More than 100 boreholes have been drilled at these sites in order to obtain rock samples for laboratory determination of geotechnical parameters of the weathered sedimentary rocks. The boreholes used standard NX-size rotary diamond drilling and continuous rock coring using a triple tube core barrel to obtain rock cores. A core size of 50mm in diameter is obtained with a maximum single core-run of 1.5m in length. Core recovery (CR) and rock quality designation (RQD) values have been measured at sites for quantitative evaluation of the quality of the rock mass. CR is the ratio of the cumulative lengths of the cores recovered to the length of the actual core-run, and the RQD is the ratio of the sum of the lengths of the intact rock cores which are more than 100mm in each length, to the length or the recovered core. Preliminary boreholes at the sites

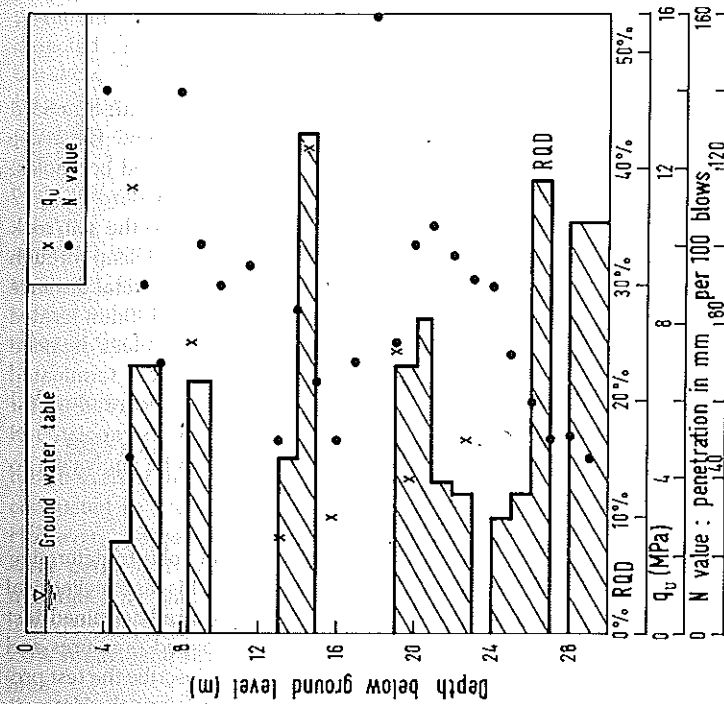


Fig. 1 Typical subsurface profile and properties.

revealed that the weathered rocks extend to great depths. As the anticipated pile penetration usually is only about 15m to 20m below the rock head, the majority of the boreholes were therefore terminated at depths around 30m.

In-situ Tests

Standard in-situ tests were also performed in the boreholes, with Standard Penetration tests being by far the most frequent test carried out. Extensive testing was occasionally conducted at 1 metre intervals in selected boreholes. Test procedures followed those recommended by the British Standard BS1377 (1975) for which a thick walled split-barrel sampler is driven into the soil/rock mass at the bottom of a predrilled borehole by a 65-kg hammer falling through a free height of 760mm. The sampler is supposed to penetrate a total distance of 450mm with the number of blows required to drive the final 300mm termed the standard penetration resistance, denoted by *N*. However, *N* values obtained for rocks are often very high and in the present work, tests were terminated when the number of blows exceeded 100. The results are recorded as for example 100 blows/100mm penetration. In the analysis, an extrapolated *N* value is employed and 100 blows/100mm penetration would be equivalent to an extrapolated *N* value of 300.

Pressuremeter tests were also performed in selected boreholes to determine the strength and deformation characteristics of the rocks. In this test a cylindrical probe is lowered into a borehole of appropriate size to a predetermined test depth and expanded laterally by compressed gas. The applied pressures and resulting deformations are measured. Mair & Wood (1987) describe the test procedures and precautions in detail, and give a concise account on the determination of various parameters such as shear strength and elastic modulus of weathered rock from the pressure-deformation relationship.

Several plate load tests were conducted to determine the deformation characteristics of the rocks. A 375mm diameter rigid plate was placed at the bottom of a predrilled pit and the penetrations of the plate under a series of maintained loads were measured. The elastic modulus of the rock may be backcalculated using elastic theory. Detailed test procedures are given in British Standard BS5930 (1981).

In addition, packer tests were performed in selected boreholes to determine the permeability of the weathered rocks. The test procedures are described in

detail in British Standard BS5930 (1981). The test essentially involves the measurement of the volume of water that can escape from an uncased section of borehole in a given time under a given pressure. In the present work, a single pneumatic packer was employed. Any leakage past the packer can be readily detected as the flow is confined between the packer and the bottom of the borehole. During the test the position of the ground water table was monitored by a water standpipe located near the borehole. An approximate value of permeability coefficient, *k*, may be calculated from the following formula:

$$k = (\pi H L Q/2) \log_e(L/r) \quad (1)$$

where *Q* is the rate of injection, *H* is the pressure head of water in the test section, *L* is the length and *r* is the radius of the test section. Tests are usually carried out at various values of *Q* and *H*, and the value of *k* determined from the slope of the flow versus pressure plot.

Laboratory Tests

A large number of good quality rock core samples were obtained using triple tube barrels at the sites. In the present work, triaxial compression tests were not conducted as they are relatively time consuming and expensive to perform. However, a large number of unconfined compression tests and point load tests were performed on the rock samples to determine the strength of the rock material. The unconfined compressive strength q_u , also commonly termed as uniaxial compressive strength, is defined as the ratio of the peak load (or load at 20% strain in the absence of peak load) to the corrected specimen cross-sectional area.

Recently, point load tests have become more and more popular as they are relatively easy to conduct and specimens of a wide variety of sizes and shapes can be performed (Brook, 1985), see Fig.2. In addition, the tests can also be performed with portable equipment in the field. The test procedures are described in detail in ISRM (1985) and the point load strength, I_s , is given as the ratio of the failure load *P* to the square of specimen diameter D_e (see Fig.2). In order to standardise results of tests on different specimen diameters, a corrected point load strength, $I_{s(50)}$, is employed based on a standard core diameter D_e of 50mm.

In addition, slake durability tests were performed on selected rock specimens to determine their slaking and durability characteristics in accordance with the

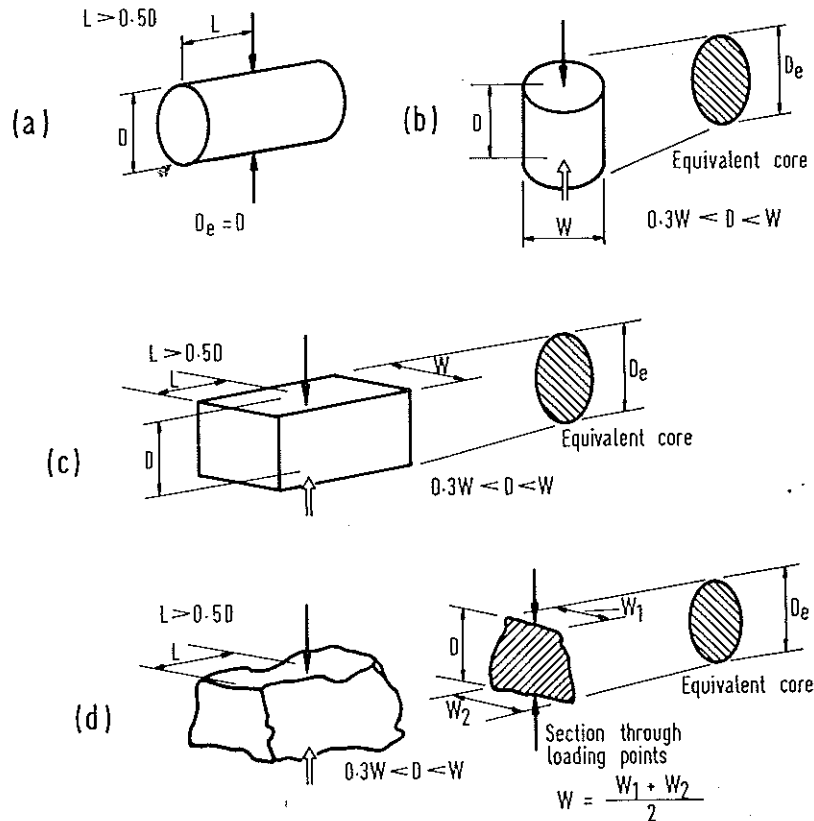


Fig. 2 Allowable specimen shapes for point load test (Brook, 1985).

test procedures described by Brown (1981). Samples of the material to be tested are placed in a wire-mesh drum that is partially immersed in water and rotated 200 times in 10 minutes. As the fragments disintegrate, the fine fractions pass through the 2-mm mesh into the water bath beneath. The slake durability index is defined as the percentage ratio of the dry weight of fragments retained in the drum to the initial dry weight of the sample placed in the drum. Standard index and classification tests were also performed to determine specific gravity, unit weights, water content, plasticity index and particle size distribution of the rocks.

STRENGTH PARAMETERS

Results of site investigation reveal that the ground at the sites mainly comprises of highly to slightly weathered and fractured sandstones, siltstones and shaley mudstones. The degree of weathering typically varies greatly with depth and the RQD, q_u and N values are highly scattered (Fig.1). Typical RQD values vary from 0% to 85% and q_u values vary from 0.2MPa to 20MPa, which would be classified as very weak to moderately strong rock strength according to BS5930 (1981). Occasionally, q_u values exceed 20MPa and reach as high as 44MPa. On the other hand, the majority of the point load strength values are below 4MPa. Standard penetration tests carried out in the boreholes show that extrapolated N values generally range from 200 to 1200.

An attempt has been made to correlate various strength parameters from a large data bank gathered from the site investigation work. Parameters are correlated with the unconfined compressive strength which is the most widely used strength parameter for most geotechnical design problems on rocks. A graph of q_u versus $I_{s(50)}$ is obtained based on results obtained from tests on the same or adjacent rock core specimens, see Fig.3. Although there is a fair degree of scatter especially in the lower strength range, a definite trend is evident regardless of rock types. A linear regression analysis performed on the data points resulting in the following correlation relationship:

$$q_u = 6.12 I_{s(50)} \quad (I_{s(50)} < 8\text{MPa}) \quad (2)$$

This observation is in great contrast to that reported by ISRM (1985) which stated that q_u is typically about 20 to 25 times $I_{s(50)}$ for most rocks and in the extreme case between 15 to 35 times $I_{s(50)}$ for some types of rocks. Similar correlation relationships are also reported by Bieniawski (1975) and Goodman

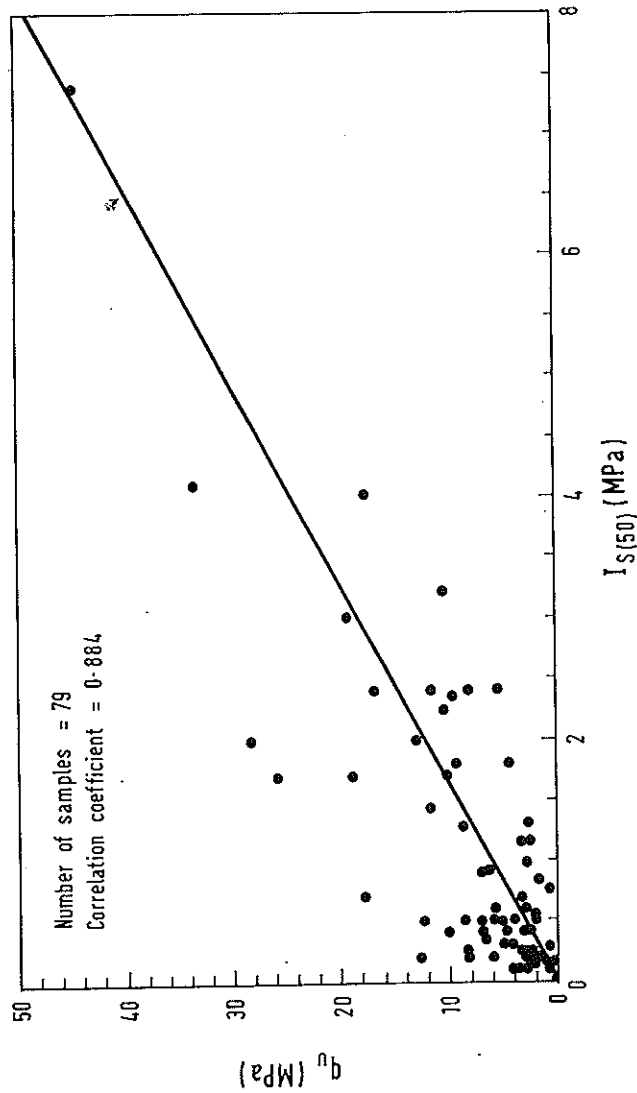


Fig. 3 Plot of unconfined compressive strength (q_u) versus point load strength ($I_{s(50)}$).

(1989). It is evident that the correlation proposed by the above researchers do not apply to weathered sedimentary rocks in Singapore and any attempt in using such relationships to determine q_u from $I_{s(50)}$ would result in very high q_u values and hence unsafe design.

In general, the point load test as mentioned earlier is a much easier test to perform than the unconfined compression test. This is especially useful for weathered sedimentary rocks as the rock cores obtained from site investigation are often highly fractured and too short for unconfined compression testing. It is considered that point load tests could replace the unconfined compression tests for general-purpose strength classification of weathered sedimentary rocks in Singapore provided that the standard test procedures given by ISRM (1985) are followed and a correlation factor of $q_u/I_{s(50)}$ of 6 is employed.

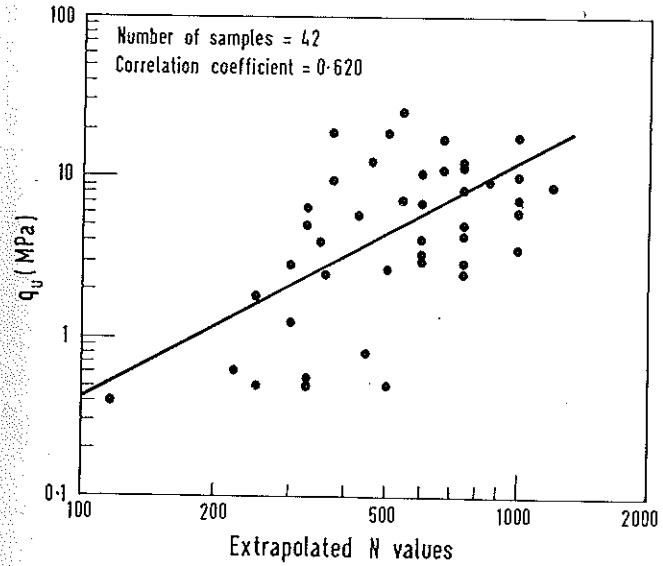


Fig. 4 Plot of unconfined compressive strength (q_u) versus standard penetration resistance (N).

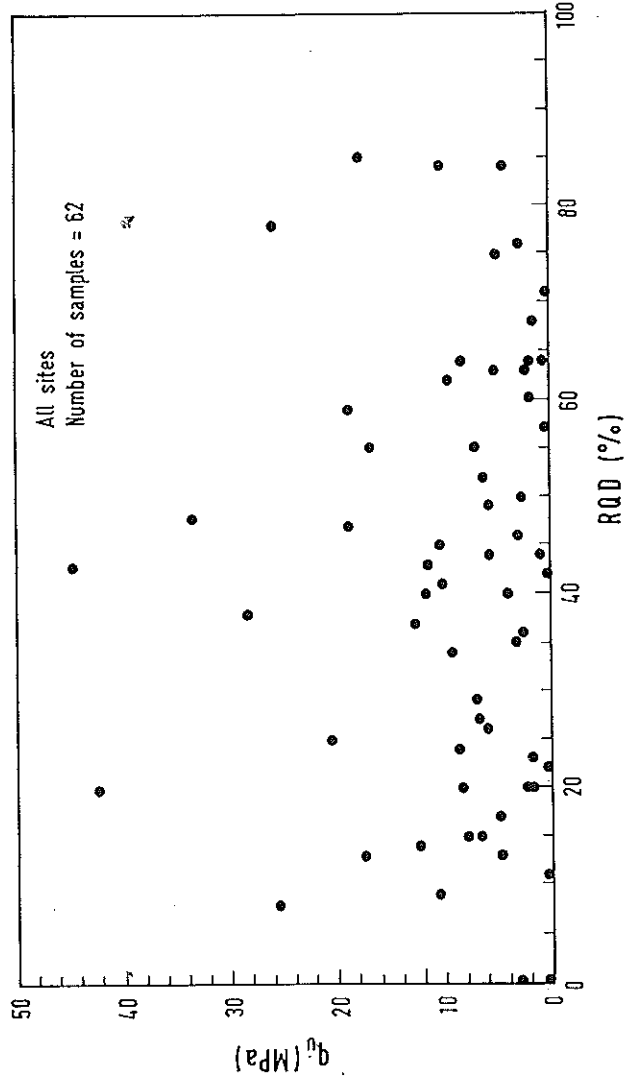


Fig. 5 Plot of unconfined compressive strength (q_u) versus rock quality designation values (RQD) for all sites.

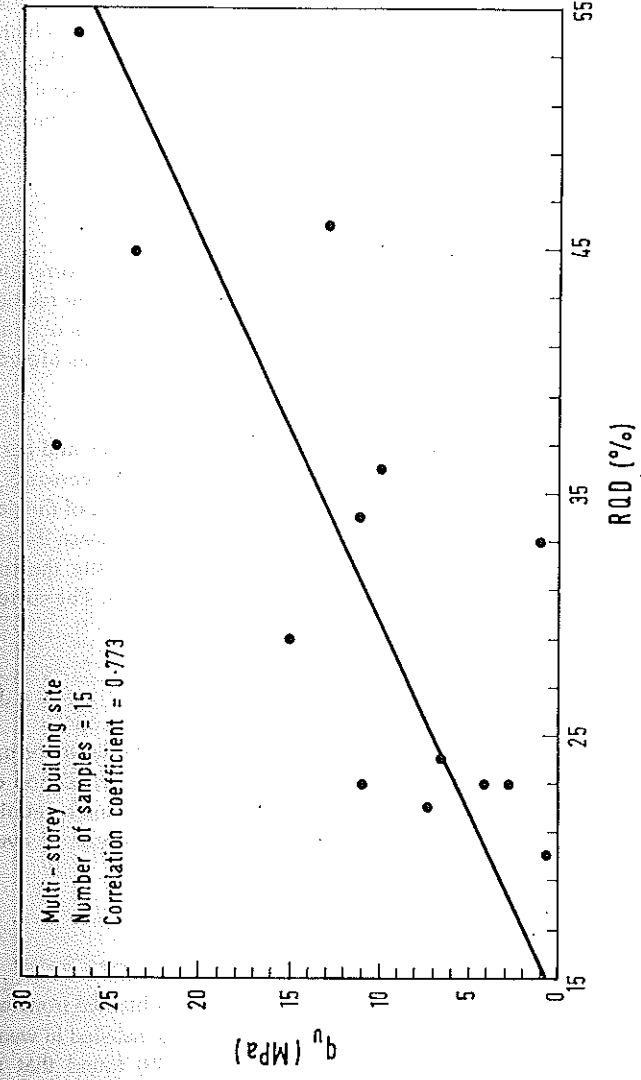


Fig. 6 Plot of unconfined compressive strength (q_u) versus rock quality designation values (RQD) for a multi-storey building site.

A plot of extrapolated N values versus q_u from data gathered from tests carried out on rocks at adjacent locations can also be obtained. The plot is highly scattered but a much improved correlation can be obtained when a log-log plot is employed, as shown in Fig.4. Rock type does not appear to be a significant factor in the relationship between q_u and extrapolated N value. It can be established that q_u may be given as

$$q_u = 10^{[-3.29 + 1.45 \log_{10}(N)]} \quad (100 < N < 1200) \quad (3)$$

It should be noted that the above relationship has a relatively low correlation coefficient indicating a high degree of scatter. It is suggested that the relationship may be used as an approximate estimation of q_u from N values obtained in the field. Such interpretation is especially useful if the rock cores are very highly or completely fractured.

Based on q_u values obtained from unconfined compression tests and corresponding RQD values given for the same rock core, a plot of RQD versus q_u is shown in Fig.5 and no definite trend is observed. However, analysis of the data for individual sites reveals that there is a reasonable correlation between the two parameters at one particular site, see Fig.6. At this particular site the rock materials are fairly uniform and predominately consist of siltstones. The correlation between the two parameters is given as

$$q_u = 0.633 \text{ RQD} - 8.76 \quad (15\% < \text{RQD} < 55\%) \quad (4)$$

It is suggested that if the rock type of a particular site is fairly uniform, it may be worth examining whether a relationship exists between RQD and q_u . If a correlation can be established, it would greatly enhance the interpretation of rock strength as RQD values are recorded at frequent intervals at every borehole for site investigation work in rocks.

DEFORMATION PARAMETERS

Based on the back analysis of load-settlement relationship obtained from load tests on large diameter rock-socketed cast in-situ bored piles installed in weathered sedimentary rocks, Radhakrishnan and Leung (1989) found that the elastic modulus of the rock mass, E , can be obtained from q_u values based on a relationship of $E = 215 q_u$ proposed by Rowe and Armitage (1987).

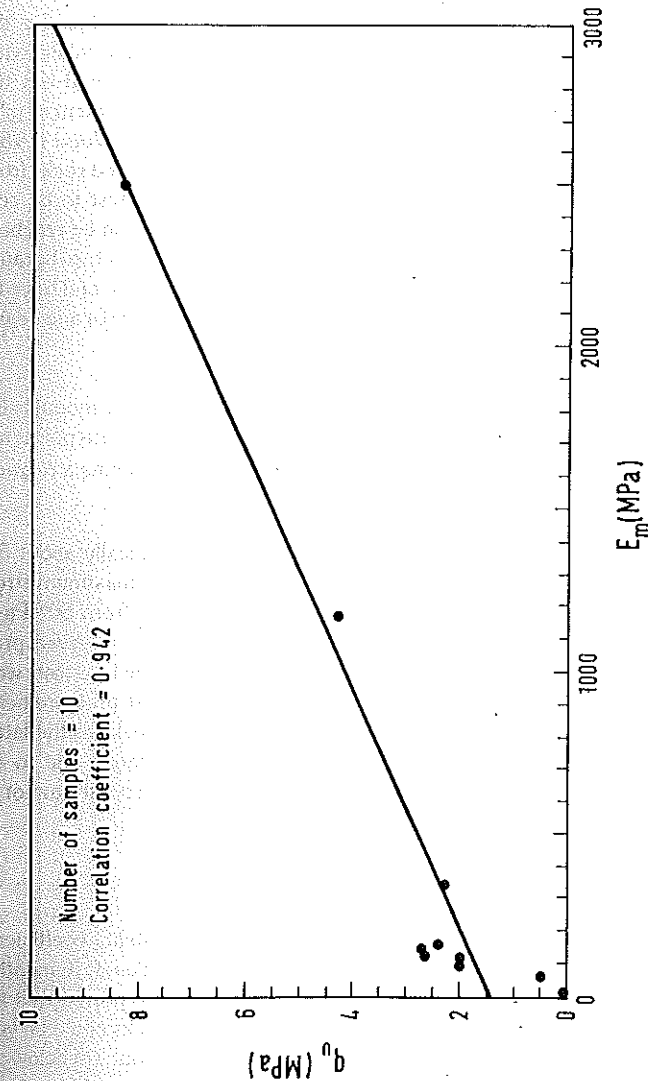


Fig. 7 Plot of unconfined compressive strength (q_u) versus pressuremeter modulus (E_m).

Results from pressuremeter tests indicated that majority of values for the pressuremeter modulus are below 500MPa with occasional readings falling with in the higher range of 500 to 3000MPa. Tomlinson (1989) pointed out the potential use of pressuremeter modulus in the computation of settlement of piles socketed in weathered sedimentary rocks in Singapore. Mair & Wood (1987) described two methods to determine the shear strength of weathered rocks from their pressure/deformation history. Both methods require the test to be conducted well into the plastic phase such that a limiting pressure can be reached. However such values cannot be obtained in the present test setup because pressuremeters of extremely high capacity are not readily available and have to be specially fabricated such as those described by Ervin et al., (1980) and Jewell & Fahey (1984).

However, an attempt has been made to correlate pressuremeter modulus E_m with q_u and the results are shown in Fig.7. Unfortunately, only 10 data points are available at the present time. Clearly more data are needed to define a relationship.

Plate load tests conducted at relatively shallow depths (typically about 5m below ground surface) gave settlements of less than 10mm at a maximum stress of 4MPa. Typical rock elastic modulus values obtained varied from 50MPa to 120MPa. Such values appear to be within the lower range of observed pressuremeter modulus values and this is considered reasonable as the load tests were conducted at relatively shallow depths. It is recommended that pressuremeter tests rather than plate load tests be performed on weathered rocks as the latter tests are expensive and time consuming, the ground disturbance due to pit excavation is far more severe and the variations of modulus with depth cannot be rigorously investigated.

PERMEABILITY

Packer tests performed at sites indicated very low permeability coefficients ranging from 0 to 2m/year. In the course of construction of a pile-raft foundation supporting a highrise building, Leung et al., (1985 & 1988) reported that the actual coefficient of permeability of weathered sedimentary rocks could be very much higher. The original ground water table at the site was about 1m below the original ground surface before construction and had been drawn down to the foundation base level of 7m just before commencement of construction. Readings obtained from pneumatic piezometers and open standpipes throughout the

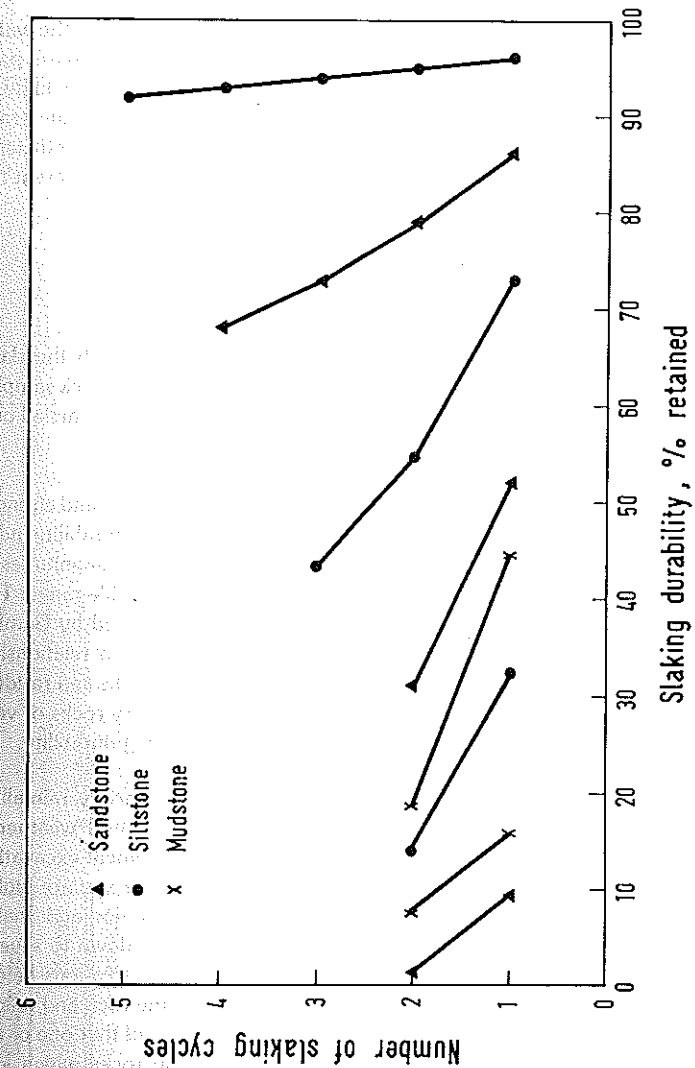


Fig. 8 Typical slake durability test results.

construction period of the foundation and superstructure revealed that the water table soon rose back to its original position and the dissipation of excess pore water pressures was rather rapid. This indicates that the actual permeability of the rock mass is high and is considered to be due to the existence of numerous natural fractures and fissures in the rock mass. Thus permeability coefficients obtained from packer tests in weathered rocks may not necessary represent the true permeability of the rock mass.

SLAKE DURABILITY INDEX

Typical slake durability test results are shown in Fig.8 in which the slake durability index is plotted against the number of slaking cycles. For rock samples of high slaking durability, up to five cycles of slaking and drying are carried out, as suggested by Brown (1981).

A summary of the slake durability index against weathering state and strength for all rock types is given in Fig.9. In the present work, the slake durability index after two test cycles, I_{d2} , is employed and it is observed that the magnitudes of I_{d2} for weathered sedimentary rocks span almost the entire possible range. The rock classification according to slake durability index as proposed by Gamble (1971) is also given in Fig.9 which clearly shows that there is a relationship between the index and rock strength. Completely weathered rocks and residual soils have very low slaking durability and weathered sedimentary rocks of very weak strength ($q_u < 1.25\text{MPa}$) have very low to medium slaking durability.

In recent years, many slope failures have occurred after heavy rainfall in Singapore. For example, Lo et al., (1988) reported that several weathered sedimentary rock slopes failed during the course of a deep basement excavation in the Central Business District of Singapore. The rocks at the site are highly stratified and consist of highly to slightly weathered sandstones and shaley mudstones to great depths. Rocks of very low strength occur down to several metres below the base of excavation level. Ground water observations before failures indicated repeated cycles of wetting and drying on the rock and failure occurred after a prolonged period of heavy rainfall. It is believed that one of the major causes of failure is the low slaking durability of the rocks which lose substantial amount of rock material and suffer great reduction of strength after repeated cycles of wetting and drying. It is hence suggested that for excavations in weathered rock, extensive slake durability tests should be performed to

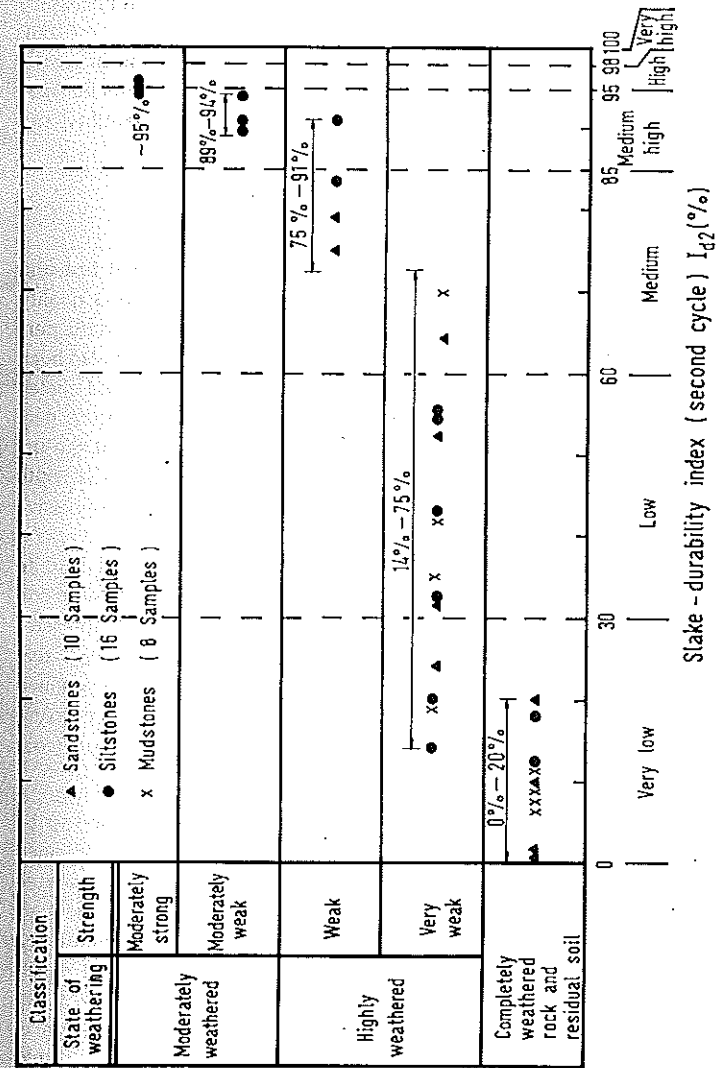


Fig. 9 Plot of slake durability index versus rock classification.

establish the slake durability index of the rock. Extra precautions and necessary actions may be considered if the rock has a low slaking durability ($I_{d2} < 60\%$). Such measures may greatly enhance the safety of excavation design in weathered rock. Slake durability tests are preferred over other types of tests because they are relatively inexpensive to perform, the test results can be quantified and disturbed rock specimens can be tested.

CONCLUSIONS

Laboratory tests such as unconfined compression test, point load test and slake durability test have been performed on a large number of good quality weathered sedimentary rock core samples. In-situ tests such as standard penetration test, pressuremeter test, packer test and plate load test have also been carried out. The rocks investigated include sandstones, siltstones and shaley mudstones. Statistical analyses have been performed to correlate various geotechnical parameters of weathered sedimentary rocks. It is noted that the unconfined compressive strength is only about six times the point load strength regardless of rock type. Hence the commonly used unconfined compressive strength/point load index ratio of 15 to 35 given in existing published works is not valid for weathered sedimentary rocks in Singapore and would lead to excessively high unconfined compressive strength values. An approximate correlation between standard penetration resistance and unconfined compressive strength is also proposed. For uniform weathered siltstones, it appears that there exists a correlation between rock quality designation values and unconfined compressive strength. Based on limited test data, a correlation between pressuremeter modulus and unconfined compressive strength is indicated but more work has to be done in this area to confirm this.

Permeability coefficients of weathered sedimentary rocks are found to be high due to the presence of natural fissures and faults. However, values obtained from packer tests were very low and are unrepresentative of the demonstrated permeability of the rock mass. Tests performed on the three types of sedimentary rocks revealed that rocks of very low strength have low slaking durability. This observation helps to explain why some slope excavations in highly weathered rock fail after repeated cycles of wetting and drying and it is suggested that slake durability index could be used as a parameter in the design of excavations in weathered rock. Although these conclusions are based on results obtained from weathered sedimentary rocks in Singapore, it is believed that they may also be valid for similar rock conditions elsewhere.

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