THE ORIGIN AND PROPERTIES OF BOULDERY CLAY IN SINGAPORE

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SYNOPSIS

The Bouldery Clay in Singapore is a stiff to hard landslide material with randomly distributed sandstone boulders. The soil matrix consists of silty and sandy clay. The boulders vary in shape and size as well as the degree of weathering. The Bouldery Clay can be as deep as 120 m below the present ground surface. Bouldery Clay is mainly found in and around the central business district of Singapore and many of the high-rise buildings have been constructed on or in this formation.

The Bouldery Clay is postulated to have originated from a series of landslides along faults. Some of the faults could be observed on a map from 1819.

The strength of the soil matrix has been investigated by standard penetration tests, pressuremeter tests and plate load tests. The average undrained shear strength is 1.0 MPa. The average modulus of elasticity of this material is 280 MPa as determined from the unloading-reloading curves from the plate load tests conducted in the horizontal direction.

INTRODUCTION

The Bouldery Clay in Singapore consists of sandstone boulders which are embedded in a matrix of stiff to hard silty and sandy clay. This material has been found in and around the Central Business District (CBD) in Singapore (Fig. 1) and several high-rise buildings have been constructed on or in this formation such as the OUB Centre, the Shell Tower, the Raffles City Centre, the Ocean Building, the Ocean Tower and the UOB Plaza. The last two buildings are presently under construction. However, knowledge about the behaviour of this material is very limited. There are several cases where unsuitable foundation methods have been used in the Bouldery Clay resulting in time delays and additional costs. The lack of knowledge about the strength and deformation properties of the Bouldery Clay has led to very conservative designs.

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This article will:

- discuss the nature and the behaviour of the Bouldery Clay in Singapore and its possible origin;
- indicate the distribution of the Bouldery Clay; and
- discuss the strength and deformation properties of the Bouldery Clay.

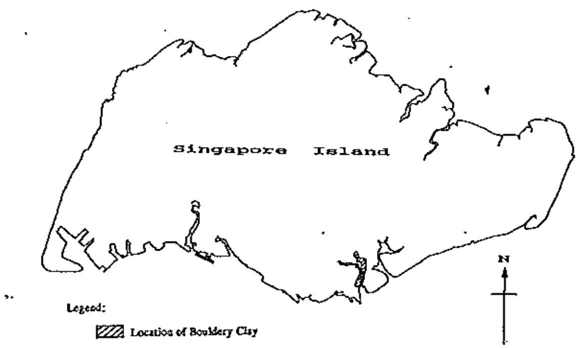

Fig. 1 Location of Bouldery Clay.

NATURE OF BOULDERY CLAY

The occurrence of Bouldery Clay in Singapore was first reported in the literature by Nowson (1954), in connection with the construction of the Asia Insurance Building. The term 'boulder-clay' was initially proposed by Sehested in 1960. This material has also been referred to as 'Bouldery Clay' by Poh et al (1987). Pitts (1984) called this formation 'boulder bed'. A photograph showing a typical exposure of a boulder embedded in the clay matrix is presented in Fig. 2.

The soil matrix of the Bouldery Clay is reddish brown and grey. It can occasionally be purple when it is moderately weathered. The soil matrix of the Bouldery Clay consists of about equal parts of clay, silt and sand size particles. The remaining 5 to 10% is gravel. The variation of the particle size with depth in small. The matrix behaves essentially as a stiff to hard, heavily over-consolidated clay and it softens easily when in contact with water.

The colour of the sandstone boulders is brown to yellowish brown. In some instances, white silstone boulders have been found. Quantitative petrographic analyses show that the sandstone boulders are composed of more than 66% quartz, 6 to 8% of polycrystalline quartz, 3 to 5% of chert and 9 to 12% of quartz overgrowths. In the caisson shaft excavations for the United Overseas Bank (UOB) Plaza, the size of boulders varied from a few decimeters to 6 m. Pitts (1984) has reported boulders

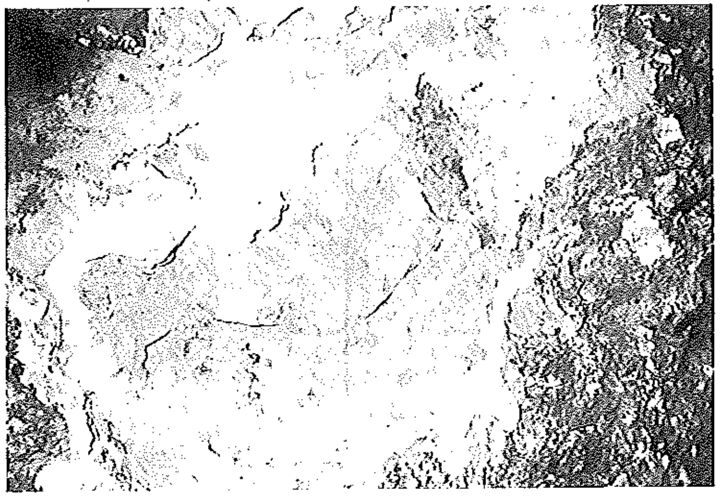

Fig. 2 A Photograph of Bouldery Clay.

of the size of a double decker bus. The size of the completely to highly weathered sandstone boulders is generally less than 1 m^3. The fresh to slightly weathered boulders are commonly 1 to 2 m^3 in size. The degree of weathering of the sandstone ranges from completely weathered to fresh. The shape of the boulders varies, it ranges from angular to subrounded.

The completely weathered and fresh sandstone boulders are always interbedded and randomly distributed in the clay matrix. The boulder content is approximately 20-30% by volume. The boulder content does not very significantly with depth.

EXTENT AND THICKNESS

The extent of the Bouldery Clay has been established from recent site investigations and re-examination of old records and is shown in Fig. 3. If the Bouldery Clay has been formed by a series of landslides, a wider distribution of this material is expected along the hills shown in Fig. 4 and illustrated in Fig. 5.

Boreholes have shown that the bottom of the Bouldery Clay can be as deep as 117 m below mean sea level, about 120 m below the present ground surface. The elevation of the surface of the Bouldery Clay is shown in Fig. 6. It can be close to the present ground surface and be covered by fill which is the case at e.g. Raffles City Centre and the Shell Tower. There are some indications that the surface of the Bouldery Clay is dipping away from the hills shown in Fig. 4 and that the surface of

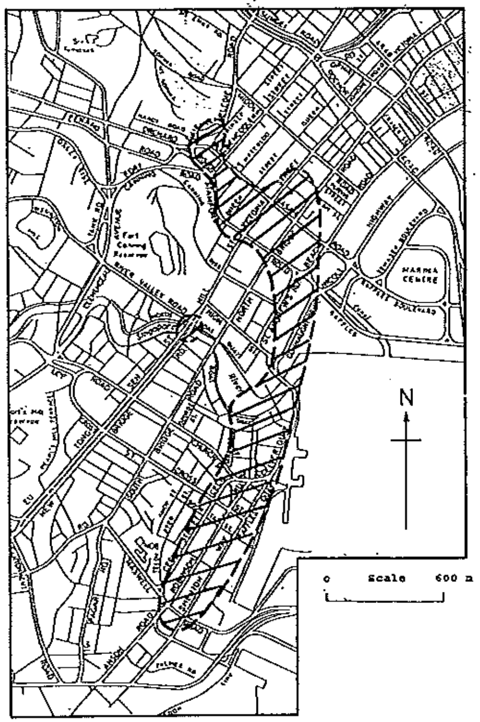

Fig. 3 Extent of Bouldery Clay.

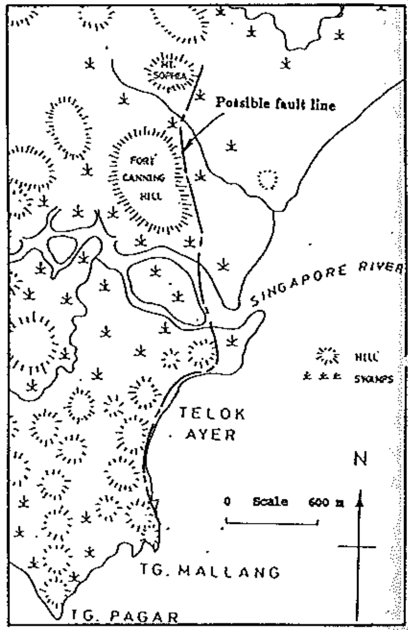

Fig. 4 Singapore CBD and its Environs in 1819 (after Wong, 1969).

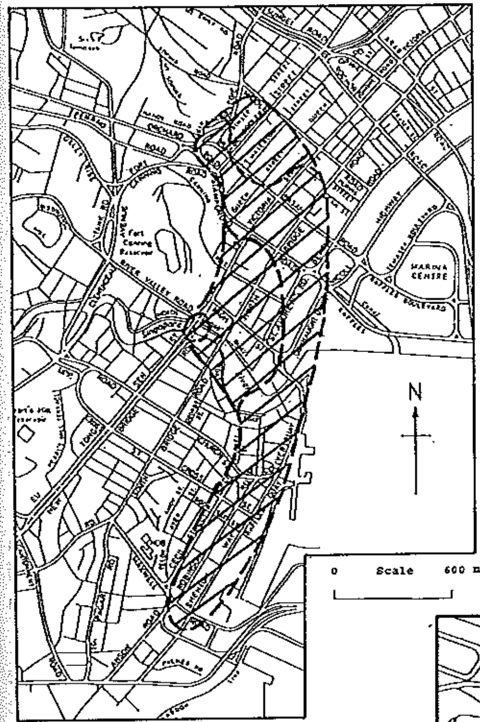

Fig. 5 Possible Distribution of Bouldery Clay in Singapore.

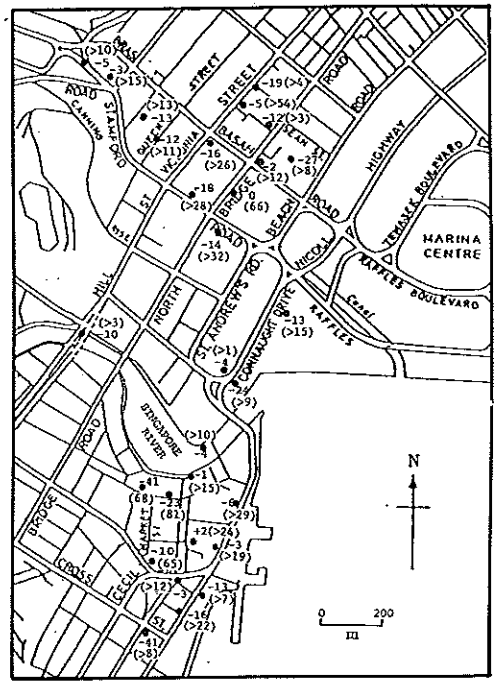

Fig. 6 Top Elevations and Thicknesses of Bouldery Clay.

Note: Elevations are in metres with respect to the mean sea level.
( ) Thickness in metres.

the Bouldery Clay can be as deep as 40 m below the ground surface. The maximum thickness of the Bouldery Clay is about 90 m. The minimum is about 30 m.

POSSIBLE ORIGINS

There are several possible explanations for the formation of the Bouldery Clay. The material could possibly have been formed by weathering of the rock in-situ or it could be a colluvial deposit.

The first mode of formation is not very likely since the Bouldery Clay occurs only within a narrow, about 300 m wide strip, at the southern part of Singapore Island. This material has not been found in other parts of Singapore or in the nearby region. If this material had originated from the rock weathered in-situ, the arrangement of the boulders should be controlled by the original joint pattern of the rock; and there should be bedding planes in the less weathered boulders. However, in reality, the boulders are located randomly and bedding planes have not been found.

It is likely that the Bouldery Clay is a colluvial deposit which originated from the Jurong Formation and it was formed by a series of landslides before and around the early Pleistocene period at about the same time as deposition of Old Alluvium was in progress.

According to Wong (1969), a map from 1819 has shown that there was a range of hills running along the beach of the Telok Ayer Basin, just south of the Singapore River (Fig. 4). The coast was rocky with high cliffs. To the north of the Singapore River, there are two hills, namely, Mt. Sophia and Fort Canning Hill which belong to the Rimau Racies of the Jurong Formation. The Rimau Facies consists of well cemented quartz sandstone and quartz conglomerate (PWD, 1976). There is also a recent alluvial deposit which was formed after the formation of the Old Alluvium to the east of these two hills.

Since the Bouldery Clay has been found immediately east of these hills, the quartz sandstone boulders in the matrix could have originated from the Rimau Facies. Laboratory tests on the recovered cores of the sandstone boulders showed that the unconfined compressive strength is very high, up to about 195 MPa. Similar high strengths have also been recorded for the boulders from the excavations for the MRT stations. Quartizite is known to have high compressive strength. Also, corestones within the sandstone beds, are known to have exceptionally high strength.

The shear strength of the soil matrix is high. The matrix has probably been formed by weathering in-situ of shale, mudstone, siltstone and sandstone of the Jurong Formation which has been broken up and transported to its present location by erosion and landslides.

Interbedded dark grey siltstone and brown sandstone have been found beneath the Bouldery Clay at the Overseas Union Bank (OUB) Centre, at the UOB Plaza and at the Ocean Tower. The bedrock is located at 65 m to 117 m depth below mean sea level (msl). Dames and Moore (1983) have also reported a similar sequence of the rock close to the ground surface (about + 3 m msl) at the Dhoby Ghaut MRT Station next to Fort Canning Hill and at Mt. Sophia. This large difference in elevation could be due to downfaulting of the Jurong Formation.

It has been reported in 'Geology of Singapore' (PWD, 1976) that block faulting, possibly accompanied by warping, had occurred prior to or during the early phases of the deposition of the Old Alluvium. This time period is sufficiently recent to control the present topography. Downfaulting could also have occurred along the hills adjacent to the Telok Ayer Basin (Fig. 4), which extended to Mt. Sophia north of the Singapore River. The downthrust had lowered the ground surface up to 120 m at the southern part of Singapore. This downfaulting could have produced the cliffs and rockheads described by Wong (1969). The slickensided Bouldery Clay exposed in the caisson shafts supports the 'downthrusting' theory.

Subsequent weathering and erosion have with time reduced the stability of the cliffs. Landslides caused the sandstone boulders to be mixed with the broken-up and completely weathered shale, mudstone, siltstone and sandstone. It was also during this period that the Old Alluvium encroached onto the Bouldery Clay, which could explain the relatively high sand content of this material.

There is a layer with loose to dense sand overlying the interbedded sandstone and silstone at the bottom of the Bouldery Clay. This layer has been found from the boreholes at the UOB Plaza, OUB Centre and Republic Plaza. This could have been caused by the impact of the falling sandstone boulders and residual soil during the landslides. A few pockets of peaty soil have been found towards the bottom of the Bouldery Clay.

PHYSICAL PROPERTIES

The properties of the Bouldery Clay do not vary greatly. Extensive soil investigations were carried out for the MRTC tunnels and stations in the early eighties by Dames and Moore (1983).

A summary of the physical properties of the soil matrix as well as the boulders are presented in Table 1 and Fig. 7.

The water content of the soil matrix is 10 to 20% which is about 5 to 10% lower than the plastic limit. The water content does not vary with depth.

The coefficient of compressibility, m_v, determined from consolidation tests at an effective vertical pressure of 400 kPa, ranged from 0.004 to 0.07 m^2/MN. The corresponding elastic modulus, E, is approximately 150 MPa at an assumed Poisson's ratio of 0.35. This modulus value is low compared with those determined from pressuremeter tests or pile load tests. The discrepancy could be attributed to sample disturbance.

Table 1 Physical Properties of the Bouldery Clay

		Soil Matrix	Sandstone
Water Content, w (%)		10-20	1.3
Average Unit Weight, (kN/m^3)		22.0	25.0
Average Specific Gravity, G_s		2.6	
Gradation (%)	Gravel	< 26	
	Sand	34 - 53	
	Silt	21 - 35	
	Clay	< 31	

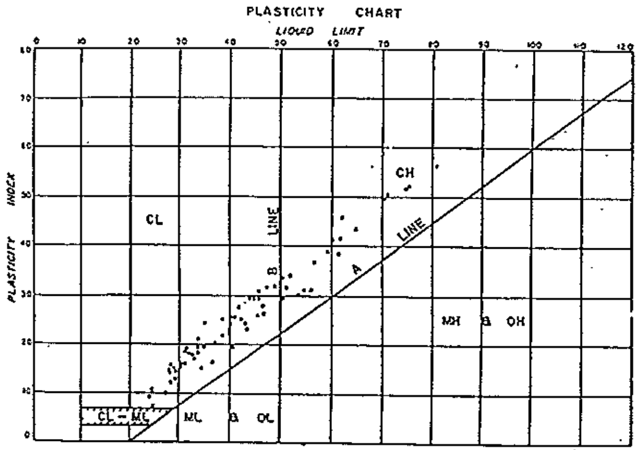

Fig. 7 Atterberg Limits.

The permeability of the soil matrix of the Bouldery Clay varies considerably depending on the particle size distribution. The coefficient of permeability can be as high as 1×10^{-5} m/sec.

STRENGTH AND DEFORMATION PROPERTIES

Standard Penetration Tests (SPT)

Most in-situ tests in the Bouldery Clay were SPT. It should be noted that the penetration resistance increases substantially when the split spoon sampler hits

gravels, cobbles or a boulder during the testing.

It is therefore desirable to carry out a large number of standard penetration tests in the Bouldery Clay so that some of the penetration tests would be done in the soil matrix. The lower bound value of the SPT index is an indication of the penetration resistance and the shear strength of the soil matrix.

Results of standard penetration tests in the Bouldery Clay at different sites are presented in Fig. 8. The lower bound value is about 175 blows/0.30 m from Fig. 8. The undrained shear strength has been estimated to be about 1000 kPa based on the correlation proposed by Stroud (1974, 1988) and Cole and Stroud (1976) with $c_u = 5N_{spt}$ to $6N_{spt}$ (kPa).

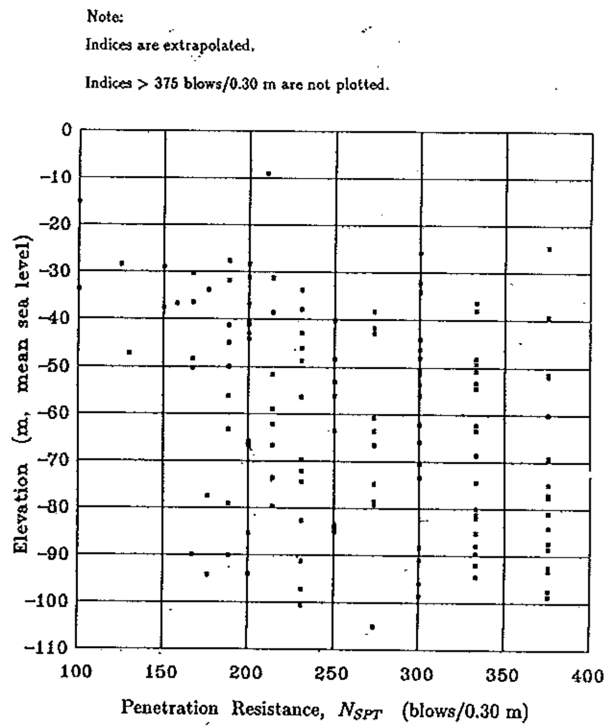

Fig. 8 SPT Indices.

Pressuremeter Tests

Another in-situ testing method which is used in the Bouldery Clay is the pressuremeter test. This test is carried out by installing the pressuremeter in a borehole.

The initial shear modulus, G_i, is calculated from the slope of the pressuremeter curve. If unloading-reloading cycle is performed, the unload-reload modulus, G_{ur}, can be computed from the slope of the bisecting line. The corresponding elastic moduli, E_i and E_{ur} have been calculated with an assumed Poisson's ratio, as shown in Fig. 9.

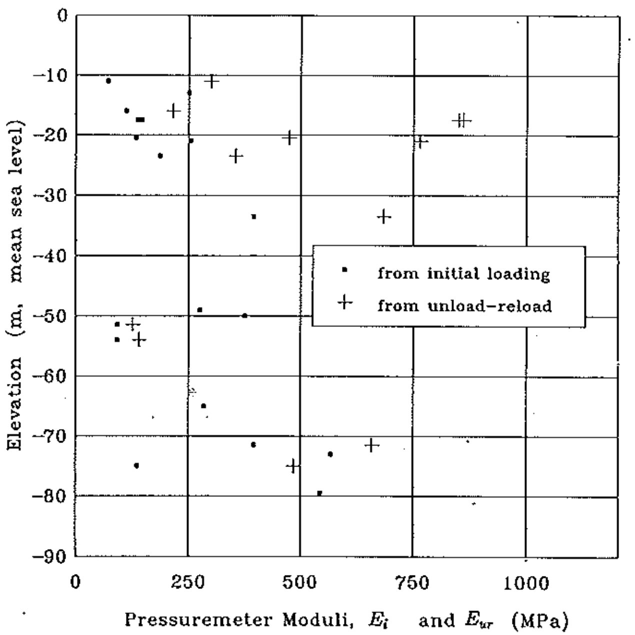

Fig. 9 Pressuremeter Modulus.

The undrained shear strength of the Bouldery Clay has been obtained from the slope of the p vs. $\log_e$ (Δ V/V) relationship or p vs. $\log_e$ (ϵ_c) curve where p is the applied pressure in the borehole, Δ V is the increase of the volume, V is the current volume of the cavity and ϵ_c is the radial strain or the circumference strain at the wall of the borehole, $\epsilon_c = (r - r_o)/r_o$ (r is the radius of the pressuremeter cavity and r_o is the initial radius). This method is valid for a perfect elastic-plastic material. This method is applicable to incompressible materials such as very stiff to hard clays and weak rocks, such as mudstone (Mair and Wood, 1987).

The undrained shear strength and the true limit pressure are plotted in Fig. 10. It is expected that most of the pressuremeter tests have been carried out in boreholes partly surrounded by the soil matrix and partly by the boulders. Hence, the lower

bound values in Fig. 10 are believed to represent the actual strength of the soil matrix. The minimum undrained shear strength and the true limit pressure so determined were found to be 1 MPa and 5 MPa respectively. The corresponding pressuremeter constant, Np, is therefore 4.2 assuming the coefficient of lateral earth pressure at rest, K_o, is 2.

Plate Load Tests

Plate load tests were conducted to determine the shear strength and the modulus of elasticity of the soil matrix. The main advantage of this test method is that the tests are carried out in-situ. The tested soil mass is thus less disturbed, as compared to samples extracted for laboratory tests. Since the volume which is tested is relatively large, the test results will also reflect the influence of any cracks and fissures in the soil.

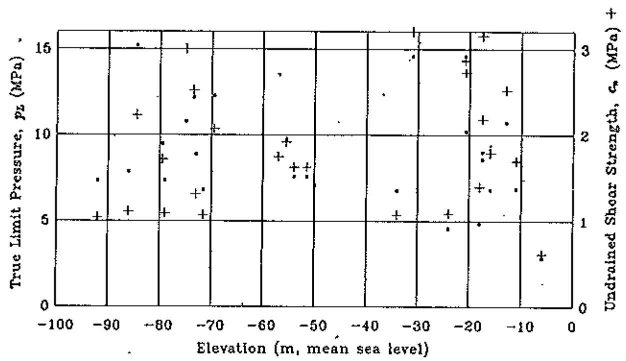

Fig. 10 True Limit Pressure and Undrained Shear Strength derived from Pressuremeter Tests.

Plate load tests were done in the caisson shafts of the UOB Plaza and in the test pits at the Shell Tower (Dames and Moore, 1983). The steel plate was loaded vertically using the lining in the caissons as reaction, whereas the tests done in the test pits were either in the horizontal or the vertical direction. The diameter of the steel plates was 0.1 m or 0.3 m. The plate could only be loaded to failure when a small diameter (0.1 m) plate was used because the shear strength of the soil matrix was very high. Tests done at the UOB Plaza were at 60 m to 77.5 m depth below mean sea level, whereas the tests at the Shell Tower were located at 1 m to 5 m below mean sea level.

Results of four plate load tests at the Shell Tower have been analysed to obtain the elastic modulus using the following formula (Poulos and Davis, 1974):-

$$E = \frac{\pi}{2} \frac{qr}{S} (1 - \nu^2) \qquad (1)$$

where q is the applied pressure, r is the radius of the loaded plate, s is the average settlement and v is the Poisson's ratio.

The average modulus of elasticity as determined from the unloading-reloading curves is 280 MPa at a Poisson's ratio of 0.35. The results were derived from tests conducted on the soil matrix and the plate was loaded in the horizontal direction. The strain level corresponded to 0.2% to 0.5% of the diameter of the plate.

As the tests at the Shell Tower were not carried out to failure or close to failure, it has not been possible to calculate the shear strength. Results of three plate load tests which have been carried out in caisson shafts are given in Fig. 11. The undrained shear strength was evaluated using the following relationship:-

$$C_u = \frac{q_{ult}}{N_c S_c} \quad (2)$$

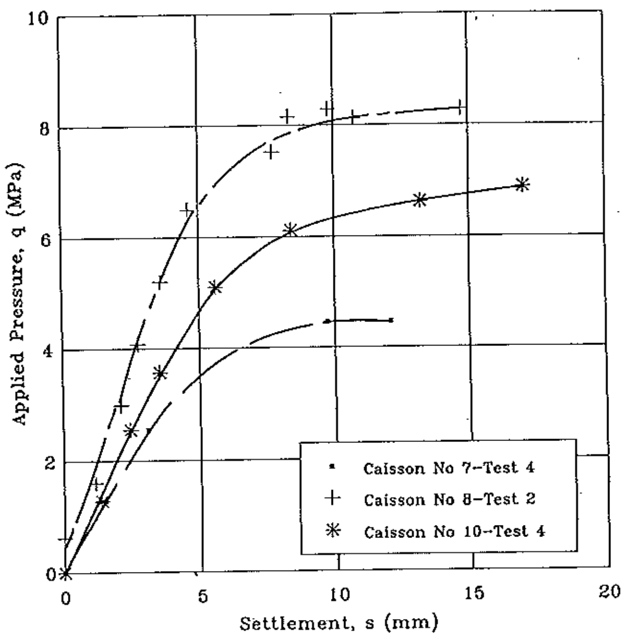

Fig. 11 Plate Load Tests.

where q_{ult} is the ultimate bearing pressure on the plate; N_c is the bearing capacity factor, which is equal to 5.14, and s_c is a shape factor, which is equal to 1.2 for a circular plate. The measured average undrained shear strength of the soil matrix was 1.06 MPa which is very close to that obtained from the standard penetration tests and the pressuremeter tests.

The modulus of subgrade reaction of the soil matrix, $k_{0.01}$ varies from 0.83 to 1.39 GN/m^3. In this case, the loaded plate was 0.01 m in diameter.

The results are plotted in a non-dimensional form in Fig. 12. These curves can be used to predict the settlement of footings, rafts and piles founded on the soil matrix of the Bouldery Clay. The displacement required to fully mobilize the bearing capacity is approximately 10% of the plate diameter. Hence, the settlement required to mobilize the ultimate pile base resistance of a bored pile of 1.0 m diameter is 100 mm, which is a very large value. If a settlement of 20 mm is allowed at the pile base, the factor of safety should be at least 3.0 assuming that there is no debris at the bottom of the borehole and the bottom has not been softened during construction.

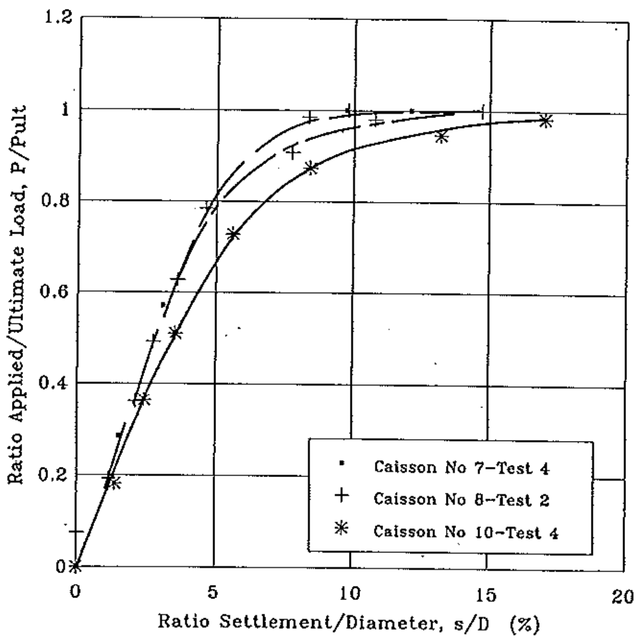

Fig. 12 Non-Dimensional Plot of Plate Load Tests.

A summary of the strength and deformation properties of the soil matrix from the in-situ tests is given in Table 2.

Laboratory Tests

The soil matrix could not be tested properly because the samples disintegrated and softened readily.

Unconfined compression tests and point load index tests were conducted on core samples to evaluate the strength of the sandstone and siltstone boulders. The

Table 2 Summary of Strength and Deformation Properties of Soil Matrix

Test	c_u, MPa	E, MPa
SPT	1.0	-
Pressuremeter	1.0	125* to 860*
Plate Load Test	1.1	280**

Note * From unload-reload cycle of tests.
** From unload-reload cycle of tests in horizontal direction.

majority of the investigated samples were cores from the sandstone boulders. The unconfined compression strength of the boulders varied considerably, from 0.1 MPa to 195.4 MPa. Such a large variation in strength is due to the different state of decomposition of the boulders.

The values of point load index, $I_{s(50)}$, have been correlated with the unconfined compression strength, q_u. Both are shown in Fig. 13. The relationship, $q_u = 6I_{s(50)}$ corresponded to the general trend of the data.

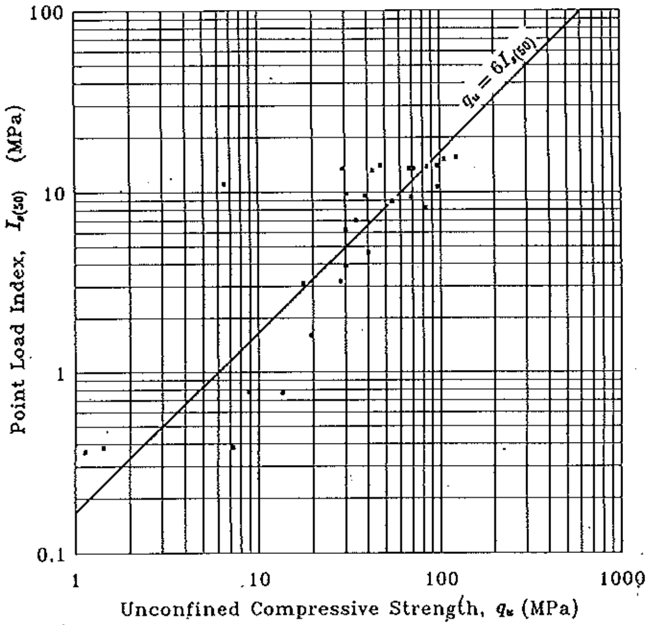

Fig. 13 Point Load Index vs. Unconfined Compressive Strength.

CONCLUSIONS

It is postulated that the Bouldery Clay in Singapore originated from landslides. It comprises strong sandstone boulders in a stiff soil matrix. The extent of the Bouldery Clay might be larger than formerly thought.

The undrained shear strength of the soil matrix is about 1.0 MPa determined from standard penetration tests, pressuremeter tests and plate load tests. The average modulus of elasticity is 280 MPa as determined from the unloading-reloading curves of the plate load tests which were conducted in the horizontal direction.

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