

PROPERTIES & ORIGINS OF SINGAPORE BOULDER BED

by

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*Reprinted from
Proceedings, 10th Southeast Asian
Geotechnical Conference, Vol. 1, pp. 463-468
Taipei, 1990*

Properties & Origins of Singapore Boulder Bed

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SYNOPSIS: Extensive areas of central Singapore are underlain by a deposit of stiff clay containing often massive quartzite boulders. This the so-called "boulder bed" lies on a flat table formed by a downthrust about 20 million years ago. The deposit appears colluvial, and data from the construction of the Singapore Mass Rapid Transit System has confirmed that rock with a similar composition and strength occurs in-situ near the area of the deposit. Deposition of this boulder bed could have been a result of massive mudflow occurred about one million years ago. MRT Construction also allowed the bulk shear strength of the boulder clay to be back-analyzed from records of excavation, anchors, piles and tunnels.

1 INTRODUCTION

The extremely rapid development of Singapore as a business and commercial centre has resulted in the central business district (CBD) being dominated by a large number of modern tower blocks, the tallest being over 70 stories high. Rapid development has also given Singapore the financial reserves to build an underground mass transit system (MRT) to service both the CBD and the outlying industrial areas. Foundation, basement and tunnel construction in the CBD area has encountered the 'Singapore Boulder Bed' (Pitts, 1984). The 'boulder bed' consists of often large, very hard, quartzite boulders in a matrix of stiff clay. The size (up to 200 m³) and strength (up to 185 mPa) of the boulders have made excavation in the bed a slow and expensive proposition. As with all boulder clays, it is also difficult to establish from small scale tests the bulk strength of the deposit, and to derive suitable design parameters for elements such as piles and retaining structures.

The extensive underground construction in the CBD in recent years has provided a wealth of new data on the nature, extent and properties of the 'boulder bed'. In this paper the general nature of the bed will be described, and the possible origins of the bed discussed.

2 EXTENT OF THE DEPOSIT

Figure 1 shows the areas in plan where the boulder bed has been encountered during MRT construction. Figures 2 and 3 show two profiles, one crossing and the other running along the MRT route. It can be noted that there are three major areas, constituting long whale shaped mounds associated with the MRT Raffles Place Station, City Hall Station, and the tunnels between City Hall and Dhoby Ghaut. Isolated areas have also been encountered near Coleman Bridge and south of Mount Sophia.

The way in which the MRT alignment has apparently been designed specifically to

maximize the length through the boulder bed is an illusion resulting from the selective development of the CBD. Large areas of the CBD have been sterilized from modern construction by the presence of old buildings such as Parliament House, the Victoria Concert Halls and the conservation areas along the Singapore River. Areas where the boulder bed is not shown in Figure 1 are often areas where no deep boreholes have been carried out, in contrast to the extensive investigation undertaken for the MRT.

3 NATURE AND DEPTH

The average boulder content of the boulder bed is typically about 25% by volume for large scale exposures. The percentage varied by relatively little, from about 20% to 30%, when looking at the overall proportion in a whole station or tunnel. On a small scale, however, the variation could be enormous. Individual boreholes recorded boulder contents as high as 70%, while other boreholes in the vicinity found only matrix material, with no large pieces of rock.

Petrographic analysis on boulders shows that quartz crystals comprise some 75% to 85% of the material, cemented by a further 10% of quartz overgrowths. Very small quantities of kaolinite or feldspars (typically about 1%) are also present. The boulders are extremely strong and resistant to weathering. Figure 4 shows histograms of the unconfined compressive strengths of samples taken from the boulders. The matrix material is a hard, red, fissured silty clay. Within the clay, fragments of weathered siltstones or mudstones can often be found.

Within the Raffles Place area, as shown in Figure 3, the level of the contact between the underlying Jurong formation of sedimentary rocks and the overlying boulder bed is remarkably constant at about RL 30m, giving a typical depth of 70m of the boulder bed. Elsewhere, the depth of the boulder bed can not be established, see Figure 2, because of the lack of deep holes.

Investigations show no noted layers of sand or organic material except at the base of the deposit, where organic material has been found in one of the boreholes.

4 POSSIBLE ORIGINS

The boulder bed is bounded by hills of the Rimau facies of the Jurong formation to the north-west, as shown in Figure 1, and the Jurong formation also underlies the bed as shown in Figures 2. At its north-eastern and south-eastern boundaries the boulder bed is overlain by Old Alluvium as shown in Figures 2 and 3.

The boulder bed was at first thought to be an insitu, weathered facies of the Jurong formation (Nowson, 1954). As further information has become available it is now clear from the way in which the quartzite boulders are completely surrounded by hard silty clay that the boulders are not 'core boulders' of the type associated

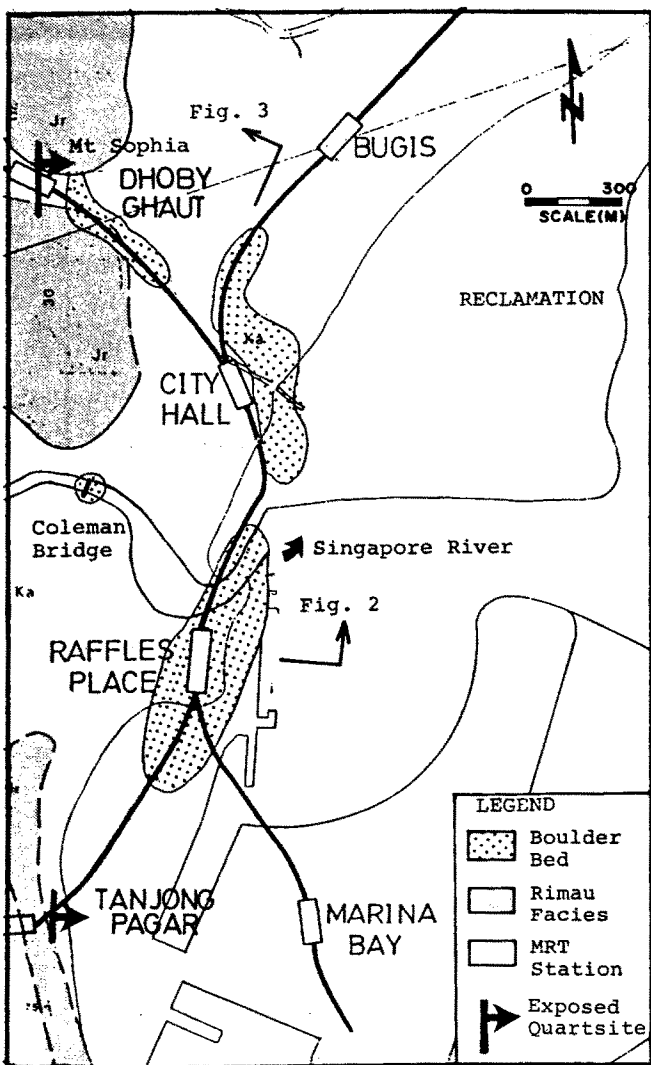


Figure 1 Distribution of Boulder Clay

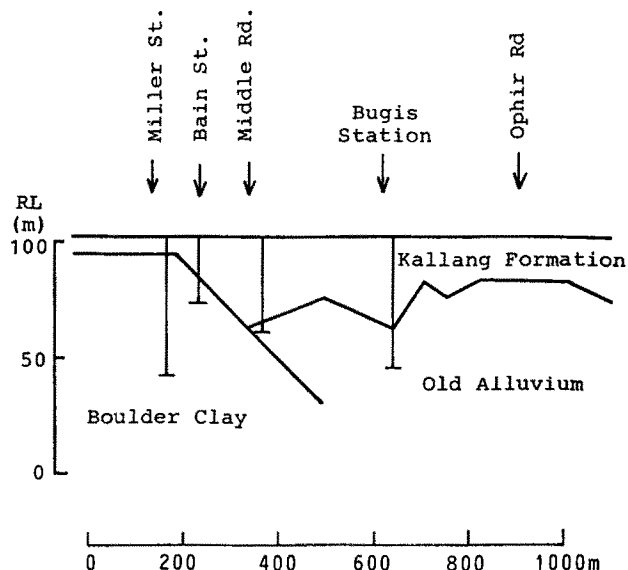


Figure 2 Profile at Bugis

with an insitu weathered rock. The general nature of the material strongly suggests a colluvial deposit (Pitts 1984, Poh et al. 1987). However this hypothesis has left unresolved two major objections:

(a) The only possible source rocks, those of the Jurong formation, are generally very significantly weaker than the quartzite boulders in the deposit. The unconfined compressive strengths of sandstones in the Jurong formation are generally less than 50 MPa, while those for the boulders range, generally, between 60 MPa to 170 MPa.

(b) The size of the deposit is huge, at least 10 million cubic meters, and difficult to reconcile with the generally low relief found in present day Singapore. Few hills of Jurong formation are more than 200m high.

The first objection was shown to be incorrect during the MRT construction work when a very hard layer of quartzite was found insitu within the Rimau facies of the Jurong formation. This occurred at two locations: in the tunnels between Tanjong Pagar and City Hall Stations, and at Dhoby Ghaut Station. In both cases the 50m wide bed of massive quartzite caused construction difficulties and claims from the contractors. The general strike of the Jurong formation at Tanjong Pagar was just east of north, and this strike direction leads almost exactly to the exposure at Dhoby Ghaut Station (Figure 1). The quartzite bed was dipping at between 50 and 70 degrees, explaining how difficult such a feature would be to find in widely spaced site investigation boreholes.

The results of strength tests on the quartzite found at Tanjong Pagar and Dhoby Ghaut are shown in Figure 5. Although the maximum strength measured was lower than that on boulders from the boulder bed, the mean value was quite similar. Petrographic examination of the quartzite found insitu within the Jurong

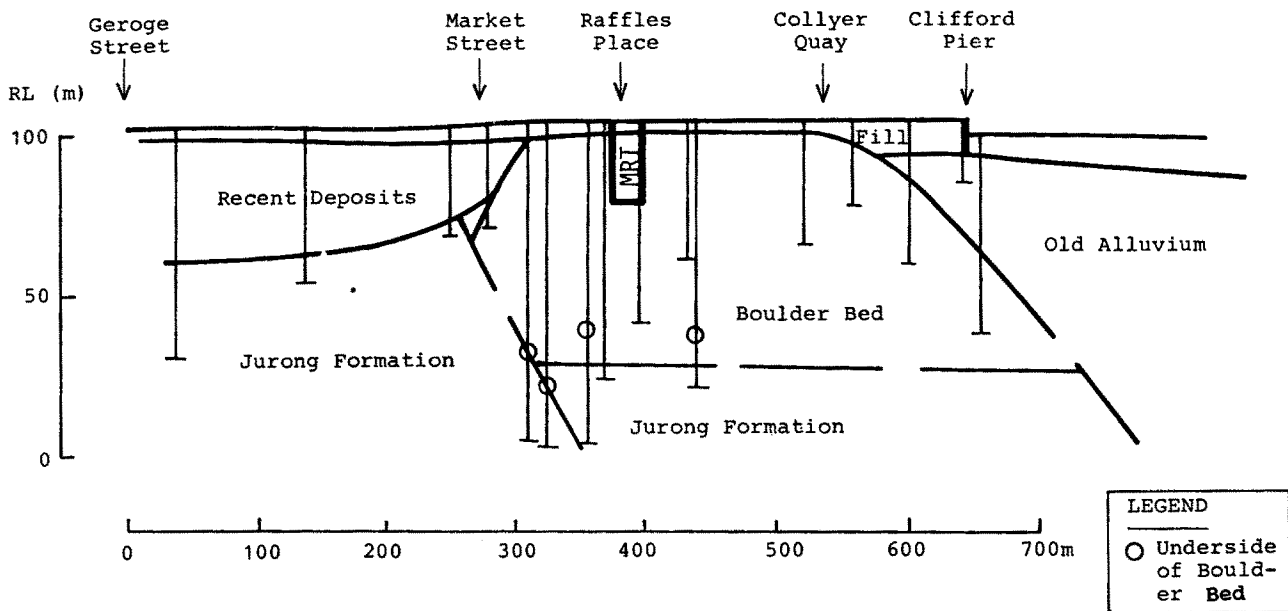


Figure 3 Profile at Raffles Place

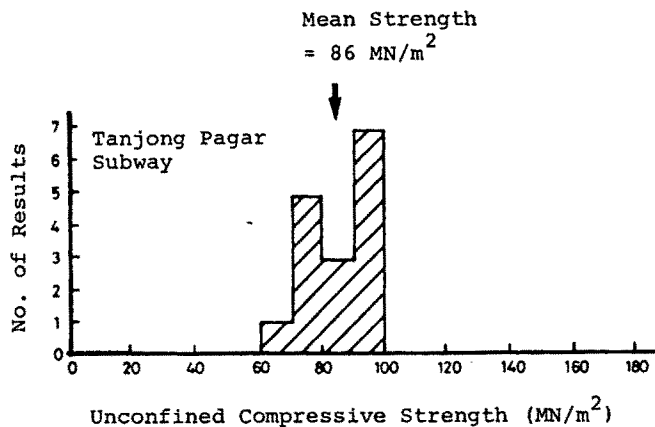
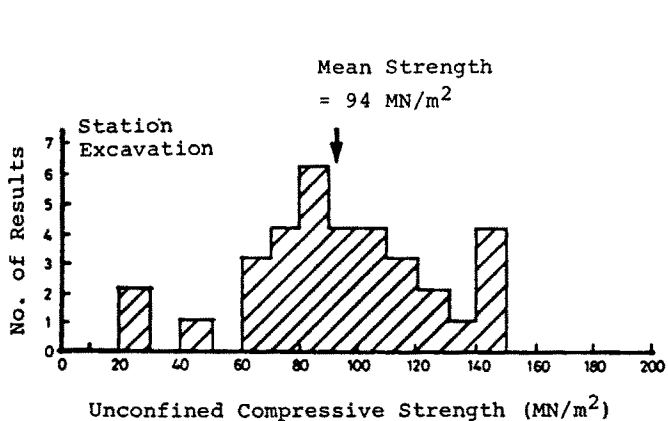
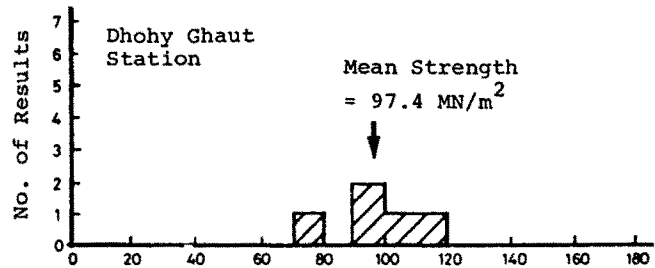
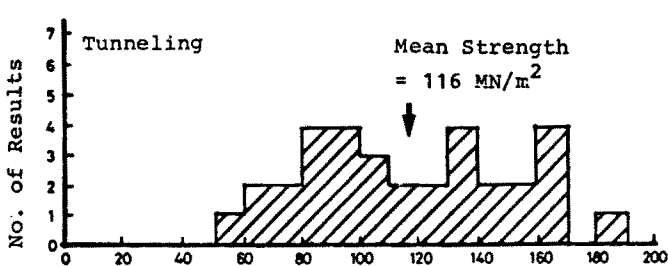


Figure 4 Strength of Boulders Found at Raffles Place

Figure 5 Strength of Quartzite in Rimau Facies

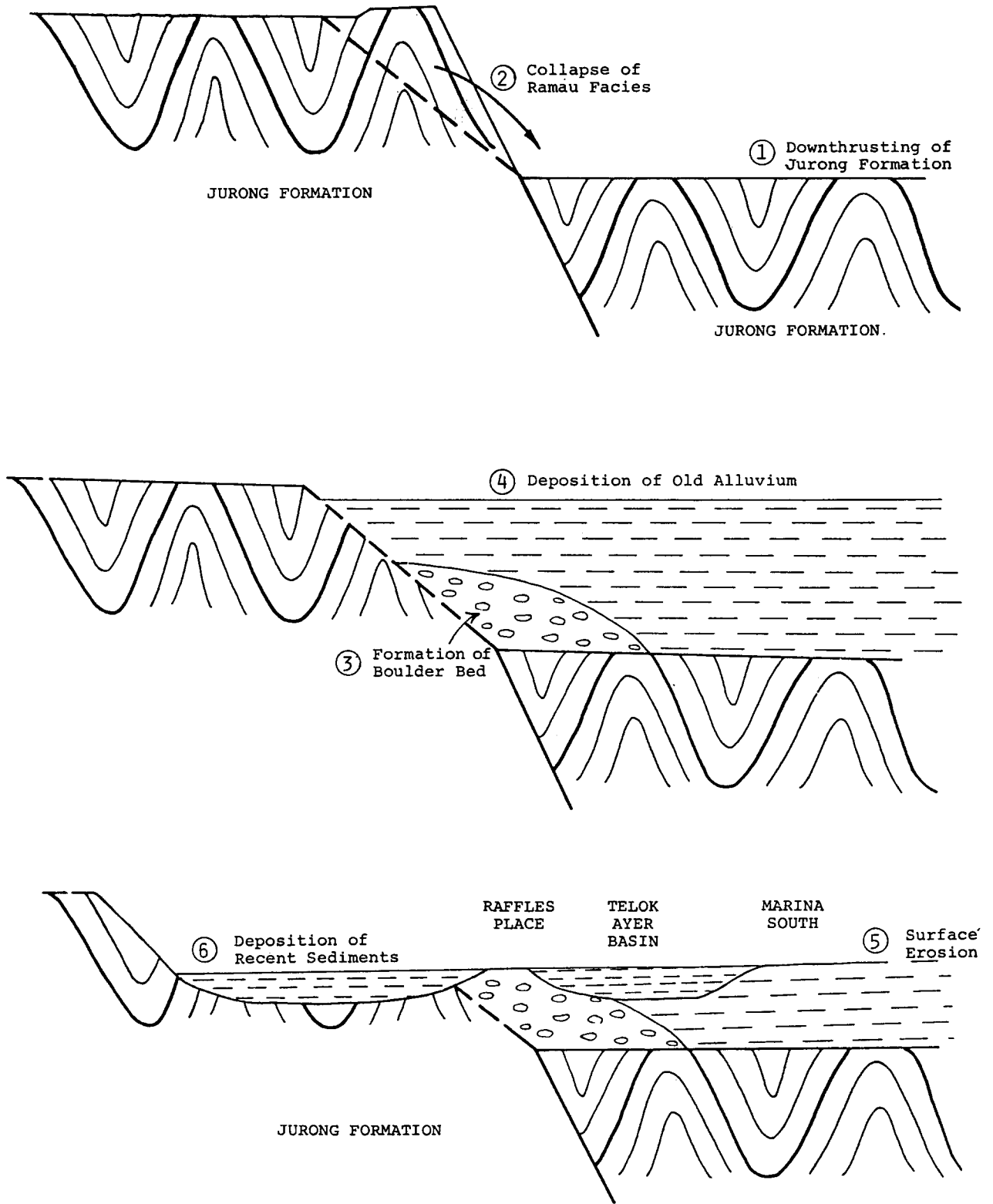


Figure 6 Geological Sequence

formation showed that it had a very similar composition to the boulder bed quartzite.

The MRT evidence appears to confirm that the source rock for the boulder bed is predominantly the Rimau facies of the Jurong formation. The possible reasons for the huge colluvial deposit can be best explained by considering the history of the Jurong formation and the Old Alluvium. According to the 'Geology of Singapore' (PWD 1976) the Jurong formation was heavily folded some 200 million years B.P. as a result of tectonic movement. Deep weathering and erosion followed. Some 20 million years B.P. there was a major downthrust, so that the surface of the Jurong formation now under the sea to the south of Singapore dropped more than 100m relative to the rocks now forming part of Singapore Island. Onto this flat table the Old Alluvium was deposited, with an original maximum thickness, estimated in Pitts, 1986, of at least 150m. Subsequent erosion has produced today's profile.

The boulder bed is clearly not a part of the Old Alluvium as the Old Alluvium is predominantly sandy, and although clay layers are present in the Old Alluvium these are generally thin (Gupta, 1987). The boulder bed occurs close to the edge of the downthrust. It is therefore suggested that the downthrust resulted in a near vertical cliff of Jurong formation, a cliff that was temporarily stable due to the strength of the quartzite bed within the Jurong formation at that point. The collapse of this cliff, either as a sequence of minor events during downthrusting or as a single catastrophic event at the end of the downthrust, occurred before the start of the deposition of the Old Alluvium. The postulated sequence is shown in Figure 6.

The collapse of the cliff was likely followed by mudflow as evidenced by the facts that (a) the boulders in the boulder bed are subangular and subround in shape, (b) the matrix material has a very high clay content, (c) the boulders appear to "float" in the clay and, relatively speaking, distribute uniformly, and (d) again, relatively speaking, there is a lack of boulder-to-boulders contacts. Judged from the fact that the clay matrix has never been lithified, the mudflow might occur within the period between the 0.5 to 1 million years B.P. The hypothesis of mudflow also explains why there are no transition materials between the Jurong formation and the boulder bed. These transition materials deposited after the downthrusting and before the mudflow could have been eroded way by the mudflow resulting in a shape contact between the Jurong formation and the overlying boulder bed.

The boreholes at Coleman Bridge found a thin layer of boulder bed overlying insitu Jurong formation rocks. Coleman Bridge is close to the base of Fort Canning Hill, which is formed of Rimau facies rock, Coleman Bridge would thus be close to the edge of the boulder bed deposit, and the thin layer found would be consistent with the hypothesis given above.

5 ENGINEERING PROPERTIES

During MRT site investigations it was found to be difficult to assess suitable strength parameters for the boulder bed material. Relatively few undisturbed samples of the matrix material were recovered, due to the large number of boulders. Where samples were recovered, the

presence of fissures made any test results on small scale samples extremely unreliable as a guide to bulk strength. The construction of the MRT, however, allowed some assessment of bulk strength by back-calculation from field measurements. Useful indicators were obtained from:

- (a) strut loads recorded during deep cut-and-cover station excavation.
- (b) settlements recorded over NATM tunnels.
- (c) values of ultimate skin friction recorded for preliminary test piles.
- (d) values of ultimate skin friction recorded for test anchors.

Strut loads recorded at the 27m deep Raffles Place Station excavation were reported by Hwang, Quah and Buttling (1987). They determined an apparent earth pressure diagram, of the type suggested by Peck, Hanson and Thornburn (1974), bounded by $0.25\gamma H$ (Figure 7). This would indicate an stability number, ie. $N = \gamma H/C_u$, of 4 or less. For a unit weight, γ , of 22 kN/m³ and a depth of excavation, H, of 27m, the corresponding C_u value will thus be at least 135 kPa.

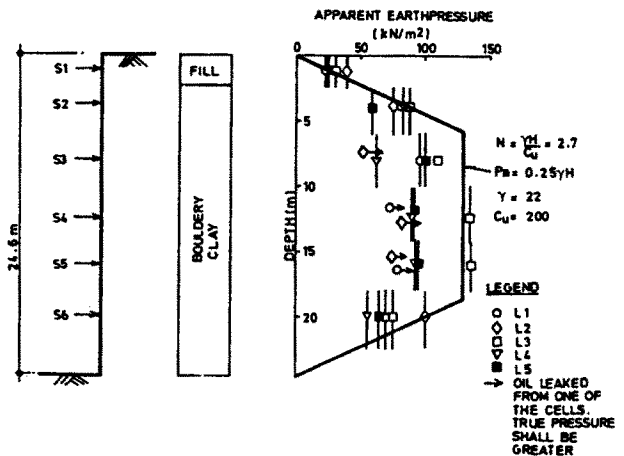


Figure 7 Apparent Earth Pressure Diagram Obtained for Construction of Raffles Place Station

Assessment of insitu bulk shear strength can also be made from the results of settlement monitoring over tunnels. Shirlaw, Doran and Benjamin (1987) recorded measurements over a pair of 6m diameter tunnels driven through the boulder bed using the New Austrian Tunnelling Method, in free air. The two tunnels were exceptionally close, with a typical separation of 2.5m. There was good evidence that the settlements recorded over the upper tunnel were anomalous, both in the width of trough and magnitude of settlement due to the closeness of the tunnels. Calculations based on the settlement over the upper tunnel would therefore not be representative of the undisturbed shear strength of the soils. Over the lower tunnels the range of settlement was between 6mm and 15mm, giving a ground loss of between 0.5 and 1.3% of the face area. Backcalculating based on the method outlined by O'Reilly (1988) gives average insitu shear strengths in the range of 120 to 180 kPa.

On one MRT contract, two preliminary piles

were constructed, and deliberately loaded to their ultimate skin friction capacity as an aid to pile design. One pile was a 1m diameter bored pile, the other a 250mm diameter mini-pile. The top portions of the two piles were sleeved, with a frictionless coating, to prevent load transfer onto adjacent MRT tunnels. Strain gauges were used to measure the load being carried at various sections down the piles. The toe of the mini-pile was deliberately voided, as there was concern that a mini-pile founded directly on a sandstone boulder would give results that were not representative of the site as a whole.

The load transfer curves for the two preliminary piles are shown in Figure 8. Average skin-friction values within the socket were 185 kPa for the large diameter pile, and 350 kPa for the mini-pile. It is not clear whether the marked difference in measured skin friction is a result of the different pile diameters, drilling method or the effect of boulders. The large diameter pile did not encounter any major boulders, and the skin friction values for this test probably provide a better basis for the assessment of insitu strength than the mini-pile test.

Assuming an adhesion factor close to unity, then the bulk shear strength of the boulder bed would be at least 185 kPa. Pull-out tests on ground anchors installed in the boulder bed showed adhesion up to 250 kPa with majority of data scattering in the range of 150 to 200 kPa. These data are consistent with the results obtained from pile load tests.

In summary, back-analysis shows a bulk shear strength of at least 135 kPa from the observed strut loads and 120 to 180 kPa from settlements over the NATM tunnels. Back-analysis from pile load test results and pull-out tests of anchors gives somewhat higher strengths, 185 to 350 kPa for the former and 150 to 200 kPa for the latter. The difference between the two sets of data could be due to the different stress paths during loading and/or scale effects.

6 CONCLUSIONS

The Singapore boulder bed has given rise to many difficulties during construction in Singapore's CBD. A possible geological origin for this deposit has been suggested, and some data both on the strength of individual boulders and on the bulk strength of the deposit has been presented.

ACKNOWLEDGMENT

The authors are grateful to Mr. Y. Kobayashi for the many useful suggestions and to Mrs. Pay for her help in preparing the manuscript.

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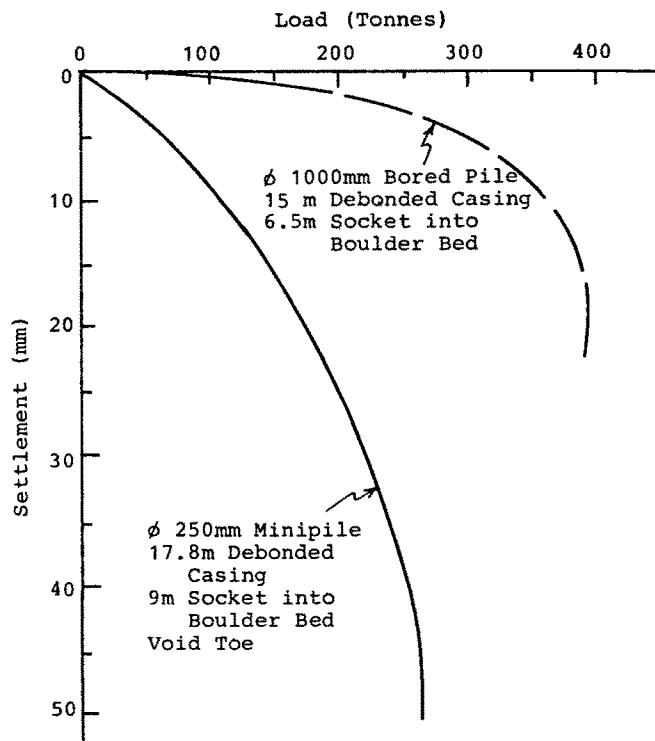


Figure 8 Shaft Friction of Piles Embedded in Boulder Clay

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