A COMPARISON OF CUT-AND-COVER WITH BORED TUNNELS THROUGH SOFT CLAY IN SINGAPORE

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A Comparison of Cut-and-Cover with Bored Tunnels through Soft Clay in Singapore

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SYPNOSIS: The construction of the Singapore Mass Transit System involved 16.8 km of twin running tunnels formed by both bored and cut-and-cover techniques. The selection of a particular method required careful consideration of a large number of variables. Soft clay deposits are widespread and one of the most difficult construction strata in Singapore. Two sections of tunnel built in this medium are used to illustrate the selection procedure. The reasons for accepting a contractor's alternative bored tunnel proposal using Earth Pressure balance shields are given and a comparison of the settlement effects of the bored tunnels and adjoining cut-and-cover stations presented. In a section in undeveloped reclaimed land the cut-and-cover method was used, and here settlement and negative skin friction were the principal design considerations. An economic pile design was developed with the aid of instrumented test piles. The excavation, carried out under water, is briefly described and the potential advantages of this method are noted.

1 INTRODUCTION

Construction of the Singapore Mass Transit system started in late 1983. The MRT has become operational in phases, between 1987 and 1989. Of the 42 stations, 27 are at or above ground level. The remaining 15 stations are underground and linked by 16.8 km of twin tunnel. 11 kilometers were formed as bored tunnel, and 5.8 kilometers by cut-and-cover methods.

As described by Hulme et al. (1987) it was found that up to a depth of about 12m it was generally cheaper to form tunnels by cut-and-cover than by bored tunnelling. The figure of 12m was however very much a generalisation, and the choice of method on the MRT was the result of careful consideration of a number of factors, including:

1.1 The availability of work sites

Bored tunnels can be driven from fairly small work areas, but cut-and-cover tunnels need plenty of open space along the whole route. The use of temporary decking, the Milan method etc only minimises space required and the disruption caused.

1.2 The number and type of utility along the route

In urban areas there are often great concentrations of public utilities. Bored tunnels can go underneath utilities, but utilities pose a considerable problem in cut-and- cover work. They must either be diverted, or special provision made for them in the temporary works. Accidental damage is generally more frequent with cut-and-cover methods than in well conducted bored tunnelling.

1.3 Adverse effects on adjacent roads and buildings

All tunnelling, whatever the type or ground condition must have some effect on adjacent roads and buildings. The effect will be different, depending on the method of construction.

1.4 Whether the tunnel can float, or whether it needs to be supported by deep foundations

This was a major problem in Singapore where some sections of tunnel were wholly in the compressible soft marine and estuarine clays. The C values used for calculation in these soils were typically 0.85 for the marine clay and between 1 and 5 for the highly organic estuarine clay. Changes in effective stress, either due to additional surface load or dewatering, generate large settlements in these soils. Large settlements of the underground railway structure were unacceptable because of the fixed track slab. To avoid such settlements the owner had two options:

i) Accept that the tunnel foundation had to be taken down to incompressible strata. This would effectively rule out bored tunnelling in most cases.

ii) Take the necessary measures to protect the works so that settlement would not occur. Such a railway protection scheme requires:

* Legislation ensuring that all proposed construction work within a defined zone is first submitted for approval.

* The employment by the owner of sufficient staff to check submisions and ensure that the agreed procedures are being carried out on site. Of course, some railway protection staff

are necessary even if the tunnels are well founded, but as 'floating' tunnels are moresensitive to settlement, the amount of work and the skill required in decision making is greater for the bored tunnels. Even if such costs are largely passed onto adjacent developers, as they were in Singapore, it still represents a cost to the society as a whole.

* Apart from the checking costs, the greater sensitivity of bored tunnels to movement may constrain the type of development in an area, thus resulting in further costs to society as a whole.

1.5 Geological conditions

Lack of suitable strata at reasonable depths to 'toe-in' temporary works substantially increases cut-and-cover costs but has little effect on bored tunnels.

1.6 Railway operating considerations

The 'hump' and 'saw tooth' profiles so beneficial to energy conservation and braking are ideally suited to bored methods but greatly increase the cost and difficulty of cut-and-cover work.

Cut and cover tunnels necessarily more or less mirror the surface contours and may impose gradients unsuitable for efficient operation. Bored tunnels can minimise these effects.

Because of the particular problems posed by tunnels formed wholly in soft clay, this paper will compare and contrast two such sections on the MRT, one of which was formed as bored tunnel and the other as cut-and-cover tunnel.

2 CONTRACT 301 TUNNELS - CITY HALL TO LAVENDER

Contract 301, as shown in Figure 1, consisted of two stations (Bugis and Lavender), a crossover, and 1.4 kilometers of twin running tunnel. The route generally follows Victoria Street, and runs through one of the oldest urban areas ofSingapore; an area originally allocated to Arab traders by Sir Stamford Raffles.

Typical conditions are shown in Figure 2. 3 to 5m of old fill overlie a variable depth (20 to 45m) of soft soils of the Kallang formation. The greater proportion of the soft ground is Singapore marine clay, a plastic clay (P.I. ' 50-70) that is normally consolidated to lightly over-consolidated. The Kallang formation overlies Old Alluvium, which is predominantly very dense sand. The original design was to form open cut tunnels, as shown in figure 2. Three reasons were given for the choice of cut-and- cover methods:

i) Concern about the practicability of bored tunnelling in the soft clays.

ii) If the tunnels were formed by cut and cover then the diaphragm walls used for the temporary support during excavation could be tied to the final structure and used as foundations.

iii) The transportation strategy planning for this area of Singapore incorporated the requirement to widen Victoria Street into a dual 3-lane carriageway road and this was intended to follow on after the railway construction. Major property clearance along this section prior to tunnelling was therefore both feasible and economical.

The MRT Corporation's tendering procedures allowed the tenderers to submit alternatives. In this case all of the tenderers proposed to bore the majority of the tunnels. The only sections which were proposed as open cut, apart from the stations, were the cross-over and a length of relatively shallow tunnel east of Lavender Station.

The winning tenderer proposed the use of Earth Pressure balance shields for the 800m long drives from Lavender to Bugis, where the tunnels were almost entirely in soft clays. For the section from City Hall to Bugis, where part of the drive was through stiff clay containing very strong sandstone boulders, a conventional

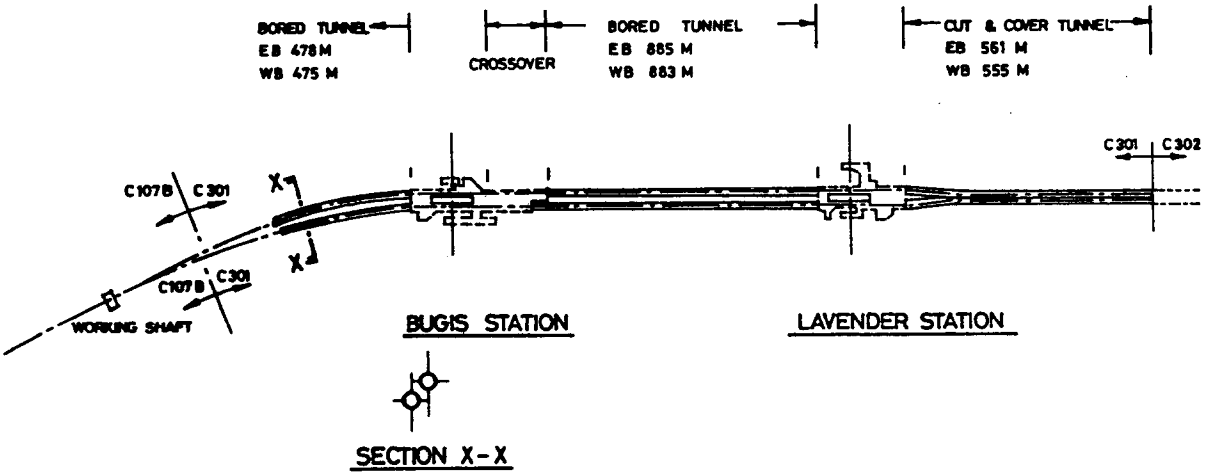


FIG. 1 CONTRACT 301 - TUNNELS - LAYOUT PLAN

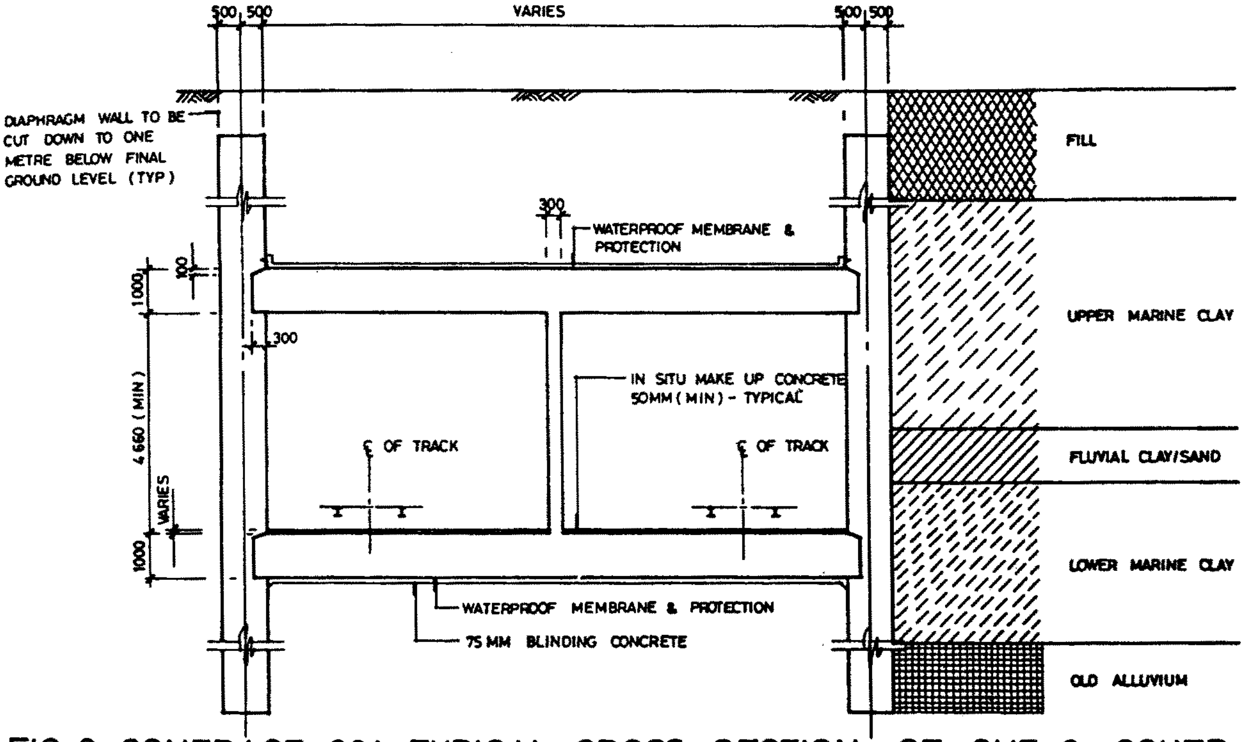


FIG. 2 CONTRACT 301-TYPICAL CROSS SECTION OF CUT & COVER TUNNEL

'Greathead', open face shield was proposed. Compressed air in conjunction with the chemical grouting of open sand lenses was suggested to ensure face stability in the soft ground.

The owner was thus presented with a choice between the original design and an alternative which would provide significant cost saving in construction, but at the cost of more stringent long term control to ensure against settlement of the tunnels. The tunnels were relatively deep, with between 14m and 19m depth to tunnel axis. The tunnels were thus located roughtly at the boundary between young, upper marine clay and the older, lower marine clay. There was good evidence that the lower marine clay was slightly over consolidated. A finite difference programme was used to assess the sensitivity of the tunnels to consolidation of the marine clay. It was found that the settlement of the tunnels should be very much less than any settlements at ground surface due to dewatering or surcharges. Given reasonable controls it was felt that this did not present a major risk, and the bored tunnel alternative was accepted on that basis.

The bored tunnelling through the marine clay, both with Earth Pressure Balance and Greathead shields, was highly successful. The tunnels passed directly under several structures and major utilities, including an old bridge dating from 1914 and main sewer pipes up to 1200mm dia, without any adverse effects. These would have been demolished or re-routed under the original design. The only building or utility which was a cause for concern during the bored tunnelling was a gas pipe which was affected by heave during preparatory chemical grouting.

Apart from the simple financial benefits of switching from cut and cover tunnels to bored tunnels, there were several other advantages:

i) Minimising road diversions

Despite the provision of a complete alternative road for Victoria Street, the cut-and-cover solution would have still required disruptive diversions at road intersections.

ii) Minimising utility diversions and damage

The cut-and-cover tunnelling would have required that utilities be either diverted or supported across the excavation. However carefully this work is carried out it is inevitable that some accidental damage occurs.

iii) Minimising muck shifting

For the tunnel with a depth to invert of 18m cut-and-cover construction would have required about seven times as many lorry journeys as a bored tunnel. This was because of the need to excavate down to the tunnel, and then replace the soil over the tunnels with suitable fill. Large numbers of slow moving lorries laden with spoil within the urban centre would have been a major disruption to existing traffic patterns.

iv) Minimising ground movements

A direct comparison can be made between the ground movements resulting from the two alternatives by comparing those from the bored tunnels and those recorded at Bugis station. Bugis had a similar depth of soft clay and depth of excavation to the projected cut-and-cover tunnels. The comparison is shown in Figure 3. Not only was the maximum settlement at Bugis nearly twice that over the bored tunnels, but the cut-and-cover technique pushed the point of maximum settlement outwards. The maximum settlement for the bored tunnels was directly above the tunnel centre line, in the road. For the station the point of maximum settlement was displaced about 14m from the track centre line, so that it occurred right at the building frontage. Two examples are shown in Figure 3, one for the section where the soft clay was deepest. It can be argued that this is an unfair comparison as the movement during deep excavation was very sensitive to the depth of soft clay below the base of excavation, while the movements due to tunnelling were insensitive to this factor. A comparison of the settlements in a smaller depth of soft clay is therefore also shown in Figure 3. It can be seen that in this case the maximum settlement was similar, but that the movement at the building line was again greater for cut-and-cover construction.

The constraints at Marina South were thus quite different to those on Contract 301. The available works area was almost unlimited. There were no utilities and few buildings to be concerned about. However no amount of controls could prevent settlement of the soft marine clay due to the large and recent surcharge imposed by the fill.

It was thus clear from the outset that design of the tunnels would require careful consideration of settlement and negative skin friction. This was not only because of the existing reclamation, but because the design had to allow for the planned future reclamation of the Telok Ayer Basin. The initial design catered for these factors by requiring the construction of 1m bored piles at approximately 3m centres along the alignment as shown in Figure 5. Over 1000 piles were required for the 1100m of twin tunnel. The piles were designed to carry a maximum of 350T on a socket 15m to 25m into the Old Alluvium, giving a total depth below existing ground surface of 50m to 70m. The working load was defined as

$$WL = \underset{\text{(at minimum bouyancy)}}{\text{Dead load}} + \frac{\text{Negative Skin Friction}}{3}$$

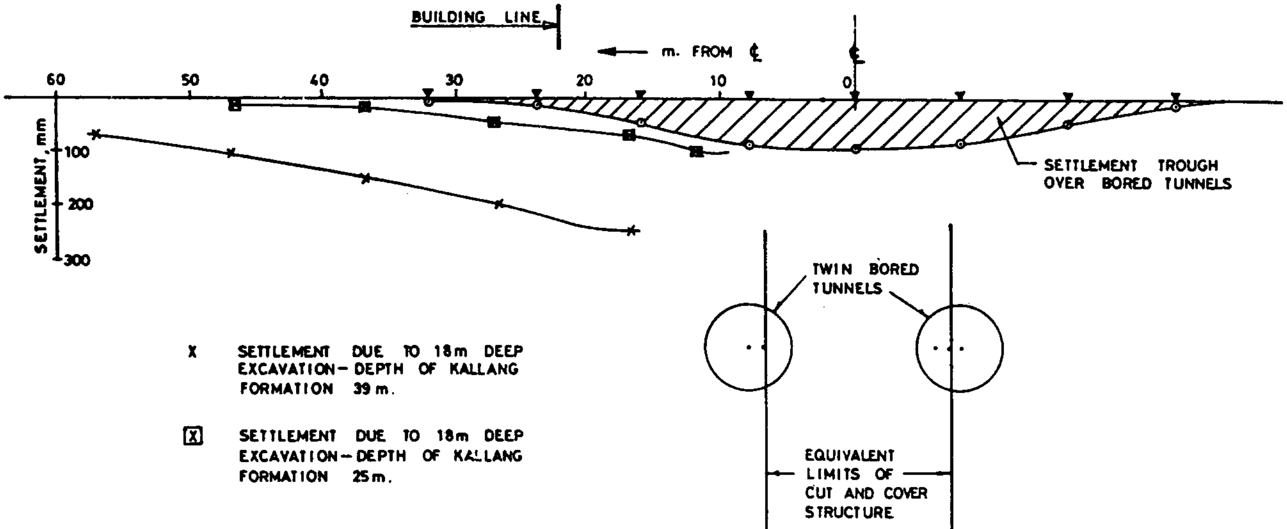


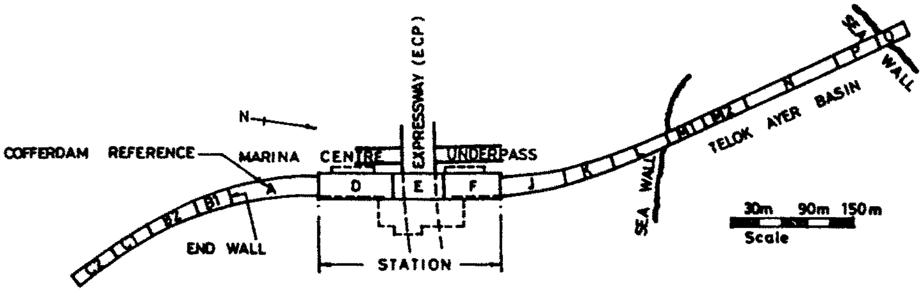
FIG 3 COMPARISON OF GROUND MOVEMENTS DUE TO BORED TUNNELS AND CUT AND COVER EXCAVATION

3 CONTRACT 310 TUNNELS - RAFFLES PLACE TO MARINA BAY

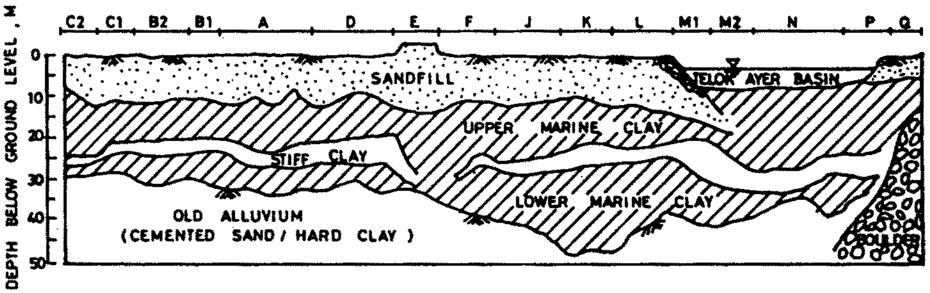
Unlike the Contract C301 tunnels, those constructed under Contract C310 were not formed in an urban environment. They ran from a shaft on the coast under the Teolok Ayer Basin to the 10 years old reclamation of Marina South. Marina South was reclaimed by placing 10m of sand over the existing 20 to 40m depth of soft marine clay, as shown in Figure 4. At the time the MRT was constructed the reclamation was still settling by 30mm a year. Apart from the Central Expressway and some warehouses and lorry parks, development of Marina South had not yet started.

The piles were designed to a factor of safety of 3, which meant that there was an effective factor of safety of 3 on dead load and 1 on the full negative skin friction. Full negative skin friction represented typically two to three times the dead load.

After further consideration it was decided that design on this basis was inappropriate due to the very high proportion of the load which would be due to negative skin friction. It was decided that the full negative skin friction and dead load should be added together and the resulting load used as the working load. This gave a maximum working load well in excess of 700T, too high for the allowable concrete stress in a 1m pile. Rather than change to larger diameter piles, three alternatives were considered:



LAYOUT OF COFFERDAMS



GEOLOGICAL SECTION

FIG. 4 CONTRACT 310 [after Clark and Prebaharan (1987)]

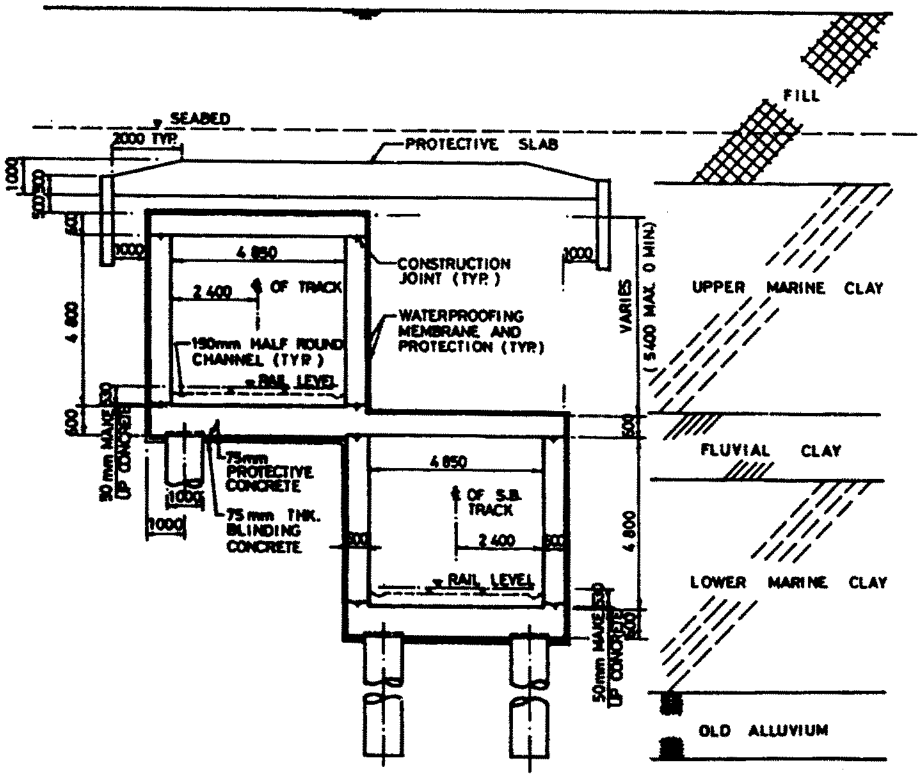
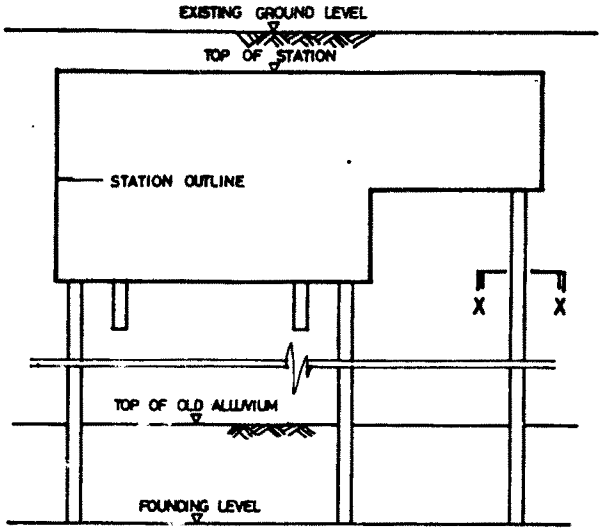


FIG. 5 CONTRACT 310 - TYPICAL CROSS SECTION

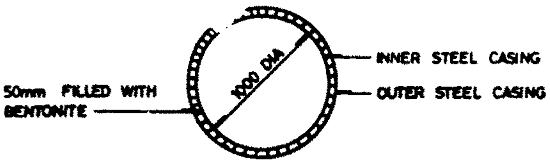
a) Use of a double casing with bentonite slurry in the gap, to minimise NSF (Figure 6a).

b) Use of a screen of independent driven piles spaced at three pile diameters around the site (Figure 6b). At this spacing it was assumed that all the NSF would be applied to the screen piles, leaving the main piles to carry just the dead and live loads.

c) Deletion of all piles and formation of an oversize box. The track support would have been changed from concrete to ballast and allowance made for periodic track realignment as the box settled.



TYPICAL SECTION



SECTION X-X

FIG. 6(a) STEEL PILE SLEEVES

Option (c) could, in theory, have been carried out by bored tunnelling with a realignment to give greater cover in the undersea crossing, but was quickly eliminated. This was due to concern over the maintenance cost of continual realignment, despite the large capital cost which would have been saved and the possibility of transverse rotation and the ability of the joints, no matter how carefully detailed, to withstand the movement satisfactorily.

The use of slipcoating to reduce negative skin friction was also ruled out, both because of concern over effectiveness and the difficulty of maintaining the coating in areas where the piles had to be formed through the hydraulic sand fill. For underground structures slipcoating the piles is, in any case, less effective than for other structures, because much of the load is on the structure itself.

Tenders were called for with all tenderers being asked to price both options (a) and (b). All tenderers concluded that option (b) was significantly cheaper and the contract was let on that basis. However during the tendering process and immediately after the tendering, afurther re-assessment was carried out. Based onthe concept of the screen piles, then the outer rows of 1m piles would screen the inner line of piles from any negative skin friciton. A computer simulation was then carried out to see how much the very stiff tunnel box would redistribute the loads from the outer piles to the inner piles. It was found that the structure was so stiff that loads in the piles were virtually identical, such that each pile only had to be designed for two-thirds of the negative skin friction. This meant that the maximum working load was reduced to 550T. This was marginally higher than would normally be allowed on a 1m pile. However in this case, with all piles permanently cased through the soft upper layers, and most of the load due to negative skin friction, it was decided that this load was acceptable.

It thus appeared possible to delete the 2000 driven screen piles, at a significant saving to the contract. However, to obtain the increased load the bored piles had to be deepened. Based on theoretical calculations total pile length would be as much as 80m, which would have significantly reduced the overall saving.

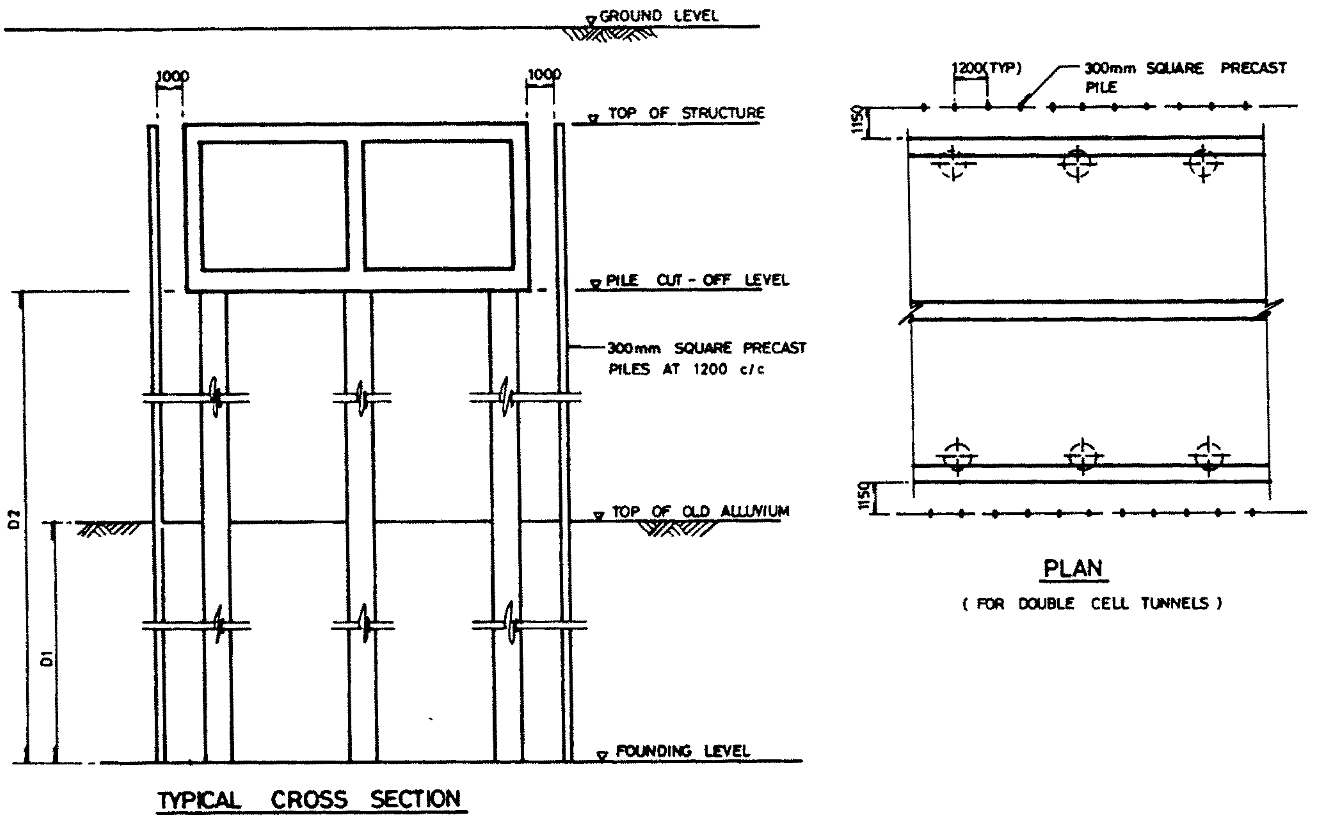
The contract required 6 preliminary test piles, of which 2 were instrumented (for results see Buttling and Robinson 1987). These test piles showed that actual skin friction values which could be obtained in the dense Old Alluvium far exceeded the values which were derived by calculation. Peak values in excess of 400 kPa were measured, with a minimum value of 200kPa. No significant end bearing was measured in these test piles, which were drilled by reverse circulation and cast by tremie pipe.

By designing for measured rather than calculated skin friction values in the Old Alluvium, significant savings could be made in the socket length.

While the overall cost of the piled foundation finally adopted was still a major factor in the total contract value, the design changes made during and after tendering produced signficant cost savings.

The tunnels were constructed within sheet-piled cofferdams using under-water excavation, as described by Clarke and Prebaharan (1987). During construction the many bored piles helped to anchor down the mass concrete tremie slab.

With the general absence of utilities, roads and structures from the area of the tunnels, the disruptive effects of cut-and-cover tunnelling and the settlements induced were not of concern. The maximum deflection of the retaining system was approximately the same as that at Bugis station. This suggested that the use of underwater excavation at Bugis, rather than conventional, strutted, bottom-up construction, would have significantly reduced settlements. This conclusion is based on the very much stiffer retaining wall and the higher soil strengths at Bugis compared with Marina



TYPICAL CROSS SECTION

PLAN

(FOR DOUBLE CELL TUNNELS)

FIG. 6(b) PROTECTIVE SCREEN PILES

Bay. It is also probable that underwater excavation would have reduced the significant consolidation settlements experienced at Bugis.

Although proposed in the Mass Transit Study Phase III (1980) the comparison is purely hypothetical. The problems of moving excavated wet clay in the centre of town, the more limited work areas and the need to provide a decking over part of the excavation would probably have made it impractical to use the underwater technique at Bugis.

One other point which should be noted was the occurrence of some very large, localised surface depressions during the C310 work. these were mostly caused by the declutching of the sheet-piles during the dewatering of the cofferdams, and consequent loss of soil into the excavation. Some localised failures of the sheet-pile structure itself also occurred, either due to over-excavation during the initial (dry) stages or due to problems in casting the underwater tremie slab up to the sheet-piles.

4 CONCLUSIONS

This paper has briefly covered the decision making process for two sections of tunnel for the Singapore MRT, looking both at some of the design considerations involved in the choice of method, and at some of the results of the final decision. The number of topics which have been briefly touched upon, including:

Negative skin friction, and long term settlement
Route protection
Work sites
Settlements
The risk of accidental damage and localised failures
Spoil disposal
Railway operation

demonstrate the complexity of the decision making process that may be required when planning an urban Mass Transit system, a process that undergoes continual change as technical developments result in newer and, hopefully cheaper, methods of construction.

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