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The relationship between face pressure and immediate settlement due to tunnelling for the North East Line, Singapore

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ABSTRACT: The construction of the North East line of Singapore's mass transit system involved the construction of 22,830m of bored tunnel. Tunnel construction on all but one section was by the use of earth pressure balance shields, with precast concrete segmental linings. The ground conditions encountered varied from near normally consolidated marine clays to igneous, sedimentary and metamorphic rocks, variably affected by tropical weathering.

Over six hundred settlement points were installed over the centre-lines of the twin 5.8m internal diameter tunnels. The ground conditions encountered during tunnelling were divided into nine broad categories. For each of these categories the settlement, expressed as volume loss, is plotted against the face pressure, normalised by the total overburden pressure. Consideration is also given to the 22 recorded occasions when there was a major loss of ground.

For the soft clays and loose sands of the Kallang Formation, the volume loss increased with reducing face pressure. This general trend is also seen in cases where the tunnels were partly in soft clay and partly in weathered rocks, and where the tunnel was in a full face of weathered rock but with less than 3m of cover to overlying Kallang Formation deposits. In a full or partial face of the soft soils the face pressure had to be maintained within a range of 0.9 to 1.2 times the overburden pressure to keep the volume loss to 2% or lower.

The boundary between the soil grades and the rock grades of weathered granite proved particularly problematic. It was difficult to maintain a face pressure due to the nature of the excavated ground. With low face pressure, the weathered granite of Grades IV and V was unstable, and large cavities resulted.

1 INTRODUCTION

The construction of the North East Line of Singapore's mass transit system involved the driving of 22,830m of bored tunnel. Tunnel construction on all but one section was by the use of earth pressure balance shields, with precast concrete segmental linings. Just over 20km of tunnel was constructed by Earth Pressure Balance Shield (EPBS), and the rest by open-face shield.

The ground conditions encountered varied from near normally consolidated marine clays to igneous, sedimentary and metamorphic rocks, variably affected by tropical weathering.

Shirlaw et al (2001 and 2002) present the result of monitoring over the centre-lines of the bored tunnels, summarising the measured immediate settlement (expressed as volume loss) at 617 points. They also record 22 major, but localised, ground losses, which occurred between settlement points. For analysis, the ground conditions were divided into nine broad categories:

- The Kallang Formation (recent deposits, mainly soft marine clays and loose sands).
- The interface between the Old Alluvium and the Kallang Formation.
- The interface between the Jurong Formation and the Kallang Formation.
- Old Alluvium (all weathering grades) – a cemented alluvial deposit derived from granite.
- The Fort Canning Boulder Bed – a colluvial deposit consisting of quartzite boulders in a hard clay matrix.
- Mixed weathering grades II to VI, Jurong Formation (sedimentary rocks), with Kallang Formation above the tunnel.

- Mixed weathering grades II to VI, Jurong Formation, no Kallang formation above tunnel.
- Residual soil derived from Bukit Timah Granite.
- Mixed weathering grades II to V, Bukit Timah Granite.

The nature of these soils and rocks is described in Shirlaw et al (2002) and Shirlaw et al (2000). The ground water level in Singapore is typically 1.5 to 2m below ground level. The open-face shields were used only in the Fort Canning Boulder Bed and the Jurong Formation.

The specifications required that the shields were equipped with pipes laid along the tailskin and through the tail seals, to allow simultaneous grouting of the tail void as the shield advanced. With the use of this system, and minimising overcutting, it is likely that the major factor controlling the immediate settlement is the face pressure employed. This paper presents the relationship between the measured settlement and the face pressures employed, for the various ground conditions given above. Consideration is also given to the local ground losses that were observed along the route. There were twenty two recorded cases of significant ground loss. Out of these, five occurred at the start or completion of the drives. Because of special factors in these fives instances, such as disturbed ground due to the extraction of temporary works, only the seventeen cases that occurred during regular tunnelling have been included in this review.

2 FACE PRESSURE MEASUREMENT

The EPB shields were equipped with 2 to 4 pressure sensors mounted in the plenum chamber. The pressure during the shove/build cycle was not constant; during the shove the pressure would fluctuate as the discharge gate was moved to allow a larger or smaller gap. During the building of the ring, when the discharge gate was closed, the pressure would tend to come back to the in-situ ground pressure. Because of the fluctuation in the pressure, there was no single pressure in the head. For the purposes of this paper, the typical average pressure during a tunnelling cycle is used.

3 RELATIONSHIP BETWEEN FACE PRESSURE AND SETTLEMENT

3.1 *Kallang Formation.*

Figure 1 shows the relationship between the face pressure, normalised by the total overburden pressure, plotted against the measured volume loss. Also

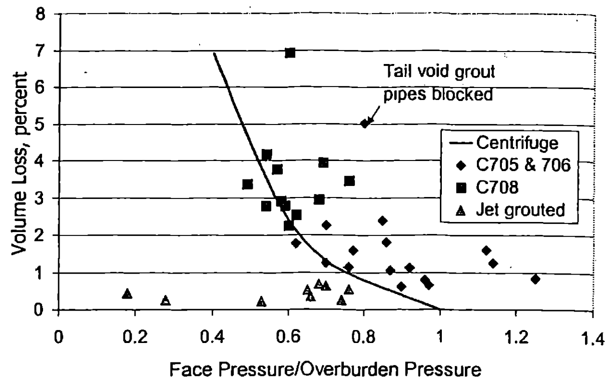

Figure 1. Relationship between face pressure and volume loss, EPB tunnelling in Kallang Formation soils.

plotted on the graph is the same relationship derived from centrifuge model test data (Kimura and Mair, 1981), assuming a depth of 18m, undrained shear strength of 28kPa and movement only at the face. It can be seen that the field data follows the same general trend, but typically with 1 to 2% higher volume loss. This difference can be ascribed to sources of ground loss other than at the face (overcut, shield inclination, grouting), and to the fluctuation in the face pressure during each tunnelling cycle. Looking at the general trend line from the centrifuge data, it is clear that transient pressures below the mean will have a greater effect than transient pressures above the mean, hence the tendency to plot above the trend line. For one point, highlighted on the graph, it was known that the tail void grouting pipes were blocked and could not be used. This point plots by 5% of volume loss above the centrifuge trend line. A distinction is made on this graph between the results for different construction contracts. It can be seen that one contractor chose to drive at a generally lower face pressure, resulting in generally higher settlements. Part of the tunnelling in the Kallang Formation was carried out through ground treated by jet grouting. This was done for various reasons: as protection for some temples, as preparatory works for a future underground expressway, and for shield launching. It can be seen that the volume loss in the jet grouted areas was low and independent of applied face pressure. Based on the graph, the ideal face pressure for tunnelling through untreated Kallang Formation soils is between 0.9 and 1.2 times the total overburden pressure.

3.2 *The interface between the Old Alluvium and the Kallang Formation*

The data is plotted on Figure 2, with the same centrifuge data derived trend line used in Figure 1. Generally, the face pressure used was high enough to keep volume loss to a low value; in one case where a lower pressure was used the volume loss was much

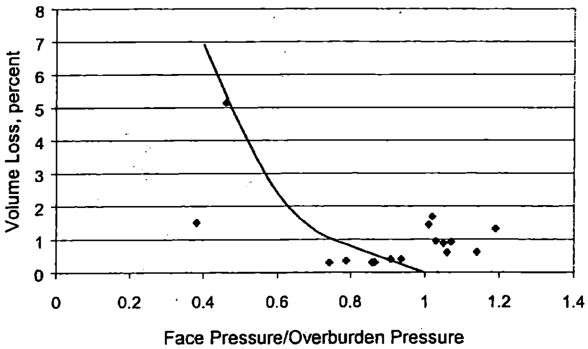

Figure 2. Relationship between face pressure and measured volume loss, EPB tunnelling through a mixed face of Kallang Formation soils and Old Alluvium

higher, at 5%, and the point plots on the trend line based on centrifuge data.

3.3 The interface between the Jurong Formation and the Kallang Formation

The data is plotted on Figure 3, with the same centrifuge data derived trend line used in Figure 1. It can be seen that the face pressure used for this interface was generally significantly lower than that used for the Old Alluvium/Kallang interface. This probably results from the greater contrast in strength between the Jurong Formation and the Kallang soils. Also shown on the figure are two points representing large observed volume losses.

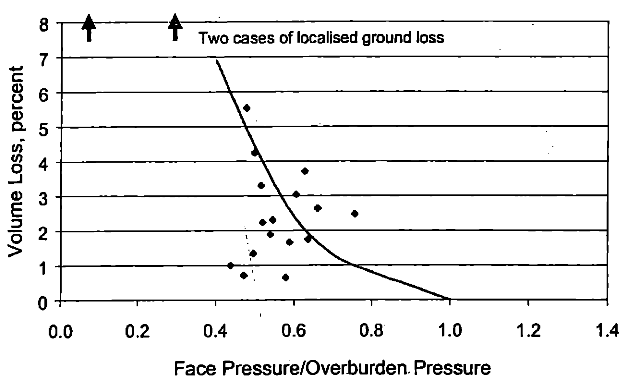

Figure 3. Relationship between face pressure and measured volume loss, EPB tunnelling through a mixed face of Kallang Formation soils and weathered rocks of the Jurong Formation

3.4 Old Alluvium (all weathering grades)

The data are plotted on Figure 4. It can be seen that the volume losses were consistently low throughout, and appear to be independent of pressure. The results for the Old Alluvium are remarkably consistent, given the variation in the material encountered. The tunnelling conditions varied from destructured material, with a Standard Penetration Test (SPT) of less

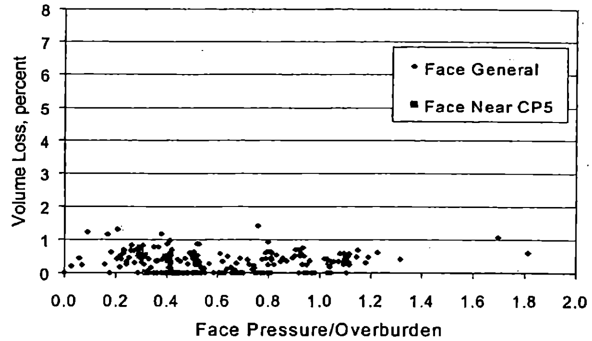

Figure 4. Relationship between face pressure and measured volume loss, EPB tunnelling through Old Alluvium

than 10 blows / 300mm to unweathered material, with an SPT of greater than 100 blows / 300mm. The shields passed through an area where there were later significant problems with flowing sand during cross-passage construction. The settlement results from this area are identified separately, but show no difference from those in other areas.

3.5 The Fort Canning Boulder Bed

Only a short stretch of tunnel was through the Bouder Bed. Settlements were consistently low as shown in Figure 5; this contrasts with much higher settlements experienced in the same material with open face shields 15 years before (Shirlaw 1987 et al). The open face shields on the North East line gave the same low settlements as the EPB shields. The improvement appears to be related to better tail void grouting practice rather than face pressure.

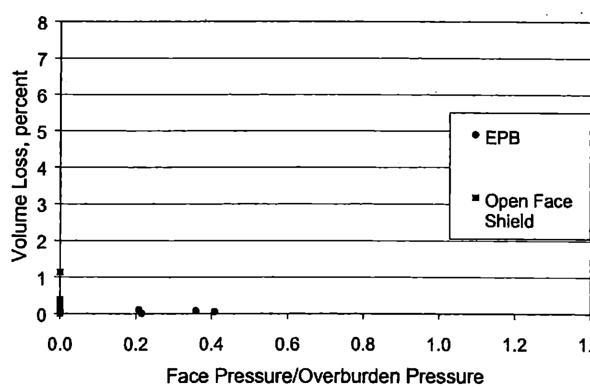

Figure 5. Relationship between face pressure and measured volume loss, EPB and open-face shield tunnelling through the Fort Canning Boulder Bed

3.6 Mixed weathering grades II to VI, Jurong Formation (sedimentary rocks), with Kallang Formation above tunnel

The data are plotted on Figure 6. Also shown are the five data points for large ground losses. In one of the cases, the visible ground loss nearly coincided with

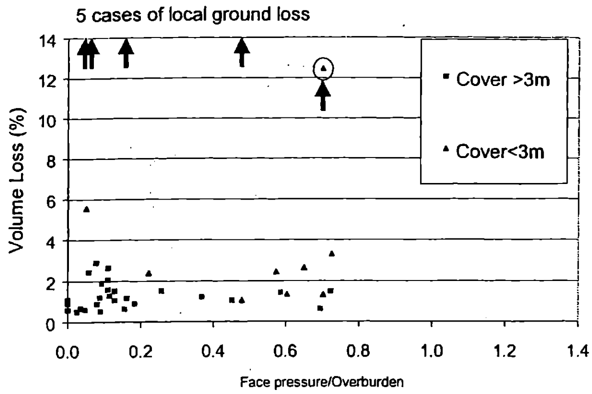

Figure 6. Relationship between face pressure and measured volume loss, EPB tunnelling through the Jurong Formation with Kallang Formation soils above the tunnel.

the location of a surface settlement point. The measured settlement was 204mm, while the estimated maximum settlement was 250mm. This is the data point that is circled on the graph. The data have also been divided between areas where there was more than 3m cover to the overlying Kallang Formation and areas where there was less. There is an increased risk of a local loss of ground at a face pressure lower than about one half of the total overburden pressure; this is equivalent to about the water pressure at axis level. The Jurong Formation covers a variety of rock types and weathering grades, so the pattern is not consistent. Many of the materials included in this category are clearly stable without face support, but not all of them. From the experience of tunnelling through this rock with open-face shields, the unstable materials consist of the highly weathered mudstones and shales, which fragment into gravel size pieces as a result of weathering, completely weathered sandstone, which behaves as a very lightly cemented sand, and fault gouge. There is a high risk of significant volume loss when the cover to the Kallang Formation reduces below 3m; at this point the low strength of the Kallang Formation deposits becomes the major factor in the stability of the tunnel.

3.7 *Mixed weathering grades II to VI, Jurong Forvation, no Kallang Formation above*

The data are plotted on Figure 7. The data points are separated between those over open-face shields and those over EPB shields. The pressure for the open face shields was provided by compressed air. It can be seen that the settlement over the open-face shields was generally higher, and more sensitive to face pressure than that over the EPB shields. It is not clear whether this reflects the face support provided by the cutting head of the EPB, or whether the open-face shields encountered more difficult ground conditions. One section of open-face tunnelling was through highly fractured, highly weathered shales and mudstones, and was close, and sub-parallel to, a

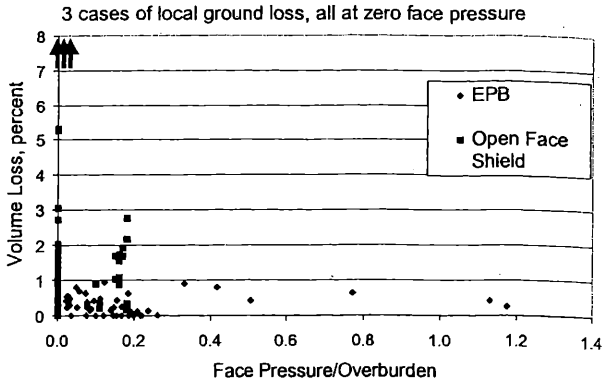

Figure 7. Relationship between face pressure and measured volume loss, EPB and open face shield tunnelling through the Jurong formation, with no Kallang formation soils above the tunnel.

fault. The tunnelling conditions on this section were difficult, and it was here that all of the higher settlements were measured over the open-face shields.

3.8 *Residual soil derived from Bukit Timah Granite*

The data is plotted on Figure 8. The Residual Soil that the tunnels were driven through had an SPT value of 15 to 45 blows/300mm, which can be related to an undrained strength of 75 to 225 kPa. It can be seen that the settlement increased for face pressures below about half of the total overburden pressure.

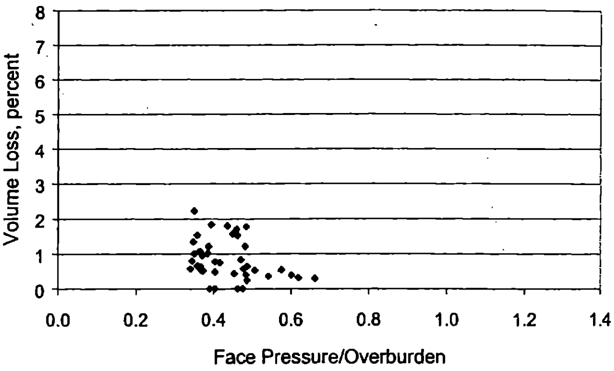

Figure 8. Relationship between face pressure and measured volume loss, EPB tunnelling through the Residual Soil of the Bukit Timah Granite.

3.9 *Mixed weathering grades II to V, Bukit Timah Granite*

The data are plotted on Figure 9. It can be seen that the general trend is similar to that for the Residual Soil. However, there were seven major losses of ground in these mixed weathering grades of granite. The ground losses occurred because the mixture of excavated rock and of excavated soils (Grades V and IV) was predominantly granular in nature. This mixture of granular material did not readily form a plug, and there was therefore no seal against the 3 bars of ground water pressure. As soon as the discharge gate was opened a mixture of soil and water blew into the tunnel and the pressure in the head dropped to, or close to, zero. Based on the other data plotted in Figure 8, it appears that the face can be kept stable, with settlements below 1% volume loss, if the face pressure is maintained at about half of the total overburden pressure. This pressure is equivalent to the ground water pressure at just below tunnel axis level. Compressed air at about this level has been successfully used to maintain stability in weathered granite. Cater et al (1984) record settlements of typically below 1% volume loss when using compressed air at this level with open-face shields in completely weathered granite in Hong Kong.

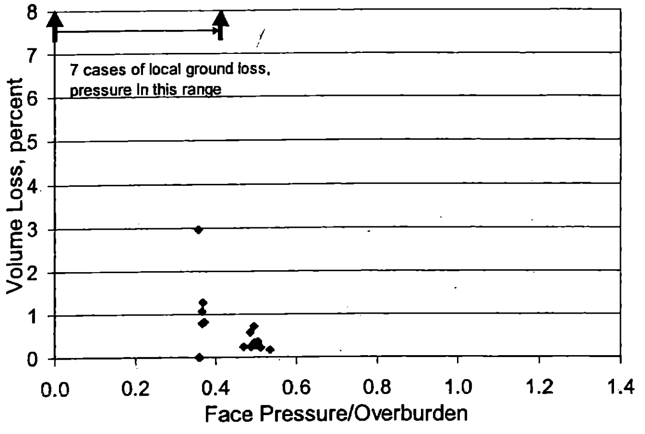

Figure 9. Relationship between face pressure and measured volume loss, EPB tunnelling through mixed weathering grades of the Bukit Timah Granite.

4 DISCUSSION

There is a very clear, and consistent, relationship between the immediate settlement and the measured volume loss in the soft soils of the Kallang Formation. This relationship extends into areas where the face is a mixture of Kallang Formation and weathered rock, and up to the point where there is less than 3m of cover above the tunnel to the Kallang Formation soils. The low strength of the Kallang Formation dominates the tunnel stability under all of these conditions. To keep the volume loss to under 2% it is necessary to maintain a face pressure in the range of 0.9 to 1.2 times the total overburden pressure, while carrying out simultaneous grouting and minimising overcutting.

The Old Alluvium appears to have sufficient residual cementation to allow tunnelling at very low face pressures while still maintaining volume losses generally below 1%. However, the problems experienced during the construction of one cross-passage would indicate that it would be unwise to carry out EPB tunnelling without some face pressure in settlement sensitive areas.

In the Fort Canning Boulder Bed, the settlement appears to be relatively insensitive to face pressure, the critical factor in keeping settlements to low values is the quality of the tail void grouting. The maximum observed volume loss, at zero face pressure, was 1.56%. This compares well with a range of 0.5% to 1.3% measured during free air NATM tunnelling in the Boulder Bed recorded by Shirlaw et al. (1987). The results from the EPB tunnelling for the North East Line, although few in number, suggest that the application of a small face pressure of 20% to 40% of the total overburden pressure can reduce settlements to extremely low values.

In the weathered rocks of the Jurong Formation, the use of a face pressure equal to about half of the total overburden pressure should keep volume losses to below about 1%, except where there is 3m or less of cover to overlying Kallang Formation soils. This pressure is equivalent to about the ground water pressure at the axis level of the tunnel. Where there is 3m cover or less to the Kallang Formation, those soils govern and a pressure in the range of 0.9 to 1.2 times the total overburden pressure needs to be applied to keep settlement to a minimum.

For the Residual Soil of the Bukit Timah Granite, there is a general trend of increasing settlement with lower face pressure. The scatter in the results probably reflects both variation in other contributing factors, such as grouting and shield orientation, as well as variation in the strength of the Residual Soil. The variation in undrained strength was at least a factor of three, and clearly was a major factor in the scatter seen.

Unlike the Residual Soil, the other soil grades of the Bukit Timah Granite (grades IV and V) behave more like granular soils. When tunnelling was carried out at about half of the total overburden pressure the measured volume loss was relatively small. However, as soon as the pressure reduced below this value the volume loss increased rapidly with reducing pressure. Low face pressures ultimately lead to several significant, local losses of ground.

Fourteen out of seventeen local ground losses (during normal tunnelling) occurred when the tunnel was fully within the weathered rocks of either the Bukit Timah Granite or the Jurong Formation, with at least 3m of cover to overlying Kallang Formation soils. This contrasts with the measured settlements, which were generally low. The primary problem was with the very localised, but very large, settlements and ground losses. This is in contrast to the more general pattern of settlements seen in soils and Residual Soils. The soils were generally weaker than the weathered rocks, but more consistent.

Due to their different nature, the two types of rock encountered pose different problems for tunnelling. In the Bukit Timah Granite the presence of the mixed grades of granite was identified in the site investigation, and the contractor intended to maintain adequate face pressure to balance the ground water pressure. The problem was in the nature of the excavated material, which was very difficult to turn into a suitable EPB material. The combination of the lack of an effective EPB spoil in the plenum and screw, and the high permeability of the ground resulted in the face pressure dropping to a very low value as soon as the discharge gate opened. In the sedimentary rocks of the Jurong Formation, the material could generally be abraded such that spoil suitable for EPB operation could be produced. However, operating in the Jurong Formation with full EPB pressure resulted in high abrasion on the cutting tools, head and screw conveyor. Where foam was used to reduce the torque on the cutter head, the abrasion was much less than where only water was injected as a conditioning agent. Some of the shields used also suffered a problem with a compacted plug of material developing in the centre of the plenum chamber. Both the layout of the mixing paddles and the reluctance to use conditioning agents affected plug development. Concerns over abrasion and plugging lead to a reluctance to use significant face pressure. For the majority of the EPB tunnelling in the Jurong Formation, settlements were relatively small even if little or no face pressure was used. However, the variation in the nature of the formation lead to local ground losses where the ground was adverse and no or little face pressure was used.

The control of settlement due to tunnelling generally relies, to a large extent, on the observational method. The settlements are monitored using regularly spaced monitoring points. Where the settlement is higher than anticipated or acceptable, measures are taken to improve the tunnelling practice to reduce the settlement. However, this approach has limitations where the nature of the ground, and the support pressure required, changes frequently. Where such changes in ground condition can be reliably identified, then measures can, and should, be taken to adjust the face pressure while there is still adequate cover (for increasing face pressure) or only after adequate cover is present (for reducing face pressure). In areas where the changes in the response of ground cannot be reliably identified, settlements can only be controlled if a face pressure sufficient to control the worst expected condition are used at all times.

5 CONCLUSIONS

The relationship between the face pressure and measured surface settlement has been assessed for various soils and weathered rocks in Singapore. For the soft soils of the Kallang formation there was a clear and consistent trend of increasing settlement with reducing face pressure. This relationship extended through mixed face zones and to areas where there is less than 3m cover above the tunnel to the Kallang formation. To minimise settlement in these areas, a face pressure of 0.9 to 1.2 times the total overburden pressure should be used, with simultaneous grouting and minimum overcutting. For the relatively stronger Old Alluvium, Fort Canning Boulder Bed and Residual Soil derived from granite, there was either a gradual trend of increasing settlement with reducing face pressure or no apparent relationship. In the weathered rocks of the Bukit Timah Granite and the Jurong Formation the response was much more varied. Locally adverse conditions resulted in highly localised, but large, ground movements.

In the soils of the Kallang Formation the use of jet grouting to create an annulus of improved soil around the tunnel route resulted in consistently low settlements.

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