SETTLEMENTS DURING THE UNDERGROUND CONSTRUCTION OF THE SINGAPORE MRT

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Settlements during the Underground Construction of the Singapore MRT

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SYNOPSIS: The two major elements of the settlements resulting from bored tunnelling or deep excavation are the immediate (ground loss) component and the consolidation component. Based on experience gained in soft clays in Singapore it is possible to distinguish three forms of consolidation settlement due to bored tunnelling. Examples of the form and magnitude of the resulting settlement troughs are given. Ground loss settlements due to bored tunnelling are illustrated by a comparison between the results of two adjoining drives one using earth pressure balance shields and the other using open face shields with compressed air. The behaviour of buildings founded on rafts or short piles is contrasted with those fully piled. Some surprising conclusions are drawn both of the respective merits of the bored tunnelling methods described and also the effect on buildings adjacent to the MRT construction.

1 INTRODUCTION

Some 20 kilometers of the Singapore Mass Rapid Transit system (MRT) was constructed underground. One of the major concerns in constructing this urban, underground railway was what effect there would be on adjacent properties and utilities. Extensive monitoring was therefore carried out during the underground work. This was done to identify the causes of settlement, and to assist in deciding how to minimise them. Analysis of the results of this monitoring also provided a useful guide to the prediction of the effects of future work.

There are two major components of settlements due to either bored tunnelling or deep excavations: immediate, or 'ground loss' settlements and consolidation settlements (Shirlaw and Doran, 1988).

It is important to distinguish between these two basic types of settlement. The mode and zone of influence of the two types are generally different, and therefore the effect on buildings will be different. Also, their magnitude is affected by quite different factors. This is important, as a major reason for studying settlements is to understand how to minimise them.

Soft clays provide certain advantages in the study of settlements:

i) It can be reasonably assumed that soft clays deform at constant volume, so that the volume of the settlement trough can be directly related to the volume of ground movement in the tunnel or due to excavation. The readily measured surface settlement trough can therefore be used as a direct measure of ground movements at source. The movements are also rapid, and there is no question of the slow collapse of voids that can occur in, say, soft rocks.

ii) Soft clays tend to be highly compressible, so there is plenty of potential for consolidation settlements.

iii) The low permeability of soft clays means that drainage occurs slowly, so consolidation settlements generally happen slowly. This is a great aid to the separation of the two types of settlement.

iv) Relatively large settlements occur during construction in soft clays, making measurement errors of little significance.

Most of the underground work for the Singapore MRT encountered some soft clays, either of marine or estuarine origin. For some 5 route kilometers the soft clays extended to the base of the excavation, or invert of the tunnels, and it is proposed to discuss mostly settlements in those areas. Due to the volume of the data and the number of previous publications on MRT settlements (Shirlaw and Copsey, 1987, Shirlaw and Doran, 1988, Broms and Shirlaw, 1989) it is not proposed to cover the data in detail here. Instead, certain general topics will be discussed and illustrated by field measurements.

Most of the literature on settlements over bored tunnels concerns 'ground loss' settlements. Consolidation settlements receive much less attention, and where mentioned tend to be as a minor supplement to 'ground loss' settlements. Here it is proposed to discuss consolidation settlements first, for reasons which will become apparent.

2 CONSOLIDATION SETTLEMENTS - BORED TUNNELS

The field data from MRT tunnelling was generally plotted in two ways, in order to separate 'ground loss' and consolidation settlements:

i) The settlement over the tunnel centre line was plotted against log. time.

ii) Lateral settlement troughs were plotted for various periods. These periods were determined from the first plot.

A typical example of results over a compressed air tunnel is shown in Figure 1.

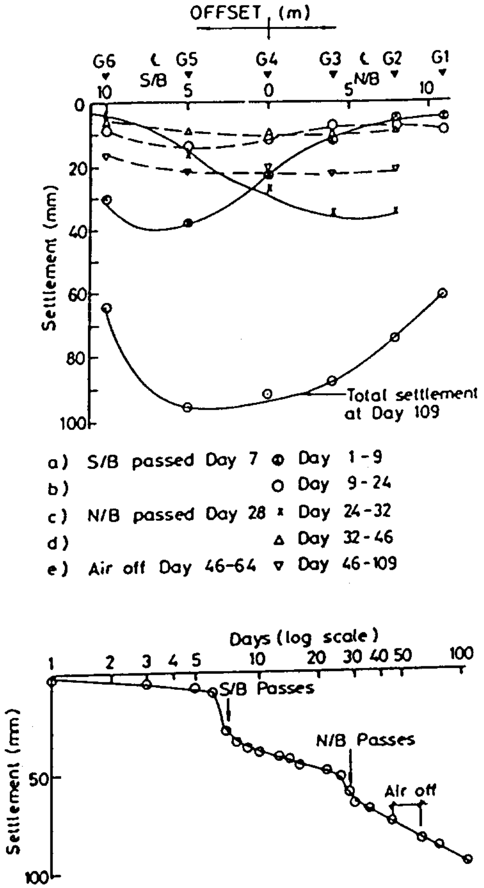

FIG.1 SEPARATION OF SETTLEMENT OVER TWIN COMPRESSED AIR TUNNELS INTO 2 'GROUND LOSS' AND 3 "CONSOLIDATION" PHASES

Characteristically, the consolidation phases followed a straight line on the settlement/log. time graph. In this example the consolidation phases also resulted in a relatively flat lateral trough. The 'ground loss' settlements occurred quickly as the tunnel passed, and resulted in a characteristic 'error function' trough.

Generally there was little good piezometer data around the Singapore tunnels, as few piezometers were installed due to concern over compressed air loss. However, from the settlement data, and the limited piezometer data, it was inferred that there were at least three distinct forms of consolidation settlements. These were:

Form 1. Drainage towards the tunnel. Either due to a permeable lining or tunnelling in free air in competent but fissured ground.

Form 2. The dissipation of positive pore pressures generated by tunnelling with face pressures less than the 'at rest' earth pressure. This was typically due to compressed air tunnelling.

Form 3. The dissipation of positive pore pressures generated by tunnelling with face pressures greater than the 'at rest' earth pressures. This only occurred with full face machines (Drum digger or Earth Pressure Balance Shield).

Examples of the three forms of settlement trough are shown in Figure 2. In each case the settlements due to 'ground loss' have been abstracted, and the trough shown is only for that period where consolidation is assumed to be occurring. The examples have been picked not for the representativeness of the magnitude of the settlements - the seepage example was over an extremely permeable temporary lining - but as good examples of the form of the trough. It can be seen that seepage (Form 1) resulted in a virtually flat trough. In this case the highly anisotropic nature of the ground must have been a major factor in the extent of the trough. The settlement due to consolidation over twin compressed air tunnels, driven with a face pressure of 0.45 to 0.50 σ_{vo}, (Form 2) was also relatively flat. Two examples are shown in Figure 2. One has a larger maximum settlement, of 24mm, but some critical points were lost during construction. The second example is more complete, but with a smaller magnitude. In total contrast, the settlements over tunnels where the face pressure was greater than σ_{vo} followed the same 'error function' form normally associated with 'ground loss' settlements. The example shown in Figure 2 was due to tunnelling with an earth pressure balance shield with a face pressure of about 1.2 σ_{vo}.

The three forms of consolidation settlement were probably not exclusive; Form 1 could follow Form 2 or 3. This is shown in Figure 3, with heave (due to high face pressure) followed by an equal and opposite phase of type 3 consolidation, and then by a phase of Form 1 consolidation.

Although piezometer data from MRT tunnel construction is extremely limited, from the form of the settlements, and work published elsewhere it is thought that the piezometer changes which give rise to these settlements are of the form shown in Figure 4.

The radius of influence of Form 1 and 2 settlements is clearly much wider than Form 3, and the effect on structures will also be quite different. The primary concern for buildings is not the absolute settlement, but the distortions induced by the settlement. For uniformly founded buildings Forms 1 and 2 consolidation are clearly much less of a concern than Form 3.

Broms and Shirlaw (1989) have shown that Form 3 consolidation settlements were, in effect, delayed 'ground loss' settlements. The use of high face pressure helped to minimise immediate settlements. However the high face pressures also caused excess pore pressures (100kPa. was measured). The dissipation of these pressures resulted in further settlement. There is good reason to believe that the final settlements were just the same as would have occurred had the tunnels been driven without over-pressuring the face.

EXAMPLE 1	EXAMPLE 2	EXAMPLE 3
SINGLE TUNNEL	TWIN TUNNELS, 16m c/c	TWIN TUNNELS, 16m c/c
6·41m O.D. DRUM DIGGER	5·91m O.D. GREATHEAD SHIELDS	5·93m O.D. EARTH PRESSURE BALANCE SHIELDS
DEPTH TO AXIS = 13m	DEPTH TO AXIS = 15·5m (E/B) = 16·0m (W/B)	DEPTH TO AXIS = 18·9m
AIR PRESSURE = 0·9 BARS	AIR PRESSURE = 1·3 BARS (E/B) 1·25 BARS (W/B)	FACE PRESSURE (SHOVE) = 3·5 BARS (E/B) = 3·8 BARS (W/B) (REST) = 2·5 BARS (E/B) = 2·3 BARS (W/B)
TEMPORARY LINING OF RIBS + WOODEN LAGGING PERMANENT LINING OF INSITU CONCRETE PLACED AFTER TUNNEL DEPRESSURISED	PRECAST CONCRETE LINING WITH HYDRO-SWELLING SEALING STRIP	PRECAST CONCRETE LINING WITH HYDRO-SWELLING SEALING STRIP

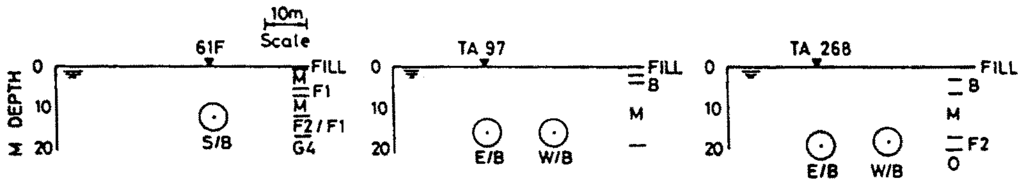

FIG 2(a) TUNNEL DETAILS

KEY

M - MARINE CLAY
F2 - FLUVIAL CLAY
F1 - FLUVIAL SAND
G4 - WEATHERED GRANITE
O - OLD ALLUVIUM
B - BEACH SAND

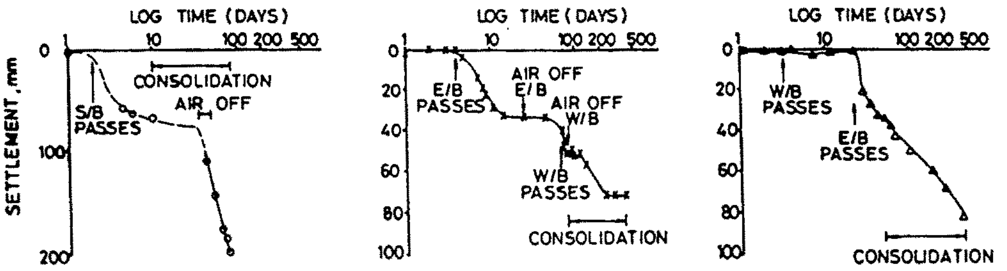

FIG 2(b) SETTLEMENT/LOG TIME FOR POINTS INDICATED IN FIG 2(a)

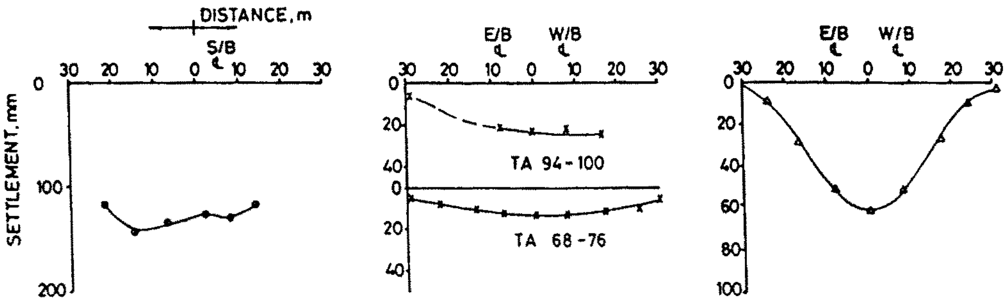

FIG 2(C) LATERAL SETTLEMENT TROUGH FOR PERIODS INDICATED IN FIG 2(b)

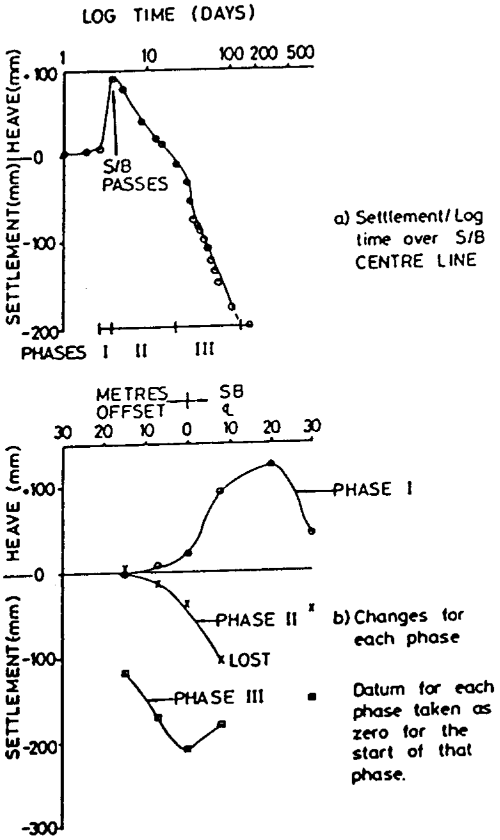

FIG.3 EXAMPLE OF FORM 3 SETTLEMENT (PHASE II) FOLLOWED BY FORM 1 AND/OR 2 SETTLEMENT (PHASE III)

For the purposes of estimating effects on buildings it is suggested that Form 1 and Form 2 consolidation settlements should be considered quite separately from 'ground loss' settlement. Form 1/2 settlement will affect many more buildings than the narrower 'ground loss' settlement trough. However the flat settlement profile should mean that only buildings with mixed foundations are in danger of major damage. For bored tunnels in Singapore it was found that if the following conditions applied:

a) The water make at the face was controlled, by compressed air, ground treatment or using full-face machines.

b) The lining immediately behind the tunnelling machine was water-tight.

then Form 1 or 2 settlements were typically small. Form 2 settlements over compressed air tunnels in the soft Singapore marine clay were typically 20-30mm., with a maximum recorded value of 60mm. This mode and magnitude of settlement was not observed to cause any major damage.

The largest Form 1 settlements were not related to tunnelling in soft clay, but to tunnelling in rock under soft clay deposits. In these cases the tunnel could be advanced quite safely without compressed air, but even relatively small water make in the often highly shattered rocks could quickly result in significant Form 1 consolidation settlements. Due to their sometimes large magnitude, up to 400mm., these settlements did have some adverse effects. For recently constructed residential and light industrial buildings in Singapore it has been common practice to support the main concrete frame on piles. However the ground floor and walls are often cast directly out the ground, without being designed to span between supports. Consolidation settlements could lead to significant adverse effects on this type of building including:

* Cracking, and even structural failure, of ground floor slabs.
* Distortion of infill walls founded on the ground floor slab.
* Separation of aprons from the structure.
* Distortion and, in severe cases, fracture of services entering the building.

By contrast, older structures (such as the characteristic Singapore shophouse) were generally founded on mats, rafts or settled closely spaced, short, timber piles. These structures largely settled with the ground, avoiding many of the problems mentioned above.

3 GROUND LOSS SETTLEMENTS - BORED TUNNELS

The amount of ground loss settlement over bored tunnels is a result of the inter-action of, inter alia:

a) The strength and nature of the ground

b) The method of tunnelling

c) The quality of the workmanship

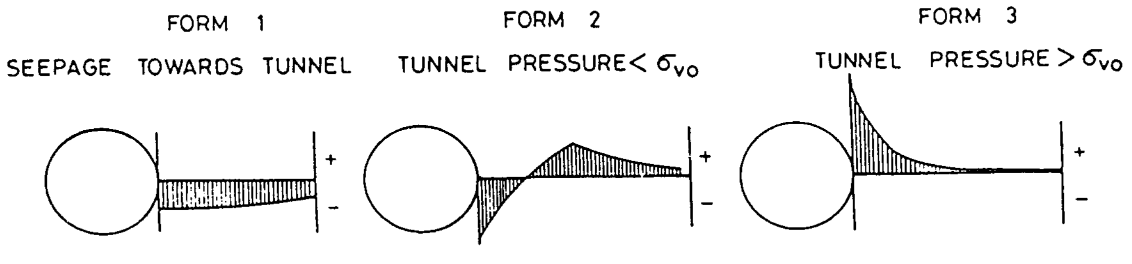

FIG.4 POSSIBLE PORE PRESSURE CHANGES GENERATED BY TUNNELLING

The sheer variability of settlements due to these factors is demonstrated in Table 1, showing various recorded ranges of settlement over tunnels within the Singapore Kallang formation. The major component of the Kallang Formation is marine clay. These figures include consolidation settlements, but demonstrate the very significant variation that can occur due to different methods.

Ground Type	Tunnelling Method	Additional Measures	Typical Range of Settlements
Kallang	Greathead Shield	Compressed Air	30 - 120mm
Kallang	Greathead Shield	JGP & Compressed Air	30 - 60mm
Kallang	Greathead Shield	JGP only	40 - 110mm
Kallang	Drum Digger	Compressed Air	200 - 400mm
Kallang	Earth Pressure Balance	None	70 - 140mm

TABLE 1 RANGE OF FINAL SETTLEMENTS OVER TUNNEL CENTRE LINES

There is no space here to deal fully with the observations of 'ground loss' settlements over the tunnels in Singapore. Anyway, much of this data has already been presented previously (see papers quoted above). However, it is worth reviewing the comparative settlements over closed and open shields, as the MRT afforded an unusual opportunity to compare their performance directly.

On contract 301 the contractor had to drive twin bored tunnels between City Hall and Bugis stations, and also between Bugis and Lavender stations (see Hulme, Shirlaw and Hwang, this conference). The tunnel shafts were located near City Hall and Lavender, and all four tunnels were driven towards Bugis station. The tunnels from City Hall to Bugis were driven using open face shields with compressed air, and for the last 300m. the tunnels were wholly in the Kallang Formation, principally soft clay. The tunnels from Lavender to Bugis were driven using EPBS, wholly in the Kallang Formation. Example 2 above is from the tunnels City Hall to Bugis, example 3 from Lavender to Bugis.

The two sets of shields were thus driven through he same formation, at roughly the same depth and separation, and by the same contractor. The resulting settlements are therefore an extremely good comparison of the results of the two different methods.

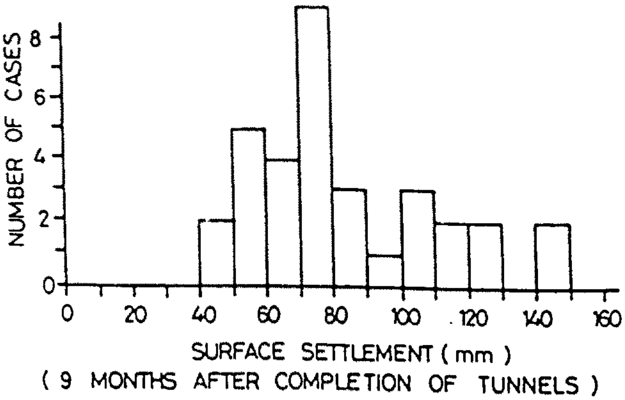

FIG.5a) HISTOGRAM OF TOTAL SURFACE SETTLEMENT MEASURED OVER THE CENTRE-LINES OF TWO TUNNELS DRIVEN USING EARTH PRESSURE BALANCE SHIELDS

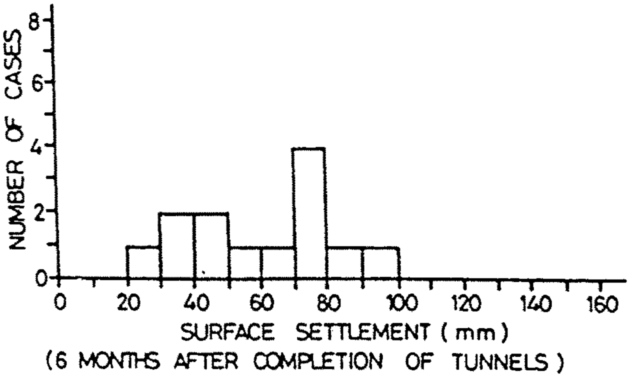

FIG.5b) HISTOGRAM OF TOTAL SURFACE SETTLEMENT MEASURED OVER THE CENTRE-LINES OF TWO TUNNELS DRIVEN USING OPEN FACE SHIELDS, COMPRESSED AIR

The total settlements over the tunnel centre lines are presented as histograms in Figures 5a & b. In each case the monitoring was continued to the point where the rate of consolidation settlement had become very slow. It can be seen from the histograms that in terms of total settlement the shields with compressed air marginally out-performed the EPBS. However, as discussed above, the consolidation settlements over the compressed air tunnels were of Form 2, whereas those over the EPBS tunnels were of Form 3. Following the logic presented above, Form 2 consolidation settlements should be excluded when considering 'ground loss', whereas the Form 3 should be included. In terms of the settlements which follow an 'error function' trough, then the true comparison between the two sets of tunnels is between the histograms presented as Figures 5a and 6. It can be seen that in this comparison the compressed air shields out-performed the EPB shields by a large

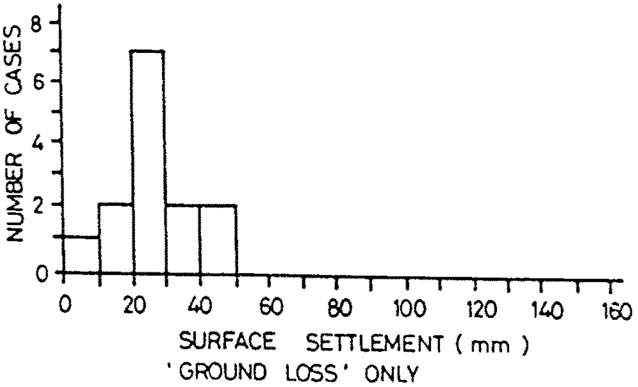

FIG.6 HISTOGRAM OF 'GROUND LOSS' SETTLEMENT MEASURED OVER THE CENTRE-LINE OF TWO TUNNELS USING OPEN FACE SHIELDS, COMPRESSED AIR

margin. This very clear cut conclusion is in direct contradiction of much of today's received wisdom.

It can be seen from the histograms that the settlement over a tunnel is not a 'unique' number that can be predicted with accuracy. Instead tunnelling produces a range of settlements, with variations accounted for by variations in the three major factors mentioned above. In particular the magnitude of the settlements will be very sensitive to both the soils and the level of workmanship. Even minor variations in soil strength will be reflected in the varying settlements. It is important to remember this when making predictions based on analytical rather than empirical analysis.

4 CONCLUSIONS

The data presented, consisting of field measurements made during the construction of the Singapore MRT, has shown that:

i) There are at least three separate types of consolidation settlement associated with bored tunnelling. Each type results in a different form of settlement trough, and results from a different pattern of negative or positive excess pore pressure.

ii) A direct comparison of settlements over tunnels constructed by earth pressure balance and open, compressed air shields in soft clay was made. Based on total settlement the open shield resulted in marginally lower settlements than the earth pressure balance shields. If the relatively flat settlement trough caused by the removal of air pressure is abstracted, then in terms of the narrow, 'error function' trough most characteristic of bored tunnelling, then the compressed air shields resulted in very much smaller settlements.

iii) Old buildings, on raft or mat foundations, often appeared to be less affected by large consolidation settlements than modern, piled buildings. This was because the older buildings moved with the ground, while the piled buildings suffered from the separation of unpiled elements. However for major complexes the relatively assured stability of the main piled structure usually outweighs the inconvenience of the minor structural damage.

6 REFERENCES

Broms, B. B. and Shirlaw, J. N. (1989). Settlements caused by earth pressure balance shields in Singapore. Proc. Tunnelling and microtunnelling in soft ground, Paris.

Milligan, G. W. E. (1983). Soil deformations near anchored sheetpile walls. Geotechnique 33, No. 1, 41-55.

Nicholson, D. P. (1987). The design and performance of the retaining walls at Newton Station. Proc. Singapore Mass Rapid Transit Conf. 147-154, Institution of Engineers Singapore.

Shirlaw, J. N. and Copsey, J. P. (1987). Settlements over tunnels in Singapore marine clay. Proc. 5th Intl. Geot. Seminar, pp 59-72, Nanyang Technological Institute, Singapore.

Shirlaw, J. N. and Doran, S. R. (1988). Ground movements and settlements caused by tunnelling for the Singapore Mass Rapid Transit system. Proc. Tunnelling '88, 295-314, Institution of Mining and Metallurgy, London.