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Bored Tunnelling Directly below Buildings in Singapore Downtown Line

K.H. Goh[1], S. S. Ng[2] and K.S. Ho[3]
[1,2,3] *Land Transport Authority, Singapore*
[1]*E-mail*: goh_kok_hun@lta.gov.sg
[2]*E-mail*: gerald_ss_ng@lta.gov.sg
[3]*E-mail*: ho_kee_sang@lta.gov.sg

ABSTRACT: Other than basement construction of building complexes for parking and other functions, many cities in the world are also embarking on major construction projects to put roads, metro infrastructure, municipal services and utilities, under the ground. One of the specific challenges faced is the construction of bored tunnels directly below buildings. This paper reports the experiences of bored tunnelling directly below several buildings in the recently implemented Downtown Line project. These case studies would include details such as the structural system and foundation details of the buildings, ground condition, geometry and clearance between the building foundation and the tunnelling works, as well as instrumentation monitoring results of ground and building settlement during tunnelling. It is hoped that these cases could be used as references in the design of future bored tunnelling works, to give greater confidence that tunnelling directly below buildings can be carried out without affecting the buildings so long as appropriate tunnelling controls are taken to mitigate ground deformation issues.

KEYWORDS: Tunnelling, Buildings

1. INTRODUCTION

The Downtown Line (DTL) will be the fifth Mass Rapid Transit (MRT) line in Singapore following the completion of the Circle Line. It links people directly from the northern and eastern parts of Singapore into the downtown area and provides a quick, convenient, affordable and comfortable means of transport. Figure 1 shows the overall map of DTL in relation to existing and upcoming MRT lines in Singapore. The DTL is being implemented in three stages. DTL Stage 1 (DTL1) with 4.3 km of underground tunnels and 6 underground stations has been completed and was opened to service in December 2013. DTL1 hugs around Singapore city, and runs from Chinatown to Bugis which are interchange stations with North-East Line and East-West Line respectively. DTL Stage 2 (DTL2) with 16.6 km twin tunnels and 12 underground stations plus a cut-and-cover box for tunnel operation, and was opened to service in December 2015. DTL2 runs from Bugis up along the corridor embodied by Bukit Timah Road and Upper Bukit Timah Road, and ends up at Bukit Panjang in the north-west of Singapore. DTL Stage 3 (DTL3) with 21 km of tunnels and 16 underground stations is under construction and scheduled for revenue service in 2017. DTL3 runs towards the eastern part of Singapore from Chinatown Station to Bedok and Tampines, and ends as an interchange with Expo station on the East-West Line.

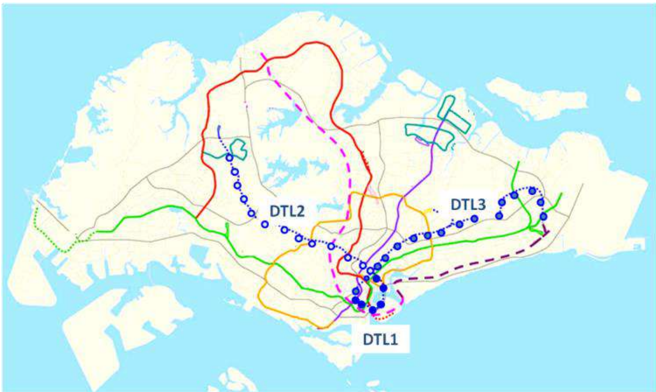

Figure 1 Map of Downtown Line in Singapore

2. GEOLOGICAL SETTING

The geology in Singapore can be broadly classified into the predominantly soft clays and loose sands of the Kallang Formation (Tan et al, 2003), the igneous rocks and weathered soils of the Bukit Timah Granite (Leong et al, 2003), the metamorphic rocks and weathered soils of the Jurong Formation, the various weathering grades of the sedimentary soils of the Old Alluvium (Chiam et al, 2003), and the colluvial deposits of very strong sandstone or quartzite boulders in a hard matrix characterizing the Fort Canning Boulder Bed (Shirlaw et al, 2003). Figure 2 shows the Downtown Line superimposed onto the Geological Map of Singapore, whilst Annex A shows the geological profile along the entire alignment of the Downtown Line with the stations and tunnel depths through various geological formations. DTL1 runs within the Central Business District of Singapore, and is mainly in the soft Kallang Formation which includes the Singapore marine clay, the fluvial sands, and the fluvial clay. DTL2 swings from the central district out into northwestern part of Singapore towards Bukit Panjang, and runs mostly along the Kallang Formation tributary through Bukit Timah corridor before moving off into the Bukit Timah Granite Formation along Upper Bukit Timah Road. DTL3 swings out into the eastern part of Singapore, cutting through the Kallang Formation at Kallang Basin before moving into the competent Old Alluvium Formation characterising the geology in the eastern part of Singapore.

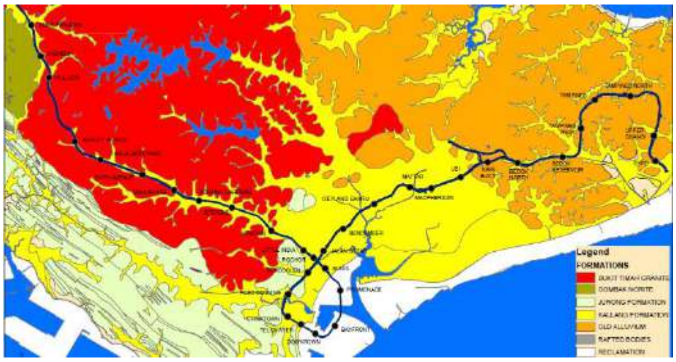

Figure 2 Downtown Line and the Geological Map of Singapore

3. OVERVIEW ON TUNNELLING DIRECTLY BELOW BUILDINGS IN DOWNTOWN LINE

The Downtown Line consists of cut-and-cover tunnels (at station and cross-over box locations) and twin bored tunnels between the cut-and-cover tunnels. A summary of the cut-and-cover construction and bored tunnelling methods are described by Goh et al (2014) and by Zhang et al (2014) respectively. Specifically, one of the challenges in constructing the Downtown Line is to tunnel directly below buildings using tunnel boring machines (TBMs). In Singapore, the impact of tunnelling on buildings is assessed using the 3-staged risk assessment approach by Mair et al (1996). In the preliminary assessment, the contours of excavation-induced settlements are drawn and buildings falling within a settlement zone of less than 10mm and having a slope of more than 1:500 are considered to have a negligible risk of damage and eliminated in this first stage. The remainder of the buildings is then subjected to the second stage assessment using the limiting tensile strain method. This is done by calculating the maximum tensile strains induced in the building using deflection ratios and horizontal strains from simple beam theory, and then evaluating the maximum strains against the limiting tensile strains in order to estimate the potential damage category for each building. The approach assumes that the building has no stiffness and conforms to the greenfield displacement profile. Buildings assessed to have 'Negligible' damage, 'Very Slight' damage, and 'Slight' damage categories (as defined by the BRE Digest 251) are considered to be at low risk of damage, and can be eliminated from the assessment at this stage. Finally, for buildings assessed to be at a high risk of damage (i.e. damage categories of 'Moderate', 'Severe' and 'Very Severe'), detailed evaluation is to be undertaken. This could involve evaluating the structural details of the building, giving full consideration of the construction method in three-dimensions rather than plane-strain, as well as including soil-structure interaction effects which means taking into account of the building stiffness. Following the detailed evaluation, consideration is then given to protective measures needed for buildings that remain in the high damage categories.

So long as the risk assessment shows that the potential risk to buildings are within the "Slight" damage category, occupants would be allowed to carry on with their normal activities in the buildings whilst the bored tunnels are being constructed concurrently below the buildings. Measures such as close instrumentation monitoring of building and ground response, applying suitable face pressures in the TBMs, cutterhead maintenance before the TBM reaches the building, and contingency structural propping, are implemented to mitigate any residual risks from the tunnelling activities. Notwithstanding these, there is considerable anxiety to such tunnelling activities, and understandably so. There were concerns over the loss of support directly below the building foundations, thereby causing severe building damage. This is also aggravated by the lack of local information related to such works, as published local case histories of tunnelling directly below buildings in local conditions are few and far in-between.

Annex B tabulates the cases of bored tunnelling going directly below the buildings in the Downtown Line, which are all within the DTL3 sector and on the eastern side of Singapore. This does not include the numerous cases where tunnelling was carried out adjacent to the buildings. The buildings in Annex B range from low-rise shophouses to high rise apartments, from masonry structures on shallow foundations to reinforced concrete frame structures on pile foundations, and the functions vary from commercial and industrial to institutional and even residential uses. For all of these cases, tunnelling was carried out without disrupting any of the functions within the buildings, even though detailed contingency plans (such as temporary propping and activating the decanting sequence) were designed in case the tunnelling did not go smoothly as planned.

The ground is predominantly the Old Alluvium and Kallang Formations which are both sedimentary in nature but differing vastly in geological age. There are some areas nearer the city area which is in Jurong Formation and the Fort Canning Boulder Bed. The tunnelling is carried out using Earth Pressure Balance (EPB) machines. EPB TBMs need to maintain substantial support to the excavated face at all times in order to control ground movements during tunnelling excavations. This is done mainly by controlling the rotational speed of the screw and the amount of muck discharge at the outlet of the screw conveyor, and also ensuring that the soil within the head chamber is properly conditioned using bentonite, foam and polymers as mediums. A minimum face pressure of slightly higher than hydrostatic pressure was always applied, and in particularly when going below the buildings. Another feature to reduce ground movements is the injection of tail-void grouting to seal the gap as the TBM shield slides out from the tunnel linings, and this seal material is usually made of cement grout with an accelerator such as sodium silicate. Other good tunnelling practices include pre-planning for cutterhead interventions just before the TBMs go below the buildings for checking cutterhead condition and replacing the cutting tools.

Comparing the various tunnelling locations identified in Annex B, the ground settlement is highest when tunnelling near Jalan Besar shophouses where the ground is transitioning between the Kallang Formation and the Old Alluvium along the tunnel. Otherwise, the maximum ground settlements are not more than 18mm, especially during tunnelling in the very competent Old Alluvium, and are well within the 1% volume loss assumed in design when assessing the impact of tunnelling to the buildings.

The building settlements were generally observed to be less than the ground settlements at the ground surface. Through observations on field studies and centrifuge models (Jacobsz et al 2001, Kaalberg et al 2005, Selementas et al 2005), it is generally proposed that the tunnelling-induced settlements of pile foundations can be estimated depending on where the pile foundations are in relation to the tunnel. Using the simplified illustration in Figure 3, piles with toes in Zone A would settle more than the ground surface due to some reduction in their base load but increased mobilization of shaft friction, whilst piles with toes in Zone B would settle by the same amount as the ground surface and piles with toes in Zone C would settle less than the surface.

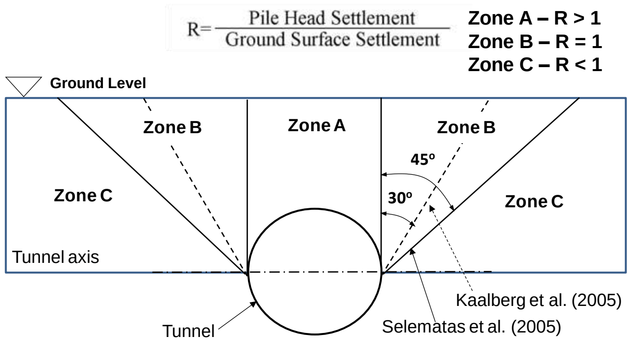

Figure 3 Zones of tunnelling

For most practical applications, the building usually straddles over the tunnel and covers all the three zones of tunnelling. As such, it is not possible to see the different pile behaviour in the above simplified illustration using the Downtown Line case studies. Moreover, the building settlement is also influenced by its stiffness. There is a propensity for buildings to re-distribute the tunnelling-induced movements such that stiffer buildings would experience much less differential settlement than flexible buildings – this has been illustrated by several researchers and more recently by Mair (2013). Through field studies, centrifuge modelling, and numerical modelling, Mair (2013) further proposed a new simplified design approach to take account of relative building stiffness and predict building response to tunnelling-induced ground movements with greater certainty, as shown in Figure 4 which plots a relative response of building in relation to the greenfield using the modification factor concept to the relative bending stiffness of the building defined with respect to the ground. The resultant building settlement monitored would be a combined effect of foundation location with respect to tunnel construction, and the distributive effect of building stiffness. More recently, Mair and Williamson (2014) reported from centrifuge observations that there are only relatively small changes in load distribution in the pile during tunnelling, with some reduction in pile skin friction under negative relative displacements and an increase in pile skin friction under positive relative displacement. Pile failure does not occur even at high tunnel volume loss and there is little or no loss of capacity of the piles.

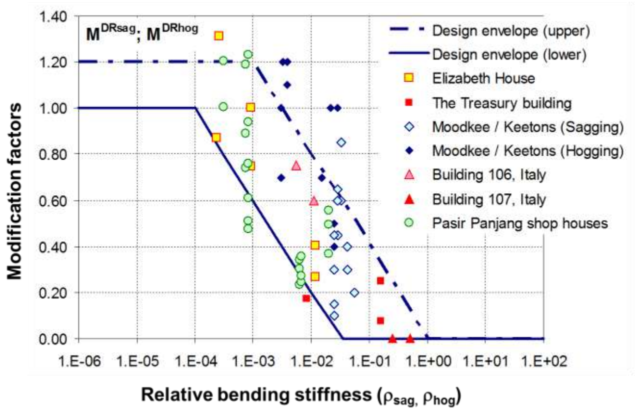

Figure 4 Field data of building response to tunnelling using new definition of relative building stiffness (Mair, 2013)

Some of the case histories in Annex B have been reported by Goh et al (2016). These are the cases where the buildings were low-rise in nature and included the Jalan Besar shophouses, the Lavender Street shophouses, the hotel at Foch Road, and the National Museum of Singapore. For the latter half of this paper, the cases associated with tunnelling directly below the mid-rise buildings in Annex B will be reported. Together, it is hoped that these case studies would illustrate that tunnelling directly below buildings, sometimes in close proximity to the pile foundations, does not cause a building to settle significantly. Concerns about loss in pile carrying capacity are often misplaced and with appropriate tunnelling controls, it is possible to keep the building movements within the normal range of ground settlements expected. This will meet a key objective of this paper, which is to report on the experiences of bored tunnelling directly below several buildings in the Downtown Line project so that greater confidence can be accorded to future works of similar complexity.

4. CASE HISTORY OF TUNNELLING DIRECTLY BELOW HOUSING BLOCKS AND SCHOOL BLOCKS IN TAMPINES

The first case history refers to the bored tunnelling directly below a cluster of buildings with total length of approximately 280m along both bounds of DTL3 bored tunnels at the eastern part of Tampines. The tunnel drives went through underneath in sequence of 2 blocks of low rise school buildings, 3 blocks of high rise housing buildings, a multi-storey car park building as well as a petrol kiosk (Figure 5). The first drive which is Bukit Panjang bound tunnel was completed in July 2013 whilst the second drive (Expo bound tunnel) was completed 3 months later. The bored tunnels were constructed using EPB TBM at approximately 35m below existing ground level at this location.

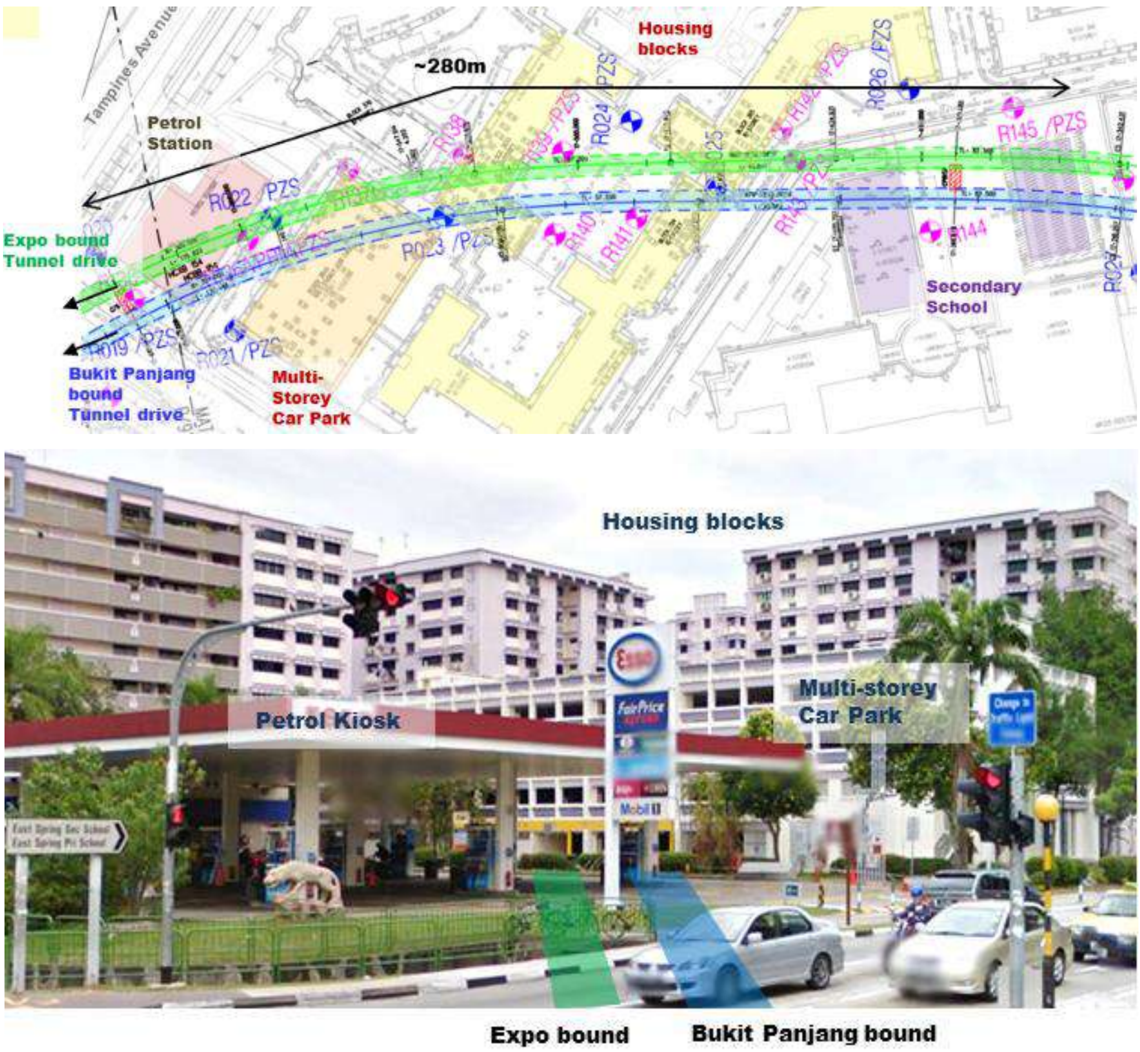

Figure 5 Location of a cluster of structures along tunnels alignment in Tampines

Figure 6 shows the foundation type of existing structures along the tunnels' alignment. Other than a petrol kiosk which is single storey structure on footing foundation, all the structures along the tunnels' alignment are generally reinforced concrete structures supported by deep foundations. All the housing blocks and 4-storey car park buildings are founded on bored pile. Meanwhile, the low rise school blocks are supported by micropile and RC pile foundation. The clear vertical distance between the piles of existing housing blocks and multi-storey car park from the bored tunnels are 9.1m and 4.3m respectively (Figure 7).

Figure 8 shows the soil profile encountered at this location. The geological formation is predominantly of the Old Alluvium Formation. Specifically, the bored tunnelling was carried out in the very competent partially weathered to unweathered Old Alluvium (i.e. OA(A) and OA(B)), and the SPT-N value is at least 50 blowcounts. The pile foundations of the structures along the alignment are generally founded in OA(A) and OA(B) layer.

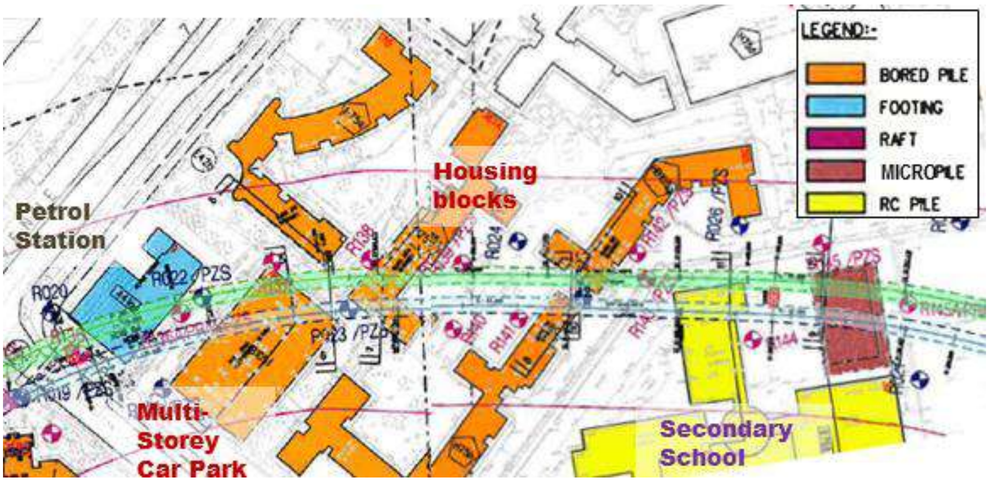

Figure 6 Foundation type of a cluster of structures along tunnels alignment

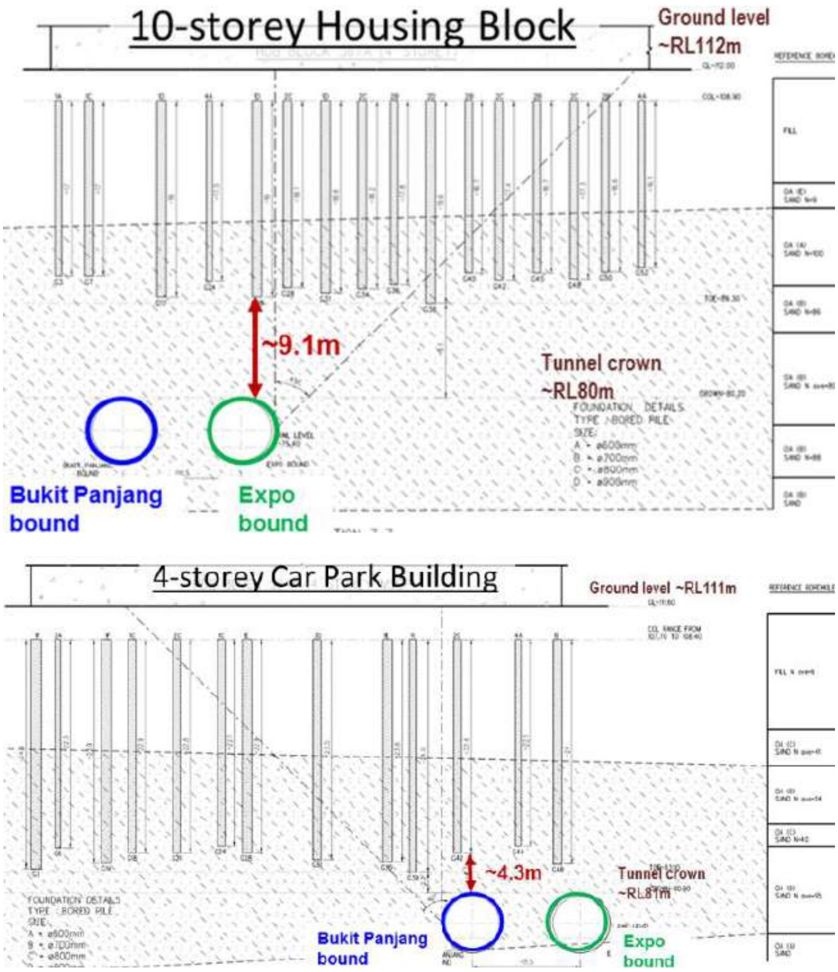

Figure 7 Cross-section of housing blocks and multi-storey car park with respect to bored tunnels

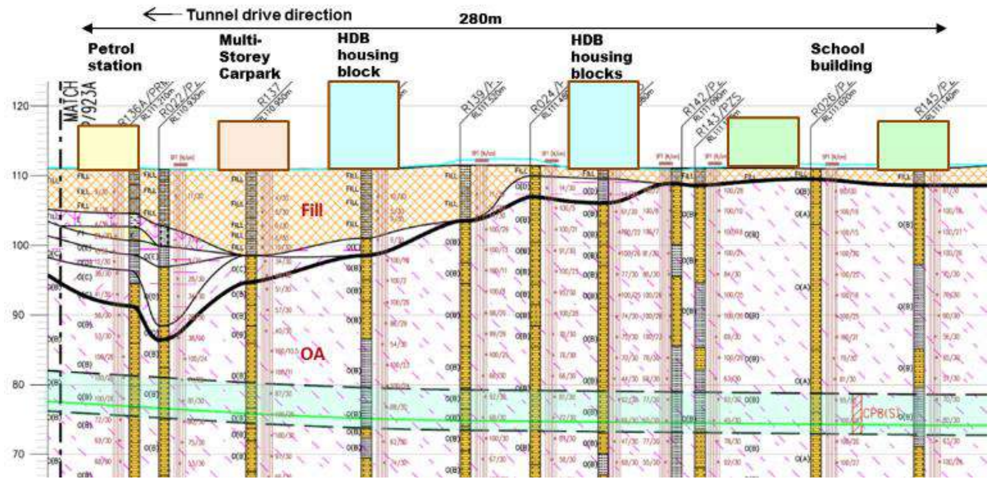

Figure 8 Geological profile of tunneling directly below the structures in library

To monitor the response of ground building due to the bored tunnelling works, ground settlement markers and building settlement markers were installed along the bored tunnels alignment. Figure 9 shows the readings of ground and building settlement markers that were monitored near the housing blocks and multi-storey car park location. The maximum induced ground settlement and building settlement due to bored tunnelling were 8mm and 4mm respectively. That the building settlement was very low even though the bored tunnelling works was carried out directly below the pile foundations, show that the pile carrying capacity of the building is not adversely affected by the tunnelling works taking place directly below it. This is a testament that tunnelling in close proximity directly below pile foundations can be carried out successfully if there is favourable ground conditions with appropriate tunnelling controls to limit the ground deformations.

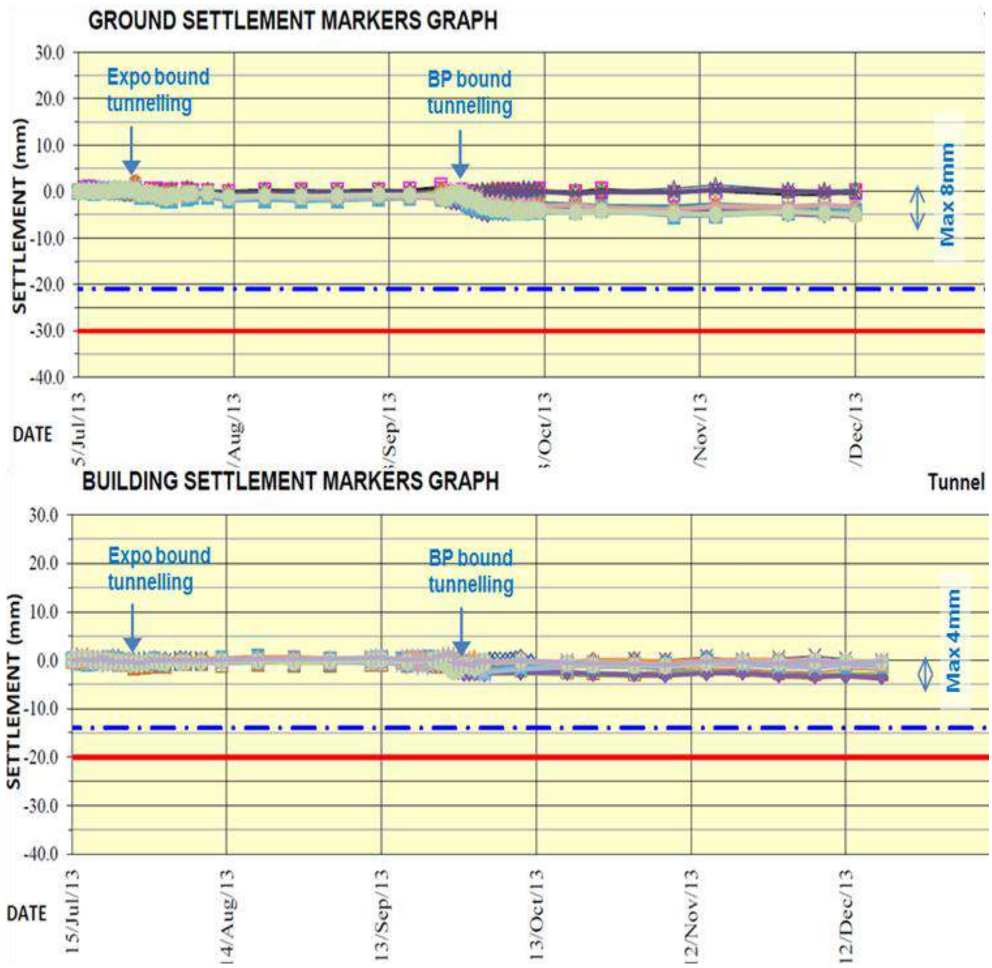

Figure 9 Monitoring of ground and building settlement during tunnelling at the housing blocks and multi-storey car park

5. CASE HISTORY OF TUNNELLING DIRECTLY BELOW TAMPINES REGIONAL LIBRARY

This case history refers to the bored tunnelling directly below the Tampines Regional Library which is a 3-storey reinforced concrete building founded on pad footings. The bored tunnels were constructed using by EPB TBMs. As seen in the location map in Figure 10, the Bukit Panjang Bound passed directly below the building whilst the Expo bound tunnel alignment was constructed approximately 4m away from the building. The bored tunnels are about 25m below the ground surface at this location, and the clear vertical distance between tunnel crown and footing soffit is 19m. See Figure 11.

Figure 12 shows the soil profile encountered at this location. The geological formation is predominantly of the Old Alluvium Formation. The bored tunnelling was carried out in unweathered Old Alluvium of SPT-N value greater than 100 blow counts. The soffit of library's footing is at 1.5m below existing surface level, and founded in Fill layer.

To monitor the response of ground and building due to the bored tunnelling works, ground settlement markers and building settlement markers were installed along the bored tunnel alignment. Figure 13 shows the readings of ground and building settlement markers that were monitored around Tampines Regional Library building. The maximum induced ground settlement and building settlement due to bored tunnelling were 3mm and 2mm respectively. This is another case of EPB tunnelling in competent Old Alluvium where the ground deformation was very well controlled.

6. CASE HISTORY OF TUNNELLING DIRECTLY BELOW OFFICE BUILDINGS IN TAMPINES

The case history involves bored tunnelling directly below two office buildings at Tampines Central. Figure 14 shows the location plan of the office buildings. The first building is a 9-storey reinforced concrete structures with one basement. The second building is a 8-storey building with two levels of basement. Both buildings are supported by raft foundation of 1.2m thick.

Figure 16 shows the soil profile below the office buildings. This consists of a thin layer of Fill overlying the Old Alluvium Formation of various weathering grade. The raft foundations of the buildings are founded in OA(C) layer. Meanwhile the bored tunnels were constructed in the OA(A) and OA(B) layer.

During tunnelling, ground settlement markers and building settlement markers were installed to monitor the settlement behaviour. Figure 17 shows the readings of ground and building settlement markers that were monitored at this location. The maximum induced ground settlement and building settlement due to bored tunnelling were 4mm and 3mm respectively – another example where the induced ground and building settlement were very low due to good tunnelling control in competent ground conditions. Annex A & B show the Longitudinal geological profile along Downtown Line alignment and the Summary of bored tunnelling directly below buildings in Singapore Downtown Line project respectively.

Figure 10 Location of Tampines Regional Library

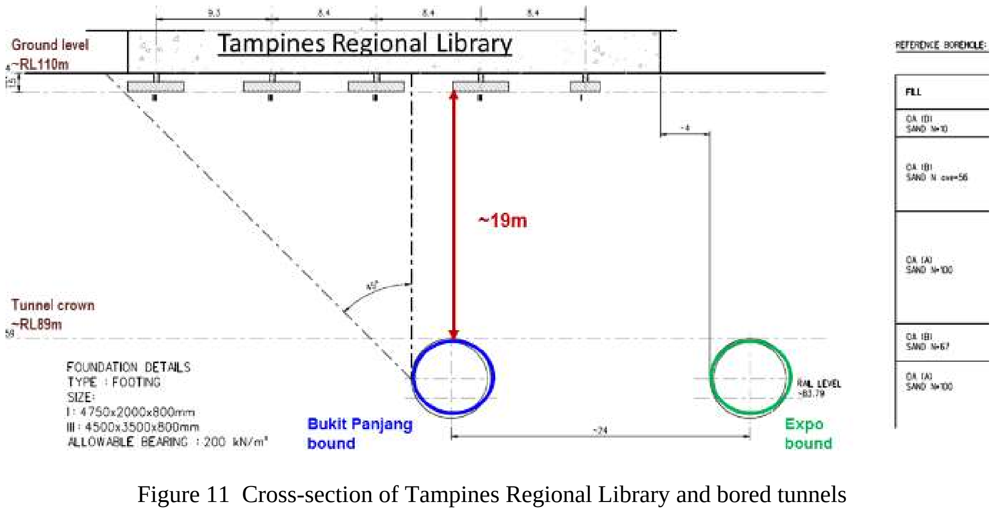

Figure 11 Cross-section of Tampines Regional Library and bored tunnels

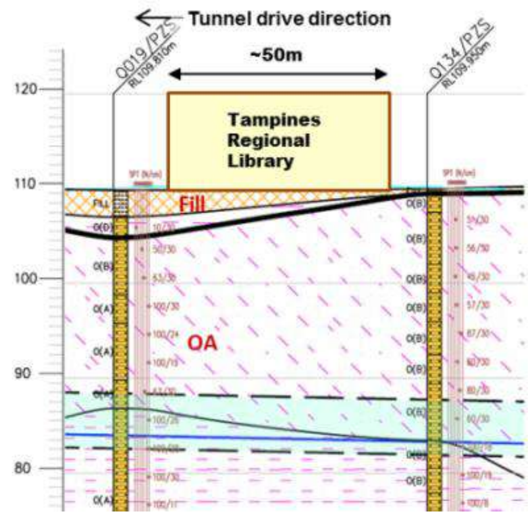

Figure 12 Geological profile of tunneling directly below the library

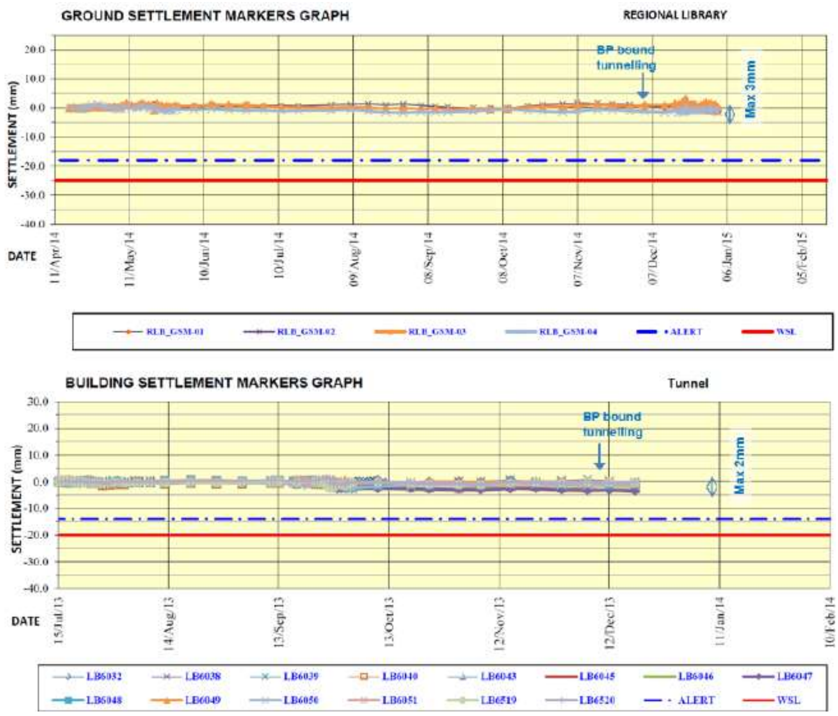

Figure 13 Monitoring of ground and building settlement during tunnelling at library

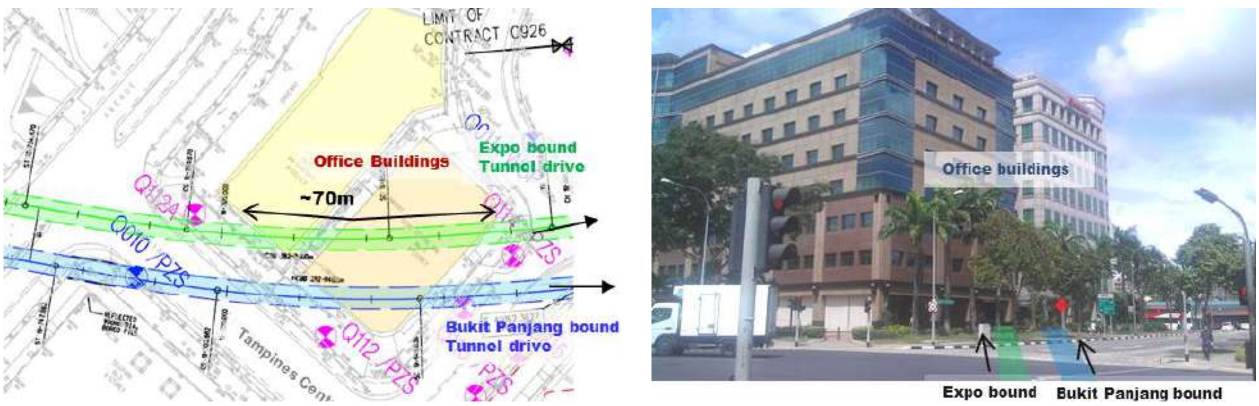

Figure 14 Location of office buildings in Tampines

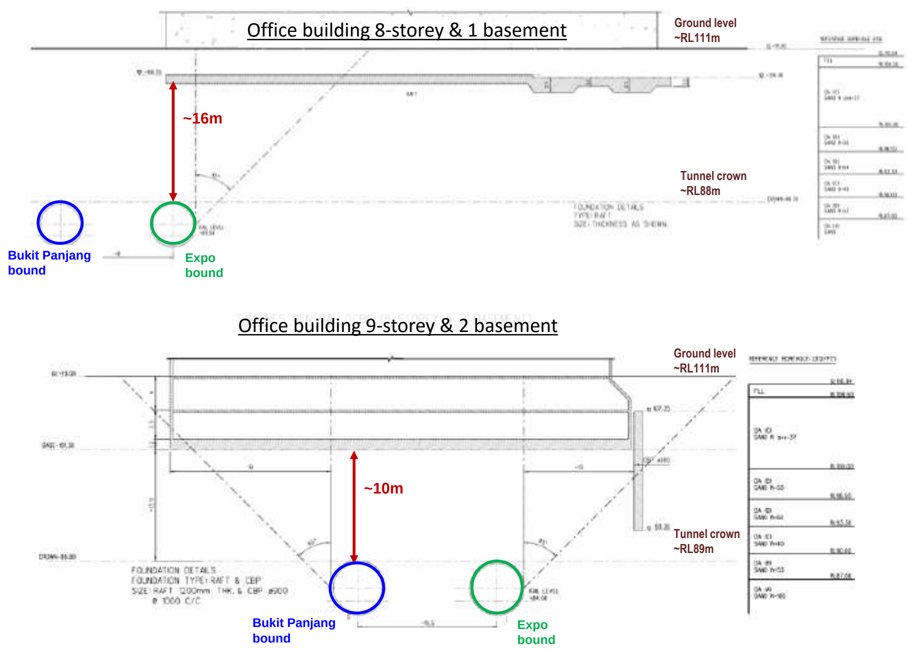

Figure 15 Cross-section of office buildings and bored tunnels

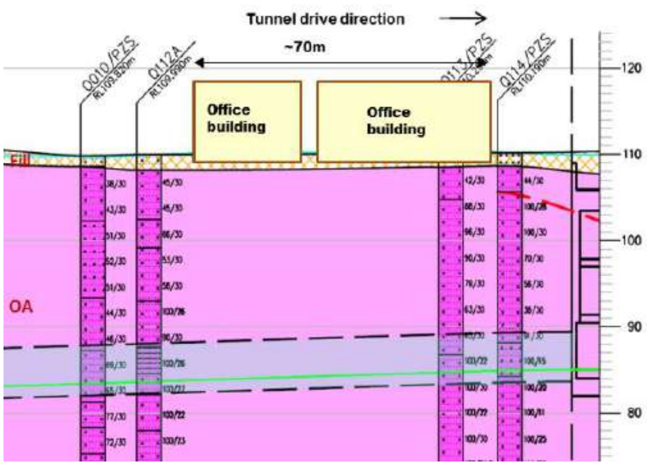

Figure 16 Geological profile of tunneling directly below the office buildings

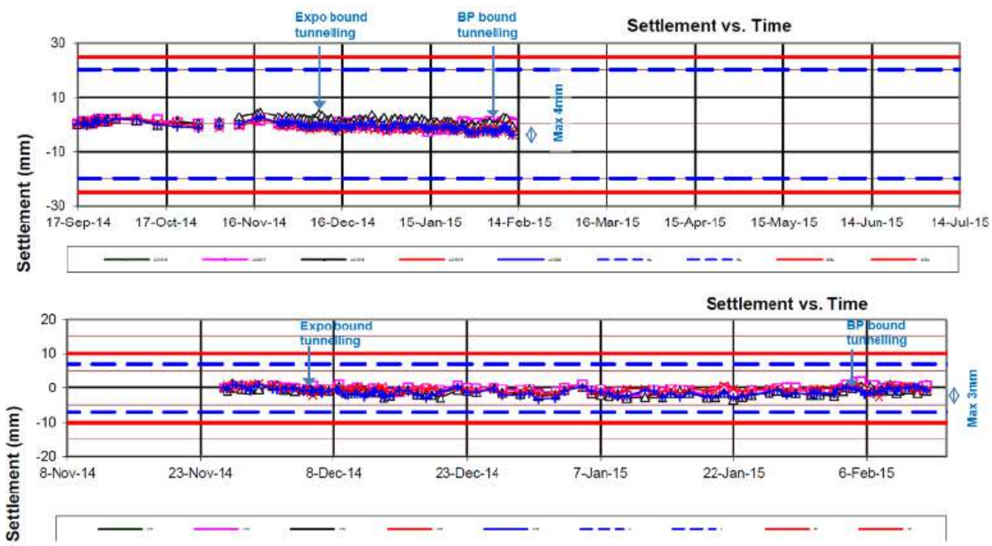

Figure 17 Monitoring of ground and building settlement during tunnelling at office buildings

7. CONCLUSION

One of the biggest challenges in undertaking underground construction in a highly urbanised environment is to tunnel directly below buildings and their foundations. This paper summarised the cases of bored tunnelling going directly below the buildings in the recently implemented Downtown Line project, and provided specific details for three case histories in terms of location of buildings in relation to tunnels, ground conditions and tunnelling operations, structure and foundation details, and instrumentation monitoring results. For all these cases, it was observed tunnelling delow buildings (sometimes in close proximity to the pile foundations) do not cause a building to settle significantly, provided that appropriate tunnelling controls are applied to limit ground deformations. Influences such as building stiffness and competent ground can further help to mitigate impact to buildings so that the tunnelling works can be carried out successfully without affecting the occupants of the buildings. It is hoped that these case histories would give greater confidence for undertaking future tunnelling developments in such challenging requirements.

8. ACKNOWLEDGMENTS

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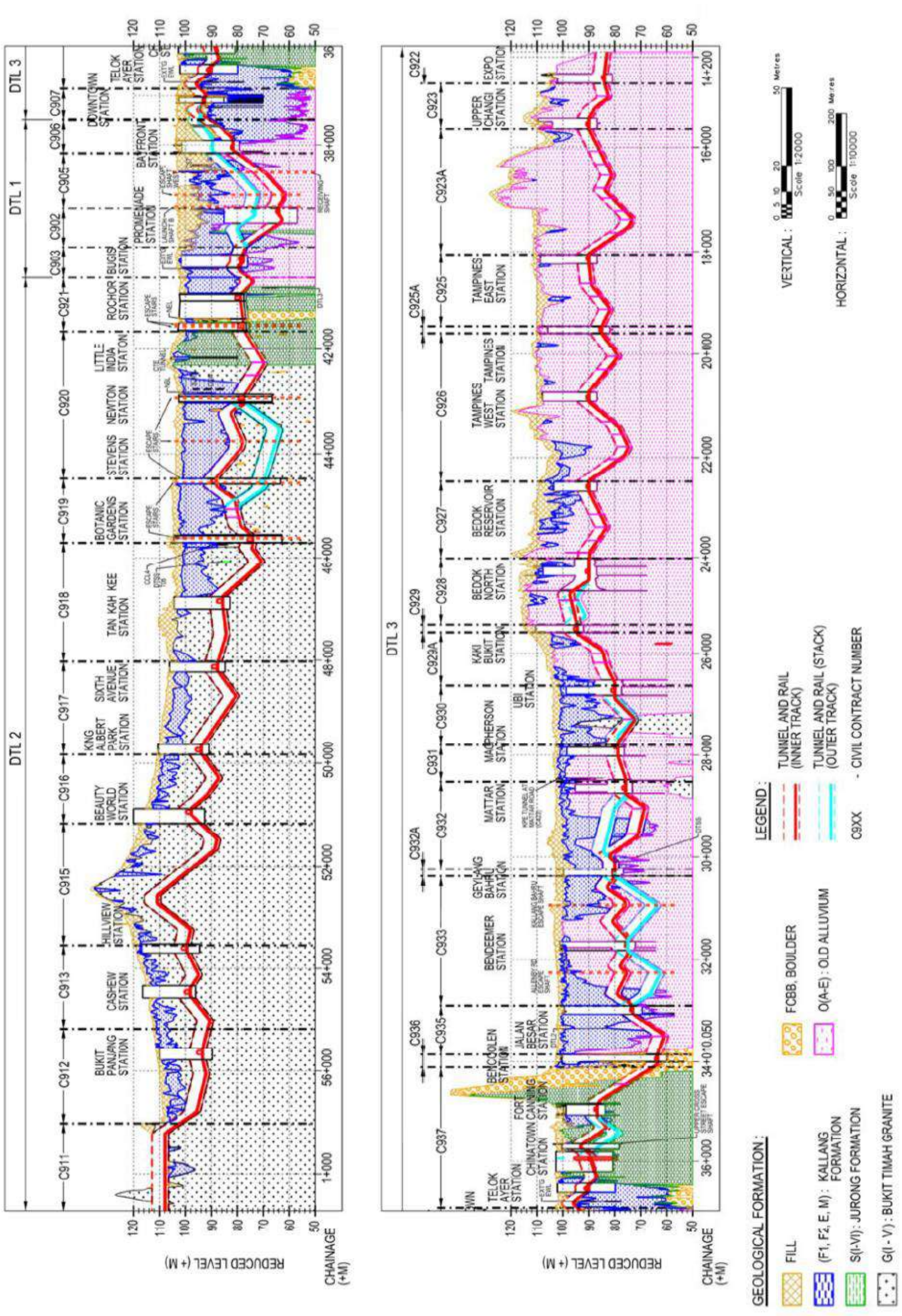
ANNEX A – Longitudinal geological profile along Downtown Line alignment



ANNEX B – Summary of bored tunnelling directly below buildings in Singapore Downtown Line project

S/N	Building	Structural Details	Soil Condition	Vertical clearance from tunnel	Tunnelling method	Maximum ground settlement	Maximum building settlement
1	Jalan Besar shophouses	2-storey shophouses, RC structure on shallow and mixed foundations	Kallang Formation, Old Alluvium	Shallow foundations are ~20m above bored tunnels	EPB tunnelling with face pressure at 3.8-4.7 bars.	45mm	30mm
2	Lavender Street shophouses	2-, 4-storey shophouses with RC structure on micro pile/ bored piles	Old Alluvium	Pile foundations are 4.5m above bored tunnels	EPB tunnelling with face pressure at 2.1-3.2 bars	10mm	7mm
3	Hotel at Foch Road	5-storey reinforced concrete structure on bored piles	Old Alluvium	Pile foundations are 2.6m above bored tunnels	EPB tunnelling with face pressure at 2-3 bars	N.A.	6mm
4	National Museum of Singapore	Main block is 2-storey masonry building on shallow foundation; whilst extension block is reinforced concrete on d-walls and piles	Fort Canning Boulder Bed	Pile foundations are 4m-10m above bored tunnels	EPB tunnelling with face pressure at 1.5-2 bars	18mm	11mm
5	Mall at Magazine Road	2-storey RC building on micropiles	Jurong Formation	Obstructed piles are cut just above tunnel crown	EPB tunnelling with face pressure at 2-3 bars	13mm	5mm
6	Industrial building at Kaki Bukit	7-storey reinforced concrete structure on bored piles	Old Alluvium	Pile foundations are 5m above bored tunnels	EPB tunnelling with face pressure at 2.6 to 2.7 bars	17mm	<2mm
7	Housing blocks at Tampines	10 storey reinforced concrete structures on bored piles	Old Alluvium	Pile foundations are 9m above bored tunnels	EPB tunnelling with face pressure at 2.5 to 3.5 bars	8mm	4mm
8	Secondary School in Tampines	3-storey reinforced concrete structures on micropiles and RC piles	Old Alluvium	Pile foundations are 5.3m above bored tunnels	EPB tunnelling with face pressure at 2.2 to 3.4 bars	4mm	3mm
9	Tampines Regional Library	3-storey reinforced concrete structure on footings	Old Alluvium	Shallow foundations are ~19m above bored tunnels	EPB tunnelling with face pressure at 2.2 bars	3mm	2mm
10	Office buildings in Tampines	8-, 9- storey reinforced concrete structures with 2 basement levels on raft foundation	Old Alluvium	Raft foundations are ~10m above bored tunnels	EPB tunnelling with face pressure at 1.8 to 2.5 bars	4mm	3mm