Case Histories of Bored Tunnelling Below Buildings in Singapore Downtown Line

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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 in Singapore. These case studies 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

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INTRODUCTION

The continuing growth of population density in key urban centres around the world has placed greater emphasis on the development and utilisation of underground space to meet the demands of the city. 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.

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 its intent is to provide 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 will be open 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.

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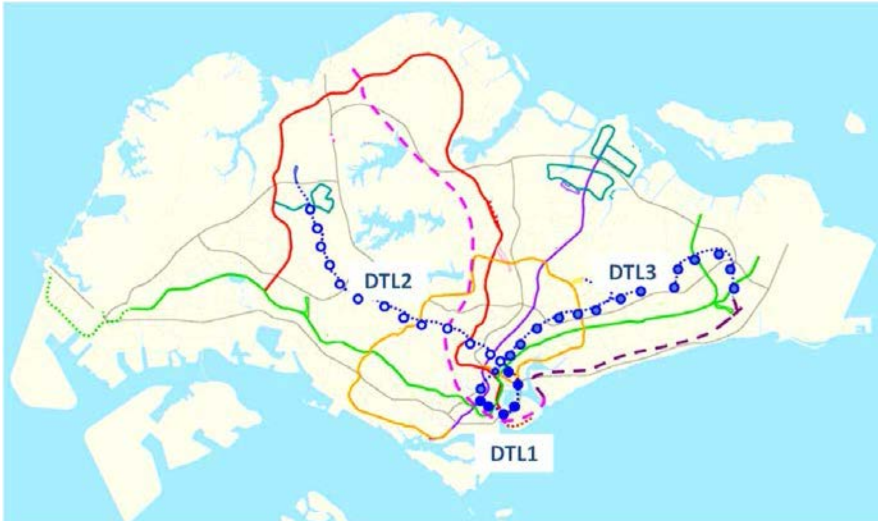

Figure 1. Map of Downtown Line in Singapore.

Geological Setting of the Downtown Line

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. Specifically, Bayfront and Downtown stations are within the reclaimed Marina Bay area. DTL2 swings out from the central district into the 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 at Upper Bukit Timah Road. DTL3 swings out into the eastern part of Singapore, cutting through the Kallang Formation along the Kallang Basin before moving into the competent Old Alluvium Formation characterising the geology in the eastern part of Singapore.

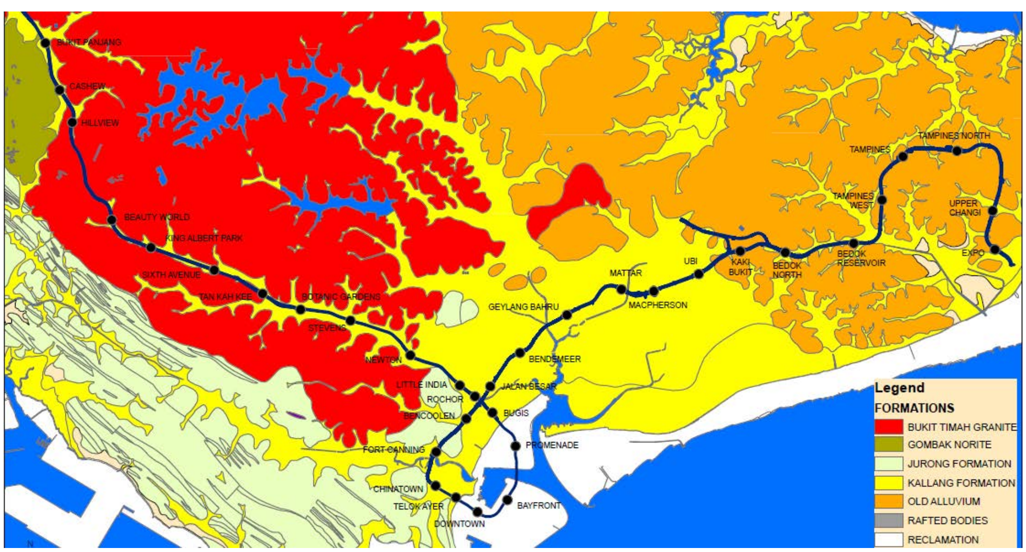

Figure 2. Downtown Line and the Geological Map of Singapore.

AN OVERVIEW ON THE CASES OF TUNNELLING DIRECTLY BELOW BUILDINGS IN DTL

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 are 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 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.

Table 1 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 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 closer to 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 slightly higher than hydrostatic pressure was always applied, and 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.

Table 1. *Summary of bored tunnelling directly below buildings in the 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.	40mm	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

Comparing the various tunnelling locations, 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 18 mm, 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. This is consistent with local experience that tunnelling in the Kallang Formation and the mixed face conditions, are causing more movements that tunnelling consistently in the Old Alluvium. Shirlaw et al (2003) compiled the settlement monitoring data from the North-East Line project during the tunnelling works across various geological formations, and presented the relationships between geological conditions and tunnelling volume loss. Whilst the volume loss of EPB tunnelling in Old Alluvium is generally less than 1%, the volume loss of EPB tunnelling in Kallang Formation and in the mixed-soil conditions of Kallang Formation with Old Alluvium could go up to 5%.

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 (Jacobs 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.

For most practical applications, the building usually straddles over the tunnel and covers all three zones of tunnelling. As such, it is not possible to discern 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. 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.

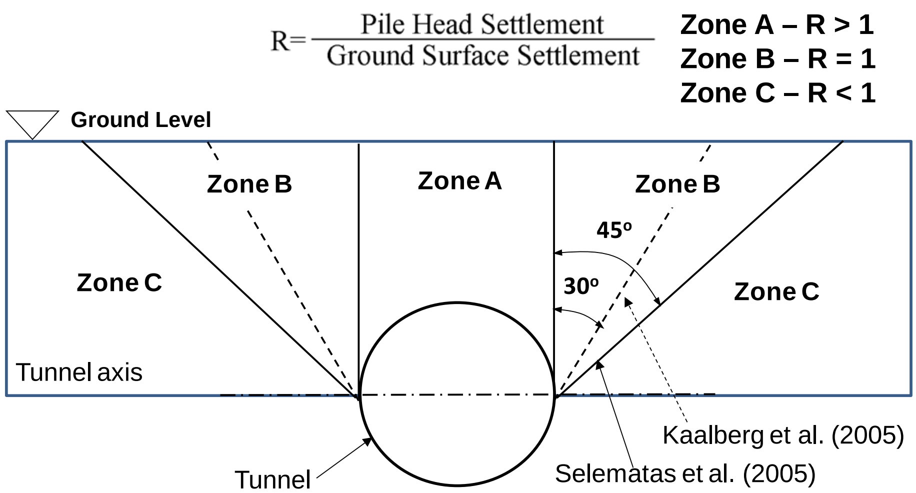

Figure 3. Idealised zones of pile settlement during tunnelling.

For the latter part of this paper, some of the case histories in Table 1 will be reported in greater detail. Basically, these cases 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.

CASE HISTORY A: TUNNELLING BELOW SHOPHOUSES AT JALAN BESAR

The first case history involved tunnelling directly below a row of shop houses between the proposed Jalan Besar and Bendemeer stations. Figure 4 shows the tunnel alignment with respect to the shop houses, where the twin tunnels are transitioning from a stacked configuration to a side-by-side configuration. The TBMs were driven from Bendemeer station towards Jalan Besar station, with the first tunnel drive passing directly below the building (Bukit Panjang bound tunnel) in June 2014 followed by the second drive directly below the road Jalan Besar (Expo bound tunnel) in July 2014. The tunnels are about 28 m below ground surface at this location. As mentioned earlier, these were constructed using EPB TBMs.

Figure 4. Location map and cross-sectional view of tunnelling directly below Jalan Besar shophouses.

The buildings are mostly two-storey shophouses built many years ago and many of them do not have any as-built drawings to show the structure and foundation information. From the limited as-built information, it can be inferred that the shophouses are reinforced concrete framed structures and supported on shallow foundations, either using pad / strip footings or bakau piles. Due to the incomplete foundation information, a trial pit was conducted at one of the shophouses to verify the foundation scheme (Poea et al. 2014). A trench deep enough to expose the foundations was constructed to show the existence of the bakau piles, and this confirmed that the tunnelling works would not clash into the building foundations. Several of the units had also undergone some internal addition and alteration (A&A), and whilst some of these A&A works caused the units to be partially supported on deep foundations (such as steel H-piles, micropiles).

The geological formation consists of a thick layer of Kallang Formation ranging from 10 m to 35 m – these are recently deposited soils of marine and fluvial origins – and overlying the Old Alluvium Formation which is of sedimentary origin. Figure 5 shows the soil profile encountered in both tunnel drives. The bored tunnels underneath the shophouses were constructed in a mix of Kallang Formation and Old Alluvium.

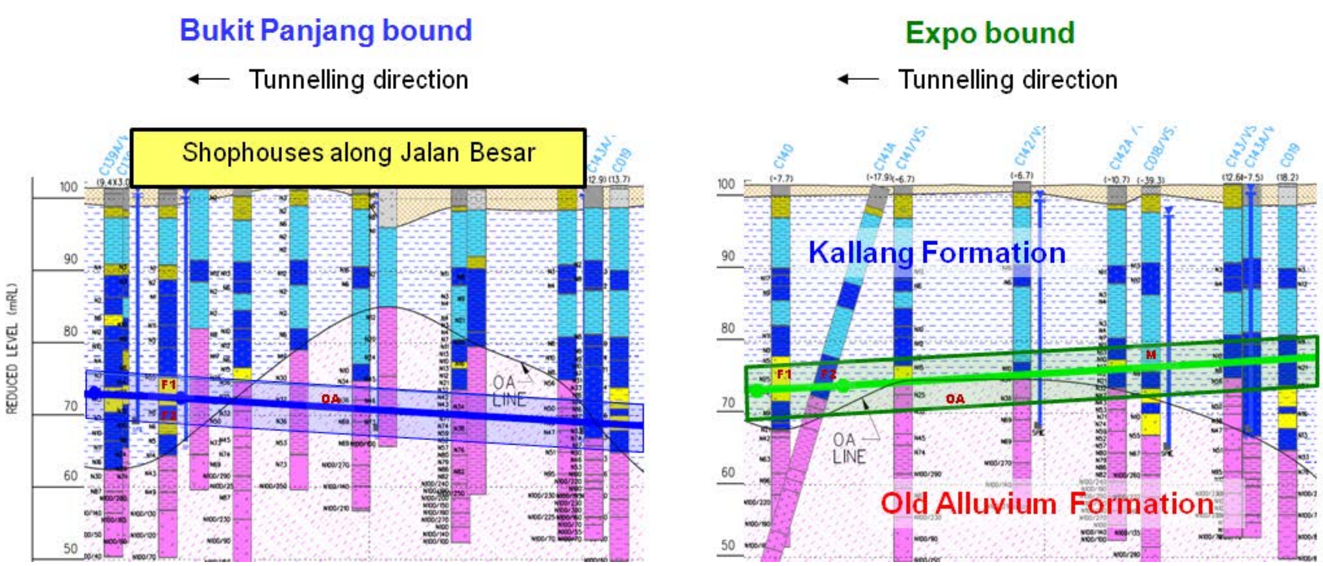

Figure 5. Geological profile of tunnelling directly below Jalan Besar shophouses.

To monitor the response of ground and building due to the bored tunnelling works, ground settlement markers and building settlement markers were installed. Figure 6 shows the readings of ground and building settlement markers that were monitored near the shophouses at Jalan Besar. There were some ongoing ground and building settlement prior to the bored tunnelling works, but the ground surface settled up to 20 mm during the bored tunnelling works between June and July

2014. Thereafter, the ground surface continued to settle for another three more months after the second tunnel drive was completed, and the maximum tunnelling-induced ground settlement was 40 mm. This corresponded with a 1 m drop in piezometric level of the marine clay coinciding with the bored tunnelling works and shows the sensitivity of the compressible clays to changes in groundwater conditions.

In contrast, the maximum building settlement monitored on the shophouses was about 30 mm about two months after the bored tunnels had passed below the buildings. One reason for the difference in settlement response between the building and the ground could be due to the inherent stiffness of the building. For example, using the monitored settlement response of Pasir Panjang shophouses during the tunnel drives for the Circle Line project and using a series of parametric studies using numerical analysis, Goh and Mair (2014) illustrated how the inherent stiffness of a framed structure can modify the building settlement behaviour from that of a greenfield condition. Building stiffness restricts distortion and this modification would enable buildings to tolerate much larger ground deformations than otherwise predicted using a greenfield model.

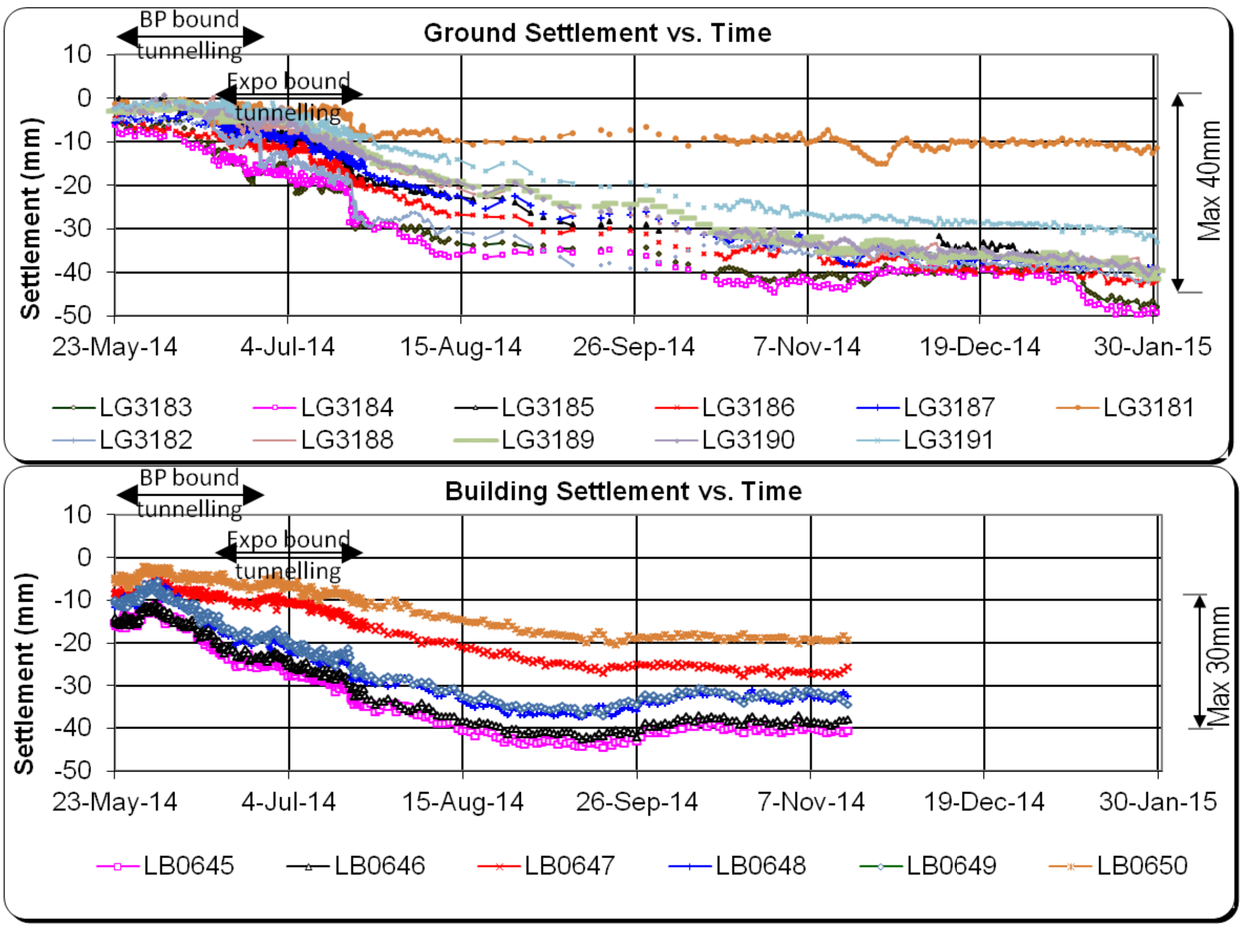

Figure 6. Monitoring of ground and building settlement during tunnelling below Jalan Besar shophouses.

CASE HISTORY B: TUNNELLING BELOW SHOPHOUSES NEAR LAVENDER STREET

The second case history refers to tunnelling directly below a row of conserved shophouses along Lavender Street, just after the proposed Bendemeer station. The shophouses consist of reinforced concrete frame structures supported by micropile and bored pile foundations, with pile lengths ranging from 9 m to 18 m indicated in the as-built drawings. The 2-storey shophouses were built in the 1930s, and further A&A works were done in 1992 to add the attic and the 4-storey rear extension. Figure 7 shows the tunnel alignment with respect to the shop houses where the twin tunnels are in a side-by-side configuration and were constructed using EPB TBMs.

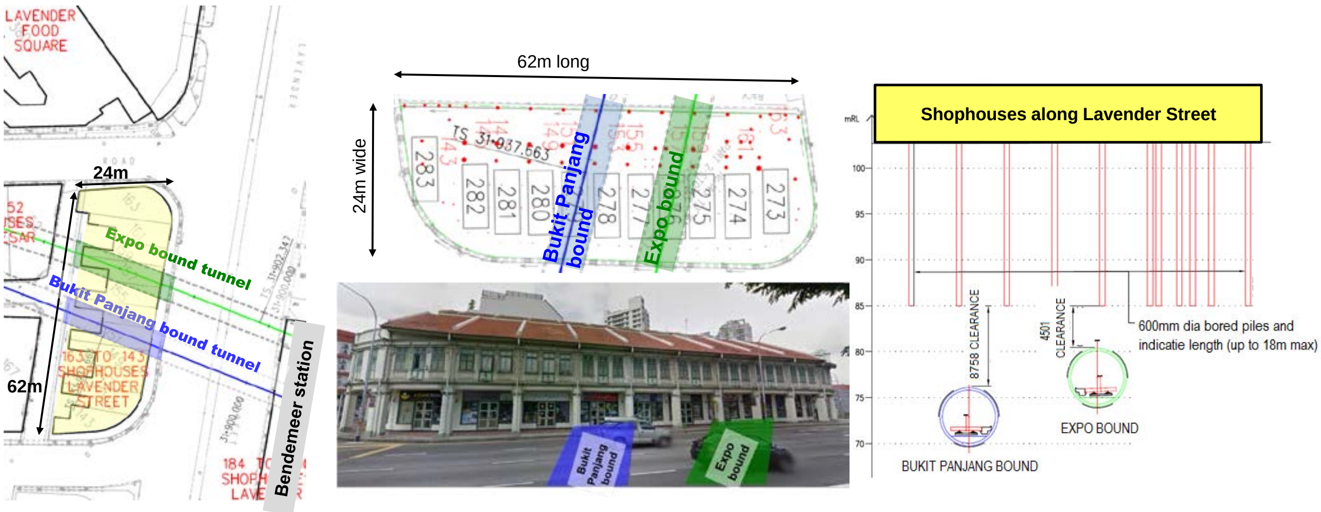

Figure 7. Location map and cross-sectional view of tunnelling directly below shophouses at Lavender Street.

The first tunnel drive directly below the building (Bukit Panjang bound tunnel) took place in July 2013 whilst the second tunnel drive went below the building in September 2013. The tunnels are about 25 m~28 m below ground surface at this location. Based on the as-built information on the lengths of the foundation, the bored tunnels would be about 4.5 m away from the pile foundations for the Expo bound and 8.7 m away for the Bukit Panjang bound. To confirm the as-built information, parallel seismic logging tests were conducted to detect the pile toe and determine the pile length at a few locations. This was done by sending and receiving sound waves through various depths along an adjacent borehole to detect pile toe where there is a change in the reflected waves. Poea et al. (2014) reported the results for one of these tests where the seismic logging showed that the detected pile toe was 13.5 m below ground surface and approximately 9 m clear above the Bukit Panjang bound tunnel.

Figure 8 shows the soil profile encountered in both tunnel drives below the Lavender Street shophouses. Other than the overlying thin layer of Fill and Kallang Formation (of not more than 3 m), the geological formation is predominantly of the Old Alluvium Formation. Specifically, the bored tunnelling was carried out in very competent and unweathered Old Alluvium of SPT-N value greater than 100 blowcounts.

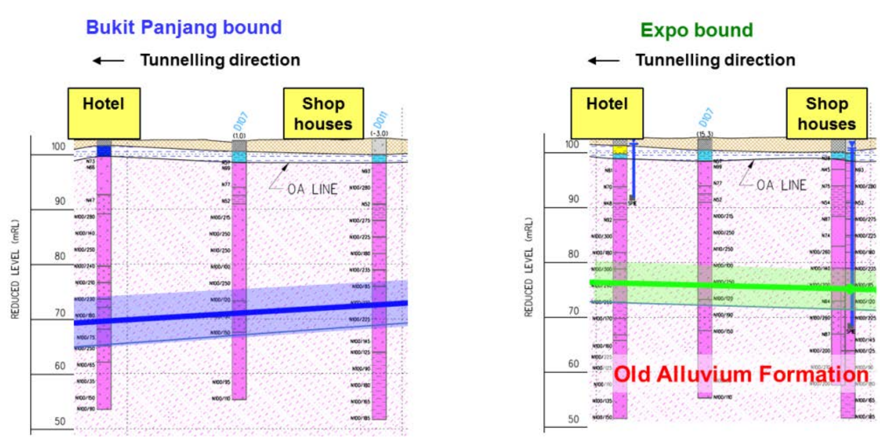

Figure 8. Geological profile of tunnelling directly below Lavender Street shophouses.

During tunnelling, ground settlement markers were installed along Lavender Street whilst building settlement markers were installed along the row of shophouses to monitor the settlement behaviour of the building. As seen in Figure 9, the maximum ground settlement and building settlement during the bored tunnelling works were 10 mm and 7 mm respectively.

The settlement readings were much lower than the settlement readings observed at Jalan Besar, and the low settlement readings can be attributed to better ground deformation control for tunnelling in competent ground conditions. Also, the building settlement was very low even though the foundations are in closer proximity to the face of the bored tunnelling works. That the building settlement is in the same range as the ground settlement, suggests 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.

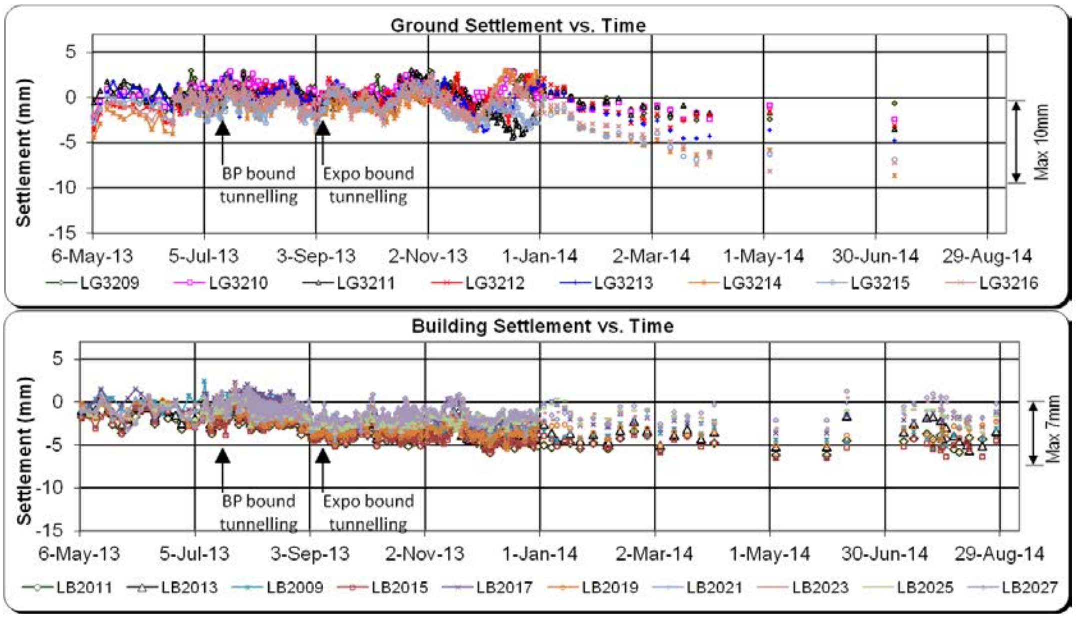

Figure 9. Monitoring of ground and building settlement during tunnelling below Lavender Street shophouses.

Similarly, along the same tunnel drive but about 60 m away from the Lavender Street shophouses, both TBMs also went directly below a 5-storey hotel at Foch Road in a similar ground condition of competent Old Alluvium. This is a newer reinforced concrete structure supported on deep foundation with bored piles (500 mm to 800 mm diameter) that are 12 m to 18 m long. Figure 10 shows the location map and cross-sectional view of the tunnelling in relation to the hotel. Even though the pile clearance above the TBM was much smaller and the pile toe was only 2.6 m away from the tunnels, the maximum building settlement readings monitored was 6 mm. This is consistent with the earlier observation made at Lavender Street where induced settlement of piled buildings can be very small if the ground is competent and tunnelling operations are well-controlled.

Figure 10. Location map and cross-sectional view of tunnelling directly below hotel at Foch Road.

CASE HISTORY C: TUNNELLING BELOW THE NATIONAL MUSEUM OF SINGAPORE

With a rich history dating back to 1887, the National Museum of Singapore is Singapore's oldest museum. It is located at Stamford Road, and was gazetted as National Monument in 1992. The third case history looks at how tunnelling was successfully carried out below such a sensitive structure. Figure 11 shows the tunnel alignment with respect to the National Museum building. The twin bored tunnels were constructed using EPB TBMs, and were driven from Fort Canning Station towards Bencoolen Station. The first tunnel drive was for constructing the Bukit Panjang bound tunnel and went directly below the extension building of the National Museum in February 2014 before undercrossing the National Museum main building. This was followed by the second tunnel drive (Expo bound) which went directly below the National Museum in May 2014.

The National Museum building consists of two blocks primarily, which are the main block building and the extension block. The main block of the museum is a 2-storey masonry building supported on shallow foundation, with some parts that have undergone A&A that are reinforced concrete and supported on piles. The extension block was constructed in 2006 by cutting back the Fort Canning Hill behind the main block. It is a 2-storey reinforced concrete structure with a basement supported by diaphragm walls (1.2 m to 1.5 m thick) and internally supported using a mix of micropiles (250 mm diameter) and bored piles (1.2 m diameter) below a 2 m thick raft. The clear vertical distance between the micropiles and the bored piles from the bored tunnels are 4 m and 10 m respectively, whilst the diaphragm walls are about 16m above the bored tunnels.

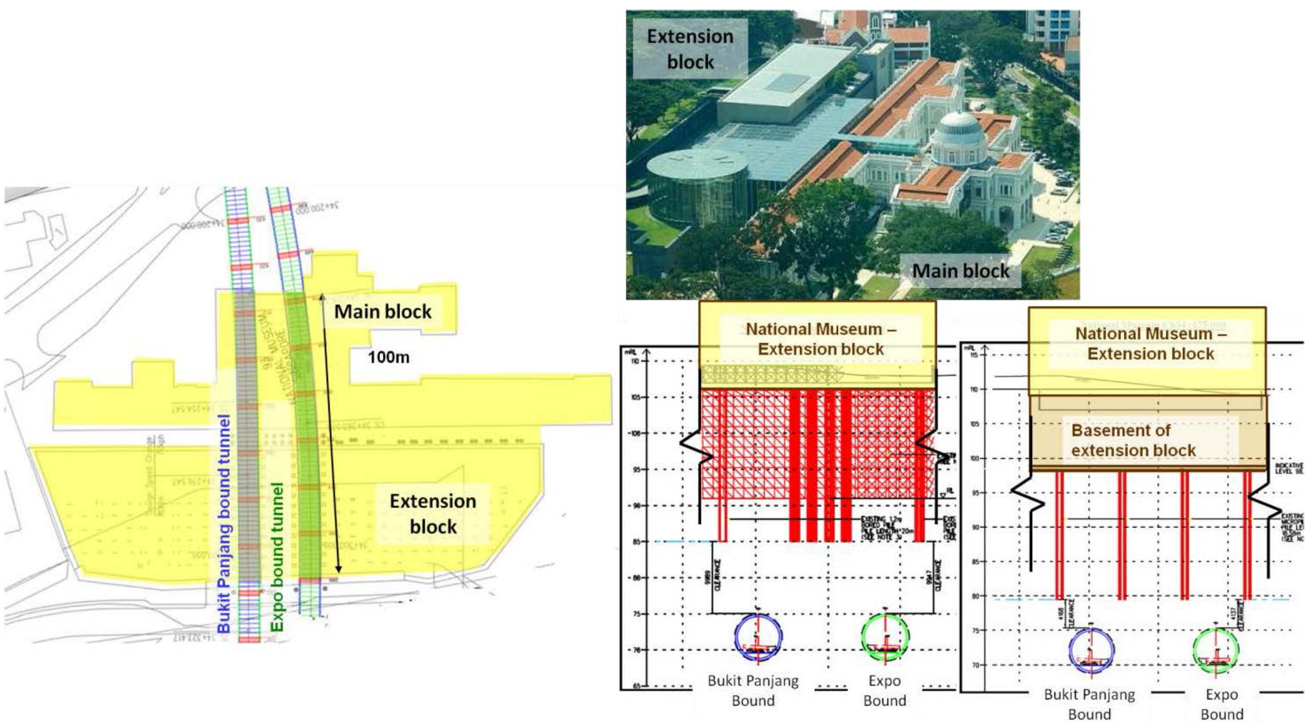

Figure 11. Location map and cross-sectional view of tunnelling directly below the National Museum of Singapore.

Figure 12 shows the soil profile encountered in both tunnel drives below the National Museum. The ground surface level is slightly higher coming down from Fort Canning Hill towards Stamford Road. The soil stratigraphy is characterised by a 40 m to 60 m thick layer of Fort Canning Boulder Bed, overlying the Jurong Formation of various weathering grades. Consequently, the foundations and diaphragm walls of the National Museum are founded within the Fort Canning Boulder Bed material, and both bounds of bored tunnel are also constructed within the boulder bed.

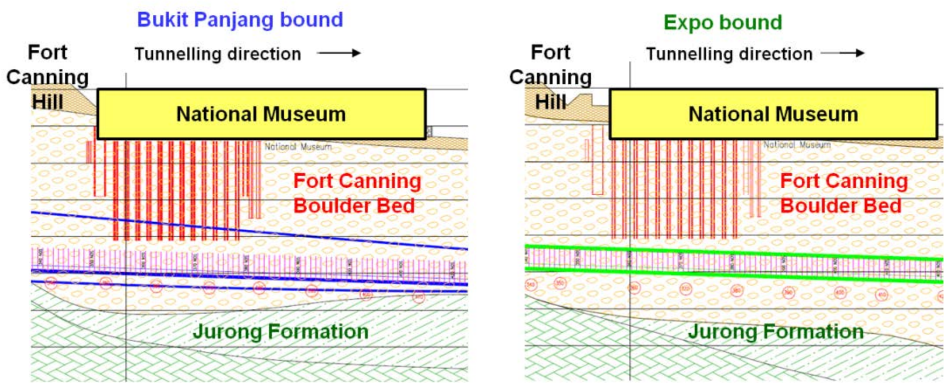

Figure 12. Geological profile of tunnelling directly below the National Museum building.

There was an array of ground settlement markers monitored just before the bored tunnels passed directly below the National Museum on Fort Canning Hill, along with the numerous building settlement markers on both the extension block and the main block of the National Museum. Figure 13 shows the monitoring of ground and building settlement during both tunnelling drives. The maximum ground settlement monitored during tunnelling was 18 mm, which were equally attributable to both drives. The maximum building settlement was only 11 mm, and this is similar to the cases at Lavender Street and Foch Road where the building settlement was very low even though the tunnelling was carried out directly below the foundations. This is another indirect evidence of tunnelling having little impact on the piles supporting the buildings in terms of its settlement behaviour.

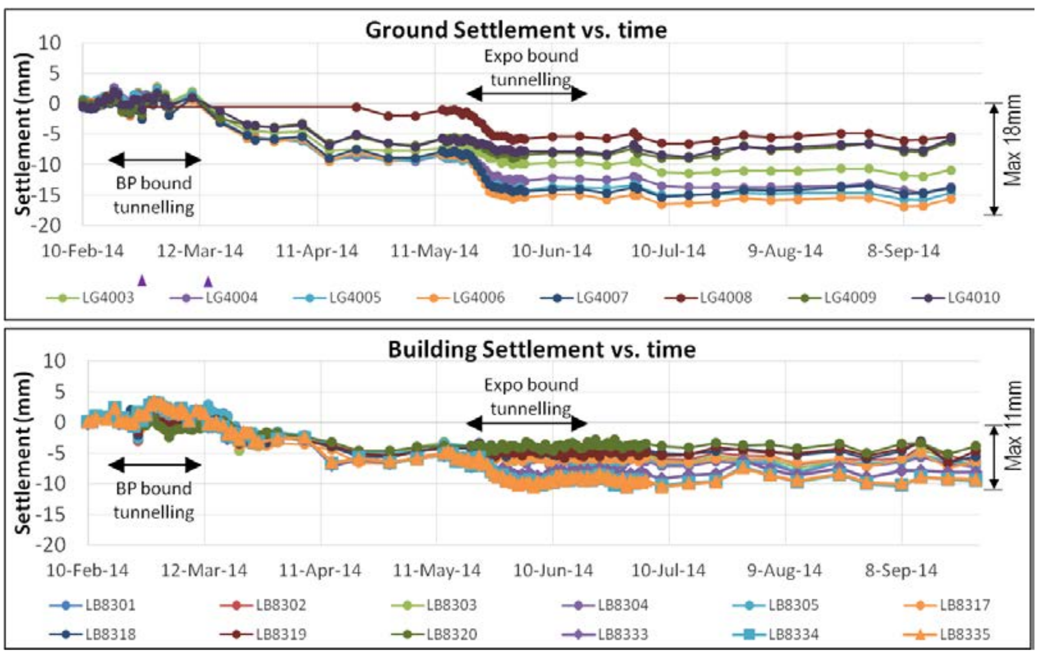

Figure 13. Monitoring of ground and building settlement during tunnelling below the National Museum building.

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 important 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 that tunnelling directly below 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 safety of occupants of the buildings. It is hoped that these case histories would give greater confidence for undertaking future tunnelling developments in such challenging requirements.

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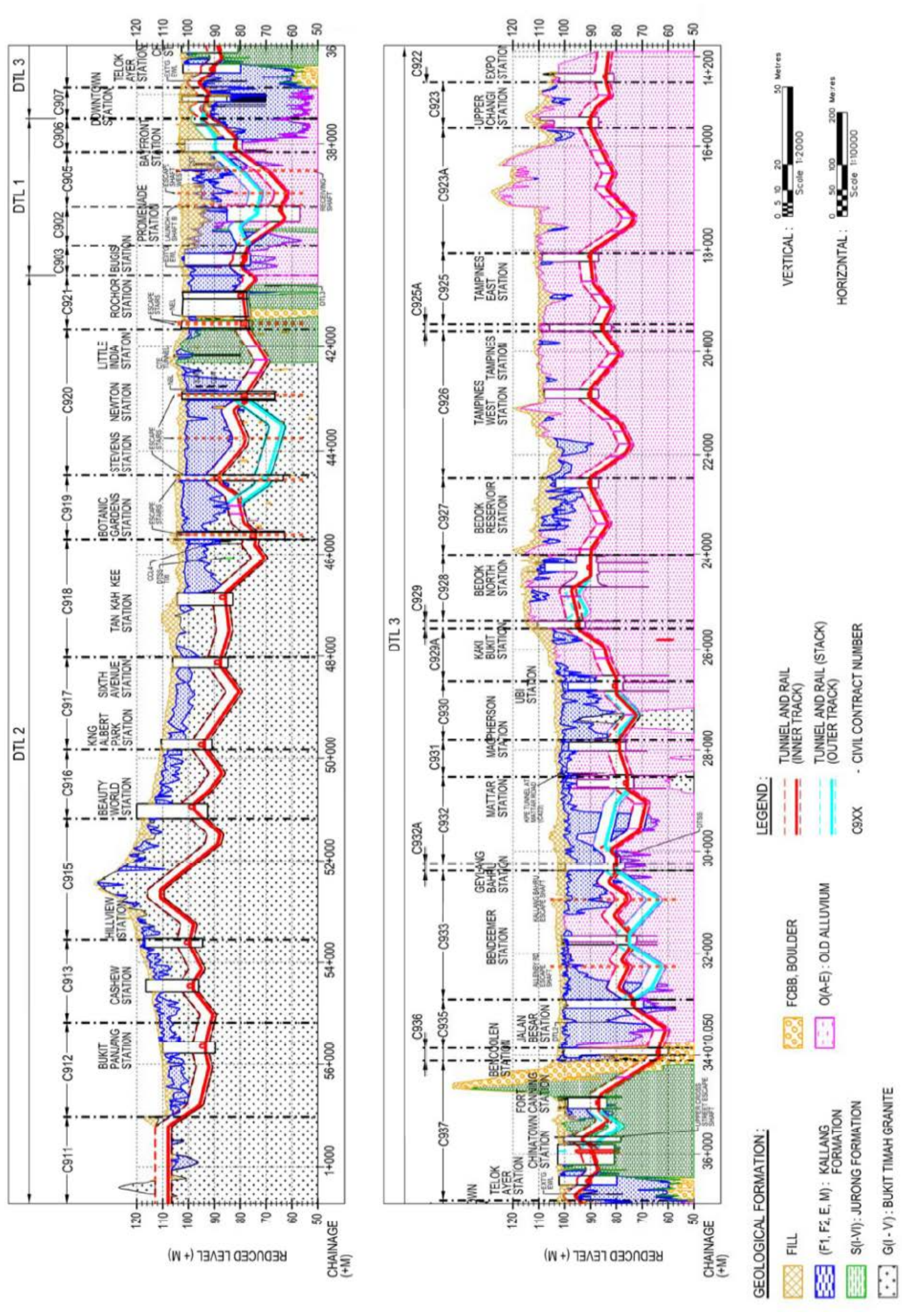
ANNEX A – Longitudinal geological profile along Downtown Line alignment



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