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Singapore Downtown Line 3 - Tunnelling Challenges in Soft Soil and under Conserved Structures

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ABSTRACT: The opening of Downtown Line 3 (DTL3) in October 2017 marked the longest underground and driverless MRT line in Singapore. The complicated technical challenges in DTL3, especially Package A, were associated with the nature of its geological strata and construction of underground infrastructure below existing buildings and structures which were conserved by the Authority to some extent of the alignment. Due to its vertical alignment, tunnelling works in DTL3-A was carried out within the Kallang Formation which was recent deposits consisting of soft/loose soils. At some extent of the alignment, tunnelling works was significantly close to conserved shophouses which were very sensitive to induced settlements. Settlement predictions, risk assessments and mitigation measures were therefore carried out to ensure safety during TBM tunnelling. The monitoring regime and protection measures were successfully implemented with actual ground movements to be well within the design predicted movements. This paper presents some of the technical challenges in DTL3 Package A in relation to tunnelling works in soft soil condition and under conserved shophouses at some extent of the alignment.
Keywords: Downtown Line Stage 3, control tunnelling, face pressure, damage assessment, building protection measures.

1. INTRODUCTION

The Downtown Line (DTL) is the fifth Mass Rail Transit (MRT) line in Singapore and was opened in three stages (i.e. DTL Stage 1, 2 and 3). The opening of DTL3 in October 2017 marks DTL as the longest underground rail line at 42 km with 34 stations. It connects the north-western and central-eastern regions to the downtown of Singapore enhancing linkages between the historic Chinatown and Little India districts of Singapore and enhances access to the historic civic areas of Fort Canning and Jalan Besar district. It is the longest rapid transit line to use completely automated driverless trains.

Figure 1 DTL3 alignment route

Arup was appointed by the Land Transport Authority (LTA) as the lead design consultant to provide Architectural/ Engineering (A/E) Consultancy Services for the 5 km long Downtown Line Stage 3 Package A (DTL3A) comprising of five underground stations running from Chinatown to Kallang Bahru. Details of civil contracts in DTL3A is shown in Table 1.

Table 1 DTL3A Civil Contracts

Contract	Scope	Contractor
C937	Fort Canning Station and Associated Tunnels	GS E & C
C936	Bencoolen Station	Sato Kogyo
C935	Jalan Besar Station and Associated Tunnels	Leighton Offshore – John Holland JV
C933	Bendemeer Stattion and Associated Tunnels	Penta Ocean Construction
C932A	Kallang Bahru Station	China State Construction

This paper presents tunnelling works challenges encountered in DTL3A, particularly ones related to tunnelling in soft soil and under conserved structures.

2. DOWNTOWN LINE 3 PACKAGE A

2.1 Tunnel Alignment

Due to various site constraint along DTL3A alignment, some extent of the bored tunnels configuration have to apply stacked arrangement before transitioning to parallel one at the station interfaces. This arrangement is quite prominent in Contract C933 where the tunnelling works needs to be carried out in a very close proximity to quite a number of sensitive structures along Jalan Besar area. The depth of tunnel to its axis is in the range of 16.5 m to 38 m.

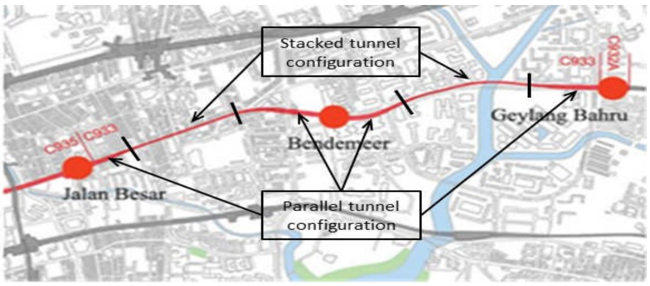

Figure 2 DTL3A – C933 alignment layout

2.2 Geological Condition

The geological condition encountered in DTL3A tunnelling works is summarised in Table 2.

Table 2 DTL3A Geological Conditions along Tunnel Alignment

Contract	Geology at Tunnel Face
C937	Kallang Formation, Jurong Formation and FCBB
C935	Kallang Formation, Old Alluvium and FCBB
C933	Kallang Formation and Old Alluvium

At some of the alignment extent, tunnelling works will encounter full face of Kallang Formation beneath the made ground along DTL3A, notably in Contract C933. Underlying the Kallang Formation is the Old Alluvium formation. The Kallang Formation soils itself comprise the marine clay, fluvial sand, fluvial clay and estuarine clay. Marine clays notably present at Jalan Besat and Kallang Bahru area, sandwiching the fluvial sand and/or fluvial clay layers. The existence of both upper and lower marine clays are found at Jalan Besar area.

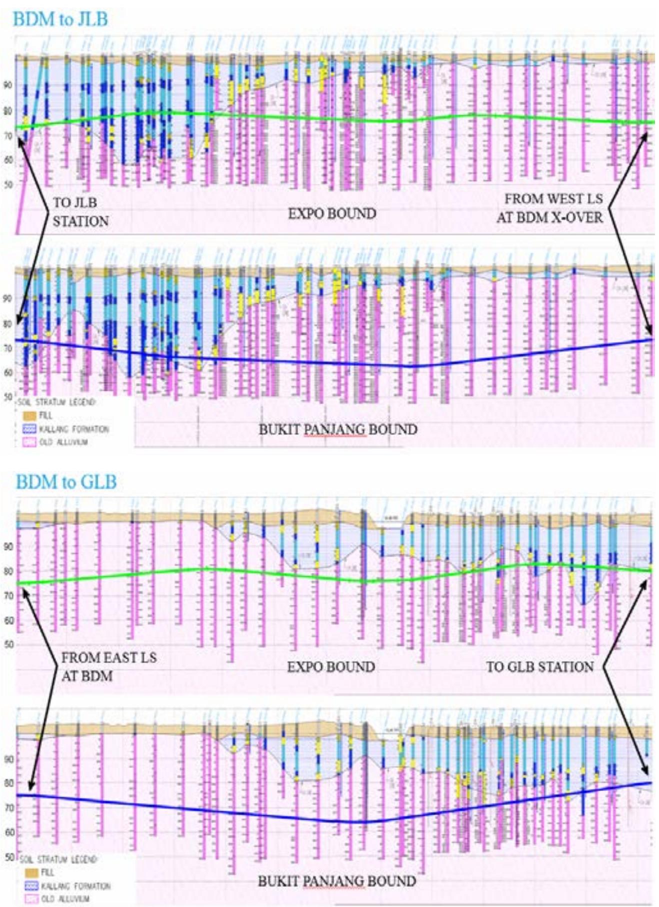

Figure 3 Geological profile along DTL3A – C933 bored tunnel

2.3 Bored Tunnel Segmental Lining

In general, the bored tunnels are lined with 1.4 m-wide, 275 mm-thick precast segment, incorporating Grade 8.8 M24 bolts at both segment to segment joint and ring to ring joint.

Table 3 DTL3A Segment Reinforcement and Erector System

Item	C937 & C935	C933
Precast Segment	Reinforced Concrete (RC)	Steel Fibre Reinforced Concrete (SFRC) in general; Hybrid Reinforced Concrete @ tunnel opening and close tunnel proximity
Segment Erector System	Mechanical Erector	Vacuum Erector

3. TUNNELLING IN SOFT SOIL

3.1 Control Tunnelling

A total of four Earth Pressure Balance (EPB) TBMs were deployed to perform the tunnelling works in DTL3A Contract C933 covering approximately 4 km tunnel drives. The face pressure of EPB TBM is maintained by proper combination of propulsion thrust and removal of muck at the correct rate matching the TBM advance rate. As highlighted by Shirlaw et al (2013), TBM face pressure has to be applied at all times to prevent face collapse during tunnelling in Kallang Formation. Furthermore, a face pressure provision in the range of 0.9 to 1.2 total overburden pressure will also reduce the potential settlements during the tunnelling particularly in this soft soil condition. The target TBM face pressures for each tunnel bound and drive are shown in Figure 4.

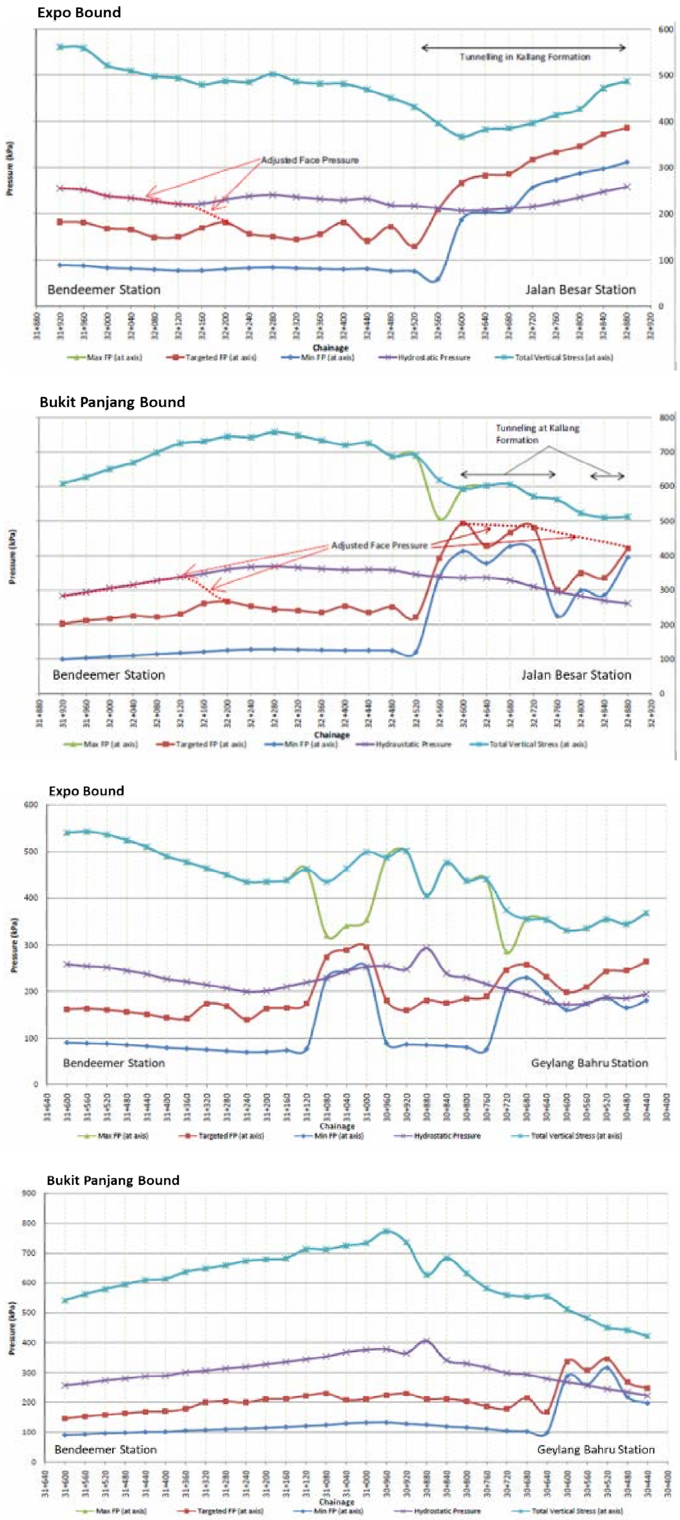

Figure 4 Target TBM face pressure in DTL3A Contract C933

3.2 TBM Specifications

One specific requirement on EPB TBM in DTL3A is that they have to be equipped with an automatic face control (AFC) system where bentonite slurry will be automatically pumped into the cutter head pressure chamber to compensate for deficiencies in the face support pressure, i.e. when pressure at the tunnel face drops below the agreed minimum target face pressure and maintain minimum pressure in the plenum chamber independently of the shield jacks, screw rotation or other soil conditioning system. This system will ensure that no loss of face pressure will be encountered resulting in excessive ground movement during TBM excavation.

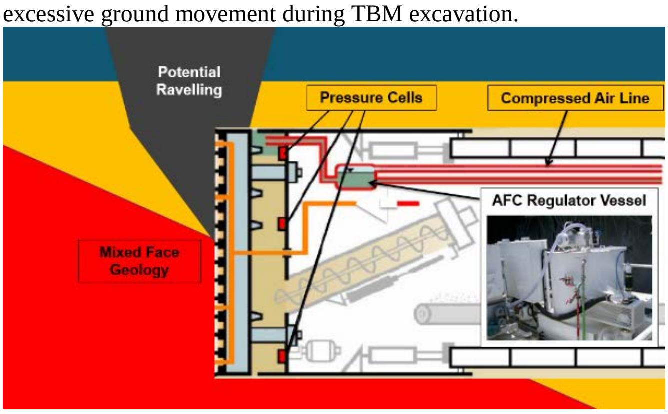

Figure 5 AFC schematic diagram inside EPB TBM

4. TUNNELLING UNDER CONSERVED STRUCTURES

4.1 Old Shophouse Along Jalan Besar

In Contract C933 and C935, DTL3A tunnel alignment runs below Jalan Besar, one of the area safeguarded as conservation districts under Secondary Settlement category by the Urban Redevelopment Authority (URA). The area is located outside the central city district developed after the end of World War I and have established its own distinct identities over time. The shophouses sandwiching the tunnel alignment are two- to four-storeys high, built in contiguous blocks with common party walls in the late 19th & early 20th centuries and traditionally designed to provide for business premises on the ground floor and residential accommodation on the upper storeys. The shophouses architecture styles comprise of Late, Transitional and Art Deco styles.

Other characteristic of these shophouses is the distinct five-foot way feature, indented into the ground floor of shophouses from the road with overhanging upper floors, serving as a sheltered space for social activities and circulation.

Case study on the tunnelling works under conserved shophouses has been highlighted by Poea, et. al. (2014).

4.2. Damage Assessments

The empirical prediction of ground movements due to bored tunneling works assumed transverse ground settlement profile above a single tunnel is of normal probability distribution curve, or Gaussian form which generally produce a greenfield settlement trough. The ground displacement is assumed to occur at constant volume, specified as a 'volume ground loss' at the tunnel. For multiple tunnels effect, the movements induced by each tunnel can be superimposed. Better prediction of ground movements can be carried out using advanced methods of numerical analyses, based on the finite element method, such as Plaxis and Oasys FREW computer programs.

The LTA Civil Design Criteria for Road and Rail Transit Systems prescribes a three-staged approach to the assessment of damage to buildings for ground movements due to deep excavation and tunneling as shown in Figure 6.

The first stage applies a very simple and conservative approach for the preliminary assessment. Ground surface settlement contours along the alignment can be determined to filter all buildings experiencing a maximum slope of 1:500 and a settlement of less than 10 mm. This approach is quite conservative as it neglects any interaction between the stiffness of the buildings and the ground.

In the second stage, the building is represented by a simple beam whose foundations are assumed to follow the displacement of the ground in accordance with the greenfield site assumption. The maximum resultant tensile strains are calculated for both the hogging and sagging settlements. This result is then plotted on the relevant interaction diagram of deflection ratio versus horizontal strains. The resultant damage category is compared to the building damage classification table first put forward by Burland et al. (1977) as shown in Table 4.

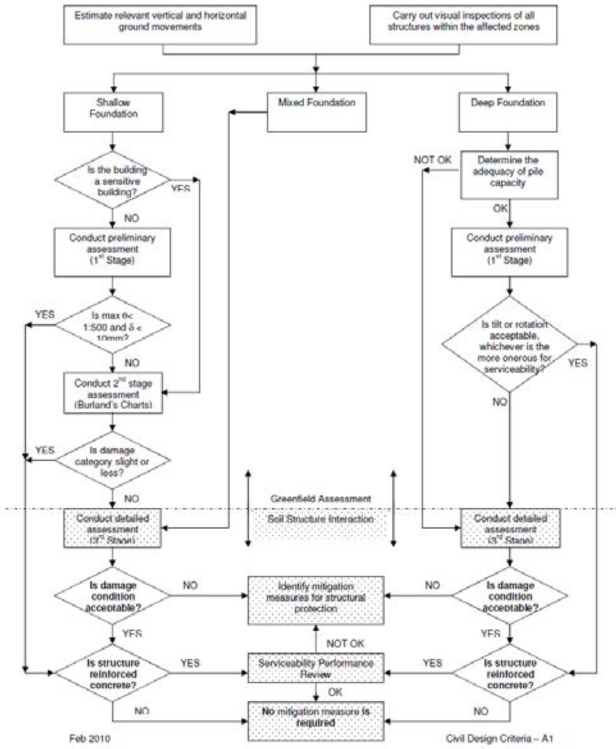

Figure 6 Damage assessment methodology to buildings

The third stage evaluation of the structure will be carried out if the building damage assessment is not satisfactory after the second stage assessment, considering more factors such as: soil structure interaction, structural continuity, foundation systems, construction sequence, orientation to alignment, etc.

Table 4 Building Damage Classification after Burland et. al.

Building damage classification (for masonry walls, cladding and finishes)			
Predicted degree of damage	**Description of damage**	**Approximate width of cracks (mm)**	**Limiting tensile strain (%)**
0 Negligible	Hairline cracks	< 0.1	0 to 0.05
1 Very slight	Fine cracks that are easily treated during normal decoration. Damage generally restricted to internal wall finishes. Close inspection may reveal some cracks in external brickwork or masonry.	0.1 to 1	0.05 to 0.075
2 Slight	Cracks easily filled. Redecoration probably required. Recurrent cracks can be masked by suitable linings. Cracks may be visible externally and some repointing may be required to ensure weather-tightness. Doors and windows may stick slightly.	1 to 5	0.075 to 0.15

Building damage classification (for masonry walls, cladding and finishes)			
Predicted degree of damage	**Description of damage**	**Approximate width of cracks (mm)**	**Limiting tensile strain (%)**
3 Moderate	The cracks may require some opening up and can be patched by a mason. Repointing of external brickwork and possibly a small amount of brickwork may need to be replaced. Doors and windows sticking. Service pipes may fracture. Weather tightness often impaired.	5 to 15 or several cracks > 3mm	0.15 to 0.3
4 Severe	Extensive repair work involving breaking-out and replacing sections of walls, especially over doors and windows. Windows and door frames distorted, floor sloping noticeably. Walls leaning or bulging noticeably, some loss of bearing in beams. Service pipes disrupted.	15 to 25 but also depends on number of cracks	> 0.3
5 Very Severe	This requires a major repair job involving partial or complete rebuilding. Beams lose bearing; walls lean badly and require shoring. Windows broken with distortion. Danger of instability	> 25mm but also depends on number of cracks	

The greenfield surface and sub-surface ground movements due to tunnelling works were predicted after which each building along the alignment was assessed for possible building damage based on the described methodology above.

Table 5 Building Damage Assessment Summary in DTL3A

DA Stage	**C937**	**C935**	**C933**
2nd Stage	14 buildings pass	81 buildings pass	25 buildings pass
3rd Stage	-	11 buildings pass	13 buildings pass

4.3. Site Investigation

At some occasion, foundation detection works (i.e. seismic logging and trial pit) needs to be carried out as part of investigation works in order to verify the type of foundation and to ascertain whether it impedes the TBM tunnel construction.

A typical seismic logging set-up and test result are shown in Figure 7 and Figure 8, respectively. Based on the logging test result, the toe level of bored pile was estimated at13.5m below ground level, approximately 9 m above the tunnel.

Figure 9 shows trial pit involving a careful mining process to expose the foundation. Existence of bakau pile foundations was found confirming foundations were of shallow type and will not impede the tunnel construction.

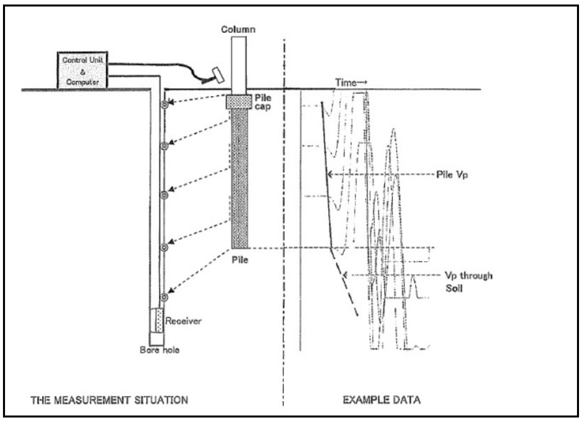

Figure 7 Seismic logging set-up

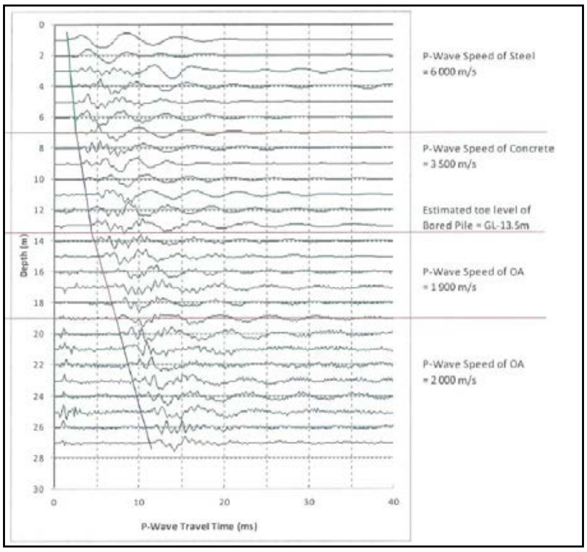

Figure 8 Seismic logging result

Figure 9 Trial Pit

4.4. Protection Measures

Building protection measures were installed for conserved shophouses along Jalan Besar area that did not pass the damage assessment criteria. The reason of these buildings not passing the damage assessment criteria was often due to the differential settlement between five-foot way façade and the rest of the building. The adopted strategy was then to allow the differential settlement and install adjustable props to stabilize the five-foot way façade and provide tie beams at first floor level to anchor the base of the five-foot way façade to the main building. Extensive instrumentation and monitoring regime was implemented to facilitate better observation on the affected structures. A typical arrangement for building protection propping is shown in Figure 10.

Figure 10 Typical arrangement for building protection propping

Based on visual inspection report, a number of shophouses were found to be in poor condition. The defects recorded included very large structural cracks and large areas of concrete spalling. Fot these particular shophouses, enhanced strengthening and protection works were installed prior to commencement of the bored tunnelling works.


Figure 11 Typical enhanced external building protection measures

In addition to the building protection measures, temporary five-foot way propping system was installed to restrain potential differential movement of the five-foot way columns as shown in Figure 12, comprising of a steel casing wrapped around the five-foot way column joined to a steel frame that was then tied into the existing shophouse frontage.


Figure 12 Five-foot way protection system

4.5. Instrumentation & Monitoring

Instrumentation comprising of strain gauges was installed to the building protection proppings for close monitoring of the loadings in the propping systems. Two sensors were installed at the instrumented props to measure the strain values. The load carried by the props was estimated by the changes in strain values using the following formula:

$$\varepsilon_{strain\ (ave)} = [\varepsilon_{(sensor1)} + \varepsilon_{(sensor2)}] / 2 \quad (1)$$

$$\Delta\varepsilon_{raw} = \varepsilon_{strain\ initial\ (ave)} - \varepsilon_{strain(ave)} \quad (2)$$

$$\Delta\varepsilon = \Delta\varepsilon_{raw} * \text{calibration factor} \quad (3)$$

$$\text{Load (F)} = \Delta\varepsilon * E * \text{Area} \quad (4)$$

where E= Young's Modulus of structural steel (i.e. 205 GPa)

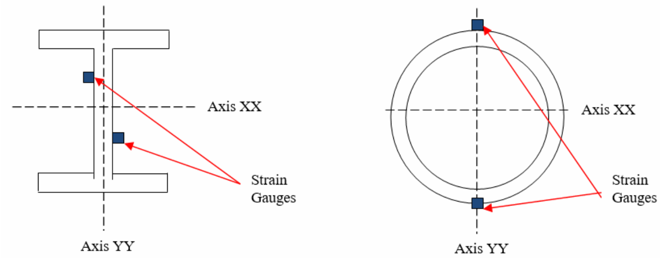

Figure 13 Typical Strain Gauges Arrangement

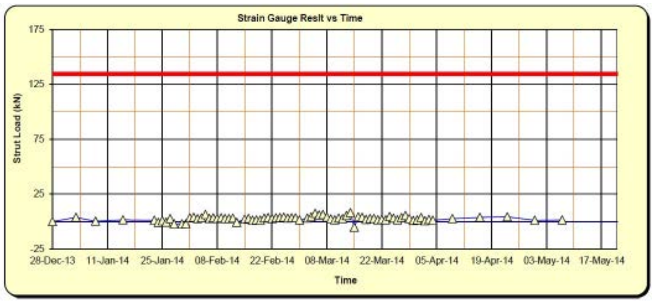

Figure 14 Plot of strain gauge at one of the prop

As shown in Figure 14, the loading in the one of the shophouses at Jalan Besar was quite insignificant during the period when TBM tunnelling works was carried out. This result trend was found to be consistent for the shophouses along Jalan Besar and Lavender Street.

5. CONCLUSION

Tunnelling in soft ground and under conserved structures pose its own challenges and complications. Proper design, planning (including site investigation, mitigation measures & specifications) and execution prove to be the decisive factors that allows tunnelling works to be successfully completed without causing significant impact to any of the existing structures in the vicinity.

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