Field Performance of Twin Bored Tunnelling in Different Geological Conditions – Construction of MRT Downtown Line 3 in Singapore

Thiri Su, Yunhuo Zhang, Kok Hun Goh

Geotechnical & Tunnels, Land Transport Authority, Singapore, SU_Thiri@lta.gov.sg

ABSTRACT: The construction of several underground railway lines in Singapore over the recent years has yielded useful field data on the ground response to tunnelling works. This paper presents the field performance of twin bored tunnelling from one of the major Mass Rapid Transit (MRT) lines called Downtown Line (DTL). The construction of DTL was planned in 3 stages, DTL1, DTL2, and DTL3 which were constructed under several different contracts. The paper mainly focuses on the study of ground responses associated with closed-face tunnelling under different geological conditions along the DTL3 tunnel alignment. Settlement monitoring data measured during the drive of twin bored tunnels were reviewed and accessed with respect to the recorded soil response to the tunnelling. The resulted volume losses and findings on the ground responses under different geological conditions are discussed. The review and field information presented in this paper will also be utilised as a reference for future MRT line constructions and design.

KEYWORDS: tunnelling, ground response, geological conditions, Downtown Line.

1 INTRODUCTION

The 42km long Downtown Line (DTL) is the fifth and the longest automated underground metro in Singapore. With 34 MRT stations including 10 interchange stations, DTL targeted to expand the rail networks from the North-Western to Central area and Eastern regions of Singapore. The last construction phase, DTL3, forms the eastern part of DTL and covers about half of the total DTL route. DTL3 will be connecting Central to Eastern area of Singapore. It comprises of 16 stations including three major interchange stations. The construction was planned for 6 years (2011 to 2017). The map of MRT Downtown line in Singapore including the respective stations of DTL3 is shown in Figure 1.

Figure 1. Map of MRT Downtown Line in Singapore

1.1 Tunnel Configuration Along the DTL3 Alignment

Construction of DTL3 was implemented under 18 civil contracts in which 12 contracts involved closed face Tunnel Boring Machine (TBM) works. Earth Pressure Balance Machine (EPBM) TBMs were used for underground tunnelling works in all DTL3 contracts. There are two tunnel bounds named Bukit Panjang Bound and Expo Bound. The twin TBMs started in parallel configuration and formed the double stacked tunnels at some parts of the central area. The typical tunnel diameter is 6.6m. Along the tunnel alignment, tunnel depth to tunnel horizontal axis (H) varies from 16m to 55m below ground level in Bukit Panjang Bound and 8m to 55m in Expo Bound. Being built through highly developed urban areas, there are a few number of scenarios where the tunnel alignment passes directly underneath or very close to existing structures and foundations.

Table 1 summarized the tunnel specifications and geological conditions encountered at each civil construction contracts in DTL3 MRT construction. Details of the TBM features was reported by Zhang et. al. 2014.

Table 1. Tunnel specification and geological condition at DTL3

Civil Contract	*Soil Condition*	*D_o (mm)*	*L (m)*	*Tunnel-Tunnel Configuration*	*x (m)*	*H (m)*
923	*OA*	*6630*	*1026*	*Parallel*	*15*	*18-26*
923A	*OA*	*6720*	*4750*	*Parallel*	*11-15*	*16-44*
925	*OA*	*6630*	*1600*	*Parallel*	*14-24*	*17-29*
926	*KF, OA*	*6720*	*5240*	*Parallel*	*10-18*	*19-30*
927	*KF, OA*	*6650*	*2653*	*Parallel*	*14-33*	*19-28*
928	*OA*	*6700*	*1450*	*Parallel*	*11-20*	*17-24*
929A	*KF,OA*	*6640*	*2110*	*Parallel*	*19-24*	*17-22*
930	*KF, OA, G*	*6720*	*942*	*Parallel*	*8-18*	*22-30*
931	*OA*	*6350*	*928*	*Parallel*	*16-65*	*21-27*
932	*KF, OA*	*6630*	*1354*	*Parallel/ Double Stacked*	*6-18*	*17-31*
933	*KF, OA*	*6630*	*4495*	*Parallel/ Double Stacked*	*0-15*	*18-39*
935	*KF, OA*	*6660*	*775*	*Parallel*	*13-22*	*27-39*
937	*KF, FCBB, S*	*6650/ 6630*	*1800*	*Parallel/ Double Stacked*	*0-22*	*8-55*

Note: D_o - Tunnel outer diameter, L - Tunnel drive length, x - Centre to centre distance between two tunnels, H- Tunnel depth, G- Bukit Timah Granite Formation, S- Jurong Formation, FCBB- Fort Canning Boulder Bed, OA- Old Alluvium, KF- Kallang Formation.

1.2 Geological Condition

In Singapore, there are five major types of geology namely Bukit Timah Granite Formation (G), Jurong Formation (S), Old Alluvium (OA), Kallang Formation (KF) and Fort Canning Boulder Bed (FCBB). The Bukit Timah Granite Formation is the earliest formation of Singapore, and was believed to form about 200 to 250 million years ago. This formation is found in the central and northern region of Singapore. Jurong Formation of sedimentary rock origin is normally composed of sandstone, mudstone, limestone, dolomite and shale. Deposition was formed about 175 to 235 million years ago. It is distributed along the western and southern part of Singapore. In this formation, severely folded or faulted formations are usually found due to weathering. Old Alluvium which was formed in 0.5 to 5 million years ago is the sediments deposited by river basin and located around the eastern region. It is composed of stiff clayey sand including pebbles and has abrasive in nature due to the composition of quartz. Kallang Formation is the latest formation in Singapore deposited about 0.14 million years ago in river valleys and low-lying land area, coastal region and offshore line. It generally comprises of Marine clay, organic peaty clay, fluvial clay, fluvial sand and beach sand. The deposit is highly undulating and often deeply infilled inside valleys above older formations. The Fort Canning Boulder Bed, a colluvial deposit comprising of sandstone matrix boulders with sandy clay or sandy silt is located in the central region of Singapore.

All these types of major geological formations were encountered along the DTL3 MRT tunnel route. The geological map and sub-soil geological profile of the proposed tunnel alignment are shown in Figure 2 and 3. As can be seen, the tunnel alignment is predominately within Old Alluvium in the eastern area. Towards the central area, localized valleys of soft soil deposits of Kallang Formation were encountered overlying Old Alluvium. A typical depth of Kallang Formation in DTL 3 varies from 2 m to 42 m below ground level. The top layer consists of 2.0m to 2.5m of sandy fill. There are few locations where tunnel alignment passed through FCBB, Jurong and Bukit Timah Granite Formation in the central area. A number of mixed-face soil conditions were found at the interface of two different soil media such as the interface of Old Alluvium and the Kallang deposits, the interface of Granite residual soil and Old Alluvium and the interface of FCBB and Jurong Formation.

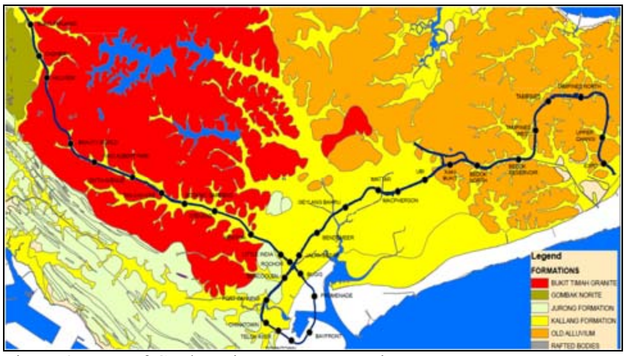


Figure 2. Map of Geology in DTL construction

Despite all the soil types being encountered along DTL3 alignment, the study will focus mainly on OA, KF and mixed-face of KF and OA due to the higher soil percentage encountered at the tunnel face.

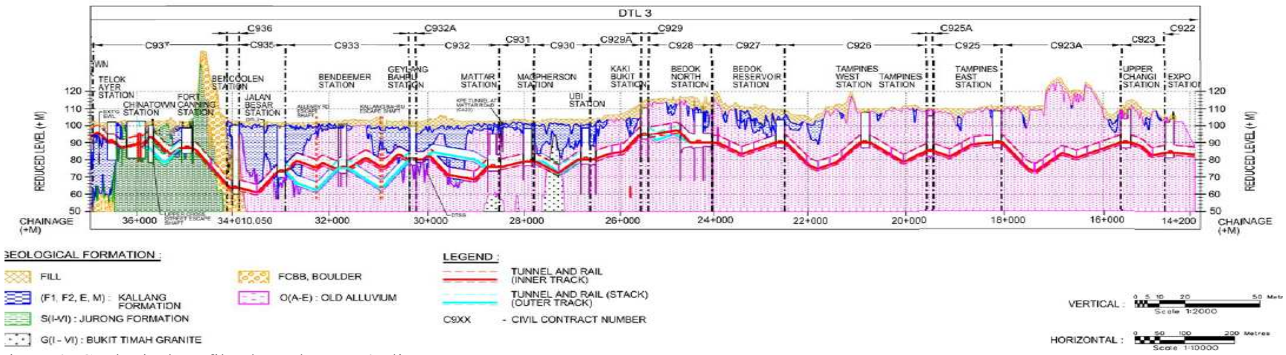


Figure 3. Geological profile along the DTL3 alignment

2. FIELD MONITORING PROGRAMME

Extensive instrumentation and monitoring arrays were installed along the tunnel alignment. The provision of monitoring arrays and instruments generally follows the guidelines of Land Transport Authority (LTA) Civil Design Criteria (CDC). At least one settlement maker was provided at the top of the tunnel alignment at every 25m intervals. A series of ground settlement markers commonly known as settlement arrays were installed perpendicular to the tunnel alignment for the assessment of transverse surface settlement profile. More than 200 numbers of arrays were installed along the stretch of tunnel drive over the 21km long which means every 100 m interval of settlement arrays in average.

In addition to ground settlement markers, several arrays of instruments were installed which include in-soil inclinometers, magnetic and rod extensometers for monitoring of soil movements and water standpipes and piezometers for monitoring of pore pressure responses. Since this study is focused on the ground settlement behavior due to tunnelling, the surface settlement results will mainly be reviewed and discussed.

3. GROUND SETTLEMENT READINGS

3.1 Tunnelling in Old Alluvium and Kallang Formation

The typical trend of settlement development with time is plotted in Figure 4 mainly for two geological conditions; tunnelling in KF and tunnelling in OA. The presented field data were collected from the surface settlement points installed directly above the double stacked tunnels between Bendemeer and Jalan Besar Station, where the tunnels were driven from OA to KF. The respective locations and TBM passing dates of each settlement points are shown in Table 2.

Table 2. Settlement markers location and tunnel passing dates

Settlement Marker ID	Chainage (m)	Tunnel Passing Date	
		BP	EX
LG3107	32+525	18/03/2014	19/04/2014
LG3108	32+536	23/03/2014	25/04/2014
LG3109	32+549	03/04/2014	26/04/2014
LG3110	32+561	23/04/2014	28/04/2014
LG3111	32+574	24/04/2014	29/04/2014
LG3112	32+585	25/04/2014	30/04/2014
LG3113	32+597	26/04/2014	03/05/2014
LG3114	32+610	27/04/2014	04/05/2014

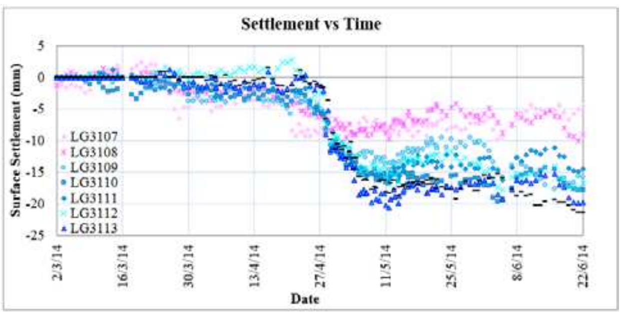
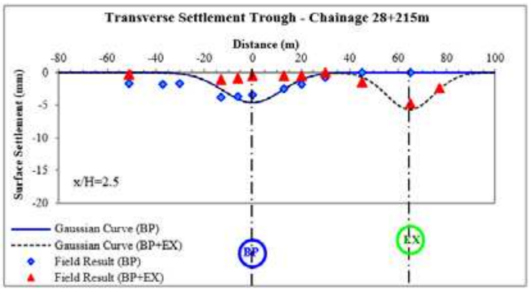


Figure 4 Settlement developed with time between Bendemeer and Jalan Besar Station

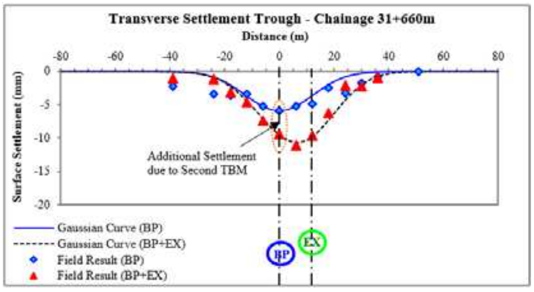
Generally, comparatively small responses were observed in Old Alluvium. When the tunnels are driven entirely in OA without KF above, the recorded surface settlement right above the tunnel centre line varies from 2mm to 8mm for single tunnel and 3mm to 15mm for twin tunnels. The volume loss derived from the best fitted Gaussian curve are in the ranges of 0.2% to 1.2%. These values are found to be reasonably consistent with typical volume loss recommended in LTA CDC which is about 0.5% for single tunnel and 1% for twin tunnel. As for generalized trend of surface settlement, it was noticed that surface settlement started to occur when the TBM reached 3D (D=tunnel diameter) distance before the array location. The settlement increased as the TBM advanced and was observed to stabilize when the TBM passed 3D to 5D distance beyond the monitoring point. In some occasions, while TBM approaching to the monitoring array, heaving was recorded before the settlement. Owing to the face pressure used to control the face stability, this heaving is fairly common in closed face TBM operation.

Figure 5 shows the comparison of transverse settlement troughs resulted by twin tunnels with different tunnel positions. Different plots are shown for different center to center distances between two tunnels; 65m, 12m and 0m. Settlement values are taken at 5D distance after the TBM passed through the monitoring array (5D is considered to be the stabilized point beyond which there is no further increment in immediate settlement). Gaussian curve is also plotted for a comparison with field data. It can be seen that the transverse surface settlements reasonably follow Gaussian Curve. The principle of superposition equation from empirical formula (O'Reilly & New, 1982) is also found to be applicable in twin tunnel cases. The settlement due to twin TBMs in general is the combination of settlement caused by the first and second TBM. These additional settlements caused by second TBM becomes significant at the first TBM location when the two tunnel alignments become closer. As shown in Figure 5a, only 4mm and 5mm of settlements were recorded due to parallel tunnels with x=65m (i.e., x=2.5H). However, in double stacked tunnel case, the settlement of 5mm was observed after the first tunnel had passed and another 5mm after the second tunnel, resulting in a total settlement of 10mm (Figure 5c).

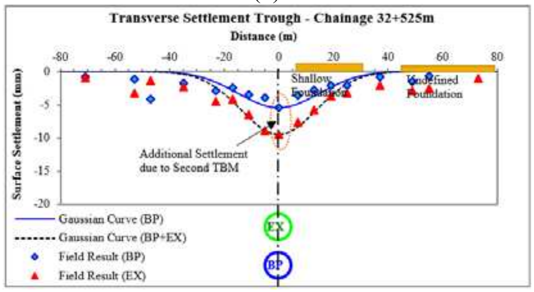
As expected, bigger soil responses were experienced when TBM drive continued in Kallang Formation. Higher range of settlement up to about 15mm was recorded after single drive and total surface settlement up to 30 mm was recorded after twin TBM drive. The associated volume losses for TBM drive through KF is as high as 3%. This is in good agreement with the published values, as reported by Shirlaw et al. (2003) who stated that volume losses in Kallang Formation vary within the range of 1.4 to 4% based on the measured data from North-East MRT line construction.



(a)



(b)



(c)

Figure 5. Transverse settlement profiles due to tunnelling in Old Alluvium (a) x=65m, (b) x=12m, (c) x=0m

3.2 *Tunnelling in Mixed-Face of Old Alluvium and Kallang Formation*

A number of mixed-face of Old Alluvium and Kallang Formation occurred in Contract C932, C933 and C935. The effect of tunnelling under mixed-face condition can be captured in field monitoring data. Generally, the results showed significant settlement when the tunnel approaches the mixed soil zone. This changing state of settlement from OA to KF can be clearly seen in the settlement plots of Figure 4. The settlement in OA was about 8mm in average and the settlement increased with the TBMs location approaching to mixed-face zone where most of the readings ranged from 12mm to 18mm after the passage of two TBMs.

The measured transverse surface settlement troughs from monitoring array at chainage 32+610m, plotted together with Gaussian distribution curves is shown in Figure 6.

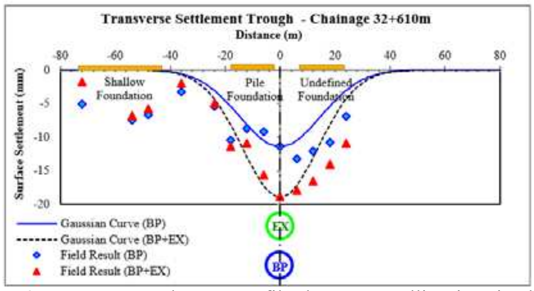


Figure 6 Transverse settlement profile due to tunnelling in mixed-face soil area

About 2% volume loss calculated based on fitted Gaussian curve is recorded when the Bukit Panjang bound tunnel (BP) passed through the mixed soil location. Approximate volume loss of 0.6% was recorded when the Expo tunnel bound (EX) was driven under the Marine Clay and Fluvial Clay (F2) location. Since the tunnel alignments are located at highly built-up area, some of the surface settlement points are affected by the presence of adjacent foundations and structures. Larger settlements are recorded below the shallow foundations whereas the presence of pile foundation resulted in shallower settlement points.

3.3 *Maximum Settlement Observed in DTL3 projects*

Figure 7 below shows the plots of maximum settlement experienced in each ground settlement arrays installed along the DTL3 alignment. Generally, the geological condition encountered along the alignment can significantly attribute to the shapes and magnitude of longitudinal settlement. From the overall review of field data, surface settlement due to tunnelling entirely in OA was about 15mm for twin TBMs drive. The settlement increased up to about 20mm in Old Alluvium with Kallang Formation above and 30mm in Kallang Formation and up to 60mm in mixed-face soil zone. It is also worth to note that dramatic changes in tunnelling medium from hard to soft soil medium at the tunnel face can induce high localized settlement as well. The significantly higher settlements usually occurred when TBMs approached to mixed-face of KF and OA zones. Over the mixed-face zone, the OA cover above the tunnel gradually decreased and the settlement increased accordingly. The increment of settlement over this transition zone can be up to 4 times of settlement occurred at the mixed-face of OA and KF. Therefore, it is also recommended that pro-active actions and proper control of face pressure and other operating factors should be carefully undertaken well ahead of the expected mixed-face location. The available information from factual SI data may not be accurate enough to capture the actual mixed-face location at tunnel face and insufficient application of face pressure can result in higher chance of localized settlement. Whilst higher settlement values recorded in contracts C926 and C927 were partly due to mixed face condition, there were some occasions where other factors such as tunnel operating parameters, workmanship and construction activities nearby are likely to attribute to the higher localized settlement results.

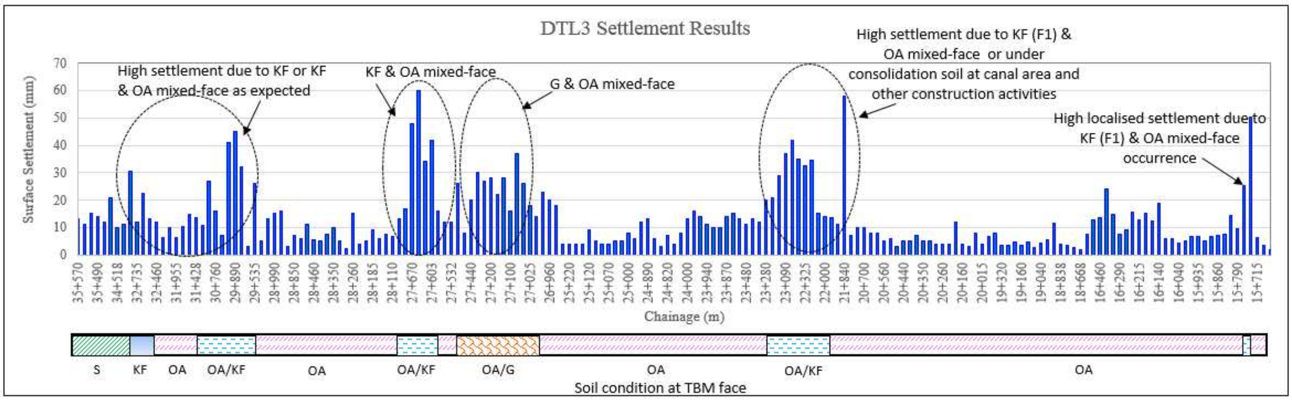


Figure 7 Maximum surface settlements at DTL3 project

4 CONCLUSION

The construction of bored tunnels for DTL3 MRT line had been successfully completed without causing major damage to the existing structures and foundations. The movements and volume losses were well controlled with the carefully chosen face pressure and tunnel operating parameters. Volume losses were well controlled less than 3.5% in most cases of Kallang mixed soil types. For tunnelling in Old Alluvium without Kallang Formation above, volume loss was even less than 0.7% with the use of EPB machines. Volume losses less than 1.6% were obtained for Old Alluvium with Kallang Formation above. These successful completion was achieved by the detailed and prudent planning, design and execution of the various project parties' members. Proper site investigations should be carried out to locate the mixed-face and to determine the engineering properties of the various soil layers. TBM Key Operating Parameters needs to be well designed and most important is properly executed so as to ensure the ground movement and volume loss due to tunnelling is controlled to the minimum.

Despite the study in this paper mainly focus on the tunnelling case in OA, KF and mixed-face of OA and KF which are the main geologies encountered in DTL3, other types of geological conditions were also encountered along the whole DTL MRT route, based on which, further studies can be explored for better understating of different soil behavior with respect to different tunnel positions as well as to different geological conditions.

5 ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to DTL3 project teams and GDIS team from Geotechnical and Tunnel division, Land Transport Authority of Singapore for providing the required tunnel information and field instrumentation data of the projects.

6 REFERENCES

LTA (2010): Civil design criteria for road and rail transit systems, Land Transport Authority, Singapore.

Ong C.W., Ee J. P., Thiri Su, Yong K. Y. Kulaindran A. 2015. A case study of twin bored tunnelling under mixed-face soil - Bendemeer MRT station project, Downtown Line 3, Singapore. Japanese Geotechnical Society Special Publication, Vol.2 (2), 176-181.

Ong C.W., Thiri Su, Yong K.Y., Kulaindran A. 2014. Understanding of soil responses due to tunnelling-3D numerical analysis and case study of Bendemeer Station (DTL-3) Singapore. Proceedings of the ISSMGE Technical Committee 207 International Conference on Geotechnical Engineering. 16-18 June 2014, Saint Petersburg.

O'Reilly M.P. and New B.M.1982. Settlements above tunnels in the United Kingdom - their magnitude and prediction. Tunnelling '82, Inst. Mining & Metallurgy, London, p. 173-188.

Zhang Y.H., Cham W.M., Kumarasamy J. 2011. Volume loss caused by tunnelling of Circle Line projects. Underground Singapore 2011, Singapore, p. 114-121.

Zhang Y.H., Kumarasamy J., Wen D., Hoblyn S., Ho K.S. 2014. Tunnel boring machines (TBM) and TBM tunneling for the Downtown Line. Underground Singapore 2014, Singapore.