Productivity analysis of diaphragm wall construction in Jurong Formation

Mark Smith
Land Transport Authority, Singapore

ABSTRACT: Diaphragm walls are widely used in Singapore as the earth retaining structure for basements, tunnels, stations, and other underground infrastructure. Construction of the diaphragm wall is often a programme critical activity with high preliminary costs, therefore any improvements in productivity can provide both time and cost savings. This paper analyses 274no. diaphragm wall construction records from Land Transport Authority (LTA) Contract 885 – Construction of Prince Edward Road Station and Tunnels for Circle Line 6 – to assess the effect of panel geometry on productivity and overbreak. It is hoped that this information may be applied to improve productivity and reduce waste during diaphragm wall construction. The study also provides typical production rates for each stage of diaphragm wall construction which may be used as a planning tool for future projects. The user should note that the findings are derived from a single project constructed in Jurong Formation, and they may not be directly applicable to other projects with different geology.

1. INTRODUCTION

A diaphragm wall is a type of earth retaining structure typically used for basements, tunnels and deep excavations. It is a reinforced concrete wall that is cast in sections (or panels) within an excavated trench. The trench is temporarily supported by a stabilising fluid during the excavation process, which is then displaced during the placement of concrete.

As a foundation element, construction of the diaphragm wall is often a programme critical activity, preceding excavation of the basement or construction of the superstructure. It is also an activity with high preliminary costs due to the large specialist plant required during construction. A better understanding of diaphragm wall productivity can therefore offer both programme and cost benefits.

This paper provides an empirical analysis of the diaphragm wall construction records from Prince Edward Road Station (LTA Contract 885) with two objectives:

1) Assess the effect of panel geometry (length, thickness, depth) on productivity to provide improved planning tools for diaphragm wall construction in Jurong Formation; and,
2) Reduce waste by identifying the variables that contribute to increased panel overbreak.

Overbreak is the term used to describe the caving of loosened material along the edge of an excavation. During diaphragm wall construction, the volume of over-excavated material is replaced with concrete during the casting process. This excess concrete is not required in the structural design and can be considered redundant. Whilst not a direct measure of productivity, overbreak should be considered a wasteful and unproductive activity – incurring additional time and cost to dispose of the over-excavated material, and again when replaced with the equivalent volume of concrete.

To allow a reliable comparison of the data, all construction records are from the same project, undertaken by a single specialist contractor using the same construction method, and with similar ground conditions throughout.

2. PROJECT DESCRIPTION

2.1 General description

Circle line 6 (CCL6) is a fully underground Mass Rapid Transit (MRT) System currently under construction in Central Singapore. It comprises three stations with a route length of approximately 4km; once completed, CCL6 will close the Circle Line loop by connecting HarbourFront Station and Marina Bay Station (Figure 1).

Contract 885 (C885) comprises the construction of Prince Edward Road Station (PER), cut and cover tunnels extending towards Marina Bay Station, bored tunnels to the adjacent Cantonment Station and a tunnel escape shaft. The contract was awarded to China Railway Tunnel Group Co. Ltd (Singapore Branch) in October 2017.

PER is a three level underground station located to the east of Shenton Way, and north of Keppel Road. The station is 297m in length, up to 48m wide, and 28m deep; it has two entrances, located on either side of Shenton Way. Construction of the diaphragm walls and barrette piles was subcontracted to Bachy Soletanche Singapore Pte Ltd.

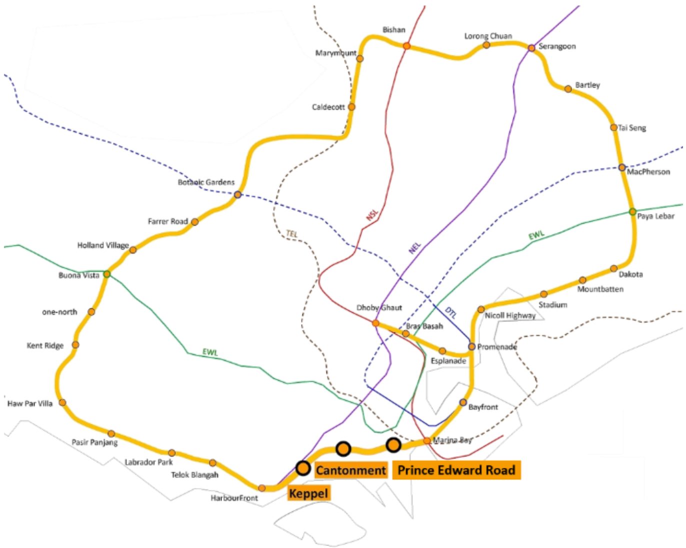

Figure 1- Location of CCL6 and PER (Image source: LTA)

2.2 Geotechnical site conditions

Figure 2 show the geological profile for Prince Edward Road Station from the available bore logs. The ground conditions consist of 1m to 10m of Fill (gravels, rock fragments, organic matter, other foreign material), overlaying Kallang Formation up to 12m thick (Estuarine Clay, Fluvial Clay, Marine Clay), including some pockets of sand (F1). Beneath the Kallang Formation is residual soil (SVI) and completely weathered rock (SV) of the Jurong Formation, extending more than 30m deep in some

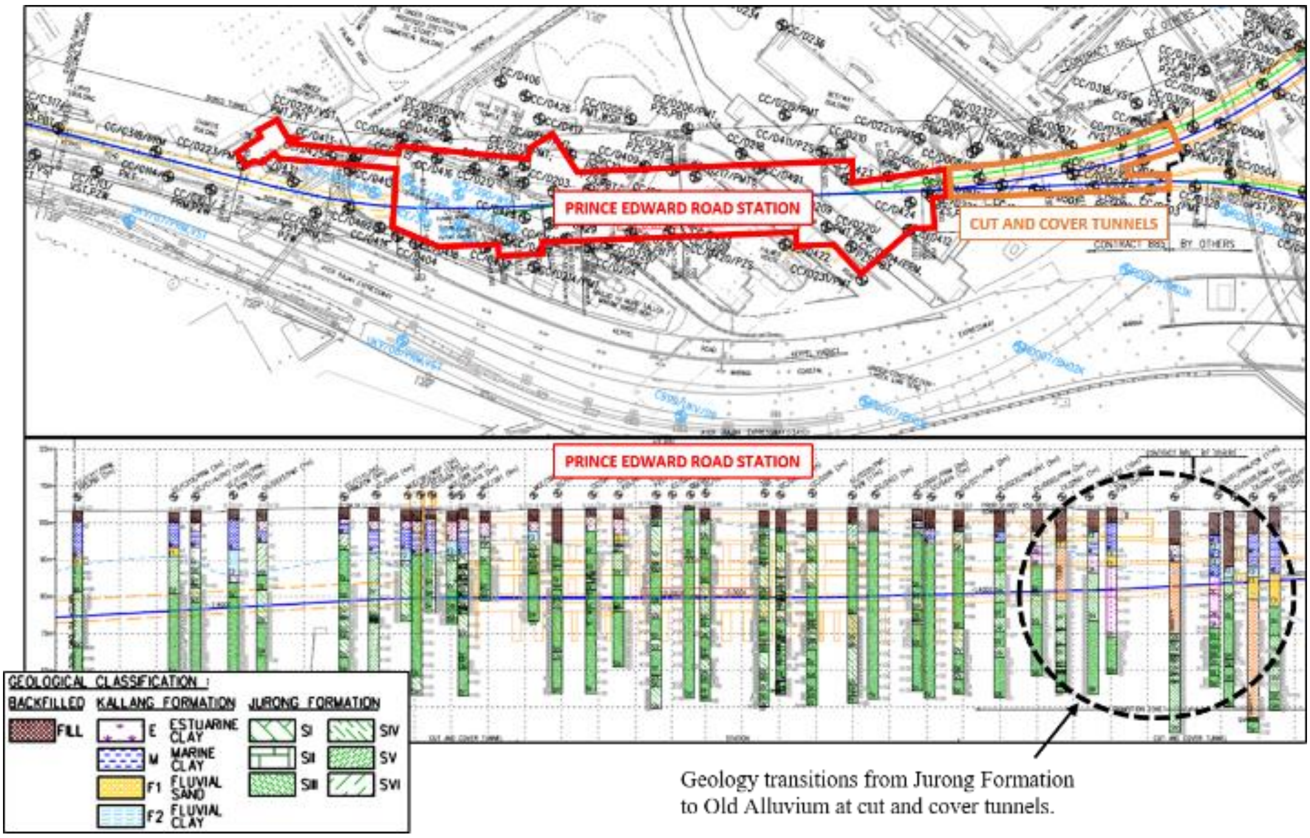

Figure 2- Prince Edward Road Station geological profile

places[1]. The location of the highly and moderately weathered siltstone/sandstone (SIV & SIII) varies considerably across the station and was found from depths of 10m below ground level. The bore log information is consistent with the conditions experience during diaphragm wall excavation, with highly variable and irregular rock conditions encountered throughout the site.

C885 includes the construction of 126m of cut and cover tunnels extending to the east of the station. The geology changes in this area as the Jurong Formation transitions to Old Alluvium, with Fort Canning Boulder Beds (FCBB) identified in some bore logs. To allow a reliable comparison of the data, the diaphragm wall construction records from the cut and cover tunnels are not included in this study.

2.3 Construction Process

A simplified illustration of the diaphragm construction process is shown in Figure 3; the main construction stages being as follows:

- Construction of guide-wall,
- Excavation of trench,
- De-sanding of bentonite support fluid,
- Installation of reinforcement cage,
- Placement of concrete.

The construction of guide-walls is not considered in this study as it can be undertaken independently and is usually not a programme critical activity.

For PER, mechanical and hydraulic grabs were used to excavate the soft ground (Fill and Kallang Formation), and reverse circulation trench cutters (hydrofraise) were used to excavate the rock mass. All excavation tools (grabs and hydrofraises) were 2.8m in length, and sized to match the diaphragm wall thickness, e.g. tool widths ranged from 0.8-1.5m. Where necessary, chisels were used to remove hard ground and to trim the excavation profile.

The panel layout was developed by the diaphragm wall specialist, however the project specification limited to the maximum panel length to 6.0m; with 3.0m panels specified near to sensitive structures.

Steel stop-ends were temporarily installed between all panels to a depth of 3m below the station base slab. Stop-ends were used to improve the joint quality and facilitate the installation of water-stops between panels.

As diaphragm wall works are considered to be a safety critical activity, they were undertaken on a 24hr schedule and the construction process was continuous once excavation had commenced. The quality of the diaphragm walls adhered to the requirements stipulated in the LTA's Material and Workmanship Specification.[3]

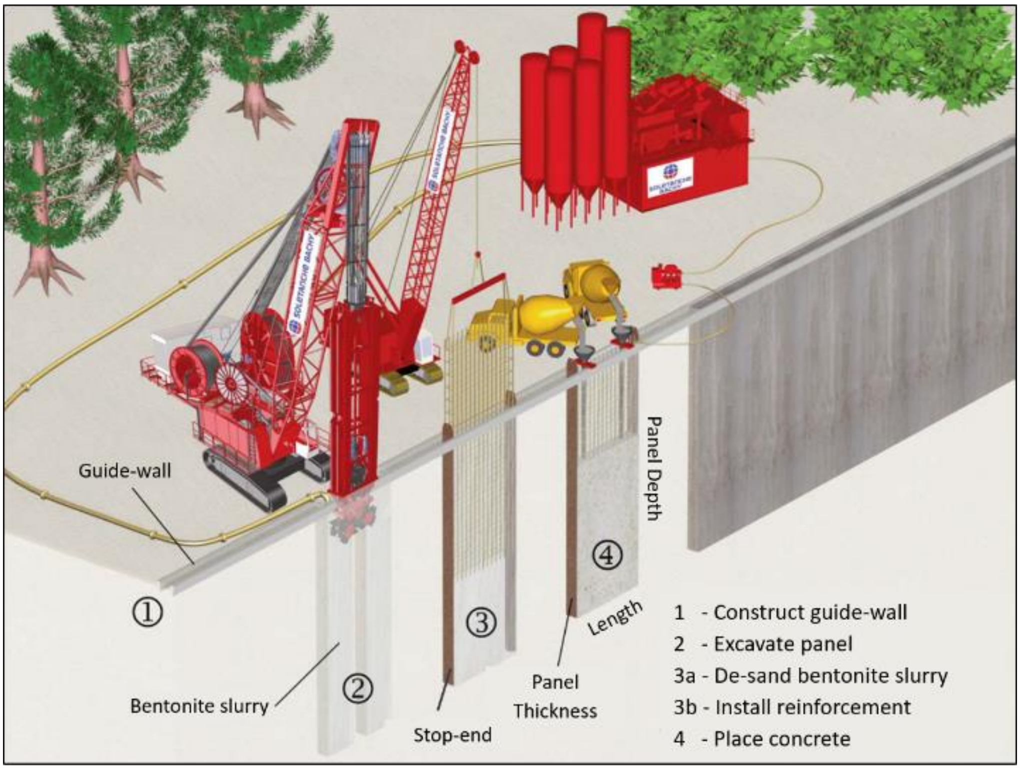

Figure 3- Illustration of diaphragm wall construction stages (Image source: Soletanche Bachy [2])

2.4 Data Set

The construction process for barrette piles differs slightly from that of a diaphragm wall panel, therefore the construction records for barrette piles are not included in this study. Similarly, irregular shaped diaphragm wall panels used to form corners and intersections have been excluded from the study as these are known to have increased overbreak[4].

Prince Edward Road Station includes 1587 linear meters of diaphragm wall and barrette piles. At the time of study, these works were approximately 90% complete. Allowing for the above exclusions, this provided a sample size of 274 panels, with the following data ranges:

- Panel length: 2.8m to 6.0m
- Panel thickness: 0.8m to 1.5m
- Excavation depth: 19.6m to 74.3m
- Theoretical excavation volume: 44m^3 to 586m^3
- Weight of reinforcement: 9.9t to 138.1t

Construction records are produced by the specialist and then verified by the Main Contractor, Resident Technical Officer, and LTA staff.

3. PRODUCTIVITY ANALYSIS

The productivity rates have been compiled for the four diaphragm wall construction stages: trench excavation, de-sanding of bentonite slurry, installation of reinforcement, and placement of concrete.

3.1 Trench Excavation

Trench excavation is considered to be the critical activity in the diaphragm wall construction process[5]. For programming and resource planning, productivity is typically measured in linear meters per day – i.e. the length of wall that each rig can excavate within a 24hr period. As this is common practice within the industry, the following assessment uses linear meters per day (m/day) to measure productivity.

To assess the effect of panel thickness on excavation duration, production rates were compared for 1.2m and 1.5m thick panels of depths 45-50m – providing a sample size of 105 panels (Figure 4). A similar comparison was carried out for 0.8m, 1.0m and 1.2m thick panels of depths 20-25m – providing a further sample size of 39 panels (Figure 5).

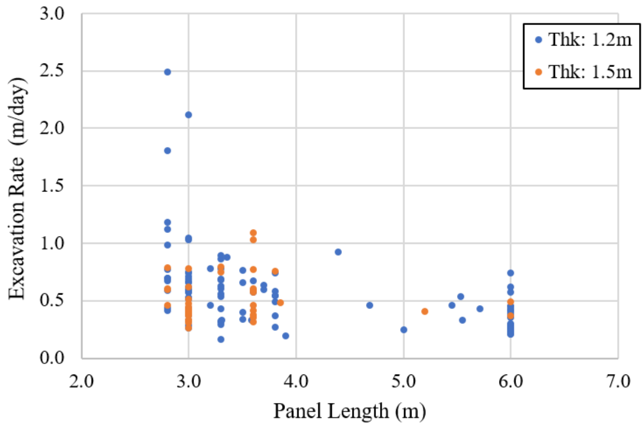

Figure 4 - Trench excavation rate (linear meters per day) for panel depths 45-50m, panel thickness 1.2m & 1.5m

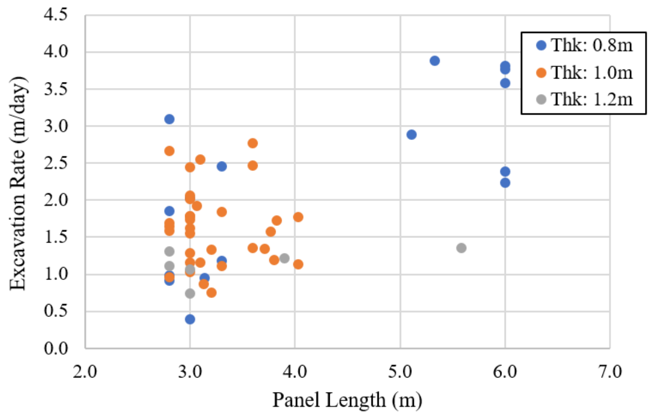

Figure 5 - Trench excavation rate (linear meters per day) for panel depths 20-25m, panel thickness 0.8m, 1.0m & 1.2m

In both sample groups, the data does not support a strong correlation between diaphragm wall thickness and the excavation rate. Whilst some individual construction records and anecdotal evidence suggests that increasing panel width may reduce the excavation rate, it is deemed not to have a significant effect in this data set. This may be because the excavation tools were sized appropriately to match the wall thickness i.e. a 1.5m wide grab/cutter was used to excavate a 1.5m thick trench.

By assuming that panel thickness has an insignificant impact on excavation rate, the relative effect of panel length and depth may be compared. Table 1 shows the average trench excavation rates categorised by panel length and depth, the table also shows the sample size of each group.

The data shows a general trend of excavation rates decreasing with increased panel depth; however, the change is most significant between shallow panels (20-25m), and panels over 37m deep. Average excavation rates dropped from 1.5-2.6m/day for panels 20-25m in depth, to 0.3-0.7m/day for panels over 37m in depth. Whilst the shallow panels are

	Panel Length = 3m		Panel Length = 4m		Panel Length = 5m		Panel Length = 6m	
Panel Depth (m)	No of panels	Excavation Rate (m/day)	No of panels	Excavation Rate (m/day)	No of panels	Excavation Rate (m/day)	No of panels	Excavation Rate (m/day)
20-25	37	1.5	10	1.7	2	3.4	6	2.9
37-42	13	0.7	5	0.7	0	-	0	-
45-50	92	0.6	32	0.6	4	0.4	30	0.4
61-66	11	0.4	2	0.3	2	0.4	23	0.6
70-75	4	0.3	0	-	0	-	1	0.7

Table 1 – Average diaphragm wall excavation rates (linear meters per day) categorised by panel length and depth

predominantly founded in soft ground, the data suggests that productivity is significantly reduced when excavating the rock below. For PER, typically the rock becomes less weathered with depth, increasing in strength and density, and resulting in longer excavation times. However, the specialist also reported that the variability of the Jurong Formation at PER reduced productivity. The hydrofraise uses three different types of cutting attachments depending on the rock strength and consistency; as the ground conditions vary between SV, SIV and SIII, time is lost changing between these different cutting attachments.

For shallow diaphragm wall panels (20-25m) the productivity increases considerably as panel length increases – averaging 1.5m/day for 3m panels, rising to 2.9m/day for 6m panels. This may be attributed to the time taken to install and remove stop-ends at the panel joints, an activity that is proportionately more frequent for shorter panel lengths. This trend is less prominent for deeper panels where stop-end installation/removal contributes less to the excavation duration.

The average trench excavation rate for Prince Edward Road Station was 0.8m linear meters per day.

3.2 *De-sanding of Bentonite Slurry*

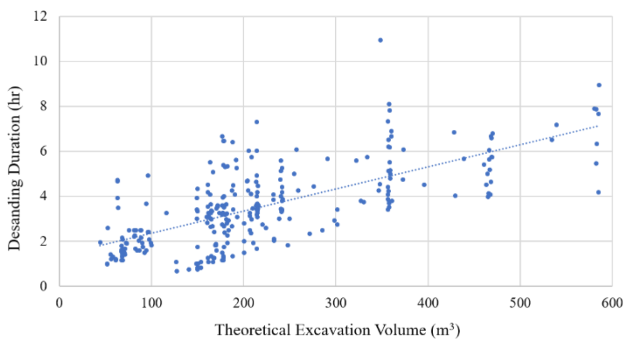

Figure 6- Duration of de-sanding process by panel volume

The data suggests a linear relationship between the panel volume – taken as the theoretical excavation volume – and the duration taken to complete the de-sanding process (Figure 6).

For PER, the de-sanding rate appears to have been determined by the pump and plant capacity used to process the bentonite slurry. As a planning tool, it may be assumed that the de-sanding duration is directly proportional to volume and is not affected by panel geometry.

3.3 *Installation of Reinforcement*

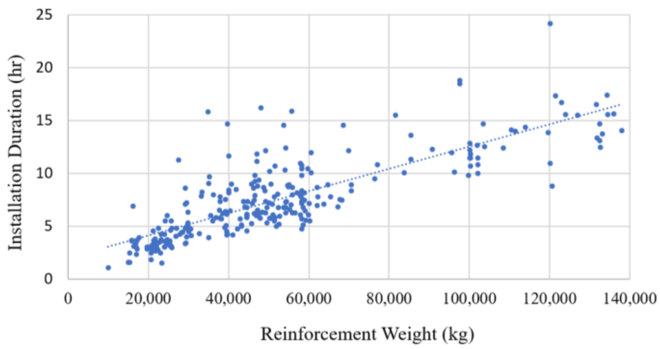

Figure 7- Duration of reinforcement installation by cage weight

The relationship between reinforcement weight and installation duration is shown in Figure 7.

As a planning tool, it may be assumed that the installation duration is directly proportional to the total reinforcement weight. For example, a 100t reinforcement cage is likely to take 10-14hours to install.

3.4 *Placement of Concrete*

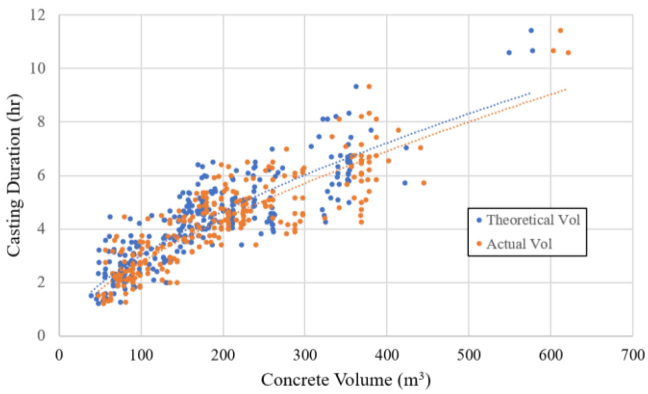

Figure 8 - Duration of casting by concrete volume

The duration taken to place concrete within each panel is shown in Figure 8. The blue data series shows the theoretical concrete volume based on the panel geometry, the orange data series is the actual volume of concrete used; the difference between these two sets of data represents the volume of overbreak with the panel.

The data shows a non-linear relationship between volume and the duration taken to place the concrete, with larger panels achieving a faster casting rate. This is because several tremie pipes can be inserted into longer panels allowing multiple concrete trucks to discharge simultaneously. For PER, typically two tremie pipes were inserted into panels over 4m in length, thus increasing the rate of concrete placement. For irregular shaped panels, such as corners and intersections, it is sometimes necessary to install three or more tremie pipes[6], however this was not required at PER.

4. OVERBREAK ANALYSIS

Overbreak is not a direct measure of productivity; however increased overbreak results in additional spoil excavation, more bentonite slurry to be processed, and increased concrete volume. The following analysis will study the effect of panel thickness, length, depth and excavation duration on overbreak.

4.1 Panel Thickness

To assess the effect of panel thickness, the overbreak volumes were compared for panels of similar length and depth (Table 2).

	Panel Thickness = 1.2m		Panel Thickness = 1.5m	
Panel Length (m)	No of panels	Overbreak volume (m^3)	No of panels	Overbreak volume (m^3)
3	56	19.2	23	17.8
4	18	23.4	13	20.0
5	3	28.3	1	33.2
6	28	22.8	2	20.3

Table 2- Average overbreak volume for panels 45-50m in depth

The average overbreak volumes were compared for 1.2m and 1.5m thick panels of 45-50m depth - providing a sample size of 144. The average volume of material lost from the trench perimeter was approximately equivalent for 1.2m and 1.5m thick panels; similar behavior was observed in 0.8m, 1.0m and 1.2m thick panels of 20-25m depth. For panels of similar depth and length, the data suggests that panel thickness does not have a significant effect on overbreak volume.

4.2 Panel Length

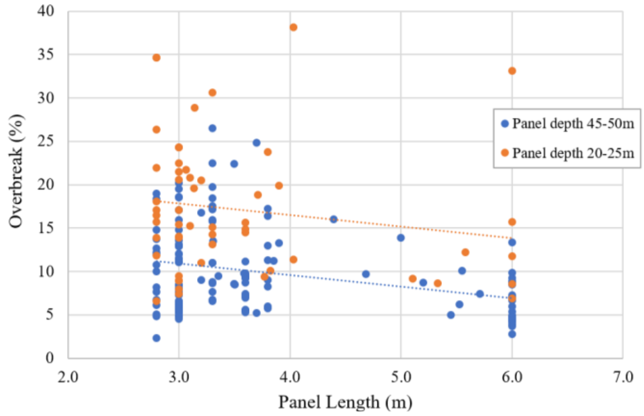

Figure 9- Overbreak (%) for varying panel lengths at fixed depth

In weak soils it is known longer panels can lead to trench instability and increased overbreak at the panel face[7]; this behavior was not observed at PER.

Figure 9 shows the percentage of overbreak relative to panel length for depths of 45-50m and 20-25m (sample size 199). Both data sets demonstrate a reduction in overbreak when the panel length was increased from 3m to 6m – typically reducing by 3-5%. One explanation, is that 3m panels have a greater surface area relative to volume; any overbreak at the panel ends is overcut during excavation of the adjacent panel, therefore as the number of panel joints increases so does the cumulative volume of overbreak.

Both Figure 9 and Table 2 also show a relative increase in overbreak for panels 4-5m in length. The standard excavation tools used at PER were 2.8m in length, therefore 3m and 6m panels allow for 1 and 2 full ‘bites’ respectively (a central trimming bite may be required for 6m panels). 4-5m panel lengths are not preferred because the second bite is partial, requiring the excavation tool to cut unsymmetrically. The grab/hydrofraise can move more freely within the trench during a partial bite as it is not fully enclosed, as the tool moves it will come into contact with the trench wall and may cause additional overbreak.

4.3 Excavation Duration

Using the same sample set as Section 4.2, the effect of excavation duration on overbreak volume was studied for panels of similar length and depth. For PER, the data did not support any correlation between

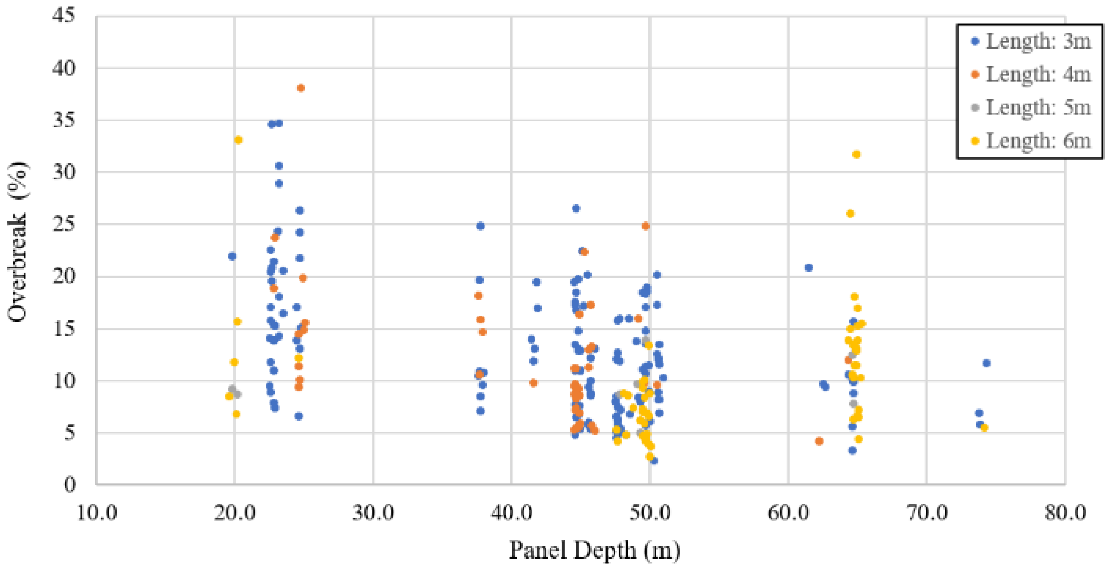

Figure 10- Scatter graph of overbreak (%) by panel length and depth

excavation duration and the volume of overbreak. This observation is consistent with the findings of Puller[8] when studying diaphragm wall construction in the UK.

4.4 Panel Depth

Figure 10 illustrates the relationship between panel depth and overbreak for diaphragm wall panels at PER (sample size 274). For all panel lengths, a reduction in overbreak percentage was observed with increased panel depth. For example, 3m panels saw overbreak rates reduce from 6-35% at 20-25m depth, to 3-21% at 60-65m panel depth; similar trends were also observed for longer panels. As the geology generally becomes more competent with depth, and the head of bentonite slurry increases, a reduction in overbreak at the panel face can be expected.

5. CONCLUSIONS

Whilst Prince Edward Road Station provides a large quantity of diaphragm wall data, the study is limited to one site, specifically in Jurong Formation. The analysis and conclusions drawn may not be applicable to other projects in different geology.

The productivity analysis undertaken in Section 3 showed that the thickness of the diaphragm wall panel did not have an appreciable effect on the excavation rate at PER. For shallow panels (20-25m) there was a significant increase in excavation rate as the panel length increased from 3m to 6m – measured in linear meters per day; however, this trend could not be substantiated for panels over 37m in depth.

As anticipated, excavation rates decreased with increasing panel depth, with a significant drop in productivity observed in panels over 37m deep. This represents slower progress when excavating rock, which is further compounded if the cutting tool needs to be changed frequently because of variable ground conditions.

Analysis of de-sanding duration shows a linear relationship with panel volume, suggesting that productivity was determined by the pump and plant capacity. Similarly, the duration of reinforcement installation was directly proportional to cumulative cage weight.

The data shows that the rate of concrete placement increases for larger panels because longer panels allow several tremie pipes to be used simultaneously. Figure 8 also demonstrates that the increased concrete volume caused by overbreak leads to longer casting times.

For PER, the volume of overbreak was not affected by panel thickness or excavation duration. However, increasing the panel length from 3m to 6m could reduce the percentage of overbreak by 3-5% - thus reducing soil disposal and concrete material costs. These benefits are only applicable if the trench stability can be safely maintained for a longer panel, and may not be appropriate if the diaphragm wall is located near to sensitive structures. Panels 4-5m in length, requiring a partial bite of the excavation tool, appear to provide the least favorable overbreak conditions.

Estimated total duration and overbreak for constructing a specific diaphragm wall panel in Jurong Formation: Sample panel: *Thickness = 1.5m, Length = 6.0m, Depth = 45m, Reinforcement = 80t*			
Activity	**Reference**	**Calculation**	**Likely duration (hours)**
Trench excavation	Figure 4 / Table 1	6m ÷ 0.4-0.6m/day x 24hrs/day	240 to 360 hrs
De-sanding of bentonite slurry	Figure 6	1.5m x 6.0m x 45m = 405m^3	4 to 6 hrs
Installation of reinforcement	Figure 7	80t x 1000kg/t = 80,000kg	9 to 13 hrs
Placement of concrete	Figure 8	1.5m x 6.0m x 45m = 405m^3	6 to 8 hrs
		Total duration	**259 to 387 hrs**
Overbreak	Figure 10	405m^3 x 5-15%	**20-60m^3**

Table 3- Example of using productivity data to estimate construction duration and overbreak

Table 3 provides an example of how the productivity information contained within this paper may be used as a planning tool for future diaphragm wall works in similar ground conditions.

6. ACKNOWLEDGEMENTS

Diaphragm wall construction records were provided by Bachy Soletanche Singapore Pte Ltd. and compiled by Goh Jen Yang of Nanyang Technological University during his internship at LTA. This paper was made possible with their support.

7. REFERENCES

[1.] Land Transport Authority, 2017. *Geotechnical Interpretative Baseline Report – Contract 885 – Station CC32 and bored tunnel from Station CC31 to Station CC32*, pg 6-32.

[2.] Soletanche Bachy. *Technical Guide – Build in us*, pp 19-28.

[3.] Land Transport Authority, 2010. *Materials & Workmanship Specification for Civil and Structural Works*, Chapter 6.

[4.] [6.] Institution of Civil Engineers, 2007. *ICE specification for piling and embedded retaining walls – second edition*, pg 180, 182-184

[5.] [7.] [8.] Malcolm Puller, 2003. *Deep Excavations: a practical manual – second edition*, pg 121, 128-130,

BSI Standard Publication, 2015. *BS EN 1538:210+A1:2015 Execution of special geotechnical work – Diaphragm walls.*