Evaluation of Over-Excavation for Earth Pressure Balance (EPB) Shields through Data Analytics

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ABSTRACT: The utilization of EPB shields has advanced tunnel construction but there are still certain tunneling risks such as settlements, sinkholes and movement of neighboring existing infrastructures (Shirlaw, & Boone, 2005). Due to the risks, Building and Construction Authority (BCA, 2017) enforced a regulation that over or under- excavation should not exceed ±15% (over 115% or below 85%). However, in the local industry, the over-excavation ratios (OERs) reported by tunneling contractors are based on rough estimation since factors such as spillages during the muck skips transportation, error from the crane measurement were unaccounted for. This paper reviews data retrieved from past tunnelling works, establishes a framework for back analyzing excavation data and proposes correction & bulking factors to better estimate the OERs.

1 INTRODUCTION

Underground tunneling works have been carried out in Singapore since the early eighties, extending the railway system over the decades (Ow, Kulaindran, Knight-Hassell & Seah, 2004). Some of these tunnelling works were carried out utilizing a type of tunnel boring machine (TBM) called the Earth Pressure Balance (EPB) Shields for soft ground conditions (Herrenknecht, & Rehm, 2003 & EFNARC, 2003 & EFNARC, 2005).

EPB shields has brought about numerous tunneling risks such as settlements, sinkholes and movement of neighboring existing infrastructures (Shirlaw & Boone, 2005). Building and Construction Authority (BCA, 2017) thus enforced a regulation that over or under-excavation should not exceed ±15% (over 115% or below 85%). In the local industry, the OERs reported by tunnelling contractors may not be reliable since certain factors such as spillages from muck skips transportation, soil sticking within muck skips and discrepancy from weighting of muck skips by gantry crane were unaccounted for.

This paper focuses on establishing a realistic framework or a set of values by estimating the bulking & correction factors by back-analysis and evaluating the OERs. The values and factors applied aims to determine more accurate OERs and could be considered for future tunnelling works. The realistic OERs are determined by two methods: Volume and Weight approach. Details of these methods are discussed in the following sections.

2 ESTIMATON OF BULKING & CORRECTION FACTORS

As discussed above, the determination of realistic OERs is carried out by: (i) Volume approach (Back-Analyzed Bulking Factor) and (ii) Weight approach (Correction Factor).

2.1 Volume Approach (Back-Analyzed Bulking Factor)

This approach analyzes the ratio of the net measured volume to the theoretical volume for every set of specific rings through the derivation of new bulking factors. In this paper, the bulking factor is defined as the ratio of the measured excavated material volume to the expected excavated material volume tabulated based on the cutter head size. The volume method is defined as follows:

1) The measured excavated material volume is obtained from the volume of the muck skips used to transport the excavated material out of the tunnel. There is inherent uncertainty in this measured volume since the excavated material is not leveled in every muck skip.
2) The cutter head size information is processed to obtain the expected excavated material volume for each tunnel ring.
3) The bulking factor is calculated as:

$$\text{Bulking Factor} = \frac{\text{Measured excavated volume}}{\text{Expected excavated volume}} \tag{1}$$

4) For every set of specific rings, an average of the bulking factor is tabulated.
5) Averaged bulking factor is applied back to obtain the corrected excavated volume for each ring in the set of specific rings used to calculate averaged bulking factor as follows:

$$\text{Corrected excavated volume} = \text{Averaged Bulking Factor} \times (\text{Expected excavated volume}) \tag{2}$$

6) The over excavation ratio for each ring is tabulated using the following equation:

$$\text{OER} = \frac{\text{Measured excavated volume} - \text{Additives volume}}{\text{Corrected excavated volume}} \tag{3}$$

Where: Additives volume refers to the amount of soil conditioners added during tunnelling, as measured by the tunnel boring machine.

2.2 Weight Approach (Correction Factor)

This approach shall derive correction factor with the ratio of site investigation density to back-analyzed density for every set of specific rings to achieve revised density and more realistic OERs.

It was noted that the OERs tabulated by the tunnelling contractor is significantly lower than the OERs tabulated based on back-analyzed density. After seeking advice from the tunnelling team, it was understood that the discrepancy could be due to spillage from the muck skips during transportation between the point of TBM excavation and dispatch for weighting, swaying of muck skip during weighting by gantry crane and/ or soil sticking at the bottom of the muck skips. Along with that, the whole tunnel bound may not have a homogenous soil profile (such as full-face rock, mixed face or full-face soil profile) which would also create variations/ fluctuation of OERs.

Correction factor shall be derived for each and every set of specific rings to minimize the discrepancy between the density obtained from the site investigation report and the back analyzed density. The correction factor to derive revised density and OER before comparing with the Volume approach. A correction factor of more than 1.0 indicates loss in excavated material while a correction factor of less than 1.0 will be indicative of bulking or possibility of excavated material remaining in the muck skips from previous batches of excavation (muck skips may not have been cleaned/ cleared before reusing).

The further study of the Weight Approach shall be carried out in a three steps analysis:

- Step 1 - Derive Correction factor of spillage (x) per ring:

$$\frac{x * \text{Measured Excavated Weight} - \text{Additives weight}}{\text{Measured Excavated Weight} - \text{Additives Weight}} = \frac{\text{Site investigation density}}{\text{Back Analyzed density}} \quad (4)$$

Where: Back-analyzed density = (Measured Excavated Weight – Additives Weight)/ Expected Excavated Weight

- Step 2 - Revise Density using x (check if it is close to SI report density):

$$\text{Revised Density} = \frac{x * \text{Measured Exacavated Weight} - \text{Additives weight}}{\text{Expected Excavated Volume}} \quad (5)$$

- Step 3 - Derive OER% with the above revised density:

$$\text{OER} = \frac{x * \text{Measured Weight} - \text{Additives weight}}{\text{Theoretical Volume} \times \text{SI Report Density}} \quad (6)$$

3 PRELIMINARY RESULTS AND DISCUSSION

The preliminary analysis shall showcase the detailed results, graphs and charts based on a completed tunnelling project where tunnelling works were carried out in the Bukit Timah Formation. The selected tunnelling project shall be term as Project A in this paper.

From the evaluations conducted for Project A, the net excavated volumes are lower than the expected excavated volume, which should not be the case and is deemed unrealistic. Calculations of excavated volume and weight from the data collected also revealed large variations along the tunnel alignment and typically "under-excavation". As a result, the bulking factors are back analyzed to estimate over-excavation by volume. Additionally, the site investigation density will be compared to the density estimated by the tunnelling contractor. Thus, this study aims to develop a new framework objectively and realistically for muck reconciliation and estimate over-excavation ratios.

3.1 Project A (Bukit Timah Formation)

Volume Approach

The back-analyzed bulking factors are calculated from the ratio of the Net Measured Volume to Theoretical Volume, assuming that there is no over-excavation for a particular ring.

Figure 1 shows the assumed bulking factor 1.2 adopted by the contractor in Project A. The back-analyzed bulking factors, indicated by grey dots in the two plots, show that they are typically lower than those utilized by the tunnelling contractor.

The over-excavation ratios derived from three different sets of bulking factors are shown in the plots for Project A (Figure 2(a)). the grey dots, are over-excavation ratios derived from the ratio of the Net Measured Volume to Expected Excavated Volume. The Expected Excavated Volume is multiplied by the assumed bulking factor of 1.2. The results show that majority are below the 100% excavation line and several data points are below the 85% excavation line, which is unrealistic and could also indicate measurement errors. On the other hand, the average value of 1.1 in orange points determined from back analysis shows the over-excavation ratio closer to 100%. In actual tunnelling work, over-excavation should be expected. However, the aim is not to use a single or an average value throughout tunnelling work, and it is necessary to ensure that the over-excavation ratios are determined reasonably.

The third set of over-excavation ratios is derived from the Net Measured Volume and Expected Excavated Volume ratio, which is averaged in set of 20 rings. The average value is then applied to the Expected Measured Volume of the set of 20 rings. The blue points in Figure 2 (a) show more promising results, though there are still many fluctuations and scattering of up to approximately 800 rings. The results stabilized for the latter half of the rings and yielded more realistic over-excavation ratios. The corresponding box plots (Figure 2 (b)) also showed fewer variations compared to the tunnelling contractor's and the averaged values.

- Bulking Factor Plot

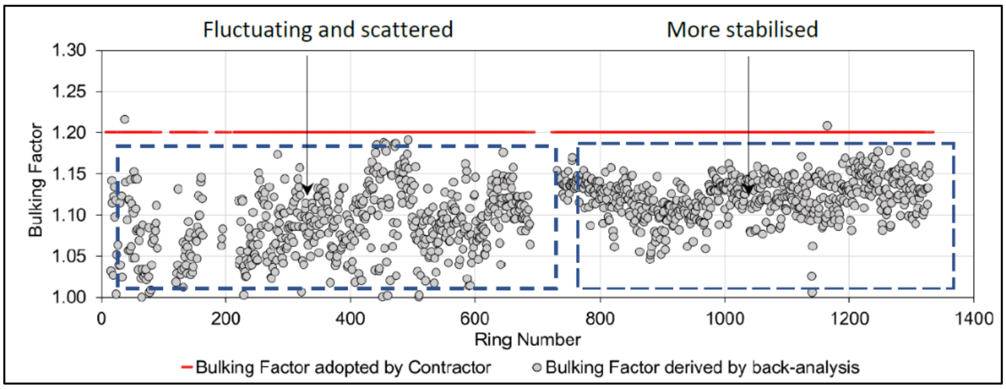

Figure 1. Bulking Factor Plot – Project A

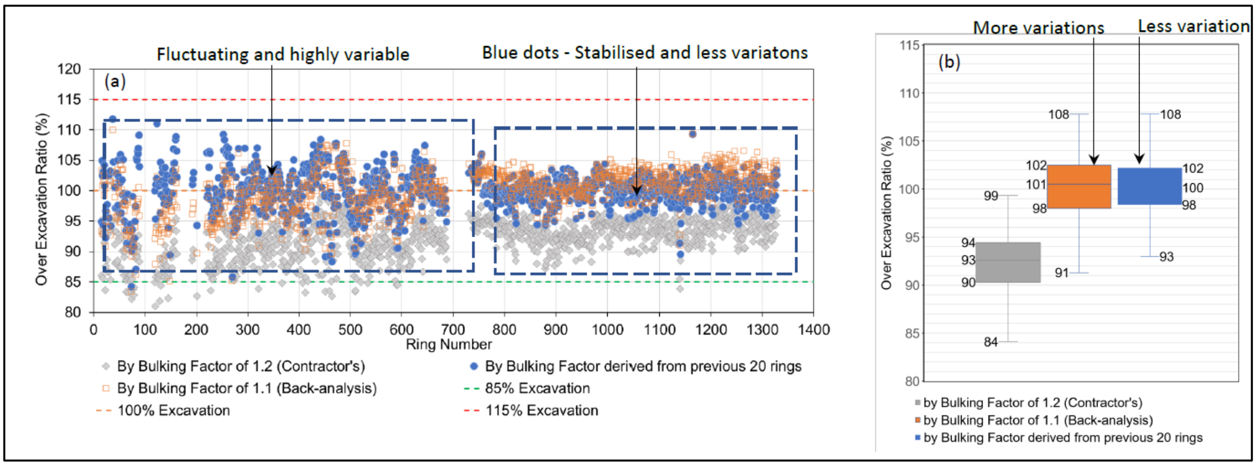

Figure 2. (a) Project A Over-Excavation Ratios (b) Box Plots

Weight Approach

From Table 1, the density adopted by the contractor is significantly lower throughout the tunnel drive as compared to the average density determined factually from the nearest borehole at the tunnel depth. The reason why the tunnelling contractor used a lower density to estimate OER could not be determined. Correction factors are therefore established to minimize the discrepancy and bring the density closer to the density in site investigation reports to derive realistic OERs.

Table 1. Density utilized by tunnelling contractor and the density obtained from site investigation reports at tunnel depth

Section	Ring No	Density Used by Contractor (kg/m3)	Density from SI Reports at Tunnel Depth (kg/m3)
1	377 to 496	1600	1750
2	800 to 1009	1700	1800
3	1141 1440 '	1650	1800

➢ Correction Factor Plot

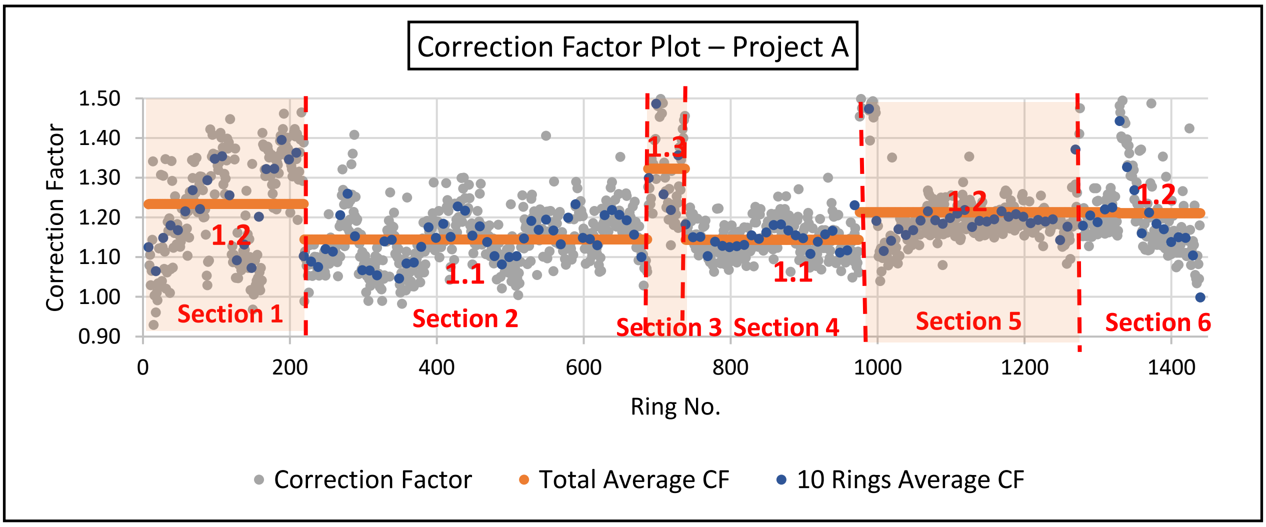

Figure 3. Correction Factor Scatter Plot – Project A

As shown in figure 3 correction factor plot, the results are separated into sections based on the specific soil types. The soil type also corresponds to the difference in density which would result in fluctuations for the correction factors. For section 1,3 & 6, the values have bigger variations and higher total average values as these sections of the tunnel are within GV and/ or GVI + Rock mixed formation while the remaining sections are in full soil face.

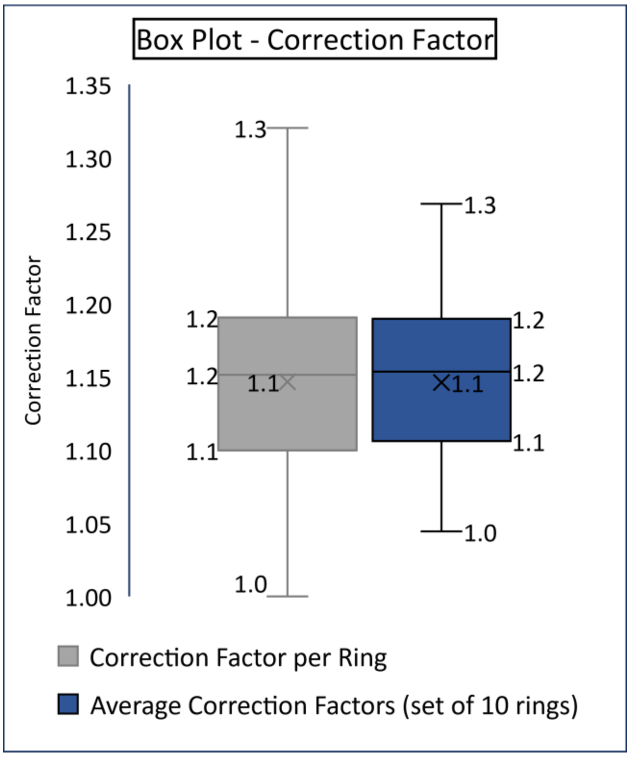

Figure 4. Correction Factor Box Plot – Project A

Based on Project A data results, charts and plots, both back analyzed and derived correction factor for each tunnel ring and 10 rings average does not have much difference and variation where the mean results are 1.1 for both.

- Revised Bulk Unit Weight/ Density Plot

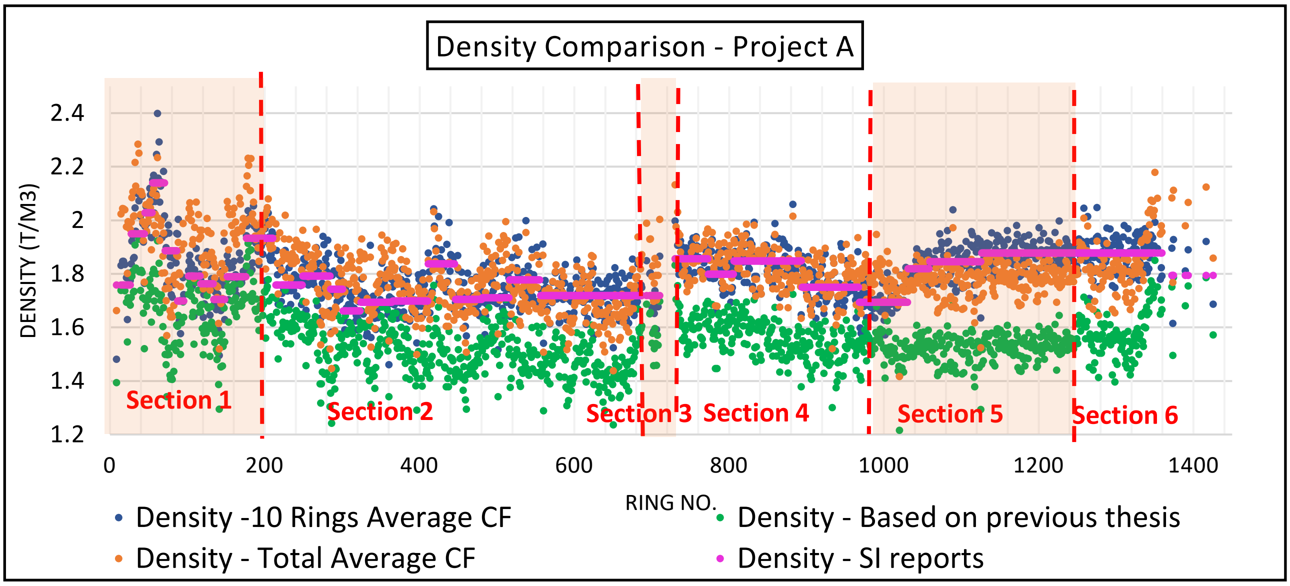

Figure 5. Revised Density Scatter Plot – Project A

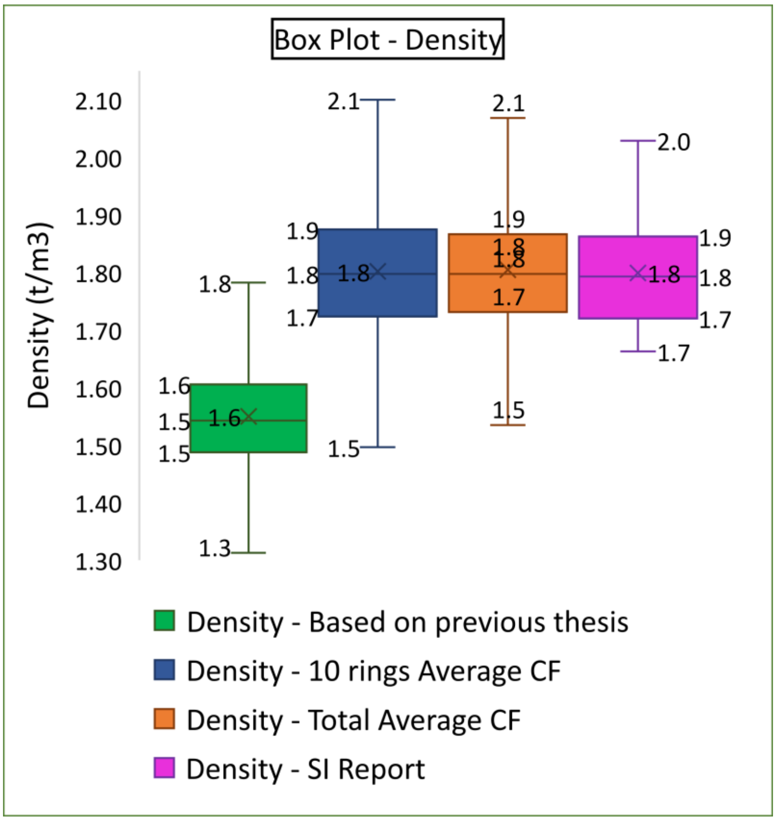

Figure 6. Revised Density Box Plot – Project A

Refer to Figure 5 for revised density comparison application of back-analyzed 10 rings, the average correction factor managed to achieve much precise/ accurate results (Blue – ranging between 1.5 to 2.1 T/m3) through rectifying the discrepancy difference from previous thesis back-analyzed density (green – ranging between 1.3 to 1.8 T/m3).

- Revised Over-Excavation Ratio Plot

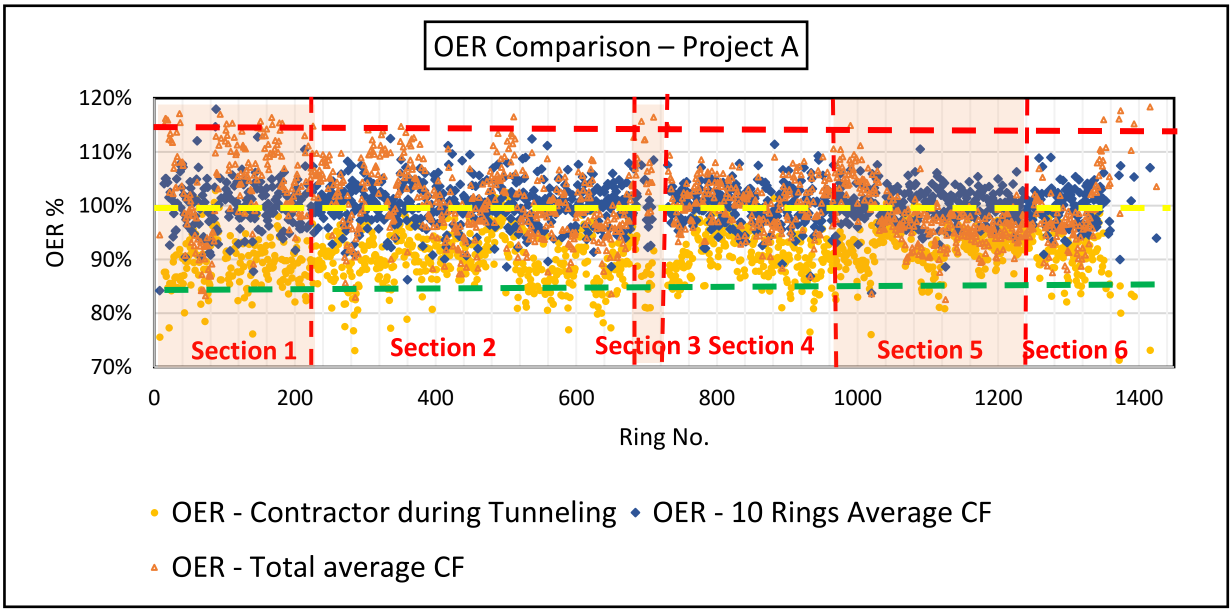

Figure 7. Revised Over-Excavation Ratio Scatter Plot – Project A

Where: For all OER graphs and plots, Red dash line = 115%, Yellow dash line = 100% and Green dash line = 85%

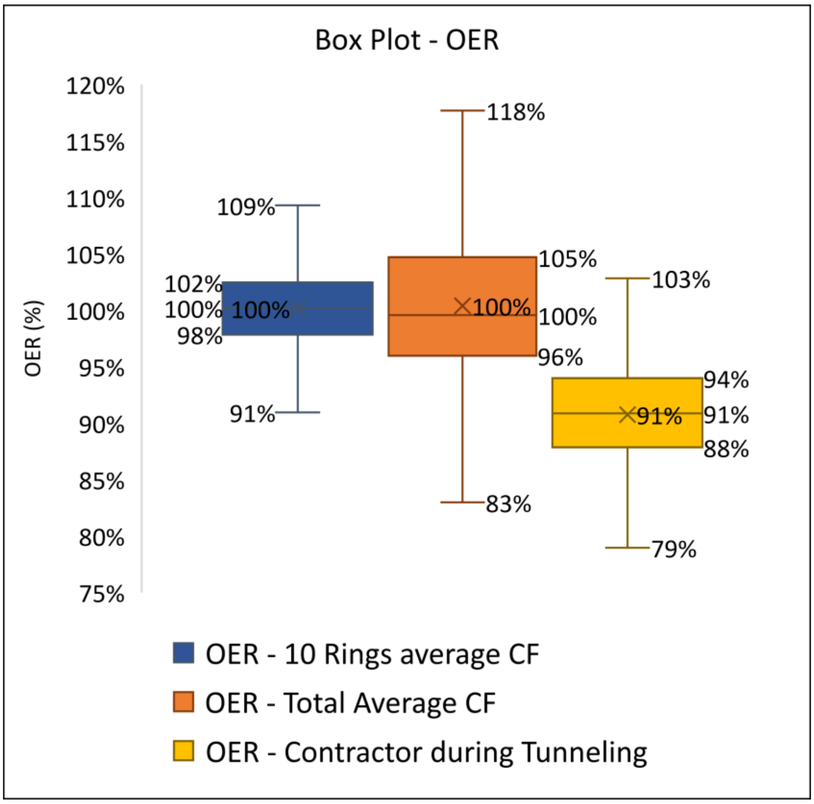

Figure 8. Revised Over - Excavation Ratio Box Plot – Project A

Likewise referring to Figure 7. for revised OER comparison, revised OER results are derived from the application of revised density therefore portraying the same data analytical behavior. The discrepancy between back-analyzed 10 rings average correction factor (Blue - ranging between 91% to 109%) is more comprehensive/ realistic as compared to OER tabulated by tunnelling contractor (yellow – ranging between 80% to 95%) which seems to be pending towards "under-excavation".

- Over-Excavation Ratio Comparison Plot for both Volume and Weight Approach

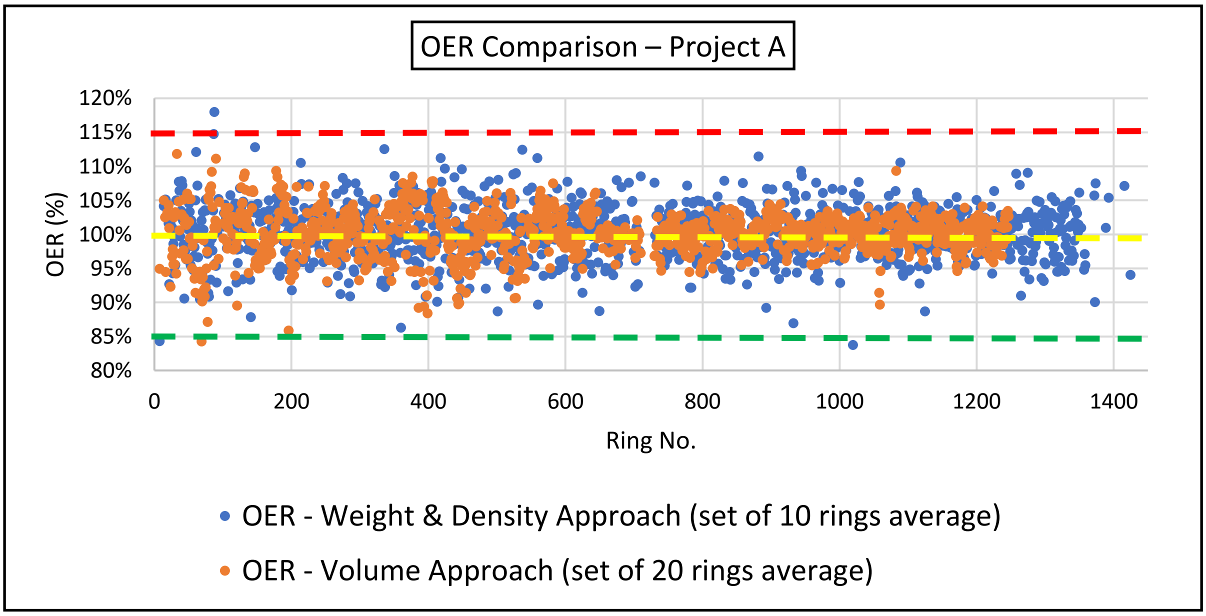

Figure 9. Revised OER Comparison Scatter Plot – Project A

With the application of the new correction factor framework, the OER compared between both approaches are comparable.

4 CONCLUSIONS FROM PRELIMINARY RESULTS

Based on the preliminary results above in clause 3, the data tabulated shows that the fluctuation and scattering of results could have indicated errors in measurements and using a single value of bulking factor throughout the tunnelling work for Volume approach. While the Weight approach proved that derivation of correction factors for weight approach indeed minimize the discrepancy by bringing the revised density closer to the SI report density.

Both approaches have resulted in improvement of OER results to be in more acceptable range of ±15% (over 115% or below 85%) as compared to OERs tabulated by tunnelling contractors which seems to be siding towards "under-excavation". It is concluded that most tunnelling works have results reflecting lower OER than what the actual OER should have been. Estimation of bulking and correction factor is therefore essential to correct the values to achieve a realistic outcome.

Based on Table 2. below and preliminary results above, it is also taken into notice that the charts and plots showcase on different behavior pattern depending on the soil profile such as higher correction factors, density and OER values for tunnelling works within full rock face.

Table 2. Results summary for both Weight (Correction Factor) and Volume (Bulking Factor) approach

Project	No. of Rings	Section	Geological Formation	Total Average Correction Factor	Correction Factor (@ 25 & 75 percentile)	Total Average Bulking Factor	Bulking Factor (@ 25 & 75 percentile)
Project A	8 – 219	1	GIII -GVI	1.2	25 percentile – 1.2 75 percentile – 1.4	1.1	25 percentile – 1.0 75 percentile – 1.1
	220 – 687	2	GVI	1.1	25 percentile – 1.1 75 percentile – 1.2	1.1	25 percentile – 1.1 75 percentile – 1.1
	688 – 738	3	GIII - GVI	1.3	25 percentile – 1.2 75 percentile – 1.4	1.1	25 percentile – 1.1 75 percentile – 1.2
	739 – 975	4	GVI	1.1	25 percentile – 1.1 75 percentile – 1.2	1.1	25 percentile – 1.1 75 percentile – 1.1
	976 – 1328	5	GVI	1.2	25 percentile – 1.2 75 percentile – 1.3	1.1	25 percentile – 1.1 75 percentile – 1.1
	1329 - 1440	6	GIII - GVI	1.2	25 percentile – 1.1 75 percentile – 1.3	No Data	No Data

Along with that, the OER comparison for both approaches are also more comparable and conclusive after application of correction factor.

All in all, each tunnelling construction project is carried out by different tunnelling contractors which applies different methods or application to calculate OERs. It is recommended that further study for all formation and soil type could be established based on above two approaches. Derivation of suitable range for both bulking and correction factor could also be established for future tunnelling works for all tunnel projects. Different sets of value/ factor range could be considered for different formation (refer to example in Table 3 below).

Table 3. Example of factor range to be established for each soil type			
Geological Formation	Soil Type	Correction Factor Range	Bulking Factor Range
Bukit Timah Granite	GI	xxxx - xxxx	xxxx – xxxx
	GII	xxxx – xxxx	xxxx - xxxx
	GIII	xxxx – xxxx	xxxx – xxxx
	GIV	xxxx – xxxx	xxxx – xxxx
	GV	xxxx – xxxx	xxxx – xxxx
	GVI	xxxx - xxxx	xxxx - xxxx
Old Alluvium	. .	. .	. .
Jurong Formation	. .	. .	. .
Kallang Formation	. .	. .	. .

With this framework established, future tunnelling works could derive OER results/ values that are of the same consistency.

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