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VOLUME LOSS CAUSED BY TUNNELLING IN KENNY HILL FORMATION

*Chee-Min Khoo[1,2], Thanath Gopalan[2], Nurfatin 'Afifah Abdul Rahman[2] and Hisham Mohamad[1]

[1] Civil & Environmental Engineering Department, Universiti Teknologi PETRONAS, Malaysia;
[2] Mass Rapid Transit Corporation, Malaysia

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ABSTRACT: The Klang Valley MRT Sungai Buloh – Kajang (SBK) Line, Malaysia's first mass rapid transit line involved the construction of 9.5km twin bored tunnels in the densely populated urban area of Kuala Lumpur city. The underlying geological conditions can be distinctly demarcated to two main formations namely Kuala Lumpur Limestone and Kenny Hill Formation, of which 5.262km of bored tunneling was carried out in the Kenny Hill Formation. The bored tunnel construction in the Kenny Hill Formation was undertaken with the use of Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM). The ground settlement due to tunneling is largely dependent on the volume loss induced by the tunnel excavation. At present, little information has been published on actual volume loss encountered during tunnel construction in the various soil types in Malaysia. Surface settlement markers among other instruments that were placed at selected intervals along the SBK Line tunneling route as an instrumentation and control measure offer an opportunity to evaluate and back analyze the ground response due to tunneling works. This paper presents and discusses the volume loss caused by EPB TBM tunneling in the Kenny Hill Formation. Back analysis on trough width parameter from the available data has also been carried out. The findings of this study could be useful as a reference for future tunneling projects in similar ground conditions.

Keywords: Volume loss, Ground settlement, Trough width parameter, TBM tunneling, Kenny Hill formation

1. INTRODUCTION

Malaysia's first mass rapid transit (MRT) line, the 51km-long Klang Valley MRT Sungai Buloh – Kajang (SBK) Line features a central 9.5km underground section within the densely populated urban area of Kuala Lumpur city. It comprises of seven underground stations with twin bored tunnels running through two distinctive geological formations, namely the Kuala Lumpur Limestone and Kenny Hill Formation, and is connected to the adjacent elevated sections via the north and south portal. The twin bored tunnels have an internal diameter of 5.8m. The lining is 275mm thick precast steel fibre reinforced concrete comprising of 7 segments plus one key. The bored tunneling works commenced in June 2013 and were successfully completed in April 2015 and subsequently followed by the SBK Line opening for passenger service on 17 July 2017.

Based on the published geological map of Kuala Lumpur and corroborated with a total 496 number of boreholes carried out during tender and detailed design stage of the project, it was established that the tunnel alignment from Ch. 1+048 to Ch. 6+310 (approximately 5.262km) is within the Kenny Hill Formation and the remaining Ch. 6+310 to Ch. 10+307 (approximately 3.997km) is in the Kuala Lumpur Limestone Formation. The Kenny Hill Formation consists of layers of highly weathered metamorphic rock of sedimentary origin with typically more than 15% silt and some quartize and phyllite.

In the Kenny Hill Formation, the soil is expected to be slightly cohesive which had resulted in the selection of Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM) for the tunnelling works. The EPB TBM utilizes the excavated soils to exert support pressure to the tunnel face where a mixture of foam and water was used as a conditioning agent in the cutting face and excavation chamber. The TBM drive, with excavated diameter 6.684m, was done in closed mode operation with an operational pressure of about 135kPa to 275kPa maintained at the face. High penetration of more than 20mm/rev and average production rate of 9.8m advance per day with a maximum production of 19.6m/day were reported by Chin *et al.* [1]. The overburden above the tunnel crown generally ranges from 9m to 26m. The lateral distance between the center line of the twin tunnels varies from 12.7m to 17.5m. For most parts, the tunnels were at a parallel configuration and located at the same elevation except where it approaches the stacked Bukit Bintang Station.

In this paper, the data from the instrumentation measurements collected during the construction of tunnels have been used to study the volume loss caused by tunneling in the Kenny Hill Formation. The volume loss is obtained by best fitting the Gaussian curve to the measured settlements along the traverse sections of the tunnels. Back analysis of the trough width parameter has also been carried out. The findings of this study could be useful as a reference for future tunneling projects in similar ground conditions. Efforts to continually build up the field database to further refine the deduced volume loss is in progress over the course of construction for subsequent Klang Valley MRT tunnels.

2. THE KENNY HILL FORMATION

Kenny Hill Formation is a sequence of clastic sedimentary rocks consisting of interbedded shales, mudstones, siltstones and sandstones of the Upper Palaeozoic period. Typically characterized by undulating terrain of low hills and shallow and broad valleys in its outcrop as observed in the Klang Valley of Peninsular Malaysia, in particular, Kuala Lumpur Business District and its surroundings. Figure 1 shows the geology of the Kuala Lumpur area with an indication of SBK Line tunnel alignment.

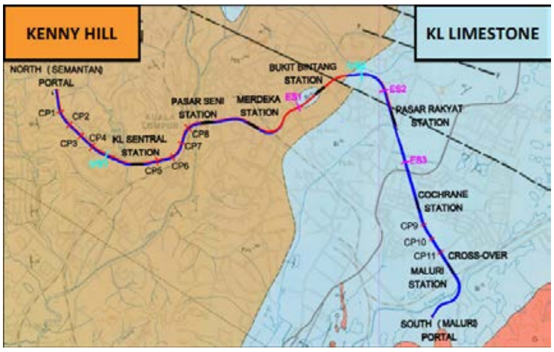

Fig.1 Geology of Kuala Lumpur superimposed with tunnel alignment

The subsurface investigation confirmed that the Kenny Hill Formation along the alignment to be a sequence of interbedded sandstone, siltstones and shales/ mudstones overlain by stiff over-consolidated soils predominately of sandy-silty Clay and silty Sand. At certain stretches, the formation has undergone metamorphic event resulting in changes of sandstone/ siltstones to quartzite and schist/ phyllite respectively.

2.1 Its Engineering Properties

In the Kenny Hill Formation it is typical that beyond a depth of about 10m below existing ground level, the formation becomes very hard with SPT greater than N = 50 [2]. Toh *et al.* [3] and Wong & Singh [4] discussed some engineering properties of Kenny Hill Formation in Kuala Lumpur.

From site-specific data, the measured bulk unit weights typically ranged from 15.8kN/m^3 to 21.9kN/m^3 for residual soils; and increases up to 24.0kN/m^3 for highly weathered rock (Grade IV). The fines composition of the residual soils is generally made of SILT and CLAY with low to high plasticity as shown in Figure 2.

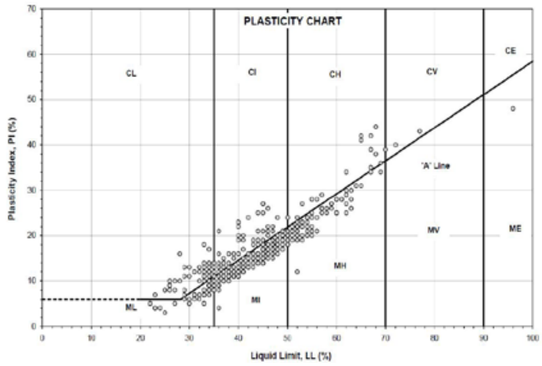

Fig.2 Plasticity chart for residual soils

The effective shear strength parameters interpreted from CIU and direct shear tests are c' = 5kN/m^2 – 10kN/m^2 and Ø' = 28° for residual soils with SPT ≤ 100; c' = 15kN/m^2 and Ø' = 29° with SPT greater than 100. These values are generally within the range of effective shear strength parameters suggested by Wong & Singh [4]. For highly weathered rock (Grade IV), the equivalent Mohr-Coulomb strength parameters are c' = 30kN/m^2 and Ø' = 34° assessed using the method proposed by Hoek and Brown [5].

In general, the permeability of residual soils ranges from 7.1x10^{-7}m/s to 1.6x10^{-5}m/s based on the variable-head field permeability tests.

3. APPLICATION OF THEORY TO SETTLEMENT ANALYSIS

The empirical formulation commonly used in engineering practice for the estimation of tunnelling-induced ground settlements had been developed by Schmidt [6] and Peck [7]. Peck [7] assumed that the transverse ground settlement trough can be reasonably represented by a Gaussian distribution curve - an idealization which has considerable mathematical advantages. Two parameters, namely the ground loss V_l (sometimes referred to as volume loss) and the point of inflection i of the curve, are needed to fit the surface settlement. Cording and Hansmire [8] defined the ground loss as the volume of soil that is displaced across the perimeter of a tunnel. Whatever the soil type, it is convenient to express the volume loss in terms of the volume of the surface settlement trough V_s expressed as a percentage fraction of the excavated area of the tunnel per unit length of tunnel constructed, i.e. for a circular tunnel. The percentage volume loss V_l is defined as follows,

$$\boldsymbol{V_l = \frac{V_s}{V_t}.100\%} \tag{1}$$

where V_s = settlement trough volume
V_t = tunnel opening volume ($\pi.D^2/4$)
D = diameter of the tunnel

Based on the shape of the normal distribution curve, Peck [7] showed that the maximum settlement occurring above the tunnel axis, S_{max} can be given by,

$$\boldsymbol{S_{max} = \frac{0.314.V_l.D^2}{i}} \tag{2}$$

where i = the horizontal distance from the tunnel centre line to the point of inflection of the settlement trough

The settlement at various points of the trough, $S_v(x)$ is then given by,

$$\boldsymbol{S_v(x) = S_{max}.\exp(\frac{-x^2}{2i^2})} \tag{3}$$

where x = the horizontal distance from the tunnel centre line

The definition is illustrated in Figure 3.

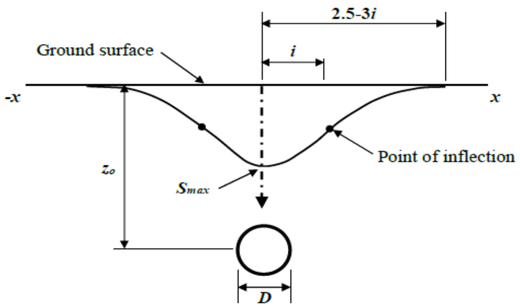

Fig.3 Definition of settlement trough of Gaussian form

O'Reilly and New [9] showed that the trough width i is an approximately linear function of the depth z_o in relation to a trough width parameter K and broadly independent of tunnel construction method and tunnel diameter (except for very shallow tunnels where the cover to diameter ratio is less than one). The validity of the proposed simple approximate relationship of

$$\boldsymbol{i = K.z_o} \tag{4}$$

where K = trough width parameter
z_o = depth to the tunnel center line

was generally confirmed by Rankin [10] for a wide variety of tunnels and for most soil types from around the world. Generally, for tunnels in clay strata, the full width of the transverse settlement trough is about three times the depth of the tunnel [11]. The choice of an appropriate value of K may require some judgment since it depends on whether the ground is primarily cohesive or frictional. Numerically, the parametric study conducted by Khoo *et al.* [12] revealed that for the majority of cases, $K \geq 0.5$ would be applicable for the typical soil types encountered in the Klang Valley of Malaysia and hence confirms the conclusion of O'Reilly and New [9] that $K = 0.5$ is appropriate for practical purposes.

It should be noted that Gaussian function is normally applied to the immediate surface settlements associated with tunnel construction. The immediate settlement mainly results from the ground loss at the tunnel face, the overcut effects of the shield passing and tail void closure. Additional post-construction settlement due to consolidation tends to cause wider settlement troughs and this complicates the interpretation of the settlement data. Softer clays are more susceptible to appreciable consolidation settlement, which could develop rapidly and can be difficult to separate from the immediate construction settlement; this may partly explain the observation by Peck [7] that wider settlement troughs are observed above tunnels in soft clays than in stiff clays.

In addition to the settlement volume V_s one has to consider the ground loss V_l which is the volume of the ground that has deformed into the tunnel after the tunnel has been constructed. For tunnelling in undrained soil (constant volume), the settlement volume is more or less equal to the ground loss, but the settlement volume trends to be somewhat smaller for water-drained excavations. The dilation and swelling due to the unloading may result in soil expansion, such that $V_s < V_l$. However, differences tend to remain small and it can be assumed that $V_s = V_l$. Nevertheless, it should be noted that the trough width parameter is independent with volume loss [13].

4. GROUND SURFACE SETTLEMENT MONITORING

Arrays consisting of several settlement markers are generally needed to deduce information about the shape and width of the surface settlement profiles. The concept hinges on the assumption that the shape of transverse settlement profiles developed during tunnel construction can be characterized by a Gaussian distribution.

Considering factors such as site constraints, surface topography and ground condition, a total of 18 representative monitoring arrays along the tunnel alignment in Kenny Hill Formation were selected and analysed in this study. The arrays consisted of 5 to 9 numbers of settlement markers to monitor the ground settlements prior to, during and after the excavation of tunnels. All the instruments were aligned along the transverse direction of the tunnel drive. A sectional view showing the general arrangement of the instruments is depicted in Figure 4.

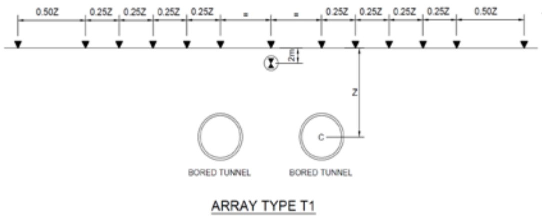

Fig.4 Typical array of surface settlement monitoring

4.1 General Ground Condition at Monitoring Array

From the SPT values, the ground conditions at the monitored arrays appear to be fairly homogeneous with two distinct sub-divisions at N value 50. The overlying fill and residual soils generally extend down to a depth of 4.5m to 12m below the ground surface. Below this layer, the hard-weathered materials (N ≥ 50) of Kenny Hill Formation is encountered where the tunnels are located. Groundwater tables were measured at about 2m to 3m below ground level. The corresponding ground information and tunnel alignment data at the selected monitoring arrays are presented in Figure 5.

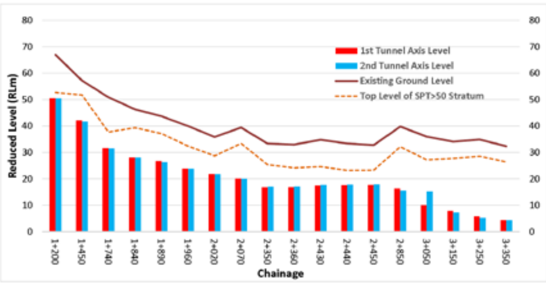

Fig.5 Anticipated ground conditions and tunnel depth at selected monitoring arrays

4.2 Settlement Data and Considerations

Figure 6 shows the settlement trend plotted against time for the respective settlement markers located within the array. The magnitude of settlement induced by TBM passages of both tunnels bound was obtained from reading the surface settlement at the relevant dates when the TBMs crossed the monitoring array. Negative displacements indicate settlement whilst positive displacements indicate ground heave. Based on the settlement trend, it is observed that the settlements are mostly immediate settlements that happened upon the TBM passage and within a short period thereafter. The short-term settlements are usually found to be almost complete when the TBMs are at a distance of about approximately 20m to 30m beyond the monitoring array, i.e. about 3-5 times the tunnel diameter.

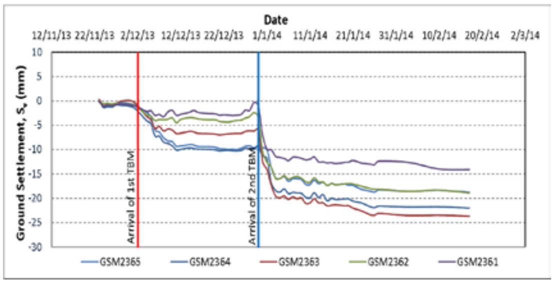

Fig.6 Typical surface settlement trends when TBM passed through

In the interpretation of the data, influences such as TBM operating parameters, construction timing and cutter-head intervention, long-term settlements due to consolidation are not considered in the study.

5. BACK ANALYSIS OF VOLUME LOSS AND TROUGH WIDTH PARAMETER

5.1 Study of Volume Loss

Theoretically, the volume of a measured settlement trough per unit length, V_s can be obtained by integrating Eq. (2)

$$V_s = \sqrt{2\pi}.i.S_{max} \tag{5}$$

By assuming the volume loss is equal to the volume of settlement trough, the loss V_l can be written as in Eq. (1) as

$$V_l = \frac{4V_s}{\pi D^2}.100\% \tag{6}$$

The above methodology requires the reasonable assumption of appropriate trough width parameter to rationalize the Gaussian curve. For the purpose of this study, the actual volume loss is also obtained by adjusting the volume loss and trough width parameter input to match the measured settlement trough. The process is repeated for the second tunnel to match the combined settlement trough plotted from monitoring data to obtain the second set of parameters. Figure 7 shows an attempt to approximate measurement results by a Gaussian settlement trough.

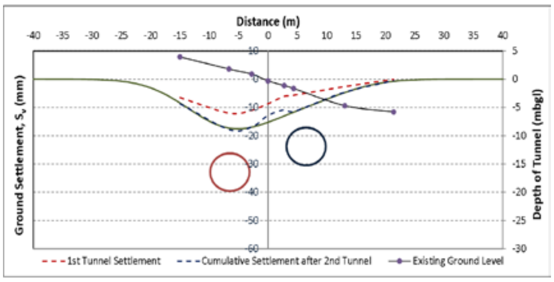

Fig.7 Indicative cross section settlement trough

Based on the curve matching technique adopted to derive the actual volume loss, the 18 array sections were analyzed. Figure 8 shows the volume loss derived. The volume loss ranges from as minimum as 0.10% to a maximum of 1.35%. Statistically, 95% of the data points show the magnitude of volume loss is well below 1%.

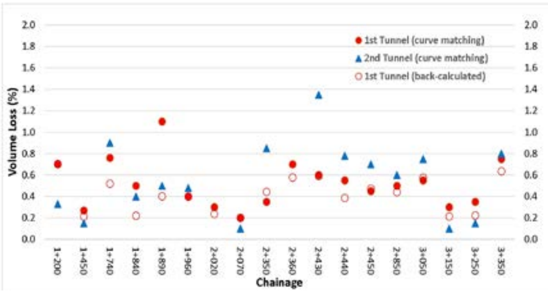

Fig.8 Back-analysed volume loss in Kenny Hill Formation by EPB TBM

The back-calculated magnitudes of volume loss based on the maximum settlement of the field measurements (with the assumption of K = 0.5) for the 1st tunnel are also included in Figure 8.

5.2 Study of Trough Width Parameter

Determination of the settlement trough width parameter K based on the approach described by Mair *et al.* [13] requires the maximum settlement S_{max} as an input value for each settlement profile. In the absence of data, the maximum settlement can be estimated by fitting a theoretical settlement profile to the measured data.

According to Eq. (4), the parameter i/z_o is required to determine the trough width parameter K and this can be obtained by plotting $\log_e(S/S_{max})$ versus $(x/z_o)^2$. Substituting K into Eq. (3) and rearranging gives

$$\log_e\left(\frac{S}{S_{max}}\right) = -\frac{1}{2K^2}\cdot\left(\frac{x}{z_o}\right)^2 \quad (7)$$

Once the $\log_e(S/S_{max})$ versus $(x/z_o)^2$ is plotted for each monitoring array, K can be calculated from the slope of the best fit linear line as

$$K = \sqrt{\frac{1}{2[slope\ of\ \log_e\left(\frac{S}{S_{max}}\right) versus \left(\frac{x}{z_o}\right)^2]}} \quad (8)$$

Again, the basis of this expression is derived assuming that the shapes of the settlement profiles are characterized by a Gaussian distribution.

The values of the apparent trough width parameter K as defined in Eq. 8 determined based on the slope of the best fit lines for the 1st tunnel data set are given in Figure 9. From the back-calculation plot, the K value is computed to be 0.61.

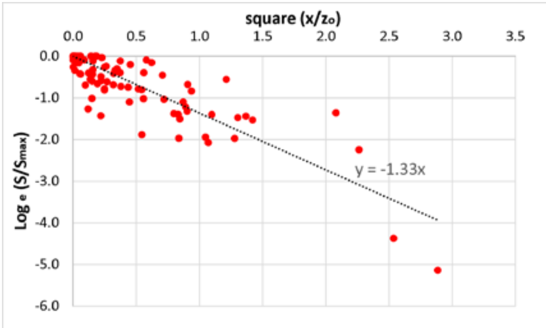

Fig.9 Back-calculated trough width parameter

Apart from the back-calculated K via the above equation, the trough width parameter is also obtained by fitting a theoretical settlement profile to the measured data as discussed earlier. It can be seen from Figure 10 the curve-matched K values exhibit some scatter ranging from 0.4 to more than 0.8 but with the majority being within 0.5 and 0.7. This shows that the settlement profile calculated based on K defined by Eq. (8), in general, yielded similar results.

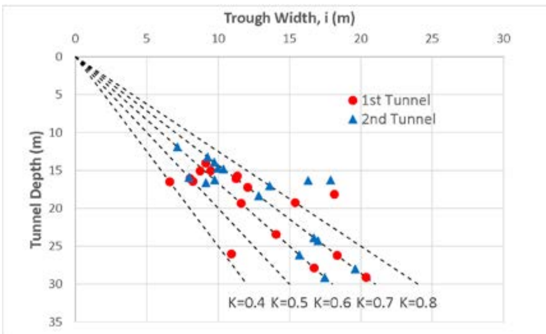

Fig.10 Values of trough width parameter obtained from curve matching

In summary, K value of 0.5 as had been adopted for the residual soil of Kenny Hill Formation in the original design is reasonable for practical purposes. However, this study has shown that the K value is slightly higher between 0.5 to 0.7 with an average value of 0.6 based on the measured data set. It shall also be noted that the linear expression developed for Kenny Hill Formation may not be a unique expression for all soil layers but could differ due to differing overburden depth, soil stiffness, tunnelling method, face pressure, and various other factors. A more comprehensive study of the surface settlement profiles together with the geological conditions and TBM operating parameters is however essential to further confirm the results and this is currently in the progress.

6. CONCLUSION

This paper had presented and discussed the volume loss caused by tunnelling in Kenny Hill Formation by EPB tunnel boring machine. Back analysis of trough width parameter had also been carried out. Tunnelling in Kenny Hill Formation has achieved a volume loss ranging from 0.10% to 1.35%. However, the majority of the volume loss is below 1.0%. Trough width parameter, *K* of between 0.5 and 0.7 was obtained with an average value of 0.6. The results provide valuable knowledge on ground responses to tunnelling in Kenny Hill Formation.

However, a generalization of the volume loss magnitude for use is cautioned against, owing to the specific nature of this project where the tunnel horizons were mostly at depths where the SPT values are above 50 and where typically an overburden of 2D above the tunnels crown was evident which can be viewed as favourable for tunnelling.

With more tunnelling projects on-going and coming up in Malaysia, more monitoring data will become available. Further work is needed to expand the current database of monitoring results to confirm and refine these findings.

7. ACKNOWLEDGEMENTS

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