EFFECT OF TUNNEL CONSTRUCTION TECHNIQUES, GROUND PROPERTIES AND TUNNEL GEOMETRICAL TO THE AMOUNT OF VOLUME LOSS

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Abstract: Ground deformation and settlement caused by underground construction and tunneling works are inevitably avoided. Nevertheless, the impact of it can always be minimized and improvised by investigating amount of volume loss occurred from past historic data. This paper explores the amount of volume loss, in relates with tunneling techniques, ground properties as well as tunnel geometry. Early study explained two phases of volume loss, which are immediate ground loss during tunneling and long term volume loss occurred over the time. Preceding research conducts to identify the range of volume loss, in percentage. As the range of proposed volume loss is not self-dependent, therefore, it is deemed important to understand and investigate the volume loss with close proximate to the local geological property and tunneling techniques. This paper concluded that there are significant impact of tunnel construction techniques, ground properties and tunnel geometric to the percentage of volume loss. With this, the outcome and recommendation of the study will provide future direction for further comprehensive and better justification for ground settlement analysis occurred, during tunnel excavation.

Keywords: *volume loss, tunnel, ground movement, ground settlement, deep excavation.*

1.0   Introduction

Volume loss (VL) sometimes is referred to ground loss, is the amount of loss material in the region of tunnel, occurred through sub-surface construction process. During tunneling, the amount of sub-surface excavated material tends to lead localized ground movement inward to the tunnel. This ground disturbance that caused settlement trough is due to difference in ratio between amount of subsurface excavated material (ΔV) and it void replacement, known as volume of finished void (At) per unit length.

$$\mathrm{V}L = \Delta V / At \ \ x \ 100 \tag{1}$$

For tunneling, where *At* is measured by tunnel area, therefore:

$$At = \pi D^2/4 \qquad (2)$$

Golpasand *et al.* (2016) illustrated convergence of the soil around TBM, in Figure. Hence, when tunneling in clay where ground movement is assumed in undrained condition (constant volume), it is generally accepted that the volume of settlement through (Vs) is equal to ΔV in unit length (Mair & Taylor, 1997a)

$$Vs = \Delta V \qquad (3)$$

By considering Eqs. (2) and (3) into (1) therefore, volume loss can be expressed as

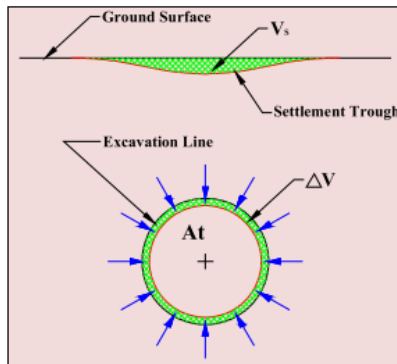$$VL = Vs/(\pi D^2 / 4) \qquad (4)$$

Figure 1: Inward displacement of the ground around the tunnel due to stress relief after
(Golpasand *et al.*, 2016)

Thus, from previous historical data and by knowing the maximum settlement occurred (S_{max}), actual volume loss can be interpret by using equation proposed by O'reilly & New (1982)

$$VL = Smax(i)/(0.313D^2) \qquad (5)$$

Where D is diameter of tunnel and i is horizontal distance from tunnel centerline to the point of inflection in Gaussian Distribution Curve.

The value of i can be derived from formula proposed by O'reilly & New (O'reilly & New, 1982) which based on

$$i = kz_0 \qquad (6)$$

Where k is a constant depending on soil parameter and also known as trough width parameter and Z is depth of tunnel to centerline (Figure 2)
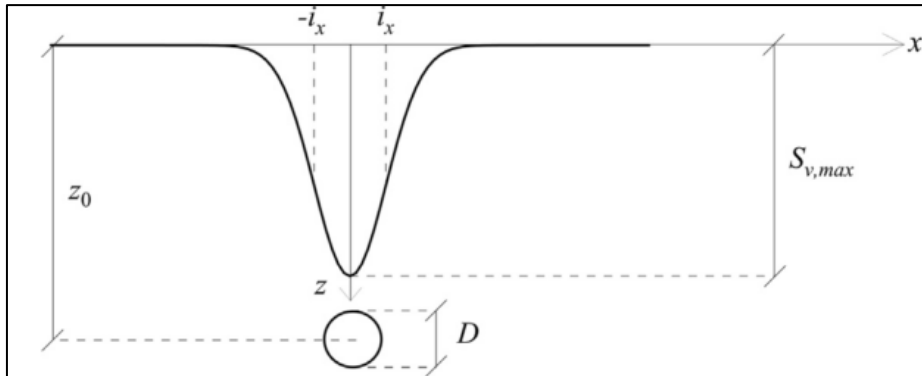

Figure 2: Transverse aspect of ground settlement profile, after (Fargnoli *et al*. 2013)

Early study conducted in 1974 by Attewell (Attewell & Farmer, 1974) suggested two main categories influenced the ground loss; constructional techniques and ground properties. The construction techniques is then further distinguished by Mair and Taylor (Mair, 1996; Mair & Taylor, 1997b) as open face tunneling and closed face tunneling. Open face tunneling describes as the tunneling method where there is no permanent support applies at tunnel face, during excavation process. The stability at tunnel face much relies on existing ground strength and also temporary support such as shortcrete and anchors. Thus, open face tunneling are widely used for tunnel construction in high ground strength and stand-up time (Möller, 2006). For the unstable ground where the tunnel face required support at all time, closed face tunneling method are commonly adopted. This to reduce ground deformation occurred during earth excavation. The principle is that, active pressure is applied to the tunnel face in order to control face stability and provides continuous support to the tunnel face.

Ground properties play important role in defining amount of volume loss. For most cases, the influences of ground type being considered as one of important parameter in estimating maximum settlement (Hajihassani *et al*., 2014. Attewell and Farmer (Attewell & Farmer, 1974) highlighted the ground properties into four categories ; (1) Ground strength (2); Ground material rheological properties; (3) Inhomogeneity, anisotropy, discontinuities in and drainage of the ground; (4) The coefficient of earth pressure at rest

2.0   Factors Governed Amount of Volume Loss

2.1   Construction Techniques

2.1.1   Open Face Tunneling

Preceding studies indicates the tunneling method applied often associated with amount of volume loss. Open face tunneling where the face is unsupported during excavation process is explained in two scenarios; conventional open face tunneling method; open face shield tunneling. The choose of each techniques depend of many factor include project requirement and geotechnical aspect (Möller, 2006)

One of the widely practice in conventional open face tunneling method is sequential excavation (SEM), see Figure 3.It often describes as New Austrian tunneling Method (NATM)and Spray concrete Lining (SCL). It was developed Austrians Ladislaus von Rabcewicz, Leopold Müller and Franz Pacher in the 1950s and is name was introduced by Rabcewicz in 1962 (Chapman *et al*., 2010a) differentiated NATM works from other tunneling method with specific criterion ;

1. Support by sprayed concrete;
2. support by systematic anchoring if necessary
3. using measurements to control the effectiveness of the support
4. A flexible approach to support measures, i.e. increasing or decreasing the support according to the geological conditions.

Effect of NATM tunneling method to the amount of volume loss has been continually explored by several researchers. O'relly and New (O'reilly & New, 1982) described that range of volume loss in open face tunneling in the range of 1.0% - 1.4%.Whereby more recent study conducted by Shirlaw *et al*. (Shirlaw *et al*., 1988) based on case study NATM work through Singapore boulder bed clay quoted the volume loss in range of 0.27 % and 0.248%. Ground movement observed by Bowers *et al* (Bowers *et al*., 1996) over three years Heathrow Express Trial Tunnel constructed by using NATM tunnel excavation shows good agreement with O'relly and New (1982), where the volume loss quoted in range of 1.05% to 1.3%.

Ground deformation that lead to the volume loss summarized by Moller (Möller, 2006) in three principal components (Figure 4);

a. Movement of the ground towards the non-supported tunnel heading.
b. Radial ground movement towards the deforming lining.
c. Radial ground movement towards the lining due to consolidation.

Apart from NATM Methods, open face shield tunneling (Figure 5) has drawn researcher's attention in ascertain amount of volume loss. Court D.J (Court, 2011) quoted that open face shield tunneling are likely to be alternative for station tunnels construction and also as an option in term of cost operation study , in comparison with full face tunnel boring machine. Based on case history of open face shield tunneling in London Clay, Umney and Health (Umney & Heath, 1996) recorded volume loss in the range of 1.5% to 1.8 % . Whereby Standing (Standing *et al*., 1996) recorded relatively high value of volume loss (2.9% - 3.3%) for the same tunneling method, in London Clay. In a research findings by PS Dimmock (Dimmock, 2005) for open face shield tunneling of Jubilee Line Extension which occurred in London clay ground condition, it is noted two phases of volume loss . The first phase is volume loss due to stress relief ahead of tunnel shield whereby the second phases occurred due to radial ground movement around tunnel shield and lining. Based, on previous historical data, summary of volume loss occurred in open face tunneling construction tabulated in table 1.
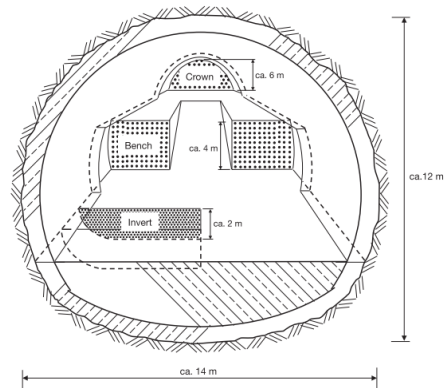

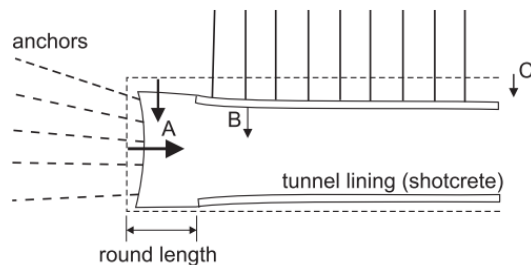Figure 3:Example cross section through a tunnel constructed using NATM (Chapman *et al*., 2010b)

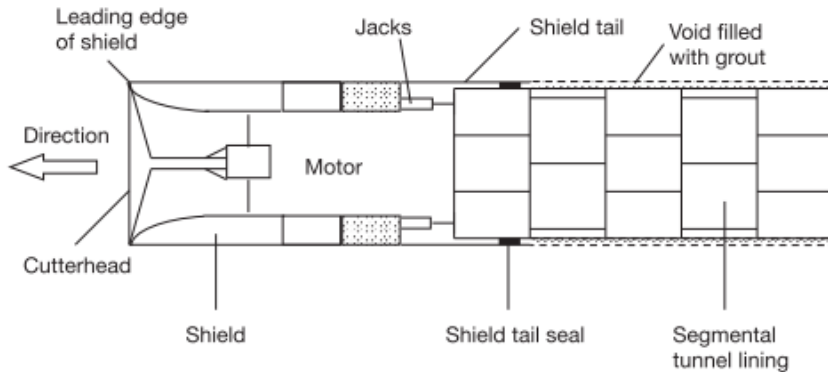Figure 4: Principle component of ground deformation for open face tunneling

Figure 5: Open shield tunneling :Circular tunnel shield with segmental lining (Chapman *et al.*, 2010b)

Table 1: Volume Loss in open face tunneling based on actual case history data

References	year	Construction Method	Ground Condition	Volume Loss (%)
Bowers *et al*	1996	Open Face-NATM	London Clay	1.1-1.5
Umney and Health	1996	Open Face-Shield + Segments	London Clay	1.5-1.8
Standing *et al*	1996	Open Face-Shield + Segments	London Clay	2.9-2.3
Grose and Eddie	1996	Open Face-NATM	London Clay	1
Grose and Eddie	1996	Open Face-Shield + Segments	London Clay	0.5
Kavvadas *et al*	1996	Open Face-NATM	Weak Rock (athenian Schists)	0.1-0.2
Sauer and Lama	1973	Open Face-NATM	frankfurt Clay	1.8
Shirlaw *et al*	1988	Open Face-NATM	Singapore Boulder Bed Clay	0.27
Shirlaw *et al*	1988	Open Face-NATM	Singapore Boulder Bed Clay	0.48
Attewell and farmer	1974	Open Face-Manual Excavated shield tunnel	London Clay	1.44
McCabe *et al*.	2012	Open Face-Shield	Boulder Clay	0.21-1.66
	2012	pipe jacked tunnel	Mullingar glacial gravels	0.76-8.3
Elwood & Martin	2016	Open Face- Conventional sequential tunneling method	heavily overconsolidated soils	1st tunnel - 0.04-0.85 2nd tunnel -0.08-0.77 generally accepted VL is less than 0.2

2.1.2   *Closed Face Tunneling*

In principle, closed face tunneling involves continuous face support, in order to reduce ground deformation. According to Mair (Mair, 1996), this methods are used in unstable ground condition and principally applies to permeable ground below water table, such as in sands or soft clay. The shield tunneling was first introduced by Brunel in 1825-1821 during construction of underpass river Thames, in London (Möller, 2006) .

There are four typical shield tunnel machine widely commonly used; mechanical Support, Compressed air and Earth Pressure Balance and slurry support. The selection of face support much depends on ground condition and properties. Brief description of each support pressure shown Table 2

For closed face TBM tunneling, component associated with ground deformation is described in four particular items (Attewell & Farmer, 1974; Cording & Hansmire 1975) (see Figure 6) ;

1. Volume Loss at tunnel face (VL_f)
2. Volume Loss along the shield (VL_s)
3. Volume loss at tail (VL_t)
4. Volume loss behind the shield tail due to consolidation (VL_c)
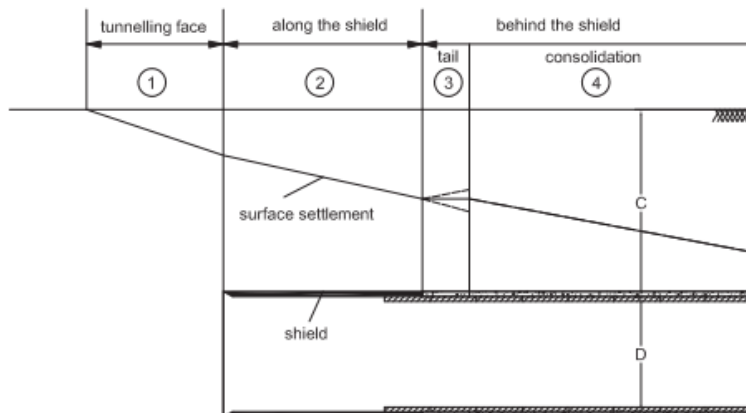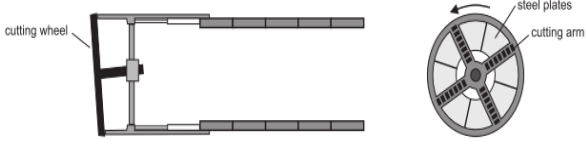
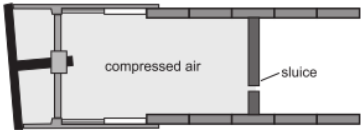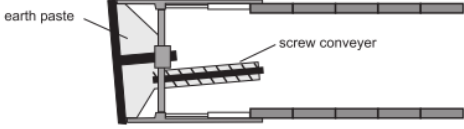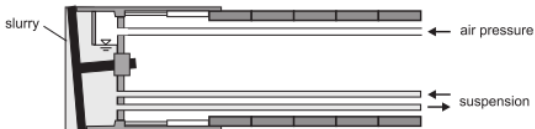$$VL = VLf + VLs + VLt + VLc \qquad\qquad (7)$$

Figure 6:Volume Loss Component (Ngan *et al*., 2016)

Table 2: Tunneling Shield Face Support Pressure (Möller, 2006)

Type of Shield Tunneling Support Pressure	Description	Diagram
Mechanical support (MS)	Face pressure formed by cutting wheel. Suits to cohesive ground condition, above water table.	
Compressed air (CA)	Apply to tunneling underneath ground water table to avoid influx	
Earth pressure balance Earth (EPB)	Widely used in soft ground. Excavated material is used to create support pressure.	
Slurry support (SS)	Pressurized bentonite slurry is applied to create support pressure. Mostly applied in sandy soils and well suited for all types of soils	

Mair (Mair, 1996) suggested from various research paper for closed face tunneling using EPB and SS method, the volume loss is often as low as 0.5% . In the recent study by Fargnoli (Fargnoli *et al*., 2013) in new Milan Underground Line 5 tunneling , where EPB were adopted, the amount of VL shows good agreement with Mair, with average value of VL is about 0.5% . Based on various case history in sandy and clay, Ngan *et al* (2016) quoted a VL of 1% as a reasonable minimum. Summary of recent volume loss occurred in closed face tunneling construction, based on case historic data shown in Table 3.

Table 3: Volume Loss in closed face tunneling based on actual case history data

References	Year	Construction Method	Ground Condition	Volume Loss (%)
Mair	1996	EPB/SS	Soft Clays	0.5
Sugiyama et. al	1999	SS	Sandy soils Cohesive soils	0.85 0.45-0.78
Guglielmetti *et al*.	1999	SS	Sands Clay	1.0 0.8
Loganathan	2011	EPB	Clay	1.15
Toan	2012	EPB	sand	< 0.5
Fargnoli *et al*.	2013	EPB	Sandy soils	0.5
Gui and Chen	2013	Double –O-Tube (DOT) shield tunneling (Twin Tunnel)	Silty Clay	1.05-1.82
Ngan *et al*	2016	Close face tunneling	Sandy and Clay	<1

2.2   Soil Properties

Selection of tunnel construction technique is governed by characteristic of ground condition. One of the parameter that has to be taken into account during pre-tunneling method selection is stability of the ground. In the scope of volume loss, influence of ground properties to the amount of ground deformation is inevitable. From early research by Attewell & Farmer (Attewell & Farmer, 1974) for tunneling in stiff clays, they emphasizes the exponential relationship between increment of tunnel depth which result on decreasing maximum surface settlement. This finding is widely accepted and become fundamental reference to future research study. Coefficient of trough width parameter, k often dependent with soil type. For the homogenous ground , Peck (Peck, 1969) suggested the relationship between depth of tunnel to centerline, z and tunnel diameter, D in relation with ground condition, see Figure 7.From various field data analysis, Mair and Taylor (Mair & Taylor, 1997b) suggested value of k in range of 0.4-0.6 for clays and 0.25-0.45 for sand and gravel. Whereby Guglielmetti (Guglielmetti *et*

al., 2008) proposed that in cohesive soil with c> 0, k is equal to 0.5 . For cohesionless soil with c= 0, *k* value of 0.3 can be adopted. In a recent study of *k* value by McCabe (McCabe *et al*., 2012), result and findings has a good agreement with Mair & Taylor. Range of k found to be in range of 0.2 to 0.3 for Mullingar glacial gravels (coarse soils) and 0.4 to 0.6 for boulder clays (fine soils). Mair (Mair, 1996) summarized from various case history tunnel project in London clays, the volume loss found to be in range of 1% to 2%. Whereas based on tunneling by EPB in Milan Underground Line 5, Fargnoli *et al*. (2013) suggested Volume loss in range of 0.5% for coarse grained soil.
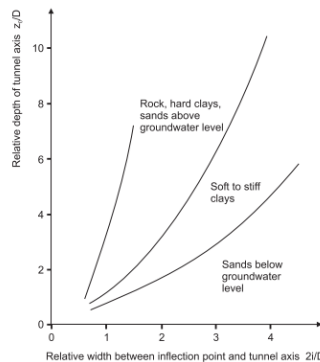

Figure 7:Relation between settlement trough width and tunnel depth for different grounds (Peck, 1969)

2.3   *Geometrical Properties*

As per described by Attewell and Farmer (Attewell & Farmer, 1974) geometrical aspects has to be another parameter that effect amount of volume loss. Based on case study in London Clay, it's quoted the exponential relationship between increasing tunnel depth, z and decreasing of maximum surface settlement. This finding gained interest for other researcher to further investigate the geometrical aspect in relation with ratio of volume loss. In recent case study by Ngan *et al*., (Ngan *et al*., 2016)for tunneling in sands and clays, the result shows that the range of volume loss increase at shallower overburden area. This means when ratio of cover-to-depth (C/D) reduced, the amount of volume loss occurred will exponentially increase. The result from case historic for C/D ratio with less than 2 shown in Figure 8. Findings by Marshall *et al* (2012) shows good agreement with this as it conclude that volume loss decline with increasing of depth of tunnel to centerline *z*, decreasing of C/D as well as trough width *k*.
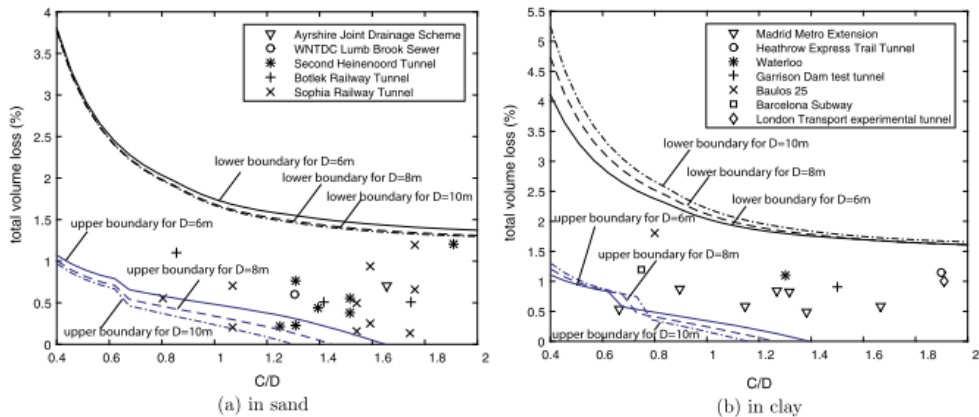
Figure 8: Validation for volume loss in shallow tunneling in (a) Sand and (b) clay after (Ngan *et al*., 2016)

In term of tunnel cross section, Moldovan & Popa (Moldovan & Popa, 2013) pointed interesting results from finite element analysis, see Figure 9. In the analysis where soil properties, input parameter as well both horizontal and vertical stress are set in constant, vertical ovoid shape induces smallest ground settlement, compared to circular shape. Although it may not practical to have vertical ovoid shape of tunnel especially in big scale, but this demonstrate that tunnel geometry has major effect to the amount of settlement and also rate of volume loss, indirectly.
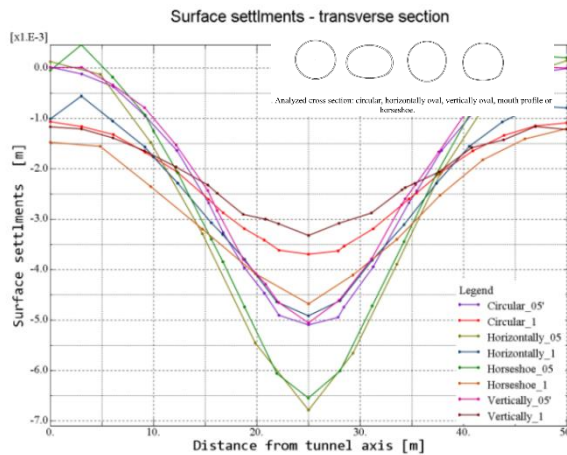

Figure 9: Surface settlement with variance of tunnel shape after (Moldovan & Popa, 2013)

For tunneling in overconsolidated clay, Broms and Bennermark (Broms & Bennermark, 1967)proposed the idea of stability number (N) as a method of analyzing volume loss at tunneling face.

$$N = (\gamma(C + D/2) - s)/Cu \qquad (8)$$

Where γ is soil bulk unit weight, s is support pressure at tunnel face and Cu is undrained shear strength of soil.

Despite of stability ratio, O'Reilly (O'Reilly, 1988) then further established the load factor (LF) with respect to volume loss as a function ratio of N over stability number at collapse, $N_{tc.}$ value of N_{tc} can be extrapolated from Figure, suggested by Kimura & Mair (1981)
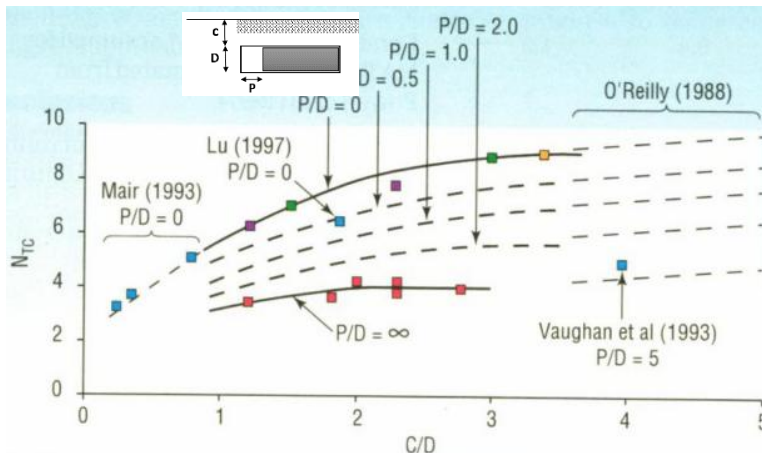
Figure 10: Relation between stability number at collapse, Ntc and C/D (Kimura & Mair 1981), after (Macklin 1999)

$$LF = N/Ntc \qquad (9)$$

Based on various case history of tunneling in London Clay, , Macklin (Macklin, 1999) proposed a linear regression of Load Factor LF with volume loss at tunneling face, $V_{Lf.}$ The relation of LF and Volume loss shown in Figure 11.

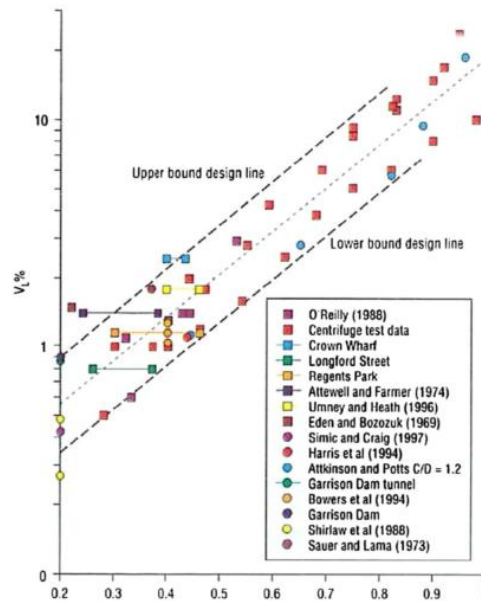$$VLf\,(\%) = 0.23e^{4.4LF} \text{ for LF} \geq 2 \qquad (10)$$

Figure 11: Volume loss and load factor from field monitoring data of overconsolidated clays
(Macklin, 1999)

From Figure 11 above, it can be seen that as the load factor higher, the amount of volume loss will also increase.

3.0   Conclusions

Underground excavation often leads to ground deformation and settlement. Thus, it is deemed important to understand the cause of settlement as well as amount of volume loss occurred from case historic data. The findings results will then can be further used as design guidelines and improvement. The effect of C/D ratio and k value is also another important variable to be considered during assessing volume loss. Results from case historic data ascertain some key point;

1. Based on observation of case historic data, closed face tunneling contributes minimal amount of volume loss compared with open face tunneling. This due to the ability of controlling ground loss components in closed face tunneling, by applying appropriate grout flows and support pressure.
2. In term of tunnel geometric, result from numerical analysis studies shows that tunnel in circular shape demonstrates less amount of volume loss.
3. The relations C/D ratio decrease, amount of volume loss will be increased.
4. k value often higher in cohesive soils compared in cohesionless soils. As the k value getting higher, volume loss will also increase.

5. k value of 0.5 for cohesive soils and 0.3 for cohesionless soils generally accepted for design purposes of estimated volume loss in relation with tunnel settlement analysis

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