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Volume loss assessment in soft ground mechanised shield tunnelling using cutterhead - soil interaction approach

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Research Article

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ABSTRACT

An inevitable aspect of the urban tunnel construction in soft grounds is the settlements or ground deformations due to the volume loss or the additional excavation undertaken to accommodate TBM advance. The volume loss can be further sub-categorized as face, shield and tail loss, based on the stage of the TBM advance. Technical advancements have now allowed minimization of the settlements now owing to their adverse impact on the existing infrastructure in the vicinity, yet there still lies scope for further optimization and even automation. Current study reviews and assesses the observed trends of short-term settlements and volume loss using TBM advances from Kolkata East-West Metro UG-1 project data. The study reviews the probabilistic assessment of the range of volume loss and the settlements due to tunnel, and compares it with the measured trends of transverse and longitudinal settlements. The iterative back-calculation of the measured trends allowed for assessment of the volume loss and face loss using the time-response analysis in different ground types. Considering the results, the study further presents correlations using the cutterhead – soil interaction approach, that is, use of TBM as a tool for geotechnical interpretation ahead of the TBM, for real time assessment of face loss and volume loss as a function of TBM boring parameters. The results confirm that the approach allows reasonable assessment of face and volume loss in real time. The approach also presents potential for automation and optimization of TBM operational parameters for subsequent minimization of settlements.

Keywords: Tunnel Boring Machines, volume loss, face loss, settlements, cutterhead-soil interaction

1. Introduction

Dimensional limitations of surface infrastructure have now caused incremental surge in development of underground infrastructure using construction of network of tunnels in urban regions. Urban tunnel construction essentially requires for minimized ground surface deformations, as it may cause detrimental impact on the existing infrastructure. Use of mechanised tunnelling using the Tunnel Boring Machines (TBMs), particularly the use of the

closed pressurized shield TBMs such as Earth Pressure Balance (EPB) or Slurry Shield TBMs, have substantially minimised the surface deformations in soft ground conditions, yet there still lies a potential for its further minimization and even its automation. Tunnelling is essentially a cyclic process of excavation and subsequent lining installation. The ground deformations or the surface settlements due to TBM tunnels inevitably occur due to the ground volume loss due the difference between the ground volume excavated and the volume installed using tunnel linings during this cyclic process. Closed form solutions, numerical modelling and lately machine learning models, are largely used for assessment of trends of surface settlements, generally in form of a normal or gaussian curve resulting due to this ground or volume loss. The quantum of volume loss, generally expressed in percentage, is largely a function of the ground and the TBM operation parameters. The ground parameters such as the type, strength and stiffness along with the TBM operating parameters like face and grout pressure, which in-turn are partly function of the ground conditions and the geotechnical parameters, hence may largely vary over the length of the tunnel due to the uncertain and variable geological and geotechnical conditions associated with soft ground tunnelling. The general design practice deterministically assumes the volume loss, which may then often lead to deviation between the predicted and measured settlement trends and values. Considering that, current study undertakes a detailed review of the components of volume loss using probabilistic approach for soft ground conditions. The study then iteratively back-evaluates the volume loss using the measured settlement data from Kolkata East West Metro UG-1 project. The study then compares the transverse and longitudinal settlements trends as observed under single and twin-tunnel TBM operations. The progression trend of longitudinal settlements in context with the time-response analysis allows for classification of volume loss into components such as face loss and tail loss and the impact of TBM operation parameters such as face pressure and tail grout pressure under different ground types. Next section discusses and reviews the components and assessment of volume loss during TBM tunnelling.

2. Settlements and Volume Loss due to mechanised tunnelling

Earliest studies on settlements due to underground excavations can be traced to Litviniszyn (1955) and Martos (1958) based on research on mining excavations. Earliest models for ground deformations prediction due to tunnelling were proposed empirically by Peck (1969) and Schmidt (1969) as detailed in Equations 1 and 2, as shown in Fig. 1.

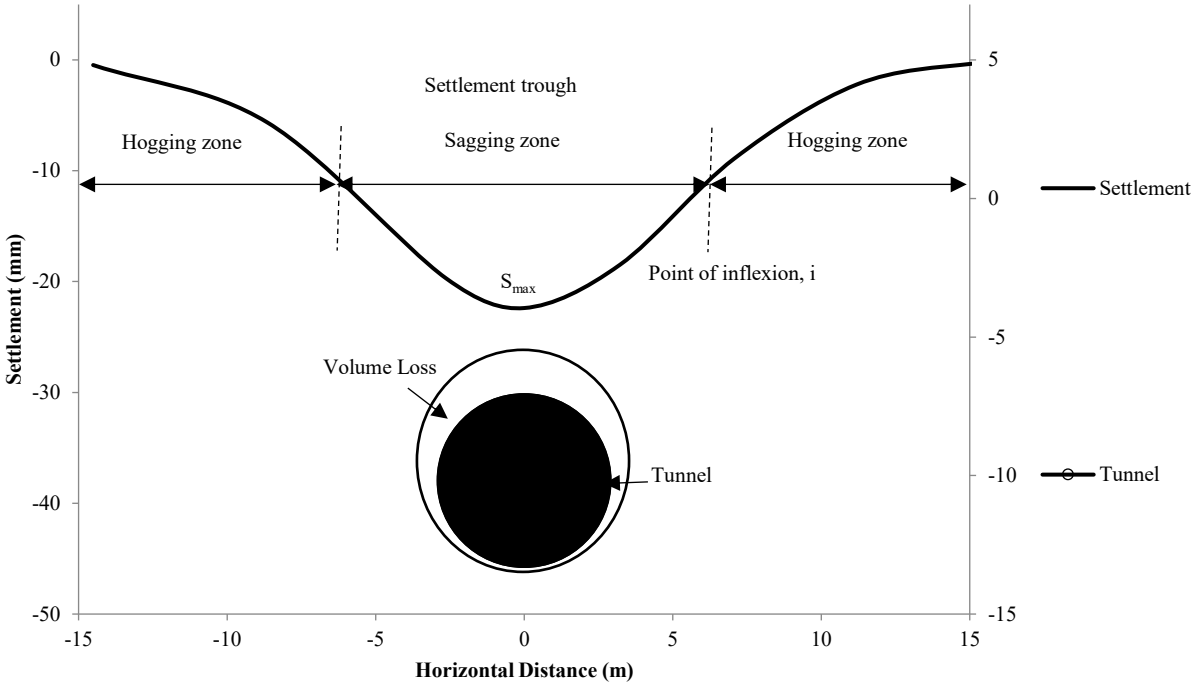


Fig. 1. Typical settlement trough and transverse settlement pattern

$$s = S_{max} \cdot e^{\left(-\frac{y^2}{2i^2}\right)} \quad (1)$$

$$V_s = \sqrt{2\pi}.k.z.S_{max} \quad (2)$$

where, s is settlement at any horizontal distance (y), S_{max} is the maximum settlement, while V_s is Volume of settlement trough (%) or volume loss. Z is the depth to tunnel axis; i is the point of inflexion (calculated as z.k) and k is the trough width parameter (assumed as 0.5 for clayey soils and 0.3 for sandy soils). Initial studies proposed transverse settlement trough using a gaussian or normal distribution curve and suggested width of settlement trough to be function of tunnel depth and ground type as shown in Fig. 1. The point of infection i, was further suggested to be function of tunnel diameter, depth and trough width factor, k (Attewell et.al (1982), O'Reilly and New (1982), Rankin 1988, Mair et al. 1996). For homogeneous ground conditions such as clayey soils, the trough width factor, k, was reported in range of 0.4 to 0.6 while a range of 0.45 to 0.25 was reported for sandy soils considering a detailed overview of field case studies for tunnelling by Mair and Taylor (1997). For layered heterogeneous soils, New and O'Reilly (1991) proposed relationship (Equation 3), which were again confirmed by Mair and Taylor (1997).

$$i = k_1.z_1 + k_2.z_2 \quad (3)$$

Overtime several field and physical models studies such as Cording et al. (1975), Atkinson et al. (1977), Burland et al. (1978), Clough and Schmidt et al. (1981), O'Reilly et al. (1982), New and Bowers (1994), Mair et al. (1993), Kim and Kim (1996), Simic and Gittoes (1996), Mair et al. (1996), Ahmed and Iskander (2011), Fillibeck and Vogt (2012), McCabe et al. (2012) reported observed range of trough width factors. Bogusz et al. (2021) undertook a detailed study of reported literatures on trough width parameters (k) for different soil types.

Theoretical closed form solutions considering cavity-expansion theory using boundary conditions were proposed for prediction of settlements due to tunnelling (Sagaseta 1987). The theory was later developed and extended by Verrujit and Booker (1998) for homogeneous elastic half space. Further, Loganathan and Poulos (1998) modified the theory by incorporating realistic ground loss boundary conditions as detailed in Equation 4. The results were found to be in good agreement with the measured test results (Phienwej et al. 2007). Yu (2013) and Vu et al. (2016) further modified the theory by considering a range of support pressures to the cavity expansion theory for assessment of surface settlements.

$$Uz = -\acute{\varepsilon}R^2\left(\frac{z_1}{r_1^2} + \frac{z_2}{r_2^2}\right) + \delta R^2\left(\frac{z_1(kx^2 - z_2^2)}{r_1^2} + \frac{z_1(kx^2 - z_2^2)}{r_2^2}\right) + \frac{2\varepsilon R^2}{m}\left(\frac{z_1(m+1)}{r_2^2} + \frac{mz(x^2 - z_2^2)}{r_2^2}\right) - 2\delta R^2 h\left(\frac{(x^2 - z_2^2}{r_2^2} + \frac{m}{m+1}\frac{2zz_2(3x^2 - z_2^2)}{r_2^6}\right) \quad 4$$

where, ε is uniform radial ground loss, δ is the long term settlement due to lining ovalization, ν is the Poissons ration, R is the tunnel radius, h is the tunnel depth,

$z_1 = z\text{-}h$, $z_2 = x+h$, $r_1^2 = x^2+z_1^2$, $r_2^2 = x^2+z_2^2$, $m = 1/(1-2v)$, $k = v/(1-v)$

Over the last decades, numerical approaches such as finite element methods (FEM), finite and difference methods (FDM) have been largely used for computation of tunnel settlements owing to complex and heterogeneous ground conditions and several numerical models have simulated the field excavation process (Pourtaghi and Lotfollahi-Yaghin, 2012, Vermeer 2002, Broere and Brinkgreve 2002, Kasper and Meschke 2004 and 2006, Mroueh and Shahrour 2008, Viggiani and Soccodato 2004, Moller et al. 2006, and Dias and Kastner 2013). Impact of factors such as face pressure, grout pressure, geotechnical parameters, lining, TBM weight and conicity on ground settlements have been studied (Kasper & Meschke 2006, Chortis et al. 2014). Last decade has further witnessed surge in use of machine learning tools for assessment of settlement due to TBMs by incorporating various TBM operation parameters as function for assessment of settlements (Ambrogio et al. 2017, Isam and Zhang 2021, Marcher et al. 2020, Ren et al. 2023, Huat et al. 2025).

In an overview, the studies; field, laboratory, numerical methods and lately machine learning methods, have been used for prediction of surface settlement due to the tunnel, characterized using normal or gaussian distribution curve, as a function of the geometrical parameters, geotechnical parameters and volume loss due to tunnel operations (Mair and Taylor 1997, Marshall et al. 2012, Ren et al. 2023, Huat et al. 2025). Tunnelling-induced ground surface settlements can be described by a Gaussian distribution curve with two key factors; the displacement trough width and the volume loss (Le et al. 2025). The element of short-term volume loss due to tunnel operations has been detailed by Rowe and Lee (1992) whereby it was categorised primarily in three main stages; ahead of the face, over the shield, and upon the erection of the lining and introduced a gap parameter g to describe the volume loss as Equation 5, as shown in Fig. 2. Further, additional or long-term volume loss can be attributable to consolidation, creep, and variations in hydraulic conditions.

$$g = G_p + U + \omega \quad (5)$$

where G_p is the geometric clearance between the outer skin of the shield and the lining, corresponding to a physical gap; U refers to the three-dimensional elastoplastic deformation of the soil due to the release of stress at the tunnel face and ω is the gap due to the overcutting.

The longitudinal trend of settlements due to tunnel was proposed by Attwell and Woodman (1982) based on several case studies in conventional tunnelling in cohesive soils without face support. The model suggested 50% of maximum surface settlement attained at the tunnel face while the remaining part followed with tunnel advances. Panet in 1995, considered convergence-confinement for elastic material with support pressure and suggested 28% of maximum surface settlement mobilized at the tunnel face while the remaining part followed with tunnel advances. Based on several case studies, Mair et al. (1996), observed broad variations in the results and suggested construction methodology and workmanship an important factor for pattern of longitudinal settlements. Leca and New (2007), suggested evolution of settlements along the tunnel being largely associated with the stability at tunnel face and characteristic conditions of installation of support systems, that is the construction staging and support system in case of conventional sequentially excavated tunnels and shield and liner characteristics in case of shield tunnels. Similar trends were reported in other studies as well (Mair et al. 1996, Leca and New 2007, Vu et al. 2016). Rattia et al. 2022 highlighted control of short-term components of longitudinal settlements in controlled excavation, that is, due to face loss, shield loss & tail loss considering face support and tail grout pressure.

Abdelaziz Ads et al. (2023) using a physical model considering transparent soil studied trends of longitudinal soil deformations and concluded relatively greater influence by face losses than by overburden depth while the shape of the longitudinal settlement is more dependent on the overburden depth of the tunnel in comparison to face losses. The conclusion for impact of face loss on overall settlements has been concluded by several studies (Vu et al. 2015 and 2016, Skvortsov and Cherepetskaya 2016, Rattia et al. 2022, Ren et al. 2023, Chen et al. 2025).

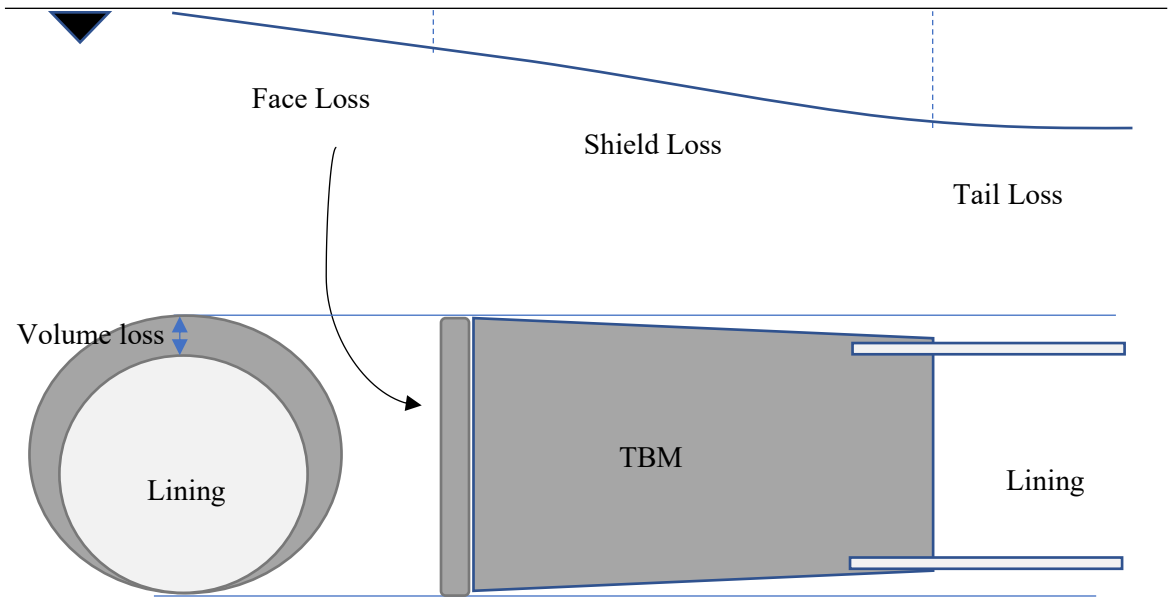


Fig. 2. Short term Volume loss and its components

Conventional practice of assessment of ground deformations comprises of assuming volume loss based on prior cases in similar geological context (Leca and New 2007). Several studies have highlighted the importance of volume loss in precise estimation of ground deformation in urban tunnels (Golpasand 2016, Vu et al. 2015 and 2016, Skvortsov and Cherepetskaya, Rattia et al. 2022, Ren et al. 2023, Chen 2025). The volume loss due to shield tunnels has been sub-categorised as follows (Mair et al. 1996, Leca and New 2007, Vu et al. 2016, Rattia et al. 2022):

- Face Loss: The component of volume loss that is generated ahead of TBM due stability at tunnel face. Accounts for 10% to 20% of the overall volume loss.
- Shield Loss: Shield loss component of the volume loss is due to the conical or tapered geometry of the TBM, leading to loss of ground. This component usually accounts to 40% to 50% of overall volume loss.
- Tail & Lining Loss: The tail loss can be attributed to thickness of the TBM and the space between the TBM and lining. Settlements due to shrinkage of grout also is

considered in this component. The lining loss, although minimal, owing to deformation undergone by lining, can also be considered in this component. Overall this contributes 30% to 40% of overall volume loss.

- Consolidation Loss: The consolidation loss is portion attributed as the long-term settlement undergone by the soil due to changes in pore pressure owing to excavation and lining installation.

As evident from the Fig. 2 above, the volume loss or settlement commences from the face of the TBM, hence is largely function of applied face pressure during TBM advance. Lee et.al. 1992 proposed closed form solutions based on numerical modelling for assessment of volume loss due to tunnel face or face loss, as detailed in Equation below:

$$V_f = \frac{g_f}{R}.100\% \quad (6)$$

where, g_f is the equivalent gap of the face loss as shown in Fig. 2, calculated as Equation 5 and R is the tunnel radius.

$$g_f = \frac{k}{2}\frac{\Omega R P o}{E} \quad (7)$$

where, k is the interface co-efficient between TBM and intruding soil (0.9 for soft ground and 0.7 for stiff ground), Ω is the axial displacement ahead of tunnel face (1.12 for N_r <3, 0.63N_r-0.77 N_r for 3<N_r<5), where $N_r = \gamma H\text{-}P_i/c_u$, where c_u is undrained cohesion, R is the tunnel radius, E is the elastic modulus of soil, P0 is the total stress removal at tunnel face, estimated as k0.P_v + P_w - P_i, where k0 is the lateral earth pressure co-efficient, P_v = Effect earth pressure, and P_w is the water pressure and P_i is the support earth pressure.

Macklin et.al. (1999) also proposed solutions for estimation of face loss as detailed in Equation 8

$$V_f = 0.23.e^{4.4.LF} \quad (8)$$

where LF is the load factor, that is the ratio of working stability number N and critical stability number N_{TC}

$$LF = \frac{N}{NTC} \quad (9)$$

where N is the working stability number while N_{TC} is critical stability number as suggested by Mair et.al. 1979.

$$N = \frac{\gamma(C+D/2)-\sigma t}{cu} \quad (10)$$

As evident, face loss is a function of tunnel geometrical parameters, geotechnical parameters and face stability. Face stability or required support face support pressure hence forms an important parameter for face loss. A range of required support pressures, considering the hydro-geological uncertainties, from minimum support or active pressure required to maximum blowout or passive pressure is required to be ensured during tunnelling (DAUB guidelines). Over time various models have been proposed for estimation of minimum or required face support pressure during the tunnelling operation (Jancsecz & Steiner 1994, Anagnostou & Kovári 1994, Broere 2001, Mollon et al. 2010).

Further, the estimation of shield loss, that is the components of volume loss along the TBM was proposed by Bezuijen and Baker (2007). Based on the change is stresses and subsequent radial movements, following closed form solutions were proposed:

$$V_s = \frac{g_s}{R}.100 \quad (11)$$

$g_s = 0.5\ U_i$, if $Ui < t_t + t_b$ else $g_s = 0.5\ (t_t + t_b)$

$$Ui = \frac{R\ (1+\nu)\ (\gamma H + p_w - p_i)}{E} \quad (12)$$

where, V_s shield loss, R is the radius of tunnel, ν is the poisons ratio, p_w is the water pressure, p_i is the support pressure, E is the young's modulus of soil, H is the depth and γ is the soil unit weight. The shield loss is again function of tunnel geometry and bentonite pressure as applied along the shield. Generally, the bentonite pressure along the shield is considered around 50 kPa above the considered operational face support pressure.

The tail loss component estimation of TBM volume loss was proposed by Lagerblad et al. (2010) as shown in Equation 13, which details the settlement due to machine geometry features such as tail skin thickness and settlement due to shrinkage of annulus grout.

$$V_t = \frac{g_t}{R}.100 \quad (13)$$

where, $g_t = 0.1\ (t + \delta)$, where t is the tail skin thickness and δ is the gap, as shown in Fig. 2

The overall sum of all components, that is face loss, shield loss and tail loss can be cumulatively termed as short-term ground or volume loss, which is usually adopted for estimation of surface settlements due to tunnels. As detailed, volume loss components such as the face, shield and tail losses are mainly function of the TBM geometry features such as conicity and steering along with operational parameters such as bentonite and annulus grout pressure and ground and geotechnical properties. Vu et al. (2016) undertook a theoretical study on volume loss in shallow tunnels and concluded that total volume loss decreases with the increase of the cover-to-diameter ratio. Volume loss at tunnel face, that is the face loss, was highlighted to have a major impact on total volume loss (Figure 2). Similar results were confirmed by Rezae and Ahmadi-adli (2020) and Chen et al. (2025) using field data and numerical analyses. Golpasand et al. (2016) and Ren et al. (2023) have highlighted the importance of volume or ground loss for assessment of surface settlement, yet in general practice the parameter is usually assumed due to lack of exact formulation. Considering the above discussion, current study compares the field measurements from the project case-study data and proposes closed form solutions considering the geometrical, geotechnical and tunnel operation parameters for real-time assessment of volume loss due to TBM tunnel.

3. PROJECT CASE STUDY

3.1. Project Details

To connect the twin cities of Kolkata and Howrah, underground mass transit using metro rail system was proposed to be developed using 3.8 km of underground twin-tunnels as Project UG-1. The underground construction were undertaken in urban region comprising of several structures within its influence zone and hence detailed assessment of the ground movements was critical design aspect. For design assessment, a detailed geotechnical investigation was undertaken using field tests such as standard penetration tests (SPT), 04 self-boring pressuremeter tests (SBP), over 10 permeability tests (constant head and falling head tests) carried out in over 20 boreholes, along with laboratory tests such as triaxial tests (UU/CU), unconfined compression tests (UCS), tests, consolidation tests on undisturbed samples at regular intervals as per relevant standards. The observed range of geotechnical parameters (shear strength/stiffness parameters) as obtained using field and lab tests were further compared and validated using various relevant correlations. The unit wise range of geotechnical parameters in context of depth have been tabulated in Table 1. The ground water table was in

the range of 1 to 4mbgl based on short term measurements while long term measurements indicated water table to be at 7 to 10mbgl. Considering the geological conditions, Earth Pressure Balance (EPB) TBMs of cutterhead diameter of 6.38m were deployed for the Kolkata East West Metro UG-1 Project. The TBM cutterhead with opening ratio of 40% primarily comprised of buckets, knives for rippers for excavation. The cutterhead is followed by excavation chamber which receives the excavated soil during TBM boring/advance and provides the required support pressure. The chamber was equipped with (06) pressure sensors for monitoring the maintained support earth/face pressure. The required support face pressure in turn is regulated using inflow - outflow of excavated soil using TBM advance rate (inflow) and screw conveyor rotation rate (outflow). Fig. 3 shows the geological profile along with the tunnel alignment while Table 1 details the geotechnical details along with parameters as observed using various tests. The TBM traverses its alignment through various geologies including soft and stiff clayey silt and silty sand. Fig. 4 further shows the trend of face and volume loss as estimated using approaches as detailed in previous section. For minimum volume loss, maximum face pressure or blow out pressure was considered while for minimum volume loss, lower bound face pressure as per Fig. 3 were considered.

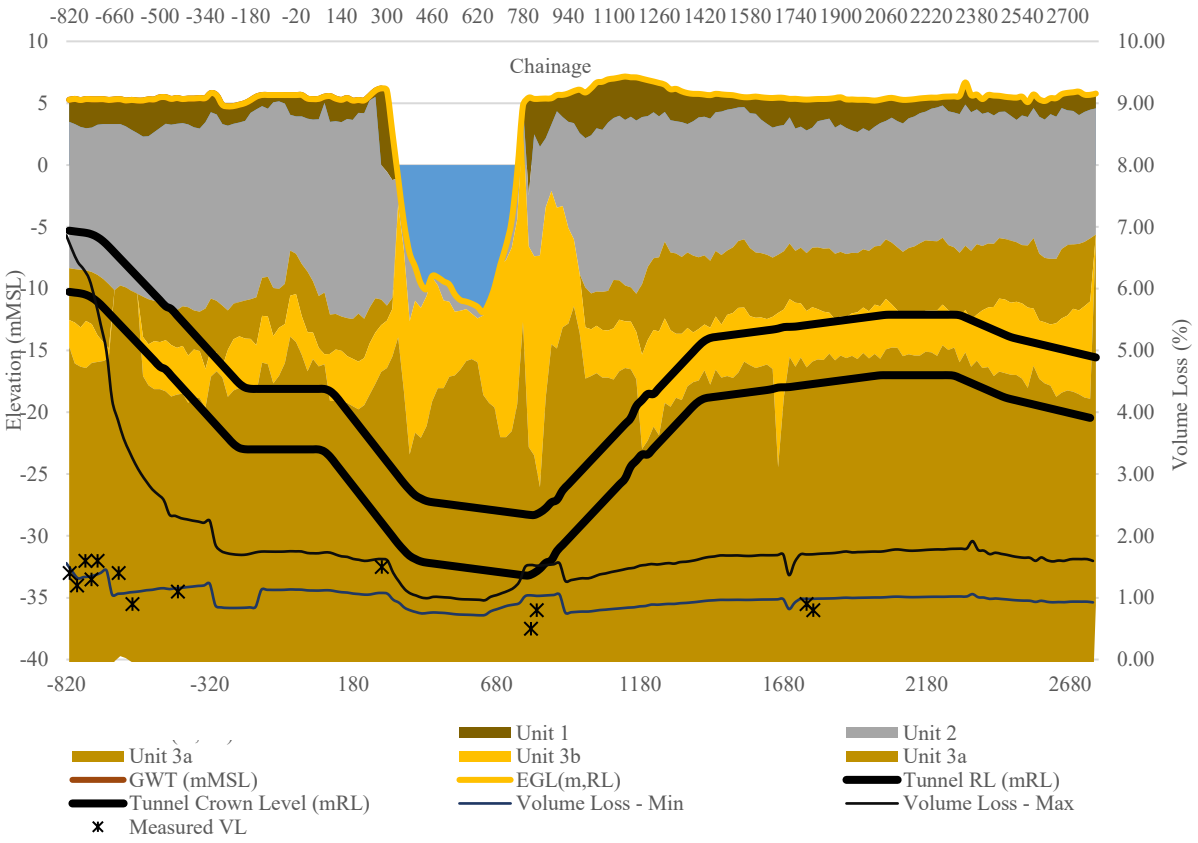


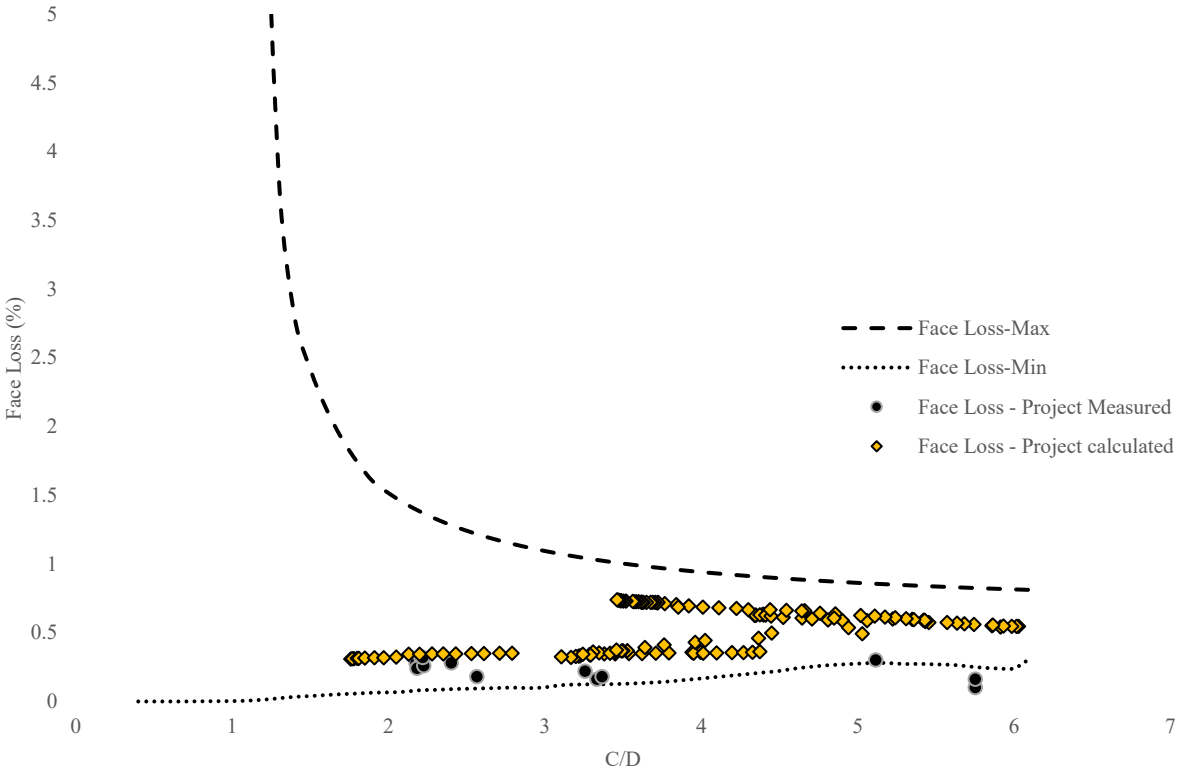
Fig. 3. Range of face and volume loss calculated and observed, in geological context

Figure 3 shows the trend of volume loss, as measured, plotted in context with the minimum and maximum calculated volume loss for the project in context with the geological profile. As can be observed, the trend was found to vary with tunnel cover and different soil types. Higher range of volume loss was estimated for soft clays at low cover (Unit 2) as compared with stiffer soils at greater soil cover. The trend of observed/back-calculated face and volume losses during TBM tunnelling were found to be in line with the calculated volume loss. Fig. 4 further show the trend of measured face and volume loss along with minimum and maximum calculated face and volume losses as estimated using the above approaches for the Project UG1, in context with tunnel geometric parameters.

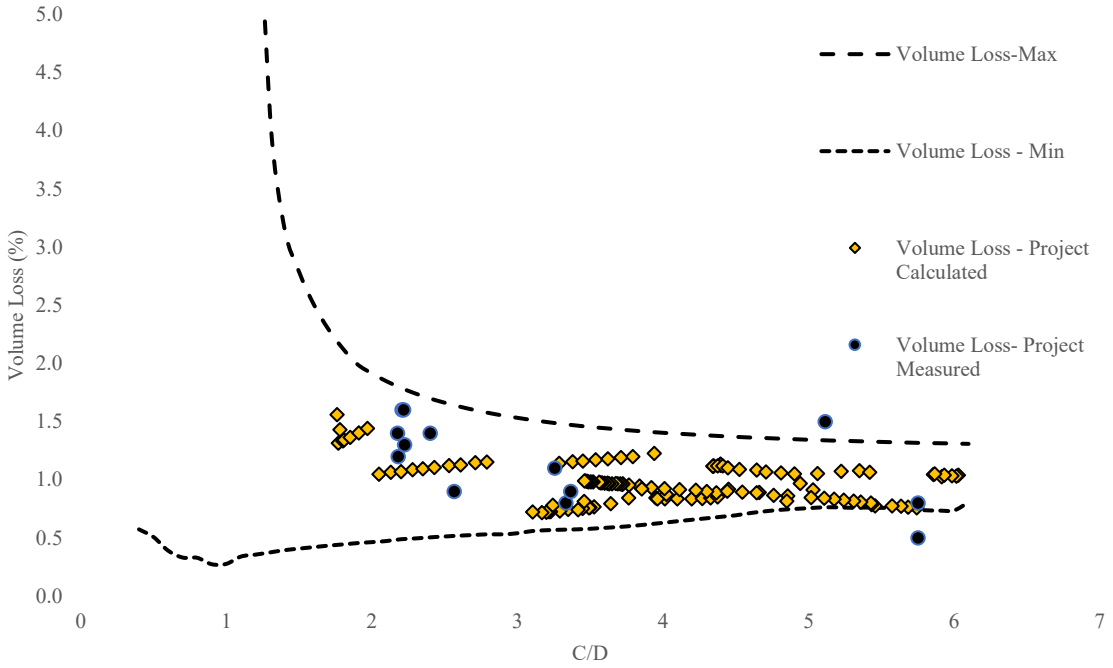
Table 1 Geotechnical conditions and material parameters

Soil Type & Description	Depth (mbgl)	Shear Strength		Permeability (m/s)	Stiffness parameters (MPa)
		Undrained Shear Strength (kPa)	Effective angle of friction (Degrees)		
Top Fill Soil (Unit 1)	0-3	-	27.5±1	10^{-5}	-
Soft greyish clayey silt (Unit 2)	03-20	50±25	29±1.25	10^{-8} - 10^{-9}	11±5
Intermittent silty sand lenses (Unit 3b)	20-25	-	33±3	10^{-5}	35±15
Yellowish stiff clayey silt; (Unit 3a)	25-45	100±35	32±1.5	10^{-8} - 10^{-9}	32±1.5

Figure 3 shows the range of calculated and observed or back-calculated, face and volume loss for the UG-1 project in context with the geological profile while Fig. 4 shows the face and volume loss in tunnel geometrical context. As evident from the figures, the observed trend for all soil types were found to be comparable with the estimated range of face and volume loss.



(a)

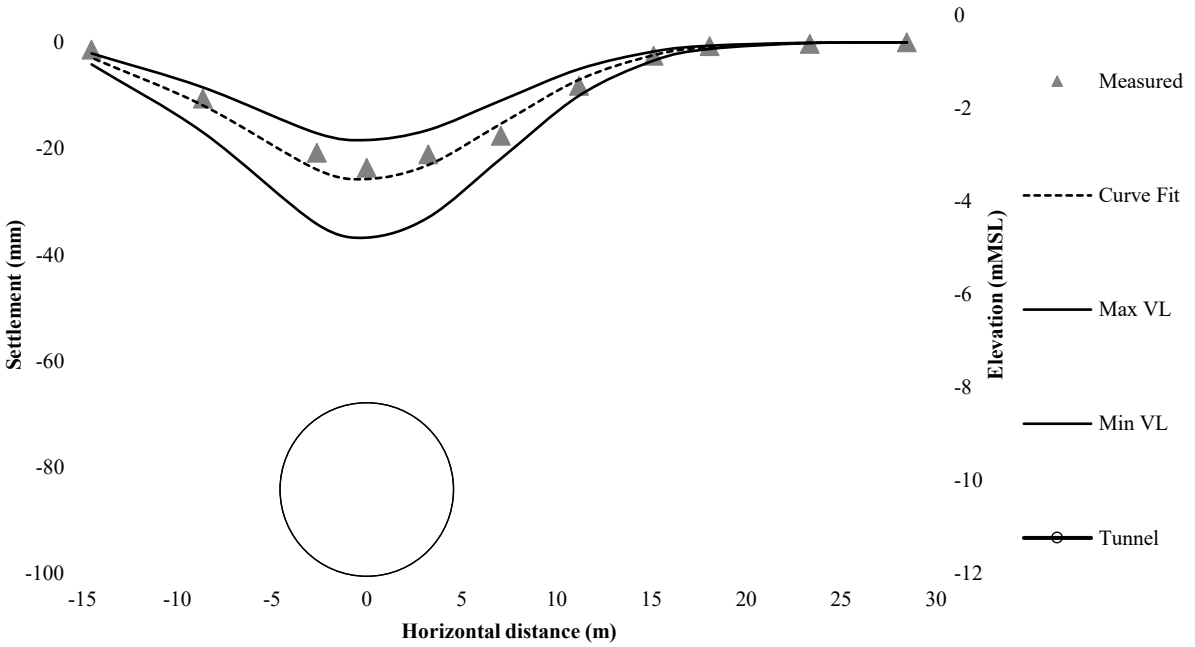


(b)

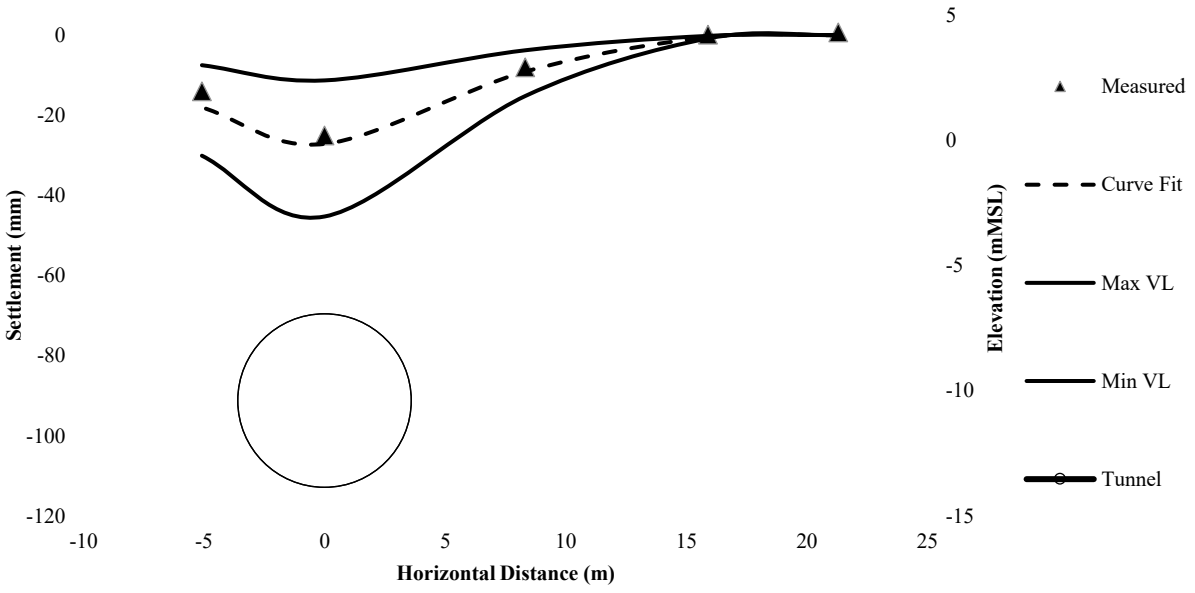
Figs. 4a-b Estimated and observed (a) face loss and (b) volume loss in context with tunnel geometrical parameters

The trends of volume losses in different geological conditions were further compared with the observed transverse settlement trends. Figure 5 shows the typical transverse settlements trends, as estimated considering minimum and maximum volume loss, and as measured during tunnelling. Figures depict the estimated transverse settlement trend considering minimum and maximum volume loss along with the measurements. As evident, the measured results were found to be within the limits of calculated range of settlements. Further curve fitting was undertaken considering the measured readings to ascertain the volume of settlement trough and the trough width factor. Figs. 5 (a to d) show the transverse settlement trend for soft soil (Unit 2), while Figs. 5 (e-g) and Figs. 5 (h-j) show settlement trends for stiff clayey silt (Unit 3a) and silty sand (Unit 3b). The curve fitting was undertaken in an iterative manner considering the measured settlements and the volume of settlement trough within 10% to 15% of the measured settlement trough volume (Golpasand et al. 2016). The width and volume of settlement trough too were found within calculated ranges. Figs shows the plot of width of settlement trough in context with the trough width factor along with its general range as per geological conditions. The extent of settlement trough observed was found to broader or wider for the clayey soil types with trough width factor ranging from 0.35 to 0.55 while the range of trough width factor

was found to vary from 0.3 to 0.5 for silty sands. Higher value observed for silty sand soil can be inferred due to the high silt content and presence of clayey layer above.



(a)



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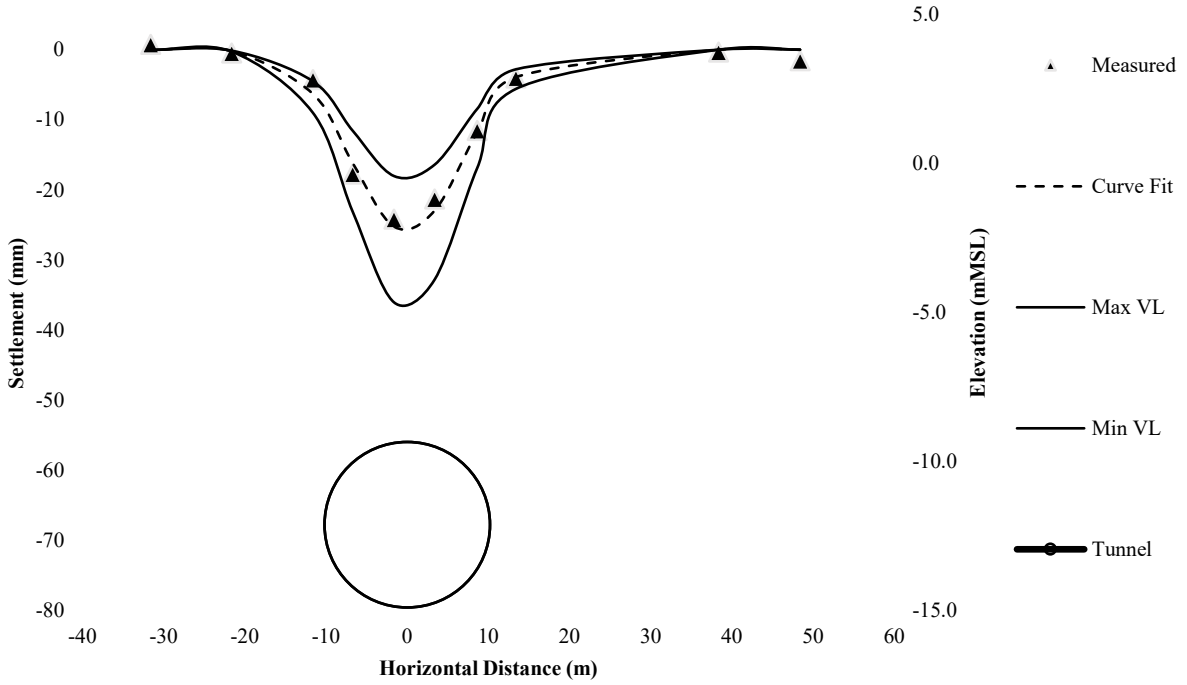
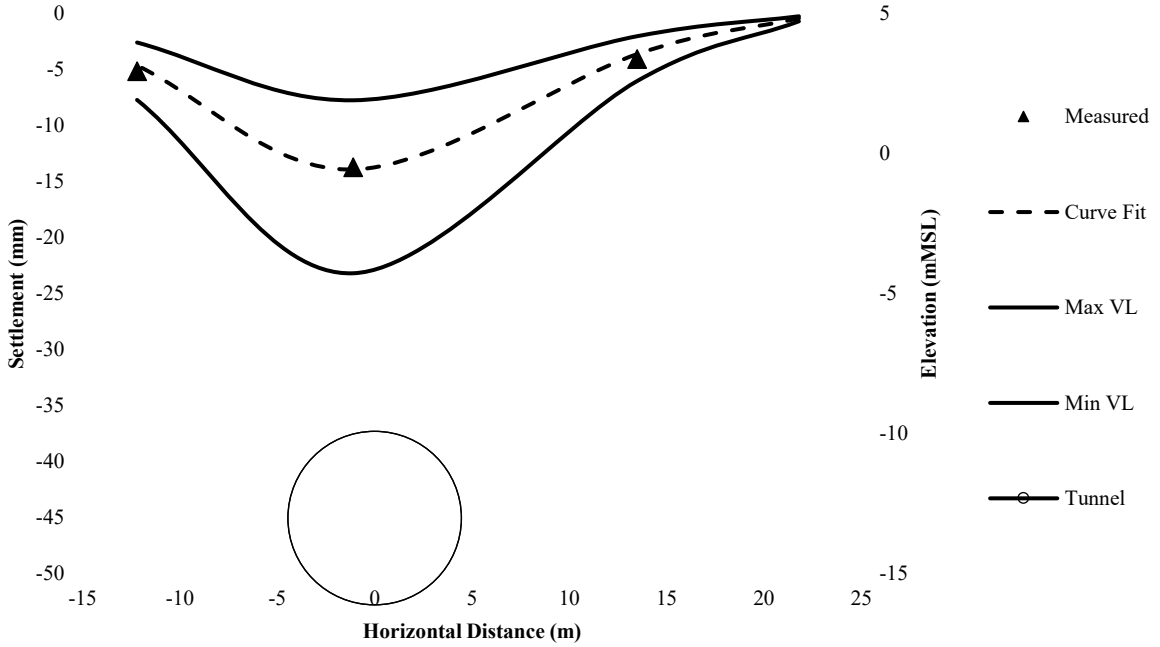
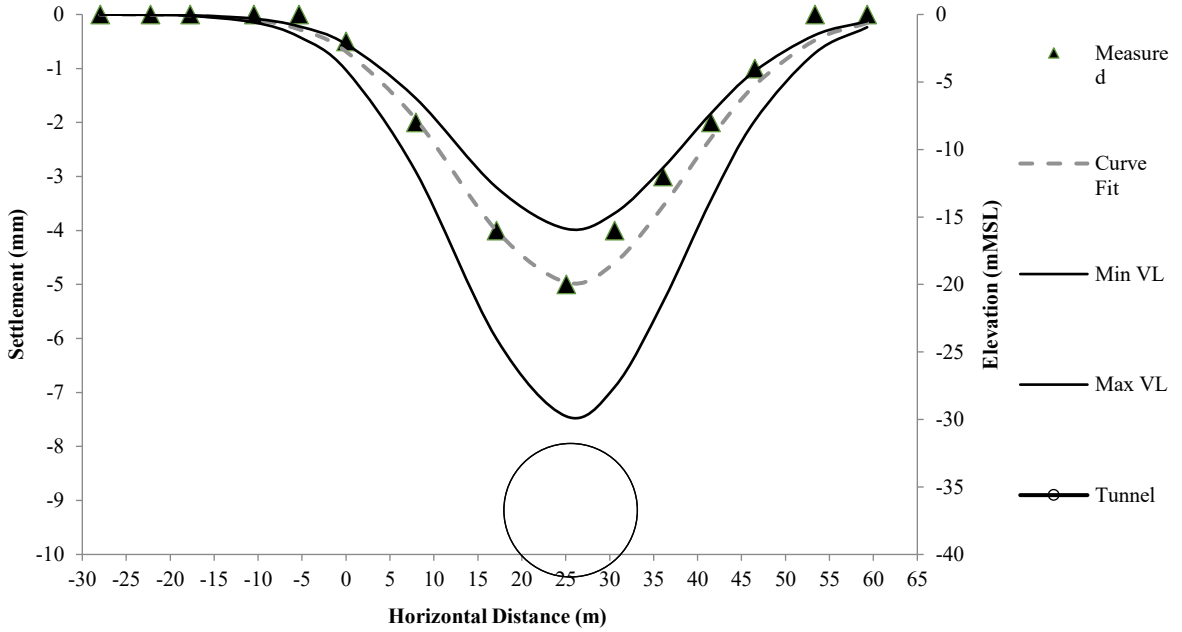

Settlement (mm)
Elevation (mMSL)
Horizontal Distance (m)
Measured
Curve Fit
Max VL
Min VL
Tunnel

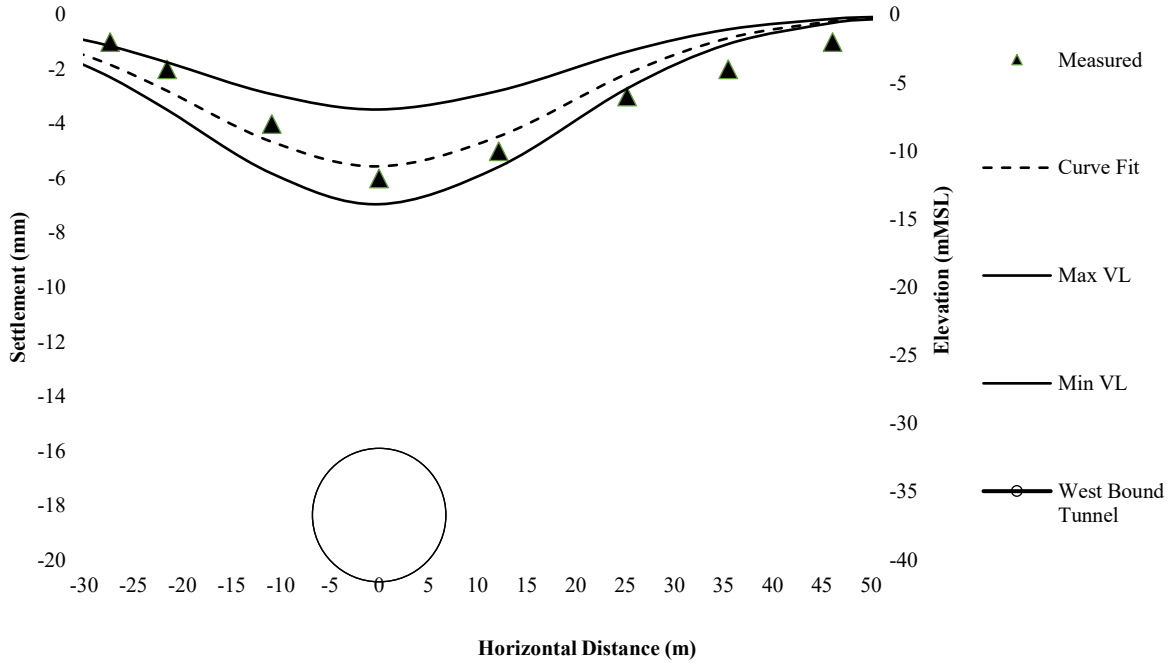
(c)


Settlement (mm)
Elevation (mMSL)
Horizontal Distance (m)
Measured
Curve Fit
Max VL
Min VL
Tunnel

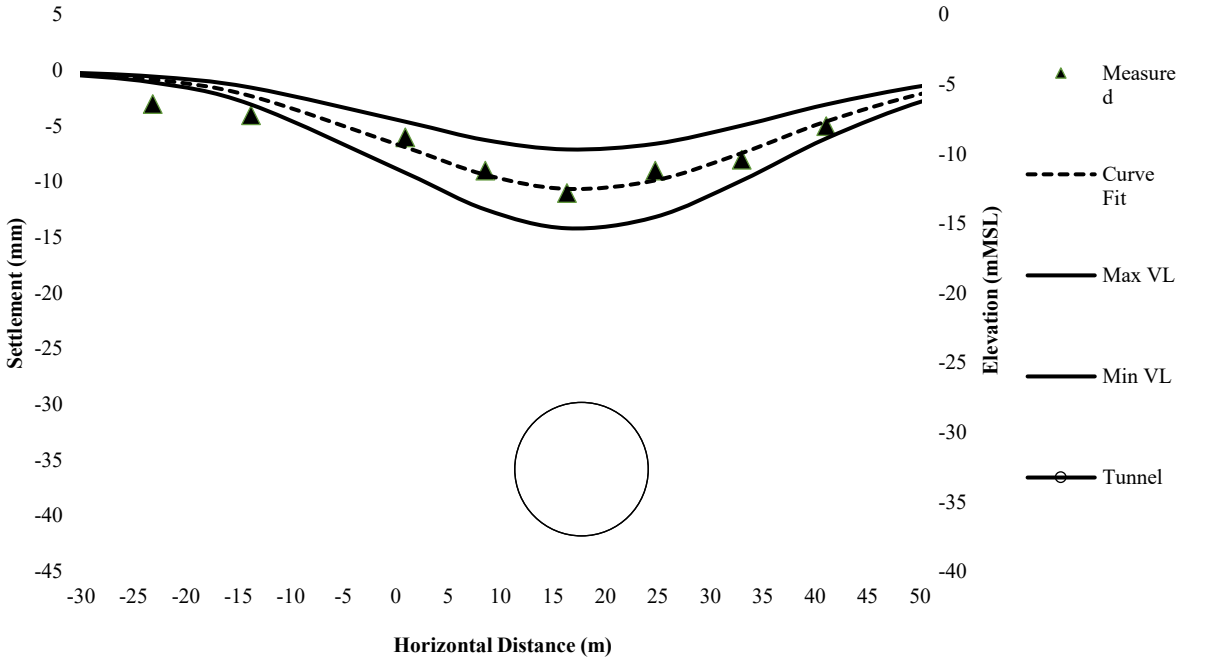
(d)


Settlement (mm)
Elevation (mMSL)
Horizontal Distance (m)
Measured
Curve Fit
Min VL
Max VL
Tunnel

(e)


Settlement (mm)
Elevation (mMSL)
Horizontal Distance (m)
Measured
Curve Fit
Max VL
Min VL
West Bound Tunnel

(f)



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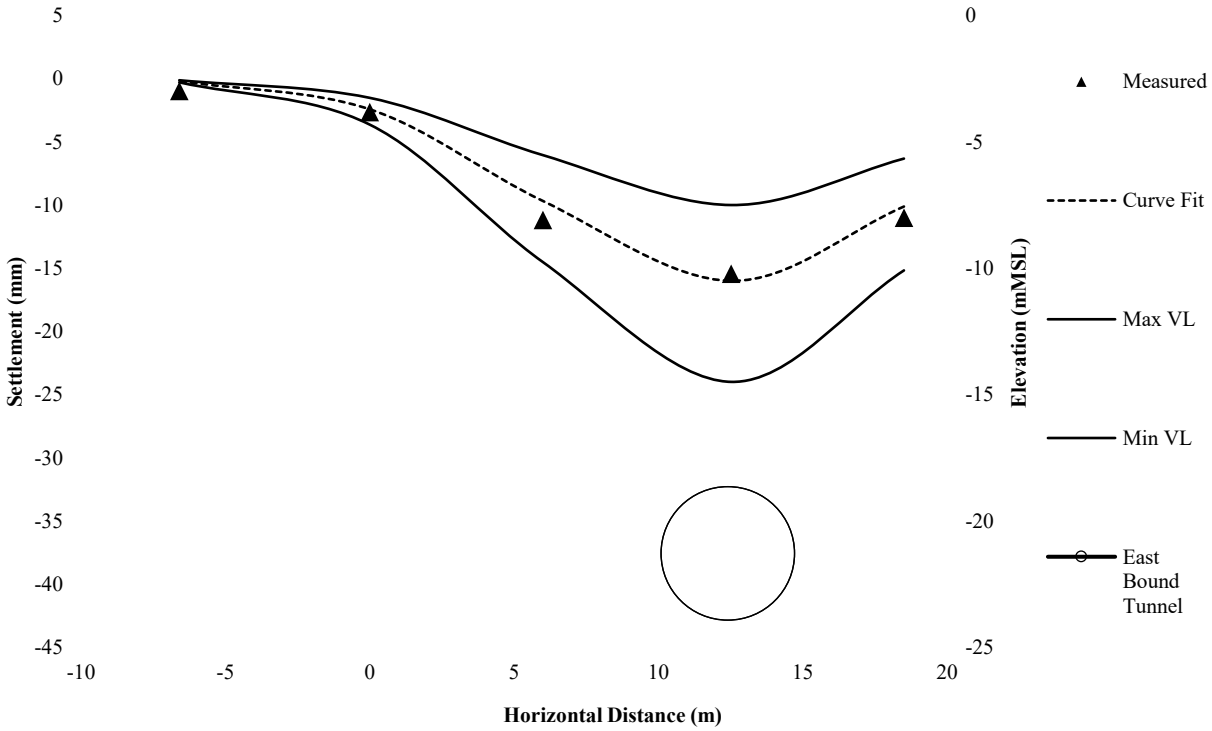
329 (g)



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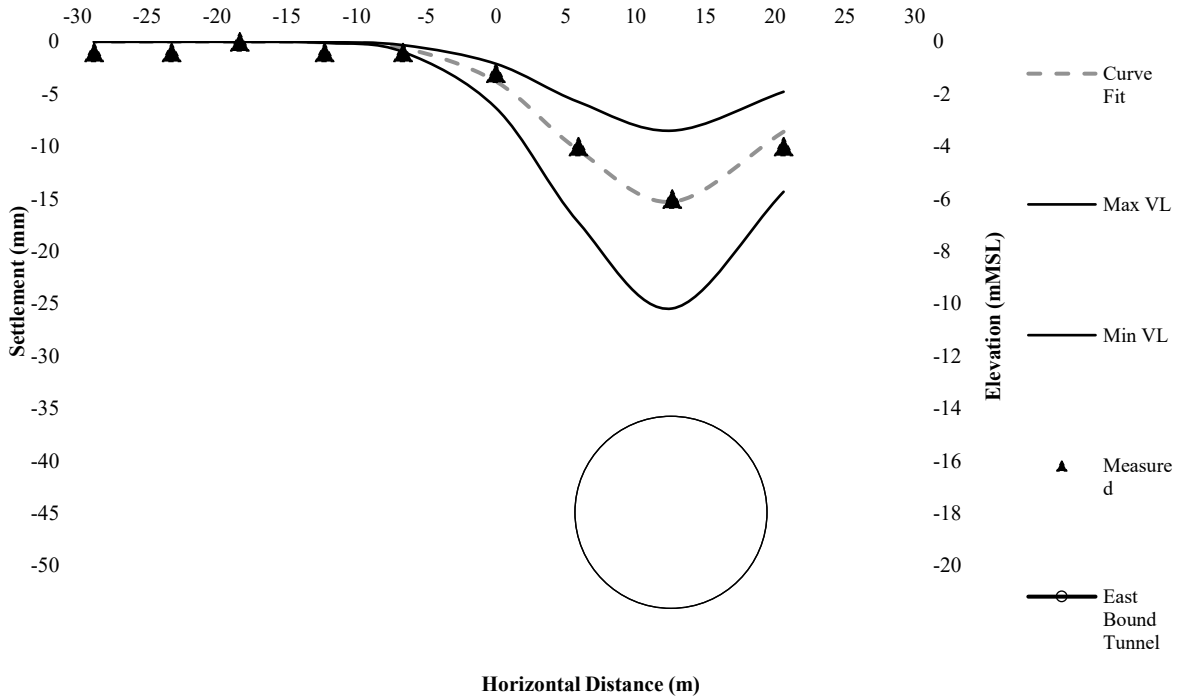
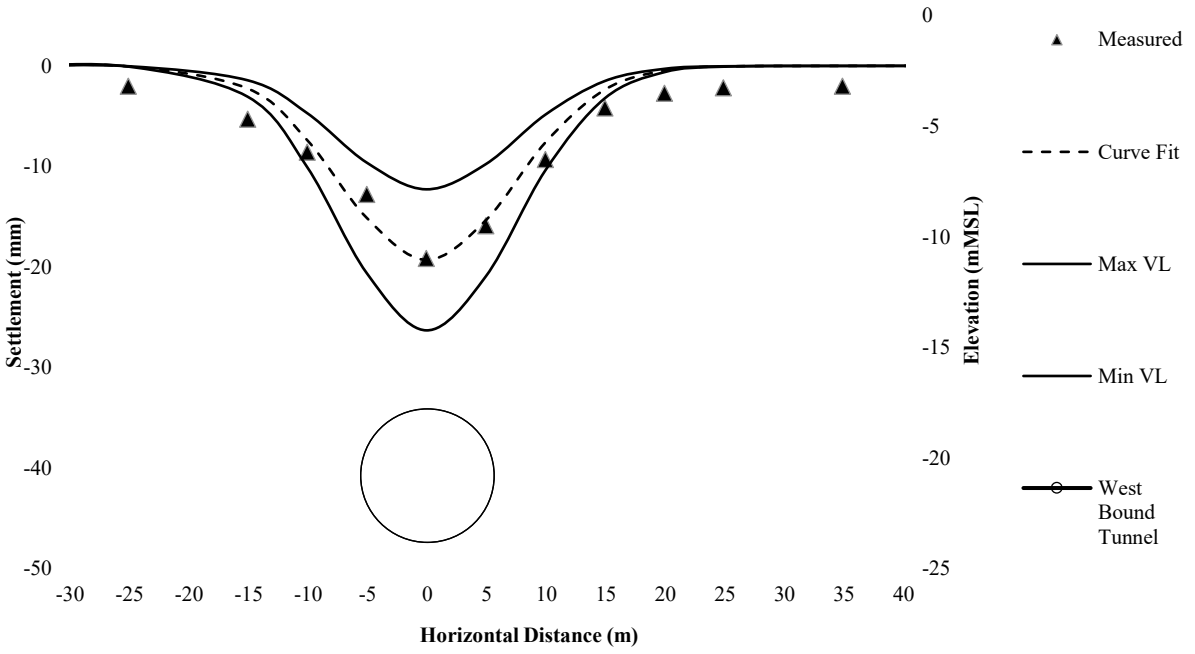
331 (h)

332



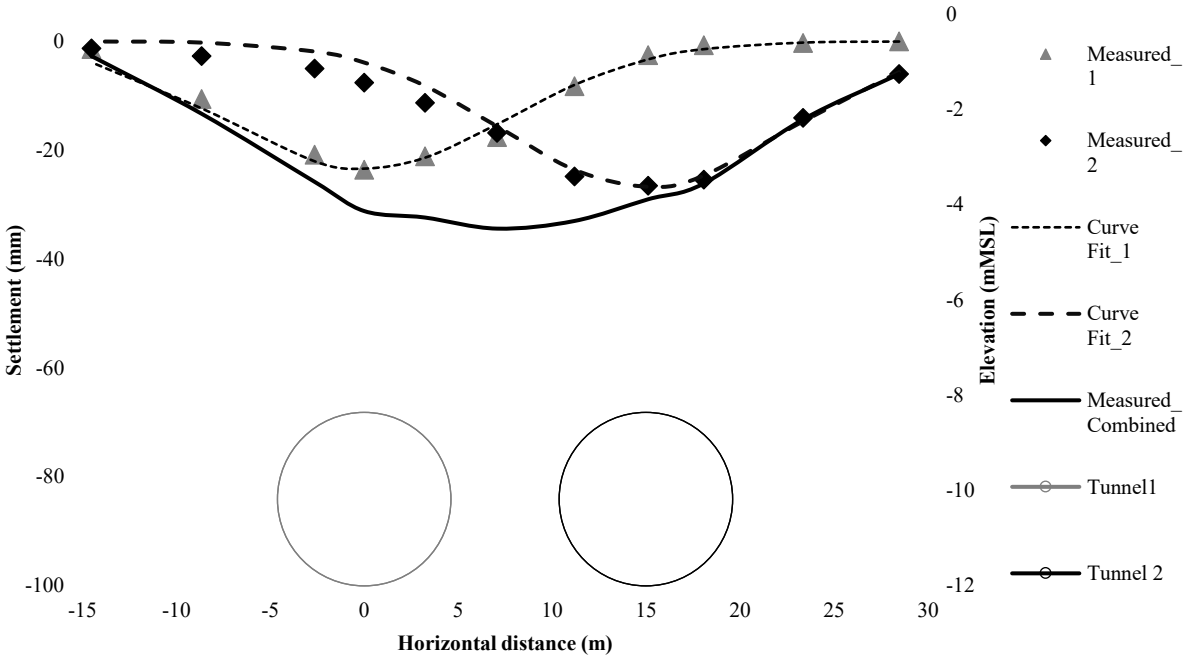
(i)



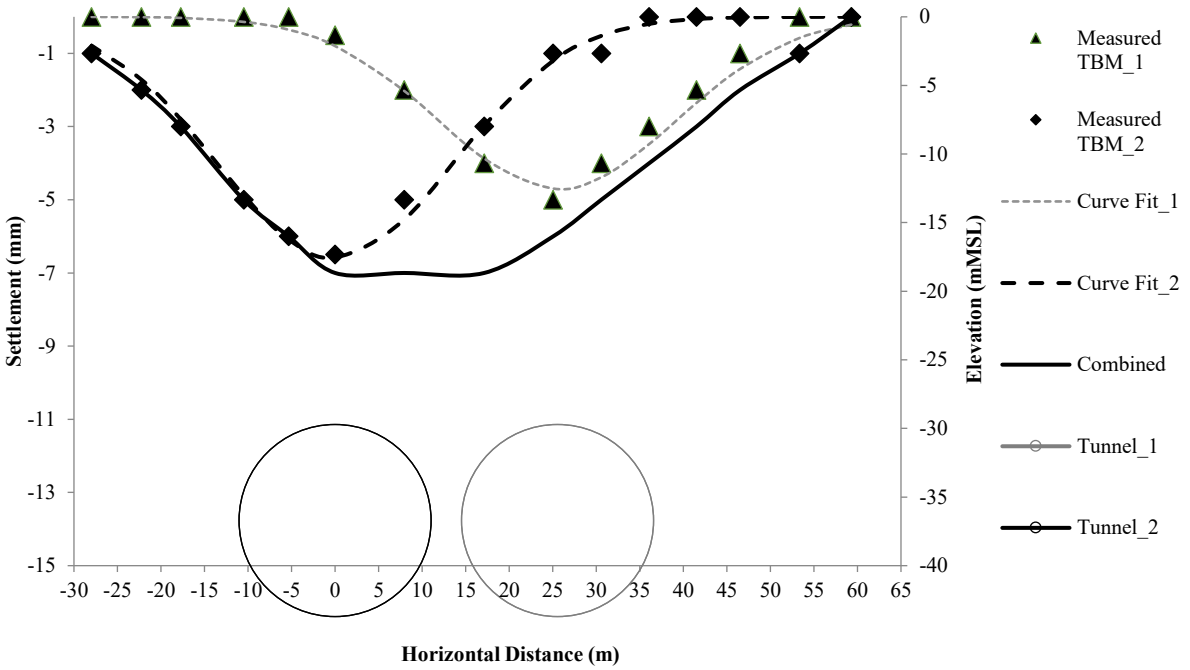
(j)

Figs. 5a-j Typical transverse settlement plots comparing estimated (max and min volume loss) with measured settlements (a-d) Soft soil - Unit 2 (e-g) Stiff soil - Unit 3a (h-j) Sandy Silt (Unit 3b)

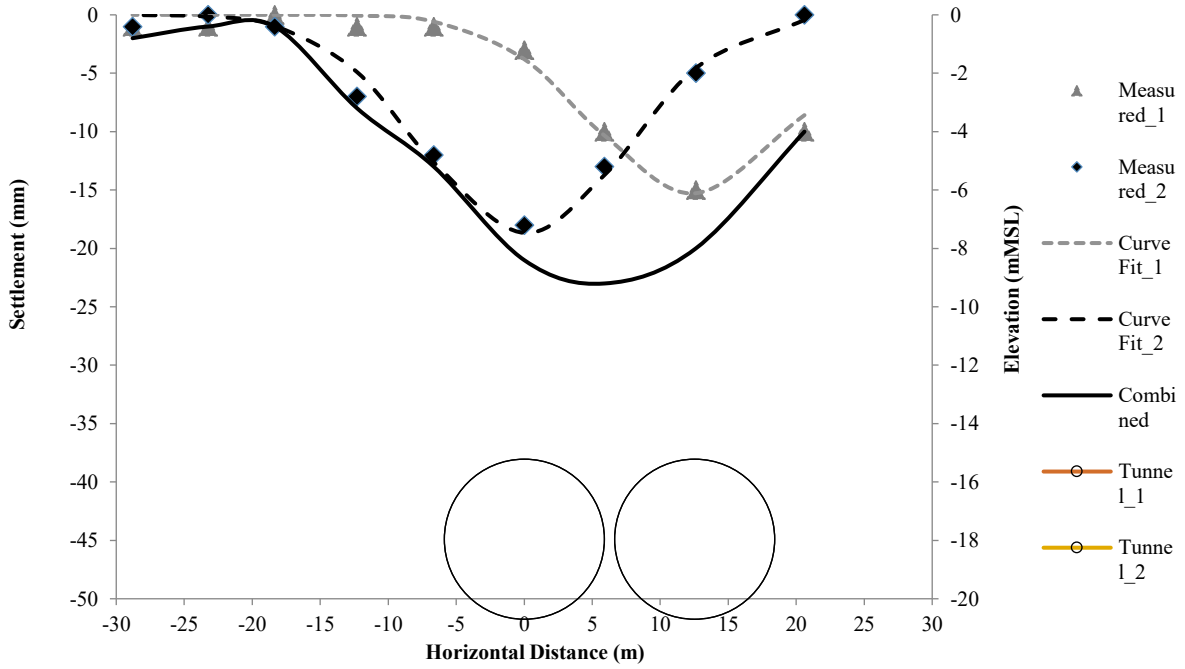
Figure 6 further shows the typical trend of twin-tunnel or settlements due to the second tunnel construction as observed in different geology types. As was observed, the maximum settlement and settlement trough and hence overall volume loss, was consistently greater for the second tunnel as compared with the volume loss due to the first tunnel construction by 10% to 20%. This observation is again in line with the literatures for twin tunnelling whereby the second tunnel has reported relatively higher volume loss (Addenbrooke and Potts 2001, Chapman et al. 2007, Hunt 2005, and Divall and Goodey 2015)). The trend and extent of settlement trough for volume loss due to second tunnel was found to be similar with the volume loss due to first tunnel.



(a)



(b)



Figs. 6a-c Typical plots for twin settlements (a) Unit 2 (b) Unit 3a (c) Unit 3b

Typical values of trough width factor, k, were back-calculated from the measured data by considering the curve fittings from Fig. 5 and have been show in Fig. 7. The measured back-calculated trough width factors, k, for single tunnels and twin tunnels, as shown in Fig. 5 and

6, have been compared with the typical ranges of trough width factors for various geologies (Mair et al. 1999, Fang et al. 2014). Relatively higher value for k, ranging from 0.4 to 0.6 were reported for clayey silts while values around 0.3 to 0.4 were reported for sandy silts. The observed or measured trend has been further compared with reported values of trough width factors as reported in various literatures (Vu et al. 2016, Wan et al. 2017).

The measured volume loss, as back-calculated from the settlement trough, as shown in Fig. 5 has been plotted in in geometrical context in Figure 8 along with the assessed range of minimum and maximum volume loss and has been again represented in Fig. 10 along with the observed volume loss, as reported in various from literatures in context with the tunnel geometrical ratio (Rezaei and Ahmadi-adli 2020, Farrokh et al 2021,). As evident from the plot, the estimated and are found to be in good agreement.

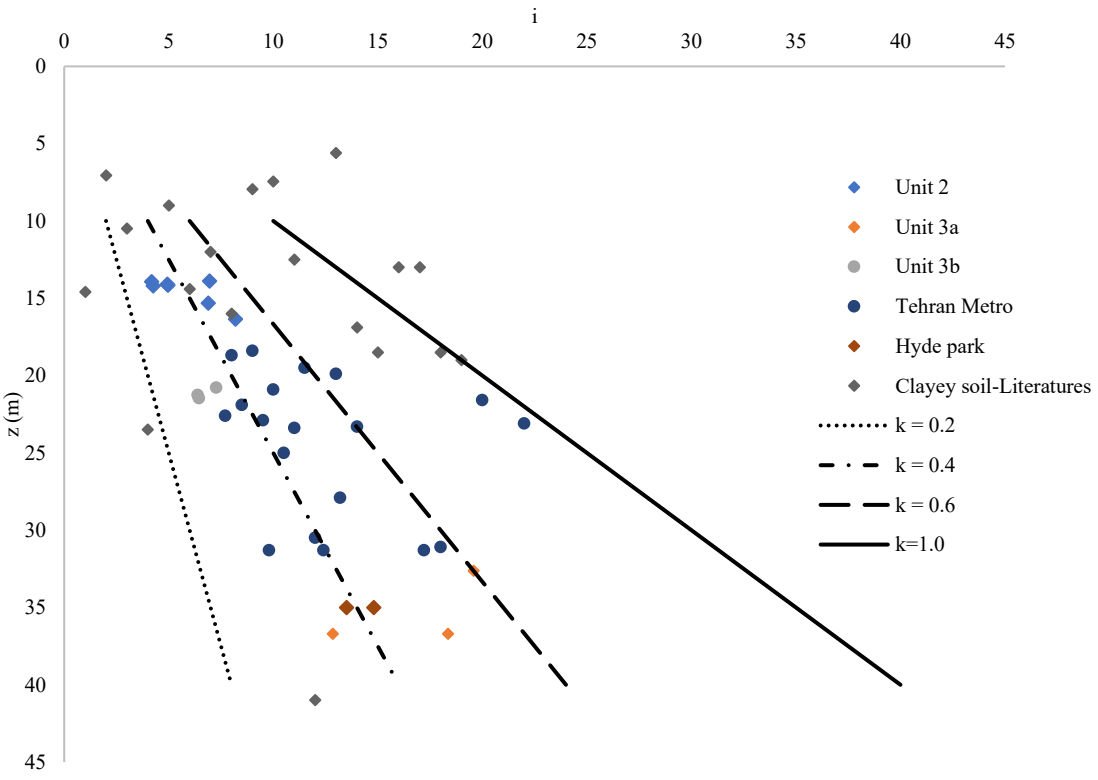
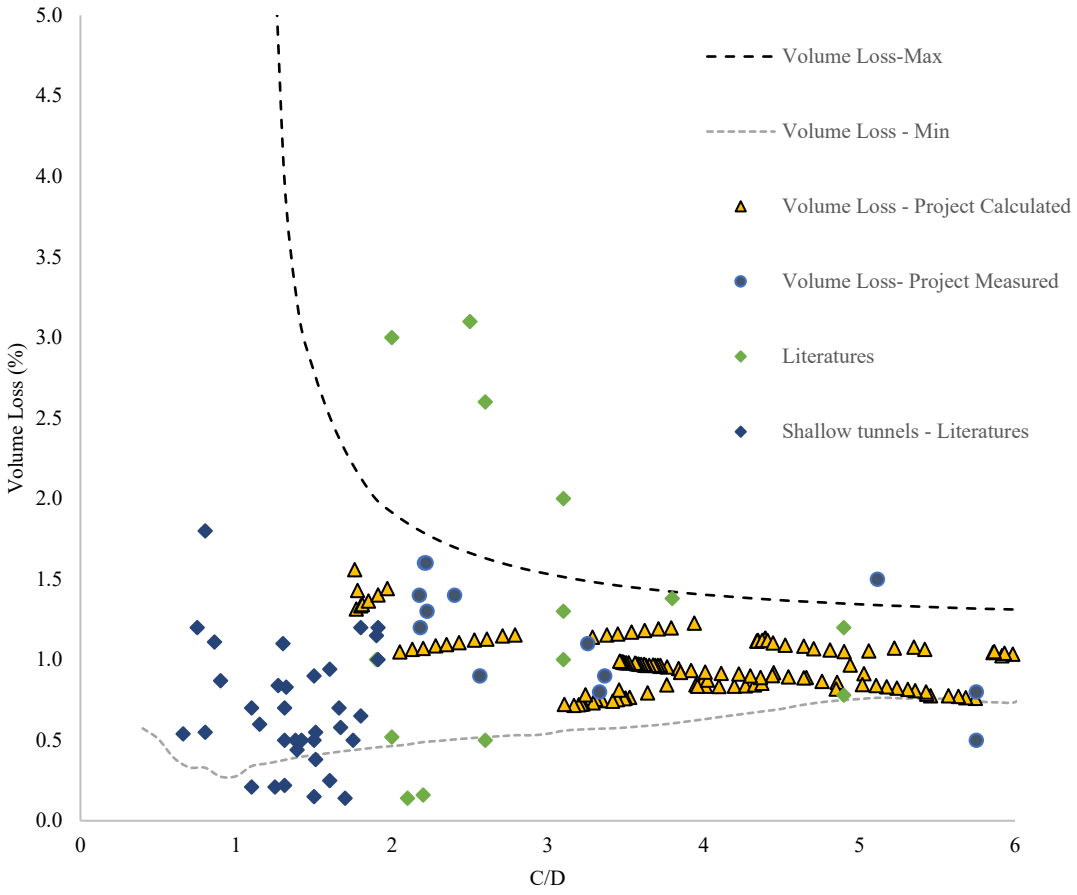


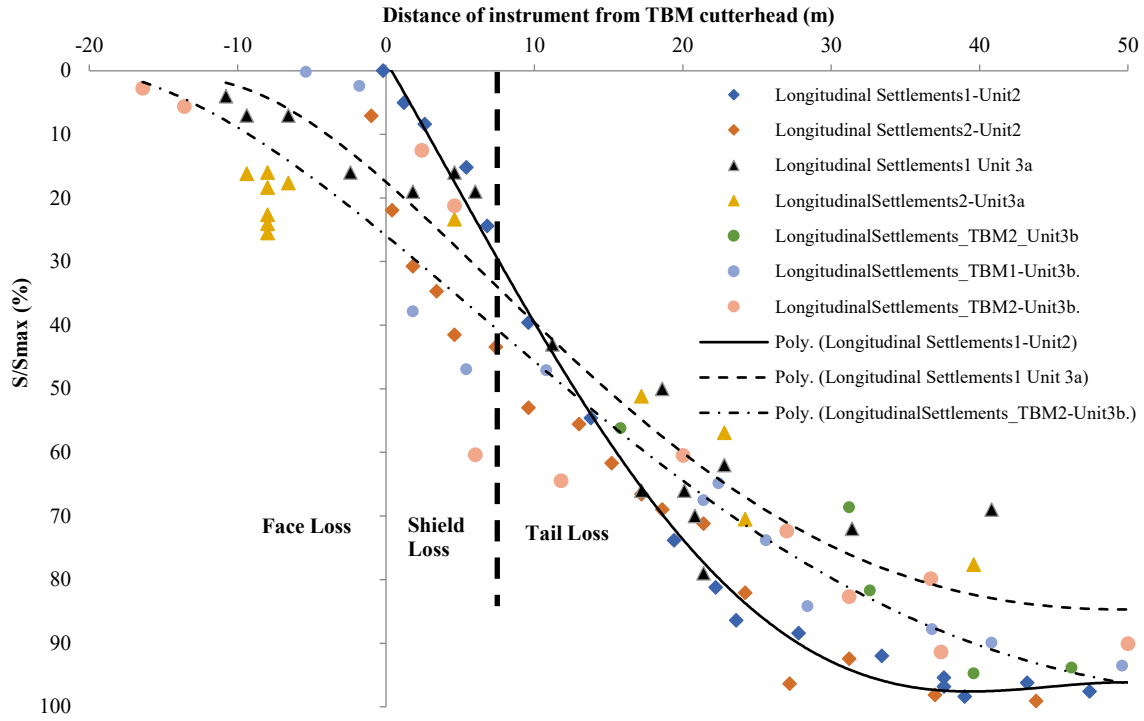
Fig. 7 Trends of trough width factor as back-calculated



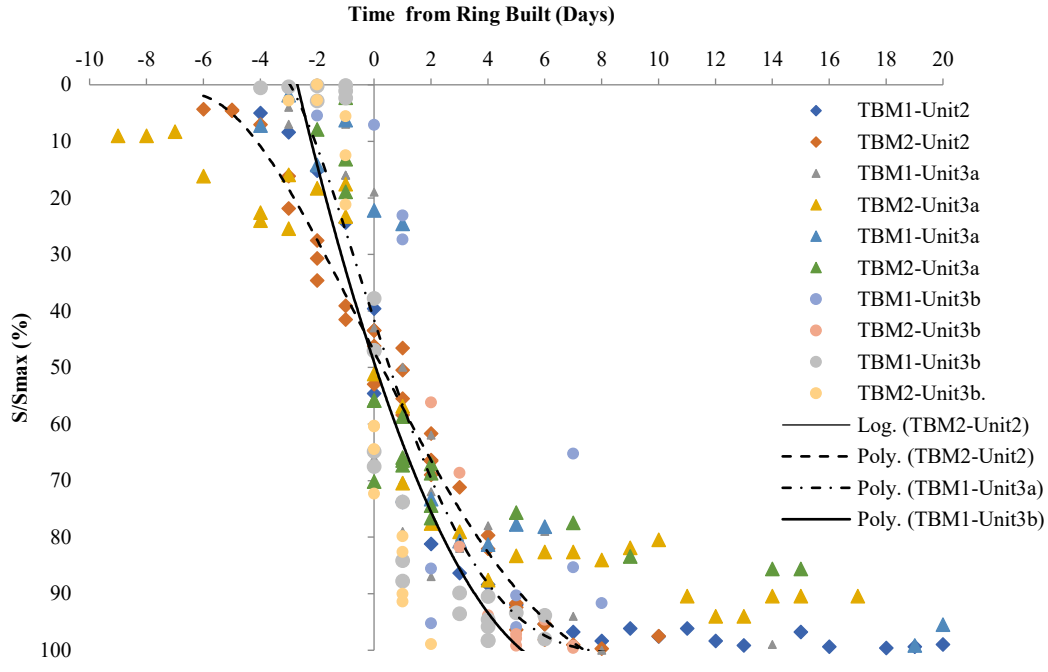
372

373 Fig. 8 Volume loss in geometrical context

374 To ascertain the amount of face loss incurred from the volume loss, the trends of longitudinal
375 settlements are further plotted. Fig. 9a shows the measured trends of normalized settlements
376 with relative positions of TBM cutter head. Fig. 9b shows the measured trends of normalized
377 settlements in context with time from the shield crossing. The dashed lines in Fig. 10 shows
378 TBM length, that is 8.8m for current study. It can be noted from Fig. 9a that settlements in the
379 tune of 10% to 20 % commence at the TBM cutter head itself, which further extends to approx.
380 50% during the shield crossing, while the remaining 50% of settlements can be observed after
381 shield crossing, post which the short-term settlements stabilize. Fig. 9b shows the observed
382 time bound response of settlements with respect to TBM movements in context with the
383 distance to TBM cutter head and time from ring build respectively in different soil conditions.



(a)



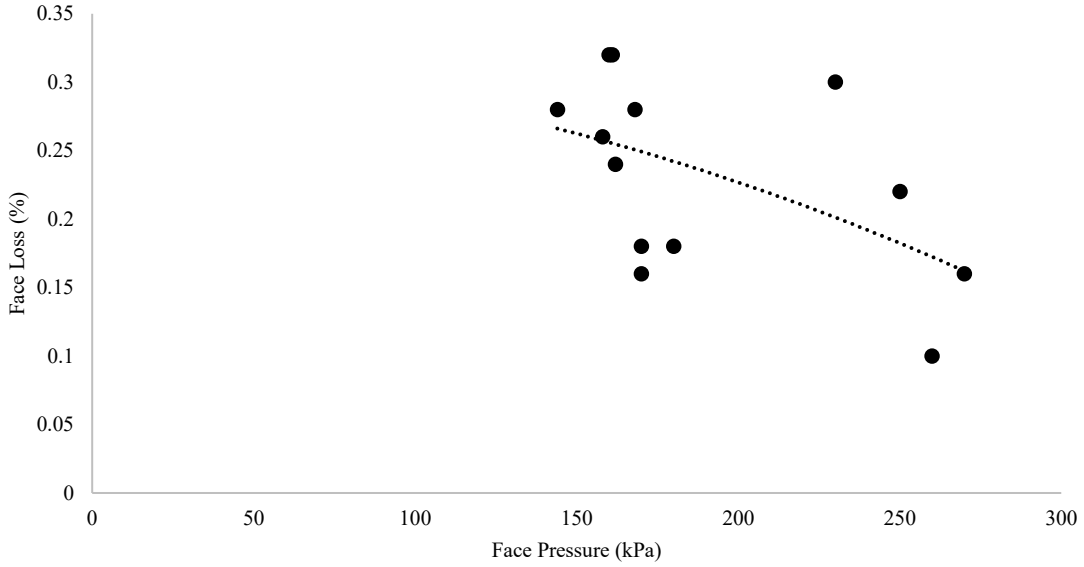
(b)

Figs. 9a-b (a) Trend of normalized maximum settlements with respect to distance from TBM cutterhead (b) with respect to time from lining build in different geologies

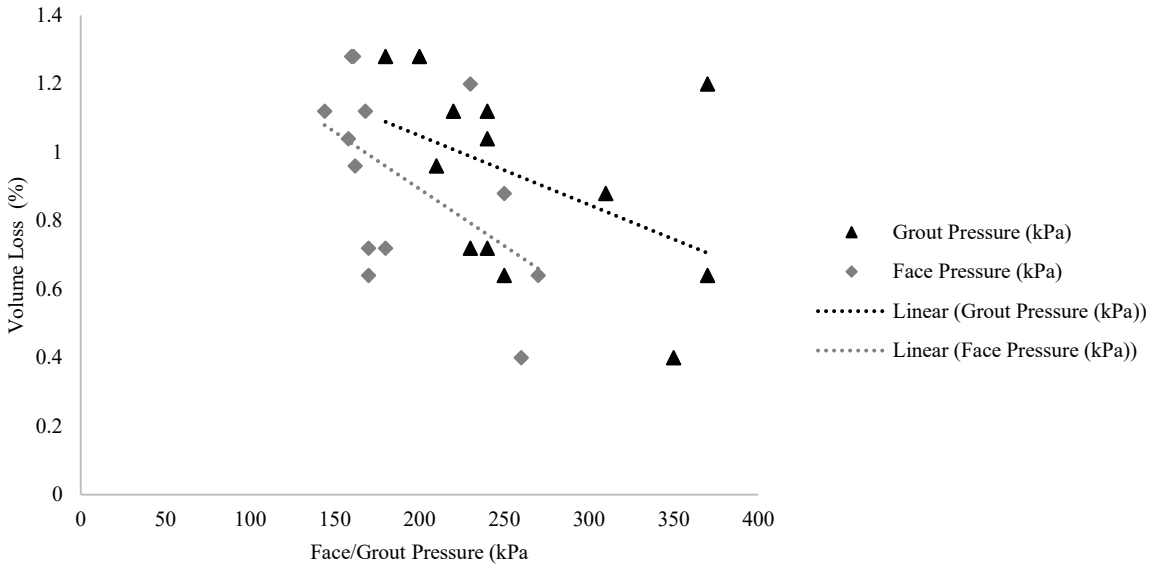
Again, as evident, since the ring is built at the tail of TBM shield, hence by the time 50% of the settlements can be observed post which again the remaining settlements take place. It can also be noted that for stiff clay ground type, a nominal delay for final settlement can be noted in both plots Figs. 9a-b. From both figures it also be established that roughly 15% to 20% of observed settlements can be attributed to face loss or soil deformations before the TBM cutter head enters. Incrementally 20% to 30% of settlements can be attributed to shield loss summing up to 40% to 50% of total settlements by the time tail shield moves. 50% to 60% of settlements can be attributed to tail void loss.

Figure 9b takes into account the time bound tail void settlements observed after passing of tail shield. It can be noted from the figure that settlements reach the maximum value in a time frame of 2-5 days from the time of ring built and further undergoes a minor deformation that might be contributed to lining deformation.

Face loss, as back-calculated from the volume loss considering the transverse and longitudinal settlement curves, have been plotted in context with the respective face pressures in Fig. 10a. Inverse correlation between the face loss and face pressure can be observed thereby confirming reduced trend of face loss with increasing face pressure. Further trend of overall volume loss, incorporating the tail and void losses, have been further compared in context with face pressure and annulus grout pressure in Fig. 10b. Again, an inverse correlation between the applied support face and grout pressure with the volume loss was observed thereby confirming reduced volume loss with increase in pressure (Chen et al. 2025).



(a)



(b)

Figure 10 (a) Actual face pressure v/s actual face loss plot (b) Tail and Shield loss v/s bentonite/grout pressure

4. Face and Volume Loss predictions using cutterhead - soil interaction approach

Based on the literatures and discussions above, the face loss can be further categorized into functions of factors such as tunnel geometry, geotechnical parameters and TBM operation parameters as; tunnel geometry parameters, that is tunnel depth (z) and tunnel diameter (d), hydro-geological parameters: shear strength of soil, Youngs Modulus of soil (E) and water pressure (Υ_w) and TBM operational parameters such as face pressure (σ_t). Considering the discussed literatures for assessment of face loss as presented in sections above and cutterhead-soil interaction approach (Sharma et al. 2024, Sharma and Juneja 2025), the real-time assessment of face loss is proposed as function of TBM boring parameters during TBM operation. Equation for face loss as a function of machine parameters is as follows:

$$FL = \frac{\gamma H - \sigma t}{E}.100 \quad (14)$$

The volume loss due to the TBM is considered as function of the tunnel geometry parameters, that is the tunnel depth (z), tunnel diameter (d) and TBM gap parameter; hydro-geological parameters such as shear strength of soil (c_u), Youngs modulus of soil (E) and water pressure (Υ_w) and TBM operational parameters such as face pressure (σ_t), bentonite and annulus tail grouting pressure. Considering the discussed literatures for volume loss and cutterhead-soil interaction approach (Sharma et al. 2024, Sharma and Juneja 2025), the proposed equation for

real-time assessment of volume loss, as function of TBM boring parameters during TBM operation is as follows:

$$VL = FL + \Omega.\frac{(1+v)\,(YH - \sigma_g)}{E} \quad (15)$$

where, Ω is the soil parameter, 1 for soft soil and 2 for stiff soils, v is the poisons ratio, σ_g is the grout pressure

$$E' = k.g.\frac{T}{\pi.\frac{d^2}{4}.A_r} \quad (16)$$

where, d is the tunnel diameter, A_r is the ratio between the opening area of TBM cutterhead and the total area of cutterhead (40%) and g is the acceleration due to gravity/mass to force conversion factor (9.81m/s^2) and k is the soil co-efficient factor, 2 for soft clay, 2.7 for stiff clay and 2.4 for silty sand. The value of k is found nearing to co-efficient of passive earth pressure of soil. Considering field/lab test results (Table 1) and Rankine's equation ($\frac{1+sin\phi}{1-sin\phi}$), the co-efficient of earth pressure, k_p for clayey silt and silty sand is calculated to be ranging between 2 and 3.2 and hence the suggested soil co-efficient k would likely signify the mobilized or applied earth pressure during TBM advance (Sharma 2023).

$$\gamma = (\xi)T^{0.13} \quad (17)$$

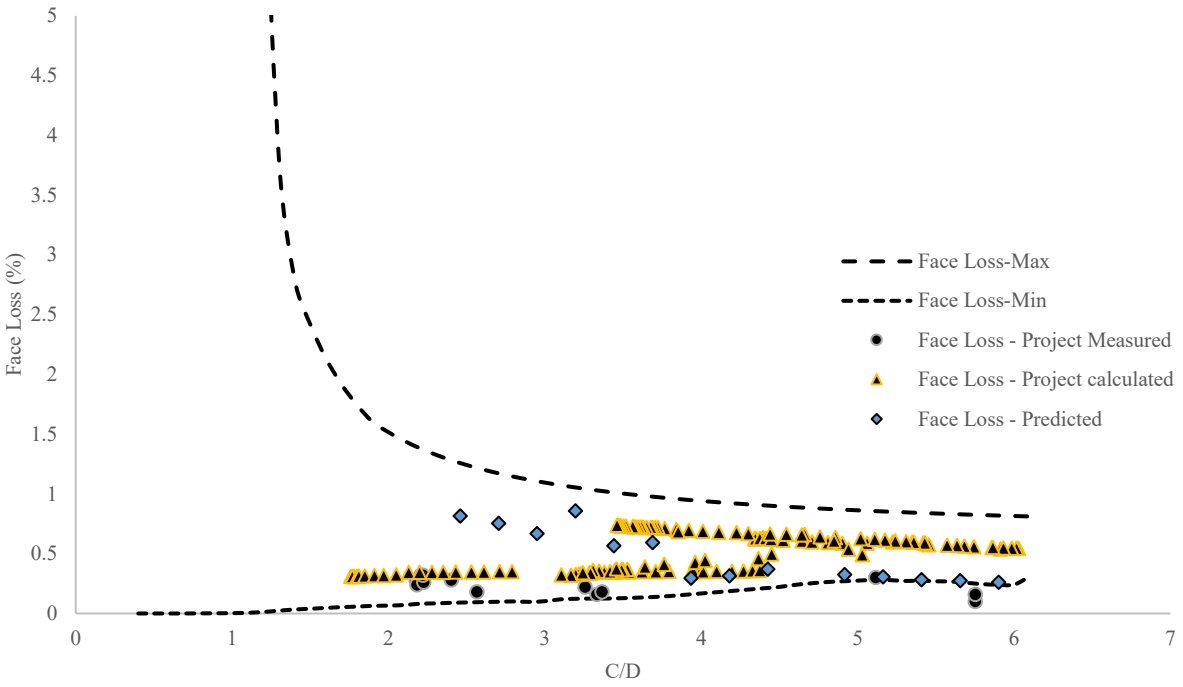
where ξ is constant defined as 5.5 for fine grained soils and 5.7 for coarse grained soils

$$\sigma_t = \frac{k_p.T}{\pi.\frac{d^2}{4}.A_r.g} \quad (18)$$

Where, maximum vertical overburden pressure ($\gamma.h$) is restricted to depth of 3 times the diameter.

$$\sigma_g = \frac{k_p.T}{\pi.\frac{d^2}{4}.A_r.g} + 50 \quad (19)$$

The above equations using machine-soil interaction approach allows estimation of face and volume loss, inherently as function of real time TBM operation parameters. Fig. 11a-b show the plots of face and volume loss predicted using the above method by considering TBM boring parameters considering machine-soil interaction approach. As can be observed from the results that the predicted values were found within the range and comparable with the measured values.



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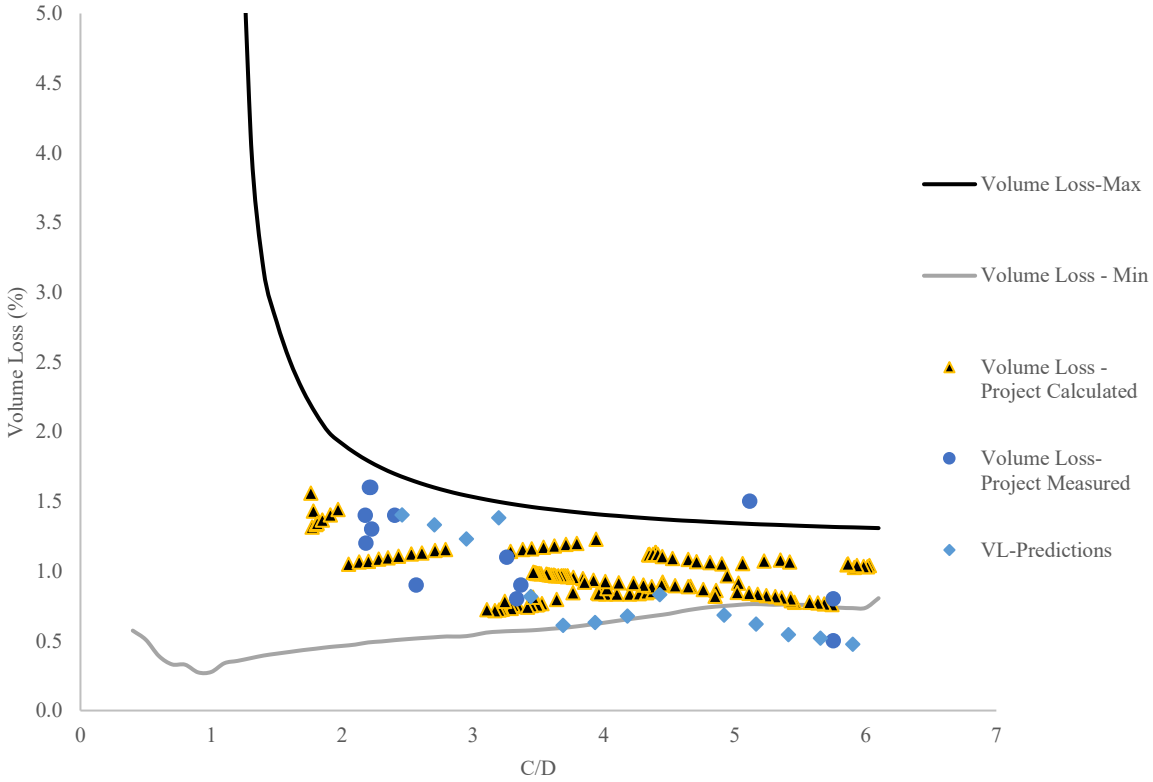
460 **(a)**



461

462 **(b)**

463 Figs. 11a-b (a) Face loss and (b) volume loss as predicted versus calculated in C/D

5. CONCLUSION

The study reviews aspects of settlements due to mechanised shield tunnelling such as face and volume loss, trends of transverse and longitudinal settlements due to tunnels. Study evaluates face and volume losses considering range of face and grout pressures using project application for Kolkata East–West Metro UG-1. The evaluated face and volume loss were compared with the measured values from the project and are found to be reasonably within the assessed range. The measured settlements were further compared for various aspects such as transverse, longitudinal settlements trends and trough with factor for single and twin tunnelling and were again found to exhibit a good agreement with each other. The trend of ground settlements was studied with respect to time and distance from TBM for different soil types. The results confirmed around 20% of volume loss attributable as face loss while around 30% as shield loss while around 50% settlements as tail losses which occur after the shield passes. Study further proposes model for real time assessment of face and volume loss using cutterhead - soil interaction approach that is mechanical response to stress/strain applied by machine (TBM). Correlations have hence been proposed for assessment of face and volume loss during TBM operations as function of TBM boring parameters. These correlations have been validated by comparing the predicted face and volume loss with the estimated range and measured values for the project data. The results were again found to be in good agreement.

Limitations and Discussions

The proposed models are based on relatively homogeneous soft ground conditions and for mid-range tunnel diameters. The models would require suitable amendments for heterogenous conditions and larger diameter TBMs.

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