Expanding Underground. Knowledge and Passion to Make a Positive Impact on the World – Anagnostou, Benardos & Marinos (Eds)

Semi-analytical prediction of ground surface settlements due to EPB tunnelling in Kolkata

H. Jain & Th. G. Sitharam
Department of Civil Engineering, Indian Institute of Science Bangalore, Bengaluru, India

ABSTRACT: A novel Gaussian distribution function is used to model the ground volume loss around the tunnel periphery based on which an attempt has been made to predict the ground settlements by using linear elastic analytical solutions. A set of around 6 m diameter twin-tunnels spaced 6 m apart are being constructed in Kolkata using Earth Pressure Balance (EPB) Tunnel Boring Machines (TBMs) at a cover depth of around 20 m. The ground strata is predominantly silty clay, clayey silt with concentration of sand around the tunnel region. A ground volume loss of around 1-2% has been observed at different transverse sections on the tunnel alignment. Field monitoring reported after the tunnelling appears to conform with the analytical solutions. The disparity in the analytical and the field observations can be attributed to non-linear, anisotropic and non-homogenous soil behaviour around the tunnel opening. The simplicity of the solution allows it to be used by the engineers without having to go for complicated analytical and numerical solutions.

1 INTRODUCTION

Analytical methods provide mathematically rigorous solution to a boundary value problem and are simple and time-efficient to use. These solutions for tunnelling problems are predominantly based on plane strain approximation of three-dimensional tunnelling problem. Face loss and radial loss around a tunnel can be incorporated indirectly using a broader term known as ground volume loss. The volume loss around the tunnel periphery could be modelled by prescribing (i) displacement or (ii) traction as a tunnel peripheral boundary condition. The displacements on the tunnel periphery could be either (i) uniform, or (ii) non-uniform (Figure1).

During shallow mechanized tunnelling, the non-uniform tunnel peripheral movement is observed (Lee et al. 1992, Rowe & Lee 1992). Therefore, to better predict the ground surface movements, the tunnel peripheral displacements should be modelled non-uniformly.

In this study, the non-uniform tunnel peripheral movements are modelled using a novel Gaussian distribution function (Jain & Kumar 2022). Sagaseta (1987), Verruijt & Booker (1996) provided closed form solution for a uniformly deforming tunnel using virtual image technique. The solution for ground displacements is then obtained by modifying the solution offered by Verruijt & Booker (1996) by incorporating non-uniform tunnel peripheral displacements. The ground surface movements for 8 different case studies are analyzed from the field measurements during twin tunnelling in East-West Metro, Kolkata. Further, semi-analytical solution is then compared with the field measurements.

DOI: 10.1201/9781003348030-236

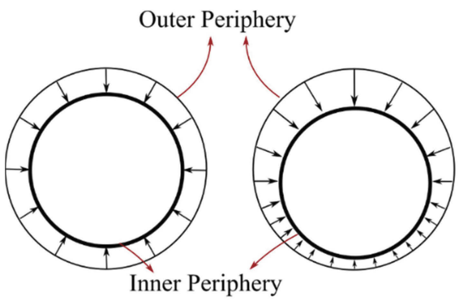


Figure 1. Tunnel periphery movements: (a) uniform distribution and (b) non-uniform distribution.

2 SEMI-ANALYTICAL MODEL: GAUSSIAN DISTRIBUTION FUNCTION

A tunnel of radius R embedded at a depth h from the ground surface is considered (Figure 2a). The long cylindrical shallow tunnel is represented by a circular cavity in plane strain condition. A polar coordinate system is w.r.t. the centre of the tunnel with $\tilde{\theta}$ measured from the negative z-axis.

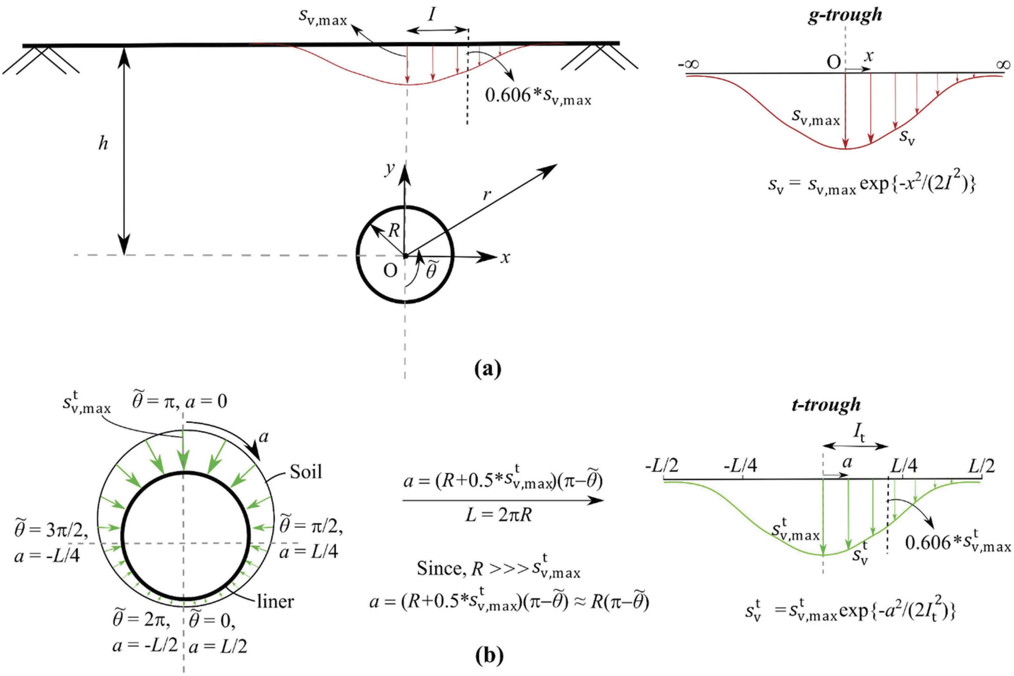


Figure 2. (a) Vertical ground surface settlement trough, (b) the distribution of radial displacement around tunnel periphery.

The vertical settlement at any point x on ground surface is represented by the following equation (Peck 1969):

$$s_v = s_{v,max} \exp\{-x^2/(2I^2)\} \quad (1)$$

where, $s_{v,max}$ is the maximum ground surface vertical settlement (the dip of the trough), and I is the trough width. It is proposed that the tunnel peripheral ground movement can be modelled using a Gaussian function (Figure 2b) given by

$$s_v^t = s_{v,max}^t \exp\{-a^2/(2I_t^2)\} \tag{2}$$

are obtained when the soil is taken to be undrained, i.e., v = 0.5. In such a case, all the volume loss around the tunnel is reflected on the ground surface, i.e., the area of the two troughs should be equal: Area of the ground surface trough = $\sqrt{2\pi} s_{v,max} I$; area of the tunnel peripheral trough = $\sqrt{2\pi}\, s_{v,max}^t I_t$. Therefore,

$$s_{v,max} I = s_{v,max}^t I_t \tag{3}$$

Ground volume loss (*GVL*) is defined as follows (Loganathan & Poulos 1998):

$$\mathrm{GVL} = \frac{\pi(2R + s_{v,max}^t)^2 - \pi(2R)^2}{\pi(2R)^2} \tag{4}$$

From Equation 4, $s_{v,max}^t$ can be found once the value of *GVL* is known. Substituting $s_{v,max}^t$, $s_{v,max}$ and I in Equation 3, the value of I_t can be obtained. Once the parameters $s_{v,max}^t$ and I_t are known, the complete tunnel peripheral displacement field becomes known. The ground loss parameter ε_0 for present study is obtained as follows:

$$\varepsilon_0 = s_v^t / R \tag{5}$$

Using virtual image technique, Verruijt & Booker (1996) obtained the following equations for the displacements of a uniformly deforming tunnel including the effect of ovalisation:

$$u_x = -\varepsilon R^2\left(\frac{x}{r_1^2} + \frac{x}{r_2^2}\right) + \delta R^2 x\left\{\frac{(x^2 - kz_1^2)}{r_1^4} + \frac{(x^2 - kz_2^2)}{r_2^4}\right\} - \frac{2\varepsilon R^2 x}{m}\left(\frac{1}{r_2^2} - \frac{2mzz_2}{r_2^4}\right) - \frac{4\delta R^2 xh}{m+1}\left\{\frac{z_2}{r_2^4} + \frac{mz(x^2 - 3z_2^2)}{r_2^6}\right\} \tag{6}$$

$$u_z = -\varepsilon R^2\left(\frac{z_1}{r_1^2} - \frac{z_2}{r_2^2}\right) + \delta R^2\left\{\frac{z_1(kx^2 - z_1^2)}{r_1^4} + \frac{z_2(kx^2 - z_2^2)}{r_2^4}\right\} + \frac{2\varepsilon R^2}{m}\left(\frac{(m+1)z_2}{r_2^2} - \frac{mz(x^2 - z_2^2)}{r_2^4}\right) - 2\delta R^2 h\left\{\frac{(x^2 - z_2^2)}{r_2^4} + \frac{2mzz_2(3x^2 - z_2^2)}{(m+1)r_2^6}\right\} \tag{7}$$

where δ = ovalization of tunnel over long time duration, v = Poisson's ratio of media, ε = ground loss parameter, m = 1/(1-2v), $k = v/(1-v)$, $z_{1,2} = z \mp h$, $r_1^2 = x^2 + z_1^2$, $r_2^2 = x^2 + z_2^2$, $x = r\sin\tilde{\theta}$; $Z = h + r\cos\tilde{\theta}$. Equations (6) and (7) can be modified by substituting δ = 0 and v = 0.5 as:

$$u_x = -\varepsilon R^2\left(\frac{x}{r_1^2} + \frac{x}{r_2^2}\right) + 4\varepsilon R^2 x\left(\frac{zz_2}{r_2^4}\right) \tag{8}$$

$$u_z = -\varepsilon R^2\left(\frac{z_1}{r_1^2} - \frac{z_2}{r_2^2}\right) - \frac{2\varepsilon R^2 z(x^2 - z_2^2)}{r_2^4} \tag{9}$$

The ground loss parameter in Equations 8 and 9 is replaced by non-uniform ground loss parameter of Equation 5 to obtain ground displacement corresponding to non-uniform tunnel peripheral movements.

3 CASE STUDY: EAST-WEST METRO, KOLKATA

In the deltaic region of Bengal basin lies flood plains of Hooghly River. Kolkata is a historical and densely populated city located on the banks of Hooghly River. A 16.4 km line East-West Metro consisting of 10.6 km of underground length is constructed beneath Kolkata as shown in Figure 3a. A set of twin tunnels spaced around 7-10 m apart with R = 3.19 m and h = 22-25 m are excavated using Earth Pressure Balance Tunnel Boring Machines (details given in Table 1). A 450 m section considered in this study lies between New Mahakaran and Esplanade metro stations as depicted in Figure 3b.

Table 1. Tunnel specifications.

Diameter of opening	6.380 m
Cover	22 - 25 m
Avg. centre to centre spacing of tunnels	12.760 m
Liner outer diameter	6.100 m
Thickness of liner	0.275 m

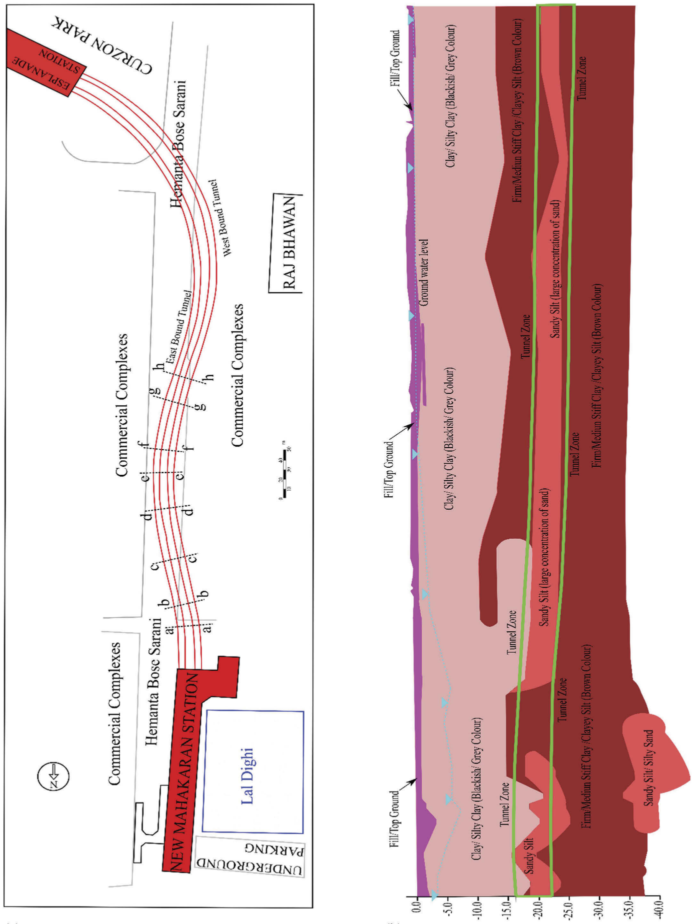
The longitudinal gradient of the tunnel along this stretch is around -1.00%. Further, the zone is traversed by many geological faults, however, the frequency of major earthquakes is quite low. The soil classification as per Indian Standard Classification System is CL, CI, CH, i.e., low, medium and high plastic clay, respectively. The soil is found to show plastic behaviour with Liquid Limit = 50, Plastic Limit =35 despite high level of silt content (details given in Table 2).

Table 2. Soil properties.

Description	SPT-N value	Undrained Shear Strength [kPa]	Unit weight, γ [kN/m^3]	Moisture Content [%]	Elastic Modulus E [MPa]
Fill	< 5	—	18.5	30	3
Clay/ silty clay	< 10	75	19	27.5 - 35	3.3
Silty sand/sandy silt	22	175	19.5	25 - 27	10
Firm/medium stiff clay	30	225	20	22.5 - 25	20

The soil is predominantly medium stiff silty clay, clayey silt, with concentrations of sand around the tunnel region. The Standard Penetration test (SPT) N-values around the top 10 - 12 m are around 10 suggesting medium stiff soil. Stiffer stratum is observed around the tunnel zone with SPT-N values ranging between 20 - 40. The undrained shear strength around the top 15m of the soil is varying from 50 - 120 kPa, which increases to 150 - 200 kPa around the tunnel zone. The permeability of the ground is higher near the top layers around 5 x 10^{-6} cm/sec while beneath the tunnel zone, it is between 1x10^{-7} - 2x10^{-7} cm/sec. For soft to medium soft clay, silty clay, the Youngs' Modulus is observed to be around 3 - 5 MPa in the top layers. Around and below the tunnel zone, this is varying between 5 - 20 MPa. Hence, the selection of tunnel zone at 20 - 25m depth is justified on account of stiffer stratum and more competent ground conditions.

Twin tunnelling is carried out initiating from Howrah Maidan Station with a gap of around 150 m between the two TBMs. The advancement rate of tunnel varied between 5-25m/day with intermittent halts. Tunnelling involves excavation of soil, transportation of muck from inside to outside, installation of segment liner and advancement of TBM. During twin tunnelling, the presence of the first tunnel affects the ground deformations generating due to the second tunnel



(a) (b)

Figure 3. East-West Metro Alignment: (a) Section between New Mahakaran and Esplanade Stations, (b) Stratigraphy.

construction. Therefore, for the West Bound (WB) Tunnel (first tunnel) construction, greenfield conditions prevail. The solution presented in this study is valid for greenfield condition, therefore the ground displacements after the construction of the WB Tunnel are discussed herein. For second tunnel, the ground displacements are affected by the proximity of the first tunnel. The ground volume loss observed after the East Bound (EB) Tunnel construction is marred by displacements of the first tunnel. However, an approximate prediction can be made even for the second tunnel.

Table 3 shows the ground loss parameters obtained from observed volume loss for eight different sections along the tunnel alignment (Section a-a to Section h-h) in East West Metro. The *GVL* is defined as the percentage ratio of area of ground surface settlement trough to the cross-sectional area to the tunnel. To obtain *GVL*, the two relevant parameters $s_{v,\max}$ and I are back-analysed from the field measurements of ground surface settlement trough. The area of the trough, as defined before, can be written as $\sqrt{2\pi}s_{v,\max}I$ which when divided by the tunnel cross-sectional area yields *GVL* values. In order to predict such a trough for future cases, previous tunnelling history, experiences in similar geotechnical conditions or some nominal values of *GVL* can be taken, say 0.5-1%, and the vertical settlement of the ground can be obtained before construction. The field measurements are obtained 1-2 day after the TBM pass a particular section. Thus, only short-term deformations are considered in this study. Long-time settlements continue to happen due to consolidation of the soil.

Table 3. Ground loss parameters observed at different sections of the East West Metro (EWM).

S. No.	Section	h [m]	GVL [%]	$s^{t}_{v,max}$ [mm]	I_t [m]
1	a-a	21.0	0.555	17.676	4.014
2	b-b	21.2	1.111	35.352	4.019
3	c-c	22.2	1.530	48.533	4.024
4	d-d	23.0	0.947	30.150	4.018
5	e-e	23.0	0.921	29.312	4.018
6	f-f	23.2	1.575	50.046	4.024
7	g-g	23.4	0.976	31.052	4.018
8	h-h	23.4	1.160	36.967	4.020

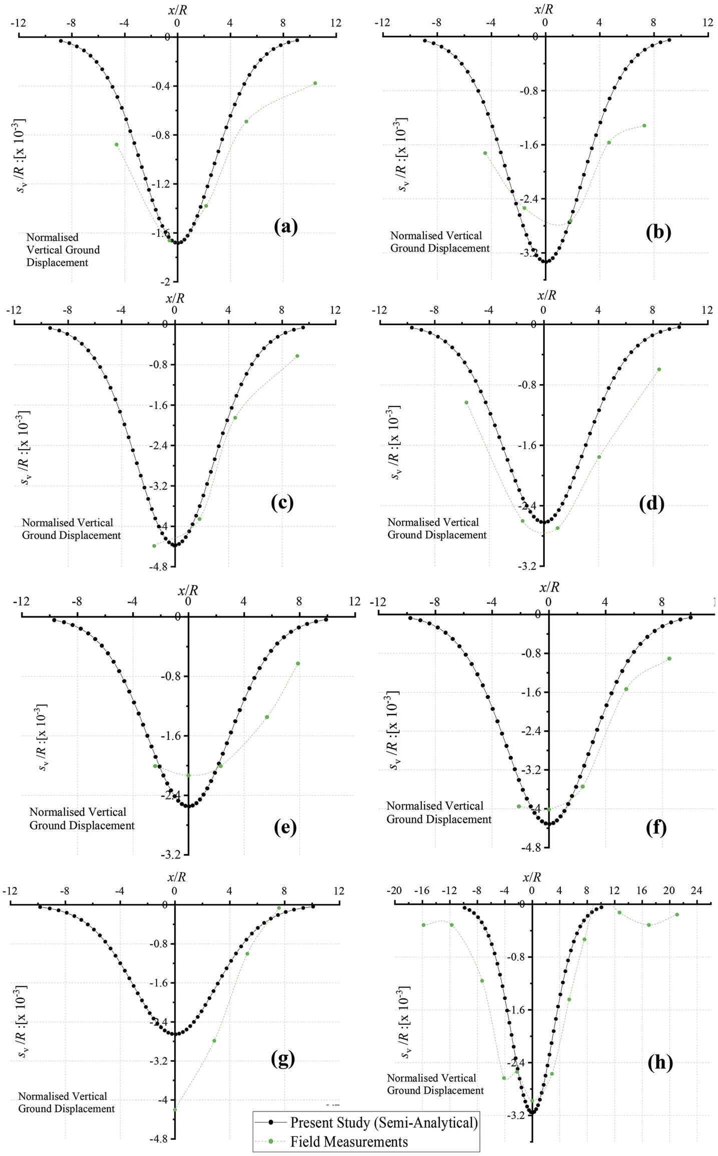


Figure 4. Vertical ground surface settlement (s_v) observed at different sections along the alignment: (a) Section a-a; (b) Section b-b; (c) Section c-c; (d) Section d-d; (e) Section e-e; (f) Section f-f; (g) Section g-g; (h) Section h-h.

The field observed vertical ground settlement at these sections and the analytically obtained ground movements are presented in Figure 4 in a non-dimensional manner. The solution appears to predict the ground movements closely to the field measurements.

4 CONCLUSIONS

Using the Gaussian distribution function, the non-uniform tunnel peripheral displacements are modelled and the ground deformations are predicted semi-analytically. The tunnel geometry, ground conditions, and field measurements for tunnelling in East West Metro are presented as a case study. Using the provided solution, the predictions are made for 8 different sections along the tunnel alignment which are quite close to the field measurements. The discrepancy between the analytical and the field observations can be attributed to non-linear, anisotropic, and non- homogenous soil behaviour around the tunnel opening. Tunnelling is a three-dimensional phenomenon with variables like grouting, soil consolidation, pore pressures, soil-structure interactions, tunnel face-pressure, TBM workmanship etc. governing soil behaviour around the tunnel. Therefore, this study is a first step solution towards predicting ground settlements via simplistic semi-analytical solution. By developing a computer code, the tunnelling induced horizontal and vertical displacements can be obtained for any ground loss.

REFERENCES

Jain, H. & Kumar, J. 2022 Ground displacements and stresses around a non-uniformly deforming circular tunnel in elastic media using complex variable method. *Acta Geotechnica*.

Peck, R. B. 1969. Deep excavations and tunneling in soft ground. In *7th International Conference on Soil Mechanics and Foundation Engineering*: 225–290.

Lee, K. M., Rowe, R. K., & Lo, K. Y. 1992. Subsidence owing to tunnelling. I. Estimating the gap parameter. *Canadian Geotechnical Journal*, 29: 929–940.

Loganathan, N., & Poulos, H. G. 1998. Analytical Prediction for Tunneling-Induced Ground Movements in Clays. *Journal of Geotechnical and Geoenvironmental Engineering*, 124(9): 846–856. https://doi.org/10.1061/(ASCE)1090-0241(1998)124:9(846).

Rowe, R. K., & Lee, K. M. 1992. Subsidence owing to tunnelling. II. Evaluation of a prediction technique. *Canadian Geotechnical Journal*, 29: 941–954.

Sagaseta, C. 1987. Analysis of undrained soil deformation due to ground loss. *Géotechnique*, 37(3): 301–320. https://doi.org/10.1680/geot.1987.37.3.301.

Verruijt, A., & Booker, J. R. 1996. Surface settlements due to deformation of a tunnel in an elastic half plane. *Géotechnique*, 46(4): 753–756.