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Prediction of Single and Twin-Tunnelling Induced Ground Settlements: A Comprehensive Review of Methodologies

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Abstract: Estimation of tunnelling-induced ground settlements is vital for the stakeholders of the underground projects to take necessary precautions for the safety of surface structures. The estimation of these settlements become more important in case of shallow tunnelling in urban areas. However, complex geological conditions, construction sequence, tunnelling methods, and twin tunnel arrangements lend complexity to the estimation process. Therefore, it is important to understand the influence of these factors on the ground response during the tunnelling excavation, and correspondingly assess their effect on the settlement estimation methodologies.

The present study comprehensively reviews the reported studies on estimation of ground settlements due to underground tunnelling excavations. The paper first addresses the reported prediction methodologies for single tunnel excavations. It discusses the effect of tunnelling methodology, ground conditions, and behaviour of soil around the excavated section on the ground response parameters, namely, greenfield settlement and heave. The paper then discusses the change in these ground response parameters when another tunnel is constructed next to an already existing tunnel. Summarily, the paper condenses the available knowledge on estimating the values of maximum surface settlement, ground loss, and width of settlement trough for different cases of single and twin tunnelling arrangements.

Keywords: Tunnelling Excavation, Shallow Tunnelling, Twin Tunnelling, Surface settlement, Ground Loss, Tunnelling Methodology.

1 Introduction

Due to rapid urbanization, the construction of underground tunnels has emerged as a viable option to address the issue of traffic congestion and limited land availability. The complexity in tunnel construction induces ground settlements causing extensive damage to the existing structures. In order to limit the damage, it is important to predetermine the ground settlements. Several researchers have attempted to model the ground settlement. Initially, based on field results and observations, a surface settlement curve resembling a Gaussian curve was proposed by [1]. This model is widely used because it requires very few parameters to find the ground settlement and its shape exhibits similarity with the observed settlement in the field. However, this model does not take into account the effect of different ground conditions and tunnel excavation techniques. Hence, several other models were proposed using analytical and numerical method[1]–[7].

The present study reviews different models to predict tunneling induced settlements occurring in single as well as twin tunnels. This study also discusses the effects of different tunneling techniques in various ground conditions along with ground settlements.

2 Single tunnelling induced settlements

Table 1 provides the detailed information regarding the proposed models and estimation methods about the surface settlement induced by single tunneling operations. Empirical relation for quantification of the volume of ground loss due to the tunnelling

operation was first developed by [1]. The proposed equation of the surface settlement profile was derived based on the observational data obtained
from the field measurements of various tunnel. The tunnels considered for the comparison and assessment of [1]'s model in this study are Toronto subway tunnel with medium to fine uniform dense sand[1], the San Francisco Mission Line, BART with dense silty fine sand [1], the G.N.R.R. Seattle tunnel with hard clayey till [1] and the Ottawa sewer tunnel with sensitive clay [1]. The proposed shape of the settlement profile resembled to a trough like depression similar to a Gaussian distribution or probability function[1]. The analytical solution to obtain the equation of the surface settlement profile for the incompressible medium by taking the help of virtual image technique and elastic half space solution was proposed by [2]. This estimation method was further validated which by considering the case study of the Caracas metro tunnel constructed through the weathered schists [2]. It was further modified for the case of compressible medium by [3]. The effect of uniform radial displacement of the tunnel periphery and its ovalization was considered by the introduction of the volume loss parameter in the proposed analytical solution[3]. Furthermore, the ground loss parameter was redefined as the gap parameter which considered factors associated with tunnelling technique such as tunnel geometry, elastoplastic deformation at the interface between tunnel lining and the ground, and qualitative aspect of workmanship. Apart from that, the effect of non-uniform ovalization was also considered in the solution by [4]. The validation of this model was carried out by considering various field cases such as the Heathrow Express Trial Tunnel, U.K. with stiff London clay[4], the Thunder Bay Tunnel, Canada with soft to firm clay[4], the Green Park Tunnel, London, U.K. with stiff fissured clay[4], the Barcelona Subway Network Extension Tunnel, Spain with clay having some gravel content[4] and the Bangkok Sewer Tunnel, Thailand with stiff clays[4]. [5] developed the equation for the surface settlement profile by modifying the [4]'s equivalent ground loss model by carrying out the back-analysis of field measurements of ground movements caused due to tunnelling operation by considering the cases of different tunnels in Taipei, out of which, the Nankang Line, TMRS, Taipei with sandy and clayey ground conditions for the purpose of comparison and assessment in this study[5]. The optimization of the equivalent ground loss model was performed by using conjugate gradient method[5]. [6] derived the analytical solution for the surface settlement profile for shallow tunnels with ground conditions such as stiff clays and rocks by improving the analytical solution developed by [6] for deep tunnels in saturated ground. Also, the solution considering the intricate details about the tunnelling operation such as tunnel liner-tail shield interface interactions, the cross-sectional area of the tunnel face, gap between lining and the shield of TBM and ground water conditions. It also considered the short term and long term effects of the construction methodology on the ground above the tunnel[6]. The model proposed by [6] was compared with the field measurements obtained from 28 tunnel case studies including the Green Park Tunnel, U.K.[7], the Bangkok Sewer Tunnel, Thailand[7], the Belfast Sewer Scheme Tunnel, Sydenham, Belfast with saturated silt[7] and Central Interceptor Tunnel, Mexico with soft silty clay as ground conditions[7]. It was found that the predicted and the observed trend of values of the surface settlements were in good agreement, especially for the medium to stiff clays[7]. The detailed information regarding the case studies considered in the settlement models are given in Table 2. It may also be noted that the in-situ stress condition plays a significant role in the final tunneling-induced surface settlements, and the same has been considered by [3], [6], and [7].

3 Twin tunnelling induced settlements

In urban tunnelling, the settlement due to twin tunnels becomes critical when there is a need of more capacity and the tunnelling construction needs to be done through shallow and weak soils. This necessitates the requirement for prediction methods for twin tunnel settlements. The factors in which the twin tunnel settlement depends are tunnel geometry, geologic conditions, shield operation factors, among others[4], [21]. The most vital parameter affecting the settlement due to twin-tunnelling is the distance between them. Researchers have primarily used numerical modelling for analysing this interaction when another tunnel is constructed in the vicinity of an existing tunnel. The accuracy of numerical analysis depends on selection of correct parameters regarding constitutive relationship of soil/rock, sequence of excavation and structural details. When the excavations are larger in extent, the field and numerical analysis show high variations[22]. In such cases, empirical methods are widely used. In such cases, [23] modified the empirical equation given by [1] for single tunnels to develop a new equation in which the individual Greenfield settlements of each tunnel are added together. This superposition method does not consider the interaction effect between the two tunnels and hence may not be accurate [24]. Superposition can be applied if the ratio of gap between tunnel centers to the tunnel diameter is larger than 2.7[25] [26]. [21] proposed that the additional settlement occurring due to second tunnel can be found using a Gaussian curve and final settlement of the twin tunnel can be determined by superposing the additional settlement curve to the greenfield settlement curve of the first tunnel excavation. When the construction of the twin tunnels are not simultaneous, it results in asymmetry of settlement curve and eccentricity of maximum settlement. Since these changes are not considered in the method given by [23]. [27] incorporated this consideration and gave design charts for eccentricity of maximum settlement and volume loss increase of the second tunnel by conducting numerical analyses [27]. This variation in volume loss is used to find the modified settlement of second tunnel which is then added to the Greenfield settlement of the first tunnel to obtain final total settlement. The charts showed that there is an increase in eccentricity and settlement as the distance between tunnels reduces. The variations observed in the settlement curve is attributed to the straining induced into the soil due to the excavation of first tunnel and overlapping of strains due to second tunnel. [28] considered this overlapping strained region and proposed a modification factor to account for the effect of this overlapping zone. Case studies of Heathrow Express tunnel(UK)[29], Lafayette Park tunnel(USA)[30], St James Park tunnel(UK)[31] was used to check the accuracy of the prediction and it was found that the case history data matches well with the predicted values[28]. The details of these considered cases are given in Table 4. Another factor known as 'disturbance factor' was given by [32] to incorporate the disturbance produced by the excavation of first tunnel. The case study of Otogar Kirazli metro tunnel, Istanbul was used for comparison and the curves show good agreements with the proposed model. [33] proposed graphs for additional volume loss and assymetry in the settlement curve based on centrifuge test results.

4 Effect of tunneling methodologies on settlements

Table 5 lists the details of the cases showing the effect of tunneling methodology on induced settlements. The data shows that among methods of open face excavation with closed face Earth pressure balance Tunnel Boring Method, and NATM method with sequential excavation, the Closed Face Earth pressure balance Tunnel Boring Method has the least displacement, distortion, volume loss, while the Open Face Shield Tunneling induces highest displacement, distortion and volume loss. The NATM with sequential excavation is observed to induce displacement, distortion and volume loss greater than the Closed face tunneling but lesser than the Open Face Shield Tunneling[36]. But the same shield tunneling in mixed face soil conditions is occasionally unable to control the ground movement. In such cases, grouting had to be adopted for controlling the ground movement[37],[38]. Shield tunneling with large diameter also induces volume loss of 15-25% before the face of the tunnel ,35-45% along the shield, 25-35% at the tail and 5% after the tail[39]. In Jacked Box Tunneling, the longitudinal settlements are triggered when there is overcrossing of box tunnels[40]. However, these settlement values are observed to be the same as NATM sequential Tunneling.

Hence, based on the reported observations, it can be inferred that the Shield Tunneling with Closed face Earth pressure Balance Tunnel Boring Method gives minimum settlements in case of medium diameter tunnels. On the other hand, Shield Tunneling in mixed face soil conditions for large diameter tunnels induces maximum settlements, which can only be controlled by grouting.

Table 1. Single tunnel settlement models

Sr. No.	Authors	Assumptions	Type of soil	Referred Case Studies	Technique used	Final solution	Remarks
1	Peck (1969)[1]	Normal probability distribution curve for representation of settlement trough	Non-cohesive & cohesive granular soils, hard & soft clays	Torronto subway San Francisco Mission Line, BART G.N.R.R. Seattle Ottawa Sewer	Empirical method based on the observational data	$S = S_{max} \cdot e^{(-\frac{x^2}{2 \cdot i^2})}$	Difficult to address the cases of mixed soil conditions
2	Sagaseta (1987)[2]	A quasi displacement-displacement problem with soil to be of homogenous, isotropic and incompressible in nature	Incompressible soils	Caracas Metro	Analytical method with the help of virtual image technique and solution for the elastic half space.	$S = 2\frac{a^n}{n}(\frac{h}{(x^2+h^2)^{\frac{n}{2}}})$	Analytical solution for the cases of the soil of incompressible nature
3	Verruijt A. & Booker J.R. (1996)[3]	Soil is linear elastic material with other assumption identical to Sagaseta's	Incompressible & compressible soils	-	Analytical method by considering uniform radial displacement and ovalization of tunnel as the deformation mechanism for the soil	$S = 2\varepsilon R^2\left(\frac{m+1}{m}\right) \cdot \left(\frac{h}{x^2+h^2}\right) - 2\delta R^2\left(\frac{h(x^2-h^2)}{(x^2+h^2)^2}\right)$	An extension of Sagaseta's solution even valid for compressible medium
4	Loganathan and Poulos (1998)[4]	Long-term ovalization effect of tunnel lining is neglected due to the consideration of short term undrained conditions with other assumptions identical to Verruijt A. & Booker J.R.'s	Soft to stiff clays	Heathrow Express Trail Tunnel, U.K Thunder Bay Tunnel, Canada Green Park Tunnel, U.K Barcelona Subway Network Extension, Barcelona Bangkok Sewer Tunnel, Thailand	Analytical method by redefining the ground loss parameter of Verruijt et al.'s to gap parameter considering the tunnel geometry, interfacial elasto-plastic deformations and quality of workmanship. Non-uniform ovalization was also considered.	$S = 4 \cdot (1-\vartheta) \cdot R^2 \cdot \frac{H}{H^2+x^2} \cdot \frac{4gR+g^2}{R^2} \cdot e^{(-\frac{1.38x^2}{(H+R)^2})}$	Modification in the solution of Verruijt et al. by taking into account the aspect of tunneling technique upto a certain extent
5	Chi (2001)[5]	The effect of soil consolidation during tunneling is neglected with all other assumptions identical to Loganathan et al.'s	Sands & clays	Nankang Line, TMRT (Taipei Mass Rapid Transit)	Back-analysis of tunneling induced ground movements was carried out by using conjugate gradient method as the optimization technique in	$S = R^2 \cdot \left\{-\frac{y-H}{x^2+(y-H)^2} + (3-4\vartheta) \cdot \frac{y+H}{x^2+(y+H)^2} - \frac{2y[x^2-(y+H)^2]}{[x^2+(y+H)^2]^2}\right\} \frac{4gR+g^2}{4R^2} e^{\left\{-\left[\frac{3.12x^2}{(R+H\tan\beta)^2}\right]+\frac{0.69y^2}{H^2}\right\}}$	Modification of Loganathan et al.'s solution is carried out by incorporating the angle of influence zone of ground settlement and factor of backfill grouting

					the modified equivalent ground loss model		for the gap parameter to consider the effect of construction technique
6	Bobet (2001)[6]	Soil is homogenous and isotropic with cicular cross-section, gap between tail of shield and the liner is constant along the perimeter with full slippage conditions between ground and liner and depth to radius ratio is larger than 1.5	Stiff clays and rocks	-	Extension of analytical solution derived by Einstein and Schwartz (1979) for deep tunnels in dry ground and by Bobet (2001) for deep tunnels in saturated ground	For dry ground: $S = -\frac{w r_o}{h} + \frac{1+\nu}{E}\left\{ \gamma {r_o}^2 \left[\frac{1}{8}\left(k - \frac{\nu}{1-\nu}\right)\left(\frac{r_o}{h}\right)^2 - \frac{1}{4}\frac{3-4\nu}{1-\nu}\ln h\right] + \gamma h(1-k) r_o \left[-2(1-\nu)\frac{r_o}{h} + \frac{1}{8}(9-4\nu)\left(\frac{r_o}{h}\right)^3 - \frac{1}{4}\left(\frac{r_o}{h}\right)^5\right]\right\}$ For saturated ground: $S = -\frac{w r_o}{h} + \frac{1+\nu}{E}\left\{-\frac{1}{2}\gamma {r_o}^2 \ln h + \gamma_b h(1-k) r_o \cdot \left[-\frac{r_o}{h} + \frac{3}{4}\left(\frac{r_o}{h}\right)^3 - \frac{1}{4}\left(\frac{r_o}{h}\right)^5\right]\right\}$ For saturated ground with air pressure: $S = -\frac{w r_o}{h} + \frac{1+\nu}{E}\left\{-\frac{1}{2}\left[\frac{3-4\nu}{2(1-\nu)}\gamma {r_o}^2 \ln h + \gamma_b (1+k) {r_o}^2\right] + \frac{1}{8}\frac{1-2\nu}{1-\nu}\gamma h r_o \left(\frac{r_o}{h}\right)^3 + \gamma_b h(1-k) r_o \left[-2(1-\nu)\frac{r_o}{h} + \frac{2-\nu}{2}\left(\frac{r_o}{h}\right)^3 - \frac{1}{4}\left(\frac{r_o}{h}\right)^5\right] + \gamma_w h r_o \left(\frac{r_o}{h}\right)^2\right\}$	Analytical solution developed in this study is valid for shallow tunnels with focus on the effect of construction methods and soil-liner interaction properties on settlements, not applicable for depth to radius ratio smaller than 1.5, shear stresses between the soil and liner is not considered and also not applicable for cohesionless ground conditions.
7	Chou and Bobet (2001)[7]	Same as that of Bobet's assumptions	Stiff clays and rocks	Green Park Tunnel, U.K Bangkok Sewer Tunnel, Thailand Belfast Sewer Scheme, Sydenham, Belfast Central Interceptor Tunnel, Mexico City	Same as that of Bobet's	Same as that of Bobet's	Not applicable for tunnels other than shield driven and for the soils other than medium to stiff clays

S-Total settlement, S_{max}-Maximum settlement, x-Lateral distance from the tunnel axis, i-Trough width parameter, a- radii, h- depth of tunnel, n – constant, ε & δ - parameters indicating the relative displacement of the tunnel surface, R – Radii of tunnel, m - auxiliary elastic constant, ν – poison's ratio, H- Depth of tunnel, g – gap parameter, y – longitudinal distance from the face of tunnel, β – angle of influence, *k* = coefficient of earth pressure at rest, *ro* = radius of tunnel, *w* = gap between ground and liner, g = total unit weight of ground, γ*b* = buoyant unit weight of ground, γ*w* - unit weight of water, E – Modulus of elasticity.

Table 2. Case studies of single tunnel settlement

Sr. No.	Author	Location	Type of soil	Details of tunnel			Observation regarding settlements
				Diameter (m)	Overburden depth (m)	Tunneling Technique	
1	Pers. comm.[1]	Torronto, Canada	Med. to fine uniform dense sand	5.185	10.37-13.42	Hand mined shield. No air	Largest settlement value was recorded as 0.1 m, while normal settlement value was recorded as 0.03 m
2	Pers. Files[1]	San francisco, USA	slightly cemented dense silty fine sand	5.34	10.98	Digger shield, air 9 psi	Largest settlement value was recorded as 0.01 m, while normal settlement value was recorded as 0.003 m
3	Hussey et al. (1915)[1]	Seattle, USA	Hard clayey till	11.9	37.52	Hand mined,	Largest settlement value was recorded as 0.24 m, while normal settlement value was recorded as 0.18 m
4	Eden and Bozozuk 1968[8]	Ottawa, USA	Leda clay, (sensitive clay)	3.05	18.3	Digger shield, , air 4-5 psi	Largest settlement value was recorded as 0.006 m, while the data for the normal settlement value was unavailable
5	Oteo & Sagaseta 1982[9]	Caracas, Venezuela	weathered schists	5.7	9	-	The calculated and observed values of the surface settlements are found to be in good agreement with the Sagaseta (1987)'s study with some overestimating trend for the distance far from the center line of tunnel. The heaving effect is also demonstrated on the surface settlement curve.
6	Deane & Bassette 1995[10]	Heathrow, UK	fill ground,terrace gravel, stiff London clay	8.5	19	Open face tunneling shields with precast concrete lining segments	The predicted surface settlements were found to be in good agreement with observed settlements for the Loganathan et al. (1998)'s model. The largest observed value for the surface settlement was recorded around 39 mm while the predicted value for it was around 36 mm.
7	Palmer and Belshaw (1978)[11]; Rowe and Lee (1992)[12]	Thunder Bay, Canada	silty sand with occasional clay seams;soft to firm clay;firm to stiff clay	2.47	10.7	TBM together with a segmented precast concrete lining	The predicted settlement trough was found to be wider than that of the reported for the loganathan et al. (1998)'s model with largest settlement values of 40 mm and 50 mm respectively
8	Attewell and Farmer (1974)[13]	Green Park, London, UK	sand and gravel,stiff fissured clay	4.14	29.4	Hand excavation	As per the Loganathan et al. (1998) model, the observed and predicted surface settlement values were in good agreement with a very little degree of under-prediction. The observed largest surface settlement value was 6 mm while the predicted value was around 5.8 mm.
9	Ledesma and Romero (1997)[14]	Barcelona, Spain	Red and brown clay with some gravel	8	10	-	As per the Loganathan et al. (1998) model, the observed and predicted surface settlement values were in good agreement with a very less degree of over-prediction. The observed largest surface settlement value was 24 mm while the predicted value was around 25 mm.
10	Phienwej (1997)[15]; Ramasamy (1992)[16]	Bangkok, Thailand	very soft to soft clay ;stiff clay fine sand, ;very stiff silty clay	2.66	18.5	Semi-mechanical backhoe and hard mining method.	As per the Loganathan et al. (1998) model, the observed and predicted horizontal surface settlement values were in good agreement with a reasonable amount of over-prediction especially for point at the tunnel axis (approx. 25%).
11	Moh et al. (1996)[17]	Nanking line, taipei	Soft clay, undrained shear strength	6	13	EPB shield machine	As per the model proposed by Chi et al. (2001), predicted surface settlements are in good agreement with reported values at the left hand side of tunnel axis, but for the right hand side of tunnel axis, the values are underpredicted. The largest surface settlement values for predicted and reported cases are around 22 mm and 25 mm respectively.

12	Attewell and Farmer (1974)[13]	Green Park, London, UK	London clay	4.15	28.9	Hand-excavated with cast iron segments	As per the model proposed by Bobet (2001), the comparison between predicted and observed values for the largest surface settlement holds good with values of 6 mm and 7.9 mm respectively with a certain degree of over-prediction in the trend for the region above the crown of tunnel
13	Phienwej (1997)[15]	Bangkok, Thailand	Soft to stiff clay	2.67	18	EPB TBM	As per the model proposed by Bobet (2001), the comparison between predicted and observed values for the surface settlement is reasonably good with some degree of under prediction except for the region around the crown of tunnel. The reported and predicted values of the largest surface settlement are 12 mm and 13 mm respectively.
14	Glossop and Farmer (1977)[18]	Sydenham, Belfast, UK	Soft saturated silt	2.74	4.85	Shield with precast concrete segments with compressed air	As per the model proposed by Bobet (2001), the comparison between predicted and observed values for the surface settlement is reasonably good with some degree of over-prediction except for the region around the crown of tunnel. The reported and predicted values of the largest surface settlement are 15 mm and 16 mm respectively.
15	Schmitter et al., 1981[19]; Schmitter and Rendon, 1981[20]	Mexico city, Mexico (Section 6)	Soft clay with silt	27	6.28	Precast segments with compressed air	As per the model proposed by Bobet (2001), the trend of predicted and observed values for the surface settlement holds good relationship with mixed degree of both over and under prediction. The reported and predicted values of the largest surface settlement are 12 cm and 15 cm respectively.

Table 3. Twin tunnel settlement models

Sl. No	Authors	Type of soil	Assumption	Case studies	Technique Used	Final Solution	Remarks
1	O'Reilly and New (1982)[21]	Clay	The interaction between the two tunnels are not taken into account		Empirical	$S = S_{max}[\, e^{-\frac{x_1^2}{2i^2}} + e^{-\frac{(x_1-d)^2}{2i^2}}\,]$	If there is a gap in time between the construction of two tunnels, this strategy is shown to be erroneous. When locating settlement, this strategy does not consider geological conditions, construction techniques, or operating characteristics.
2	Addenbrooke and Potts(2001)[22]	Clay	The tunnel models are for stiff clay with high Ko using non linear elastic perfectly plastic soil models and coupled consolidation	Fleet Line Satge I, Reagent Park	Finite Element Analysis	Peck's equation[1] is used and the variations incorporated using the values from graphs given by Addenbrooke and Potts(2001)	The limiting value of spacing above which there is no further variation from Greenfield settlement is 7 times the diameter of the tunnel.
3	Chapman et al. (2003)[23]	Clay	The variation of settlement curve from greenfield curve occurs due to variation in overlapping zone.	Heathrow Express tunnel Lafayette Park tunnel St James Park tunnel	Modification of Peck's formula by using results from model tests.	$W_{mod} = \left(1 + \left(M\left(1 - \frac{\lvert d^I + x\rvert}{AK_1Z^*}\right)\right)\right)W$	The empirical equation given by Peck can be used along with modification factor to find twin tunnel settlement
4	Suwansawat and Einstein(2007)[24]	Clay	Settlement procedure given considering EPB Sheilds	Bangkok MRTA project	Analytical and case study	Peck's equation[1] is used in which additional settlement due to second tunnel is found by adjusting the value of 'i' and is then superimposed with the settlement of first tunnel	In the case of EPB shields the operational parameters like face pressure, penetration rate and quality of tail void grouting becomes important for finding settlements.The proposed technique is in the descriptive form and further case studies are required for developing it to a predictive approach.
5	I.Ocak(2014)[25]	Mixed soil condition with both sand and clay	The disturbance factor account for the effect of disturbed soil due to excavation of first tunnel on the settlement of second tunnel.	Otogar Kirazli metro tunnel	Analytical	$S = S_{max}[\, e^{-\frac{x_1^2}{2i^2}} + [1 + \frac{D}{d}]e^{-\frac{(x_1-d)^2}{2i^2}}\,]$	The surface settlement curve is inclined to the second tunnel. Further studies are required to check the accuracy of the proposed equation.
6	Divall and Goodey(2015)[26]	Clay			Using results from centrifuge tests	The extra volume loss and asymmetry was predicted using centrifuge tests by Divall and Goodey(2015)[26]. These values obtained can be substituted in equation predicted by Peck(1969)[1] to get the settlement of second tunnel. This can be added with the Greenfield settlement of the first tunnel to get the total twin tunnel settlement.	The extra volume loss and asymmetry was predicted using centrifuge tests.For spacings above 3D the settlement trough produced by the second tunnel is symmetrical.

S-Total settlement, S_{max}-Maximum settlement, x_1-Lateral distance from the centerline of first bored tunnel, d- Distance between the centers of the two tunnels, i-Trough width parameter, A - Multiple of i to make a half trough width, Z* - Zo-Z, Z-Depth at which settlement is measured,Zo-Depth of tunnel, d^I -Distance between tunnel axes, K_1- Value of K for first tunnel, M -Modification factor , Zo-Depth of tunnel, x-Lateral distance from the centerline of first bored tunnel, K-Coefficient, k-Disturbance factor, Zo-Depth of tunnel, S-Total settlement, S_{max}-Maximum settlement, D-Tunnel diameter

Table 4. Case studies of twin tunnel settlement

SL No	Author	Tunnel	Type of soil	Details of tunnel			Observations
				Diameter (m)	Cover depth (m)	Spacing (m)	
1	Barratt and Tyler[27]	Fleet Line Satge I, Reagent Park	Thames gravel and Lodon Clay	4.146	34	8,12,16,32	There is an eccentricity for maximum settlement towards the first tunnel in the settlement curve of second tunnel. When the spacing increases this eccentricity decreases. Also when the spacing increases the volume loss into the second tunnel also reduces.
2	Cooper and Chapman,2002[28]	Heathrow Express tunnel(UK)	Clay	9	26	23	Gives accurate results that matches with case history data-Based on model given by Chapman(2004)
3	Cording and Hansmire, 1975[29]	Lafayette Park tunnel(USA)	Clay	6	14.6	11	The new profile for settlement matches with field results and also gives improved predictions of horizontal movements-Model given by Chapman(2004)
4	Nyren, 1998[30]	St James Park tunnel(UK)	Very Stiff London Clay	4.8	20.5	22.5	The settlement curve accurately fits with the case history data-Based on model given by Chapman(2004)
5	Suwansawat and Einstein, 2006[31]	Bangkok MRTA project	Stiff Clay	6.3	15-25		The observed data fits with the superposition curves obtained.
6	I.Ocak, 2014[25]	Otogar Kirazli metro tunnel,Istanbul	Sand, Clay, Gravel and some pieces of masonry	6.5	6-30	14	The proposed equation and field results show good agreement,Settlement curve inclined to second tunnel

5 Summary

The present study reviews the estimation methods of surface settlements for single and twin tunnels. It also reviews the effect of tunneling technologies and ground conditions on the settlements. It was observed that the effect of the settlement trough for a single tunnel extends to the distance equal to 3 to 4 times the radii of the tunnel. To assess the settlements for twin tunnel, most of the researchers used Peck's model and numerical analysis to predict the total settlement. When the distance between the centers of the two tunnels is greater than 2.7 times the diameter of the tunnel, the superposition of the Greenfield settlements result in the final total settlement values. Further, to accommodate the overlapping effects of the twin tunnels, modification and disturbance factors were introduced. These improved models displayed reasonably good match with the case history data. The review of effect of different types of tunneling techniques in various soil conditions showed that the shield tunneling induces minimum settlements in case of medium diameter tunnels; but the same tunneling technology induces maximum settlements in case of larger diameter tunnels in mixed soil conditions. It can be further inferred that the type of tunneling methodologies, diameter of the tunnel, and the type of soil have a combined and significant effect on the induced surface settlements.

Table 5. Effects of different tunneling methodologies on induced settlements.

Author	Location	Single/Twin Tunnel	Type of Soil	Tunnel Details	Settlement Observations
JACKED BOX TUNNELING					
Wei Liu, Yinlong Wu, Huajing Zhao, Xiangyang Xu, Lingyi[32]	China	Single Tunnel	Clay and Silty Clay and water table 1m below ground surface	Length: 72 m, Width: 6.9 m, Height: 4.2 m, Depth: 4.1 m	From the measurements of field and in situ observations, it is understood that the movement of the tunnels (subway) is triggered by overcrossing of the box tunnels.If the friction caused during tunneling is more, more is the deformations in these tunnels. To reduce the friction, lubricants can be used.The deformation in the longitudinal direction is more and also the shape of the deformed cross section is in ellipse.
NATM SEQUENTIAL TUNNELING					
Evangelia,Andrew Whittle,H.H. Einstein (Heatthrow Express Tunnel)[33]	London	Single Tunnel	Stiff Clay	Width: 9m, Height :8m, Length : 100m, Quasi Elliptical shape	The maximum surface settlement of 39 mm due to the large cross section
EARTH PRESSURE BALANCE –TUNNEL BORING MACHINE					
Evangelia,Andrew Whittle,H.H. Einstein(Cross Rail Tunnel)(Closed face excavation using EPB TBM)[33]	London	Twin Tunnel	Miscellaneous fill, London clay(Silt, River terrace) Ground water table is top of clay	Outer Diameter : 6.8 m, Cutter head diameter : 7.1 m	The expected and field measurements of the cavity deformation, tunnel convergence are almost similar and minimal ovalization in the Cross Rail Tunnel , This is due to EPM used are under pressure shield
SHIELD TUNNELING					
HongZhan Cheng ,Jian Chen, GuoLiang Chen (EPB Shield Tunneling)[34]	Beijing, China	Single tunnel (Twin Track)	backfill soil, fine and medium sand, silty and silt clay	Large diameter of 10.22m, Overburden of 16 to 22m	Settlement happens in stages At tunnel face: Due to the imbalance between soil in-situ stress, even before the shielding machine comes, soil ahead may be extruded or intruded Volume loss along shield: If cutter head larger than front portion of shield, may also take place due to misalignment, yawing, pitching. In long term, this excavation may cause the change in predicted post – construction settlement.
Evangelia,Andrew Whittle,H.H. Einstein(Open Face Shield Tunneling-Jubilee Line Extension)[33]	London	Twin Tunnel	London Clay	Outer diameter: 4.85m, Overburden depth: 3.5m, Water table is 2m below ground surface	The percentage of volume loss is 3.3 % and relative distortion of 1.05
G. Wayne Clough, Eric Leca 2. (Shield TBM in mixed conditions)(Washington Metro station)[35][36]	Columbia	Twin Circular Tunnel	Mixed face, Fill, Organic clay, Silty clay, Gravelly Sand, Clay, Clayey sand	Diameter: 5.74 m	When there was sand at the crown, lower part of clay, settlements were present and the chimneys were formed from the crown of the tunnel to the surface of the ground. Tunneling is done in clay, there was a small settlement and in addition to that the clay was hard and was stuck to the shield. When silty clay, clay, clayey sand is found combined then there were ground losses at face and also had maximum settlements. The presence of cobbles and gravels worsened the situation

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