

Interactive Analysis of Twin-Tunnels using Numerical Approach

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Abstract— Tunnels have been a significant part of the energy and infrastructure development scenario since an early stage of civilisation, and their significance is increasing day by day. The essential purposes of tunnelling are hydropower, highways, railways, metro trains, sewage lines, and water storage. Large cities need to build twin tunnels or new tunnels adjacent to their current ones to develop their transportation systems. This study focuses on this type of tunnelling. The study's main objective is the soil-structure interaction of the tunnel matrix with the help of empirical and numerical approaches. Another step is added to this assessment by considering settlement optimisation in twin tunnels with construction sequence and volume loss. Empirical formulas are employed to simplify the variability of tunnel design; however, it has been observed that the results are way more convergent on the safer side. The studies of different numerical models show that constructing both tunnels simultaneously gave optimum results in horizontal twin tunnels.

Index Terms — Tunnel Boring Machine (TBM), Finite Element Analysis (FEA), Settlement Analysis, Modelling, Tunnels.

I. INTRODUCTION

The design of an underground structure is done by understanding how excavation under the current geological circumstances can cause stress and displacements in the surrounding rock or soil. A broad range of factors, including the shape and size of the opening, geological conditions, construction techniques, the initial stresses of the media, mechanical properties, the length of time the opening is left unsupported, and the features of the support system, influence the stresses and displacements that develop around an underground opening, the depth at which the hole is being excavated, how many openings interact, the breadth of the space between them, and the relative positions of the openings. Furthermore, if the behaviour of the rock/soil is in the plastic range, the order in which excavation is done has a significant impact.

The studies include horizontal and vertical twin tunnels and nearby building settlement profiles due to the construction with linear and non-linear soil characteristics. Some of them not only analyse parallel tunnels but also cross tunnels. The studies observed the settlement by varying the Cover-to-diameter ratio (C/D), diameter, Pillar Depth-to-Diameter ratio (P/D), and distance between the tunnels, using different types of tunnels like horseshoe tunnel and circular tunnels and commented on the settlement and stress concentration. Generally, the researcher uses Mohr-coulomb, Drucker's Prager, hardening soil constitutive model for soil, and a linear model has been used for tunnel properties [1][2][3][5][6][9][10][11][12][13][15][21][27][28]. [25] Minh Ngan Vu et al. found a relationship between the volume loss and C/D ratio for shallow tunnelling.

The study discovered that overall volume loss is greatly impacted by the loss of volume at the face of the tunnel. Volume loss can be minimised by adjusting the support pressure at the face and tail. However, a direct volume loss of about 1% is a reasonable minimum for shallow tunnels. [18][17] V.B. Maji and A. Adugna's study looked at soil's horizontal and vertical displacement during tunnelling to determine the face of the tunnel's critical supporting stress and grout pressure. They conducted experiments using varying face and grout stresses to examine the impact of the heave size on surface settlements. Using the PLAXIS-3D, a numerical model was made to investigate soil mobility along tunnels under many geotechnical circumstances. The ground around the tunnel is extremely susceptible to face and grout pressure, which could cause surface settling and eventual soil collapse. Chao Liu et al. study addresses asymmetric tail-grouting, a condition in which one of the two apertures at the shield tail's upper section fails. The rise and fall of grouting pressure are not correlated with variations in grouting volume. Instead of grouting, tail-grouting pressure is primarily responsible for the ground deformation in coarse-grained soils. [22] Shui-Long Shen et al.'s study examines Shanghai's metro tunnels, which are built on soft clay with abundant water and low hydraulic conductivity. After more than a decade of use, the tunnels have seen both reminiscent and differential settlement. Long-term settlement rates were higher in the early years and gradually declined. Different soil types, the distance between the station and the tunnel, cross passages, and tunnel sections that cross rivers are some factors that cause non-uniform settlement. The long-term, uneven settlement of tunnels causes severe longitudinal deformation, which results in the division of the ballastless track bed and lining and groundwater infiltration. According to the study, long-term tunnel settling is primarily caused by soil subsidence from urbanisation.

In the exhaustive examination of existing literature, researchers have used the finite element approach and various tools to analyse the settling profile of the surface ground. They collected field data and altered factors such as tunnel diameter, depth, C/D ratio, grouting pressure, and face pressure. The researchers employ a variety of constitutive models for soil mass and rock. This study looks at how different levels of volume loss and building order affect soil displacement. Also, discover the best building sequence for twin tunnels. A limited study was carried out on tunnels lying on a vertical axis. Therefore, a parametric study on varying volume loss with pillar depth and Construction Sequence or soil between both tunnels can be carried out in the future.

Empirical formulas, standardised codes, and closed-form solutions are the typical analysis and design techniques professional engineers employ. The approaches described above make the highly simplistic assumption that a situation is as complex as it is. They are primarily linear and do not include the elastoplastic nature of the terrain for more realistic analysis. Further, they apply to specific regular shapes of tunnels, like circular, elliptical, and rectangle. As a result, numerical techniques like the finite element method, discrete element method, finite difference method, and boundary element method must be used. Generally, the FEM (finite element method) is used; it simulates the real-world problem into a mathematical one.

II. GEOTECHNICAL CONSIDERATION

In designing a metro tunnel, different index and engineering properties are considered, such as soil type, plasticity, SPT value, modulus of elasticity of soil, cohesiveness, angle of friction, water table depth, earth pressure coefficient, plasticity, bulk unit weight, etc. In this paper, the soil profile and TBM (Tunnel Boring Machine) consideration is taken from DPR (Detailed Project Report) [33]. The soil properties are described in Table 1. The lining material and TBM properties are included in Tables 2 & 3, respectively. The analysis considers tunnel alignment straight, and the Greenfield approach is used. The study uses the Finite element method using PLAXIS 3D, and an empirical formula [21] Equation (1) is used for the horizontal tunnel. Fig. 1 shows the profile of a single tunnel settlement as no empirical formula directly gives the settlement profile of a twin horizontal tunnel. The superposition on a single tunnel settlement profile is used to derive it.

$$S(x) = S_{\max} e^{\left(\frac{-x^2}{2i^2}\right)} \quad (1)$$

where $S(x)$ is surface settlement at a horizontal distance x from the tunnel centerline (Figure 1); $S_{\max}$ is the maximum settlement at the symmetric point (at the tunnel centerline) of the settlement curve; i is the horizontal distance from the tunnel centerline to the point of inflexion on the settlement curve. where, $i = K \cdot z_0$;
and,

$$S_{\max} = \frac{0.313 V_L D^2}{K z_0} \quad (2)$$

where,

D = diameter of tunnel

K = width parameter of settlement trough for clayey soil it is taken 0.4-0.6;

V_L = volume loss,

z_0 = distance between the centre of the tunnel and the ground surface

TABLE I: BORE LOG DETAILS [33]

BH. NO.	Layer-1					Layer-2					
	Depth(m)		SPT N-value	Shear Parameter		Depth(m)		SPT N-value	Shear Parameter		
	From	To		φ	c (kg/cm^2)	From	To		φ	c (kg/cm^2)	
15	0.0	30.0	10-71	5-6	0.85-0.95	-	-	-	-	-	Density (γ)=19.03 kN/m³
16	0.0	14.0	12-28	4-5	0.8-0.94-5	14.0	15.0	-	-	-	From 14.0–15.5, consider the same values as layer 1. Density (γ) =19.03 kN/m³
	15.5	30.0	32-76	-	-	-	-	-	-	-	From 15.5-30.0, φ and c are taken as above. Density (γ) =20.0 kN/m³

TABLE II PROPERTIES OF TBM [33]

Parameter	Proposed dimension
Tunnel internal diameter	5200 mm (minimum)*
Tunnel external diameter	5800 mm
Tunnel excavation diameter	6200 mm
TBM cutter head diameter	6270
Number of segments/rings	5 + 1 Key
Width of segments	1.2m/1.4m/1.5m
Thickness of segments	300 mm
Weight to segments	Regular segments Approx 3.0 T each Key segment 1 T
Weight of complete ring	16 T
Grade of concrete	M-45

TABLE III: ASSUMED PROPERTIES [31]

Properties	Name	TBM	Unit
Type of behaviour	-	Elastic	-
Isotropic	-	Yes	-
Thickness	d	0.17	m
Material weight	γ	247	kN/m ³
Young's modulus	E_1	200X10 ⁶	kN/m ²
Poisson's ratio	γ_{12}	0	-
Shear Modulus	G_{12}	100X10 ⁶	kN/m ²

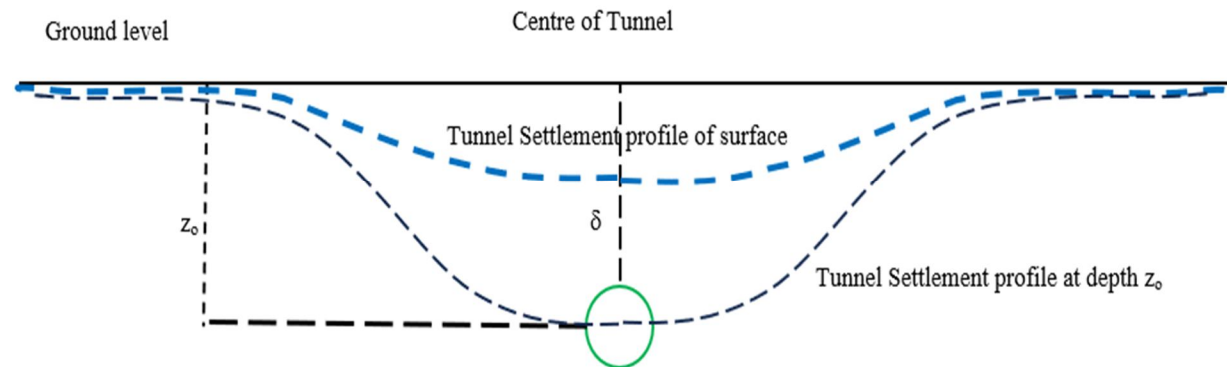


Figure 1: Settlement profile [21]

Fig 1. The Blue dotted line shows the settlement profile of the ground surface during construction; the settlement profile follows the Gaussian curve. The black dotted line shows the settlement profile at z_0 depth from the ground.

III. NUMERICAL MODELLING

A 10-noded tetrahedral element is used to develop the three-dimensional numerical model. The c/s of the tunnel is in the XOZ plane, and in the Y-direction, the TBM tunnel is progressing. According to studies, the influence zone of the tunnel is 3D–5D in width, and for depth, it is 2-3D, so we can use up to 30-40m in width, but as monuments are an essential aspect of the analysis, the width at each side is taken up to 100m. The size of the strata model is 200 m, 200 m, and 30 m for the twin tunnel, as shown in Fig.2. The concrete lining used in the tunnel is made as a linear elastic constitutive model, and the soil is considered a Mohr-Coulomb elastic-perfectly plastic model. The lower soil strata are considered fixed supports. And the other boundaries, except the upper strata, are considered roller supports. The upper strata are not restricted and can be deformed in any plane x-y, y-z, or x-z.

A. Single Tunnel

The c/s of a single tunnel has been constructed, but only half of the tunnel is built as the single tunnel shows axisymmetric along the Y-axis., as shown in Fig. 3.

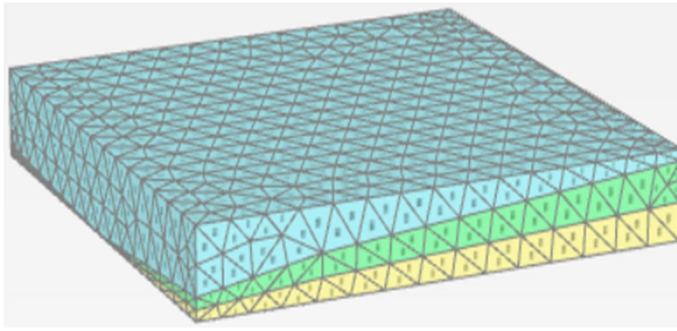


Figure 2: Soil model

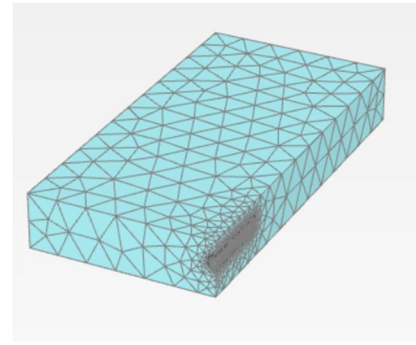


Figure 3: Single Tunnel 3-D model

B. Twin tunnel / Side-by-side tunnel

When two tunnels are constructed in horizontal alignment with each other, they are known as twin tunnels. The c/s of the model is defined in Fig. 4. The focus of this study is on the ways of construction and the effect of volume loss (0.5,1,2%). The following type of construction sequence can be done:

- Both tunnel construction is done simultaneously (Fig. 5);
- One tunnel construction surpasses the other (Fig. 6), and
- One tunnel construction was completed (Fig. 7).

The fine meshing was done automatically. Some of the meshing numbers of nodes and elements are shown in Table 4.

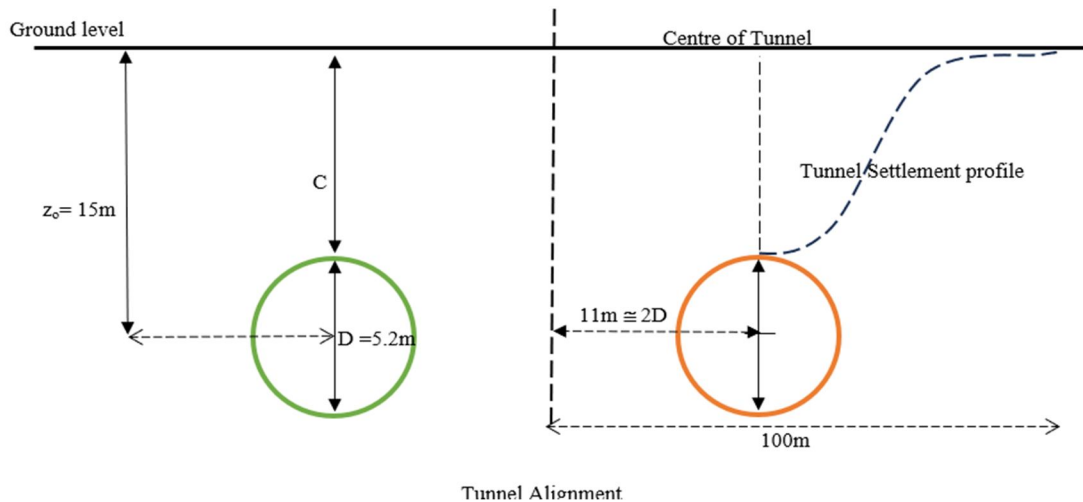


Figure 4: 2-D view of Twin Tunnel

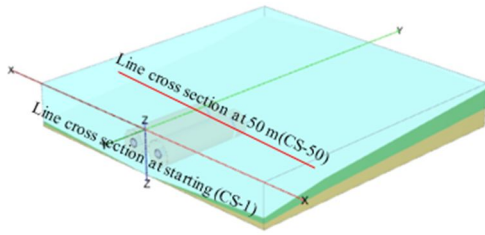


Figure 5: Both tunnel construction is done simultaneously

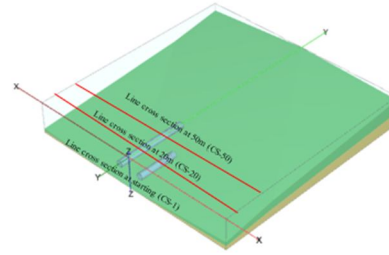


Figure 6: One tunnel construction surpasses the other

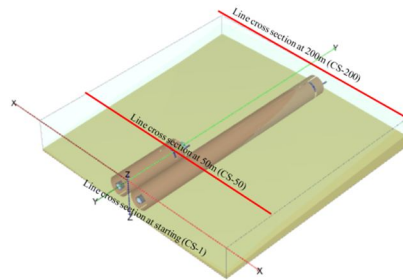


Figure 7: One tunnel construction completed

IV. ANALYSIS OF RESULT

A. Single Circular Tunnel

The single circular tunnel is an axisymmetric problem; therefore, considering half of the tunnel design will give an understanding of the settlement. The structure fulfils the condition of plane strain, but the model did not consider the unit length of the model; it took 200m because the tunnel deformation is also affected by longitudinal construction. Medium meshing has been done for the model, which has 10144 elements and 17483 nodes. This work uses Peck's empirical formula to estimate the settlement. In Figure 8, the numerical and empirical result shows a significant difference. The empirical settlement is more; the same can be seen in Figure 9, but the difference between numerical and analytical is less, and in Figure 10, it is way less. Therefore, it can be concluded that the numerical approach gave settlement at construction time more accurate and predicted high settlement, so even less volume loss cannot be accepted in empirical relation. Therefore, empirical is more conserved than numerical analysis. Figure 8-10 shows that as the longitudinal length increases, the effect of its transverse settlement is not included in the empirical study, whereas, in numerical analysis, as the longitudinal construction increases, soil stiffness is affected, and soil properties change gradually; therefore, the settlement is increasing gradually.

B. Horizontal Twin Tunnel:

In this study, as per the [33] DPR 2017, the interactive distance between the twin tunnels is preset as per all conditions. Therefore, volume loss dependency and construction sequence variation have been discussed in this work. The FEM analysis has been done in three modes of construction sequences, as mentioned above. Also, the volume losses are 0.5%, 1%, and 2%. Therefore, nine models have been made, and analysis has been done on them by considering various c/s. The empirical formula is also used in these nine models to find out the settlement of each model at a different c/s.

C. Both Tunnel Construction Are Done Simultaneously:

In this construction sequence, three types of volume loss are considered and analysed; Figure 11&12 shows the variation of settlement across the c/s as volume loss changes. The influence of volume loss at CS1 (Figure 11) is negligible, but as the c/s is taken more in the longitudinal direction, the difference in settlement can be seen. It can be observed from Figure 12 that as volume loss increases, settlement also increases. It can also be concluded from these two graphs that the empirical formula gave way higher settlement after using superposition in single tunnel settlement.

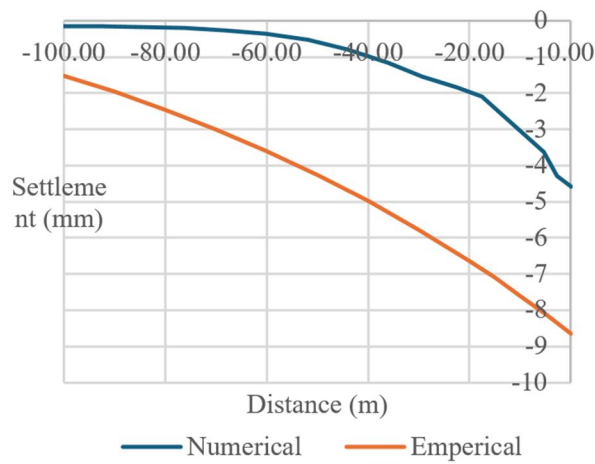


Figure 8: Settlement at the beginning c/s of the tunnel

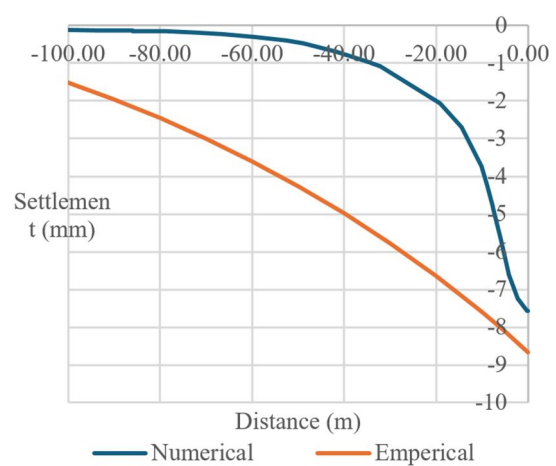


Figure 9: Settlement at 25m from tunnel starting, a c/s of the tunnel

¹CS1 means cross-section at beginning.

²CS20 means cross section at 20m and so on.

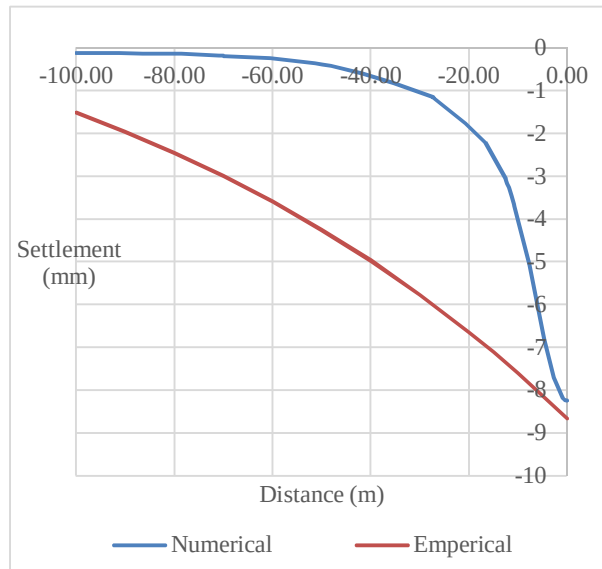


Figure 10: Settlement at 31m from tunnel starting, a c/s of the tunnel

TABLE IV: MESHING

Volume loss = 0.5%	Elements	Nodes
Both tunnel constructions are done simultaneously	30411	48373
One surpasses	26466	42198
One completed	52485	83115

D. One Tunnel Construction Surpasses the other

In this kind of construction sequence, it is considered that one tunnel's construction is well ahead of the other. This construction method results in an unequal distribution of stress, which we observe when we use the numerical methodology to evaluate the c/s. Because an axisymmetric condition has been constructed for CS1 and CS20 (Figure 13&14), only 0–100 m is shown for the empirical approach: in contrast, the model in CS50 (Figure 15) is not axisymmetric, so its entire settlement curve has been shown. In all these figures, less volume loss is given in settlement. The right tunnel settles more than the left tunnel, as seen in Figure 13-15. In Figure 14, the second tunnel suffers more settlement than the first tunnel because, during the construction of the first tunnel, nearby soil stiffness is disturbed.

E. One Tunnel Construction Completed

Here, it can be assumed that a tunnel is finished or that a new tunnel is being constructed next to an existing one. As a result, as illustrated in Figure 16-18, the new tunnel construction has more soil settling as the existing or completed tunnel reduces the earth's stiffness. The lowest settlement is observed at 0.5%, as indicated by volume loss graphs at 0.5, 1.0, and 2.0%. Consequently, it can be said that volume loss rises with increasing ground settling. Additionally, it can be seen that very high settlement is predicted by the empirical relation that is employed with the assistance of superposition and that settlement values diverge more from the numerical approach value as volume loss increases.

From the above discussion on twin tunnels, it can be concluded that for a volume loss of 0.5%, the most minor settlement occurs in every construction sequence. Therefore, at constant volume loss (i.e., 0.5%) at different c/s due to construction sequence, the settlement changes can be seen in Figure 19-21. From Figure 19, it can be said that one tunnel construction surpasses the other way and is more effective than another, but as we see in Figure 20 (CS20), it can be seen that constructing both tunnels simultaneously gives the highest settlement. Therefore, throughout the construction, the optimal solution is that both tunnels should be built simultaneously. Additionally, it can be commented on the empirical approach that it gave the same value until one tunnel existed, as seen in Figure 21. Furthermore, the construction sequence did not affect the empirical formula.

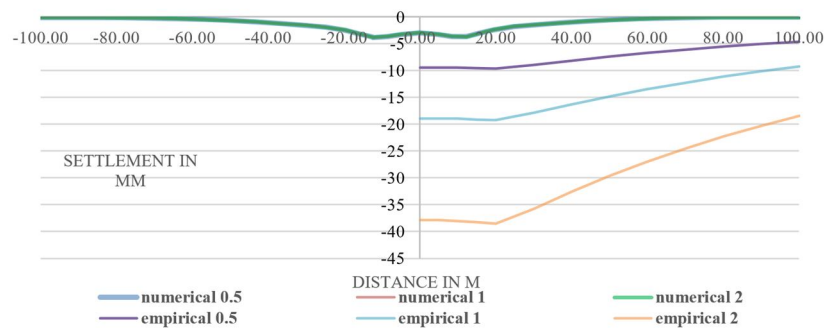


Figure 11: Settlement at CS1 according to the numerical and empirical formula for volume loss (0.5%, 1%, 2%)

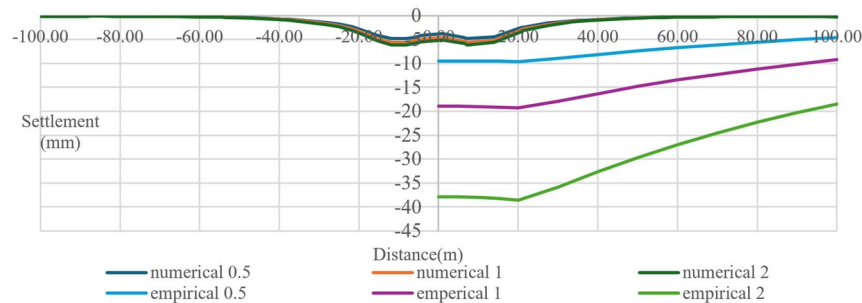


Figure 12: Settlement at CS50 according to the numerical and empirical formula for volume loss (0.5%, 1%, 2%)

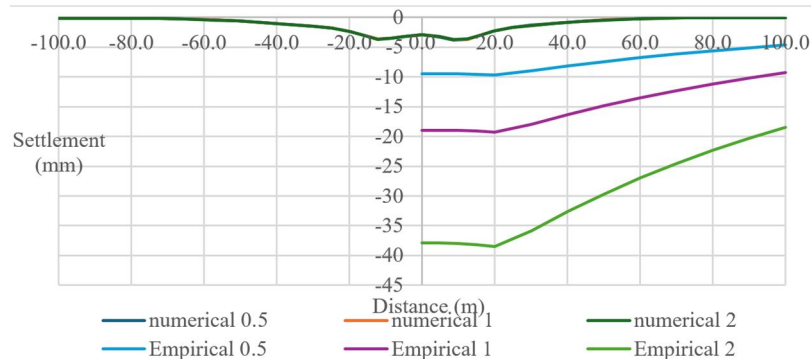


Figure 13: Settlement at CS1 according to the numerical and empirical formula for volume loss (0.5%, 1%, 2%)

3 numerical 0.5 means numerical model analysis with 0.5% volume loss.

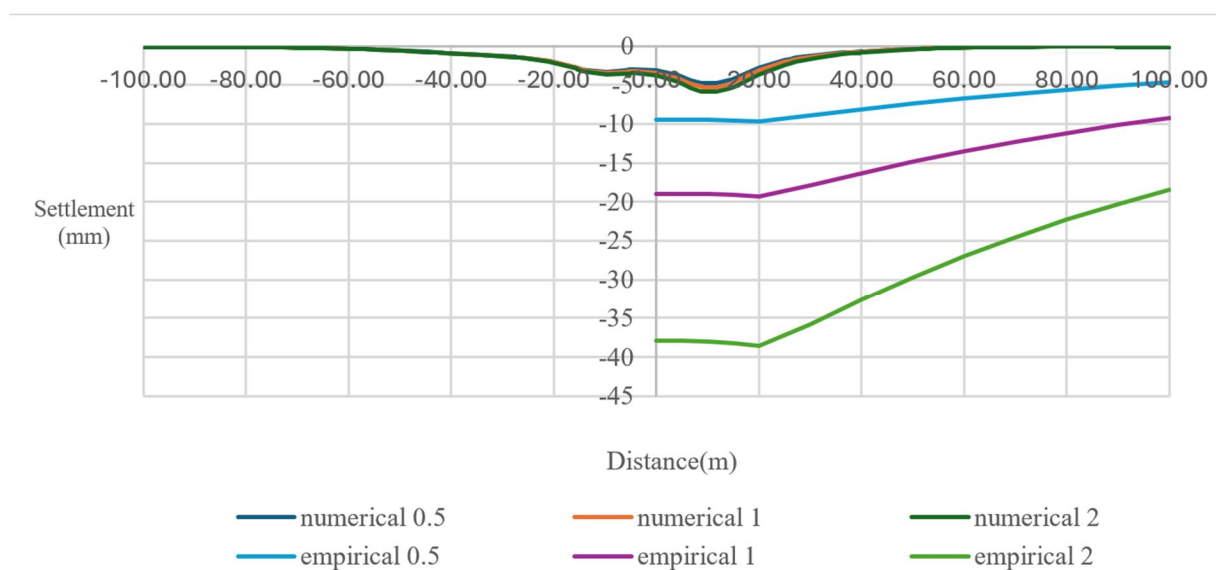


Figure 14: Settlement at CS20 according to the numerical and empirical formula for volume loss (0.5%, 1%, 2%)

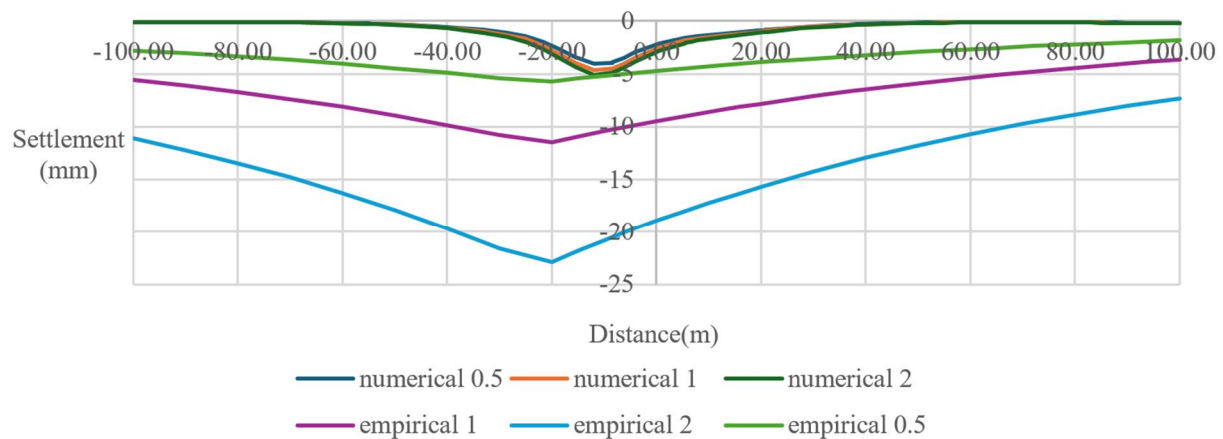


Figure 15: Settlement at CS50 according to the numerical and empirical formula for volume loss (0.5%, 1%, 2%)

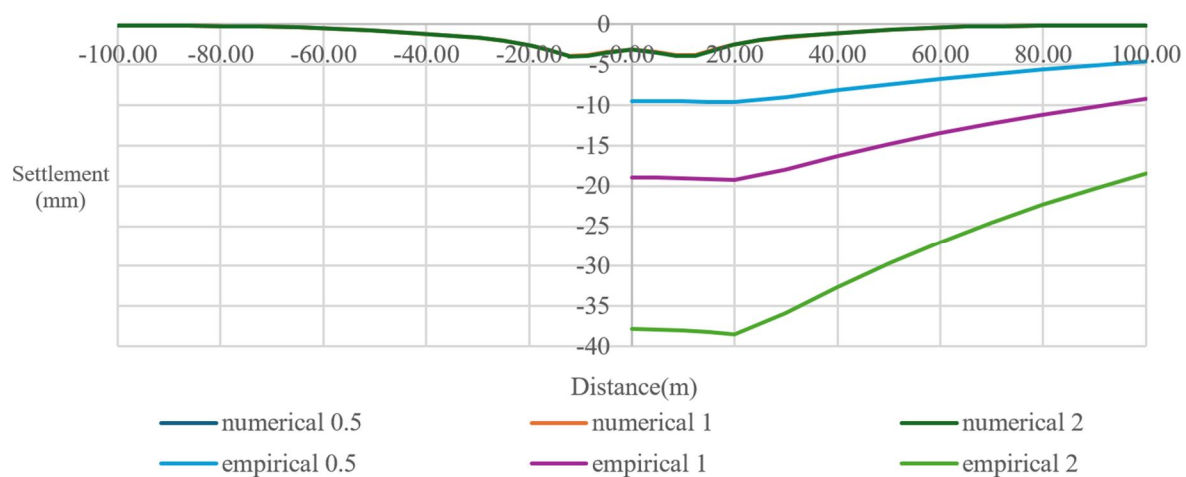


Figure 16: Settlement at CS1 according to the numerical and empirical formula for volume loss (0.5%, 1%, 2%)

4 empirical 0.5 means empirical analysis with 0.5% volume loss.

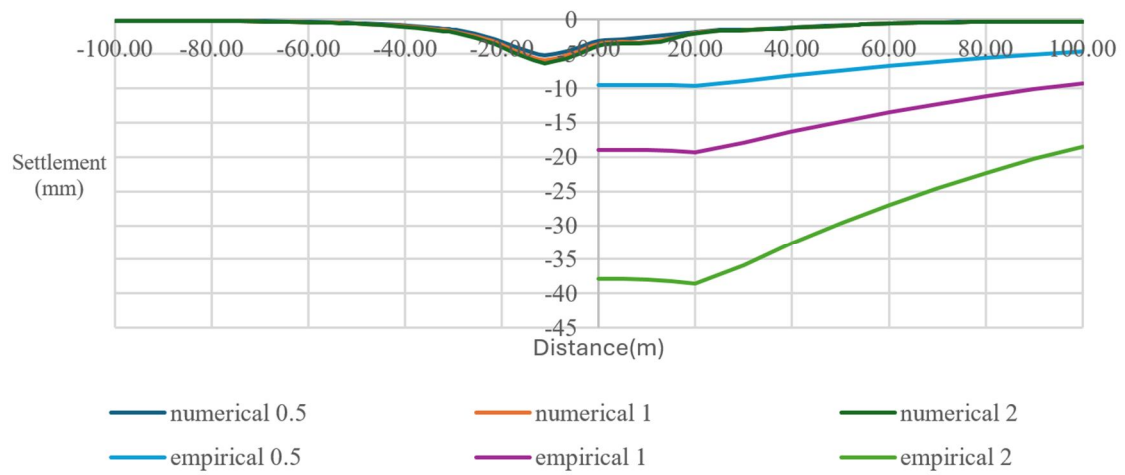


Figure 17: Settlement at CS50 according to the numerical and empirical formula for volume loss (0.5%, 1%, 2%)

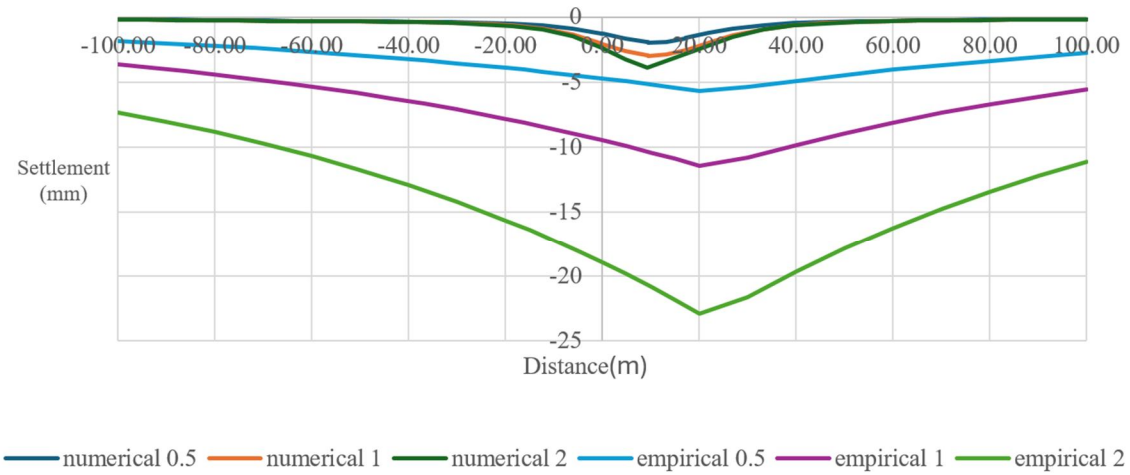


Figure 18: Settlement at CS200 according to the numerical and empirical formula for volume loss (0.5%, 1%, 2%)

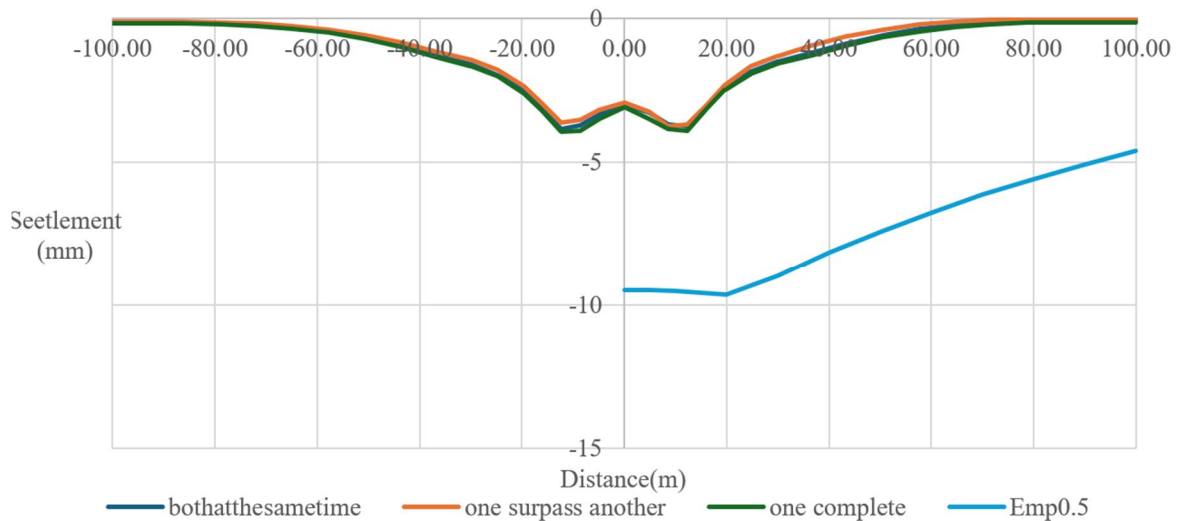


Figure 19: Settlement at CS1 according to the numerical and empirical formula for construction sequence at 0.5% volume loss

⁵Emp0.5 empirical analysis with 0.5% volume loss

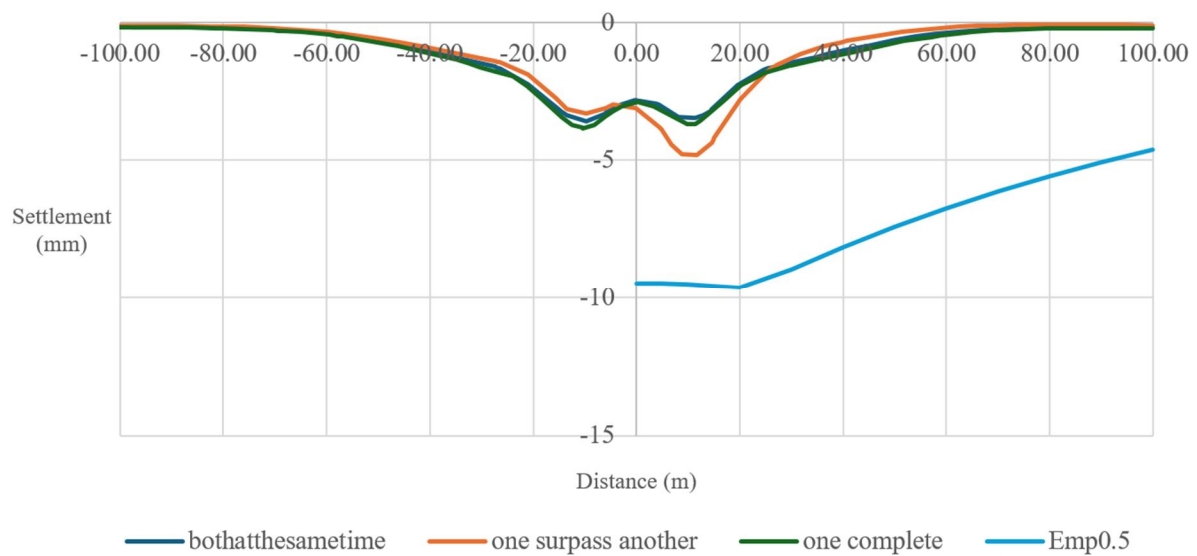


Figure 20: Settlement at CS20 according to the numerical and empirical formula for construction sequence at 0.5% volume loss

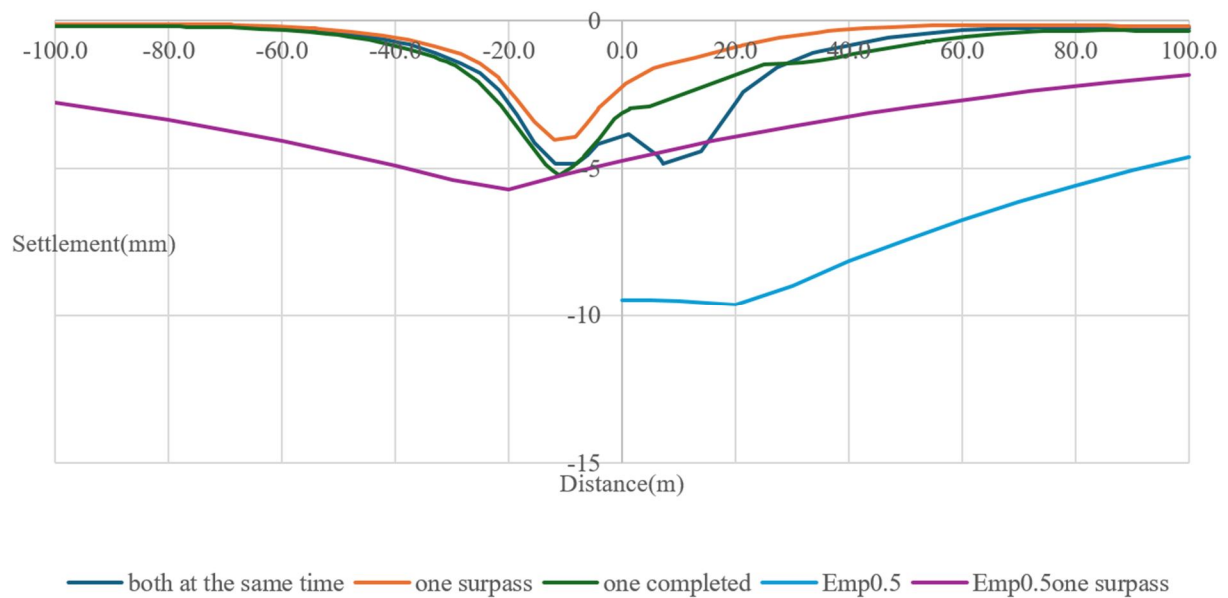


Figure 21: Settlement at CS50 according to the numerical and empirical formula for construction sequence at 0.5% volume loss

V. CONCLUSION

The following findings may be taken from the above discussion:

- Conventional or Empirical Approach estimates the high settlements of tunnels. The limitation of the conventional or Empirical method is also a governing factor in the determination of settlement behaviour as it is not influenced by the construction sequence. Further, considering the superposition in the empirical approach, it is estimated that settlement is very high.
- Comparing the compatible construction sequence for horizontal twin tunnels. It has been observed that constructing both tunnels simultaneously gave compatible behaviour in terms of settlement in this type of soil strata.
- Model analysis showed that less volume loss is acceptable during the construction sequence as volume loss also plays a vital role in the prediction of tunnel settlement,

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