Two-Dimensional Numerical Analysis of the Effects of Different Construction Sequencies on Tunnel Behavior

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Abstract. Urban population growth necessitates robust infrastructure, such as highways, public transportation and sanitation networks. Consequently, underground space utilization becomes crucial, leading to the construction of tunnels, access shafts, and galleries. This study investigates the impact of various tunnel construction sequences using the New Austrian Tunneling Method (NATM) on soil mass displacements. Numerical simulations were conducted with ABAQUS finite element software under plane strain conditions. The numerical model includes four soil and rock layers. The tunnels, excavated 17 meters below ground with an area of 161.29 m², feature primary and secondary linings. The soil and linings were modeled using Mohr-Coulomb and linear elastic failure criteria, respectively. The study examined convergence curve to incorporate three-dimensional construction effects. Seven analysis were conducted, involving full-section and partial-section excavation. Results show that partial-section excavation reduces soil displacements, with side drift excavation yielding the lowest values, while full-section excavation exhibited the highest surface displacements. Displacements varied with construction stage and depth, indicating a tendency for section flattening. The crown excavation and lining stages represented over 78% of total displacements. This study confirms the effectiveness of partial-section excavation in reducing soil displacements and highlights the importance of numerical modeling in tunnel engineering for safer construction practices.

Keywords: numerical modelling, displacement, NATM, ABAQUS.

1 Introduction

The intense urbanization in Brazil during the second half of the 20th century, driven by industrialization and agricultural modernization, led to the development of large urban centers with high population density (Brito [1]). This phenomenon significantly increased the demands on transportation, sanitation, and telecommunications infrastructures, as well as stimulating real estate speculation (Bastos [2]).

Tunnel construction is essential for modern infrastructure, facilitating urban expansion and transportation efficiency. Major metropolises like New York, London, and Tokyo rely on complex tunnel networks for subway systems, highways, and public utility distribution. However, tunnel excavation in densely populated areas presents significant geotechnical challenges, such as soil stability and impacts on adjacent buildings (Tender et al. [3]).

In the context of urban modernization through underground works, it is crucial to understand the interaction between the proposed structure, the surrounding soil, and other potentially affected buildings, pipelines, and structures, especially concerning permissible displacements (Savino [4]).

The literature highlights that the construction methodology employed in tunnel works, such as the excavation step, the timing of shotcrete application, and front treatments, significantly influences the development of stresses and deformations in the surrounding soil. Recent contributions in this area include finite element method analysis in residual soils for the São Paulo metro (Vitali et al. [5]), the influence of pile excavation (Mirsepahi et al. [6]), and the determination of the excavation influence zone (Lueprasert et al. [7]).

In this scenario, numerical modeling emerges as an essential tool for engineers, offering more accurate predictions of soil displacements resulting from tunnel excavation. By simulating different scenarios, numerical modeling helps mitigate risks and enhance safety and efficiency in operations. Given the diversity of factors influencing soil behavior during excavations, especially within the scope of the New Austrian Tunneling Method (NATM), it is crucial to understand how each technique affects soil displacements (Oliveira [8]).

2 Numerical modeling

The bidimensional numerical simulations of single and twin tunnel were conducted utilizing finite element software ABAQUS under plane strain conditions. The numerical model's geometry has 190 m of width and 70 m height. The tunnels, with an excavated area of 161,29 m² has 17 m of overburden and are equipped with primary and secondary linings. The numerical model encompasses four layers of soils and rocks, as presented in Figure 1 and is divided in three parts: the soil, the primary lining and the secondary lining. The soils/rocks and linings were modeled using the Mohr-Coulomb and linear elastic failure criteria, respectively. The specific weight (γ), internal friction angle (ϕ), dilatancy angle (ψ), cohesion (c), Young's module (E), coefficient of earth pressure at rest (k_0), Poisson's ratio (ν) and characteristic compressive strength (f_{ck}) of the soil mass layers and shotcrete shell used in the analysis are presented in Table 1 considering drained conditions. Both soil and linings had their parameters set based on the engineering project data, except for the dilatancy angle, which were determined as proposed by Cox [9] for the layers with internal friction angle larger than 30°. Thus, it is considered non associated flow. The hardening of the concrete was considered assigning different properties to the material depending on the construction stage.

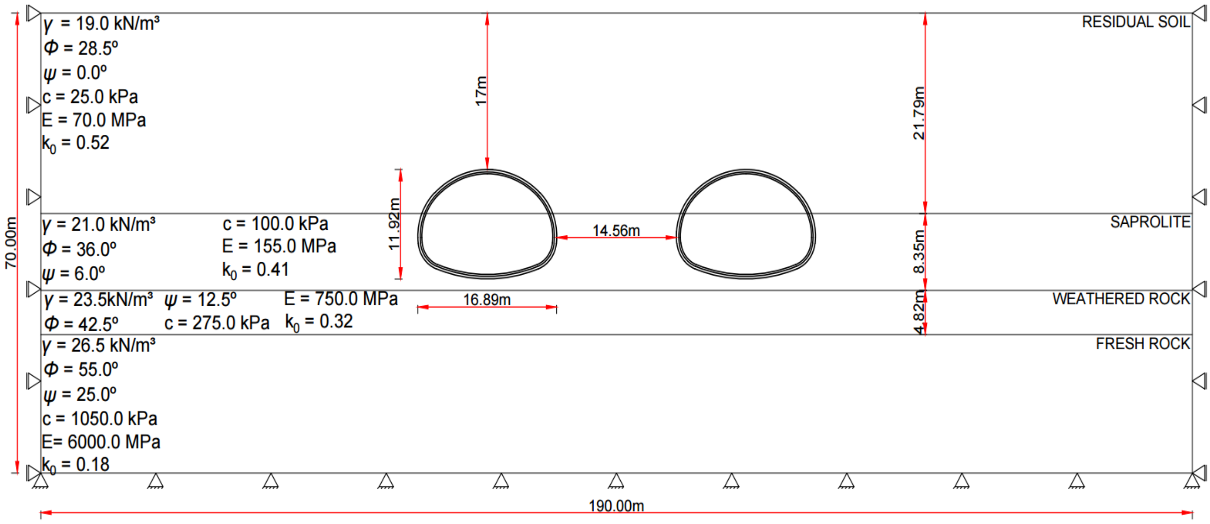


Figure 1. Model geometry

Table 1. Soil and Shotcrete properties

Layer	γ (kN/m³)	ϕ (°)	ψ (°)	c (kPa)	E (MPa)	k_0	ν	f_{ck} (MPa)
Residual soil	19.00	28.50	0.00	75.00	70.00	0.52	-	-
Saprolite	21.00	36.00	6.00	100.00	155.00	0.41	-	-
Weathered rock	23.50	42.50	12.50	275.00	750.00	0.32	-	-
Fresh rock	26.50	55.00	25.00	1050.00	6000.00	0.18	-	-
Soft Shotcrete	25.00	-	-	-	10000.00	-	0.20	30.00
Hardened Shorcrete	25.00	-	-	-	20000.00	-	0.20	30.00

The horizontal and vertical displacements were restricted at the bottom of the model, while roller boundaries were used in the lateral of the model (Figure 2). Additional vertical boundaries were applied to the bottom of the linings in the crown, until the activation of the invert. Furthermore, vertical and horizontal restrictions were applied to the top edge of the side drift until the activation of the half section's primary lining. The finite element mesh consists of four-node bilinear plane strain quadrilateral elements (CPE4) for modeling the soil mass, while four-node bilinear plane strain quadrilateral with incompatible modes elements (CPE4I), which improves the element response to bending problems, was used to model the behavior of the primary and secondary linings. A finer soil mesh is used near to the cavity where displacements are assumed to be more significant. Both primary and secondary liner elements length is 30 cm, while their thicknesses are 28 cm and 20cm, respectively.

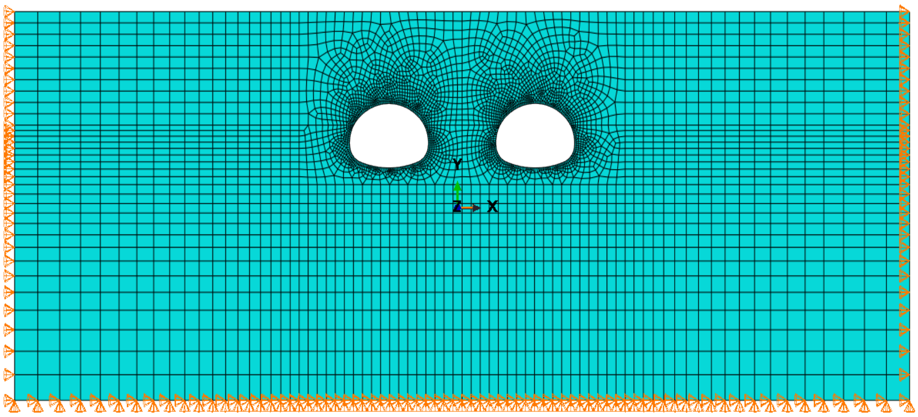


Figure 2. Finite element mesh

3 Excavation procedure and simulation

Seven analysis of tunnel construction sequences were conducted, with three for single tunnels and four for twin tunnels. These analysis involve full-section and partial-section excavations, with excavation of the crown and definitive inverted arch (DIA), in addition to the use of side drift associated with the half-section and DIA. In all 4 analysis in twin tunnel, the left tunnel was the first to be excavated. The numbering on the Figures 3 and 4 presents the studied sequences for simple and twin tunnel, respectively. There is no partialization for the Analysis 01 and 04; analysis 02 and 05 are partialized in crown and invert excavation; analysis 03 and 06 employ side drift, half-section, and invert excavation; analysis 07 combines crown and invert excavation for the left tunnel and side drift, half-section, and invert excavation for the right tunnel.

The displacements were analised in 6 nodes throughout the tunnels perimeter: outer and inner side of the left tunnel (OSLT and ISLT), outer and inner side of the right tunnel (OSRT and ISRT), left and right crown (LC and RC). Additionaly, the results were analised in 2 nodes on the surface of the model along the crown projection.

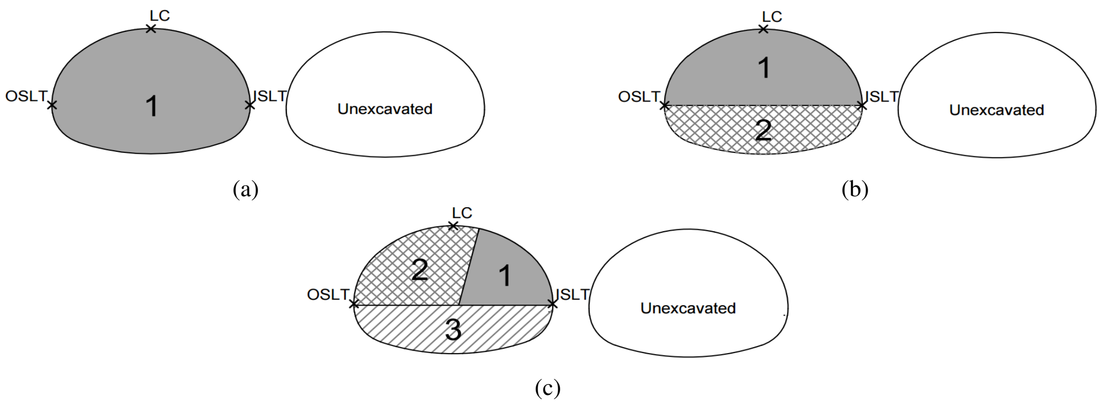


Figure 3. Excavation sequence single tunnel (a) Analysis 01 - full face excavation, (b) Analysis 02 - crown and invert excavation, (c) Analysis 03 - side drift, half section and invert excavation

The excavation was simulated using the load reduction method as proposed by Mödlhammer [10], where concentrated forces applied to the nodes of the soil elements around the tunnel perimeter are reduced along the construction stages. The magnitude of these forces, in the geostatic condition, was determined in an independent analysis with boundary conditions that restrict vertical and horizontal displacements at the excavation perimeter. These forces were reduced to zero over the stages to simulate the three-dimensional effects of the excavation.

4 Results

In both single and twin tunnels, critical displacement points are located at the crown, decreasing with distance from the cavity as presented in Figure 5. In twin tunnels, displacements and stresses are symmetrical. In Analysis 07, with distinct construction methodologies, displacements in the left tunnel (crown and invert) were greater than

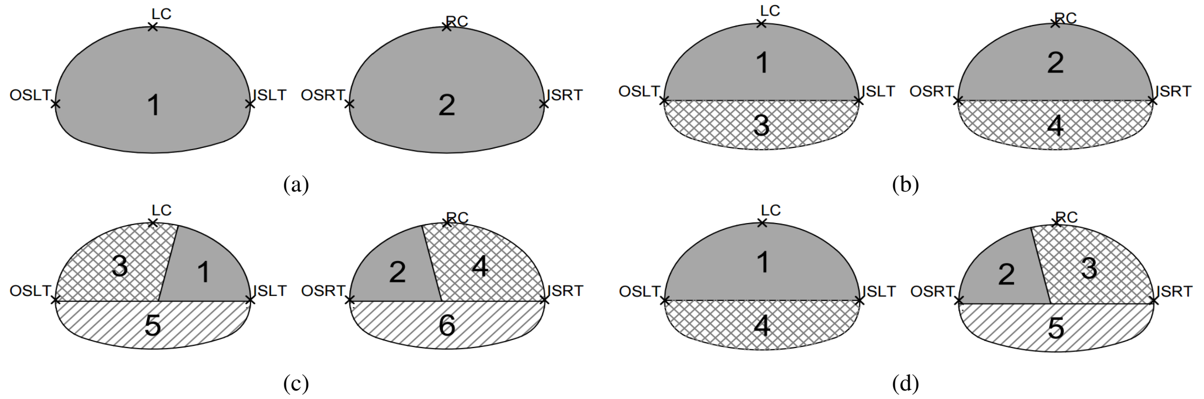


Figure 4. Excavation sequence twin tunnel (a) Analysis 04 - full face excavation, (b) Analysis 05 - crown and invert excavation, (c) Analysis 06 - side drift, half section and invert excavation and (d) Analysis 07 - crown and invert excavation for the left tunnel and side drift, half section and invert excavation for the right tunnel

those in the right tunnel (side drift, half section, and invert). Displacements at the tunnel base are smaller than at the crown due to the altered rock layer with superior mechanical properties compared to the overlying residual and saprolitic soil.

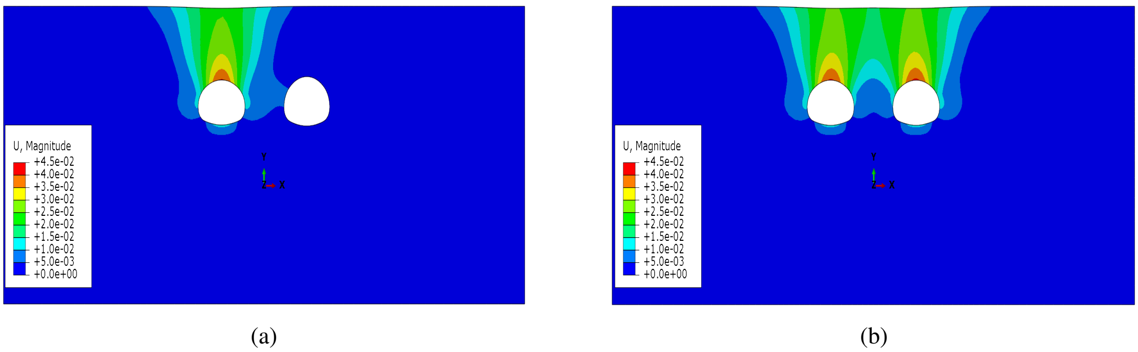


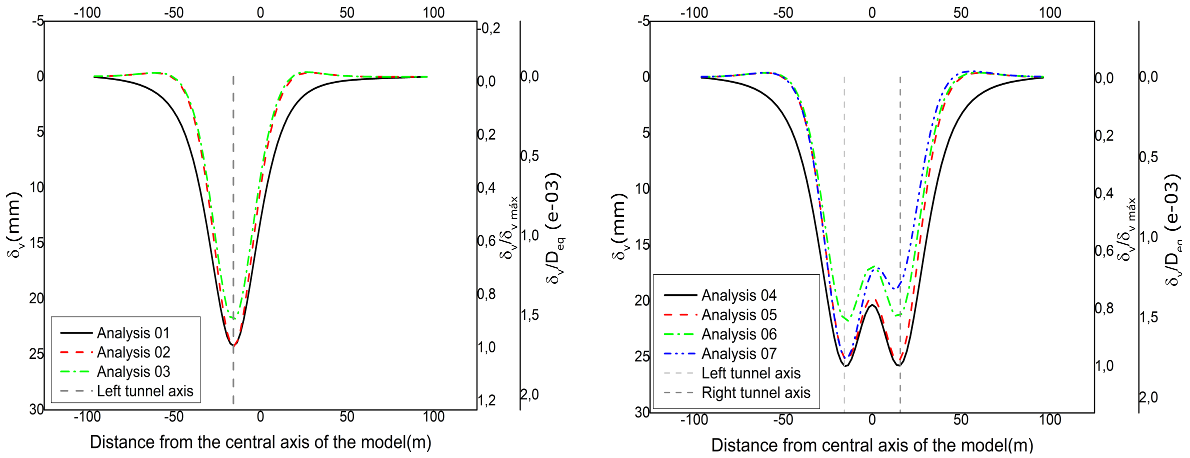
Figure 5. Tipical displacement field (a) single tunnel (b) twin tunnel

As observed by Karakus and Fowell [11], the results summarized in Figures 6a and 6b demonstrate that different construction methodologies result in varied surface settlement profiles. Specifically, the side drift analysis exhibited lower settlements when compared to the partialization in crown and invert excavation strategy for both single and twin tunnels, corroborating the findings of Mirsepahi et al. [12], Aghajari et al. [13] and Wang et al. [14].

The settlement basin geometry in all analysis indicates that settlement is a function of the execution stage and the transverse distance from the tunnel axis. This result aligns with the observations of França [15], Vitali et al. [5] and YEO et al. [16]. Additionally, the numerical results confirm that partial section excavation effectively reduces surface settlements, consistent with the findings of Vitali et al. [5] and Karakus and Fowell [11].

In all analysis, twin tunnel excavation resulted in increased surface settlements within the influence area compared to the settlement basin of a single tunnel, as observed by Do Ngoc et al. [17] and Mirsepahi et al. [12]. However, in the settlement basins of twin tunnel analysis, two settlement peaks were observed, both over the corresponding tunnel axes. This behavior contrasts with the results obtained by Dibavar et al. [18], where a single settlement peak was located at the midpoint between tunnels for a distance of two diameters apart. This discrepancy may be attributed to differences in material properties involved in the analysis, as discussed in Ağbay and Topal [19], and geometric section properties.

The results shown in Figures 7a and 7b indicate that the reduction of nodal loads around the excavation perimeter significantly impacts vertical displacements, both at the tunnel crown and the ground surface. In full-section excavation (Analysis 01), vertical displacements along the tunnel axis were higher compared to partial methodologies. The crown and definitive inverted arch (invert) excavation methodology in Analysis 02 resulted in smaller displacements, with 85.43% of crown displacements mobilized by the second excavation stage. The side drift, half section, and invert methodology in Analysis 03 presented the lowest absolute displacements, with significant increases at each construction stage. Generally, maximum surface displacements were lower than at the tunnel crown, varying with depth and construction stage. Partial excavation proved more effective in reducing



(a) (b)

Figure 6. Surface settlement to each analysis (a) single tunnel (b) twin tunnel

vertical displacements, especially on the surface, minimizing impacts on existing infrastructure.

Symmetry in vertical displacement distribution is predominant in twin tunnel excavations, except in Analysis 07, where distinct construction methodologies were used for each tunnel. Non-linear displacement distribution along the axis is common in all analysis, with displacement variation rates increasing with depth and construction progress. Surface displacements accounted for approximately 60% to 63% of tunnel crown displacements, indicating a more pronounced influence of initial excavation on superficial layers.

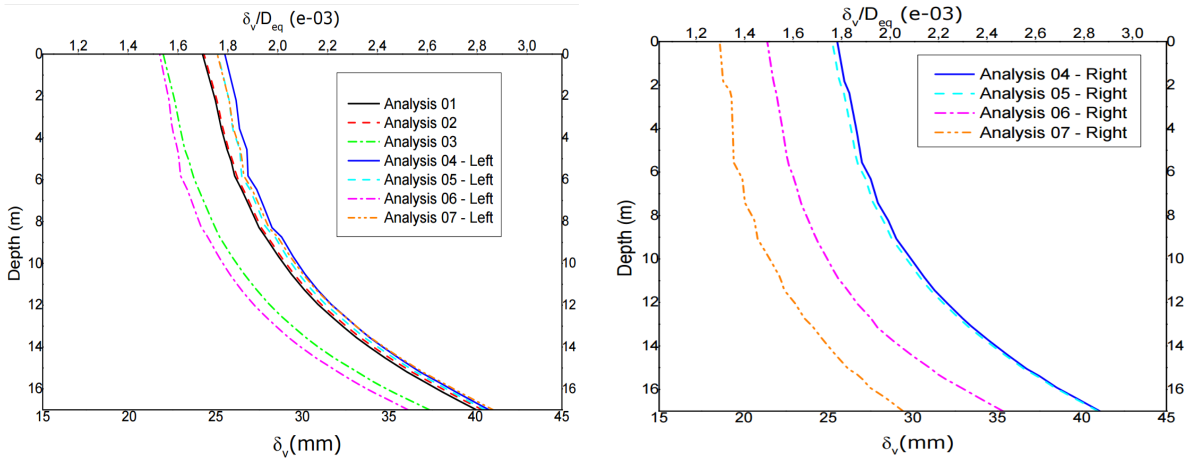
Table 2. Vertical displacement on surface and crown

Analysis	δ_v (mm)		$\delta_{vsurf}/\ \delta_{vcrown}$	$\delta_{vmax}v/D_{eq}$ (mm/m)	
	Surface	Crown	(%)	Surface	Crown
1	24.23	40.10	60%	1.69	2.80
2	24.32	40.45	60%	1.70	2.82
3	21.96	37.39	59%	1.53	2.61
4 - Left	25.52	40.82	63%	1.78	2.85
5 - Left	25.12	40.59	62%	1.75	2.83
6 - Left	21.75	36.16	60%	1.52	2.52
7 - Left	25.08	41.07	61%	1.75	2.87
4 - Right	25.54	41.10	62%	1.78	2.87
5 - Right	25.24	40.99	62%	1.76	2.86
6 - Right	21.40	35.37	60%	1.49	2.47
7 - Right	18.58	29.46	63%	1.30	2.06

Vertical displacement rates along the tunnel axis increase with depth and construction stages, differing from Vitali et al. [5]. These differences may be attributed to varying soil properties above the tunnel crown and greater thickness. Conversely, the observed behaviors align with studies by França [15] and De Farias et al. [20].

The displacements at the nodes located at the top and sides of the excavation were verified and compiled in Table 3. A flattening trend of the section was observed in all analysis, with the top node converging and the side nodes diverging. In the single tunnel analysis, Analysis 01 showed the highest vertical displacement at the top, while Analysis 03 had the lowest. There was an inversely proportional relationship between vertical displacements at the top and horizontal displacements at the sides. Hence, the analysis 01 showed the lowest horizontal displacement, while analysis 03 had the highest.

In twin tunnels, full-section excavation resulted in the highest vertical displacements and lowest horizontal displacements, while the side drift methodology had the lowest vertical and highest horizontal displacements. Analysis 07 had the lowest vertical displacement at the crown, with a 29.01% reduction compared to Analysis 04,



(a) (b)

Figure 7. Vertical displacement along tunnel axis (a) left tunnel (b) right tunnel

and the highest horizontal displacement. For twin tunnels, horizontal displacements at the inner side nodes were consistently lower than at the outer side nodes.

Partializing the section in side drift reduced crown displacements (% R) by 8.67% and 14.74% compared to non-partialized excavation for single and double tunnels, respectively. At least, 78.73% of the total displacements occurred up to the application of the secondary lining of the crown.

Table 3. Perimeter displacements

Analysis	Outer side		Crown		Inner side		δ/D_{eq}			δ_v	
	δ_h	%R²	δ_v	%R²	δ_h	%R²	Outer	Crown	Inner	δ_v	% δ_{vmax}
1	7.06	21.90%	41.10	0.00%	7.68	29.90%	0.49	2.87	0.54	0.00	0.00%
2	9.04	0.00%	40.59	1.24%	9.87	9.91%	0.63	2.83	0.69	35.89	88.43%
3	9.02	0.21%	37.53	8.67%	10.96	0.00%	0.63	2.62	0.76	31.53	84.01%
4 - Left	7.75	23.93%	41.82	0.00%	6.60	13.92%	0.54	2.92	0.46	0.00	0.00%
5 - Left	9.55	6.26%	40.83	2.36%	6.51	15.09%	0.67	2.85	0.45	35.05	85.84%
6 - Left	10.19	0.00%	36.36	13.06%	7.66	0.00%	0.71	2.54	0.53	29.92	82.28%
7 - Left	9.36	8.14%	41.32	1.19%	5.57	27.31%	0.65	2.88	0.39	35.75	86.52%
4 - Right	7.49	39.26%	41.66	0.00%	4.05	49.48%	0.28	2.91	0.52	0.00	0.00%
5 - Right	9.69	21.41%	41.08	1.39%	5.20	35.11%	0.36	2.87	0.68	36.13	87.93%
6 - Right	10.40	15.65%	35.48	14.84%	7.08	11.66%	0.49	2.48	0.73	29.63	83.51%
7 - Right	12.33	0.00%	29.57	29.01%	8.01	0.00%	0.56	2.06	0.86	23.28	78.73%

NOTES

All displacements in millimeters

² Percentual reduction compared to the maximum value of all analysis

5 Conclusions

Based on the obtained results, this study confirms the effectiveness of section partialization in reducing soil displacements, highlighting the importance of choosing the appropriate technique to ensure the stability of the soil mass and the safety of adjacent structures.

Critical displacement points were observed at the tunnel crown, decreasing with distance from the cavity. In twin tunnels, symmetrical displacement behavior was seen, except in Analysis 07, where different methodologies caused greater displacements in the left tunnel. The side drift excavation method proved to be more effective in reducing crown settlements, resulting in up to 8.67% and 14.84% less displacement in single and twin tunnels, respectively. Conversely, full-section excavation exhibited the highest displacements, underscoring the necessity for more controlled techniques in densely populated urban environments.

The analysis of displacements along the tunnel depth and excavation perimeter revealed nonlinear behaviors dependent on the construction stages, with partialization being particularly effective in reducing vertical displacements at the crown, despite showing higher horizontal displacements at the sides. Additionally, the stages associated with crown excavation and lining application were crucial, representing more than 78% of the total displacements observed in all analysis.

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