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Finite element analysis of the twin tunnels-piled structure interaction

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Abstract

The expansion of urban areas has resulted in an increasing demand for underground construction. In most cases, each tunnel line usually builds two parallel tunnels to facilitate efficient traffic management. The ground deformation mechanisms during the excavation of twin tunnels differ from that which occurs during the construction of a single tunnel. The construction of two tunnels in the urban area causes ground displacements and stress redistribution, which pose a mechanical impact on the adjacent pile foundations and underground structures. Therefore, optimization in tunnel design requires predicting the response of pile structures and adjacent underground infrasturcture. The present study delves into the interaction analysis between the twin tunnels and the piled structure through the use of the finite element method. The analysis concentrates on aspects such as surface settlements, the response of tunnel linings and the behavior of piles resulting from the interaction between twin tunnels and deep foundations. The obtained results indicate that the magnitude of the internal forces and displacements of the front pile P1 closer to twin tunnels is higher than for the rear piles P2, P3 and P4. The magnitude of the internal forces and displacements of the piles for the case of twin tunnels T1 and T2 construction are greater than that for the case of single tunnel T1. The second tunnel T2 is located near the multi-storey building, and it is strongly affected by twin tunnels-piled structure interaction and therefore the magnitude of the normal forces and bending moments of the tunnel lining for the case of construction twin tunnels T1, T2 beneath piled-structure are greater than that for case of twin tunnels T1, T2.

Keywords

Underground construction; twin tunnels; piled structure; tunnel-piled structure interaction; finite element method

Introduction

The process of constructing tunnels in soft soil causes ground movements. There have been many reports predicting ground movements due to the construction of a single tunnel, including the authors: Peck (1969), O'Reilly et al., (1982), Attewell et al., (1982). Attewell et al., (1986), Mair et al., (1996), Karasev et al., (2015), Protosenya et al., (2015) and Yifan et al., (2023). These authors considered the effect of factors such as diameter and depth of tunnels, construction method and soil type on the magnitude and distribution of ground movements. Predicting ground movements resulting from twin tunnels often involves combining the predictions of two individual single tunnels, Hunt (2005) and Zhiyong et al., (2021). Projections regarding subsurface displacements and their impact on underground utilities typically rely on extrapolating surface measurements. In a study conducted by Addenbrooke et al., (1997), surface settlements were meticulously recorded above twin tunnels, their findings indicated that the magnitudes of displacements observed above twin tunnels were greater than those measured for a single tunnel. Hunt (2005) considered the effects of twin tunnels construction on ground movements, both at the surface and within the subsurface. This study encompassed a spectrum of factors, such as the distance between two tunnels, diameters and depths of twin tunnels, all within the context of London Clay. While a semi-empirical method is employed to anticipate soil movement caused by tunnels in greenfield conditions with no other structures present, this approach falls short in predicting the reaction of existing structures when exposed to the effects of tunnel construction. Tunnelling-induced ground movements can significantly impact urban areas, potentially affecting existing structures nearby. The process of tunnel excavation induces ground movements at the foundation level, which can ultimately lead to structural damage. The effect of tunnel excavation on structures in the vicinity and the associated ground movements have been extensively documented by various authors. Loganathan et al., (2000) conducted a series of three centrifuge tests aimed at exploring the impacts of tunnelling under undrained conditions on both a single pile foundation and a 2x2 pile group foundation in preconsolidated kaolin clay. Their study elucidated the primary interaction mechanisms between a single tunnel and pile foundations. When tunnel is excavated beneath the level of the pile tips, the potential arises for substantial pile settlements and disparate movements among piles (Marshall and Mair, 2011; Bel et al., 2016). These movements can ultimately result in foundation tilt (Ng et al., 2014) and distortions in superstructures (Franza and Marshall, 2018). However, relatively little is known about the interaction between twin tunnels and piled structures. These studies focus on tunnel lining forces during the construction of a single tunnel or on the mechanical interaction between a single tunnel and piled structures. However, the interaction between twin tunnels and piled foundations remains inadequately understood. In urban settings, subway systems often require the construction of twin tunnels in close proximity to existing buildings. Consequently, this study seeks to improve the understanding of the mechanical interaction between twin tunnels and piled structures, an essential aspect for ensuring safety and optimizing design in urban tunneling projects. The primary aim of this paper is to enhance the understanding of the mechanical interaction between two parallel tunnels and pile-supported structures. In particular, the study investigates the influence of two key parameters: the horizontal distance between the tunnels and the building, and the tunnel depth. These parameters influence the distribution and magnitude of axial forces and bending moments in the tunnel linings, as well as axial forces, bending moments, lateral displacements and vertical movements of the piles.

Material and Methods

Surface settlement due to tunnelling

Estimating the magnitude and distribution of surface settlements often draws from the findings of Peck (1969). These findings predominantly rely on observed surface settlements from case studies, and the resulting settlement pattern is effectively characterized by a Gaussian distribution curve, the vertical settlement in the transverse direction is given by:

$$S_{v(x)} = S_{v,\max} . e^{-\frac{x^2}{2 i_x^2}} \tag{1}$$

where $S_{v,\max}$ is the maximum settlement on the tunnel centreline, i_x and x are the trough width parameter and distance from the tunnel centreline.

Based on the studies of pile behavior during the construction of the North-South Tunnel in Amsterdam, the Netherlands (Kaalberg et al., 2005), and the Channel Tunnel Rail Link (CTRL) project in the UK (Selemetas, 2005), the authors proposed a relationship between pile head settlement and greenfield surface settlements, which depends on the position of the pile tip, as illustrated in Fig. 1.

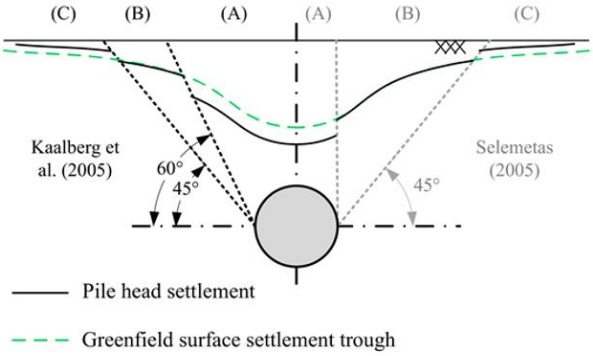


Fig. 1. The diagrammatic arrangement of the cyclosizer device (Kaalberg et al., 2005, Selemetas, 2005 and Franza, 2017)

Kaalberg et al., (2005) and Selemetas (2005) delved into the examination of analyses involving varying values for both greenfield surface settlement and pile head settlement. In their studies, these authors suggested the existence of three distinct zones: zone A, where pile head settlements might marginally exceed greenfield surface settlements; zone B, where they could roughly equate; and zone C, where pile head settlements were notably less than greenfield surface settlements.

Finite element method modelling

This study employs the Finite Element Method to investigate the interaction between twin tunnels and a piled structure. The geometry of the tunnels, along with details of the piles and soil layers, is shown in Figure 2. Three simulation cases were analyzed: (1) construction of a single tunnel (T1) under greenfield conditions; (2) construction of two parallel twin tunnels (T1 and T2); and (3) construction of twin tunnels (T1 and T2) along with the adjacent building. These cases were used to evaluate the variations in normal forces and bending moments in the tunnel linings, as well as axial forces, bending moments, lateral displacements, and vertical displacement of the piles. In addition, the study examines the influence of two key parameters: the horizontal distance L between the twin tunnels and the piled structure, and the construction depth Z of the tunnels. Their effects on the mechanical interaction between the tunnels and the pile foundation were assessed through the responses of both tunnel linings and piles.

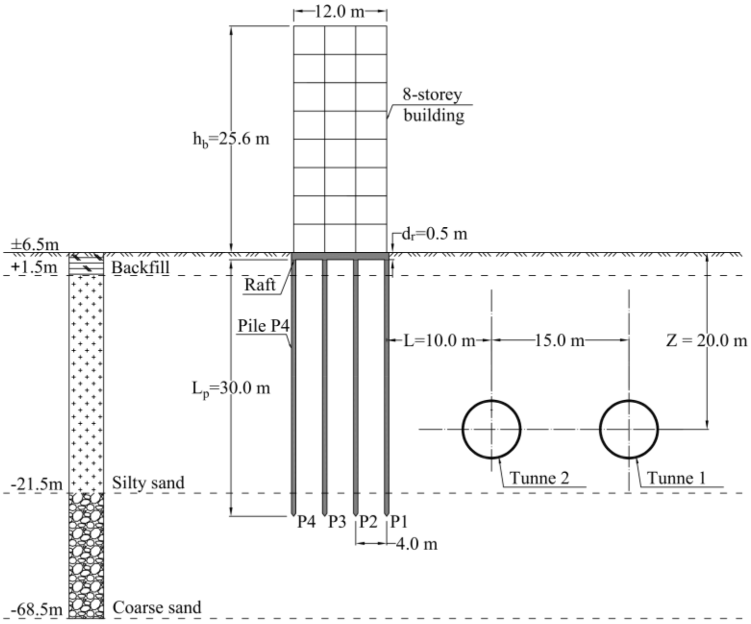


Fig. 2. The soil, twin tunnels and piled structure geometries

The numerical simulation utilized the plain strain Finite Element Method (FEM) model, specifically Plaxis 2D V20. This model incorporated three distinct soil types, with their corresponding properties outlined in Table 1.

The parallel twin tunnels have a diameter of 6.3 m and are situated at a depth of 20 m. The adjacent building is 12.0 m wide, with eight floors, and is supported by a piled raft foundation. Each pile has a diameter of 0.4 m and extends to a depth of 30 m, with a center-to-center spacing of 4.0 m. The piles support a reinforced concrete raft that is 0.5 m thick, as illustrated in Fig. 2. The size of the numerical model influences both computational efficiency and the accuracy of simulation results. According to Oteo and Sagaseta (1982), the horizontal distance from the tunnel center to the model's vertical boundary should be at least 10 times the tunnel diameter to minimize boundary effects. This recommendation has been adopted in many subsequent studies to ensure that the model boundaries do not interfere with the analysis outcomes. In this study, the distance from the tunnel center to the vertical edge is set to 85 meters, which is approximately 13 times the tunnel diameter, thereby satisfying this criterion. The overall model dimensions are 75 meters in height and 200 meters in width. The boundary conditions applied in this analysis are as follows: the bottom boundary is fully restrained, with both horizontal and vertical displacements fixed. The two vertical boundaries allow only vertical displacements, while horizontal displacements are restricted. The top boundary is free to move in both horizontal and vertical directions. The model consisted of various elements, including a 15-node element for clusters, plate elements for the tunnel lining, raft, and building components. For piles, an embedded pile row element was employed, and the soil-structural interface was adopted, (as shown in Fig. 3).

The Hardening Soil (HS) model was used for the interaction analysis between the twin tunnels and the piled structure. The mechanical properties of the tunnel linings, raft and building components used are as shown in Table 2, while the pile parameters are detailed in Table 3.

The numerical modeling process was executed following the subsequent steps:

- Delimiting the circumferential soil zone around both the tunnels and the building structure.
- Opting for a suitable constitutive model and ascertaining the necessary parameters.
- Imposing the necessary boundary conditions.
- Initiating the building activation phase.
- In the phase: constructions of twin tunnels.

Tab. 1. Material parameters for the soil layers used in this study

Parameter	Layer thickness	Unit weight	Secant stiffness from drained triaxial test	Tangent stiffness for primary oedometer loading	Unloading/ reloading stiffness	Poisson's ratio	Friction angle	Cohesion
	[m]	[kN/m^3]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[-]	[°]	[kPa]
Backfill	5.0	20.00	18500	18500	55500	0.3	28	9.6
Silty sand	23.0	20.35	32650	32650	97950	0.3	25	25
Coarse sand	42.8	20.05	45150	45150	135500	0.3	34	0.5

Tab. 2. Material parameters for the tunnel lining, raft and building

Input Parameter	Material type	Isotropic	Axial stiffness	Bending stiffness	Weight	Poisson's ratio
	[-]	[-]	[kN/m]	[kN.m^2/m]	[kN/m/m]	[-]
Tunnel lining	Elastic	Yes	10.5 10^6	78.75 10^3	7.5	0.15
Raft	Elastic	Yes	15.0 10^6	312.5 10^3	24	0.15
Building	Elastic	Yes	12.0 10^6	160.0 10^3	9.6	0.15

Tab. 3. Material parameters for the embedded piles

Parameter	Material type	Young's module	Unit weight	Beam type	Diameter	Pile spacing	Skin resistance at top, $T_{skin, start, max}$	Skin resistance at bottom, $T_{skin, sand, max}$	Base resistance, F_{max}
	[m]	[Mpa]	[kN/m^3]	[-]	[m]	[m]	[kN/m]	[kN/m]	[kN/m]
Pile	Elastic	35. 10^6	24	Predefined	0.4	4,0	10.00	100.0	1000

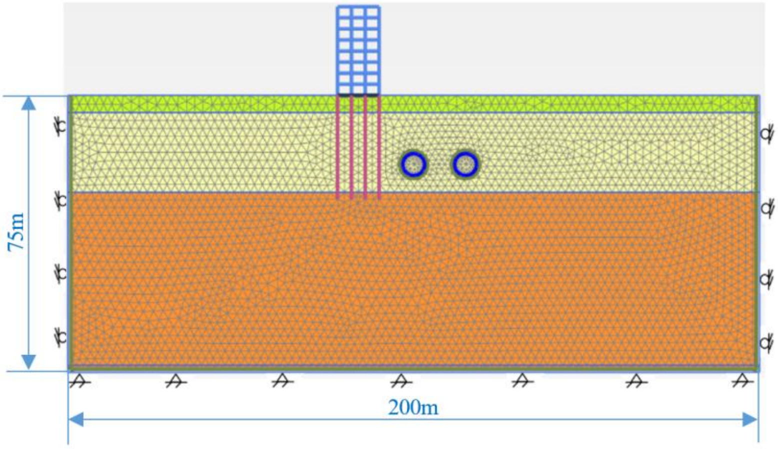
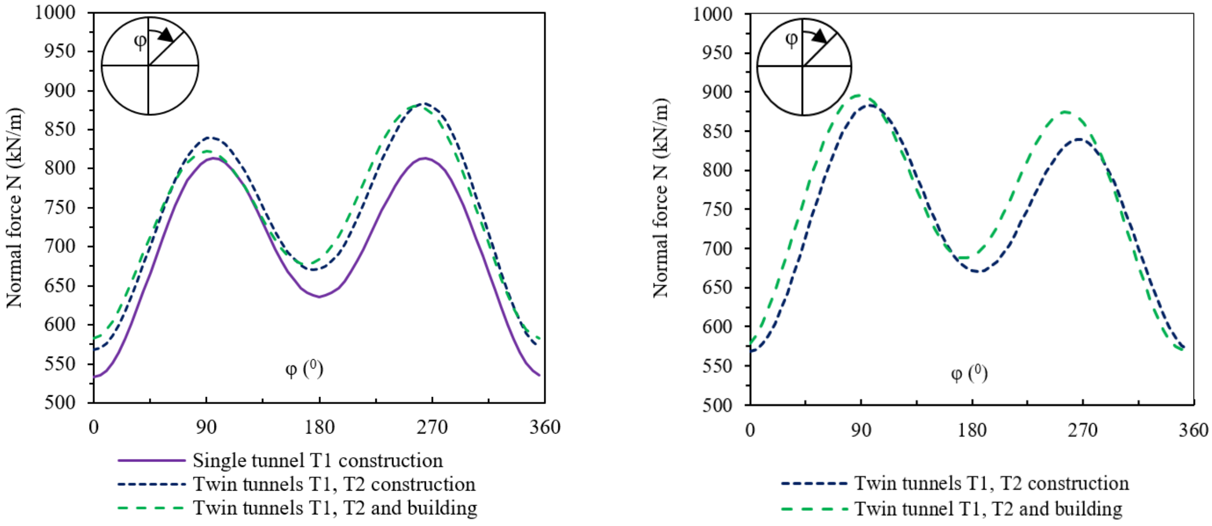


Fig. 3. Geometries and setup of the finite element model

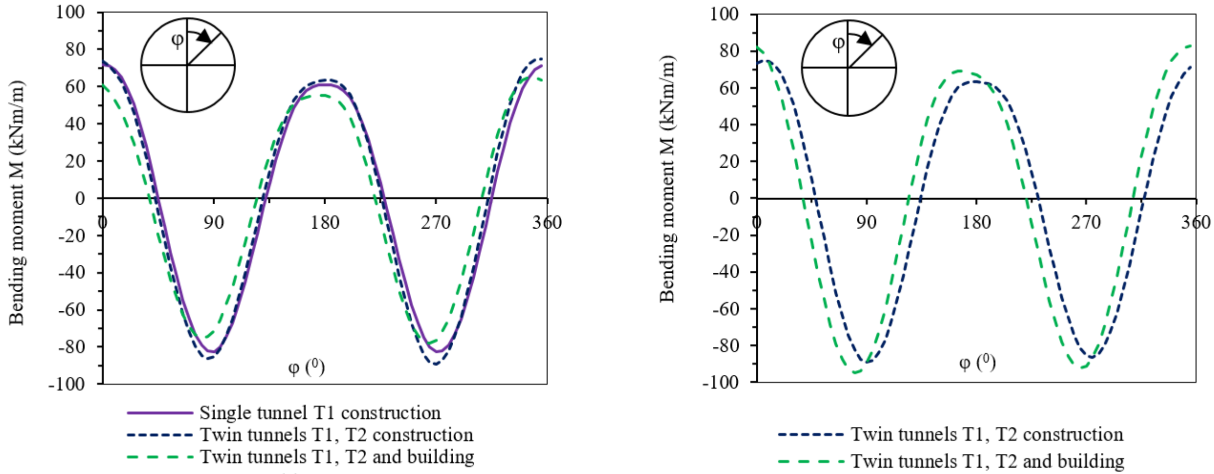
Result and discussion

Fig. 4 shows the distribution of the normal forces and bending moments in the tunnel linings. These results indicate that for the single tunnel T1 construction case under greenfield conditions, the maximum normal forces of tunnel T1 lining is 813.49 kN/m, the position of maximum normal forces are at the springlines of the tunnel T1 lining. The normal forces of the tunnel T1 lining distribution is symmetric (Fig. 4-a). For this case, the maximum positive/negative bending moments of tunnel T1 lining are 71.89/-82.59 kNm/m, the position of positive bending moments isat the crown and at the invert of the tunnel T1 lining and the position of negative bending moments is at the springlines of the tunnel T1 lining. The bending moment of the tunnel T1 lining distribution is symmetric (Fig. 4-c). For the twin tunnels T1, T2 construction case, the influence of the interaction between tunnel T1 and tunnel T2 can be seen in Fig. 4, the internal force in the tunnel T1 lining has changed, and the magnitude of the maximum normal forces of the tunnel T1 lining increased by 8.56% compared to the single tunnel T1 construction case (813.49 kN/m to 883.12 kN/m) and the position of the maximum normal forces tunnel T1 lining are in the vicinity of the springline at ~265°, the normal forces of the tunnel T1 lining distribution is not symmetric for the case of twin tunnels T1, T2 construction (Fig. 4-a).



(a)

(b)



(c)

(d)

Fig. 4. The internal forces in the tunnel lining in different construction cases, a) Normal forces in the tunnel T1 lining, b) Normal forces in the tunnel T2 lining, c) Bending moments in the tunnel T1 lining and d) Bending moments in the tunnel T2 lining

In the case of construction twin tunnels T1, T2, the maximum positive/negative bending moments of tunnel T1 lining was found to be 74.82/-89.30 kNm/m, negative bending moments increased by 8.13% compared to the single tunnel T1 construction in greenfield conditions case (-82.59 kN/m to -89.30 kNm/m), the position of negative bending moments are in the vicinity of the springline at ~270°. The bending moment of the tunnel T1 lining distribution is not symmetric for the case of construction twin tunnels T1, T2 (Fig. 4-c). The maximum normal forces of tunnel T2 lining was found to be 883.07 kN/m and the position of the maximum normal forces tunnel T2 lining are in the vicinity of the springline at ~95°, the normal forces of the tunnel T2 lining distribution is not symmetric for the case of construction twin tunnels T1, T2 (Fig. 4-b). The maximum positive/negative bending moments of tunnel T2 lining are 74.76/-89.32 kNm/m, the position of positive bending moments is in the vicinity of at the crown at ~5° and the position of negative bending moments is in the vicinity of at the springline at ~90° of the tunnel T2 lining. The bending moment of the tunnel T2 lining distribution is not symmetric for the case of twin tunnels T1, T2 construction (Fig. 4-d). For twin tunnels T1, T2 construction beneath the building , the maximum normal forces of tunnel T1 and T2 lining are 880.33kN/m and 895.95 kN/m, respectively. The second tunnel T2 is near the building, so it is strongly affected by twin tunnels-piled structure interaction. The magnitude of the maximum normal forces of tunnel T2 lining increased by 1.5% compared to the case twin tunnels T1, T2 construction (883.07 kN/m to 895.95 kN/m). The maximum positive/negative bending moments of tunnel T1 and T2 lining are 65.37/-78.28 kNm/m and 82.64/-94.77 kNm/m, respectively. The maximum positive/negative bending moments of tunnel T2 lining increases from 74.76/-89.32 kNm/m for case of construction twin tunnel up to 82.64/-94.77 kNm/m when construction twin tunnels T1, T2 beneath piled building.

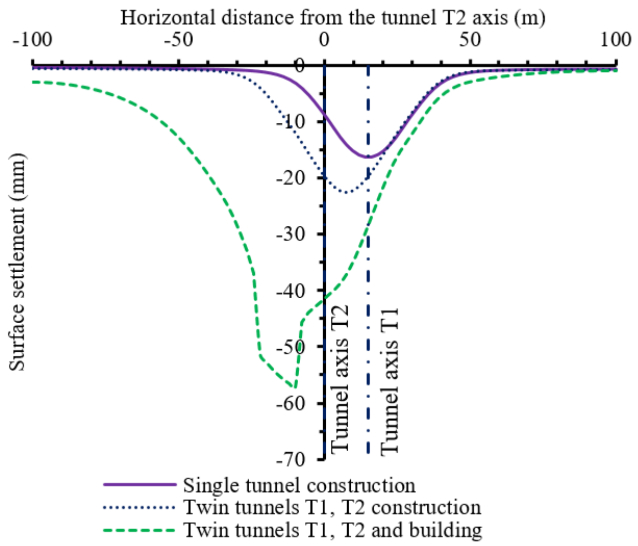


Fig. 5. Ground surface settlement

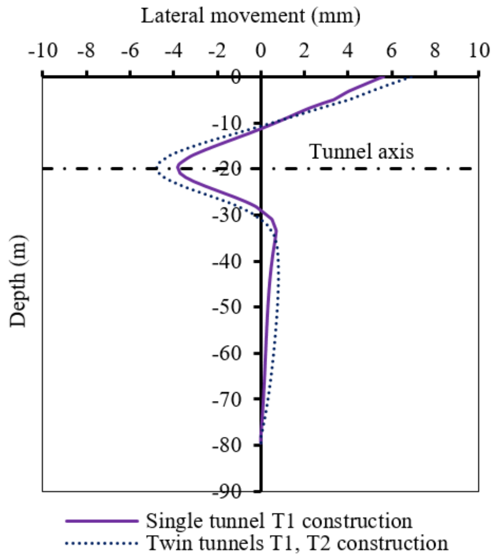


Fig. 6. Lateral ground displacement, l=10m away from the tunnel centreline

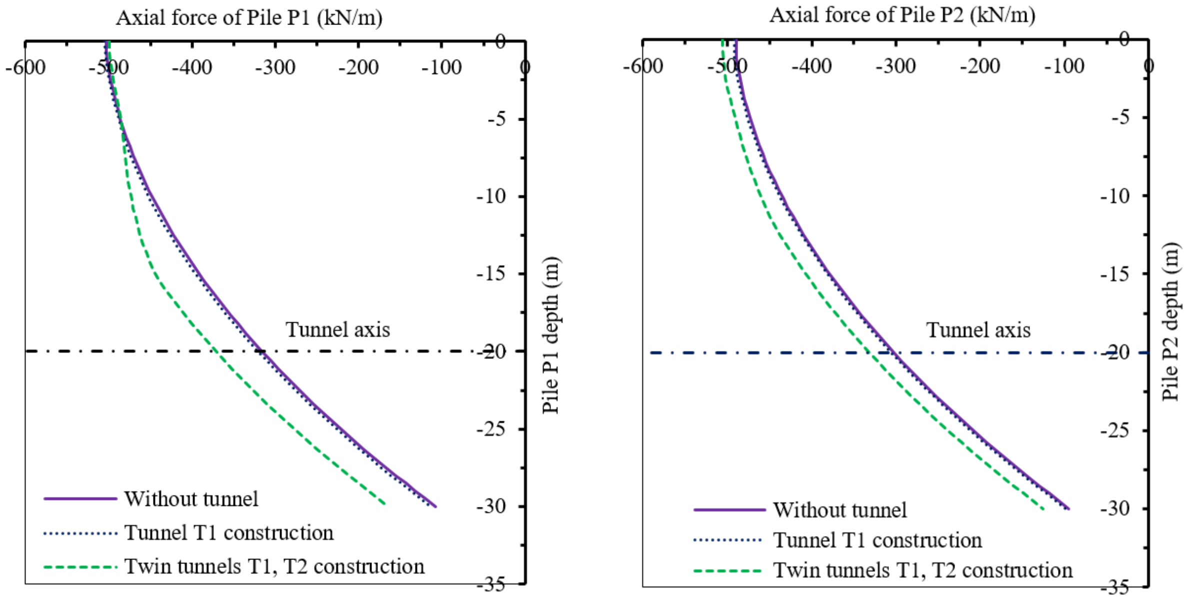
The bending moment of the tunnel T2 lining distribution is not symmetric for the case of construction twin tunnels T1, T2 beneath piled-structure, (Fig. 4-d), the position of positive bending moments is in the vicinity of at the crown at ~355° and the position of negative bending moments is in the vicinity of at the springline at ~80° of the tunnel T2 lining. The normal forces and bending moments in the tunnel lining have been compared with the results of previous studies, these results are shown to have good agreement with Marwan (2019) and Pedro et al., (2022).

Fig. 5 shows ground settlement above tunnel axis T2, after the construction of a single tunnel T1 under greenfield conditions, the maximum value of ground settlement Sv,max was found to be 16.2 mm and the position of Sv,max was situated above the tunnel axis T1. After the construction of the second tunnel T2, the interaction between the two tunnels affects the ground settlement, the magnitude of Sv,max increased by 45% compared to the case of a single tunnel T1 construction undergreenfield conditions (16.2 mm to 22.6 mm) and the position of Sv,max is eccentrically displaced 7.5m towards tunnel T1. When constructing twin tunnels T1 and T2 beneath building, the maximum value of ground settlement Sv,max was found to be 57.32 mm. This maximum ground settlement was eccentrically located, shifted 10 m toward the building. The maximum lateral ground displacement induced by twin tunnelling at a distance of l = 10 m from the tunnel centreline was 6.9 mm, which represents a 22.4% increase compared to the value observed during the construction of a single tunnel (T1) under greenfield conditions (5.6 mm), as shown in Fig. 6. The ground surface settlement and lateral ground displacement above the tunnels (Figs. 5 and 6) were compared with prediction methods outlined earlier, showing good agreement with the findings of Hunt (2005) and Zuliang et al. (2021).

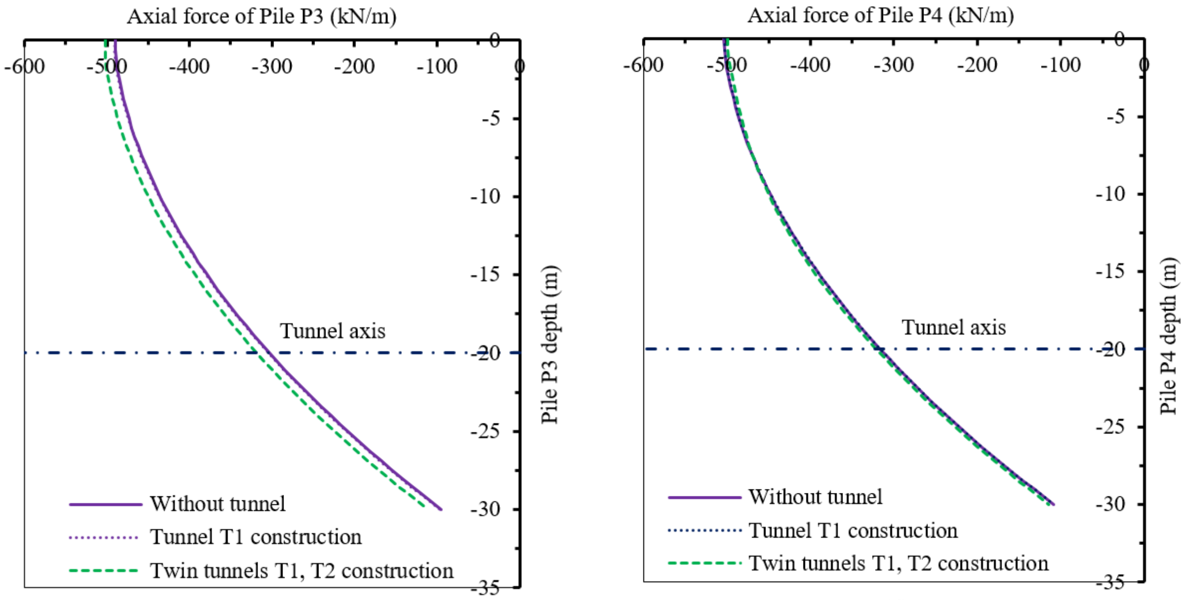
Fig. 7 shows the distribution of axial forces of piles, these results indicate that the influence of interaction between piled structure and tunnels is significant for axial forces of piles at the level tunnel horizontal axis. Considering the axial forces of piles, the outcomes suggest that for case of piled structures without the presence of any tunnel, at the level of the depth of 20 m, the magnitude of the axial forces are 316.24 kN/m; 303.53 kN/m; 303.46 kN/m and 316.69 kN/m for pile P1; P2; P3 and P4, respectively. For case of single tunnel T1 construction, at the level tunnel horizontal axis with a depth of 20 m, the magnitude of the axial forces are increased by 1.45%, 1.00%, 0.46% and 0.06% for pile P1; P2; P3 and P4 compared to piled structures without the presence of any tunnel case. For twin tunnels T1, T2 construction case, at the level tunnel horizontal axis, the magnitude of the axial forces are increased by 17.48%, 9.57%, 5.01% and 1.47% for pile P1, P2, P3 and P4 compared to piled structures without the presence of any tunnel case, as shown in Fig. 7(a-d).

The results show that the influence of the single tunnel (tunnel T1) construction on axial forces of piles is not significant, this may be because the distance from T1 tunnel axis to piled-structure is 25m and the interaction between piled-structure and single tunnel T1 is negligible. The influence of interaction between piled structure and twin tunnels on axial forces of piles is significant and is greatest for pile P1, which is the first pile loaded in the group, than piles in positions P2, P3 and P4.

Fig. 8 shows the distribution of bending moments of piles, the results indicate that the influence of interaction between piled structure and tunnels is significant for bending moments of piles at the level tunnel horizontal axis.



(a) (b)



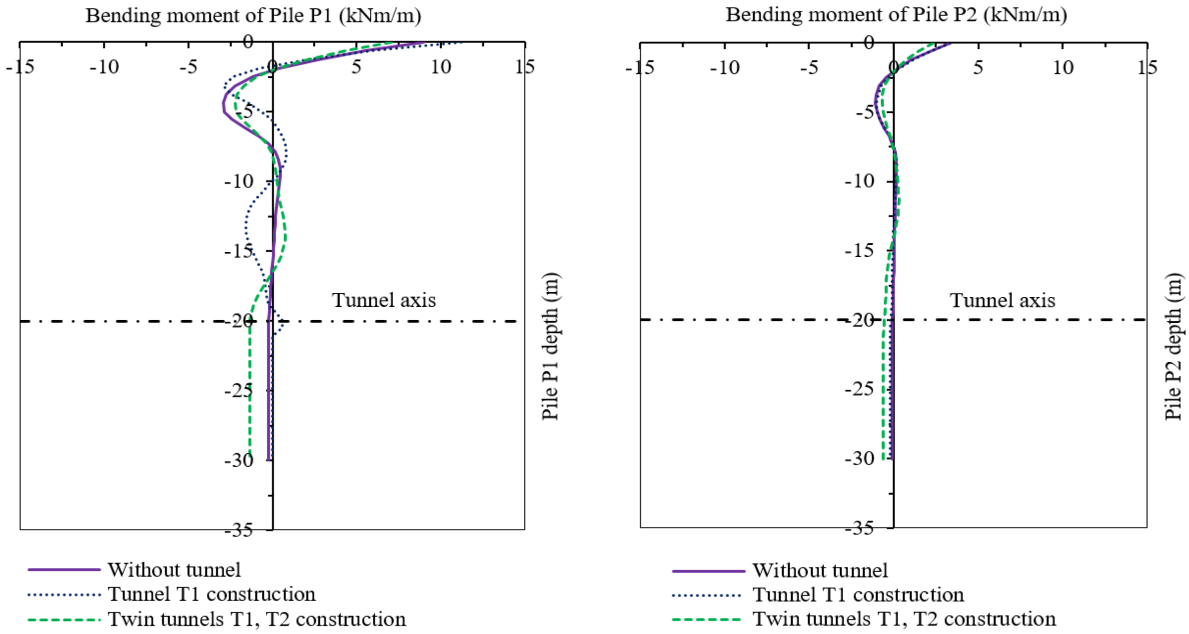
(c) (d)

Fig. 7. Influence of interaction between piled structure and tunnel on axial forces of piles: a) Pile P1, b) Pile P2, c) Pile P3, d) Pile P4

The outcomes suggest that for case of piled structure without the presence of any tunnel, at the level of the depth of 20 m, the magnitude of the bending moments are 0.21 kNm/m; 0.08 kNm/m; 0.08 kNm/m and 0.21 kNm/m for pile P1; P2; P3 and P4, respectively. The magnitude of the bending moments are increased by 363.93%, 100.40%, 70.15% and 19.08% for pile P1; P2; P3 and P4 for case of single tunnel T1 construction and increased by 530.11%, 471.86%, 346.46% and 86.89% for pile P1, P2, P3 and P4, respectively for case of twin tunnels T1, T2 construction.

Fig. 9 shows the distribution of lateral displacements of piles, the results indicate that the lateral displacements of piles are very similar to lateral ground movements (see Fig. 6) and the influence of interaction between twin tunnels and piled-structure is significant for lateral displacements of piles at the location of pile head and at tunnel axis depth of 20 m.

At the location of pile head, for case of piled structure without the presence of any tunnel, the magnitude of the lateral displacements are 0.07 mm for all piles P1; P2; P3 and P4. For case of single tunnel T1 construction, the magnitude of the lateral displacements are increased by 1.53 mm for all piles P1; P2; P3 and P4 and the magnitude of the lateral displacements are increased by 7.15 mm for all piles P1, P2, P3 and P4 for case of twin tunnels T1, T2 construction.



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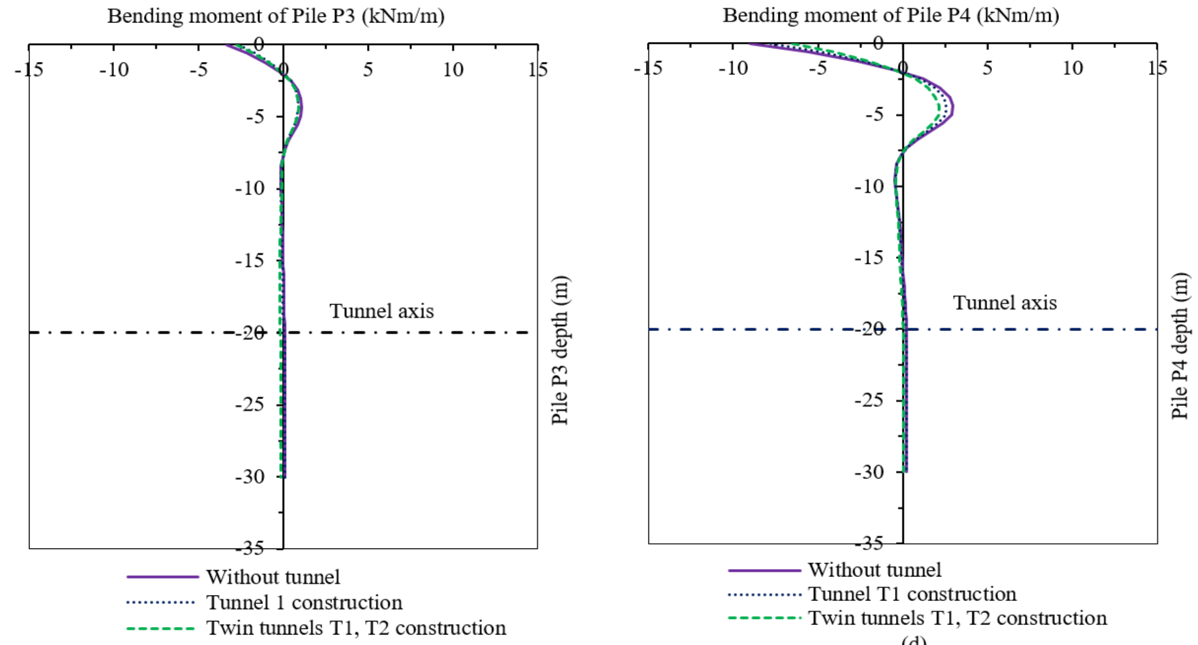


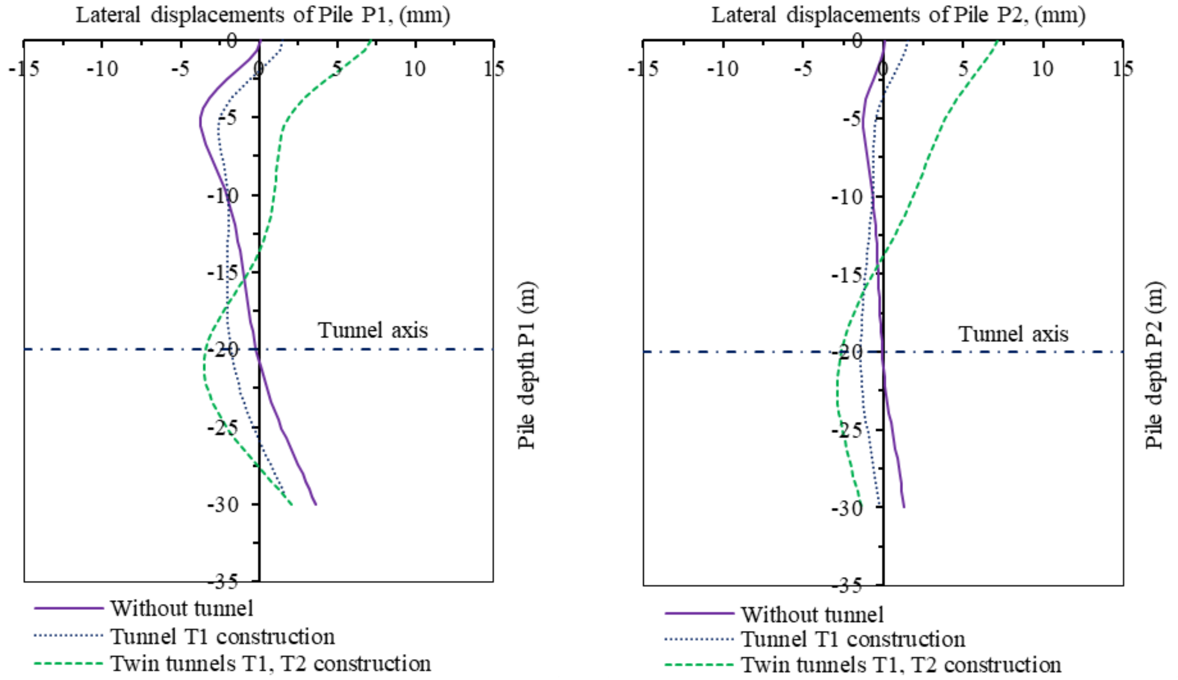
(c) (d)

Fig. 8. Influence of interaction between piled structure and tunnel on bending moments of piles: a) Pile P1, b) Pile P2, c) Pile P3, d) Pile P4

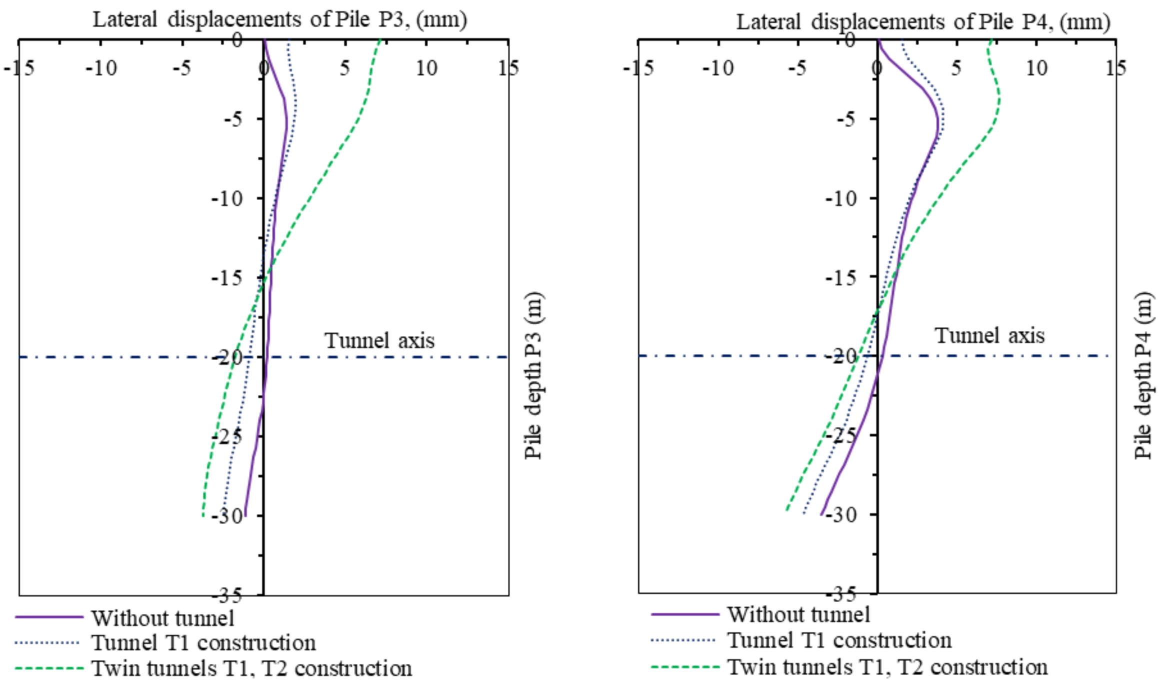
At the location of the tunnel horizontal axis with a depth of 20 m, for case of piled structure without the presence of any tunnel, the magnitude of the lateral displacements are 0.22 mm; 0.07 mm; 0.18 mm and 0.33 mm for pile P1; P2; P3 and P4, respectively. For case of single tunnel T1 construction, the magnitude of the lateral displacements are increased by 1.8 mm, 1.4 mm, 0.89 mm, 0.6 mm for pile P1; P2; P3 and P4, respectively and increased by 3.39 mm, 2.46 mm, 1.74 mm, 1.15 mm for pile P1, P2, P3 and P4, respectively for case of twin tunnels T1, T2 construction.

These findings indicate that the magnitude of the lateral displacements of the piles for case of twin tunnels T1, T2 construction is greater than that for case of single tunnel T1 and the magnitude of the lateral displacements of the front pile P1 closer to twin tunnels in the group is higher than for the rear pile: P2; P3; P4.

Fig. 10 shows the distribution of vertical movement of piles, the results indicate that the influence of interaction between piled structure and tunnel is significant for vertical movement of piles at the location of pile head and at tunnel axis depth of 20 m.



(a) (b)



(c) (d)

Fig. 9. Influence of interaction between twin tunnels and piled-structure on lateral displacements of piles: a) Pile P1, b) Pile P2, c) Pile P3, d) Pile P4

At the location of pile head, for case of piled structure without the presence of any tunnel, the magnitude of the vertical movement are 48.71 mm, 49.24 mm, 49.21 mm and 48.64 mm for pile P1; P2; P3 and P4, respectively. For case of single tunnel T1 construction, the magnitude of the lateral displacements are increased by 4.67%, 3.81%, 2.99% and 2.21% for pile P1; P2; P3 and P4 and the magnitude of the lateral displacements are increased by 17.85%, 13.65%, 9.76% and 6.02% for pile P1, P2, P3 and P4 for case of twin tunnels T1, T2 construction.

At the level tunnel horizontal axis with a depth of 20 m, for case of piled structure without the presence of any tunnel, the magnitude of the vertical movement are 38.39 mm, 39.21 mm, 39.19 mm and 38.31 mm for pile P1; P2; P3 and P4, respectively. For case of single tunnel T1 construction, the magnitude of the vertical movement are increased by 5.72%, 4.62%, 3.70% and 2.84% for pile P1; P2; P3 and P4, respectively and increased by 21.06%, 15.72%, 11.41% and 7.6% for pile P1, P2, P3 and P4, respectively for case of twin tunnels T1, T2 construction.

The internal forces and displacements of the piles have been compared with the results of previous studies, these results are shown to have good agreement with Loganathan (2001) and Franza et al., (2021).

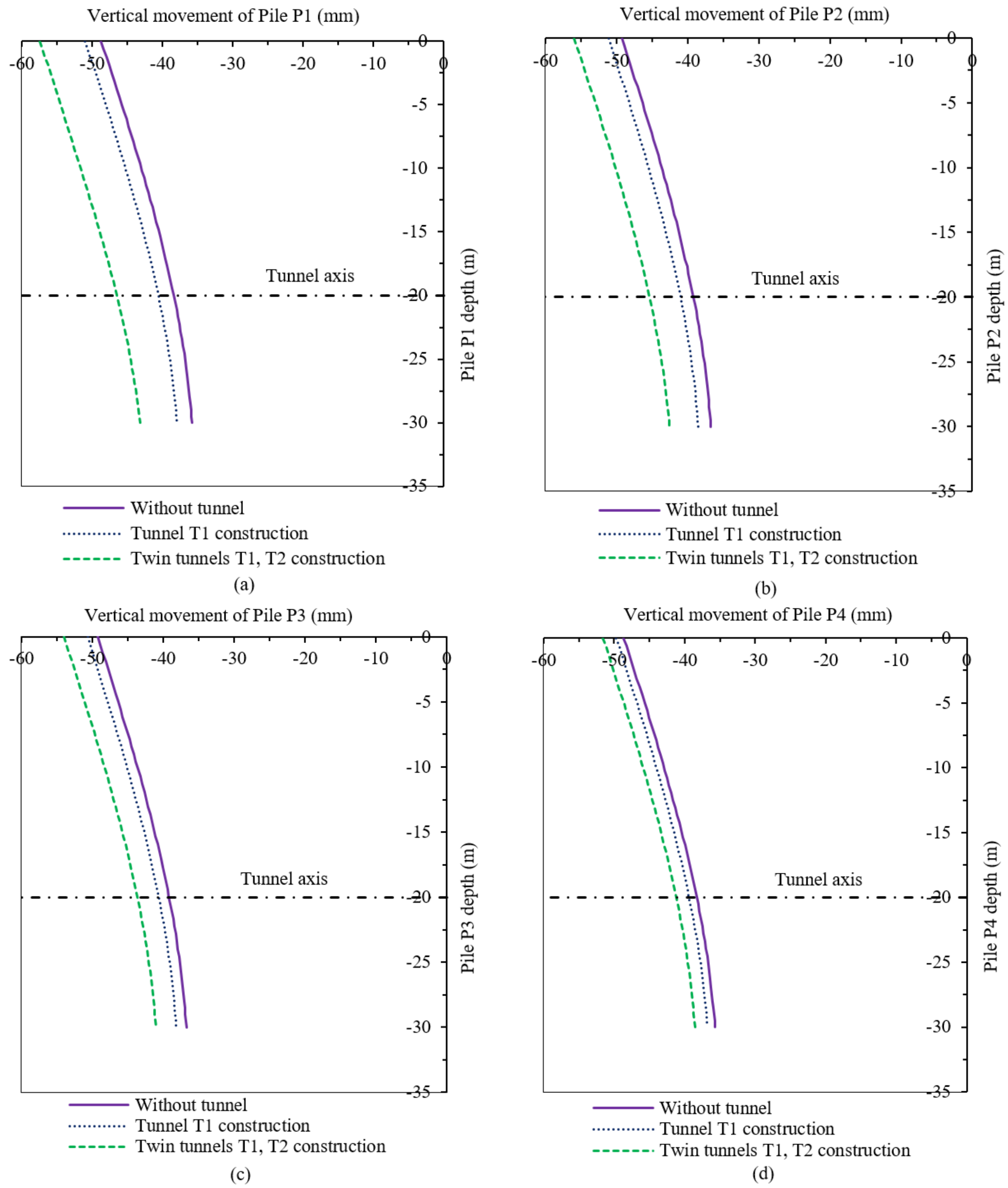


Fig. 10. Influence of interaction between twin tunnels and piled-structure on vertical movement of piles: a) Pile P1, b) Pile P2, c) Pile P3, d) Pile P4

The Fig. 11 investigates the influence of distance from the piled structure to the twin tunnels (L) on the response of tunnels linings, while keeping the depth of twin tunnels Z = 20 m and the distance between two tunnels of 15m constant. The normal forces in tunnel T1 lining are 890.58 kN/m, 877.19 kN/m, 872.76 kN/m, 872.25 and 876.91 kN/m for distance between piled-structure and twin tunnels of 1D, 2D, 3D, 4D and 5D, respectively. These results indicate that normal forces on tunnel T1 lining had been reduced from 890.58 kN/m to 872.25 kN/m for distance between piled-structure and twin tunnels increased 1D to 4D, the magnitude of normal forces on tunnel T1 lining had been increased from 872.25 kN/m to 876.91 kN/m for distance between piled-structure and twin tunnels increased 4D to 5D. As the result in the Fig. 4, when twin tunnels construction no piled-structure near the twin tunnels, the maximum value of normal forces on tunnel T1 lining was found to be 883.12 kN/m. The results indicate that the distance between piled-structure and twin tunnels (L) has no significant influence on the normal force in tunnel T1 lining, when the distance between piled-structure and twin tunnels of 4D (L = 4D) normal force on tunnel T1 lining is smallest.

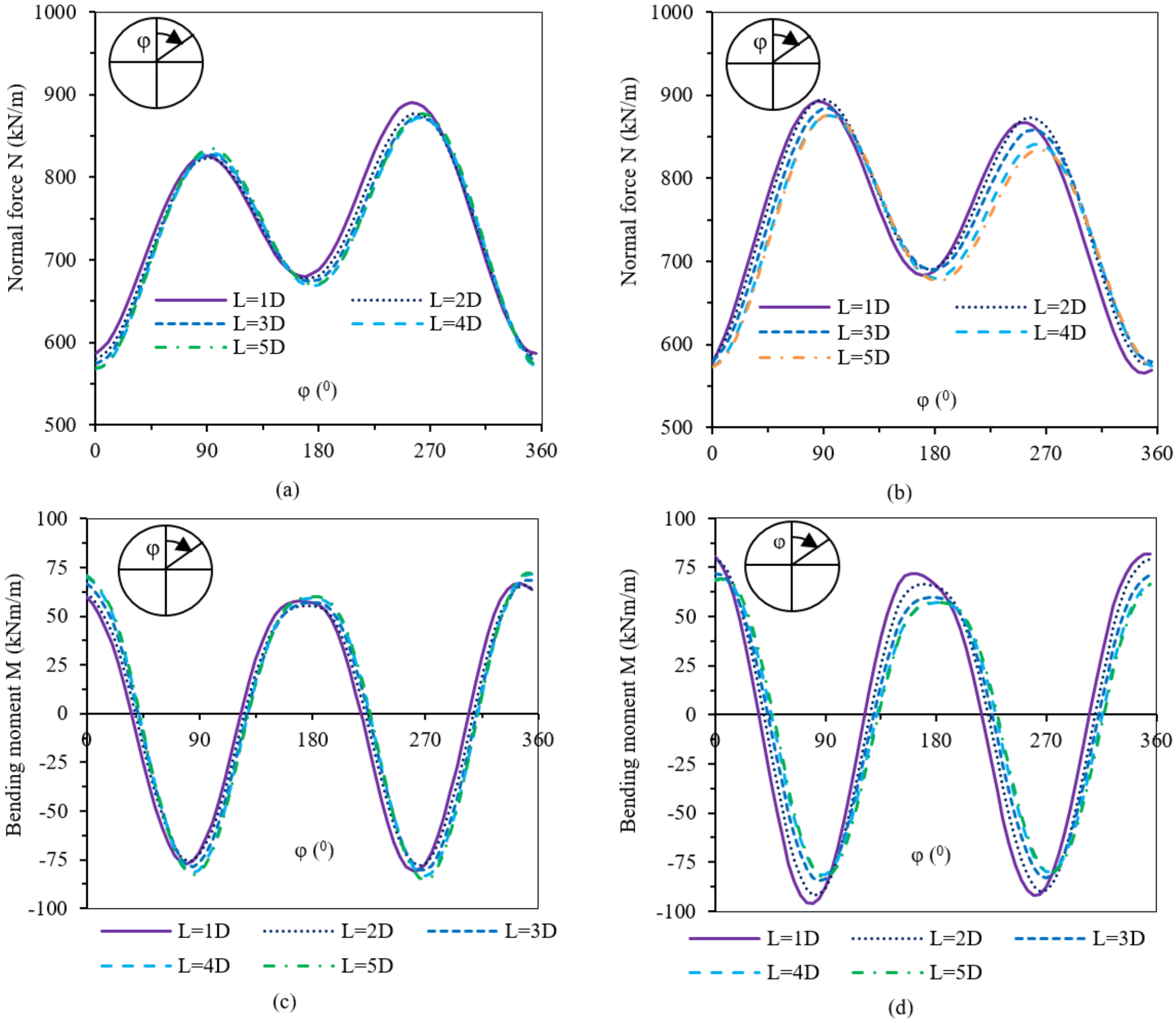


Fig. 11. Distribution of the normal forces in the tunnel T1 lining (a), normal forces in the tunnel T2 lining (b), bending moments in the tunnel T1 lining (c) and bending moments in the tunnel T2 lining (d) with varying distance from the piled structure to the twin tunnels, L

The normal forces on tunnel T2 lining are 894.91 kN/m, 892.41 kN/m, 883.83 kN/m, 875.75 and 877.04 kN/m for distance between piled-structure and twin tunnels of 1D, 2D, 3D, 4D and 5D, respectively. When twin tunnels construction no piled-structure near the twin tunnels, the maximum value of normal forces on tunnel T2 lining was found to be 883.07 kN/m (see Fig. 4). The result was shown that the distance between piled-structure and twin tunnels (L) have no significant influence on the normal force in tunnel T2 lining, when the distance between piled-structure and twin tunnels of 4D (L = 4D) normal force on tunnel T2 lining is smallest.

The maximum positive/negative bending moments in tunnel T1 lining and tunnel T2 lining are 67.00/-80.86 kNm/m, 65.64/-78.13 kNm/m, 68.46/-80.37 kNm/m, 71.36/-83.52 kNm/m, 72.07/-85.52 kNm/m and 82.03/-96.12 kNm/m, 79.50/-91.61 kNm/m, 71.88/-84.58 kNm/m, 69.21/-81.57 kNm/m, 69.28/-82.93 kNm/m for distance between piled-structure and twin tunnels of 1D, 2D, 3D, 4D and 5D, respectively. The location of T2 tunnel is near the piled-building, so it is more affected by the interaction between the twin tunnels and the building. When the distance from the pile to the tunnel is 1D, the negative bending moments on tunnel T2 lining has the maximum value of -96.12 kNm/m.

The Fig. 12 investigates the influence of distance from the piled structure to the twin tunnels (L) on surface settlements, while keeping the depth of twin tunnels Z = 20 m and the distance between two tunnels of 15m constant, the value of maximum vertical surface displacement Sv,max decrease with the increase of the distance from the piled structure to the twin tunnels, with values of 60.1mm, 55.6mm, 52.5mm, 50,8mm and 50.1mm were found to be at the distance from the piled structure to the twin tunnels of 1D, 2D, 3D, 4D and 5D, respectively.

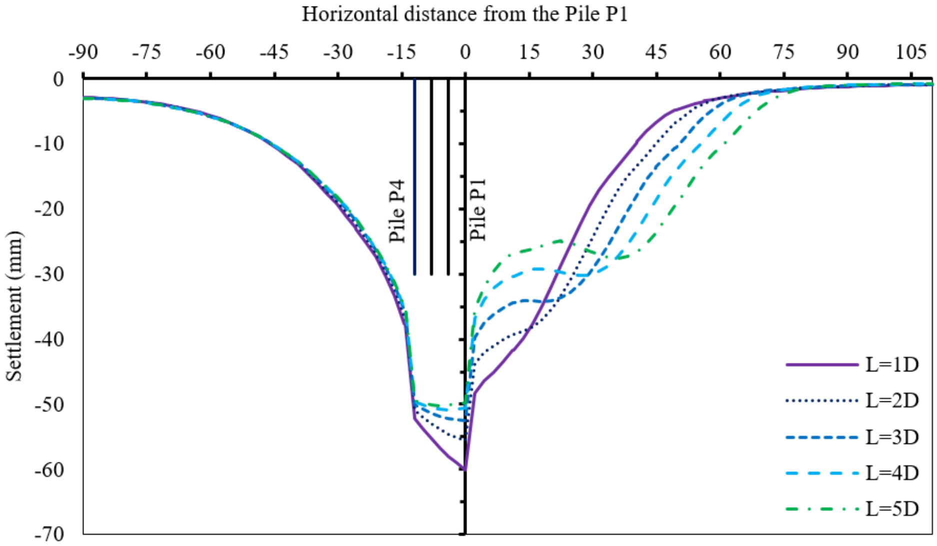
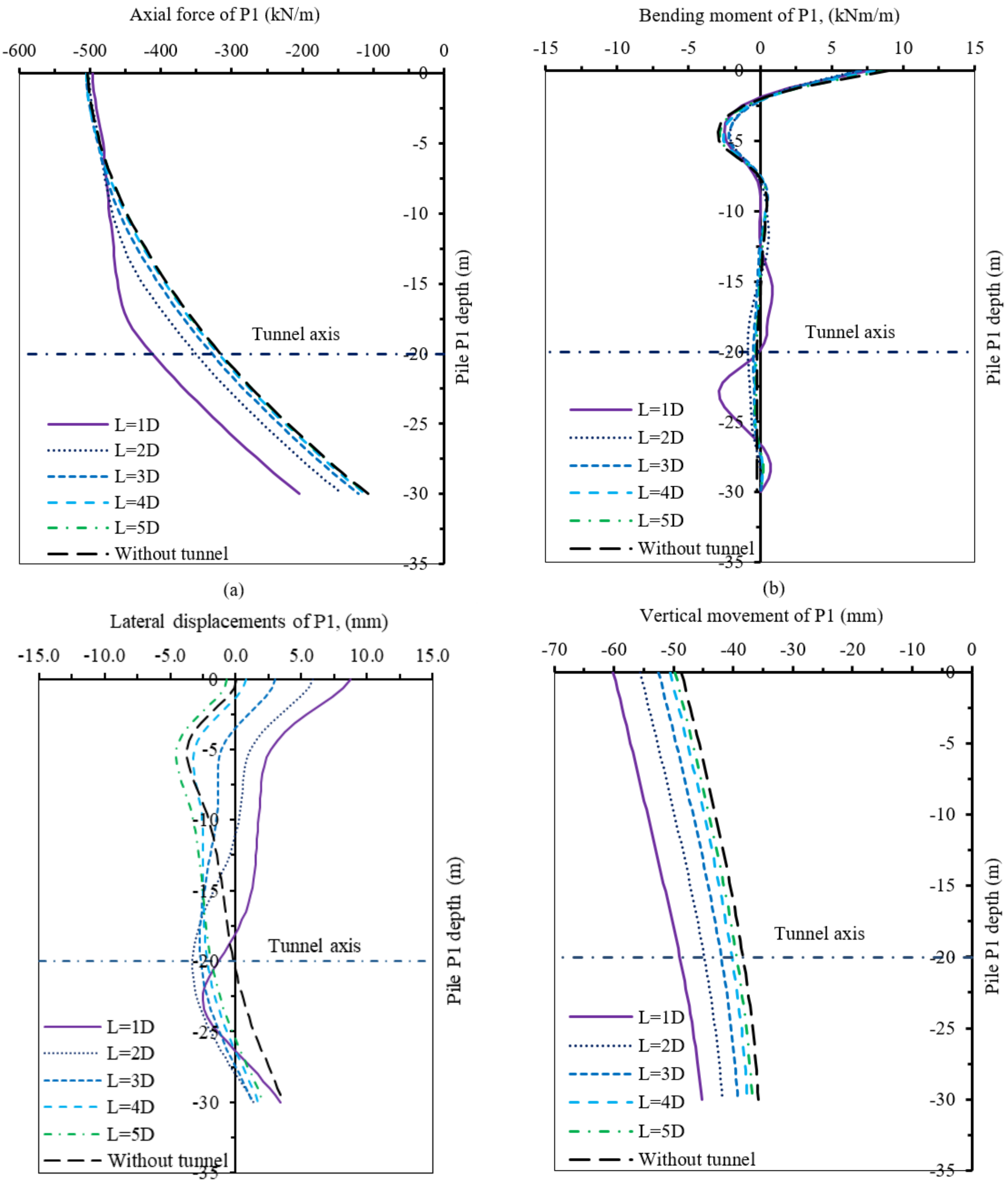


Fig. 12. Ground surface settlement trough with varying distance from the piled structure to the twin tunnels, L

The different responses of piles due to twin tunnels construction is analysed. These results are observed that the influence of interaction between piled structure and twin tunnels on responses of piles is significant and is greatest for pile P1, which is the first pile loaded in the group, than piles in positions P2, P3 and P4. The effect of distance from the piled structure to the twin tunnels (L) and the twin tunnel depth (Z) on the response of pile P1 due to twin tunnels were investigated from the finite element method can be seen in Fig. 13 to Fig. 16. The Fig. 13 investigates the influence of distance from the piled structure to the twin tunnels (L) on the response of pile P1, while keeping the depth of twin tunnels Z = 20 m and the distance between two tunnels of 15m constant. The axial forces and bending moments of Pile P1 of varying distance from the piled structure to the twin tunnels are presented in Fig. 13-a and b, these results suggest that a decrease in the axial forces and bending moments of Pile P1 with increasing L, this effect is small for axial force of P1 with a great distances from the piled structure to the twin tunnels (L=4D, L=5D) but is more significant for the L=1D and 2D cases. The influence of interaction between piled structure and twin tunnels is significant for axial forces of pile P1 occurring at the level tunnel horizontal axis. At the location of 20 m depth of the tunnel axis, the magnitude of axial forces of pile P1 are 412.72 kN/m, 351.45 kN/m, 328.67 kN/m, 319,55 kN/m and 316.84 kN/m for L = 1D, L = 2D, L = 3D, L = 4D and L = 5D, respectively. The influence of distance from the piled structure to the twin tunnels (L) is significant on bending moments of Pile P1 occurring at the depth of invert of the tunnels, the magnitude of bending moments of pile P1 are 2.82 kNm/m, 0.67 kNm/m, 0.44 kNm/m, 0.35 kNm/m and 0.31 kNm/m for L = 1D, L = 2D, L = 3D, L = 4D and L = 5D, respectively. The change in lateral displacements and vertical movements of Pile P1 with L shown in Fig. 13-c and d, these results indicate that the influence of distance from the piled structure to the twin tunnels (L) is significant on lateral displacements and vertical movements of Pile P1 at the location of pile head, the magnitude of lateral displacements of pile P1 are 8.72 mm, 5.91 mm, 3.04 mm, 0.77 mm and 0.65 mm and the magnitude of vertical movements of pile P1 are 60.11 mm, 55.64 mm, 52.54 mm, 50.65 mm and 49.78 mm for L = 1D, L = 2D, L = 3D, L = 4D and L = 5D, respectively. This influence reduces the greater the distance from the piled structure to the twin tunnels, as shown in Fig. 13(a-d).



(a)

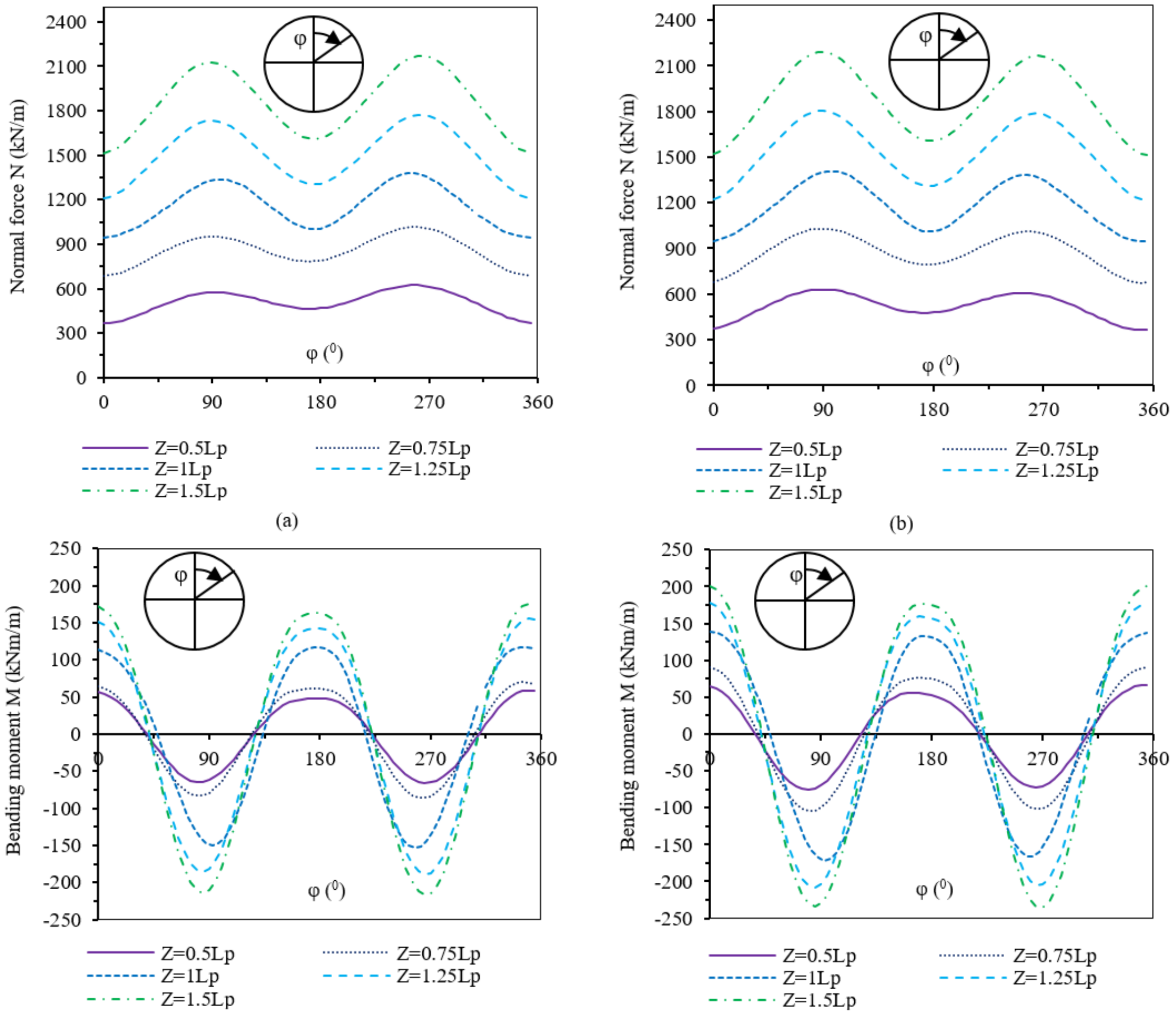
(b)

(c)

(d)

Fig. 13. Distribution of the axial forces (a), bending moments (b), lateral displacements (c) and vertical movements (d) in pile P1 with varying distance from the piled structure to the twin tunnels, L

The Fig. 14 investigates the affect of the twin tunnel depth (Z) on the response of tunnels lining, while keeping distances from the piled structure to the twin tunnels L = 10 m and the distance between two tunnels of 15m constant.These results show that the depth of tunnels has a significant influence on the normal forces and bending moments in the tunnel linings. The maximum normal forces in tunnel T1 lining and tunnel T2 lining are 622.65 kN/m, 1014.38 kN/m, 1378.66 kN/m, 1774.14 kN/m, 2170.15 kN/m and 630.55 kN/m, 1030.74 kN/m, 1407.74 kN/m, 1802.68 kN/m, 2189.42 kN/m for depth of twin tunnels of 0.5Lp, 0.75Lp, 1Lp, 1.25Lp and 1.5Lp, respectively. The maximum positive/negative bending moments on tunnel T1 lining and tunnel T2 lining are 59.00/-65.80 kNm/m, 69.89/-86.39 kNm/m, 117.31/-153.73 kNm/m, 155.24/-189.35 kNm/m, 175.43/-216.43 kNm/m and 66.30/-75.54 kNm/m, 90.11/-104.42 kNm/m, 138.83/-171.57 kNm/m, 178.05/-207.60 kNm/m, 200.64/-234.85 kNm/m for depth of twin tunnels of 0.5Lp, 0.75Lp, 1Lp, 1.25Lp and 1.5Lp, respectively. The increases in the normal forces and bending moments with increasing depth of twin tunnels.



(a) (b) (c) (d)

Fig. 14. Distribution of the normal forces and the bending moments in twin tunnels with varying depth of twin tunnels Z, a) Normal forces in the tunnel T1 lining, b) Normal forces in the tunnel T2 lining, c) Bending moments in the tunnel T1 lining and d) Bending moments in the tunnel T2 lining

Fig. 15 shows the influence of the twin tunnels depth, while keeping distances from the piled structure to the twin tunnels L = 10 m and the distance between two tunnels of 15m constant, the value of maximum vertical surface displacement Sv,max increase with the increase of the tunnel depth, with values of 54.1mm, 58.6mm, 62.0mm, 64,8mm and 66.2mm were found for the tunnel depth of 0.5Lp, 0.75Lp, 1Lp, 1.25Lp and 1.5Lp respectively, the Sv,max point was located at the bottom of the piled structure. The influence of twin tunnels depth is significant on bending moments of Pile P1 occurring at the depth of the tunnel axis, the magnitude of bending moments of pile P1 are 0.66 kNm/m, 0.71 kNm/m, 0.43 kNm/m, 0.22 kNm/m and 0.20 kNm/m for Z = 0.5Lp, Z = 0.75Lp, Z = 1Lp, L = 1.25Lp and Z = 1.5Lp, respectively.

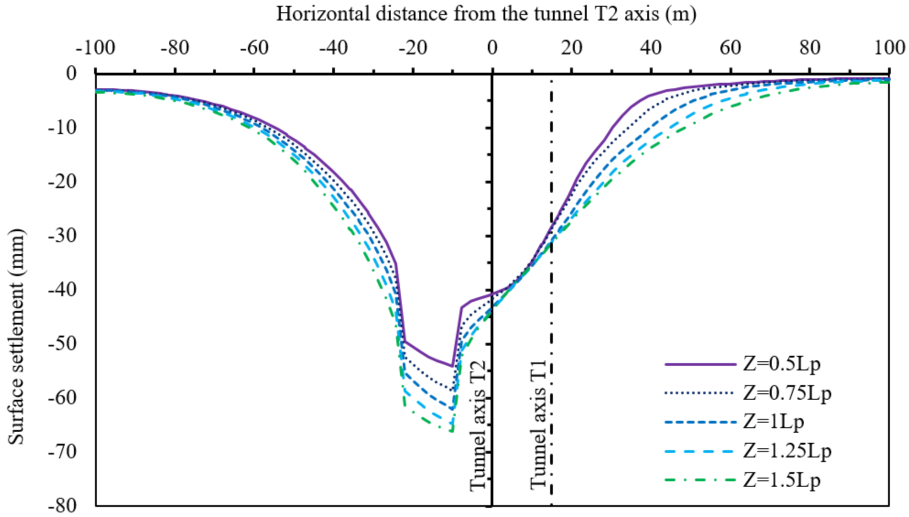
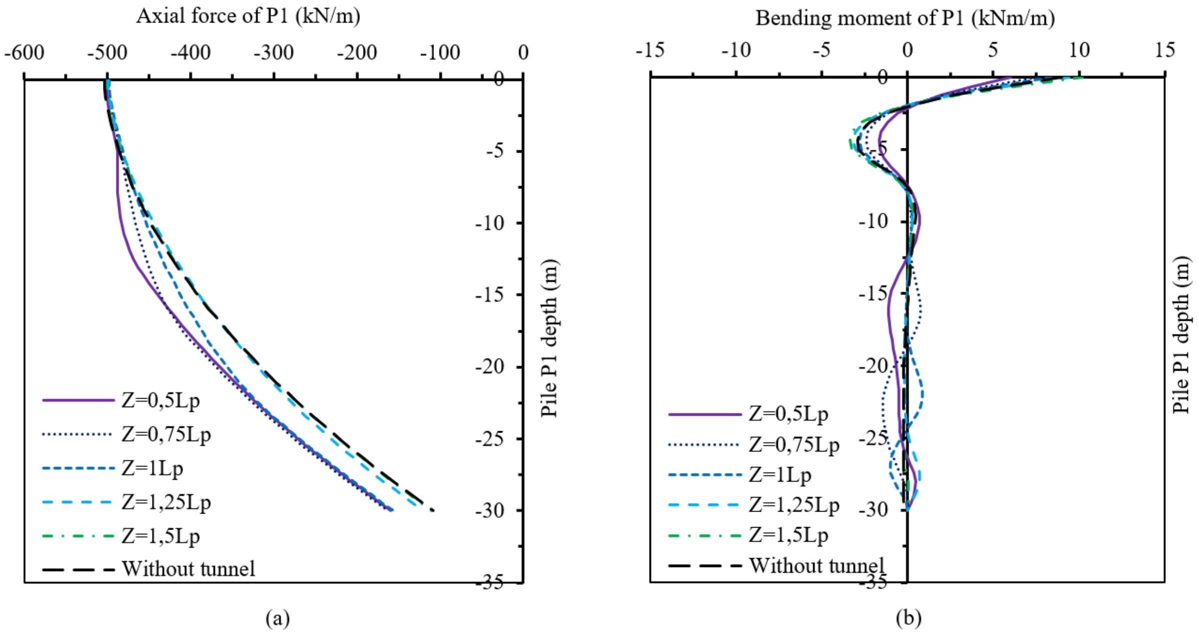
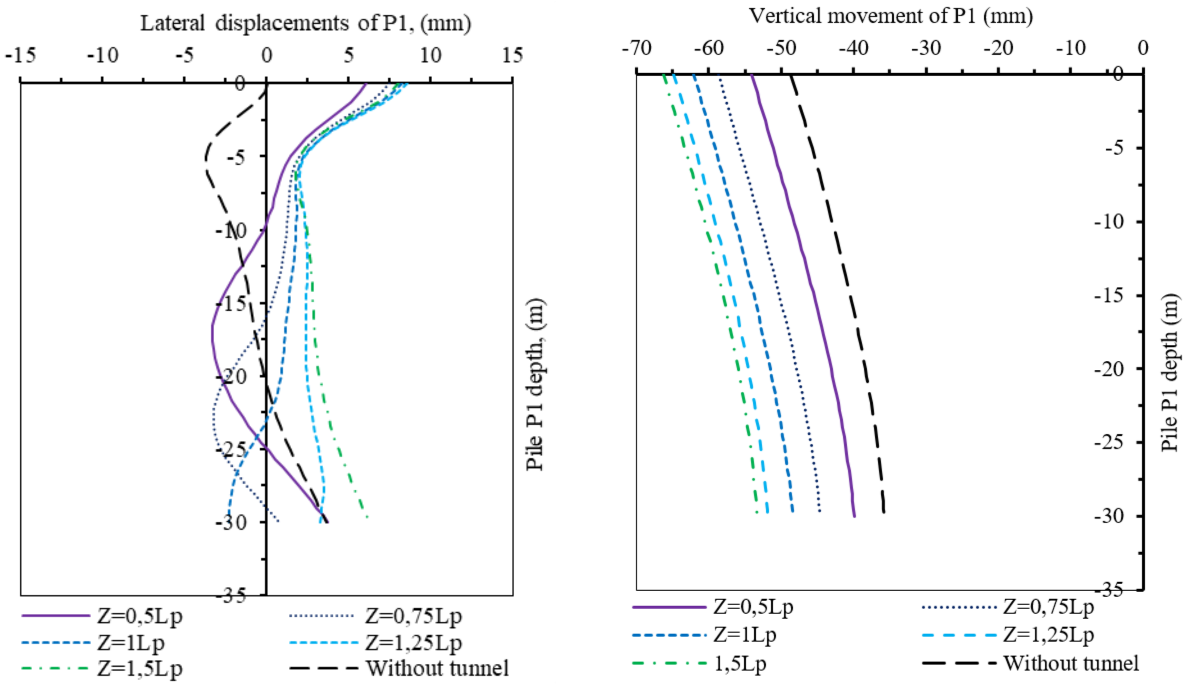


Fig. 15. Ground surface settlement trough with varying depth of twin tunnels, Z

The Fig. 16 investigates the influence of the twin tunnel depth (Z) on the response of pile P1, while keeping distances from the piled structure to the twin tunnels, L = 10 m and the distance between two tunnels of 15m constant.



(a) (b)



(c) (d)

Fig. 16. Distribution of the axial forces (a), bending moments (b), lateral displacements (c) and vertical movements (d) in pile P1 with varying depths of twin tunnels, Z

The influence of interaction between piled structure and twin tunnels is significant for axial forces of pile P1 at the pile tip, the magnitude of axial forces of pile P1 are 159.04 kN/m, 162.45 kN/m, 155.95 kN/m, 119.85 kN/m and 110.19 kN/m for Z = 0.5Lp, Z = 0.75Lp, Z = 1Lp, L = 1.25Lp and Z = 1.5Lp, respectively. These results suggest that a decrease in the axial forces of Pile P1 with increasing the depth of twin tunnels (Fig. 16-a). Fig. 16-b shows the distribution of bending moments of pile P1, the results indicate that the influence of interaction between piled structure and tunnels is significant for bending moments of piles at the location of pile head and at tunnel axis depth of 20 m.

The change in lateral displacements and vertical movements of Pile P1 with Z shown in Fig. 16-c and d, these results indicate that the influence of Z is significant on lateral displacements and vertical movements of Pile P1 at the location of pile head, the magnitude of lateral displacements of pile P1 are 6.02 mm, 7.47 mm, 8.24 mm, 8.52 mm and 8.05 mm and the magnitude of vertical movements of pile P1 are 54.10 mm, 58.70 mm, 62.08 mm, 64.83 mm and 66.27 mm for Z = 0.5Lp, Z = 0.75Lp, Z = 1Lp, Z=1.25Lp and Z = 1.5Lp, respectively. These results suggest that a increase in the lateral displacements and vertical movements of Pile P1 with increasing the depth of twin tunnels.

Conclusions

This study presents the findings of a series of finite element simulations conducted to investigate the mechanical interaction between twin tunnels and piled structure. The results provide valuable insights into the distribution and magnitude of axial forces and bending moments in the tunnel linings, as well as axial forces, bending moments, lateral displacements and vertical movements of the piles, which may provide useful guidance for tunneling engineers in urban areas:

1. The distribution of the normal forces and bending moments in the tunnel lining for single tunnel T1 construction in greenfield conditions are symmetric.
2. The normal forces and bending moment of the tunnel linings distribution are not symmetric for the case of construction twin tunnels and case of construction twin tunnels T1, T2 beneath piled-structure. The second tunnel T2 is near the building, so it is strongly affected by twin tunnels-piled structure interaction and therefore the magnitude of the normal forces and bending moment of the tunnel lining for case of construction twin tunnels T1, T2 beneath piled-structure is greater than that for case of twin tunnels T1, T2.
3. For a single tunnel T1 in greenfield conditions, the position of the maximum value of surface settlement Sv,max was situated above the tunnel axis T1. After the construction second tunnel T2, the interaction between the two tunnels affects the surface settlement Sv,max, the magnitude of Sv,max increased compared to the case of a single tunnel T1 construction and the position of Sv,max is eccentrically displaced towards the second tunnel.

4. The magnitude of the axial forces, bending moments, lateral displacements and vertical movements of the piles for case of twin tunnels T1, T2 construction are greater than that for case of single tunnel.
5. The influence of a single tunnel T1 construction on the response of piles is not significant, this may be because the distance from T1 tunnel axis to piled-structure is 25m and the interaction between piled-structure and tunnel T1 is negligible. The influence of interaction between piled structure and twin tunnels on the response of piles is significant and is greatest for pile P1, which is the first pile loaded in the group, than piles in positions P2, P3 and P4.
6. The magnitude of the axial forces, bending moments, lateral displacements and vertical movements of the front pile P1 closer to twin tunnels in the group are higher than for the rear pile: P2; P3; P4.
7. The distance L from the tunnels to the piled structure does not significantly influence the maximum axial forces and bending moments in the tunnel linings. However, the distance L from the tunnels to the piled structure significantly influences the maximum axial forces and bending moments of the piles.
8. The depth of twin tunnels Z does not significant influence on the maximum axial forces and bending moments of the piles. However, the depth of twin tunnels Z significantly impacts the maximum axial forces and bending moments in the tunnel linings.

The finite element analysis results conducted in this study provide initial insights into the mechanical interactions between twin tunnels and piled structure. In practice, twin tunnels are often constructed sequentially; therefore, future research will incorporate simulations of the construction process of each tunnel step by step, with a particular focus on the development of interaction mechanisms with piled structure during different stages of the twin tunneling process.

References

Addenbrooke, T. I., Potts, D. M., Puzrin, A. M. (1997). The influence of pre-failure soil stifiness on the numerical analysis of tunnel construction. *Geotechnique,* 47(3). https://doi:10.1680/geot.1997.47.3.693

Antonio M. G. Pedro, José C. D. Grazina, Jorge N. V. Almeida e Sousa. (2022). Lining forces in tunnel interaction problems. *International Journal of Geotechnical and Geoenvironmental Engineering. Soil. Rocks, São Paulo*, 45(3). https://doi.org/10.28927/SR.2022.077221

Attewell, P. B., & Woodman, J. P. (1982). Predicting the dynamics of ground settlement and its derivitives caused by tunnelling in soil. *Ground Engineering*, 15(7). https://doi.org/10.1016/0148-9062(83)90142-0

Attewell, P. B., Yeates, J., Selby, A. R. (1986). Soil movements induced by tunnelling and their effects on pipelines and structures. *Tunnelling and Underground Space Technology*, 2(1). https://doi.org/10.1016/0886-7798(87)90195-7

Bel, J., Branque, D., Wong, H., Viggiani, G., & Losacco, N. (2016). Impact of tunneling on pile structures above the tunnel: Experimental study on a 1g reduced scale model of TBM. *In ITA-AITES World Tunnel Congress*.

Franza A., Marshall A.M. (2018). Centrifuge modeling study of the response of piled structures to tunneling. *Journal of Geotechnical and Geoenvironmental Engineering*, 144(2). https://doi.10.1061/(ASCE)GT.1943-5606.0001751

Franza A., Zheng C., Marshall A.M., Jimenez R. (2021). Investigation of soil–pile–structure interaction induced by vertical loads and tunnelling. *Computers and Geotechnics*, 139(2021). https://doi.org/10.1016/j.compgeo.2021.104386

Hunt, D. V. L. (2005). Predicting the ground movements above twin tunnels constructed in London Clay. *Ph.D. Thesis* - University of Birmingham. Birmingham.

Kaalberg, F. J., Teunissen, E. A. H., van Tol, A. F., and Bosch, J. W. (2005). Dutch research on the impact of shield tunnelling on pile foundations. *In: Proceedings of the 5th International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground*. Amsterdam, the Netherlands.

Karasev M.A., Belyakov N.A. (2015). Estimation of Surface Settlements Troughs Due to Subway Station Construction in Claystone. *Biosciences Biotechnology Research Asia*, 12(3).

Loganathan N., Poulos H.G., Xu K.J. (2001). Ground and pile-group responses due to tunnelling. *Soils and Foundations*, 41(1).

Loganathan, N., Poulos, H. G., and Stewart, D. P. (2000). Centrifuge model testing of tunnellinginduced ground and pile deformations. *Géotechnique*, 50(3).

Mair, R.J., Taylor R.N.Burland, J.B. (1996). Prediction of ground movements and assessment of risk of building damage due to bored tunnelling. *In: Proceedings of International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground*. Mair & Taylor, London.

Marshall, A. and Mair, R. (2011). Tunneling beneath driven or jacked end-bearing piles in sand. *Canadian Geotechnical Journal*, 48(12).

Marwan A. (2019). Computational Analysis of Segmental Linings in Mechanized Tunneling. *Ph.D. Thesis*, Ruhr University Bochum.

Ng C., Soomro M., Hong Y. (2014). Three-dimensional centrifuge modelling of pile group responses to side-by-side twin tunnelling. *Tunnelling and Underground Space Technology*, 43, 350-361, 2014. https://doi.10.1016/j.tust.2014.05.002

O'Reilly, M.P., New, B.M. (1982). Settlements above tunnels in the United Kingdom - their magnitude and prediction. *In: Tunnelling '82, Papers Presented at the 3rd International Symposium*. Inst of Mining and Metallurgy, London, England, Brighton, England.

Oteo, C. S., Sagaseta, C. (1982). Prediction of settlements due to underground openings. *Proc. Int. Sym. On Numerical Methods in Geomechanics*, Zurich, Switzerland.

Peck, R.B. (1969). Deep Excavation and Tunneling in Soft Ground. State-of-the-Art Report. *Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering*, Mexico.

Protosenya A.G., Belyakov N.A., Thai Ngoc Do. (2015). The development of prediction method of earth-pressure balance and surface settlement during tunneling with mechanized Tunnel boring machines. *Journal of Mining Institute*, 211.

Selemetas, D. (2005). The response of full-scale piles and piled structures to tunnelling. *Ph.D. Thesis*, Cambridge University.

Yifan Guo, Junjie Zheng, Hui Liu. (2023). An early warning method for tunneling-induced ground surface settlement considering accident precursors and consequences. *Tunnelling and Underground Space Technology*, 140, 105214, 2023. https://doi.org/10.1016/j.tust.2023.105214

Zhiyong L., Jianfeng X., Jianzhong Y., Jiangu Q. (2021). A simplified two-stage method to estimate the settlement and bending moment of upper tunnel considering the interaction of undercrossing twin tunnels. *Transportation Geotechnics*, 29, 100558, 2021. https://doi.org/10.1016/j.trgeo.2021.100558

Zuliang Z., Chao L., Xinrong L., Yifei F., Ninghui L. (2021). Analysis of ground surface settlement induced by the construction of mechanized twin tunnels in soil-rock mass mixed ground. *Tunnelling and Underground Space Technology,* 110, 103746, 2021. https://doi.org/10.1016/j.tust.2020.103746