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Impact of Tunneling on Stress-Displacement Response of Existing Batter Piles

Technical note

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Abstract

Batter piles up to 45° inclination are used in some giant projects such as bridges, oil platforms, store pits, power plants, vertical car parks, and even some constructed buildings on poor soils. However, the effects of tunneling on the pile tip strength, buckling of piles and surface settlement are various. This research intends to study the stress-displacement behavior of surface ground during tunneling in vicinity of batter piles. Finite-element method (FEM) has been used to investigate the effect of position and inclination of the piles on the induced surface displacement. After validating and estimating the efficiency of the Finite element (FE) code, model development has been carried out by comparing the inclination in three degrees (10°, 20° and 30°) and three different lengths of the piles (15, 21 and 27 m). The results showed that in all the lengths and inclinations of piles, the maximum settlement of pile element is higher than the maximum surface settlement and it is higher than the maximum settlement of pile head.

1. Introduction

Batter piles are used as amplifiers of foundations in some giant structures such as bridges, store pits, power plants, vertical parking, and even these buildings have been constructed on undesirable soils. Nowadays, by developing urbanism and infrastructures such as subways and underground tunnels, it would be possible to intersect tunnel with deep foundations. Before starting underground excavation, the effect of tunneling on the pile foundation, which is near to the tunnel axis should be studied. If there is a conflict, the design and planning should be modified. Passing tunnels under these structures have been investigated on the basis of theoretical analyses and experimental observations. Many of these researches focus on pile-tunnel interaction and the effects of piles on lining. Classical approaches are beneficial just in simple cases and are not able to present the pattern of soil-lining response,

Particularly in complex topographies. Finite-element method (FEM) and finite-difference method (FDM) are two common approaches in numerical analyses, which have been used by Mroueh and Shahrour (1999), Lee and Ng (2005), Lee and Jacobsz (2006) and Cheng et al. (2007) to simulate three-dimensional soil-pile interactions during excavation. The other method is to run a model, including the effect of tunnel excavation on surface ground motion, and then, pile modeling at the presence of the tunnel (Chen et al., 1999;

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Loganathan et al., 2000 & 2001; Xu and Poulous, 2001; Kitiyodom et al., 2005; Heama et al., 2017; Naqvi and Farooqi, 2018; and Lueprasert et al., 2017).

Most researches have concentrated on the concept of tunnel effective zone. This zone has been defined as guidance for engineers to control the position of tunnel-pile from each other. Kaalberg et al. (1999) and Jacobsz et al. (2001) set a centrifuge model and proposed a line with inclination of 60° and 45° from tunnel axis, respectively. Morton and King (1979) estimated the influence zone on the basis of shear surfaces, equal to 45-Φ/2 to vertical. Lee and Basset (2007) normalized the influence zone on the basis of normalized settlement of pile head, attained from experimental and numerical modeling.

Some studies concentrated on soil-pile-tunnel interaction to detect the possible adverse risks of tunnel construction on the vicinity of foundations. Site investigations made by Mair et al. (1993) and Forth and Thorley (1996), real scale studies on piles carried out by Kaalberg et al. (1999), Coutts and Wang (2000) and Selemetas et al. (2005), researches on physical modeling using centrifuge sets performed by Bezuijen and Van de Schrier (1994), Hergarden et al. (1996), Loganathan et al. (2000), Jacobsz et al. (2004) and Lee and Chiang (2007), researches on numerical modeling made by Vermeer and Bonnier (1991), Loganathan and populous (2001), Cheng et al. (2007) and Mroueh and Shahrour (2002) are some examples of pile-tunnel interaction studies. Selemetas et al. (2005) introduced three different zones above a tunnel in which pile displacements are significant (see ***Figure 1****).*

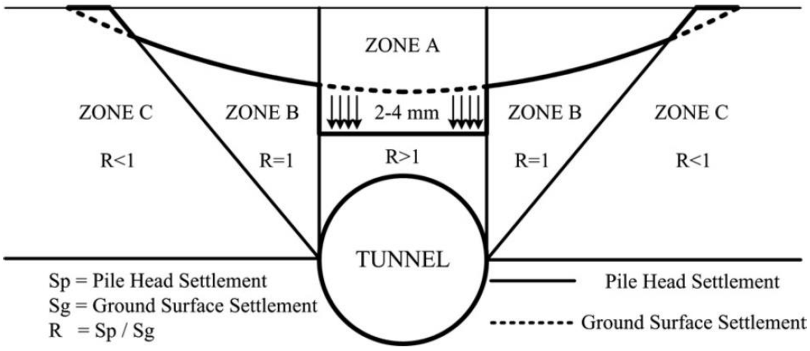

Figure 1.The proposed zones of influence of pile settlement due to earth pressure balance shield tunneling in London clay (Selemetas et al., 2005).

Jongpradist et al. (2013) investigated the responses of single piles and pile group of various lengths, pile space, free space from tunnel lining, and pile diameter during tunnel excavation. Having run FEM analyses and extracted results, they introduced three continues zones to classify the behavior of existing piles in the vicinity of new tunnel, as shown in ***Figure 2****. Zones 1 and 3 show the tendency of pile to settle further and the piles in zone 2 present more changes in the pile forces than settlement due to the excavation.*

Yang et al. (2011) provided three-dimensional (3D) numerical models and some centrifuge tests, and showed that two lines with the angle of 45° to the tunnel axis could be proposed. Moreover, in the influence zone, the pile was affected by more tensile stress and settlement. Finally, pile groups experienced less settlement than single piles during the tunnel construction.

Boonyarak and Ng (2012) declared that the nearer piles to the face of excavation showed higher deformation than the piles in farther distance during excavation.

Lee (2012a & 2012b) studied the effects of tunneling in weak weathered rock on the behavior of a pre-existing single pile and pile groups (3 × 3 and 5 × 5 pile groups) in weathered residual soil above a tunnel by performing 3D elastoplastic numerical analyses. He found that the computed tunneling-induced *pile head settlement was larger than the ground surface settlement computed from the greenfield condition. Moreover, the ground settlement trough deviated somewhat from the Gaussian settlement distribution. Thus, the zone of influence on the pile head settlement in the longitudinal direction was identified as ±2D from the pile center (behind and ahead of the pile axis in the longitudinal direction) based on the concrete analysis conditions assumed in the study, where D is the tunnel diameter.*

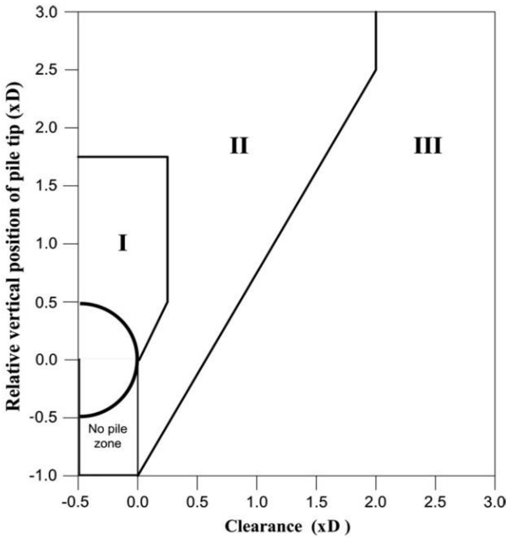

Figure 2. Proposed influence zones (Jongpradist, et al., 2013)

Pinto and Whittle (2013) studied ground deformation due to tunneling by considering superposition of displacements (contraction of top and bottom of tunnel + ovaling + vertical displacement of tunnel) in soft clay, numerically and analytically. The results of their study showed that plastic failure had no effect on incompressible deformations.

Zidan and Ramdan (2014) set some 3D models to investigate the displacements of pile cap and pile element due to tunneling. The results of their research showed that the maximum response of pile and cap did not occur at the end of excavation, necessarily.

Chungsik (2014) set a 3D numerical investigation into the interaction between conventional tunneling and a pile supported bridge. Besides, the pile-ground interface to allow for possible slip between the piles and the ground during tunneling was included in the model. The results indicated a progressive development of the pile tip settlements. The piles, situated exactly above the tunnel, showed the largest tip settlement and most of the pile tip settlements exhibited when advancing the tunnel heading from -1.0D to 0.0D (D is the tunnel diameter). Furthermore, single piles above the tunnel experienced 60% of their total settlement before the passage of tunnel face was completed. The pile tip settlement decreased with increasing the lateral distance between the tunnel and a pile, and became negligible when x/D > 2.0 (x is the free horizontal distance of pile from the center of the tunnel), indicating that the effect of the tunneling on piles located laterally beyond 2.0D from the tunnel might be ignored. The piles located directly above the tunnel, i.e., x/D < 0.5, might experience pile tip settlements 70–100% of the tunnel crown displacement.

Soomro et al. (2015) numerically concluded that the influence zone of the settlement of loaded 2 × 2 pile group in saturated stiff clay had to be defined 3D behind and 1D in front of the pile group. It stopped settling once the tunnel face moved beyond a distance of 2D away from its center. Moreover, according to 3D elastoplastic coupled consolidation FE analyses, the final amounts of induced settlement of the pile group were about 0.23%, 0.53% and 0.58% of the pile diameter in the cases of C/D = 1.5, 2.5 and 3.5, *respectively.*

The results obtained from a modified version of the load transfer method presented by Dias and Bezuijen (2018) showed that pile settlement was inversely proportional to the clearance between pile and tunnel. Even though the surface settlements increased at the tunnel gets closer to the surface, the induced vertical pile settlements decreased. This was related to how the ground settlements were distributed along the pile.

As mentioned above, there is a literature gap as there is no research about tunneling under batter piles whereas many studies have been carried out on vertical piles. In this paper, the effects of tunneling on adjacent batter pile foundations are investigated and the best inclination degree is determined. In fact, the main goal is to predict how a single batter pile reacts when subjected to ground displacement due to tunneling and to estimate four series parameters, affected by excavation: a) maximum pile head settlement, b) maximum settlement of surface ground above the tunnel, c) maximum pile displacement, and d) maximum changes in pile forces. Four different inclination degrees (0°, 10°, 20° and 30°) from vertical axis and three different depths/lengths of piles (15, 21 and 27 m) are studied by the 3D FE code developed in this research work.

2. Base Study

Jongpradist et al. (2013) employed 3D FE analyses to investigate the key responses of piles due to adjacent tunneling and the influences of various parameters on them, by using PLAXIS software. The reference case was a circular tunnel with outer diameter of 6.3 m having lining thickness of 0.6 m, excavated in a stiff clay layer of typical Bangkok subsoil with a cover depth of 21 m. The tunnel represented an MRT tunnel. Asingle pile with pile diameter of 0.5 m (representing a pile of a building) having various lengths was assumed to be located at cleardistance (C) from the edge of the tunnel spring line (C=0.5D). The dimension of the mesh was 50 m (8D) in the longitudinal direction, 60 m (9.5D) deep in vertical direction and 80 m (12.5D) wide in transverse direction. Four different pile lengths (15, 17.85, 21m, 24.15 and 27 m) have been set to run. Other information is listed below:

** Not considering the pile cap and the interface element between the pile and the soil.*

** Restraining with roller supports on all vertical sides and pin supports to the base of the mesh.*

** Water table location at 1 m below the ground surface.*

** Impervious tunnel lining.*

** Undrained condition analysis,*

** Six-node brick, four-node shell and two-node beam elements are used to model the soil, concrete lining and pile, respectively,*

** No interface description has been defined like Jongpradist's model.*

** Roller supports and pin support applied to all vertical sides and the base of the mesh, respectively.*

The accuracy of simulations for geotechnical work in Bangkok subsoil by the selected models with the calibrated material parameters had been validated with measured data of well-documented case histories of tunnel excavations, deep excavations and pile load tests (Rukdeechuai et al., 2009).

Tables 1 and 2 represent the soil, lining, and pile characteristics, used in the Jongpradist's model. The constitutive model of weathered crust, soft clay, medium clay, stiff clay, and sand was considered to be MC, HS, HS, HS, MC, respectively; where MC and HS are representative of Mohr Columb and Hardening Soil model, respectively.

Table 1. Soil model properties (Rukdeechuai et al., 2009)

Soil Layer	**E'**	**E_{oed}**	**E_{50}**	**E_{ur}**	**C**	**p_{ref}**	**γ_{sat}**	**ν'**	**φ'**	**m**
	(kPa)						**(kN/m^3)**		**(°)**	
Weathered Crust	*6e3*	*-*	*-*	*-*	*8*	*_*	*17*	*0.32*	*22*	*_*
Soft clay	*-*	*5e3*	*5e3*	*15e3*	*5*	*100*	*16*	*0.33*	*22*	*1*
Medium Clay	*-*	*2e4*	*2e4*	*1e5*	*10*	*65*	*18*	*0.33*	*22*	*1*
Stiff clay	*-*	*6e4*	*6e4*	*1.8e5*	*18*	*95*	*18*	*0.33*	*22*	*1*
Sand	*8e4*	*-*	*-*	*-*	*0*	*-*	*20*	*0.3*	*36*	*-*

Where E', E_{oed}, E_{50}, E_{ur}, C, p_{ref}, γ_{sat}, v', φ' and m are drained modulus of elasticity, tangent stiffness for primary oedometer loading, unloading/reloading stiffness, cohesion, reference stress for stiffness, saturated density, poison ratio, and internal friction angle, respectively.

Table 2. Material properties of lining and bored pile.

Element	E (kN/m^2)	$v'_{concrete}$	$\gamma_{cocrete}$ (kN/m^3)
Tunnel lining	3.1 e 7	0.2	24
Bored pile	3.1 e 7	0.2	24

Where E, $v'_{concrete}$, and $\gamma_{cocrete}$ are elasticity modulus, poison ratio and density of concrete. Validation has been carried out by using the soil, pile and lining specifications given in Tables 1 and 2. The definition of analyses phase includes two parts: 1) Excavation 3 m every step, 2) Activation lining elements, and excavation the next step simultaneously. **Figure 3** exhibits the deformed mesh of model after analyses for 15 m length of single pile. Note that there is not any allocation to pile loading in the present study; therefore, the amounts of displacements are in micro scale. However, the first stage of Jongpradist's model concerns the application of the pile axial loading, which is the design working load determined from the ultimate capacity of the pile divided by the safety factor of 2.5, to a wished-in-place concrete pile. At the beginning of the second stage, the displacements induced by loading have been set to be zero. The contribution of deformation and the pattern of layer displacement due to the tunnel construction are shown in **Figure 3**.

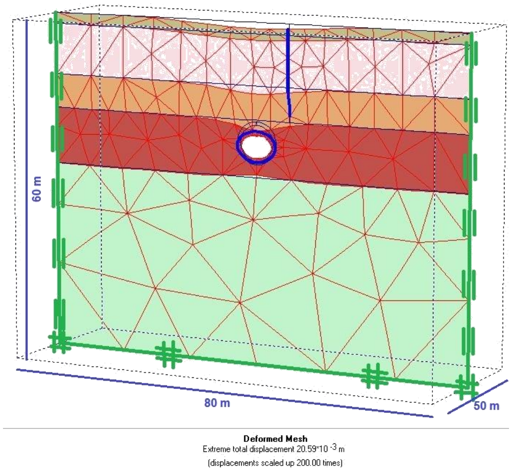

Figure 3. Cross section of deformed geometry and mesh of model (Pile length=15 m).

The maximum total displacement recorded after analysis is 20.59 mm. This amount has not been reached in pile/ground surface location and allocates to tunnel movement. **Figure 4a** shows a comparison of vertical pile movements between 0.5 m-diameter single-pile and this research validation, having the same pile size for various lengths due to nearby 6.3 m tunneling at 21 m depth for the same clearance of 3.15 m. The normalized vertical and horizontal displacements have been also exhibited in **Figure 4b** where Model Disp./Base Disp. is the displacement ratio of the present study to Jongpradist's study. As can be seen from **Figure 4a**, there are some harmonies between two groups of results. The horizontal curves are the same but the obtained settlements of model in this study are a bit higher than those of the Jongpradist's study. Therefore, the maximum error could be estimated 14%. The cause of this error is some considerations exerted to the base study and not mentioned in Jongpradist's paper such as the mesh dimensions, pile loading, and the number of irritations. Moreover, the maximum pressure on the excavation face had not been determined. Hence, according to the small error, it can be concluded that the present model is effective and has proper efficiency.

3- Main Study

After verification, the improvement of model has been done by setting three different inclinations of single pile from the vertical axis (10°, 20° and 30°) as shown in **Figure 5**, and three different pile length (15, 21 and 27 m).

The new simulation trend and procedure were the same as those in the verification model. At first, the model was run without any pile and tunnel to get the initial static balance. Then, the batter pile was activated. After that, the *excavation and lining phases were started. The excavation steps at nearer distances from the batter pile were set to be shorter but the intervals were 3 m at all other distances. All the specifications (soil, lining and pile characteristics, boundary conditions, water level, constitutive models and undrained behavior, …), have been applied for simulating the tunnel under batter piles as mentioned for the validation model.*

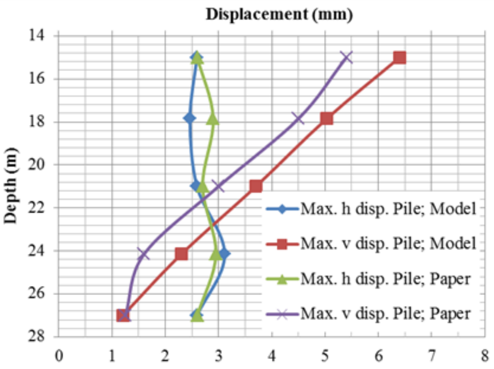

Figure 4a. comparison of the attained results

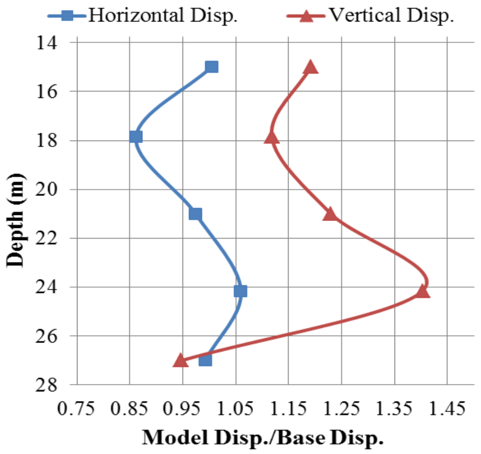

Figure 4b. normalized results of model

Figure 4. Numerical models verification with the main study on the maximum horizontal and vertical displacements of single pile tip at corresponding depths

4- Results

After verification and development of model by change in the inclination, length, and type of positioning of batter piles, the obtained results were reported in four main group of data, separately: 1) maximum settlement of batter pile, 2) maximum settlement of batter pile head and 3) maximum settlement of ground surface above the tunnel and 4) maximum induced forces along the pile.

***Figure 6** shows a comparison between the amount of surface settlement above the tunnel in existing vertical piles and batter piles. According to **Figure 6**, the maximum settlement of surface ground above the tunnel decreases when the vertical pile length increases. It is because of stress transferring from pile to surrounded soil on the lower level of tunnel floor. By increasing the inclination of shallow batter piles, the surface settlement presents constant amount which is a bit higher than vertical piles response. In addition, by increasing the batter pile length and reaching the tunnel cross section, the amount of batter pile settlement increases that causes vertical interaction of the batter piles to the beneath soil, which helps soil settling.*

***Figure 7** shows a comparison between the maximum settlements of batter pile head as piles inclination changes. As shown in **Figure 7**, an increase in the inclination causes a decrease in the pile head settlement of the piles with the same lengths.*

*When the lengths of batter piles increases, the decline in the pile head settlement become more and more. In deeper piles, pile function with 10° inclination is more than that of the others because of the direction of settlement and failure surface, which are approximately close together. During analysis of pile-tunnel interaction, the value of pile element displacement is crucial to estimate the pile behavior and deformability. Therefore, the maximum settlement of the pile elements can be compared as shown in **Figure 8**.*

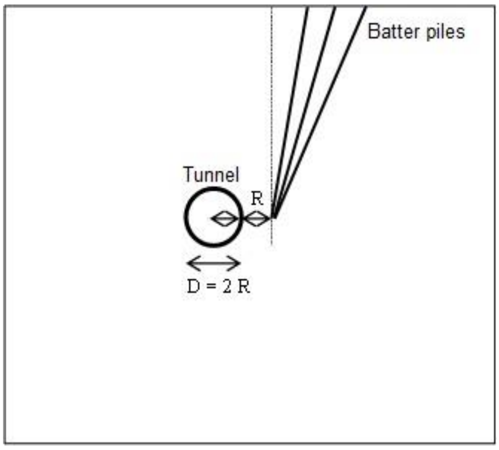

Figure 5.Three different inclinations of the batter pile

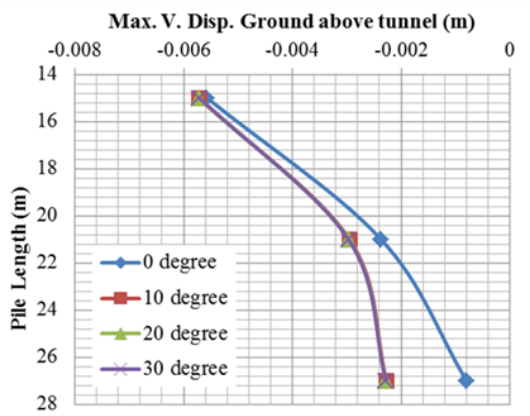

Figure 6. Comparison between vertical and batter pile in maximum settlement of surface ground above the tunnel

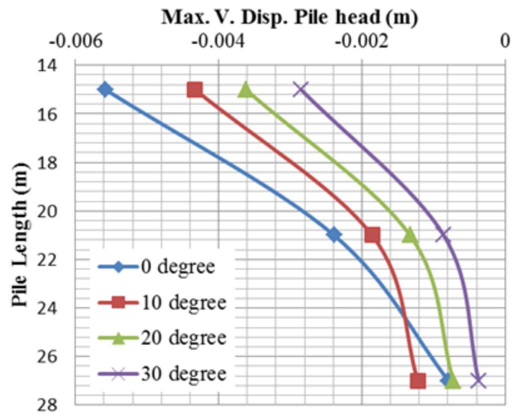

Figure 7. Comparison between vertical and batter pile in maximum vertical displacement of pile head

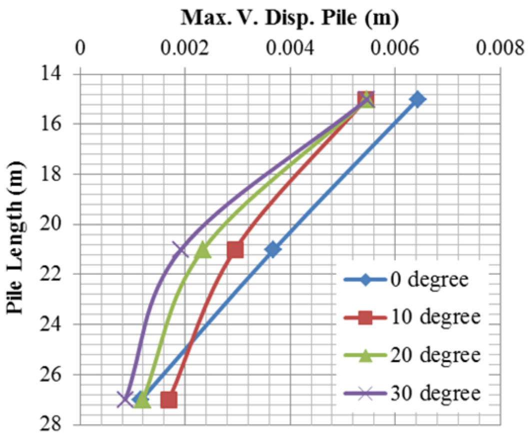

Figure 8. Comparison between vertical and batter pile in maximum vertical displacement of pile elements

*According to **Figure 8**, the maximum settlements of shallow pile structures are equal at all three different inclinations and these maximum settlements are generally lower than vertical pile response. To clarify, pile inclination is not a proper and decisive parameter in stability and settlement of buildings constructed on shallow batter piles. What is more, deeper piles show much lower amount of vertical movement by increasing pile inclination up to the depth of tunnel center. In some cases, vertical displacements of batter piles are higher than those in vertical piles, especially when the pile tip takes place at deeper depths than tunnel floor. Thus, longer and steeper piles show lower settlements.*

*The bending moment changes in the pile length have been shown in **Figure 9**. The induced bending moments decrease when pile lengths are constant and pile inclinations increase; however, the maximum bending moment induced in batter piles is lower than the minimum induced bending moment in vertical pile at the same depth. In general, from shallow depth to deeper one, and from 30° to 0° inclination, the induced bending moments increase. The rate of increase in the induced bending moment rises in deeper lengths of piles due to stress effect of the tunnel structure.*

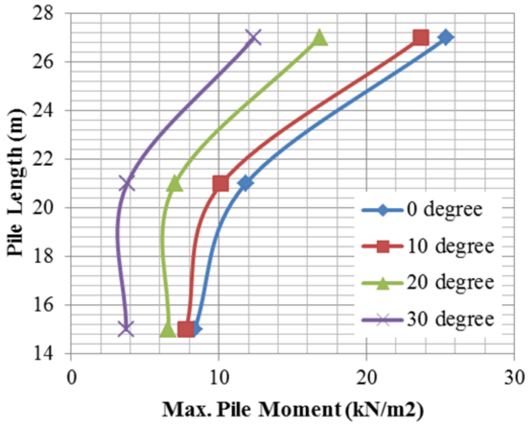

Figure 9. Comparison between vertical and batter pile in maximum bending moment through pile elements

*According to **Figure 10**, lower shear stresses are observed in shallow batter piles than the vertical ones. By increasing inclinations of shallow piles, the amount of induced shear stress decreases intensively. For those batter piles* *which have continued up to the tunnel center or further, the amount of shear stress has grown and exceeded the response of vertical piles.*

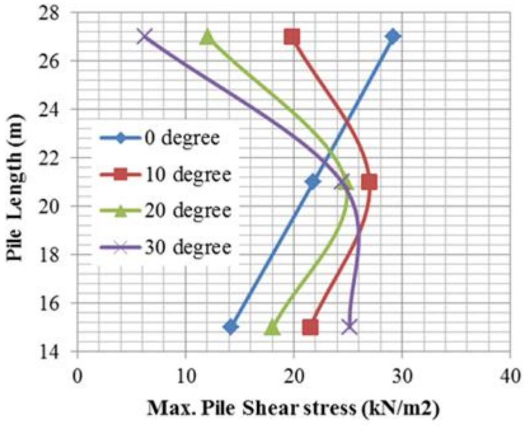

Figure 10. Comparison between vertical and batter pile in maximum induced shear stress through pile elements

When pile head reaches top level of the tunnel, the induced shear stress increases for all inclinations due to interaction of lining oval-shape deformation. Moreover, as the inclination is steeper, the induced shear stress in piles above the tunnel center is lower because pile head gets further than the lining. For the piles longer than the depth of the tunnel center, as the inclination increases the induced shear stress in pile elements decreases. The cause of this phenomenon is that the angle of pile-failure line intersection under the tunnel is close to 90°.

The changes in maximum induced axial stresses through vertical and batter piles, due to tunneling, have been shown in ***Figure 11****. Shorter batter piles show a decline trend of induced axial stress by increasing inclinations. Axial stress has increased in 15 m pile under 10° inclination because the pile position is close to and aligned with the probable failure surface of soil block above the tunnel. For long piles up to the depth of the tunnel center, the induced axial stress increases and deeper piles experience lower amount of axial stress.*

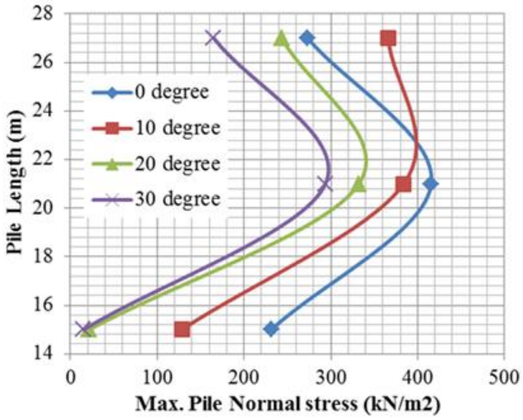

Figure 11. Comparison between vertical and batter pile in maximum induced axial stress through pile elements

Taking these results into account, **Table 3** *summarizes the attained results of batter pile modeling. Note that 0 and 1 are representatives of the ratio lower and higher than 1, respectively. SG, PH, and PE are representatives of surface ground, pile head, and pile element.*

As shown in ***Table 3****, the maximum settlement of surface ground above the tunnel is higher than the maximum settlement of pile head and vertical displacement of other pile points. This issue is on harmony with the background studies.* ***Table 4*** *shows a comparison between induced stress and bending moment on three pile lengths and three inclinations.*

Table 3. Comparison among settlements of surface ground, pile head and pile elements for 3 pile lengths and 3 inclinations, separately.

Pile Length (m)	*Inclination (°)*	Δy (SG/PH)	Δy (SG/PE)	Δy (PH/PE)
15	10	1	1	0
	20	1	1	0
	30	1	1	0
21	10	1	1	0
	20	1	1	0
	30	1	1	0
27	10	1	1	0
	20	1	1	0
	30	1	1	0

Table 4. Comparison between induced forces throughout pile elements for 3 pile lengths and 3 inclinations, separately.

Pile Length (m)	*Inclination (°)*	**(Batter pile/Vertical pile)**		
		P	***V***	***M***
15	*10*	*0*	*1*	*0*
	20	*0*	*1*	*0*
	30	*0*	*1*	*0*
21	*10*	*0*	*1*	*0*
	20	*0*	*1*	*0*
	30	*0*	*1*	*0*
27	*10*	*1*	*0*	*0*
	20	*0*	*0*	*0*
	30	*0*	*0*	*0*

It is obvious that the induced bending moment in batter pile of any inclination is lower than vertical response since the propagation of stress contours due to lining displacements and consequently, surrounding soil movements meet pile elements with an angle greater than 90°. In this situation, the radius of bending moment induced by tunneling remains constant, but the applied stress decreases. After passing through the level of the tunnel floor, the induced shear stress in batter piles becomes less than shear stress of vertical pile. There is an ovaling impact, in which we have pile elements with an angle greater than 90°.

5- Conclusions

After validation the FE code by comparison of the obtained results from the present study with the base results of vertical pile and insurance of proper function of software, model development was made by changing the angle of pile position rather than the vertical axis. For this purpose, 4 different inclinations and 3 different pile lengths were modeled. The obtained results could be summarized in the following:

1. In all cases of batter piles, the following relation has been extracted for each pile length lonely:

Surface ground settlement > Settlement of pile element > Settlement of pile head

2. When in the critical range above the tunnel, be it vertical or inclined, pile elements can provide lateral constraint to increase K_0 as a reinforcing element. Apart from this, the equality of ground surface settlements in the presence of vertical and batter piles is an illustration of deficiency of batter piles in controlling surface settlement above the tunnel.

3. The reductive patterns of settlements are observed in all the results by increasing the length of batter piles.

4. Tunnel structure does not disturb the pattern of the settlements of batter piles.

5. The model geometry in this research is representative of a tunnel under a street and near some batter pile foundation of the vicinity buildings. With this explanation, tunneling can be trouble maker for street, but the settlement of the vicinity buildings can be controlled by batter piles. However, pile diameter must be considered as large as possible while designing a batter pile in a zone where is prone to be excavated under it.

6. 27 m pile with an inclination of 30° shows the best function of all other cases. Increasing the pile length from one hand and increasing the inclination on the other hand affect the displacements of batter pile during tunneling.

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