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Assessment Of Soil-Batter Pile Displacement Due To Tunnelling

Ehsan Taherabadi[1], Vahid Hosseinitoudeshki[2], Mohammad Hossein noori Gheidari[3]
[1]Department of Civil Engineering, Imam Khomeini International University, Qazvin, Iran
Corresponding e-mail address: e.taherabadi@edu.ikiu.ac.ir
[2]Department of Civil Engineering, Zanjan Branch, Islamic Azad University, Zanjan, Iran
toudeshki@gmail.com
[3]Department of Civil Engineering, Zanjan Branch, Islamic Azad University, Zanjan, Iran
noorigheidari@gmail.com

***Abstract*— Batter piles up to 45° inclination are used in some giant projects such as bridges, oil platforms, store pits, power plants, vertical parkings 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 validation and estimation the efficiency of the FE code, model development has been done by comparing the inclination in three degrees (10°, 20° and 30°) and three different lengths of the piles (15m, 21m and 27m). 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.**

***Keywords*— Tunneling; Batter pile; Three dimensional analyses; Finite element method**

1. INTRODUCTION

Batter piles are used as an amplifier of foundation. In some giant structures such as bridges, store pits, power plants, vertical parking, and even those constructed buildings on undesirable soils. Nowadays, by developing urbanism and infrastructure such as subways and under surface tunnels, it would be possible to intersect tunnel with deep foundations. Before starting underground excavation, it should be studied the effect of tunneling on the pile foundation which are near to the tunnel axis. 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 Different Method (FDM) are two common approaches in numerical analyses which have been used by [1-4]. 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. The FEM analyses have used to investigate the above matter [5-9]. Most researches concentrate on the concept of tunnel effective zone. This zone has been defined to be a guide for engineers to control the position of tunnel-pile one another

Some studies performed on soil-pile-tunnel interaction to detect the possible adverse risks of tunnel construction on the vicinity foundations. The response of single piles and pile group with some various lengths is investigated by [10]. After running a FEM analyses and extracting results, three continues zones introduced to classify the behavior of existing piles in the vicinity of new tunnel, as shown in Figure 1. Zones 1 and 3 show the tendency of pile to settle further and the piles in zone 2 presents more changes in the pile forces than settlement due to excavation.

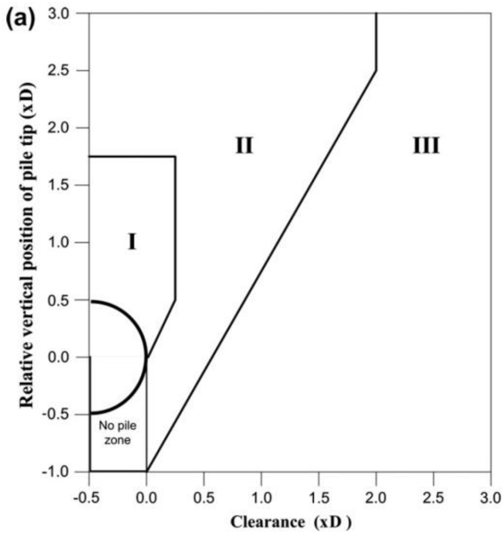

Fig.1. Proposed influence zone [10]

A 3D numerical modeling is provided by [11] to investigate the impact of tunneling on the vicinity piles. The verification was done by centrifuge test. The obtained results showed that there would be proposed two lines with the angle of 45° to the tunnel axis. Also, in the influence zone, the pile was affected by more tensile stress and settlement. Finally, pile groups experienced less settlement than single pile during the tunnel construction.

As it mentioned above, there is a gap in literature which has no research about tunneling under batter piles whereas many studies have been done on vertical piles. This paper intends to investigate the effects of tunneling on adjacent batter pile foundations and determines the best inclination degree. In fact, the main goal is 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, 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 (15m, 21m, 27m) are studied by 3D FE code.

2. BASE STUDY

A 3D FE analyses is employed to investigate the key responses of piles due to adjacent tunneling and the influences of various parameters on them, by using PLAXIS [10]. 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. A single pile with pile diameter of 0.5m (representing a pile of a building) having various lengths was assumed to be located at clear distance (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 (15m, 17.85m, 21m, 24.15 and 27m) have been set to run. Other information is listed below:

1) Not considering the pile cap and the interface element between the pile and the soil.

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

3) The water table location at 1 m below the ground surface.

4) Impervious tunnel lining.

5) Undrained condition analyses.

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.

Table 1 and 2 represent the soil, lining, and pile characteristics, used to the Jongpradist's model.

Validation has been done by using the soil, pile and lining specifications given in Table 1 and 2. The definition of analyses phase includes two parts: 1) Excavation 3m every step, 2) Activation lining's elements, and excavation the next step simultaneously. Figure 2 exhibited the deformed mesh of model after analyses for 15 m length of single pile. Noted that in both study (present and base paper), there are not any allocation to pile loading. Therefore, the amounts of displacements are in micro scale. The contribution of deformation and the pattern of layer displacement due to the tunnel construction have been showed in Figure 3. The maximum total displacement recorded after analysis is equal to 20.59 mm. This amount has not been reached in pile/ground surface location and allocates to tunnel movement.

Table 1. Soil model properties

Soil Layer	Material model *	E' (kPa)	E_{oed} (kPa)	E_{50} (kPa)	Eur (kPa)	γ_{sat} (kN/m3)	v'	φ' (˚)	C (kPa)	m	p_{ref} (kPa)
Wea. Crust	MC	6e3	_	_	_	17	0.32	22	8	_	_
Soft clay	HS	_	5e3	5e3	15e3	16	0.33	22	5	1	100
Me. Clay	HS	_	2e4	2e4	1e5	18	0.33	22	10	1	65
Stiff clay	HS	_	6e4	6e4	1.8e5	18	0.33	22	18	1	95
Sand	MC	8e4	_	_	_	20	0.3	36	0	_	_

Table 2. Material properties of lining and bored pile

Element	E (kN/m2)	v'concrete	γcocrete (kN/m3)
Tunnel lining	3.1 e 7	0.2	24
Bored pile	3.1 e 7	0.2	24

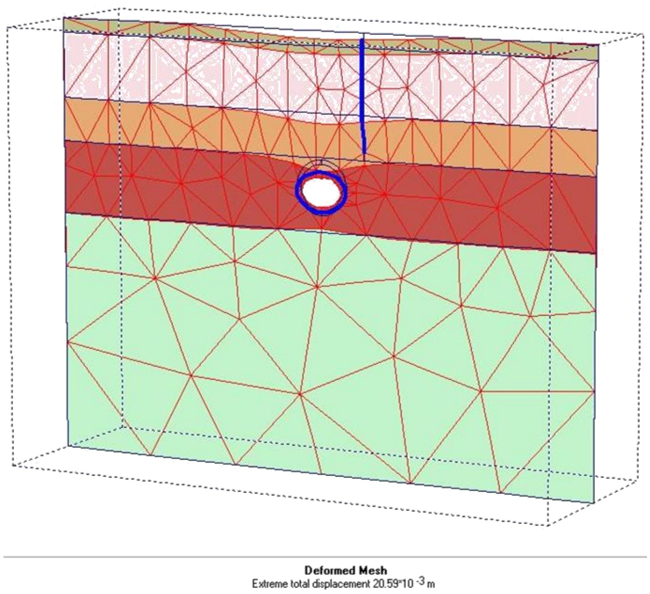

Fig.2. Cross section of deformed geometry and mesh of model (Pile length=15m)

Figure 3 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 deep for the same clearance of 3.15 m.

As it can be seen in Figure 3, there are some harmonies between two groups of result. The horizontal curves are the same but the obtained settlements of model are a bit lower than the one of the base paper. Therefore the maximum error could be estimated 16%. The cause of this error is some considerations exerted to the base study and not mentioned in the base paper. Also, the maximum pressure on the excavation face had not been determined. So according to the small error, it can be concluded that the present model is effective and has proper efficiency.

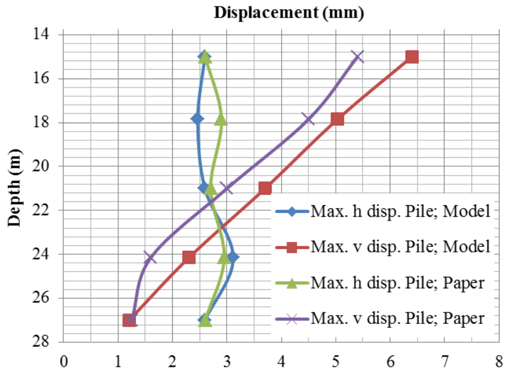

Fig.3. Comparison of single pile movement between paper and model results

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 it shown in Figure 4, and three different pile length (15m, 21m and 27m).

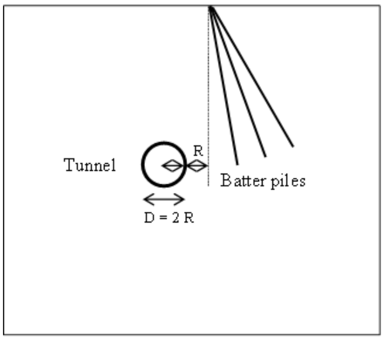

Fig.4. Three different inclinations of batter pile

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

4. Results

After verification and development of model by change in inclination, length and type of positioning of batter piles, the obtained results 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 5 shows the comparison between the amount of surface settlement above tunnel in existing vertical piles and batter piles. According to Figure 6, the maximum settlement of surface ground above 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 are a bit lower than vertical piles response. But by increasing batter pile length and reaching tunnel cross section, the amount of batter pile settlement increases, cause of vertical interaction of batter piles to the beneath soil which helps soil settling.

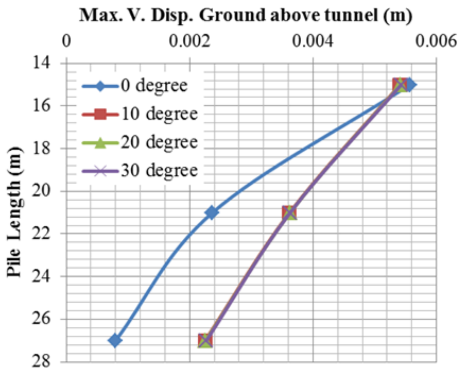

Fig.5. Comparison between vertical and batter pile in maximum settlement of surface ground above tunnel

Figure 6 shows the comparison between the maximum settlements of batter pile head by changing pile inclination. The maximum settlement of vertical pile head decreases by increasing the length of pile. However this amount is higher than the least deviant batter pile. This phenomenon is properly representative of the function of shallow batter piles during excavation under them. By increasing the inclination of batter piles, the settlement of batter pile head increases. In higher lengths, there are identical responses between every three inclinations during excavation under them.

The maximum settlement of pile elements have been shown in Figure 7. It has been concluded that all the displacement of batter piles are identical and the difference point is to the pattern and the mode of deformation.

The bending moment changes in pile length have been shown in Figure 8. In lower inclinations, by increasing the pile length, the introduced bending moment increases. These changes tend to get low rather than lower lengths of batter piles when the inclination increases.

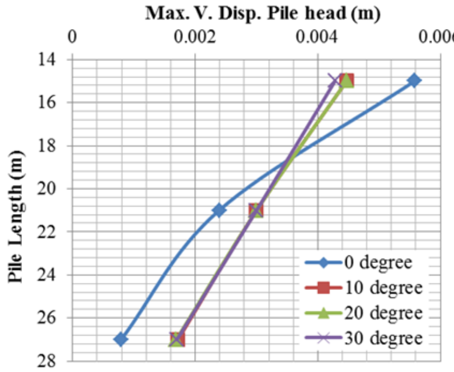

Fig.6. Comparison between vertical and batter pile in maximum settlement of pile head

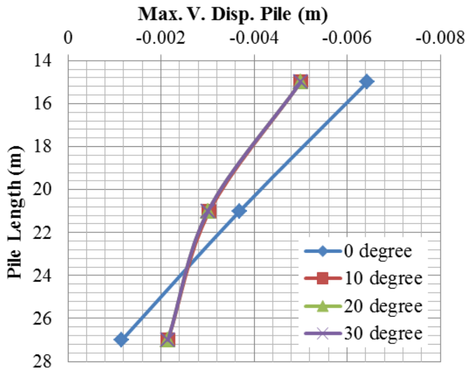

Fig.7. Comparison between vertical and batter pile in maximum vertical displacement of pile element

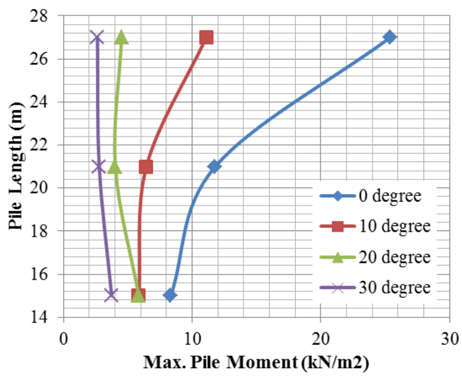

Fig.8. Comparison between vertical and batter pile in maximum induced bending moment through pile element

According to Figure 9, in smaller batter piles, higher shear stresses are observed than the vertical piles which by increasing inclinations the amount of it decreases. For those batter piles which have continued up to tunnel center or further, the amount of shear stress has remained constant which is representative of no effect of tension contours on the pile structure, due to tunneling.

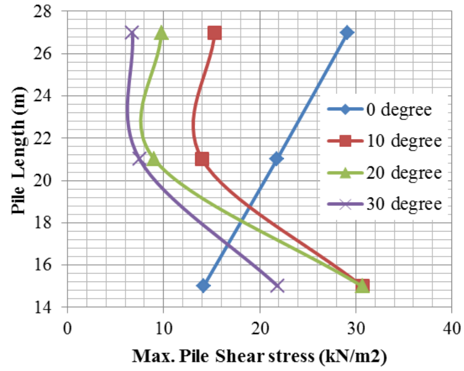

Fig.9. Comparison between vertical and batter pile in maximum induced shear stress through pile element

The changes in maximum induced axial forces through vertical and batter piles, due to tunneling, have been shown in Figure 10.

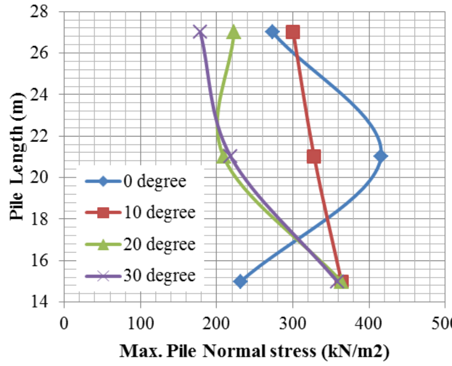

Fig.10. Comparison between vertical and batter pile in maximum induced axial stress through pile element

In vertical piles by length of up to center of tunnel, the induced axial stress increases and in longer batter piles the trend of creation of axial forces in pile is subtractive (Figure 10). In small batter piles, induced axial stress along pile length increases and is identical in all inclinations. Induced axial forces under every inclination are more than induced stress in the similar length of vertical pile because the vertical components of soil block reaction to pile element increases and then the axial component increases.

By increasing batter pile length at every inclination, the induced axial stress through pile element decreases. By increasing the inclination of longer batter piles, the induced axial stress reduction through pile element is significant. The reason is to take some distance of pile tip from tunnel position and then the loss of effectiveness of long piles from ground displacement due to excavation and subsequently, reduction in stress changes of soil mass.

Table 3 summarizes the attained results of batter pile modeling. Noted that 0 and 1 is representative of the ratio lower and higher than 1.

Table 3. Comparison between settlements of surface ground, pile head and pile element together for 3 pile length and 3 inclinations, separately.

Pile Length (m)	Inclination (°)	Δy (Surface ground / Pile head)	Δy (Surface ground / Pile element)	Δy (Pile head / Pile head)
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

As it shown in Table 3, the maximum settlement of surface ground above 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 4. Comparison between induced forces through pile element for 3 piles length and 3 inclinations, separately.

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

As it shown in Table 4, the induced bending moment in batter piles of every inclination is lower than the bending moment of vertical pile because the stresses due to lining displacement and subsequently surrounded soil arrive to pile element with an angle higher than 90 degrees. So, the torque arm remains constant and the applied force decreases. Induced shear stress in batter piles are lower than induced shear stress in vertical pile deeper than the elevation of tunnel crest as the settlement and rotation of longer batter piles increase which are in the direction of keeping out of tunnel and getting rid of lining's stress contours.

4. Conclusions

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

- In all cases of batter piles, relations (1) and (2) would be extracted for each pile length lonely:

Vertical displacement of pile element > Settlement of ground surface above tunnel axis (1)

Settlement of ground surface above tunnel axis > Settlement of pile head (2)

- The reductive patterns of settlements are observed in all results by increasing the length of batter piles.
- Lining as disturbing soil balance is the main factor of changing the settlement pattern of batter pile. By increasing batter pile length further the elevation of tunnel crest, maximum vertical displacement of pile element and pile head settlement became higher than vertical pile's. It should be because of oval deformation of lining which is the cause of rotation of batter piles. By increasing the inclination of batter piles and increasing the vertical distance of pile to the nearest point of lining structure, the deformations decrease.
- Excavation under short batter piles, if tunnel crest be under the elevation of pile tip has lower risks because short vertical batter piles present higher amount of settlement. But short batter piles exhibited higher settlements than longer batter piles.

According to the obtained results, batter pile with 21 m length and inclination of 30° shows the best function during tunneling under itself. In fact, increasing the length of pile up to the elevation of tunnel center and increasing the pile inclination are two main reason of displacement reduction of batter pile due to tunneling. But vertical piles are more effective if the pile tip takes place under the elevation of tunnel floor.

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