Geomechanics and Engineering, *Vol. 15, No. 3 (2018) 861-868*
DOI: https://doi.org/10.12989/gae.2018.15.3.861

Behaviour of vertically and horizontally loaded pile and adjacent ground affected by tunnelling

Dong-Wook Oh[a], Ho-Yeon Ahn[b] and Yong-Joo Lee[*]

Department of Civil Engineering, Seoul National University of Science and Technology,232 Gongneung-ro, Nowon-gu, Seoul 01811, Republic of Korea

(Received May 20, 2017, Revised February 3, 2018, Accepted March 23, 2018)

Abstract. Recent occurrences of earthquakes in Korea have increased the importance of considering how horizontal loads affect foundation structures as a result of wind and dynamic impact. However, to date, there are few studies on tunnelling-induced behaviour of ground and pile structures simultaneously subjected to horizontal and vertical loads. In this research, therefore, the behaviour of ground and single piles due to tunnelling were investigated through a laboratory model test. Three cases of horizontal loads were applied to the top of the pile. In addition, a numerical analysis was carried out to analyse and compare with the results from the laboratory model test.

Keywords: single pile, horizontal and vertical loads, tunnelling, laboratory model test, numerical analysis

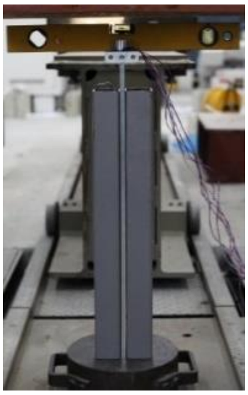
1. Introduction

As construction of high-rise buildings and occurrences of earthquakes continue to increase, the importance of horizontal loads is gaining more attention. The bearing capacity of a single pile according to the horizontal loads is determined by load test and analytical methods. A variety of analytical methods have thus far been proposed. For instance, Chang (1937) proposed an equation for the bending deflection of piles supported on elastic foundations. This method is only possible when the coefficient of horizontal subgrade reaction is constant. Matlock and Reese (1960) suggested the p-y curve of the relationship between pile displacement and subgrade reaction. This method can be considered as nonlinear in terms of ground behaviour. Equations of the pile bending moment and ground stiffness were put forward by Broms (1964) who proposed a design method to calculate the stress-strain of the pile to assume the failure mode, depending upon pile length and soil conditions. Furthermore, Matlock (1970) assumed that the subgrade reaction at a point occurs according to the displacement of the pile at that point only. Aside from above researches, theoretical approaches with respect to behaviour of pile subjected lateral loaded attempted by Broms (1965), Poulos (1971), etc., but also Ashour *et al.* (1999, 2004), Ashour and Norris (2003) mentioned pile behaviour characteristic of load-deformation due to lateral load using wedge theory. Also, Wang and Reese (1999) suggested equation to define ultimate lateral resistance force of pile through wedge theory. The studies regarding interactive behaviour of pile-tunnelling have been conducted as theoretical, numerical, model test including 1 g, centrifuge, field monitoring by many researchers including Loganathan and Poulos (1988), Chen *et al.* (1999), Loganathan *et al.* (2001), Lee (2004), Kitiyodom *et al.* (2005), Selemetas (2005), Lee and Jacobsz (2006), Pang (2006), Cheng *et al.* (2007), Huang *et al.* (2009), Lee *et al.* (2010). However, the study considering horizontal load and tunnelling at the same time have been rarely carried out, so far. Therefore, the authors analysed the behaviours of pile subjected to vertical and horizontal loads as well as ground deformation induced by tunnelling. Tunnelling is very useful and widely used to solve environmental and transportation problems resulting from population growth in urban areas. Tunnelling is represented by volume loss, as suggested by Atkinson and Mair (1981). It is controlled through water inflow and outflow for the model tunnel device (Lee 2014), and 5% of volume loss is applied. Allowable vertical and horizontal loads are estimated by the static pile load test. Settlements of pile and ground surface, as well as the pile axial force resulting from tunnelling in the laboratory model test, are compared using finite element analysis (FEA).

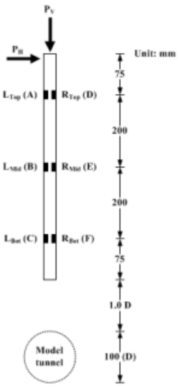
In these days, as matter of fact, it is getting important to understand long-term behaviour of infra-structure including pile foundation. In order to consider long-term behaviour of steel girder due to corrosion and time varieties, Nowak and Collins (2013), Ghasemi and Nowak (2017a, b) suggested a function with respect to reliability index for non-normal distribution of limit state. However, those studies are for steel structures, unlike condition of pile foundation assumed in the present study. In this study, model pile is made with aluminum material, in fact, the authors are considered as in-site concrete pile which is generally used in urban areas, not driven pile. A pile foundation in congested city is rarely constructed by driven pile owing to noise and vibration problem. In this study, thus, long-term behaviour of pile is not considered.

∗Corresponding author, Assistant Professor
E-mail: ucesyjl@seoultech.ac.kr
[a]Ph.D. Student
[b]M.Sc.

http://www.techno-press.org/?journal=gae&subpage=7
ISSN: 2005-307X (Print), 2092-6219 (Online)



(a) Pile calibration test



(b) Strain gauges location and dimension of model pile

Fig. 1 Strain gauges and model pile dimension for pile calibration test

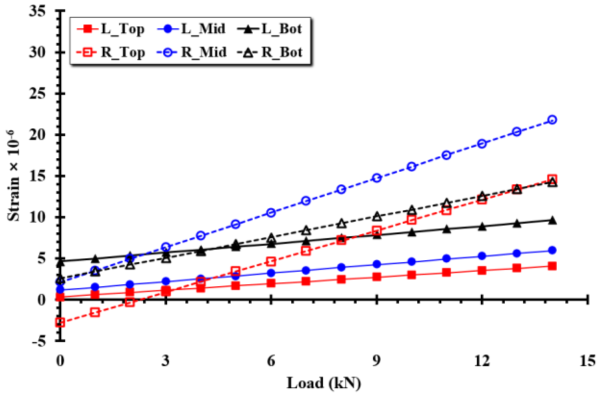
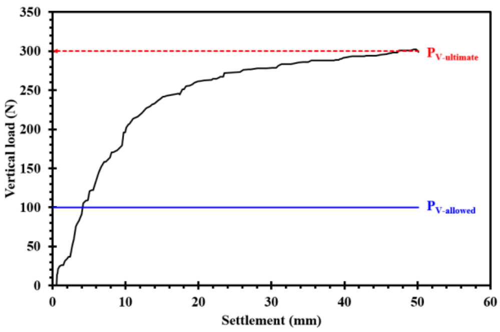
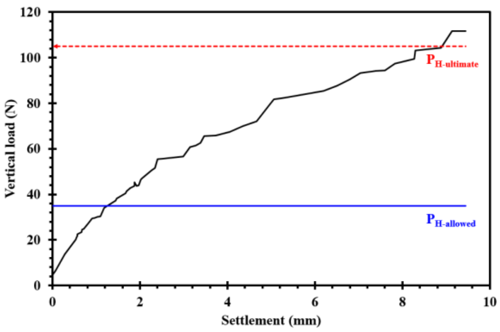


Fig. 2 Result of the pile calibration



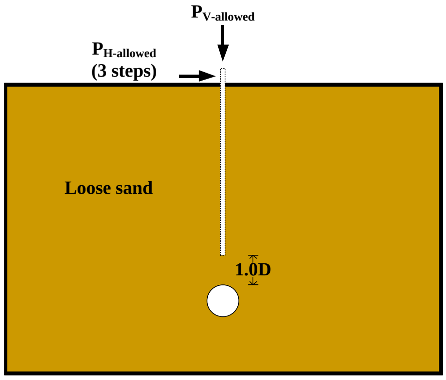
(a) P-S curve



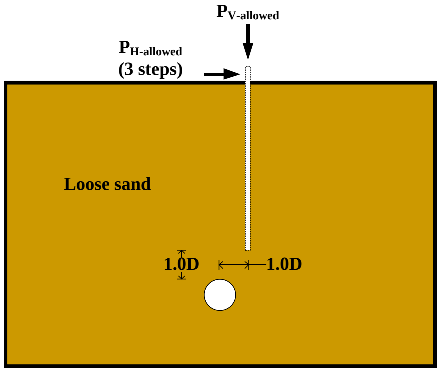
(b) P-Y curve

Fig. 3 Static pile load test ($P_{V\text{-allowed}}$, $P_{H\text{-allowed}}$)

2. Laboratory model test



(a) Scenario 1 (tunnelling directly below pile)



(b) Scenario 2 (1.0D offset between tunnel and pile)

Fig. 4 Scenarios of laboratory model test

Table 1 Cases of laboratory model test

		Allowed horizontal load (N)		
		34%	67%	100%
Horizontal offset	0.0 D	S1-C1	S1-C2	S1-C3
	1.0 D	S2-C1	S2-C2	S2-C3

Vertical and horizontal loads are applied to the pile and a tunnel is excavated under the pile. The behaviours of the pile, the adjacent ground, and the pile axial force are analysed for 6 cases according to various horizontal offsets between the tunnel crown.

2.1 Pile calibration

Before the laboratory model test, the pile calibration is performed using UTM (Fig. 1(a)).

In order to measure the load and strain, 6 strain gauges are attached to the pile, located from top to bottom on the left and right sides of the pile (Fig. 1(b)). The results of each strain gauge from the calibration test are shown in Fig. 2.

2.2 Selection of the loads

The allowable vertical load is obtained from the load-settlement relationship (Fig. 3) using the load control method (LCM), defined as 300 N by ultimate vertical load with safety factor 3.0, which gives the same load (Fig. 3(a)). The ultimate and allowable horizontal loads are 105 N and 35 N, respectively (Fig. 3(b)).

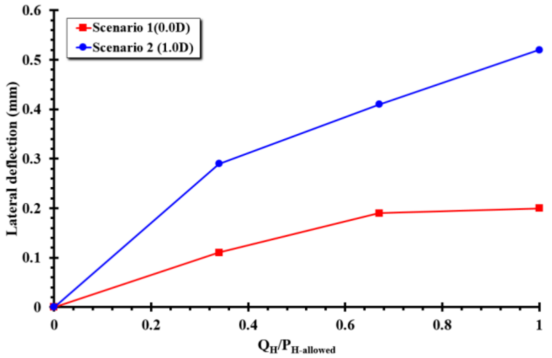


Fig. 5 Lateral displacement (V_L=5%)

This is divided into 3 cases for horizontal loads viz, 34% ($q_1=P_{H\text{-allowed}}\times\frac{1}{3}$), 67% ($q_2=P_{H\text{-allowed}}\times\frac{2}{3}$) and 100% of the allowed horizontal load (q_3). This horizontal load and the horizontal offset between the pile and tunnel are classified into 6 cases (Table 1, Fig. 4).

2.3 Results from the laboratory model test

As the horizontal load increases, displacement also increases. Fig. 5 shows that as the offset between the pile and tunnel centre increases, the pile becomes more influenced by the horizontal load.

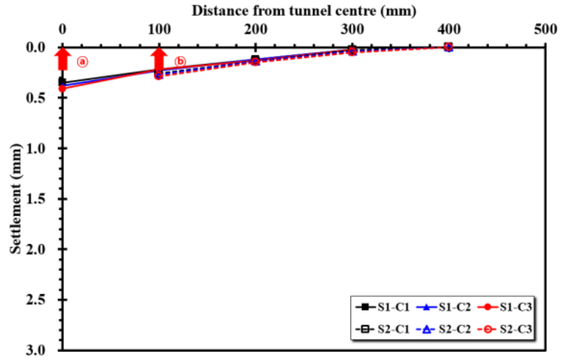
Fig. 5 shows the horizontal displacement of the pile depending on different horizontal loads for each scenario when the volume loss rate is 5%. In both scenarios, the largest horizontal displacement occurred in the final horizontal loading stage. In scenario 1, the horizontal displacement of the pile is approximately 0.2 mm; however, in scenario 2, it is approximately 0.5 mm, which is approximately 2.5 times larger. It is assumed that the horizontal displacement is relatively small in scenario 1 because of the settlement caused by the increase in volume loss, and the settlement analysis will be explained in the next chapter.

Settlements of the pile and ground surface due to tunnelling (V_L=5%) are illustrated in Fig. 6. In the X-axis, point a and b represent the locations of the pile for scenario 1, 2, respectively. 0(zero) means tunnel centre line and other numbers mean the distance of the measurement points for the ground surface settlement.

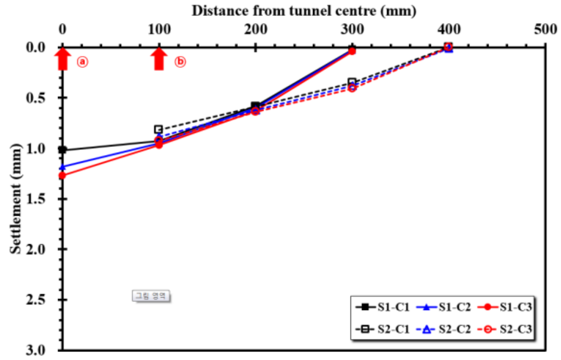
Settlements of the pile and adjacent ground surface exhibit a similar tendency to the Gaussian curve, which is mentioned by Atkinson (2007) regarding the shape of ground surface deformation due to tunnelling in greenfield condition. The pile settlement for all cases of scenario 1 is larger than in scenario 2.

Fig. 6 shows the amount of pile and adjacent ground settlement for each scenario and volume loss ratio. In the figures, ‘a’ and ‘b’ (circled) show the pile locations in scenarios 1 and 2.

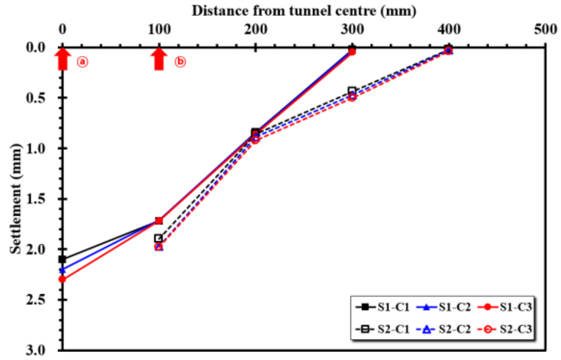
In case of volume loss 1.5% (Fig. 6(a)), the maximum pile settlements occur while 100% allowed horizontal pile load (q_3) is applied for both scenarios, 0.41 mm for scenario 1 and 0.29 mm for scenario 2. However, the amount and tendency of adjacent ground surface settlements are almost similar both scenarios.



(a) Volume loss 1.5%



(b) Volume loss 3.0%



(c) Volume loss 5.0%

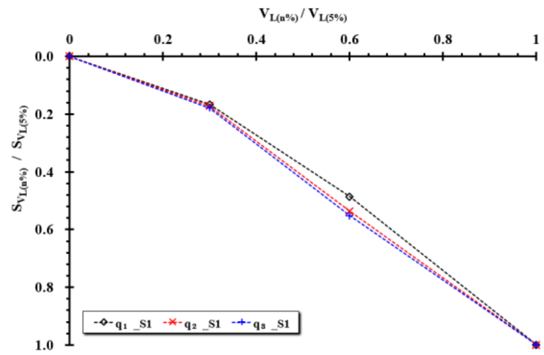
Fig. 6 Settlements of pile and adjacent ground surface for each case

The greatest pile settlement in both scenarios for 3.0% of volume loss occur 1.27 mm (scenario 1) and 0.93 mm (scenario 2).

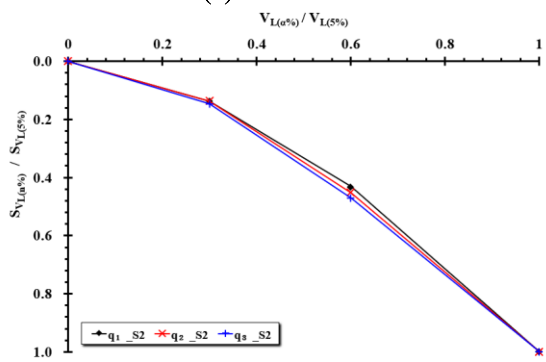
For case of volume loss 5.0% (Fig. 6(c)), the pile settlement increased from 2.1 mm to 2.3 mm in scenario 1, while in scenario 2, it increased from 1.9 mm to 1.97 mm, giving the rate of growth of 10% and 4%, respectively

Fig. 7 shows the normalised pile settlement due to the horizontal load increase in each volume loss based on the volume loss of 5% in each scenario. When the volume loss is 3% % ($V_{L(n\%)}/V_{L(5\%)}$=0.6), the two scenarios show the greatest difference, and scenario 1 has a larger effect of settlement than scenario 2.

The change of pile axial force due to the development of volume loss from 0%-5% are illustrated in Fig. 8. As shown in this figure, the change in pile axial force becomes greater because of increases in volume loss.

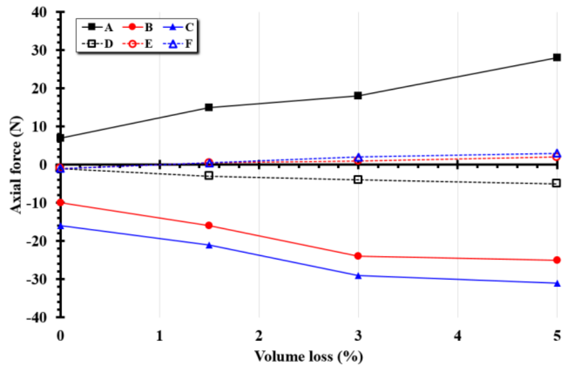


(a) Scenario 1

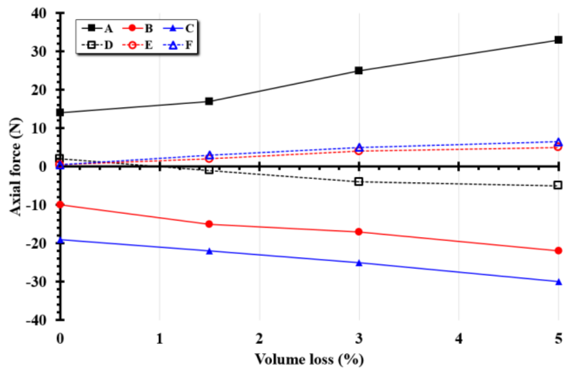


(b) Scenario 2

Fig. 7 Normalised pile settlement due to development of volume loss



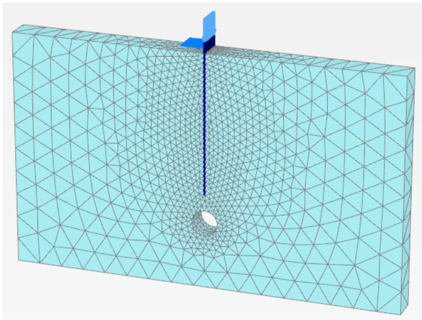
(a) Scenario 1



(b) Scenario 2

Fig. 8 Change of axial force due to the development of volume loss

The axial forces of the piles measured with increasing volume loss in each scenario are shown in Fig. 8. A, B, and C are the axial forces in the left side of the pile, i.e., the loading direction of the horizontal loads, and D, E, and F are the axial forces measured on the right side of the pile (See Fig. 1(b).). As shown in Fig. 8, there is a relatively large axial force change in scenario 2, compared to scenario 1, which is more affected by the upper part of the pile because of the settlement caused by the increase in volume loss. In scenario 1 (Fig. 8(a)), the tensile force increased rapidly (gauge B, C) when the volume loss increased from 1.5% to 3.0%, while in scenario 2, the compressive force increased dramatically (gauge A). Such tendency is due to the fact that as the volume loss increases, the displacement of the ground is concentrated at the centre of the tunnel; in case 1 of scenario 1, where the pile is located directly above the tunnel, it induces a land subsidence at the pile tip, whereas in scenario 2, horizontal displacement occurs at the pile tip, providing support to the pile as a consequence.
The axial force generated by the horizontal load is in the opposite direction in A, B, and C and in the same direction in D, E, and F, which generated a neutral axis changing the direction of the force between the upper (A, D) and the middle (B, E) parts.


(a) Scenario 1

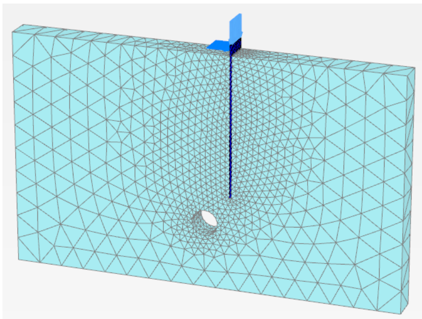

(b) Scenario 2

Fig. 9 Modelling for FEA

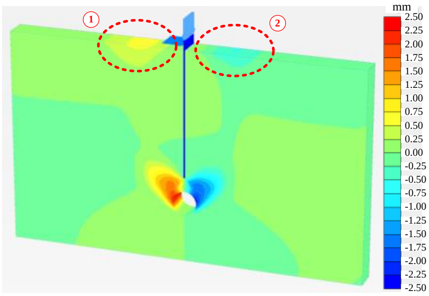
Table 2 Material properties

	Soil		Pile	
	Value	Unit	Value	Unit
Unit weight (γ)	16.0	kN/m^3	27.0	kN/m^3
Void ratio (e)	0.851	-	-	
Young's modulus (E)	11,000	kPa	7.0e6	kPa
Poisson ratio (ν)	0.3	-	0.35	-
Cohesion (c)	0.1	kN/m^2	-	-
Shear resistance angle (ϕ)	27	Deg.	-	-

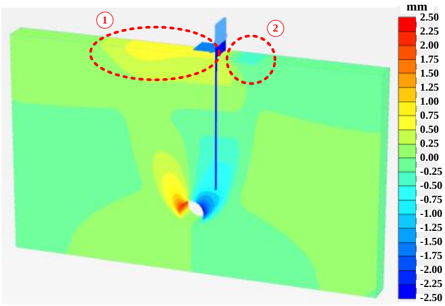
3. Finite element analysis

3.1 Material properties

The finite element analysis (FEA) method is simulated under the same condition as the laboratory model test. The properties of the soil are based on the result of the relative density (loose sand) obtained from the laboratory model test (Kim 2012). The pile is applied to have pure aluminium properties and the interface strength reduction factor (R_{inter}) (Lee 2013). The tunnelling is simulated by ground volume loss. The properties for numerical analysis are shown in Table 2, and modelling for each case is illustrated in Fig. 9.

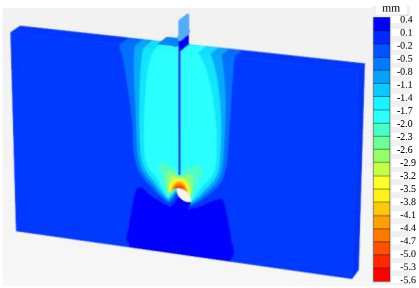


(a) Scenario 1

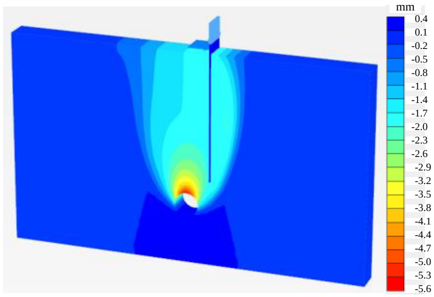


(b) Scenario 2

Fig. 10 Horizontal displacement contour

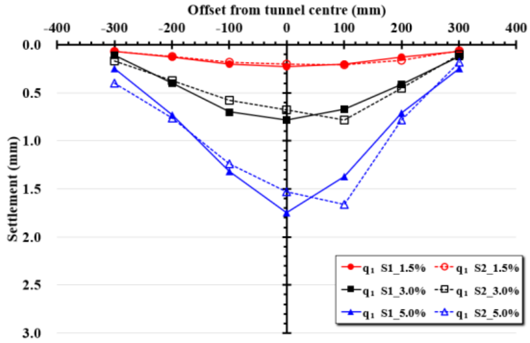


(a) Scenario 1

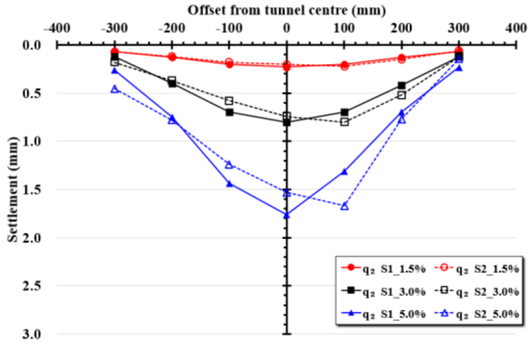


(b) Scenario 2

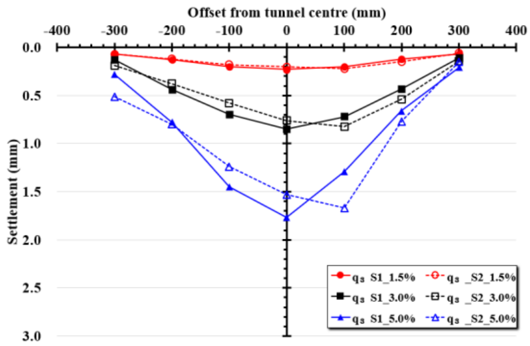
Fig. 11 Vertical displacement contour



(a) q_1



(b) q_2



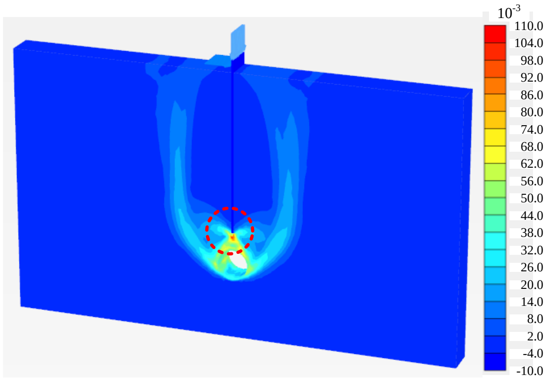
(c) q_3

Fig. 12 Settlements of pile and adjacent ground surface for each case (FEM)

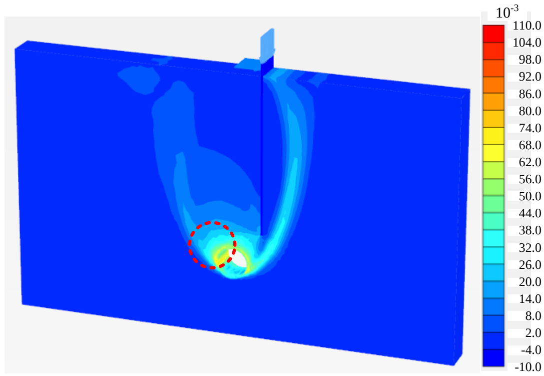
3.2 Results from the FEA 3D

The results of numerical analysis are shown in Figs. 10-15. In case 1, the effect of the horizontal load is smaller than that of the tunnelling. Settlements and shear strain are also concentrated near the tunnel crown. In case 2, however, the further the offset between the pile and tunnel centre is, the greater the horizontal displacement due to the horizontal load is than in case 1. In addition, vertical displacement and shear strain occur depending on the offset between the pile and tunnel.

Fig. 10 shows the horizontal displacement of the contour when 100% of the allowable horizontal load is applied in each scenario. In both scenarios, the horizontal displacement occurs in the direction of the horizontal load before the tunnel excavation. However, after the tunnel excavation, the displacements occurred in the (+) direction in the left pile and in the (-) direction in the right pile. This is mostly because of land subsidence caused by the tunnel



(a) Scenario 1



(b) Scenario 2

Fig. 13 Shear strain contour

excavation and pile settlement. In scenario 1 (Fig. 10 (a)), the area where the horizontal displacement occurs more than 0.25 mm in absolute value is approximately 320 mm in Area 1; whereas in scenario 2, it is 450 mm in scenario 2 (Fig. 10(b)), which is approximately 150% higher. The right side of the pile exhibits a different trend. In scenario 1, a horizontal displacement of 0.25 mm occurs from the centre of the tunnel to approximately 290 mm; whereas in scenario 2, it was in the range of approximately 250 mm, showing that horizontal displacement occurs in the range of approximately 14% smaller than scenario 1. This trend is most likely to be caused by the horizontal earth pressure from the horizontal load acting as the main force in Area 1, but as a secondary force in Area 2.

Fig. 11 shows the vertical displacement in scenarios 1 and 2 as a contour when the volume loss is -5.0%. In both scenarios, 100% of the allowable horizontal load is applied. In scenario 1, however, because the effect of tunnel excavation is greater than that of the horizontal load, the settlement appears almost symmetrically. However, in scenario 2, its effect is asymmetrical as shown by the contour.

Fig. 12 is a graph of pile settlement and subsidence of adjacent piles with increasing volume loss when the horizontal load acting on the pile is 1/3 (q_1), 2/3 (q_2), and 3/3 (q_3) of the allowable horizontal load.

Comparing the settlement amount with increasing volume loss to the horizontal load of 1/3 (q_1) of the allowable horizontal load (Fig. 12(a)), there is no significant difference between scenario 1 and scenario 2 at a volume loss of 1.5%. However, when the volume loss increased from 3.0% to 5.0%, the settlement of pile and adjacent grounds increases sharply in scenario 2, and a somewhat larger settlement occurs when compared to scenario 1. This tendency is shown in Fig. 12(b) and 12(c), which is similar to that obtained through the indoor model test.

As a result, the horizontal load and volume loss increase for scenario 2, settlement is getting great at left side of pile (negative in x-axis).

The shear strain obtained by numerical analysis is shown in Fig. 13.

In scenario 1, the maximum shear strain occurs at the pile tip, and the value was 0.11; however, in scenario 2, the maximum shear strain appeared on the left side of the tunnel, and its value was 0.07. In scenario 2, the shear strain at the pile tip was 0.012, which was approximately 1/10 of that of scenario 1. This is equivalent to the tendency in settlement and horizontal displacement obtained from the model test and numerical analysis.

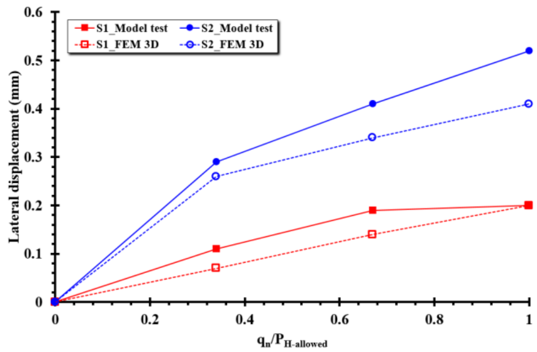


Fig. 14 Comparison of horizontal displacement

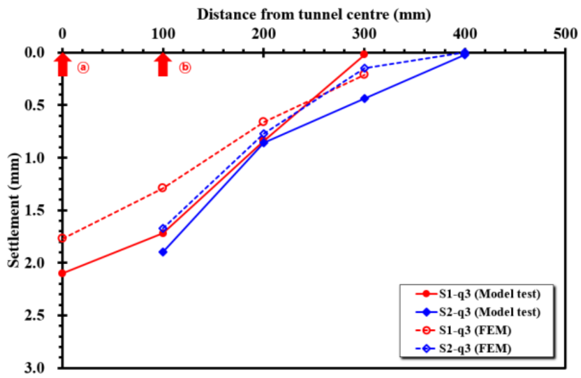
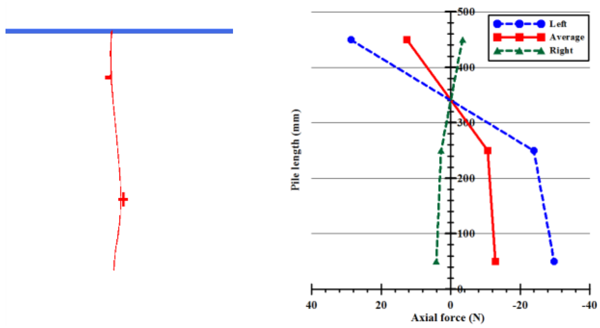
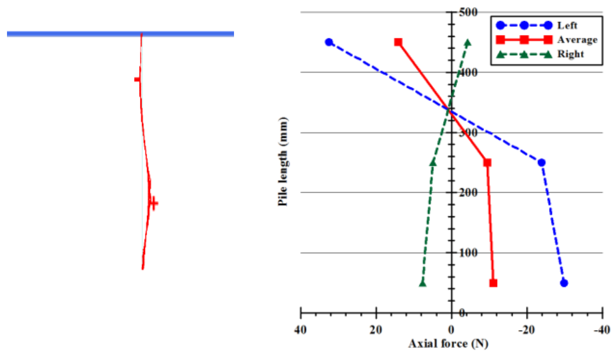


Fig. 15 Comparison of settlement (V_L=5%)



(a) FEA (b) Model test

Fig. 16 Pile axial force for scenario 1



(a) FEA (b) Model test

Fig. 17 Pile axial force for scenario 2

4. Comparison of results

The results from the laboratory model test and numerical analysis are compared. Comparisons of settlements and pile axial force are displayed in Figs. 14-17. All the results from the laboratory model test are higher than those from the numerical analysis. In Fig. 14, it can be seen that the greater horizontal load is, the bigger horizontal displacement is.

The settlement of piles and adjacent grounds obtained from the numerical analysis was compared with the indoor model test results (Fig. 15). Here, the numerical analysis results were smaller than those of the indoor model test, though the tendency for pile settlement, which means settlement at point a, b in Fig. 15, in both scenarios, while being similar, was higher in scenario 1 than scenario 2. Additionally, settlement amount the pile locations in both scenarios were also similar.

When the pile is located above the tunnel, settlement occurs and decreases towards the ground surface.

Additionally, the further the offset between the pile and tunnel centre is, the higher the horizontal displacement gets; however, settlement does not increase.

Figs. 16 and 17 show the axial force of the pile, which are measured according to the location of the strain gauges. The figures on the left are for FEA 3D, with (-) and (+) representing compression and tension, respectively. The graphs on the right display the value of the laboratory model test. Here, (-) shows tension and (+) represents compression. The results exhibit a similar tendency.

5. Conclusions

In this study, tunnelling under the pile was subjected to both the vertical and the horizontal loads. The behaviour of the pile and adjacent ground was analysed using laboratory model test and FEA. In general, the results exhibited a similar tendency, which are itemised below.

• The further the offset between the pile and tunnel centre was, the greater the effect of horizontal loads on the pile were. Thus, the effect of tunnelling was large when the pile was located directly above the tunnel (scenario 1).

• The larger the horizonal loads applied to the pile was, the higher the horizontal displacement of the pile was, and the lower the amounts of settlement of the pile and ground surface were.

• When the horizontal load was applied to the pile and tunnelling, compression occurred above the pile, and tension took place under the pile. When the horizontal load was small (34%), the settlement of the pile was large because the area under the pile was subjected to tension due to the tunnelling.

It can therefore be concluded from the above that the load applied to the pile and the horizontal offset between the pile and tunnel are important factors in tunnelling.

In this study, pile and ground behaviour tunnelling-induced after lateral pile load are investigated. The authors have plan study regarding grouped pile subjected vertical and lateral load at the same time with tunnelling, and results from this study will be compared to further research.

Acknowledgements

This study was supported by basic science and engineering research program through the National Research Foundation of Korea (NRF-2017R1A2B2055676).

References

Ashour, M., Norris, G. and Pilling, P. (1999), "Lateral loading of a pile in layered soil using the strain wedge model", *J. Geotech. Geoenviron. Eng.*, **124**(4), 303-315.

Ashour, M., Pilling, P. and Norris, G. (2004), "Lateral behavior of pile groups in layered soils", *J. Geotech. Geoenviron. Eng.*, **130**(6), 580-592.

Atkinson, J.H. and Mair, R.J. (1981), "Soil mechanics aspects of soft ground tunnelling", *Ground Eng.*, **14**(5), 20-26.

Atkinson, J.H. and Mair, R.J. (2007), *The Mechanics of Soils and Foundations*, CRC Press, 404-406.

Broms, B. (1964), "Lateral resistance of piles in cohesionless soil", *J. Soil Mech. Found. Eng.*, **90**(3), 123-156.

Broms, B. (1965), "Design of laterally loaded piles", *J. Soil Mech. Found. Div.*, **91**(SM3), 79-99.

Chang, Y.L. (1937), "Discussion on lateral pile-loading test by Feagin", *Transaction*, **91**, 272-278.

Chen, L.T., Poulos, H.G. and Loganathan, N. (1999), "Pile response caused by tunnelling", *J. Geotech. Geoenviron. Eng.*, **125**(3), 207-215.

Cheng, C.Y., Dasari, G.R., Chow, Y.K. and Leung, C.F. (2007), "Finite element analysis of tunnel-soil-pile interaction using displacement controlled model", *Tunn. Undergr. Sp. Technol.*, **22**(4), 450-466.

Ghasemi, S.H. and Nowak, A.S. (2017a), "Reliability index for non-normal distributions of limit state functions", *Struct. Eng. Mech.*, **62**(3), 365-372.

Ghasemi, S.H. and Nowak, A.S. (2017b), "Target reliability for bridges with consideration of ultimate limit state", *Eng. Struct.*, **152**, 266-237.

Huang, M., Zhang, C. and Li, Z. (2009), "A simplified analysis method for the influence of tunnelling on grouped piles", *Tunn. Undergr. Sp. Technol.*, **24**(4), 410-422.

Kim, Y.S., Ko, H.W., Kim, J.H. and Lee, J.G. (2012), "Dynamic deformation characteristics of Joomunjin standard sand using cyclic triaxial test", *J. Kor. Geotech. Soc.*, **28**(12), 53-64.

Kitiyodom, P., Matsumoto, T. and Kawaguchi, K. (2005), "A simplified analysis method for piled raft foundations subjected to ground movements induced by tunnelling", *J. Numer. Anal. Meth. Geomech.*, **29**(15), 1485-1507.

Lee, C.J. and Jacobsz, S.W. (2006), "The influence of tunnelling on adjacent piled foundations", *Tunn. Undergr. Sp. Technol.*, **21**(3), 430.

Lee, J.H. (2014), "Model tunnel excavation using close range photogrammetric technique for tunnel roof reinforcement", M.Sc. Dissertation, Seoul National University of Science and Technology, Seoul, Korea

Lee, J.M. (2013), "Investigation of bored pile behavior according to interface properties", M.Sc. Dissertation Seoul National University of Science and Technology, Seoul, Korea.

Lee, S.W., Choy, C.K.M., Cheang, W.W.L., Swolfs, W. and Brinkgreve, R. (2010), "Modelling of tunnelling beneath a building supported by friction bored piles", *Proceedings of the 17th Southeast Asian Geotechnical Conference*, Taipei, Taiwan, May.

Lee, Y.J. (2004), "Tunnelling adjacent to a row of loaded piles", Ph.D. Dissertation, University of College London, London, U.K.

Loganathan, N. and Poulos, H.G. (1988), "Analytical prediction for tunnelling-induced ground movement in clays", *J. Geotech. Geoenviron. Eng.*, **124**(9), 846-856.

Loganathan, N., Poulos, H.G. and Xu, K.J. (2001), "Ground and pile-group responses due to tunnelling", *Soil. Found.*, **41**(1), 56-57.

Matlock, H. (1970), "Correlations for design of laterally loaded piles in soft clay", *Proceedings of the 2nd Offshore Technology Conference*, Houston, Texas, U.S.A., April.

Matlock, H. and Reese, L.C. (1960), "Generalized solutions for laterally loaded piles", *J. Soil Mech. Found. Eng.*, **86**(5), 63-91.

Nowak, A.S. and Collins, K.R. (2013), *Reliability of Structures*, CRC Press, New York, U.S.A.

PLAXIS AE (2013), *Reference Manual*, 1-307.

Poulos, H.G. (1971), "Behavior of laterally loaded piles: 1-Single piles", *J. Soil Mech. Found. Div.*, **97**(SM5), 711-731.

Sabatini, P.J., Pass, D.G. and Bachus, R.C. (1999), *Geotechnical Engineering Circular No. 4, Ground Anchor and Anchored Systems,* No. FHWA-IF-99-015, Federal Highway Administration, B1-B8, Washington, D.C., U.S.A.

Selemetas, D. (2005), "The response of full-scale piles and piled structures to tunnelling", Ph.D. Dissertation, University of Cambridge, Cambridge, United Kingdom.

CC