

## **Investigation of grouped pile behaviour due to tunnelling in soft ground**

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### **ABSTRACT**

Tunnelling-induced settlement under pile foundation is an interesting topic for many researchers. It is essential to understand the development of underground space in the congested city. Generally, tunnelling in soft ground is demonstrated as volume loss, which is applied to 1~2% as the maximum value. In the present research, however, change of pile axial force and settlements of both pile and surface due to the development of volume loss by 10% are estimated to figure out the failure mechanism of tunnelling under grouped pile subjected to a vertical load. The laboratory model test was conducted as plain-strain condition and grouped pile was arranged by 2x1 and 3x1, respectively. Numerical analysis (Finite Element Method) was carried out to compare with results from the model test. Pile settlements are greater than surface one for both cases and settlement increase ratio of a 3x1 case is larger than the other case. The neutral point was investigated by results from strain gauge which is attached to assess axial forces of each pile.

### **1. INTRODUCTION**

The development of underground space is one of the most important factors for the evolving of the huge city. A tunnel is a very efficient method to meet demands occurred by the rapidly increasing population with traffic, communication, electricity etc. A foundation of many structures in the city have been applied to a variety of type of pile foundation, a number of studies have conducted to understand the influence of tunnelling under existing structures using by the various way including laboratory model test, image processing, centrifuge model test, numerical analysis etc (Loganathan and Poulos, 1998; Chen et al, 1999; Loganathan et al, 2001; Xu and Poulos, 2001; Mroueh and Shahrour, 2002; Cheng et al, 2007; Lee, 2004; Kitiyodom et al, 2005; Lee and Ng, 2005; Lee and Jacovsz, 2006; Pang, 2006; Huang et al, 2009; Lee et al, 2010; Devriendt and Williamson, 2011; Lee, 2012). Particularly, in the case that the structure

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below ground consists of soft soil, multiple piles are utilised to support loading and behave as grouped-pile. As shown in Table 1, grouped-pile is distinguished from single pile by means of space ratio between piles according to diameter of the pile (Shamsher and Hari, 1990). Tunnelling around the tip of pile foundation gives rise to displacement as necessarily, by which have an effect on settlement and load distribution of piles. A behaviour of the pile is seriously influenced by tunnel location from the tip of the pile. Although, there are so many studies for axial force distribution of the pile, the means of theoretical approach are universal. On the other hand, Selemetas (2005) reported a result of field monitoring regarding settlement and axial force distribution of below single pile due to tunnelling. Selemetas (2005) mentioned that tunnelling leads to a decrease of axial force and settlement of pile is greater than the ground surface one. Thus, the authors carry out laboratory model test concerning the axial force of grouped pile and settlement. In addition, numerical analysis is conducted to compare with the model test results.

Table 1. The criteria of single pile and grouped pile (Shamsher and Hari, 1990)

Pile Spacing (s)	Pile Action
3B to 7B	Group
Greater than 7B	Individual

## 2. MODEL TEST AND FE ANALYSIS

In the present research, laboratory model test was conducted to analyse grouped pile and ground behaviours due to tunnelling sequence below the grouped pile. Also, back analysis using Finite Element Analysis was carried out to compare with results of the model test. Axial forces of each pile were estimated using strain gauges which are attached to the aluminium model pile.

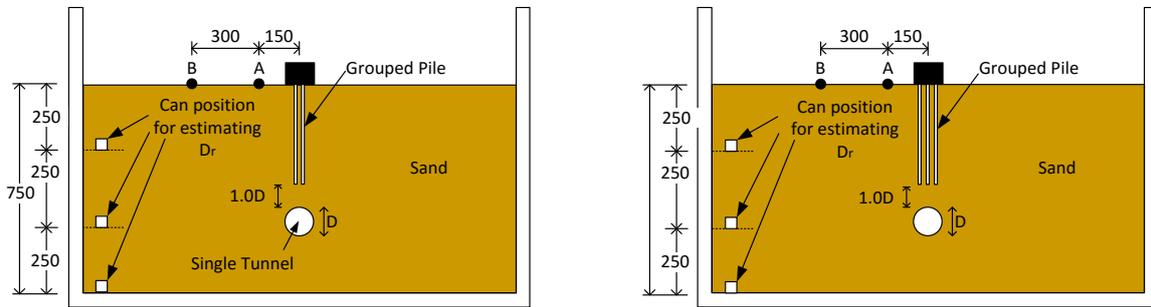
### 2.1 Laboratory model test

Model tests were performed as plane-strain conditions. The diameter of model tunnel is 100mm (prototype : 10m) and pile diameter (D) and length (L) are 8mm, 350mm, respectively (scale factor : 1/100), and spacing of piles are 2.5D (20mm). The height of sand pouring was maintained to form a uniform relative density of sand, which is estimated using cans that are installed into three part of soil tank (Fig. 1).

The static pile load test was conducted to define the allowed pile load. First, Bulter and Hoy's method (1977) was applied to assess ultimate pile capacity and safety factor was 3.0. As a result pile tests, ultimate capacities of 2x1 and 3x1 grouped pile are estimated approximately 88N, 134N, respectively (Fig. 2).

The relative density was approximately 30%, which fell under the purview of loose sand. The phase of tunnelling represents as volume loss ( $V_L$ , %), which is an ordinary method to express tunnelling in soft ground. Atkinson and Mair (1981) revealed that the shape of ground surface settlement due to tunnelling in soft ground greenfield condition was a Gaussian curve, and the relation between settlement and inflexion point was shown in Fig. 3. The offset between the tip of pile and tunnel crown assumed to be 1.0D. To measure the axial force of each pile, a strain gauge was attached on the

aluminium pile, which is carried out calibration test using UTM. Consequently, the strain was converted to force values.



(a) 2x1 grouped pile case

(b) 3x1 grouped pile case

Fig. 1. Profile of model tests

\*Note : A, B : measuring point for ground surface settlement

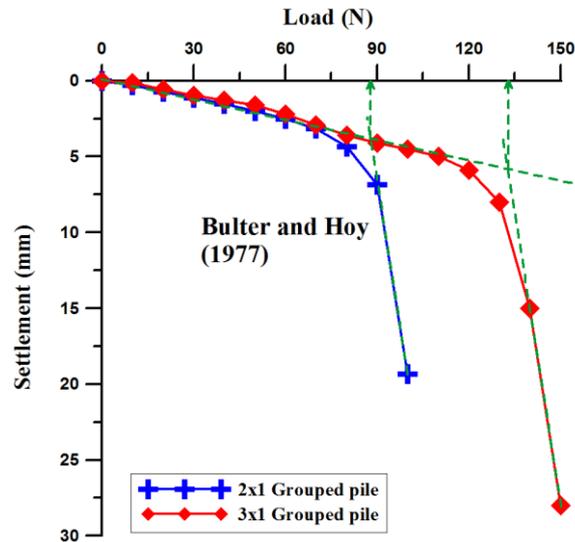


Fig. 2. Determination of allowed pile load (Bulter and Hoy, 1977)

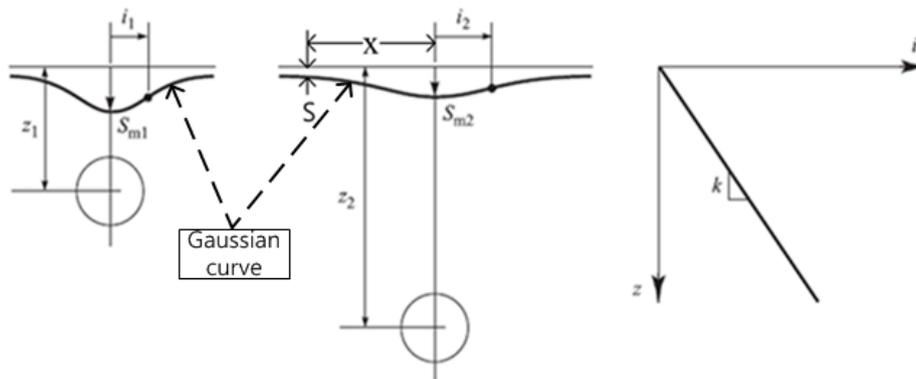


Fig. 3. Influence of tunnel depth on surface settlement profile (Atkinson and Mair, 1981)

## 2.2 Finite Element Analysis

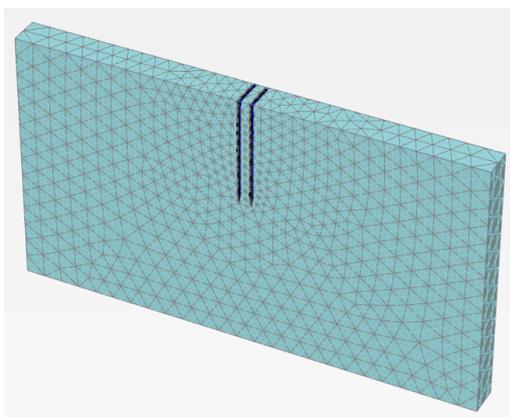
Back analysis using Plaxis (ver. 2016) was conducted to compare with the result of model tests including ground settlement, pile displacement, and ground behaviour as well as the axial force of each pile. Mohr-Coulomb model was applied to failure criterion of soil and linear elastic model referred to the pile. Initial void ratio( $e$ ) and unit weight( $\gamma$ ) by Kim et al.(2012) revealed results of the sand triaxial test that were applied to this analysis to express loose density sand (Table. 2) and dilatation angle was neglect. The material properties are shown in Table 3. The modellings of FEM are shown in Fig. 4.

Table 2. Various relative density ( $D_r$ ) (Kim et al., 2012)

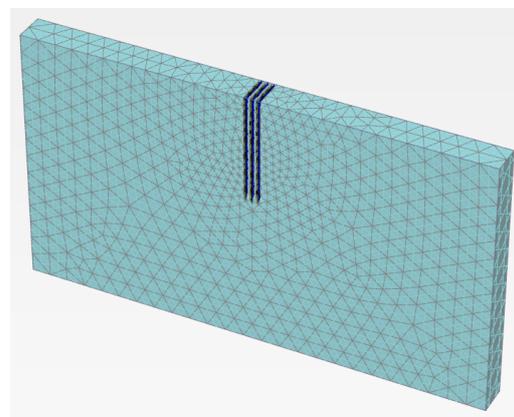
Relative Density ( $D_r$ )	Max.	80%	70%	60%	50%	40%	30%	Min.
Unit weight (kN/m <sup>2</sup> )	1.648	1.580	1.548	1.517	1.488	1.459	1.432	1.355
Voil ratio ( $e$ )	0.608	0.677	0.712	0.747	0.782	0.816	0.851	0.955

Table 3. Material properties

		Unit	Loose
Unit weight	$\gamma_{unsat}$	kN/m <sup>3</sup>	14.3
Void ratio	$e_{int}$	-	0.851
Young's modulus	E	kN/m <sup>2</sup>	10e3
Poisson's ratio	$\nu$	-	0.2
Cohesion	$c$	kN/m <sup>2</sup>	0.01
Shear resistance angle	$\phi$	deg	27
Dilatancy angle	$\psi$	deg	0
Interface	$R_{inter}$	-	0.3



(a) 2x1 grouped pile (case 1)



(b) 3x1 grouped pile (case 2)

Fig. 4. Modelling for back analysis

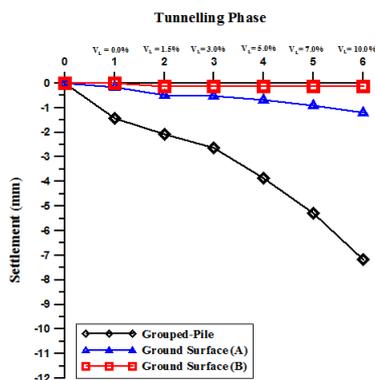
### 3. RESULTS

In this chapter, not only results of laboratory model test including settlements of ground surface settlement and grouped pile are shown, but also compared to ones from numerical analysis. It is noted that influence of cap as shallow foundation is not considered.

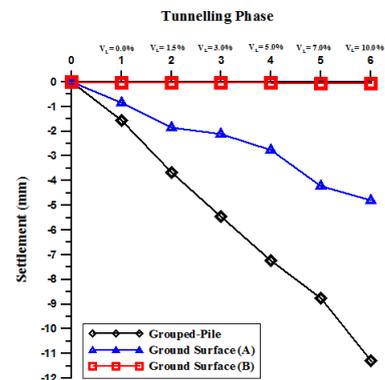
#### 3.1 Laboratory model test

The settlements of each case, first, are shown in Fig. 5, respectively. According to the result of the model test, grouped pile settlements are getting greater rely on the development of volume loss. The settlement at point B was estimated nearly zero for both cases.

The pile settlements with volume loss of 10% are approximately 6.5-times, 2.2-times greater than surface ones at point A for case 1,2, respectively. For final tunnelling phase, pile settlement and surface one at point A of case 2 (3x1) are 60%, 300% larger than case 1. It means that more underground soil adjacent pile for 3x1 grouped pile case move downward due to pile settlement. Also, development of volume loss occurred more rapid slope for case 2 than case 1, which means that a large number of pile occurs greater tunnelling-induced settlement under grouped pile.



(c) 2x1 grouped pile



(d) 3x1 grouped pile

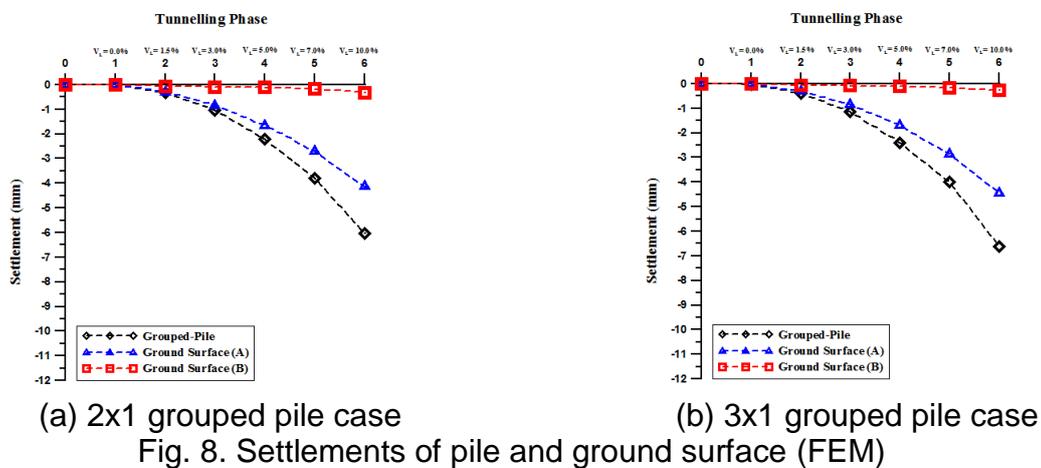
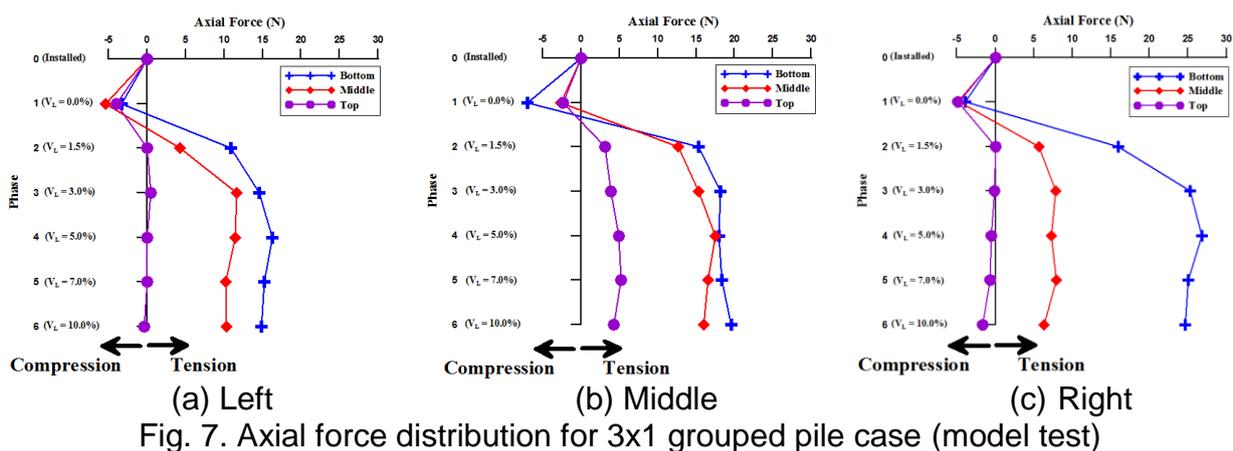
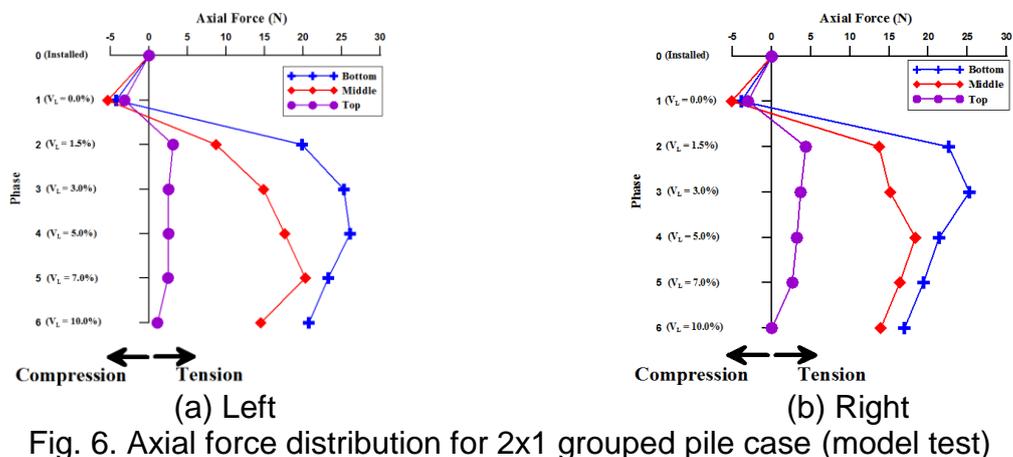
Fig. 5. Settlements of pile and ground surface (model test)

The axial forces of each pile are shown in Fig. 6,7, respectively. As shown in figures, the shape of the pile axial force resemble both side piles. A compressive force applied to pile first due to working load, however, to the contrary change into a tension force in accordance with volume loss. It is impossible that the neutral point of the pile due to tunnelling occurred when volume loss is approximately 1%. In addition, change of axial force is almost constant after 3% volume loss of case 2.

#### 3.2 Numerical Analysis

The results of the back analysis are shown in this section including settlement, pile axial force. The settlements of grouped pile and ground surface are compared

with each case in Fig. 8. The results mean that pile settlement due to the development of volume loss tends to be greater than the ground surface one which is similar to the aforementioned model test result.



The axial force distribution of each case is shown in Fig. 9,10. It is similar to model test. The lower of change force occur for upper of piles than another part, especially bottom one. The neutral point, however, is investigated top of the pile. It is not impossible to obtain the movement of neutral point for laboratory model test, whereas, it is capable of being estimated using numerical analysis. Movement of the neutral point was estimated nearly zero due to the development of volume loss.

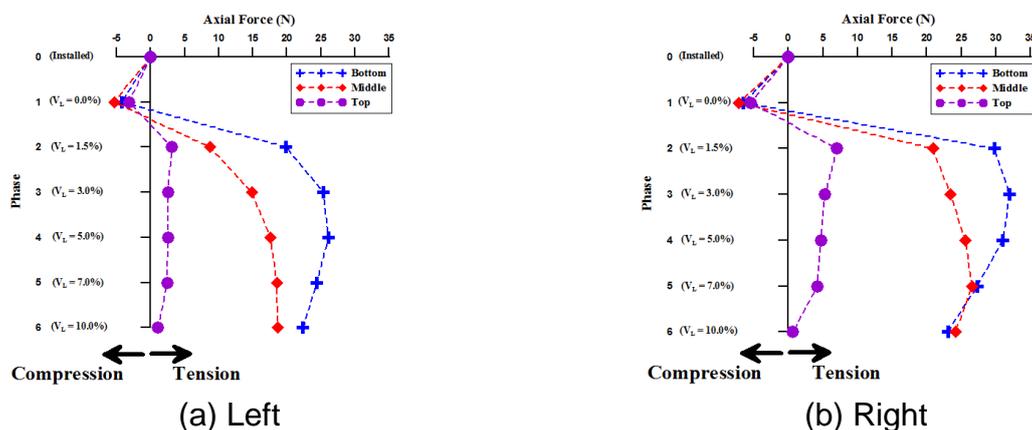


Fig. 9. Axial force distribution for 2x1 grouped pile case (FEM)

For 3x1 grouped pile case, the greater force(tension force) take place for both side piles. As shown in Fig. 7, 10, change of axial force due to the development of volume loss is constant from volume loss 3%.

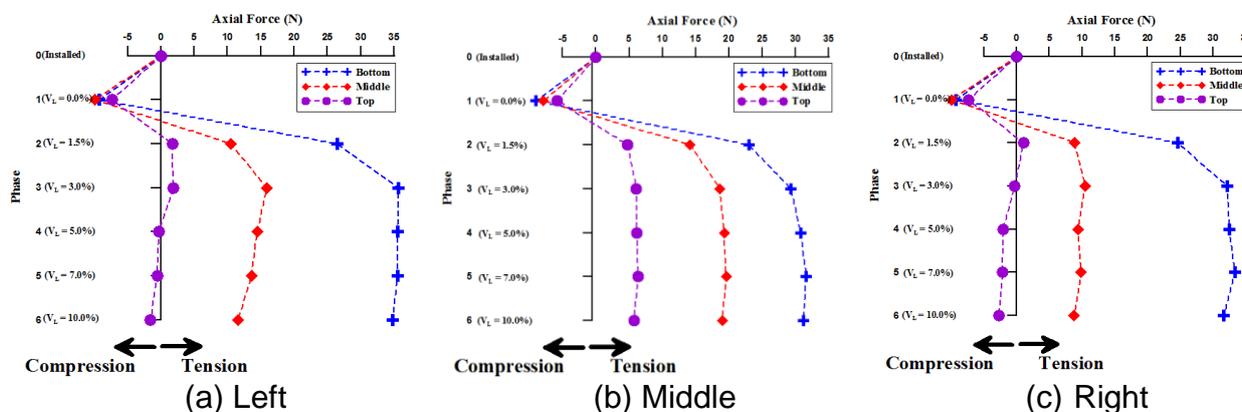
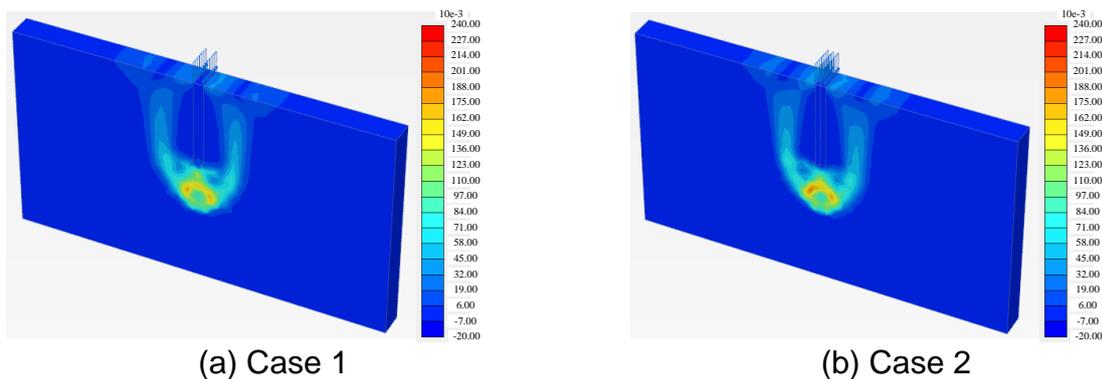
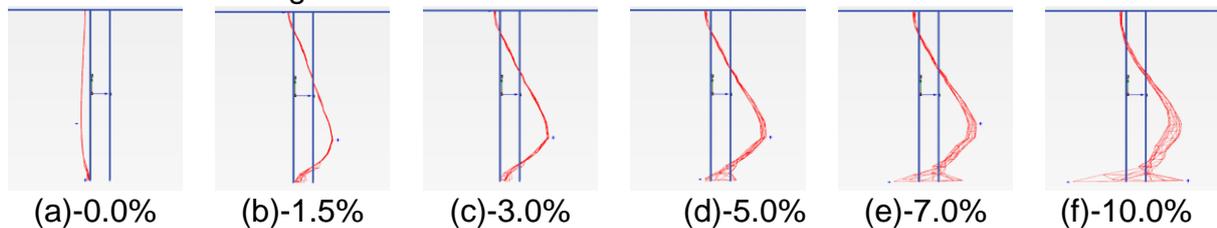


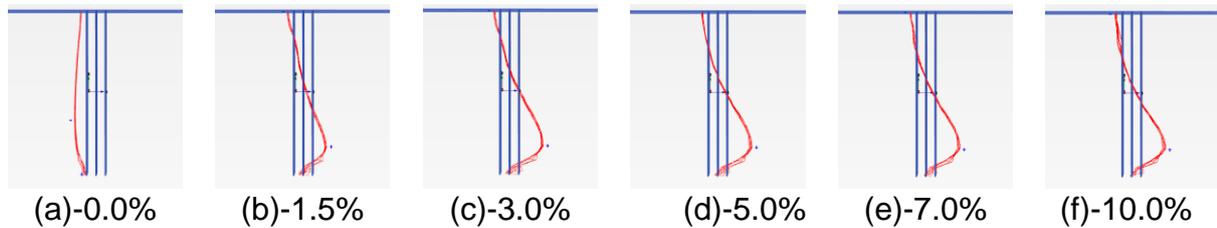
Fig. 10. Axial force distribution for 3x1 grouped pile case (FEM)



(a) Case 1 (b) Case 2  
 Fig. 11. Shear strain contour for volume loss 10%



(a)-0.0% (b)-1.5% (c)-3.0% (d)-5.0% (e)-7.0% (f)-10.0%  
 Fig. 12. Change of axial force due to development of volume loss (case 1)



(a)-0.0% (b)-1.5% (c)-3.0% (d)-5.0% (e)-7.0% (f)-10.0%  
 Fig. 13. Change of axial force due to development of volume loss (case 2)

The shear strain and axial force of each case are presented in Fig. 11~13, respectively. The left pile force distribution are only shown in Fig. 12, 13.

The depth of neutral point presented in this paper has a few difference with research of Devriendt and Williamson (2011) which is carried out to calculate analytically method and observe real pile displacement. Devriendt and Williamson (2011) presented a proposal regarding empirical methods which evaluate tunnelling-induced pile settlement on greenfield condition(2/3 depth approach and neutral axis approach). Presumably, the difference between aforementioned methods and result of this research attributes to the distinction of the ground condition and pile shaft roughness.

#### 4. CONCLUSIONS

Pile settlements are larger than ground surface ones for both cases, as mentioned previously chapter. It means that neutral point takes place by tunnelling which is represented volume loss. It is shown as aforementioned axial force distribution figures which are the result of the model test and numerical analysis.

The pile settlements with volume loss of 10% are approximately 6.5-times, 2.2-times greater than surface ones at point A for case 1,2, respectively.

For final tunnelling phase (volume loss of 10%), pile settlement and surface one at point A of case 2 are 60%, 300% larger than case 1.

A large number of pile occurs greater tunnelling-induced settlement under grouped pile.

For 3x1 grouped pile case, the magnitude of force at the pile of the corner is greater than centre one.

The authors have the additional plan to conduct a model test to define relation grouped pile behaviour not only the various offset between pile tip and tunnel crown (0.5D~2.5D) but also the 3D grouped pile model test which is able to take into account effect of influence and the various the number of grouped pile as well as pile embedded depth.

## **5. ACKNOWLEDGMENTS**

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