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To cite this article: M A Zahid *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **971** 012027

IOP Conf. Series: Earth and Environmental Science **971** (2022) 012027 doi:10.1088/1755-1315/971/1/012027

Tunnel Progression Effects to the Ground Surface and the Adjacent Pile

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Abstract. Tunnelling close to existing structure in urban area has become unavoidable. The progression tunneling activities induced ground movement and might affect the integrity of existing structure especially the one lies within the tunneling influence zone. It may cause catastrophic failures of structures and can cause losses of human lives. Therefore, considering its risk, this study focuses on the tunnel-soil-pile interaction by performing a physical model testing. By conducting a series of laboratory tests, the ground subsidence and pile behavior is presented herein. For a twice diameter distance of tunnel and pile, the pile axial settlement is 0.04% of the tunnel diameter respectively, while the maximum pile bending moment is 4928. 93kN.m. Maximum ground settlement is 0.56% respectively to tunnel diameter. To sum up, the axial displacement of pile decreases when the pile located further away from the tunneling zone. Similarly, the ground surface subsidence decreases when the pile location is more in distance during the tunneling advancement.

1. Introduction

Rapid development in the urban area led to a significant decrease of available construction land. Therefore, an alternate solution is to build either upwards or downwards. For that purpose, tunnel is one of construction method that has been used widely to overcome this problem. Tunnel excavation causes soil redistribution and settlement as a result of the ground movement, this leads to moment and movement in pile foundations. In details, tunnel excavation will induce stress relief on the soil surrounding the tunnel wall and face because the act of soil removal led to an unbalanced pressure in the soil particle. Consequently, the soil surrounding the tunnel wall and face will move inward into the tunnel cavity[1-3]. However, clay and sand have different failure mechanism

Introduced by Peck [4], analysis of the ground deformation induced by tunnelling via the empirical data suggest that the form of inverse Gaussian distribution curve as relatively the form of the settlement trough which can be seen in **Figure 1**. The Gaussian distribution curve allow the vertical settlement position at x distance from tunnel centre, S_v to be calculated based on equation (1) in which S_{max} is the maximum settlement at of the surface which likely to occur at the tunnel centre, and i_x is the horizontal distance between the tunnel centre and the point of inflection on the settlement trough.

$$S_v = S_{max} \cdot e^{\left(\frac{-x^2}{2{i_x}^2}\right)} \quad (1)$$

O'Reily [5] discovered the correlation between the parameter i and tunnel's depth and geological condition, as stated in equation (2).

$$i = Kz_0 \quad (2)$$

in which z_0 is the tunnel depth and K is the empirical constant.

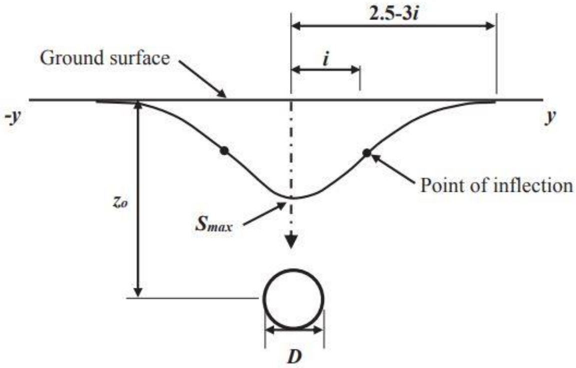

Figure 1. Settlement trough in Gaussian distribution curve after Khoo [20]

Engineers poses a major challenge in estimating the effect of tunnelling on existing pile foundation of buildings. It is particularly vital to estimate the tunnelling effects when new tunnels are to be built near an existing pile [6]. The presence of pile adjacent to the tunnel provide differ result on the ground surface settlement compared to greenfield condition. A study on tunnel-pile interaction conducted by Marshall and Haji [7] through an analytical approach, stated that the tunnelling activity affect the pile capacity due to the ground stress redistribution and displacement. Induce by tunnelling activity, pile is susceptible to reduction in end bearing capacity and shaft frictional resistance. A review of case studies from several researchers done by Dias and Bezuijen [8] conclude that the tunnelling activities have shown to cause low impact in term of damage toward the nearby existing pile. Nevertheless, it was noted due to lack of understanding in the mechanism of pile-tunnel interaction, these constructions confront a lot of uncertainty thus, future studies are needed. In addition, Jongpradist [9] reveals in his study that maximum deformation occur in influence zone. For each case, the zone of influence varies based on the tunnel depth and diameter. It is where more stress is released than its defined amount. A plenty number of previous researchers focus their studies on the existing adjacent pile to the tunnel rather than the pile above the tunnel [7][10-14]. In doing so, the affected structural integrity of a foundation has been the main interest due to increased lateral loading and bending moment from the pile induced by tunnelling [15].

It is common nowadays researcher studying geotechnical problem tend to apply centrifuge modelling technique [16]. An appealing alternative such as the physical modelling provide a better understanding upon the mechanism and reaction of complex problem relating soil structure interaction. On the contrary, due to the behaviour soil directly influence by soil stress, physical model test cannot extrapolate the result to a prototype scale. Nonetheless, this flaw can tackle by using centrifuge modelling technique. Furthermore, under the execution of a control environment, centrifuge model test can measure soil profile strength, deformation of soil, and break off time can be quantified with a reasonable preciseness in dependable test result. Therefore, this study aims to use physical modelling to estimate and analyse these effects. What make centrifuge model technique an appealing method is their ability to repeat the test with a consistency and not to mention their relatively economical.

2. Methodology

In this study, physical model development, model properties and the apparatus setup will be present for the testing. The model constructed will cover the tunnel at depth (C/D) equal to 3, with a distance 2.0D (diameter) from the tunnel centre.

2.1. Soil Model

Concerning the incorporation of sand as the soil material in this study, the basic and engineering properties of the soil that were relevant to the study was obtained and the sandy soil was a poor graded soil (SP). A controlled relative density sand was poured into the model box through a hopper that was put in position above the box until it reaches the level of necessary cover-to-diameter ratio (C/D). Variation of density was achieved by changing the flow velocity of the dry pluviator system [17]. The system itself comprise of sand hopper, shutter, fixing device, diffuser system and soil collector, whereby the hopper is manually moved within the range of the soil box area. Applying trial and error calculation to obtain the accurate distance between the sieve and the surface of the sand to incorporate a constant of 50% relative density.

2.2. Model Box, Tunnel, and Pile

In reference to the research done by Sohaei [18], the physical model was prepared. The model box shown in **Figure** with a dimension of 60 cm length x 60 cm width x 50 cm height will applied to act as a medium to replicate the underground condition for the tunnelling work. Previous researcher has also adopted similar concept in a ground loss prediction that also using box [19]. The size of the model was larged enough to minimize the influence of the rigid boundary on the measured stress. Several researchers such as Potts and Zdravkovic [20] and Tan *et al*.[21] recommend that the measurement of the model box should be at least four times of the tunnel diameter from tunnel circumference.

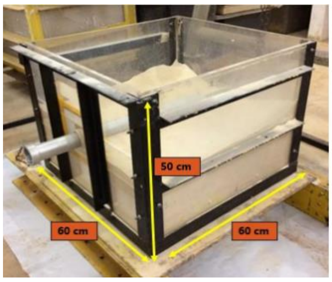

Figure 2. Model box used in physical modelling test

Taking into account the comparison of the actual condition and the physical laboratory condition, scaling factor are implemented to scale the physical model test. C/D ratio and tunnel diameter will be the main concern while the other parameter was decided accordingly. The simplified reduction scale and the tunnel and pile diameter was presented in **Table 1**. Note that, both tunnel and pile was fabricated with respective geometry. A casing method introduced by Meguid and Mattar [22], was used for tunnel model here in.

2.3. Tunnel Excavation Rate

Error! Reference source not found. depicts the revolution per minute (rpm) of similar test setup conducted by different researchers. The data in the table shows that variant motor speed is applied during the test to simulate the field excavation rate. The motor speed for this experiment is set to be higher than the previous researcher since the offset pile with two diameters of tunnel theoretically has less inducement by the tunnel excavation. Moreover Shehata *et al*.[23] in his study emphasize on the unavailability of a guideline for tunnel excavation rate in soft ground in adjacent to existing structure. Based on Table 2, Siti Ai'dah [24] have the lowest motor speed while Feras [25] and Sohaei [18] have similar motor speed.

Table 1. Reduction scale from the prototype to model.

Tunnel and Pile Parameters	Prototype (m)	Model (mm)
Tunnel Depth (C)	19.7	147
Tunnel Diameter (D)	6.57	49
Pile Length (Lp)	24.32	181.5
Pile Diameter (dp)	1.2	9
Pile Thickness	0.1	0.8

Table 2. Physical Model Motor rpm from previous researcher.

	Motor Speed (cm/sec)	Motor circumference(meter)	Rpm
Sohaei (35)	0.130	0.2316	0.337
A'idah (43)	0.097	0.2316	0.273
Feras (44)	0.137	0.2316	0.354
This study	0.194	0.2316	0.531

2.4. Testing configurations

The test for physical model system were run three times or/and more to achieve valid and verified data that is enough to be used in the data analysis. **Error! Reference source not found.** shows schematic diagram for 3D view of physical model test shows. In details, Figure 4(a) is the cross-sectional schematic diagram that illustrates the position of tunnel and pile set for the physical modelling testing while Figure 4(b) is the parallel-sectional schematic diagram. For data measurement purpose, LVDTs and strain gauge (SGs) was placed on respective locations here in. Upon the completion of the instrument set up, electric motor will pull out the barrel (tunnel shield) to stimulate the construction of the tunnel with an average speed of 0.13 cm/sec over 6 consecutive minutes that is being provided. The average speed applied is reference to the actual excavation rate at about 0.12 m/hr. The tunnelling construction will be progressively carried out until the shield is completely out of the box.

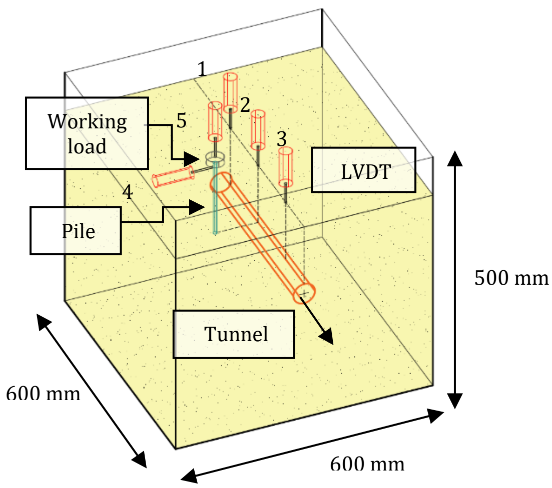

Figure 3. Schematic diagram for 3D view of physical model test.

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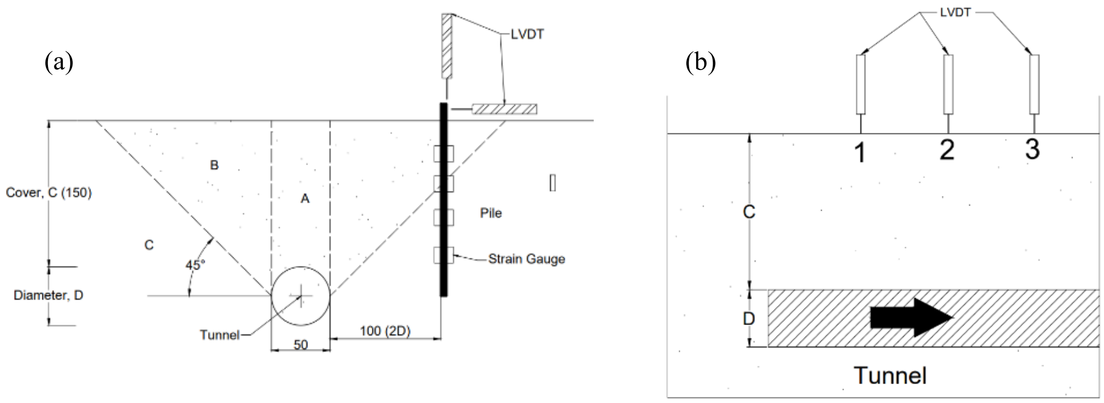

Figure 4. Schematic diagram for 2D view of physical model test (a) Cross sectional view that illustrate the test setup for pile movement and stress induce by pile from tunnel progression (b) Side view that illustrate the test setup for ground movement induced by tunnel progression.

3. Result and Discussion

The laboratory physical model test relies on other basic properties as a secondary data obtained from the previous researcher. The main focus of this study is to determine the inducement of tunnel progression on the existing pile. Therefore, it was anticipated from this study, there will be movement on the pile either vertically or laterally. The outcome from this physical modelling test will set to determine the relation of tunnel-soil and tunnel pile based on the set of data obtained. Figure 5 shows that the result presented afterwards based on tunnel influence zone by Selementas's influence line [26]. The results of this study will be compared to previous researcher which include ground surface and pile head movement, and axial force along the pile during tunnel excavation.

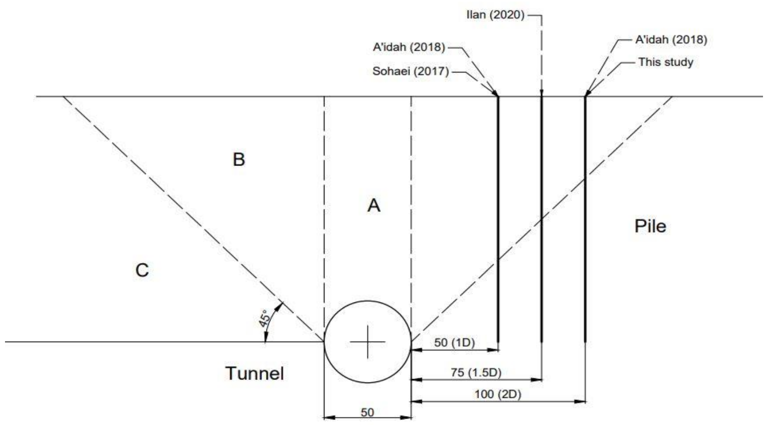

Figure 5. Previous research with variant pile distance from tunnel axis.

3.1. Ground Surface Settlement

The tunnel induced ground settlement presented here in.

3.1.1. Transverse Ground Surface Settlement

The transverse settlement troughs shown in Figure 6 were obtained through calculation using Peck's [4] formula as shown previously in equation (1) and selecting a value of 0.42 for the K in accordance to Sohaei's[18] work. **Figure** show the comparison between the transverse ground surface settlements against the transverse distance from tunnel centre. It is noticeable that the value of the maximum settlement can be seen increase as the advancement of the tunnel from the point 1(50mm) to point 3(300mm). However, there is a slight contradiction on the behaviour of the maximum settlement between point 2 and 3. Maximum settlement at point 2 can be observe to be slightly higher value than point 3. Uneven sand distribution and the rapid tunnel excavation through the simulation of the barrel pull out could cause a build up at the face pressure that would contribute a small build-up of sand on the surface at point 3. Therefore, surface at point 3 would have slight lesser settlement than point 2.

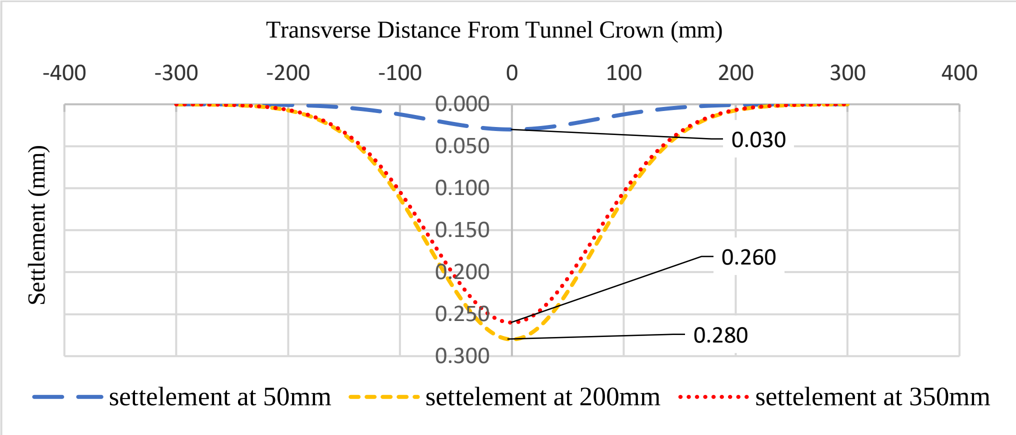

Figure 6. Comparison between transverse ground surface settlement troughs at 50mm,200mm and 350mm from tunnel face.

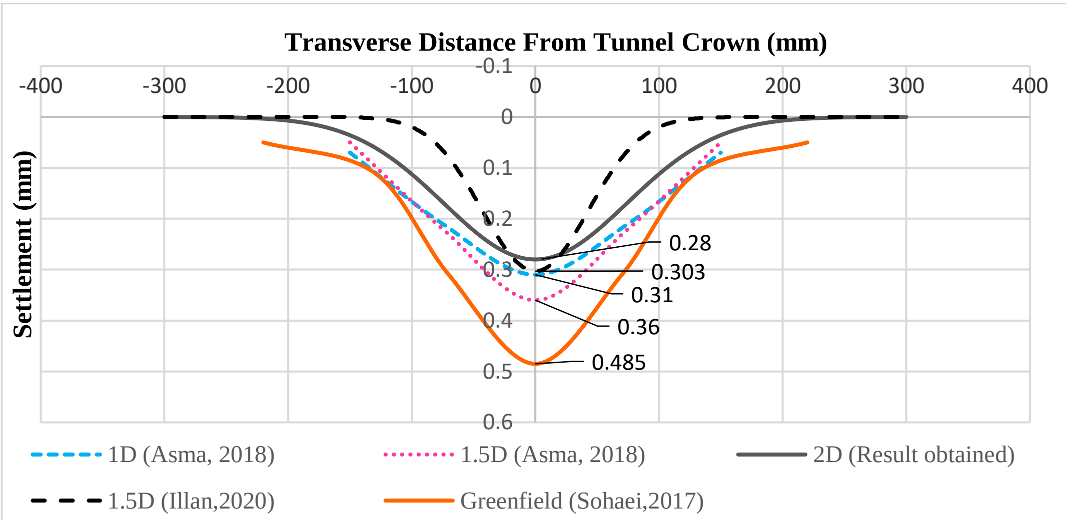

Figure 7. Comparison between transverse surface settlement troughs from previous research.

Based on **Figure** 7, the obtained result shown to have a wider trough width with a value of maximum settlement that is the lowest compare to the previous result. However, Ilan [27]'s 1.5D distance have narrower trough width while Siti A'idah's [24] 1D and 2D distance have similar wider trough width with the obtained result. Pinto and Whitttle [28] in their study revealed that the narrow settlement through measured for surface settlement of tunnels in sand was due to the influence of dilation of the free or partially draining soils. They also stated that an approximate analytical solution is well suited to describe this soil settlement behaviour. Base on Peck's equation, Kolivand [29] stated that only two parameter that influence the shape and magnitude of the trough that is the point of inflection and volume loss. However, since volume loss are similar with the previous researcher thus considered to be a constant variable, the difference of inflection point plays a major role in determining the magnitude of the settlement trough width in this result. To sum up, the trend from the previous result differs with the obtain maximum surface settlement trough, which shows pile with 2D distance from tunnel crown to have lower value than 1D and 1.5D distance. Prior discussion has stated on the excavation rate for this experiment to be higher than the excavation rate from the previous experiment. Therefore, higher excavation rate has produced a lower magnitude of maximum settlement and a wider through width of settlement profile.

3.1.2. Longitudinal Ground Surface Settlement

The longitudinal surface settlement result was obtained from three similar point from transverse settlement trough, located across the tunnel axis. Based on Hajjar's[30] calculation, the longitudinal settlement trough for each point is shown in 8, exhibit the comparison between longitudinal ground surface settlement trough and the longitudinal distance of tunnel face from each point.

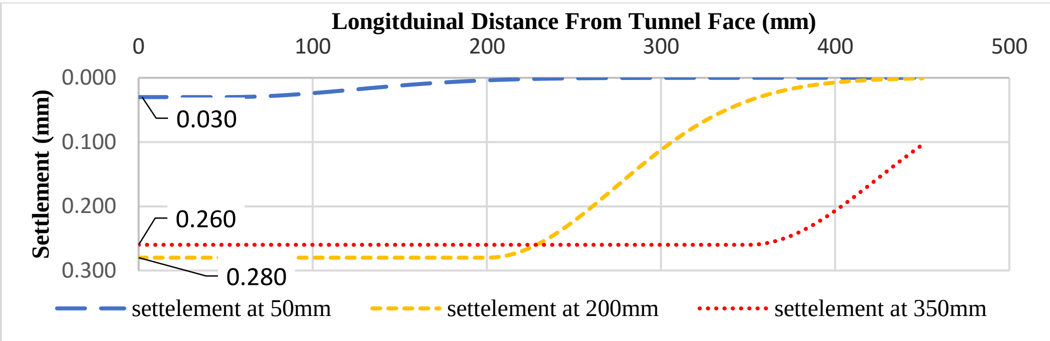

Figure 8. Comparison between longitudinal settlement trough at 50mm,200mm and 350mm from tunnel face.

As shown in Figure 8, the longitudinal settlement trough manages to showcase how the cumulative disturbance of tunnel excavation can increase the maximum settlement. Similar discussion in transverse settlement, the value of maximum settlement can be seen increase as the advancement of the tunnel from the point 1(50mm) to point 3(300mm) and there is a slight contradiction on the behaviour of the settlement between point 2 and 3.

The x-axis in **Figure** is the length of the tunnel whereby the positive direction of the x-axis is the direction of the tunnelling. It can be seen from the graph for the result obtained have a steady settlement until Y/D at 1.0 which can be seen progressively start to settle from Y/D at 2 until 5 in relatively linear trend. Meanwhile for distance pile at 1D,2D A'idah [24] and 1.5D Ilan [27], the settlement that occurred between Y/D at 1 and 2 shows a sudden increment then as it approach and after Y/D at 3 the settlement become steady. The existing pile provide reduction on the surface settlement. In can be notice that the maximum ground settlement in greenfield condition was 0.97%, whereas it gives 0.58% ground settlement in 1D. The increasing distance between a pile and a tunnel centre has less influence on the surface settlement as the pile withstand the soil movement while the tunnel excavates close to the existing pile [18][31]. However, the trend from the previous result differs with the obtain maximum surface settlement, which shows pile with 2D distance from tunnel crown to have lower value than 1D and 1.5D distance.

3.2. Pile Induced by Tunneling

Pile behavior induced by soil stress redistribution due to tunnel excavation is presented here in.

3.2.1. Pile Head Settlement

Figure 9 and Figure 10 shows the measured pile displacement (S_p/D) against normalized pile depth during the tunnel advancement. The obtained pile head settlement has a close magnitude and trend to

Ilan [27]. It can be observed in the Figure 11 that the settlement of the pile remained constant and only to occur minimal increment throughout the tunnelling progression as the settlement only gained 0.04% while 1.5D gained 0.02%. These findings indicate a good agreement with the recent studies of Ayasrah et al. [32] that have shown that an inducement of pile head settlement fades as the distance between the pile and the tunnel axis is twice the tunnel diameter. However, these behaviours are much differ from Sohaie's result which can be compared to 1D and 2D that experience an increment in their settlement gradually and began rapidly drop from -0.5D from the tunnel face.

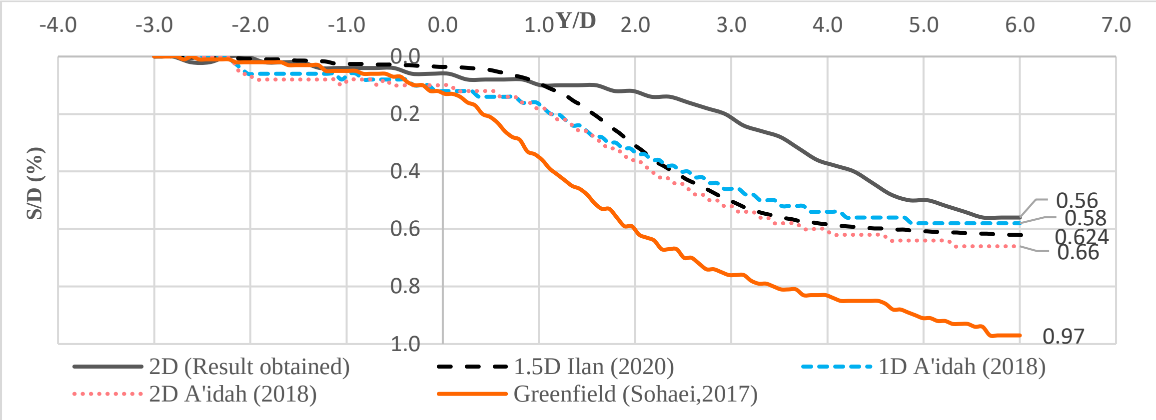

Figure 9. Comparison of longitudinal surface settlement in greenfield with a presence of pile.

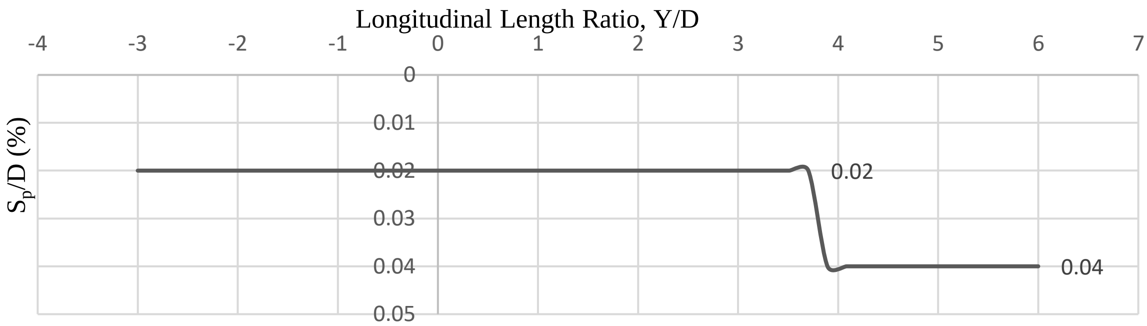

Figure 10. Pile head settlement with respect to different distance of tunnel progression.

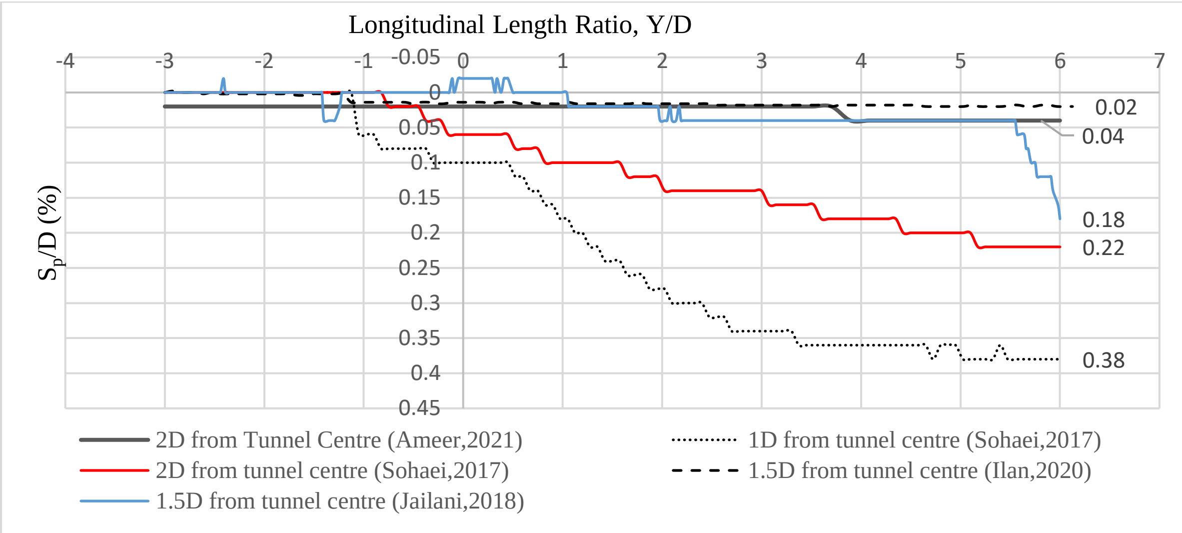

Figure 11. Comparison of pile head settlement with previous research.

3.2.2. Pile Axial Force

Figure 12 shows the plots of induced axial force against the normalized pile depth (Z/D) after tunnelling test. Mobilization of positive and negative skin friction attributed the axial force result which are induced between the movement of surrounding soil and pile during the adjacent tunnelling. Hun [33] stated that settlement by tunnelling generally caused negative skin friction on the pile shaft but the degree to such inducement depends on the distance between the pile on the tunnel. It can be observed in Figure 13 the pile with 1D distance have developed an axial compressive force as the magnitude increases to the tip of the pile as large portion of the pile are in Zone B. Meanwhile the pile with 2D distance developed a similar trend with the pile with 1D but developed an axial tensile force with a small portion of axial compressive force as small portion of the upper pile are placed in Zone B. Ayasrah [32] stated that the middle and the lower part of the pile have significant effect by the axial force during tunnel excavation. Thus, the findings are in good agreement with Jongpradist [9] and Selemetas [26] zone of influence.

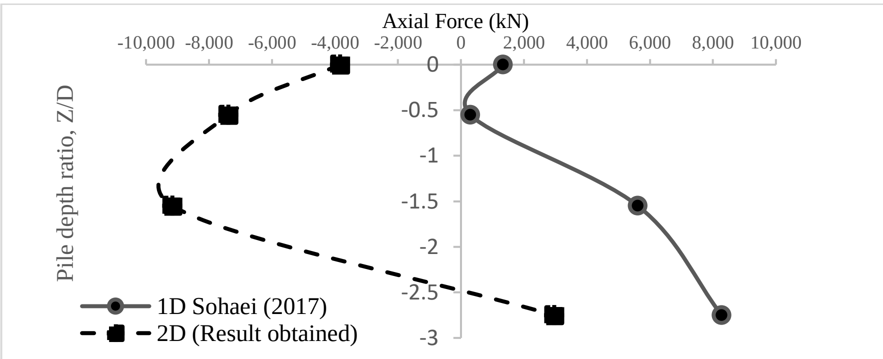

Figure 12. Comparison of axial force profile with respect to depth for pile from previous research.

4. Conclusion

The results obtained and the observation made in this study draw some conclusions. These are:

i. The tunnel progression significantly induced the surface settlement (transverse and longitudinal) but the impact is minimized as the excavation rate of the tunnel higher than the normal excavation rate.

ii. The pile exposes less in the influence zone as the horizontal distance of the pile between the tunnel axis approaches twice the tunnel diameter. Therefore less significant impact on the pile settlement as shown that the ground surface subsidence is lesser when the pile is further during tunnelling advancement

iii. Pile with 2D distance developed a similar trend of axis tensile force when compare with the pile with 1D distance but mainly developed axial tensile force with a small portion of axial compressive force near the pile toe.

5. References

[1] Chambon P, Corté JF 1994 Shallow tunnels in cohesionless soil: Stability of tunnel face *J Geotech Eng.* **7** 1148

[2] Mair R J, Williamson M G 2014 The influence of tunnelling and deep excavation on piled foundations. In: Geotechnical Aspects of Underground Construction in Soft Ground *Proceedings of the 8th Int Symposium on Geotechnical Aspects of Underground Construction in Soft Ground* 21-30

[3] Mair R and Taylor R 1999 Bored Tunnelling in the Urban Environments **53** 6–7

[4] Peck R B 1969Deep Excavations and Tunneling in Soft Ground *7th International Conference on Soil Mechanics and Foundation Engineering* **2** 25–90

[5] O'Reilly M P, New B M 1982 Settlements above tunnels in the United Kingdom - their magnitude and prediction *Tunn '82 Pap Present 3rd Int Symp* **1** 73–81

[6] Ng C W W, Boonyarak T and Mašín D 2013 Three-dimensional centrifuge and numerical modeling of the interaction between perpendicularly crossing tunnels *Can Geotech J* **50** 35-46

[7] Marshall A M and Haji T 2015An analytical study of tunnel-pile interaction. Tunn Undergr Sp Technol. **45** 43–51

[8] Dias T G S and Bezuijen A 2014 Pile Tunnel Interaction: Literature review and data analysis. ITA World Tunn Congr 2014 - Tunnels a better life

[9] Jongpradist P, Kaewsri T, Sawatparnich A, Suwansawat S, Youwai S and Kongkitkul W 2013 Development of tunneling influence zones for adjacent pile foundations by numerical analyses *Tunn Undergr Sp Technol* **34** 96-109

[10] Basile F 2012 Pile-group response due to tunnelling *Geotech Asp Undergr Constr Soft Gr Proc 7th Int Symp Geotech Asp Undergr Constr Soft Gr.* **7** 81–90

[11] Huang M, Zhang C and Li Z 2009 A simplified analysis method for the influence of tunneling on grouped piles *Tunn Undergr Sp Technol* **24**

[12] Kitiyodom P, Matsumoto T and Kawaguchi K 2005 A simplified analysis method for piled raft foundations subjected to ground movements induced by tunnelling *Int J Numer Anal Methods Geomech.* **507** 25-29

[13] Loganathan N, Poulos H G and Xu K J 2001 Ground and pile-group responses due to tunnelling. *Soils Found.* **41** 57–67

[14] Zhang R-J, Zheng J, Zhang L and Pu H 2011 An analysis method for the influence of tunneling on adjacent loaded pile groups with rigid elevated caps *Int J Numer Anal Methods Geomech.* **71**

[15] Williamson M G, Elshafie M Z E B Mair R J Devriendt M D 2017 Open-face tunnelling effects on non-displacement piles in clay - part 1: Centrifuge modelling techniques *Geotechnique* **67** 983-1000

[16] Ng C W, Leung C F, Yong K Y and Chow Y K 2007 Performance of pile due to tunneling-induced soil movements **1** 619-624

[17] Madabushi S P G, Houghton N E and Zhang L M 2006 A new automatic sand pourer for model preparation at University of Cambridge *London, Taylor: Francis* pp 6

[18] Sohaei H 2017 *Contolling Tunnel Induced Ground Surface and Pile Movements Using Micropiles* Universiti Teknologi Malaysia **1**

[19] Juneja A and Dutta S 2008 Ground loss due to circular tunnel deformation in sands *12th Int Conf Comput Methods Adv Geomech* **5**

[20] David M P and Lidija Z 1999 Finite Element Analysis in Geotechnical Engineering: Volume One Theory *Finite Element Analysis in Geotechnical Engineering: Volume One – Theory* Thomas Telford Ltd
[21] Tan T S, Setiaji R R. and Hight D W 2005 Numerical analyses using commercial software– A black box 250-258
[22] Meguid M A and Mattar J 2009Investigation of Tunnel-Soil-Pile Interaction in Cohesive Soils *J Geotech Geoenvironmental Eng.* **135**
[23] Shehata A S, El-Kelesh A M, El-kasaby A-S E and Mansour M 2018 Rates of Soft Ground Tunneling in Vicinity of Existing Structures *Int J Adv Eng Manag Sci.* **4** 35-45
[24] Siti Ai'dah M A, Aminaton M, Siti Norafida J and Sohaie H 2018 Effect of Tunnel Construction On Existing Pile In Sand **1** 1-5
[25] Feras Mousa M A 2019 *The Effects of Tunneling on Single Piles* Universiti Teknologi Malaysia;
[26] Selemetas D 2005 *The response of full-scale piles and piled structures to tunnelling* PhD Thesis, Cambridge Univ.
[27] Polanippan I 2020 Tunnel-Pile-Soil Interaction **13** 1-15
[28] Pinto F and Whitttle A 2014 Ground Movements due to Shallow Tunnels in Soft Ground. *Analytical Solutions. J Geotech Geoenvironmental Eng*. **1**
[29] Kolivand F and Rahmannejad R 2018 Determination of settlement trough width and optimization of soil behavior parameters based on the design of experiment method (DOE) *Int J Min Geo-Engineering* **52** 7–15
[30] Hajjar M, Hayati A N, Ahmadi M M and Sadrnejad S A 2015 Longitudinal settlement profile in shallow tunnels in drained conditions *Int J Geomech.* **15**
[31] Khoo C M, Idris N I S I, Mohamad H and Rashid A S A 2018 Numerical Evaluation of Settlement trough Width Parameter *MATEC Web Conf.* 203 1-9
[32] Ayasrah M, Qiu H, Zhang X 2021 Influence of cairo metro tunnel excavation on pile deep foundation of the adjacent underground structures: Numerical study *Symmetry (Basel)* **13**
[33] Hun G K, Authority L T 2016 Case Histories of Bored Tunnelling Below Buildings in Singapore Downtown Line **3** 49–61

Acknowledgments
The authors would like to acknowledge the support of the Universiti Teknologi Malaysia and the Ministry of Higher Education Malaysia through the awarded Q.J130000.2651.17J59 UTM ER grant and Collaborative Research Grant (CRG) vote number R. J130000. 7351. 48509.