Physical model on effects of tunnelling towards single piles under zoned of influence

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Abstract. Tunnel excavation usually will causes soil redistribution and settlement. Hence, for urban areas where large building used pile for foundation, tunnelling might affect the pile integrity. Engineers pose great role in order to correctly estimating the stress changes onto pile structures. It is particularly vital to estimate the tunnelling effects when new tunnels are to be built near an existing pile. Therefore, this paper presents a physical modelling to investigate the tunnel-pile-soil interaction. Sand box test with pile and tunnel model was developed to imitate the field condition. The laboratory testing conducted with constant parameter tunnel cover to tunnel diameter ratio of 2.5 with pile to tunnel distance of 1.5 of tunnel diameter. Two rate of tunnel excavation were carried out. Laboratory tests determined the longitudinal and transverse ground surface settlement induced by tunnelling, as well as the movement and induced bending moment on a single pile foundation. For validation, initial results were compared with previous findings and shows an agreement. Further test then conducted with higher tunnelling speed. With higher speed, it was found that surface settlements, pile movements and bending moment are more affected.

1. Introduction

Rapid development in the urban area lead to a significant decrease of available construction land. Therefore, an alternate solution is either to build upwards or downwards. Building upwards is possible and it has been used up to a certain limit; as a result, the size of foundations increases to stabilize those buildings. Despite that, the critical issue in tunnelling such as the effect of tunnelling to the integrity of existing pile foundations is still questionable [1]. Tunnel excavation causes soil redistribution and settlement which could lead to failure or collapse of structures as a results of stress changes on their foundations. Therefore, 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 [2].

Figure 1 demonstrates the settlement due to tunnelling, as the tunnel advance in longitudinal direction, the ground surface soil will settle in longitudinal direction where soil reaches maximum settlement in excavated part of the tunnel, and settlement decreases forward until a point where tunnel does not affect, transverse settlement is also induced due to tunnelling causing maximum settlement.
above the tunnel crown and it decreases the further the distance forming a Gaussian distribution curve. In greenfield conditions, the influence of tunnel in transverse direction is reduced the higher the distance from tunnel. According to Selemetas et al. [3] the influence can be categorized into three zones. Zone A is directly above the tunnel, this zone is influenced highly by tunnelling causing maximum settlement and high chances of failure. Zone B is the area surrounding the tunnel up until 45° angle from tunnel parameter and this zone is moderately influenced by the tunnel. The last zone is Zone C which the furthest from tunnel and as such the tunnel influence is weak. Figure 2 shows the different influence zones around the tunnel.

![Figure 1. Tunnel induced longitudinal and transverse settlement [4].](image1)

![Figure 2. Zone of influence under greenfield condition [3].](image2)

Previously, investigation on tunnel-pile-soil interaction had been conducted in various method. Numerical modelling of problem once carried out by Mroueh and Shahrour [5] and with centrifuge model by Lee and Jacobsz [6]. Both research proved that tunnelling causes nearby pile settlement and additional axial load on bending moment induced on pile with the magnitude being relative to both tunnel and piles location. However, due to the nature, difficulty and limitation of tunnelling work, research on field test is generally limited and not feasible. In opposite, physical modelling allows for a prototype (small scale tunnelling field) under certain boundary conditions to imitate the site condition [7]. Therefore, this study aims to use physical modelling to estimate and analyse these effects. In specific, this paper will cover a development of physical modelling to: i) determine the ground movement induced by tunnelling, ii) determine the behaviour of pile due to tunnel construction (i.e., axial and lateral deformation and bending moment of pile) and iii) investigate the effects of tunnel excavation rate in physical testing.

2. Physical modelling development
The physical model was fabricated to simulate the effects of tunnelling on single pile in different positions relative to tunnel influence zone with constant tunnel depth. Figure 3 presents the model which consist of soil box with tunnel and pile model, electric motor, data logger, LVDTs, and its computer for physical modelling test. Location of tunnel from soil surface is referred as Cover to Diameter ratio (C/D) is taken as 2.5 in this test. The physical model test was carried out under single gravity conditions by filled up the sand sample in perplex box with the dimensions of 60x60x50 cm for length, width and height, respectively. The soil type used is Uniform Sand with relative density maintained at 50%. The tunnel model was fabricated based on Tunnel Boring Machine technique which is represented by an outer 50 mm diameter that is act as shield covering an inner 48.8 mm diameter tube that represents the tunnel. The different sizes of tunnel is designed such that the volume loss is estimated to be 5%. The pile model is aluminum tube has 9 mm diameter and 217 mm length is placed at distance of 1.5D. All equipment was setup prior to the testing.

The construction of tunnel is done by pulling the outer tube casing (i.e. shield) around the inner tunnel model. The outer tunnel shield was pulled by using pulley machine with two different average
speeds, i) first designated speed is 0.354 RPM translating to 8.2 cm/min (Test 1 & 2), this speed is scaled down from actual TBM excavation rate of 0.12 m/hr and ii) second designated speed is 2 RPM translating to 42 cm/min, this speed is try and error speed to see the results comparison and choose as the sudden drop of soil settlement is not obviously seen (Test 3). Three LVDTs used to measure the settlement was placed at distance of 5, 20 and 35 cm, respectively from tunnel beginning. In addition, strain gauges also mounted onto pile body at both sides at 3 different depths. In details, Figure 4 explain the cross-sectional that illustrates the position of tunnel and pile set for the physical modelling testing. Figure 5 is the parallel-sectional schematic diagram.

3. Results and Discussion
Results were presented based on tunnel induced ground movement and pile behavior.

3.1. Transverse surface settlement trough
In order to conform the accuracy of the laboratory testing that had been carried out in this study, the transverse surface settlement obtained from second LVDT (20 cm from tunnel face) was compared to the transverse surface settlement data reported by previous study. The results obtained from this study was compared with Asma’on [8] that obtained $S_{\text{max}}$ equal to 0.36 mm and Radzi [9] with 0.48 mm. For validation, transverse settlement obtained in this study is 0.48 mm and 0.5 mm and shows an agreeable pattern to previous study (figure 6).

3.2. Longitudinal surface settlement trough
After confirming the validation of initial testing, the laboratory is proceeded. In longitudinal surface settlement (figure 7), Test 1 and 2 depict similar values at all three measured points (from LVDT 1, 2
and 3). However, the third test (Test 3) show a massive increase in settlement especially for initial excavation part. After tunnelling for a certain period, the disturbance is lessened at the second point with moderate increase only, and results at last point are similar to previous testing. The results obtained is agreeable with hypothesis by Hajjar et al. [10]. Test 3 shows that the high-speed effect is the highest at the beginning of tunnelling due to high static friction thus resulting significant increase in settlement when tunnelling resumes. An increase is caused by the high speed initial and secondary shock during tunnelling.

3.3. Pile movement
Tunnelling causes displacement of particle around the designed tunnel area, causing additional soil movement and settlement, thus when pile is located in tunnel zone of influence, sand moves around it and tunnelling vibration will cause the pile to move horizontally and vertically. This movement depends on pile location in in influence zone, the distance of pile from tunnel, its position in the influence zone, and if it crosses failure angle, affects the displacement. Pile distance of 1.5D in this study is in Zone B, between tunnel edge and angle of $45^\circ + \phi/2$. Figure 8 and figure 9 present pile movement in three different test conducted.

As shown in figure 8, the Tests 1 and Test 2 was performed at low speed of tunnel excavation rate. Thus, the pile movement (vertically and laterally) is similar as the tunnel pile is in influence zone B. This pile movement has a linear relationship with time, meaning that the movement happens periodically on constant time intervals. However, Test 3 shows large irregularity as the settlement behaviour isn’t linear and acts unpredictably as high-speed cause’s relatively large movement in sand. A visible jump in settlement also can be seen. This result is caused by the shock due to tunnel casing, getting a sudden pull during the operation causing high disturbance when it starts moving again. Next, pile lateral movement reported depicts similar in findings as vertical one (Figure 9). As for Test 3, lateral movement it has more constant increase with time compared to settlement, but after the tunnelling shock and movement suddenly increase, then pile stops moving.

3.4. Pile’s Bending Moment
Results of bending moment was obtained from strain gauges that are mounted on pile at different location (i.e., 12, 67 and 108 mm below ground surface). From the strain gauge readings, the bending moments were calculated.

Figure 10 presents the results of bending moment induced by tunnelling. The bending moment in Test 1 shows a systematic shape, however, the values are much larger than obtained in Test 2. Test 2 magnitude is shown in agreement with findings reported by Radzi [9] with slightly change in shape. This change in data could relate to the pile positioning as it is placed with sensor perpendicular to tunnel axis but with sample preparation it can move and cause reading in different angle. In Test 3, one can see the large disturbance on pile caused bending moment to reach much larger value. While value at first sensor is large and similar to test one, the second sensor value is unexpectedly low, and instead of counting to zero it increases again, the irregular shape of bending moment could be credited to tunnel casing being stuck, and large bending moment values are credited to high tunnel speed.

4. Conclusions
The effect of tunnelling on pile foundations in close proximity and on the surface settlement induced by tunnelling from physical laboratory testing has been drawn in this paper. In general, the pile foundation is affected by its distance from the tunnel, the depth of tunnel and the tunnelling speed. In details, i) general pattern of transverse surface settlement reported here in is agreeable with the Gaussian distribution curve of settlement that proposed by Peck [11]. However, curve from this study depicted is sharper in bell shape as the i value is corrected to consider hogging and sagging condition, ii) with different speed of tunnel excavation, longitudinal surface settlement induced is highly affected at initial part of tunnelling, once soil reach its equilibrium, the final settlement show similar pattern with others, iii) for excavation rate that imitate the rate of real TBM speed (with steady rate), it depicts much lower pile movement for both vertical and lateral and vice versa for the higher speed behaviour and iv) bending moment in each test showed different pile behaviour in both magnitude and shape.
The changes of speed from 0.354RPM to 2RPM had caused a sharp increase in bending moment at all points of pile, as well as a behaviour change.

**Figure 6.** Validation of test: Surface transverse settlement (LVDT of 20 mm).

**Figure 7.** Longitudinal Surface Settlement measured at three different locations.

**Figure 8.** Pile Vertical Movement (Settlement).

**Figure 9.** Pile Lateral Movement.
Figure 10. Pile’s Bending Moment.

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