CONTROLLING TUNNEL INDUCED GROUND SURFACE AND PILE MOVEMENTS USING MICROPILES

HOUMAN SOHAEI

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I dedicated this thesis to my beloved father and mother for their support and encouragement

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ABSTRACT

Tunnelling in densely populated areas is generally associated with undesirable ground movement and subsequent damage to adjacent buildings. Hence, the main concern of designers are to accurately predict ground movements and propose mitigation measures in severe cases. Nowadays, different techniques are used as a mitigation measure to reduce the impact of tunnel construction on ground settlement. Nevertheless, implementation of some of these methods is a source of unpredictable damage or undesirable effects such as the effect of installing micropiles between existing pile building foundation and tunnel which have yet to be understood. Hence, this research aims to establish a micropiles method as a mean to minimise ground surface settlement, and the settlement and lateral movement of the existing pile due to tunnelling through cohesionless soils. The study was carried out by means of laboratory physical model tests and numerical simulation using ABAQUS software. Three different relative densities of sand; 30%, 50%, and 75% were investigated while the overburden (cover to diameter) ratios used were 1, 2, and 3. A row of 3.7 mm diameter micropiles, d_{mp} with two different lengths (11 cm and 14.5 cm) was embedded in between the tunnel (5 cm diameter, D) and the existing pile at four different locations. In model tests, settlement, bending moment and axial force of the existing pile were monitored accordingly. Generally, the results showed that increasing the value of relative density of sand reduces the ground movements. However, shallow tunnelling in loose sand produces remarkable movement on the ground surface. With the usage of micropiles, the ground surface settlement was reduced to nearly 40%. The micropiles also reduced over 85% and 75% of the piles lateral and axial movements respectively. A good compatibility was found between the experimental and numerical approaches which illustrates that the presented numerical simulation is a reliable model to predict tunnel-pile-soil and tunnel-pile-soil-micropiles interactions. Within the limitation of the study, it is recommended that the most suitable length and location of micropiles to use is 14.5 cm or about 40dmp (closest to the tunnel crown) and located at 0.5D (in the middle between tunnel and pile), based on the reduction observed on the vertical and lateral movements of pile as well as the bending moment and axial force.

ABSTRAK

Penerowongan di kawasan penduduk yang padat secara umumnya dikaitkan dengan pergerakan tanah yang tidak diinginkan dan kerosakan bangunan berdekatan. Oleh itu, kebimbangan utama perekabentuk adalah untuk meramal pergerakan tanah yang tepat dan mengusulkan langkah-langkah mitigasi pada kes yang teruk. Pada masa ini teknik yang berbeza digunakan sebagai langkah mitigasi untuk mengurangkan kesan pembinaan terowong pada enapan tanah. Walau bagaimanapun, pelaksanaan beberapa kaedah ini adalah punca kerosakan yang tidak dapat diramalkan atau kesan yang tidak diingini seperti kesan memasang cerucuk mikro antara asas cerucuk bangunan sedia ada dan terowong yang masih belum difahami. Oleh itu, kajian ini bertujuan untuk mewujudkan kaedah cerucuk mikro sebagai kaedah meminimumkan enapan permukaan tanah dan enapan serta pergerakan sisi cerucuk sedia ada akibat pembinaan terowong melalui tanah tak jeleket. Kajian ini dilakukan melalui ujian model fizikal makmal dan simulasi numerikal menggunakan perisian ABAQUS. Tiga kepadatan relatif pasir; 30%, 50%, dan 75% telah dikaji sementara nisbah tanah atas (penutup dan diameter) yang digunakan adalah 1, 2, dan 3. Sederet cerucuk mikro berdiameter, d_{mp}, 3.7 mm dengan dua kepanjangan yang berbeza (11 cm dan 14.5 cm) telah dipasang antara terowong (diameter, D = 5 cm) dan cerucuk sedia ada di empat lokasi berbeza. Dalam ujian model, enapan, momen lentur dan daya paksi cerucuk sedia ada telah dipantau dengan sewajarnya. Secara umumnya hasil kajian menunjukkan bahwa peningkatan nilai kepadatan relatif pasir mengurangkan pergerakan tanah. Namun, penerowongan cetek dalam pasir longgar menghasilkan pergerakan yang luar biasa di permukaan tanah. Dengan penggunaan cerucuk mikro, enapan permukaan tanah dikurangkan kepada hampir 40%. Cerucuk mikro juga berkurangan masing-masing lebih dari 85% dan 75% dari pergerakan sisi dan enapan cerucuk. Keserasian yang baik telah ditunjukkan antara pendekatan eksperimental dan numerikal yang menggambarkan bahawa simulasi numerikal yang dibuat oleh model tersebut dapat digunakan bagi meramal interaksi terowong-cerucuk-tanah dan terowong-cerucuk-tanah-cerucuk mikro. Dalam keterbatasan kajian, disyorkan bahawa panjang dan lokasi paling sesuai bagi cerucuk mikro adalah 14.5 cm atau lebih kurang $40d_{mp}$ (paling dekat dengan atas terowong) dan terletak 0.5D (tengah-tengah di antara terowong dan cerucuk) iaitu berdasarkan pengurangan pada pergerakan tegak dan sisi cerucuk selain dari momen lentur dan daya paksi.

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LIST OF ABBREVIATIONS

NATM - New Austrian Tunneling Method
UTM - Universiti Teknologi Malaysia
TBM - Tunnel Boring Machine
EPB - Earth Pressure Balance
MC - Mohr-Coulomb
FE - Finite Element
P-T - Pile tunnel
P-T-M - Pile tunnel micropiles
PLM - Pile lateral movement

LIST OF SYMBOLS

C - Cover of tunnel
c - Cohesion
D - Tunnel Diameter
E - Young’s modulus
d_p - Pile diameter
d_{mp} - Micropile diameter
H - Tunnel depth to the axis level
i - Horizontal distance from tunnel centre line to inflection point
i_x - Initial position of the tunnel
k - Empirical constant
l_p - Pile lateral movement
L_p - Pile length
L_{mp} - Length of micropile
L_{exc} - Excavation length
m - Auxiliary elastic constant
R - Tunnel radius
S - Ground surface settlement
S_p - Pile settlement
S_v - Vertical settlement
$S_{v,max}$ - Maximum surface settlement
S_c - Vertical settlement at the tunnel crown
S_h - Horizontal ground movement
V_L - Ground loss
V_S - volume of any surface trough
V_d - volume lost due to dilation
z_0 - Tunnel depth
X_M - Distance from tunnel axis

X - Distance from tunnel centre
x - Distance from the tunnel centre line
Z - Pile depth
x_f - Location of the tunnel face
ε_h - Horizontal strain
ε - Uniform radial ground loss
δ - Long term ground deformation
v - Poisson’s ratio
G_p - Physical gap
δ_l - Clearance required for erection of the lining
u_{3D}^{*} - Three dimensional elasto-plastic deformation
ω - Quality of workmanship
u_z - Vertical displacements
ρ - Ovalization
α - Coefficient in elastic region
μ - Elastic constant of shear modulus
$\varphi(z)$ - Complex variable
$\psi(z)$ - Complex variable
$\varphi'(z)$ - Notation
γ - Unit weight
γ_b - Buoyant soil unit weight
γ_w - water unit weight
k_0 - Coefficient of earth pressure at rest
ϕ_p - Peak internal friction angle
ϕ_c - Critical internal friction angle
β - Angular distortion
ψ - Dilation angle

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Over the past few decades, the world has been gradually experienced elevation of the urban population. In some countries, speed of the population growth is the most difficult challenge. It is reported that this growth of population in urban areas resulted with the high demand of infrastructures. Demand for the construction of underground infrastructures has increased considerably as a consequence of the growth of urban cities. Tunnels are an inseparable component of underground infrastructures, which have been considered during the last decades. Tunnels as subsurface structures have become ultimate alternative for overcoming the ground surface congestion. Although, tunnels have effectively addressed the ground surface congestion, still a number of challenges and problems occurred when especially tunnelling under urban environment.

The environmental impacts of the tunnel construction have been known as an essential consideration in tunnel design at the urban cities. Tunnelling through densely populated areas is usually associated with undesirable ground movement and damage to adjacent buildings. Consequently, it is essential to investigate the mechanism of the soil movements around the tunnel as well as ground surface and surface structures. An important critical issue in urban tunnelling is the control of ground movement induced by tunnelling in order to protect the surface and subsurface structures and utilities. In this regard, assessment of the potential effects on structures is a necessary aspect of the design and construction of a tunnel in an urban area. Hence the prediction of the tunnelling-induced ground movements is necessary. Predictions of tunnelling-induced ground movements were first described by Peck (1969) as radial displacements towards the transverse and longitudinal displacements along the cross section of the tunnel. These two sets of movements have been difficult to define and separate, therefore displacements are usually simplified to a plane strain scenario (Franzius *et al.*, 2005).

In urban environments, tunnels are often constructed close to or just below the existing pile foundations of buildings at the ground surface (Lee *et al.*, 1994, Coutts and Wang, 2000, Tham and Deutscher, 2000). The response of a building is governed by the effects of the tunnel excavation on the soil, interaction between soil and piles, and interaction between the piles and the building (Selemetas *et al.*, 2005). The unloading effect of the tunnel excavation leads to displacements of the soil, demolition of the nature of the interface between soil and pile, and therefore soil movements around the piles, causing changes in the vertical and horizontal ground stresses on the piles.

With the increasing the quantity of tunnels in the populated areas, several methods have been developed to provide a comprehensive understanding of the various problems deal with tunnel construction. Empirical, analytical, numerical and artificial intelligence approaches besides the physical modelling techniques have been widely used in analysing the effects of tunnelling on the ground movements and existing surface and subsurface structures. Some general aspects of the surface structural behaviour, in particular pile, are affected by the construction of a tunnel have been studied by previous researchers using different methods such as case studies and full-scale field trials (*e.g.* Jacobsz *et al.*, 2005; Selemetas *et al.*, 2005; Kaalberg *et al.*, 2005), analytical solutions (*e.g.* Marshall, 2012, 2013; Marshall and Haji, 2015), numerical analyses (*e.g.* Lee and Ng., 2005; Bioltta *et al.*, 2006; Yao *et al.*, 2009; Zidan and Ramadan, 2015), physical modelling (*e.g.* Lee and Chiang, 2007; Meguid and Mattar, 2009; Ng *et al.*, 2013; Sun and Liu, 2014). However, among these methods the laboratory physical model is usually preferred as it is able to provide comprehensive results based on its repeatability. Most of previous studies identified the zones of different pile behaviours, depending on the zone in which the pile toe is located relative to the tunnel position, both in shallow and deep tunnelling work.

A number of laboratory physical model tests have been conducted under single or multiple gravities to investigate the different tunnelling aspects. The physical modelling such as trap door, pressurized air, soil augering, casing and other techniques of tunnels provide the ability to investigate the most significant factors influencing the tunnel behaviour (Meguid *et al*., 2008). These techniques have been used to investigate different aspects of tunnelling such as arching effect and tunnel stability (*e.g.* Lee *et al*., 2006; Berthoz, 2012), ground movements and collapse mechanism due to tunnelling (*e.g.* He *et al*., 2012; Sun and Liu, 2014), interaction of the ground with the existing structures (e.g. Ng *et al*., 2013; Meguid and Mattar, 2009; Lee and Chiang, 2007), and tunnel face stability (*e.g.* Berthoz *et al*., 2012; Wong *et al*., 2012).

Various studies had been carried out to improve the soil such as the usage of jet-grouting, forepoling, diaphragm wall and piles in order to minimize the surface settlement due to tunnelling. Bilotta *et al*. (2006) and Bilotta (2008) performed numerical plane strain analyses and centrifuge tests to investigate the effects of a diaphragm wall embedded between a shallow tunnel and an existing pile. A parametric study was performed to optimize the location and length of the diaphragm wall in controlling the ground displacement beneath the building. Bilotta *et al*. (2006) also conducted a series of centrifuge tests to investigate the effect of a line of piles and their spacing in controlling the ground displacement induced by tunnel excavation. They concluded that the use of more piles with shorter distances results in a more effective reduction of ground movements. In general, micropiles are used to increase the bearing capacity and reduce the settlement of weak or loose soils (Juran *et al.,* 1999 and Bruc 2002). However, the technique of using micropiles is still not well published and understood.

1.2 Problem Statement

Numerous attempts have been conducted to investigate ground deformation mechanism induced by tunnelling, particularly the shallow tunnelling in urban settings. It includes the investigation of pile and tunnel interaction based on ground surface settlement, tilting and lateral movement of pile foundation, and load transfer mechanism. Some methods of soil improvements, such as jet grouting and forepoling to stabilise the soil were used besides using the NATM tunnelling method, to minimize the surface settlement. Although these methods could reduce the surface settlement but there are reports on the occurrence of structural damages, in particular the pile foundation. Moreover, these methods are time consuming, thus increase the project cost. Limitations of existing methods urge for the needs of more research on methods of controlling the ground deformation, particularly for tunnelling through cohesionless soils. The effectiveness of the method in minimising the ground and pile settlement, and the tilting and lateral movement of existing piles due to tunnel construction is also important to be studied, using both the physical modelling and numerical analysis.

This research aimed at establishing the micropile method to control the ground movement and the movements of existing pile in cohesionless soils due to shallow tunnelling. For this purpose, a series of three dimensional (3D) physical modelling tests in dry sand were carried out under single gravity. The tests explore the optimum location and length of micropiles for controlling the pile's settlement and lateral movement. Results were simulated based on 3D finite element analysis using ABAQUS 6.11 software.

1.3 Aim and Objectives

The research aimed at establishing the micropiles method as a mean to minimise the ground surface settlement, and the settlement and lateral movement of existing pile due to tunnelling through cohesionless soils. Hence, the objectives of the research are as follows:

i. To determine the effect of depths of the tunnel and density of the soil on the surface settlements and influence zones, induced by tunnelling in greenfield condition.
ii. To determine the effects of the micropiles in reducing the ground surface settlements due to tunnelling in greenfield condition.
iii. To determine the effects of tunnel excavation on the settlement and lateral movement of existing piles.
iv. To establish the effects of micropiles in controlling the settlement and lateral movement of existing piles due to tunnelling through the development of various graphs, thus determining the optimum location of micropile in between the pile and the tunnel.

1.4 Scope and Limitation of the Study

This research involves both the numerical and the physical modelling. The numerical modelling was carried out using ABAQUS software and the physical modelling has been carried out in the laboratory under single gravity (1g) using a box of 600 mm in length, 600 mm in width and 500 mm in height. In physical modelling test:

i. The circular shape tunnel was made of aluminium tube with 49 mm inner diameter shielded by a tube of 50 mm outer diameter.
ii. The cover to diameter (C/D) ratios of the tunnel were 1, 2 and 3, and the relative densities of the sand used were 30%, 50% and 75%.
iii. The quarry sand used in this study was obtained from a supplier and only the fine sand fractions were used for the physical modelling tests.
iv. The existing pile, made of aluminium and fixed at 9 mm diameter and 220 mm length, has been placed close to the tunnel alignment at 50 mm distance from tunnel centre (zone of influence).
v. The 3.7 mm diameter steel micropiles, wrapped with sand papers, were of 110 mm and 145 mm lengths. The micropiles had been installed in a single row with 3.7 mm side to side spacing above the tunnel and at several distances (1.25, 2.5, and 3.75 cm) from the tunnel axis.

1.5 Significance of the Study

A reliable method to control the tunnelling-induced surface settlement and consequently the risk of adjacent buildings are vital. This research on the use of micropiles and the effect of tunnelling to the existing pile, draw some significant as the followings:

i. The tunnelling-induced surface settlement of different soil density obtained from this research could contribute to the existing body of knowledge. This research considers the relationship among the different tunnel depth and density of the soil on the influence zones and surface settlements induced by tunnelling to better understand the behaviour of the surface settlement due to tunnelling.
ii. The utilization of micropiles to minimize the ground surface settlement induced by tunnel in greenfield condition could be used to control the building damage in shallow foundation such as raft foundation.
iii. The used of micropiles to minimize the surface settlement due to shallow tunnelling through sand has been a breakthrough of the successful method. This method also reduced the settlement and lateral movement of the existing pile.
iv. The numerical modelling using ABAQUS, verified by physical model test results, could be used by the engineer to predict soil and pile movements due to tunnelling in sandy soils.

1.6 Hypothesis

(i) In greenfield condition; increasing the value of the relative density of sand reduces the ground movements induced by tunnelling.

(ii) Micropiles to reduce ground surface settlement; the length and the location of the micropiles affect the ability of micropiles in reducing the maximum ground surface settlement.

(iii) The pile settlement induced by tunnelling; based on the pile toe location (50 cm, tunnel centre to pile centre), it is expected that the pile settlement is less than the maximum ground surface settlement.

(iv) Micropiles to reduce pile displacements; the longer micropiles are more effective than the shorter micropiles to reduce the pile movements in terms of settlement and lateral movement of the pile. The micropiles location can be more significant in terms of the pile lateral movement. Moreover, the more the number of micropiles, the more reduction in pile movements will be achieved.

1.7 Thesis Outline

The thesis is composed of six chapters and three appendixes. The summaries of the chapters are as follows:

Chapter 1 explains the background of the study, statement of the problems, aim and objectives, scope and limitation of the study, significance of the study and hypothesis.

Chapter 2 presents and discusses the ground surface settlement and pile movements induced by tunnel construction. The existing methods were reviewed based on transverse and longitudinal surface settlements associated with tunnel construction. Moreover, a number of available methods such as; empirical, analytical, numerical and physical modelling of small-scale tunnel construction in terms of ground settlement and pile movements were reviewed.

Chapter 3 describes the research methodology using the flowchart and overall framework, which have been used for this research. It includes; basic tests on sand, physical modelling tests and numerical analysis.

Chapter 4 shows and discusses all the results obtained from physical modelling tests and numerical analysis. The results of using micropiles in controlling the ground surface settlement, pile settlement and lateral movement induced by tunnelling has been clearly shown in figures and discussed accordingly.

Chapter 5 gives research conclusion, contributions and recommendations for future works.

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