TWIN TUNNEL INTERACTION MECHANISM IN KENNY HILL FORMATION USING FINITE ELEMENT ANALYSIS

TAN YIH KEN

SCHOOL OF CIVIL ENGINEERING
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By

TAN YIH KEN

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Name of Student:

I hereby declare that all corrections and comments made by the supervisor(s) and examiner have been taken into consideration and rectified accordingly.

Signature: Approved by:

________________________ ________________________

(Signature of Supervisor)

Date:

Name of Supervisor:

Date :

Approved by:

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(Signature of Examiner)

Name of Examiner:

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ABSTRAK

Pembinaan terowong di kawasan bandar semakin popular akibat keterhadan tanah di metropolis. Walaubagaimanapun, pembinaan terowong di kawasan perbandaran melibatkan mekanisme yang kompleks disebabkan interakasi antara terowong dan tanah. Pergerakan tanah yang disebabkan oleh pembinaan terowong berpotensi mengancam kestabilan struktur permukaan ataupun subpermukaan. Oleh itu, pembinaan projek terowong yang berskala besar seperti KVMRT, reka bentuk terowong yang mempunyai anggaran tepat tentang perubahan struktur tanah dan simulasi geoteknik yang realistik adalah penting. Dalam kajian ini, penyiasatan ciri-ciri sub-permukaan tanah bagi Formasi Bukit Kenny telah dijalankan dengan menghasilkan model tanah 3 dimensi, model terowong dan keratan rentas subpermukaan tanah melalui interpolasi spasial data lubang jara melalui kaedah Inverse Distance Weighted (IDW). Enam keratan rentas tanah telah dikenalpastikan berdasarkan input daripada model terowong, konfigurasi terowong berkembar dan ketersediaan data pergerakan tanah disebabkan oleh pembinaan terowong. Model konseptual untuk pemodelan secara unsur terhingga telah dibangunkan berdasarkan profil tanah dan parameter lapisan tanah yang dikenalpastikan daripada keratan rentas tanah yang terpilih. Parameter kekuatan dan kekukuhan tanah untuk model Pengerasan Tanah (HS) telah ditentukan dengan penggunaan data yang didapati daripada penyiasatan tapak, ujian tanah di situ dan makmal serta korelasi empirikal berkaitan dengan nilai Ujian Penusukan Piawai (SPT-N). Keberkesanan korelasi empirikal telah dinilaikan oleh analisis kembali dalam 2 dimensi analisis unsur terhingga yang menggunakan kaedah kontraksi pelapik. Simulasi pembinaan terowong kembar menggunakan parameter HS yang diperolehi daripada korelasi empirical yang terpilih meramalkan keputusan yang selari dengan pergerakan tanah yang dipantau dengan penggunaan nilai nisbah kontraksi dari 0.3% hingga 0.92%.

ABSTRACT

Urban tunnelling is becoming more popular due to the limitation of land use in metropolis. However, urban tunnelling are always associated with difficulties and involved with complex mechanism due to its interaction between tunnels and ground. The volume loss during the tunnelling excavation has led to ground deformation which may potentially damage the adjacent surface or subsurface structures. Thus, for large scale underground construction like KVMRT, tunnel design with proper estimation of ground deformation and realistic geotechnical simulation is essential. In this study, the subsurface characterization of tunnel excavation section in Kenny Hill Formation was conducted to develop 3D ground model, tunnel filtered model and ground section through spatial interpolation of borehole data using Inverse Distance Weighted method (IDW). Six greenfield ground sections were selected based on input of tunnel filtered models configuration of tunnels and availability of tunnelling induced ground movement data. The conceptual models for finite element modelling were developed based on the soil profiles and corresponding soil parameters determined from ground sections. The strength and stiffness parameters for Hardening Soil (HS) model were established using data from site investigation, in situ and laboratory test and empirical correlation with standard penetration test N numbers(SPT-N). The effectiveness of empirical correlation is determined by back-analysis of twin tunnels excavation in 2D finite element analysis using lining contraction method and verified with monitored ground movement data. The numerical back-analysed results of twin tunnels excavation simulation using HS parameters obtained from selected empirical correlation showed good agreement with construction-monitored ground movements with application range of values of contraction ratio from 0.3% to 0.92%.

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LIST OF ABBREVIATIONS

CIU	**C**onsolidated **I**sotropic **U**ndrained triaxial test
EPB	**E**arth **P**ressure **B**alance
EPP	**E**ntry **P**oint **P**roject
FE	**F**inite **E**lement
FEM	**F**inite **E**lement **M**ethod
HS	**H**ardening **S**oil
HSM	**H**ardening **S**oil **M**odel
IDW	**I**nverse **D**istance **W**eighted
KHF	**K**enny **H**ill **F**ormation
KVMRT	**K**lang **V**alley **M**ass **R**apid **T**ransit
NKEA	**N**ational **K**ey **E**conomic **A**reas
NB	**N**orth **B**ound tunnel
SB	**S**outh **B**ound tunnel
SPT-N	**S**tandard **P**enetration **T**est Blow Count **N**umbers
SBK	**S**ungai **B**uloh to **K**ajang
TBM	**T**unnel **B**oring **M**achine

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Rapid development of the large cities has led to speedy growing of population resulting in limitation of land use for residential and infrastructure development. The high-density population has increased the demand on transportation environment, facilities and infrastructure development for better quality of life. Thus, the underground construction now has becoming more popular and current trend to fulfil the needs of people. Underground construction such as tunnels can provide alternative way of development to accommodate the transportation, water supply, sewerage, electricity, and other facilities to mitigate the over-occupied development on the surface spaces. Due to the multifunctional of tunnels, it can be foreseen that tunnels construction projects will continue to progressively expand in future.

There are many undergoing and future planning of tunnels construction related works and expansion of underground metro network in all parts of the world especially for over congested metropolitan centre. In order to improve an existing network of underground transportation, it is often required construction of new tunnel adjacent to existing tunnels. The construction of twin tunnels or multiple tunnels is unavoidable in congested urban environment. Moreover, the twin tunnels have the advantages to allocate higher capacity with smaller tunnel diameter and minimize the ground deformation induced by tunnelling compare to large diameter single tunnel. Urban tunnelling are usually carried out in shallow overburden depth and located underneath the existing buildings. Thus, it is very important to address the interaction of the tunnels and theirs influence to overall ground and other substructures. The volume loss during the tunnelling excavation has led to surface settlement and ground deformation which may have the potential to damage the adjacent surface or subsurface structures. Therefore, it is highly significant to evaluate the ground deformation in great details before construction. The ground movement due to tunnelling should be controlled to minimize the damage to adjacent building.

There are 3 mainly method for settlement predication approaches for mechanize tunnel excavations: numerical analysis such as Finite Element method, analytical method and semi-empirical method. Many studies about the tunnelling induced ground settlement are carried out in the past (Peck, 1969; O'Reilly and New, 1982; Attewell and Woodman, 1982; Mair et al., 1995). The semi-empirical method is the most common method use to predict the ground settlement induced by single tunnel which performed by using the Gaussian Curve approach (Peck, 1969). Meanwhile, superposition method are proposed for evaluation of twin or multiple tunnelling-induced ground settlements (New and O'Reilly, 1991) which both required two parameters δ_{max}, maximum settlement at tunnel centre line and i, distance of the inflection point).

The numerical method based on Finite Elements are the most reliable method which tend to give more accurate prediction of ground settlement as they could model the mechanisms of the soil-structures interaction and realistic soil behaviour with the inputs of soil condition surrounding tunnels, tunnels construction method, tunnel support details and tunnel configuration. A series of numerical studies related to Bangkok Clay behaviour has been carried (Likitlersuang et al., 2013, 2013a, 2013b). However, there are still lack of published and numerical studies about twin tunnel interaction in Kenny Hill Formation. The constitutive soil models available in FEM software are developed based on conceptual framework of formulation with different assumption of soil behaviour. The accuracy of modelling of soil behaviour are largely dependent on the selection of constitutive model and soil parameters input. It is recommend that the Mohr-Coulomb Model may be used for a quick and simple first analysis of the modelling (Brinkgereve and Vermeer, 2003). However, advance soil constitutive model such as Hardening Soil Model (Schanz et al., 1999) which describe the soil stiffness much more accurately should be used in an additional analysis. A few studies about FE simulation of deep excavation in Kenny Hill Formation adopting Hardening Soil Model have been carried out (Law et al., 2014; Boon and Ooi, 2016).

Tunnel exaction should be considered as 3D problem and required undergo 3D numerical analysis. However due to the complexity and time consuming, a simplified 2D analysis could be adopted since it is more economical and reasonably accepted. During stimulation of tunnel excavation in 2D plan-strain finite element analysis, the missing 3D arch can be compensated by including an artificial support pressure (Moller, 2006). Several 2D approximation such as lining contraction method proposed by Vermeer and Brinkgreve (1993), stress reduction method by Panet and Guenot (1983) and Grout Pressure Method (Möller, 2006; Möller and Vermeer, 2008) can be used to stimulate the tunnel excavation and support sequence of conventional tunnelling. The relationships among 3 calculated parameters obtained from different method of 2D modelling are well discussed (Likitlersuang et al., 2014) for case study of Blue Line Bangkok Mass Rapid Transit tunnels.

This study is focused on 2D Finite Element analysis of twin tunnels interaction using lining contraction method based on Hardening Soil model. The twin tunnel excavation of SBK line in Klang Valley Mass Rapid Transit (KVMRT) project have been selected as the study area.

1.2 Problem Statement

The geological condition and geotechnical parameters are vital to tunnel excavations as it will bring comprehensive effect to the tunnels excavation. Based on different condition of geological and geotechnical soil parameters, the most suitable method of construction, type of boring machine, tunnel configuration yet the shortest and most economical project cost can be determined. Thus, it is necessary to clearly define the subsurface condition of the project area through sufficient ground investigation such as borehole sampling. However, tunnels excavation is classified as 3D geotechnical problem but only one-dimensional ground information can only be extracted from borehole sampling. Thus, to determine the subsurface condition along the tunnel alignment, reliable and logical assumption based on 3D spatial interpolation method are required to interpret the borehole data.

It must take the consideration of the effect of the ground loss at the excavation face which will later cause the surface settlement and influence the stability of the adjacent surface or subsurface structures. Thus, it is necessary to minimize the surface settlement by accurate estimation during analysis and design of tunnelling excavation. There are many constraints and difficulties for tunnels constructions in urbanized areas especially when it comes to twin tunnel excavation. This is because twin tunnels excavation especially in Kenny Hill formation involve complex mechanisms. The twin tunnel excavation may influence by excavation factor, the tunnel to tunnel interaction and the tunnel to ground interaction. The excavation factor such as type of boring machine, operational parameters, construction method and construction sequence will bring effect to the twin tunnel interaction. In addition, the interaction between tunnel such as the geometry of tunnel, tunnel configuration, tunnel alignment and the relative tunnel distance could influence tunnelling induced ground deformation. The interaction between ground and tunnel such as ground condition, soil behaviour under loading and unloading and soil-structure interaction for urban tunnelling are complicated because the tunnels may construct nearby to existing subsurface structure or underground facilities.

Semi-empirical method based on Gaussian Curve is one of the convenient method to predict the distribution of ground movement. However, the semi-empirical method is only eligible for single tunnel and green field condition. Moreover, this curve cannot give either subsurface movement or stress distribution (Zlatanović & Lukić, 2014).

On the other hand, the finite element analysis has been widely adopted in tunnelling industry and become effective analytical tool for modelling construction works. By adopting FEM, the soil behaviour under loading and unloading can be simulated based on the selected constitutive soil model. Since Mohr-Coulomb model is a simple and clear model and involve lesser soil input parameter, it usually adopted in FE simulation. However, due to the complexity of twin tunnel excavation and involving many influence factors such as loading and unloading behaviour, so numerical analysis with simple constitutive soil model is not enough to replicate the real measured surface settlement curve. The FE analysis with advanced constitutive soil model such as Hardening Soil model can simulate the complex mechanism of the twin tunnel interaction by consider the construction sequence and predict the realistic soil behaviour more accurate to provide valid estimation on twin tunnel induce deformation.

1.3 Objectives

The objectives in this study are:

1. To develop 3D ground models for the greenfield tunnel excavation section in Kenny Hill Formation using multivariate interpolation of Inverse Distance Weighted (IDW).

2. To determine the ground model properties for the greenfield tunnel excavation section based on Hardening Soil model.
3. To back analyse the twin tunnels interaction and its ground responses based on the result of ground settlement using the FEM of Hardening Soil model
4. To determine the range of contraction ratio for Kenny Hill Formation using the 2D-FE analysis based on lining contraction method.

1.4 Importance and Benefits of the Study

The benefits of the study include:

1. Subsurface characterization of Kenny Hill formation to determine the soil profile based on the distribution of soil properties by developing 3D ground model.
2. Provide better understanding of the effect of 2D modelling method and soil constitutive model for prediction of twin tunnel induced surface settlement and its suitability to adopt for Finite Element analysis for better prediction of ground settlement in Kenny Hill Formation

1.5 Scope of Work

Basically, the scope of work of this study was separated into 3 major parts: subsurface characterization, evaluation effectiveness of empirical correlation of stiffness parameters and Finite Element simulation of tunnelling using lining contraction method.

The subsurface characterization only performed for greenfield section of KVMRT underground twin tunnels that passed through the Kenny Hill formation. The ground models were developed based on the lithology and uncorrected Standard Penetration Test (SPT-N) values which extracted from the borehole data provided by KVMRT (T) Sdn. Bhd. The Inverse Distance Weighting (IDW) method was used for interpolation of subsurface condition based on large number of existing borehole data. After the ground model was developed, tunnel filtered model was generated and the tunnel cross sections were selected to develop conceptual model which will adopt for the numerical simulation and analysis. The real field measurement data of deformation, operational parameters of TBM, soil laboratory test data and borehole log data were collected as well in this study.

The analysis of the ground deformation induced by tunnels excavation was practiced by adopting Finite Element analysis with Hardening Soil model which classified as advanced constitutive soil model. The soil parameters of Hardening Soil model were obtained from several empirical correlations proposed by previous researchers. The effectiveness evaluation of empirical correlation to estimate soil parameter that can capture the real soil behaviour is carried out. The soil profile obtained from subsurface characterization and soil parameters based on selected correlation were used to develop conceptual model for the simulation of tunnels excavation using FE analysis.

The ground responses and interaction of twin tunnels during excavation procedure were investigated using two-dimensional finite element modelling. The support sequence of the tunnels excavation was simulated using lining contraction method. The evaluation of the twin tunnels interaction focused on tunnelling induced-surface settlement. The back-analysed results were verified by comparing real field measurement data and numerically simulated settlement curve. The suitable range of values of contraction ratio for numerical simulation of tunnelling in Kenny Hill Formation were then determined.

1.6 Thesis Outline

This research project was structured into five chapters:

Chapter 1 gives a general introduction of the work contained in this research project. The main objectives and researched questions are well discussed in this section as well as the significant and scope of work in this study.

Chapter 2 consists of literature review on topics related soft ground urban tunnelling and associated geotechnical problem. Various methods such as empirical, analytical methods and finite element analysis adopted to estimate tunnelling induced ground movements were reviewed.

Chapter 3 explains the workflow and approaches that has been applied in this study. The workflow of subsurface characterization of study area, development of conceptual model for numerical analysis, preparation of constitutive model parameters, tunnelling deformation analysis using finite element method and verification of back-analysed results are explained in detail.

Chapter 4 presents the outcome of the study. The results of subsurface modelling and numerical analysis of tunnelling were discussed in this chapter. The spatial interpolated ground models, developed soil profile of tunnel section, estimation of constitutive model parameters from empirical correlation, and ground movement obtained from numerical analysis were identified. The back-analysed results of numerical simulation of tunnelling are presented.

Chapter 5 concludes the findings in this study and recommendation for future study are proposed.

CHAPTER 2

LITERATURE REVIEW

2.1 Characteristic and Challenges of Urban Tunnelling

The underground construction has become current trend in the world because it can provide an effective solution to solve the issues of limited surface space in urban area. However, compare to green field condition, the underground construction in urban area such as tunnel or deep excavation always involved greater challenges and constraints prior to construction to ensure the safety of both existing surface and subsurface.

The urban area is described as high-density population, well-developed built environment with infrastructure and utilities in it. Due to the complexity of urban environment, urban tunnelling is considered as high risk and challenging task as it involves the heterogeneity and anisotropy of geological condition but at the same time it must take account the associated effect of tunnels excavation to nearby existing surface and subsurface structure and utilities such as pipelines, foundation system, sewerage system, tunnels and electricity cable. The main characteristics of urban tunnelling in term of geotechnical, structural and environmental were summarised in Ghorbani et al. (2012) : (1) potential interferences with both surface and subsurface structures and utilities, (2) shallow overburden and carry out in shallow depth at soft ground with variable condition and possible consist of man-made features, (3) water table level upon the tunnel, (4) tunnelling induced settlement and possible damage to existing structures, and (5) difficulty in construction management and safety risk management. The primary concern of urban tunnelling is the ground deformation induced by tunnels excavation and its potential damage to surrounding pre-occupied structures. Thus, urban tunnelling faced many restriction and obstruction in the route planning, alignment, construction method, and tunnel configuration. It is required to undergo proper and adequate analysis of deformation by deliberate on all possible factors and condition of tunnelling before construction to minimize the distribution to the ground and pre-existent structures.

2.2 Geological Condition of Kuala Lumpur

The Federal Territory of Kuala Lumpur is the national capital of Malaysia and located on the west coast central region of Peninsular Malaysia. Kuala Lumpur is the largest city as well as the centre of cultural, financial and economic in Malaysia with coverage area up to 243 km^2 and 1.768 million of population density in 2015. Greater Kuala Lumpur or known as Klang Valley is metropolitan area formed by Kuala Lumpur and its adjoining cities and towns with high density of population. The Klang Valley Mass Rapid Transit (KVMRT) is a transformation project of public transportation implemented in Greater Kuala Lumpur. The twin tunnels alignment of KVMRT line 1, Sungai Buloh to Kajang (SBK line) passed through two distinct geological formation namely Kenny Hill Formation (KHF) and Kuala Lumpur Limestone (Figure 2.1)

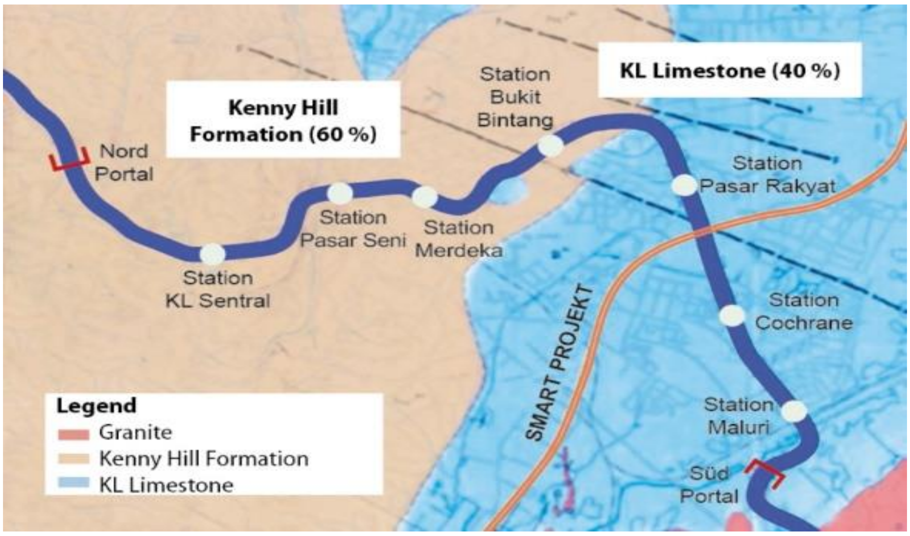

Figure 2.1: KVMRT Twin Tunnels Alignment and Station Location passes through two district geological formation (Breakthroughs line up for KlangValley MRT, 2013)

The urban geology of the Kuala Lumpur were studied by few previous researchers and the geological condition are well discussed (Samy et al., 2012; Y. C. Tan et al., 2003, 2004) . From Figure 2.2, the distribution of bedrock in Kuala Lumpur area are mostly formed by Kenny Hill Formation and Kuala Lumpur Limestone. The geotechnical engineering characterisation of Kuala Lumpur Limestone and Kenny Hill Formation varies from each other. KHF has its heterogeneous weathering profile of sedimentary rock and is overlaid with thick residual soil while KL Limestone is well-known for its karstic limestone feature.

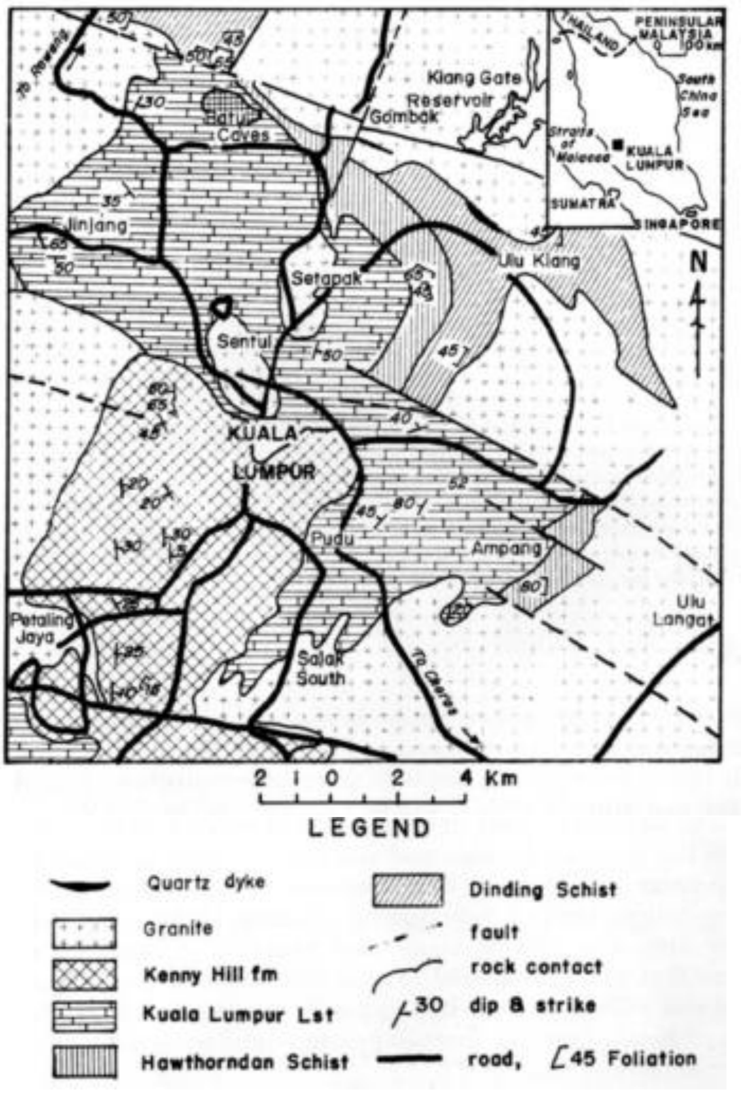

Figure 2.2: Bedrock Geologic map of Kuala Lumpur area (B.K.Tan and Komoo, 1990)

The Kenny Hill Formation is sedimentary rock formation widely present in Kuala Lumpur and Klang Valley, which consist of interbedded siltstone, sandstone and shale of Upper Silurian-Devonian and lies unconformably on limestone bedrock (Tan, 2006; Tan and Komoo, 1990). The major rock formation of Kuala Lumpur has been summarized in Table 2.1. Due to the tropical climate of Malaysia, it has produced unique weathering profile and the rock mass has underwent heterogeneous physical deterioration of rock mass. The sandstone, siltstone and shale of Kenny Hill formation has experienced low grade of metamorphism which turn sandstone to quartzite while shale to phyllite (Mohamed et al., 2007). The near surface layer of Kenny Hill Formation was covered with thick residual soil which resulted from highly weathered of rock formation.

Table 2.1: Geology of the Kuala Lumpur area (after Yin, 1976)

Age	Kuala Lumpur
Quaternary	Alluvium (Young & Old Alluvium)
Triassic	Granite & Allied Rocks
Palaeozoic	Kenny Hill Formation (quartize/ phyllite) Kuala Lumpur Limestone Hawthornden Schist

The geotechnical engineering properties of the subsoil in Kenny Hill Formation has been investigated in few of previous published. Komoo and Ho (1985) and Tan (1986) have attempted to correlate the SPT based on weathering grade for residual soil of KHF. From their studies, grade I to III are classified as rock (SPT>50) while grade IV and VI are grouped as soil (SPT<50) with weathering grade I (SPT >50/10cm), II (SPT 50/20-10cm), III (SPT 50/20), IV (SPT 30-50), V (SPT 10-30) and VI (0-10). The collapsed weak soil zone laid on the limestone bedrock with SPT value near to 0 has been discussed (B. K. Tan, 2006; Tan Boon Kong and Komoo, 1990). The stiffness of the collapsed soft soil zone can be overlain from stiff to hard residual soil with SPT value

30-50 or even more than 50. The physical deterioration of tropically weathered Kenny Hill Weak rock has been characterized and classified through a series of in-situ and laboratory index tests (Mohamed et al., 2006, 2007). The author has merged two classification system of weak rock by weathering grade for sandstone and shale (Table 2.2). The author also claimed that the shale and sandstone have absolutely differences in the physical deterioration and durability of sandstone and shale lead to complicity of geotechnical problem experienced in KHF.

Table 2.2: Recommended System for classification of Sandstone and Shale (after BS 5930:1999, 1999; Komoo and Mogana, 1988; Santi and Higgins, 1998)

<table>
<tr><td rowspan="6">Soil</td><td colspan="2">Sandstone</td><td colspan="2">Shale</td><td rowspan="7">Soil</td></tr>
<tr><td>Grade</td><td>Description</td><td>Class</td><td>Description</td></tr>
<tr><td>VI</td><td>Residual Soil</td><td rowspan="3">E</td><td rowspan="3">Residual soil or reworked soil</td></tr>
<tr><td>Vb</td><td rowspan="2">Completely weathered</td></tr>
<tr><td>Va</td></tr>
<tr><td>IVb</td><td rowspan="2">Highly Weathered</td><td rowspan="2">D</td><td rowspan="2">Destroyed</td></tr>
<tr><td rowspan="5">Rock</td><td>IVa</td></tr>
<tr><td rowspan="2">III</td><td rowspan="2">Moderately weathered</td><td>C</td><td>Visibly weathered</td><td rowspan="4">Rock</td></tr>
<tr><td rowspan="2">B</td><td rowspan="2">Partially weathered</td></tr>
<tr><td>II</td><td>Slightly weathered</td></tr>
<tr><td>I</td><td>Unweathered</td><td>A</td><td>Unweathered</td></tr>
</table>

2.2.1 Soil Stiffness Correlation for FE analyses in Kenny Hill Formation

The simulation and analysis of soil behaviour in Kenny Hill Formation under construction work was carried out by few researchers (Ahmad, 2017; Boon and Ooi, 2016; Tan et al., 2016; Liew and Gan, 2007). The performance of the diaphragm wall and the ground settlement due to the deep excavation in residual soil of KHF was reviewed by using numerical back-analysis method with Hardening Soil model (Law et al., 2014; Liew and Gan, 2007; Y. C. Tan et al., 2001). Tan et al. (2001) concluded that the prediction of displacement patterns of the diaphagram walls and surface settlement profile due to deep excavations can be modelled accurately by using Finite Element Modelling with Hardening Soil Models. He also suggested correclation between SPT-N value with the effective Young's Modulus, E' and and effective unloading/reloading stiffness, E_{ur}' for the ultizaltion of Hardening Soil Model as below Equation (2.1) and (2.2):

$$E' = 2000\ x\ SPT - N\ (kN/m^2) \tag{2.1}$$

$$E'_{ur} = 3\ x\ E' = \ 6000\ x\ SPT - N\ (kN/m^2) \tag{2.2}$$

The performance of deep excavation in KHF residual soil can be described acrccurately and provide valid prediction of soil behaviour by the adoption of FE with Hardening Soil Model (Liew and Gan, 2007). Law et al. (2014) found that the lateral wall deflection at each stage of excavation can be predicted by using simple correlation between triaxial stiffness and odemeter stiffness with SPT-N value, which is 1.5N with unloading/reloading stiffness 3 times of triaxial stiffness for Hardening Soil model. The impact of twin tunnels excavation toward the existing buildings and foundation system was analyzed using 2D Finite Element Modelling with Hardening Soil model (Boon and Ooi, 2016).

2.3 Spatial Interpolation for Subsurface Modelling and Characterization

Subsurface characterization process provides significant input for preliminary and detailed analysis of tunnels construction as the geotechnical environment is identified during the process (Chapman et al., 2017). Basically, subsurface condition is determined by adopting intrusive methods like borehole sampling. However, it is hard to identify the ground condition based on one dimensional borehole data only due to the heterogeneity characteristics of subsoil condition (Kessler et al., 2008). In the same time, the application of traditional 2D geological map also insufficient information for detailed survey especially for subsoil planning and management. The 3D modelling techniques that able to visualize the subsurface geological and geotechnical properties are developed to overcome the limitation of conventional one-dimensional borehole data for the planning and design of new civil infrastructure in subsoil of city areas.

In recent years, there were studies adopting subsurface modelling for the purpose of subsurface characterization for respective construction project (de Rienzo et al., 2008; Hou et al., 2016; Thoang and Giao, 2015; Tonini et al., 2008; Touch et al., 2014; Zhu et al., 2012). Tonini et al. (2008) reports a geological modelling procedure suitable for the reconstruction of three-dimensional models and for applications in preliminary tunnelling studies. Surarak (2011), Touch et al. (2014), Hou et al. (2016) and Thoang and Giao (2015) developed geological and engineering properties based ground model, sections and profiles from spatial interpolation of borehole data from specific cities.

There have been very few studies conducted on subsurface characterization of KHF. Ismail et al. (2011) studied the subsurface fractures and cavities beneath Klang Valley region. Mohamed et al. (2007) characterised the strength properties of weathered rock in Kenny Hill formation. However, there is no subsurface modelling study conducted to propose spatial distribution of soil properties, in which is important as a reference for geotechnical study conducted in Kenny Hill formation.

Detailed subsurface characterization is necessary to identify the geological condition of the project site to prevent unforeseen risk. The cognition of subsurface ground condition influence decision on construction methods, project cost, duration and safety measures (Chapman et al., 2017; Kessler et al., 2008). Subsurface modelling can be achieved through spatial interpolation of one-dimensional borehole data. Li, (2008) and Li and Heap, (2011) reviewed a series of spatial interpolation methods that often utilised for development three-dimensional model. With the great variety of existing methods, the spatial interpolation methods can be broadly classified into geostatistical methods and non-geostatistical methods. In particular, non-geostatistical method of Inverse Distance Weighting (IDW) is focused in the following discussion.

2.3.1 Inverse Distance Weighting method

The Inverse Distance Weighted (IDW) is a deterministic multivariate method and interpolates values of a grid point based on the influence of surrounding scattered data points. In this case, the borehole is considered as known data point while the points between borehole in the project dimension are known as interpolation point. The interpolation value $Z(X_0)$ is obtained through the inverse distance weighted spatial interpolation. The interpolation is weighted according to the inverse of distance between surrounding data points and interpolation points subjected to a power parameter. Therefore, nearby data points provide more influence to the interpolation values compare to distant data points. Eq. (2.3) and Eq. (2.4) displayed the governing equation of IDW method in the spatial interpolation. The equations of IDW method use in spatial interpolation are showed below:

$$Z(x') = \sum_{i=1}^{n} W_i Z(x_i) \tag{2.3}$$

Where n is number of data point, $Z(x_i)$ is the value of known data poin, W_i is the weighted value assigned to each data point, p is power parameter and h_i is the distance between known data point and interpolation point. The weighted relationship is defined in Eq (2.4)

$$W_i = \frac{h_i^{-p}}{\sum_{j=1}^{n} h_j^{-p}} \tag{2.4}$$

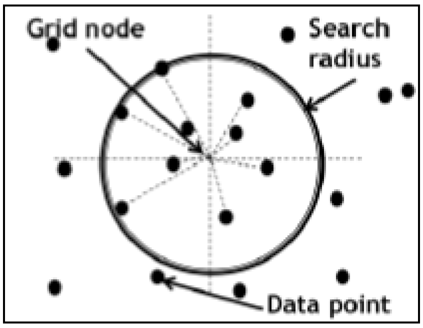

Figure 2.3: A radius is generated each grid node from which data points are selected to be used in the calculation

2.4 Twin Tunnel Interaction

To provide a better transportation system to ease the traffic congestion in urban area, underground space has been utilized for the construction of underground infrastructure and facilities. Due to the over-crowded environment of city area, it is unavoidable twin tunnels excavation or construction of new tunnel to adjacent tunnel or buildings to cater the high capacity of citizen. However, it is necessary to take account the effect of interaction between twin tunnels and impact to nearby adjacent structure. The twin tunnel interaction reflects the mechanism, soil-structure interaction or soil behaviour due to excavation of new tunnel to adjacent tunnel. The twin tunnel interaction may alter the expected tunnelling-induce ground movement and cause distortion to an existing tunnel lining. Thus, the interaction between the tunnels should be well defined due to its impaction on the ground deformation and stability of the tunnels or nearby structures.

The different issues of interaction between tunnels have been studied in the past decades. A significant amount of researchers have studied about the ground movement induced by twin tunnels excavation (Chen et al., 2011; Ercelebi et al., 2011; Hsiung, 2011). New and O'Reilly (1991) has proposed superposition formula Equation (2.5) based on modification of Peck’s formula by to evaluate the ground movement induced by twin tunnelling.

$$S_v = S_{max}. \left\lfloor exp\left(-\frac{x_A^2}{2i^2}\right) + exp\left(\frac{x_{A-d}}{2i^2}\right)^2 \right\rfloor \qquad (2.5)$$

Suwansawat and Einstein (2007) also found that the settlement trough induced by twin tunnel excavation of Bangkok Subway Tunnel project can be well-described by using superposition technique. However, superposition method do not consider the effect of interaction and the soil behaviour may not interpreted correctly (Addenbrooke and Potts, 1996; Zlatanović and Lukić, 2014).

The twin tunnel interaction may alter the ground movement which will later influence the stability of nearby surface or subsurface structures. Some of the studies investigated the impact of construction of tunnels near to surface building or subsurface structures like foundation system and existing tunnel (Afifipour et al., 2011; Fang et al., 2015; Liang et al., 2016). Meanwhile, there are also authors carried out parametric analysis to identify the influence of different tunnels configuration, relative distance between tunnels and depth of tunnels to the twin tunnel interaction (Addenbrooke and Potts, 1996; Hage Chehade and Shahrour, 2008; Elwood and Martin, 2016; Liang et al., 2016). Hage Chehade and Shahrour (2008) found that the construction of upper tunnel at first will lead to both higher settlement and bending moment, while lowest settlement for horizontal aligned tunnels. Addenbrooke and Potts (1996) concluded that pillar width for side by side tunnels excavation and pillar depth for piggy back tunnels should more than 1 diameter of tunnel to minimize the twin tunnel interaction such as ground surface settlement and magnitude of distortion.

2.5 Method to Analyse Twin Tunnel Interaction

There are three main methods that can be adopted for the prediction of ground deformation induced by tunnelling which are semi-empirical method, analytical solutions and numerical analysis. These three methods are widely adopted in the field of geotechnical tunnelling and large amount of studies have been carried out to discuss its limitations and ability to predict the tunnelling-induced ground movements. The empirical and numerical will be further discussed in next section.

2.5.1 Empirical Method

Empirical method is developed based on the field observation and data collection from study of case histories. Based on previous literatures, researchers have adopted the empirical solution to analyse the tunnelling induced ground deformation (Peck, 1969; O'Reilly and New, 1982; Attewell and Woodman, 1982; Mair et al., 1995). The classic semi-empirical method that based on the Gaussian distribution curve (Figure 2.4) proposed by Peck (1969) was widely adopted for the analysis of surface settlement induced by single tunnel excavation. The author described the transverse surface settlement induced by tunnelling in green field condition can represent by invert Gaussian function:

$$S(x) = S_{max}\ exp\left(\frac{-x^2}{2i^2}\right) \tag{2.6}$$

Where $S(x)$ is the surface settlement at a transverse distance x from centre of tunnel; S_{max} is the maximum settlement of settlement trough; x is horizontal distance from centre of tunnel; i is horizontal distance from point of inflection to tunnel centreline. The volume of settlement trough per unit length can be obtained by integrating Equation (2.7)

$$V_s = \int S(x).d_x = \sqrt{2\pi}.i.S_{max} \tag{2.7}$$

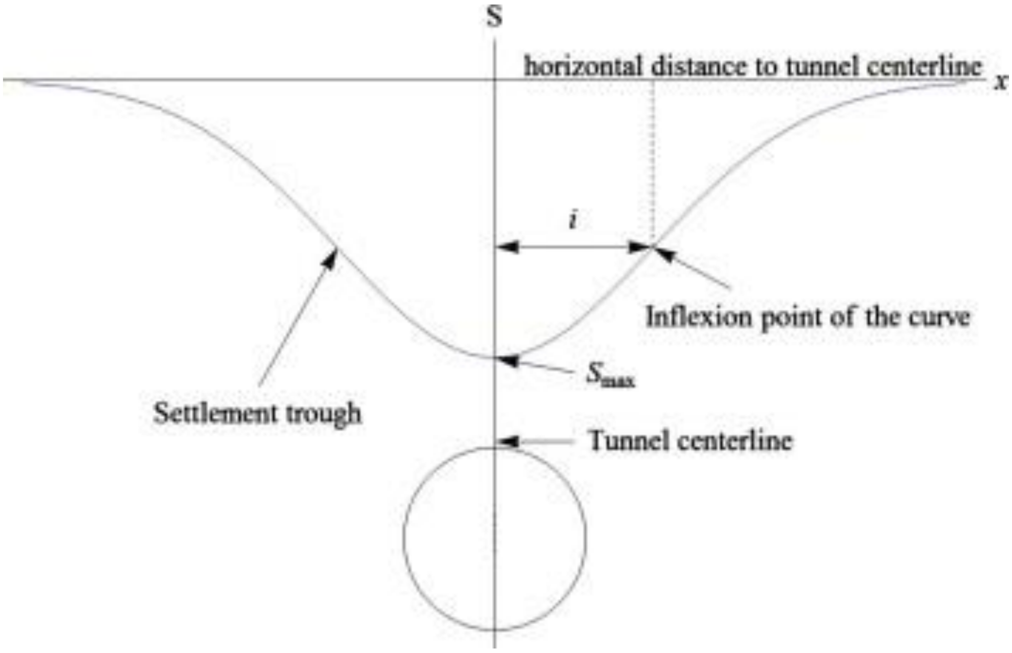

Figure 2.4: Transverse Settlement Trough induced by single tunnelling (Peck, 1969)

However, to generate a Gaussian settlement trough, it requires input parameters of distance of inflection point, *i* and the maximum settlement, S_{max}. Numerous researches have been carried out to the estimation of S_{max} and value of *i*. This is usually done by curve fitting to the field measurement data through back analysis of the tunnel excavation. Loganathan (2011) has summarized the proposed method to calculate *i* value from various studies carried out by previous researchers, as listed in Table 2.3.

Table 2.3 Proposed i value by various researchers (Loganathan, 2011)

Name	i- value	Remark
Peck (1969)	$\frac{i}{R}=\left(\frac{z_o}{2R}\right)^n$: n= 0.8 to 1.0	Based on field observation
Atkinson & Potts (1979)	$i=0.25(z_o+R)$: for loose sand $i=0.25(1.5z_o+0.5R)$: for dense sand and over consolidated clay	Based on field observation and model tests
O'Reilly & New (1982)	$i=0.43z_o+1.1$: cohesion soil $i=0.28z_o-0.1$: granular soil	Based on field observation of UK tunnels
Mair (1993)	$i=0.5z_o$	Based on field observation worldwide and centrifuge test
Attewell (1977)	$\frac{i}{R}=\alpha\left(\frac{z_o}{2R}\right)^n$: $\alpha=0.8$ and n= 1	Based on field observation of UK tunnels
Clough & Schdmidt (1981)	$\frac{i}{R}=\alpha\left(\frac{z_o}{2R}\right)^n$: $\alpha=1$ and n= 0.8	Based on field observation of US tunnels

However, the Gaussian Curve approach proposed by Peck is only suitable for the analysis of single tunnel in green field condition but not for twin tunnels excavation. Thus, superposition method is usually adopted for the prediction of surface settlement induced by twin tunnel configuration (New and O'Reilly, 1991). Superposition method may be useful for the analysis of twin-tunnelling however they cannot accommodate complex stress-strain behaviour, construction details and ignore the interaction between the tunnels (Zlatanović and Lukić, 2014). Addenbrooke and Potts (1996) proved that the assumption of superposition showed shortcomings for both side by side and piggy back tunnel geometries through numerical analysis. Thus, it is suggested to adopt numerical simulation for multiple tunnels excavation as they could consider the interaction effects between the tunnels and provide realistic soil behaviour.

2.5.2 2D Finite Element Modelling of Tunnel Excavation

Tunnel excavation is considered as three-dimensional problem in the geotechnical field (Do et al., 2014). The appearance of the interaction between the reinforcements, the excavation process and ground reaction is 3D problem (Janin et al., 2015) , especially in the section of tunnel face which has been illustrated through the analysis of stress path around it (Barla and Barla, 2004). However, 3D modelling is a very time-consuming task (Do et al., 2014) and due to its complexity, it is not suitable to apply for large tunnel project that involve kilometres of excavation. Thus, two-dimensional modelling was always adopted to simulate the tunnel excavation due to its shorter processing time and relatively simple yet user friendly. From previous studies, it were proved that 2D modelling able to reproduce well the real ground settlements. Janin et al. (2015) has carried out investigation to compare the 2D and 3D numerical back-analysis of the southern Toulon tunnel measurement in France by using PLAXIS in Hardening Soil Model. From the study, he concluded that the 3D simulation can correctly replicate the complexity of the tunnel excavation and the 2D simulation using convergence-confinement method able to reproduce well the ground settlements, provided the stress release value adopted is obtained by fitting the 2D calculation results onto 3D results. Maras-Dragojevic (2012) also compared the settlement results obtained by 3D and 2D modelling using stress-reduction method in Mohr-Coulomb model of an open-cut tunnel of circular section in the centre of Belgrade and concluded that both 2D and 3D analysed delivered similar cross-sectional profiles of settlement, provided appropriated stress reduction coefficient is applied.

In order to simulate tunnels excavation in 2D plain-strain finite element modelling, it must take account in the missing third dimension. The 3D arching around the unsupported tunnel heading able to carry the vertical ground loads P_g by transferring them around the unsupported cut stretch and the missing 3D arching effect in 2D modelling can compensate by including an artificial support pressure or displacement controlled approach as showed in Figure 2.5 (Möller, 2006). Based on review of 2D modelling, there are few of 2D approximation method can be applied to simulate tunnel excavation in 2D models: contraction ratio method (Vermeer and Brinkgreve, 1993), stress reduction method or convergence confinement method (Panet and Guenot, 1983), volume loss control method (Addenbrooke et al., 1998), gap method (Rowe et al., 1983) and grout pressure method (Möller, 2006). To simulate closed shield tunnel construction, it is suggested to adopt stress reduction, contraction ratio, gap method and grout pressure method (Möller, 2006). Therefore, this study focused on 2D simulation method using stress reduction, contraction ration and grout pressure that suitable for EPB shield.

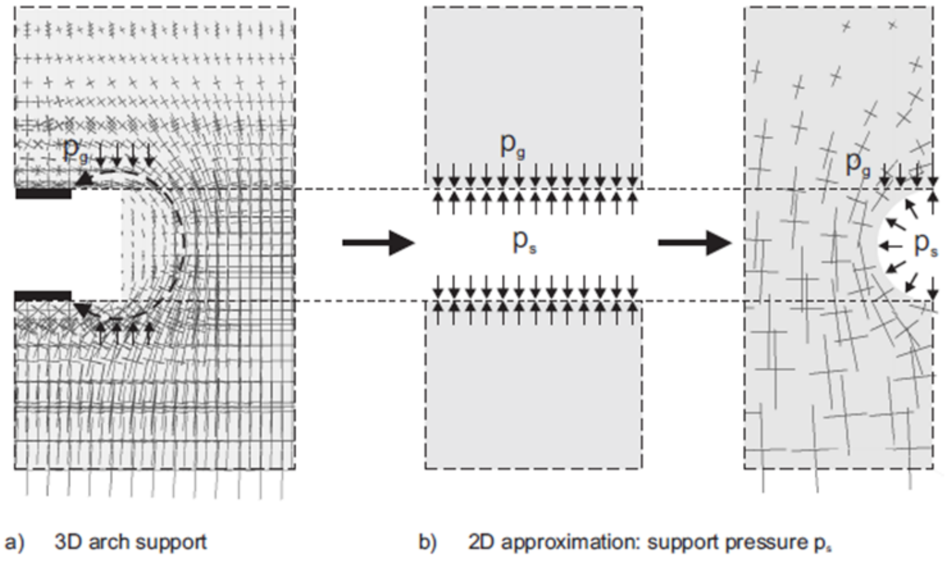

Figure 2.5: 3D arch support and 2D FE-approximation with support pressure (Möller, 2006)

2.5.2.1. Contraction Ratio Method

The contraction ratio method was introduced by (Vermeer and Brinkgreve, 1993) to simulate the tunnel installation procedure in 2D modelling. This method involved in two calculation steps as shown in Figure 2.6. The 1st step is initiated with the deactivation of soil elements inside the tunnels by removing it. At the same time, the tunnel lining is wished-in-place and activated to support the ground above tunnel. The tunnel lining is allowed to move upward due to the higher mass of removal soil compare to weight of lining resulting in tunnel uplift. During the 2nd step of calculation, the tunnel lining is stepwise contracted until it reached the prescribed value of contraction ratio.

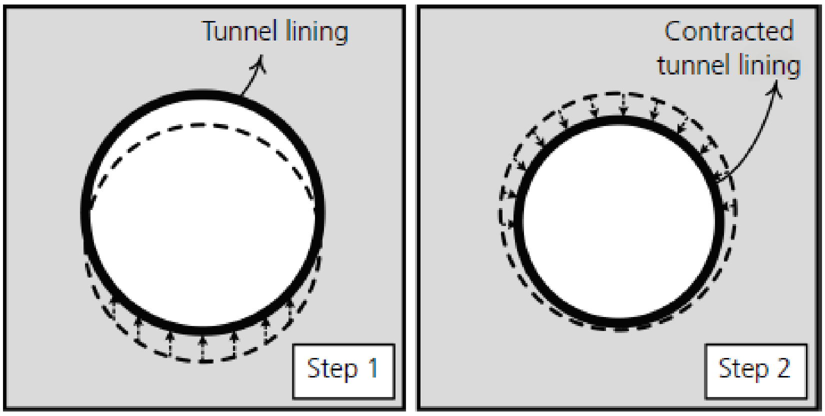

Figure 2.6: Calculation Step in Contraction (Likitlersuang et al., 2014)

2.5.2.2. Stress Reduction Method

The stress reduction method or convergence confinement method (Panet and Guenot, 1983) is one of the most popular method applied in 2D modelling. This method well defined the sharing of load between lining and ground and the relaxation of stress caused by delayed short concrete installation. This method emphasis on the application of unloading factor, β to consider the 3D tunnelling effect in the 2D plan-strain modelling. This method involved 3 phases (Figure 2.7) which the first phases started