Bulletin of the Geological Society of Malaysia, Volume 67, June 2019, pp. 119 – 125

DOI : https://doi.org/10.7186/bgsm67201915

Calibration of stiffness parameters for Hardening Soil Model in residual soil from Kenny Hill Formation

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Abstract: The underground configuration of the Klang Valley Mass Rapid Transit (KVMRT) system passes through two different geological formations namely the Kenny Hill Formation and Kuala Lumpur Limestone. However, this study only concentrates on the Kenny Hill Formation. A set of borehole data from Pasar Seni Station within the Kenny Hill Formation was analysed in order to calibrate the stiffness parameters for Hardening Soil Model of residual soil from the Kenny Hill Formation. The *in situ* and laboratory tests were simulated using the PLAXIS 2D software. The parameters were determined based on triaxial and pressuremeter tests. From the selected boreholes, the residual soil from Kenny Hill Formation is categorized into five soil types - sand, sandy clay, gravel, silty sand and silty gravel. The triaxial test was carried out for sand and sandy clay at depths of 0-4 m and 2.5-8 m under both drained and undrained conditions, respectively. The pressuremeter test was conducted for gravel at 2.5-10 m depths, silty sand at 6-36 m depths and silty gravel at 30-40 m depths. The outcome of this study is to produce a reliable set of data which will allow engineers to make assumptions more effectively and to avoid the probability of project failure due to unreliable design input parameters. It is found that the Hardening Soil Model is able to represent the real soil behaviour compared to Mohr Coulomb Model. This is due to the stress-dependent stiffness feature in Hardening Soil Model. Hardening Soil Model features a total of ten parameters and it is very renowned due to the stress-dependent stiffness attribute. The parameters of Hardening Soil Model of the residual soil from Kenny Hill Formation was also calibrated and a database was established.

Keywords: Stiffness parameters, Hardening Soil Model, Kenny Hill Formation, pressuremeter test, triaxial test

INTRODUCTION

In recent years, Kuala Lumpur and its surrounding areas have become the fastest growing part in Malaysia. This has directed to multifaceted construction which limits the space and traffic. One of the mega projects is the Klang Valley Mass Rapid Transit (KVMRT) system, of which the construction of the first line was kicked off in 2012. The project involves the complex geological conditions of the Kenny Hill Formation and Kuala Lumpur Limestone. This study only focuses on the residual soil from Kenny Hill Formation. This formation is one of the common sedimentary rock formations generally found in region of Kuala Lumpur and Klang Valley, Malaysia (Mohamed *et al.,* 2007). Soil is a heterogeneous material that behaves non-linearly. When subjected to stresses, soil shows anisotropic and time dependant behaviour (Ti *et al.,* 2009).

Soil constitutive model has been developed to understand the behaviour of soil, which is essentially a model that describes the interaction behaviour of the soil when subjected to construction induced stress. The predominant soil constitutive model is the Mohr Coulomb Model which had always been used for relating the soil mechanism based on linear elasticity and perfect plasticity concept. However, because soil behaves differently at each stage of loading condition (Ti *et al.,* 2009; Yin & Chang, 2013), it can be more complicated to be simulated by Mohr Coulomb Model. Therefore, to implement such behaviour in a constitutive model, researchers have developed the Hardening Soil (HS) Model and Hardening Soil Small Strain (HSS) Model. This study however gives priority to the HS Model because HSS Model is a more advanced constitutive model which deals with more complex parameters. In addition, the study of stiffness parameters of residual soil from the Kenny Hill Formation is not a popular scope among researchers. Therefore, it is recommended to start with the HS Model, which is formulated based on plasticity theory and stress dependent stiffness (Surarak *et al.,* 2012).

This paper discusses the calibration of stiffness parameters for HS Model in Kenny Hill Formation residual soil using data from pressuremeter test and triaxial test. When dealing with soil constitutive models, it is advisable not to apply the soil parameters obtained from laboratory or *in situ* tests directly as it may not behave accordingly in the simulation process (Brinkgreve *et al.,* 2016). This is because the simulation of the deformation and stress-strain behaviour of soil will assume the soil behave as the input of soil parameters under the constitutive model. Furthermore, the soil parameters obtained from laboratory test have a tendency to be at the lower bound due to the disturbed state of the sample that is different from those acquired from *in situ* test or empirical correlation and consequently, leading to variation from real soil behaviour (Hsiung *et al.,* 2018). To ensure the constitutive model parameters can simulate the real soil behaviour and to minimize variations between measured and computational end results, calibration of the soil parameters are necessary (Abed *et al.,* 2014).

In the case of capturing the settlement trough for a tunnel excavation, the Hardening Soil parameter should be calibrated before used in the simulation. The settlement obtained will be with a surface heave although the surface heave will only occur for certain criteria such as extremely soft soil condition. For example, the settlement will be with a surface heave as shown in Figure 1, where the reason for surface heave to happen do not exist in the particular area or section. To avoid such unrealistic settlement during simulation, the real soil behaviour must take into consideration and collaborate with the soil constitutive model. Moreover, the Hardening Soil Model is a complex model compared to Mohr Coulomb Model where it is recommended to calibrate the parameters and verify whether the parameters represent the real laboratory results. Calibration can be done by referring to the laboratory test and *in situ* test measurements. The basic calibration process includes experimental data collection, output of soil testing results, numerical simulation of soil testing and data optimization (Abed *et al.,* 2016). The soil parameters were adjusted during calibration process, to ensure that the simulated test results match the experimental test results. Both tests were simulated using the PLAXIS 2D software.

STUDY AREA

Kenny Hill Formation is located at the heart of Kuala Lumpur and hence, it exhibits numerous remarkable existing buildings above it. Figure 2 shows the bedrock in Kuala Lumpur where most of the area is underlain by Kenny Hill Formation and Kuala Lumpur Limestone. Because of the tropical condition of Malaysia, the weathering profile and the rock mass has undergone some changes and exhibit heterogenous physical deterioration. The rocks in the Kenny Hill Formation such as sandstone, siltstone and shale have been subjected to low grade metamorphism which transformed the sandstone to quartzite and shale to phyllite (Mohamed *et al.,* 2007). The Kenny Hill Formation also comprises residual soil that is mainly derived from weathered sedimentary rocks where it characterized in terms of plasticity, density and nature of the residual soil (Tan & Siti Farah Ezdiani, 2005). Many mega developments and projects had been carried out over the Kenny Hill Formation. One of it is the Klang Valley Mass Rapid Transit (KVMRT) system that was launched with the aim of improving and transforming Kuala Lumpur public transportation coverage and solve the traffic congestion issue. Figure 3 shows the Klang Valley Mass Rapid Transit (KVMRT) system route across the Kenny Hill Formation and Kuala Lumpur Limestone. The uniqueness of this project is that the tunnels were excavated using the world's first Variable Density TBM (VDM) which was designed mainly for excavation in complex and varying geological conditions (Wallis & Kenyon, 2014). The machine has the ability to change its

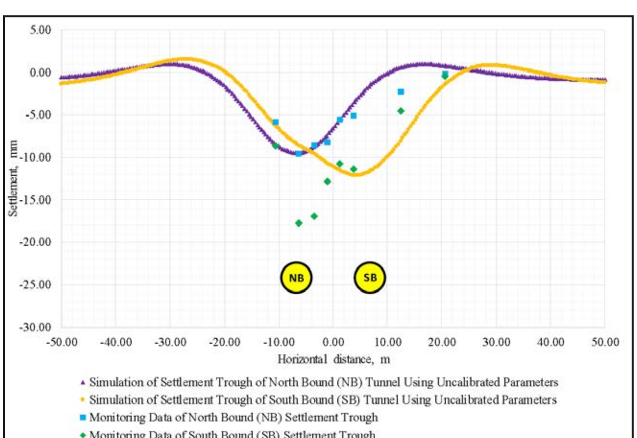

Figure 1: Simulation of tunnel settlement trough with uncalibrated parameters.

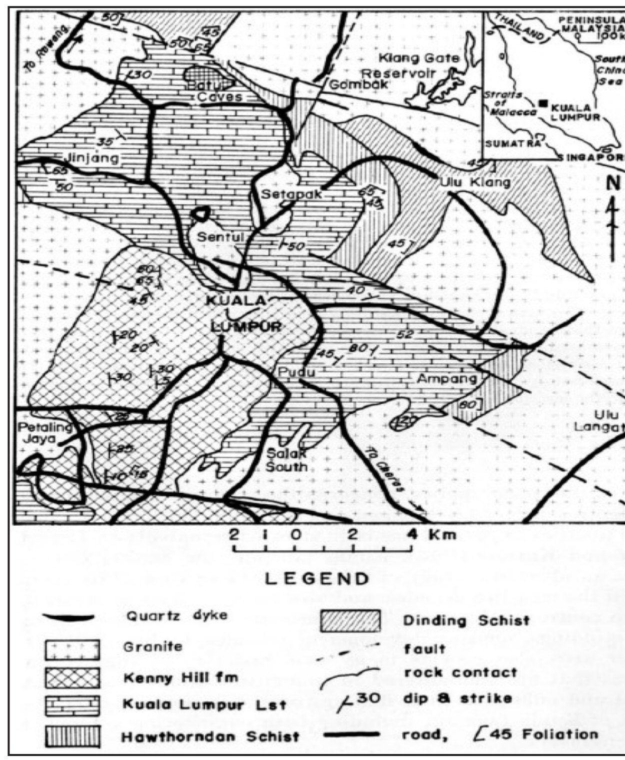

Figure 2: Bedrock Geologic Map of Kuala Lumpur area (Tan & Komoo, 1990).

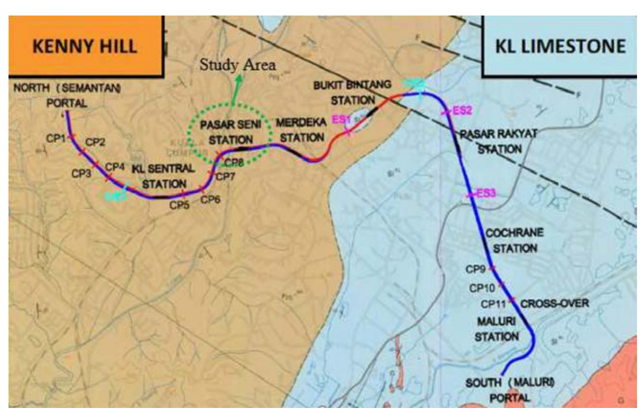

Figure 3: Klang Valley Mass Rapid Transit (KVMRT) System route and the study area (Source: Wallis & Kenyon, 2014).

mode of operation accordingly when it passes through two totally different geological formations, such as the Kenny Hill Formation and Kuala Lumpur Limestone. This study however will only concentrate on boreholes data from the Pasar Seni Station.

METHODOLOGY

Overview

This study will benefit the underground excavation projects mainly in the Kenny Hill Formation, especially in terms of HS parameters and hence enable engineers to assume adequately to avoid any unanticipated problems. Consequently, the safety of tunnel construction can be increased while allowing the most viable tunnel design and construction. This research begins with preliminary studies and data collection from relevant published papers. In depth review on Mohr Coulomb and Hardening Soil models was also conducted. Useful experimental and boreholes data from the Klang Valley Mass Rapid Transit (KVMRT) project was collected and analysed accordingly. The laboratory and field test data were used to justify the range of parameters assigned in the analysis. First, the result from the *in situ* and laboratory tests were used to derive the initial input parameters. A range of boreholes was chosen in this study and a soil profile was drawn to represent the soil condition in the study area. The *in situ* and laboratory tests involved are the triaxial and pressuremeter tests. The initial parameters for Hardening Soil Model were then derived from the borehole results. Subsequently, the simulation process was carried out after the initial input parameters were determined. The pressuremeter and triaxial tests were then simulated using the PLAXIS 2D software. Through the PLAXIS 2D software, the simulated stress strain curve was then compared to the reference stress strain curve and the stress strain curve from *in situ* pressuremeter test and experimental triaxial test. The soil is believed to be far more undisturbed with the pressuremeter test compared to the triaxial test as the soil is relatively hard to be extracted down to the 40 m depth beneath the earth surface. However, due to the limitation of pressuremeter test that it cannot be used on shallow layers, stress-strain curve from triaxial test is preferred for shallow layers. Regression analysis was then carried out to verify the assumed parameters is accurate and can be used to represent the real soil behaviour. An iteration of input parameters was carried out to ensure the reliability of data through matching the simulated pressuremeter test result to the *in situ* and laboratory test result.

Calibration process

The calibration process was broken down into three phases and is shown in Figure 4.

Initial data for simulation

For the simulation of the initial data, the initial input parameters were fixed. Among the ten parameters involved in Hardening Soil Model, the four advanced parameters, which are E^{rf}_{ur}, v_{ur}, R_f and K_0 were given a fixed value while the remaining six basic parameters were subjected to optimization in the regression analysis. Table 1 shows the Hardening Soil Model's input parameters as well as it's parameter evaluation methods. The stress strain behaviour in primary loading is highly non-linear but hyperbolic, the parameter E_{50} is a confining stress dependent stiffness modulus for primary loading. The E_{50} is used as an alternative of the initial modulus E_0 for small strain which, as a tangent modulus is harder to represent the soil behaviour. However, as E_{50} is hard to determine experimentally, it is given as in Equation 1.

$$E_{50} = E_{50}^{ref} \left(\frac{c'\cos\phi' - \sigma'_3 \sin\phi'}{c'\cos\phi' + p^{ref} \sin\phi'}\right)^m \tag{1}$$

Where E^{ref}_{50} is reference stiffness modulus corresponding to the reference stress which is 100 kPa recommended in the default setting of PLAXIS software. The amount of stress dependency, m was first assumed to be 1 to simulate

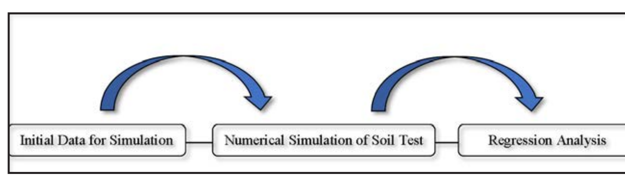

Figure 4: Calibration approach.

Table 1: Hardening Soil Model parameters (Surarak *et al*., 2012).

Parameter	Description	Parameter Evaluation
ϕ'	Internal Friction Angle	Slope of Failure Line from MC Model
c'	Cohesion	Y-Intercept of Failure Line from MC Model
Rf	Failure Ratio	0.9 (Default Setting)
φ	Dilatancy Angle	Function of $\varepsilon_a$and ε_v
E_{50}^{ref}	Reference Secant Stiffness from Triaxial Test	Y-intercept in log $(\frac{\sigma_3}{p^{ref}})$–log (E_{50}) space
E_{oed}^{ref}	Reference Tangent Stiffness from Oedometer Primary Loading	Y-intercept in log $(\frac{\sigma_1}{p^{ref}})$–log (E_{oed}) space
E_{ur}^{ref}	Reference Unloading/Reloading Stiffness	Y-intercept in log $(\frac{\sigma_3}{p^{ref}})$–log (E_{ur}) space
m	Exponential Power	Slope of trend line in log $(\frac{\sigma_3}{p^{ref}})$–log (E_{50}) space
v_{ur}	Unloading/Reloading Poisson/s Ratio	0.2 (Default Setting)
K_0^{nc}	Coefficient of Earth Pressure at Rest	$1-sin\phi'$ (Default Setting)

the logarithmic stress dependency, it was further modified based on the study of Soos (2001). The range of m should vary from 0.5 to 1.0 in different soil type and the clay soil falls in the range of 0.9-1. In PLAXIS, E^{ref}_{ur} is given as $3E^{ref}_{50}$ as the default setting for practical case. E_{ur} will be extracted from the pressuremeter test result which is more reliable than extracting it from triaxial test. However, the E^{ref}_{oed} which is the reference oedometer moduli that controls the magnitude of plastic strains does obey to the stress dependency law and the formula is as given in Equation 2. At this stage, triaxial tests of different soil layers were analysed to obtain the strength and stiffness parameters. The stiffness parameter E^{ref}_{50} can be obtained and hence finding the remaining stiffness parameters will be through correlation. The E^{ref}_{oed} is assumed to be 0.8 to $1.2E^{ref}_{50}$.

$$E_{oed} = E^{ref}_{oed}\left(\frac{c'\cos\phi' - \sigma'_1 \sin\phi'}{c'\cos\phi' + p^{ref}\sin\phi'}\right)^m \qquad (2)$$

Numerical simulation of soil test

With the key initial input parameters being fixed, simulation of pressuremeter test and triaxial test can be carried out. As the pressuremeter test result was available, the stress-strain curve from the pressuremeter test was used as the reference curve and serves as the target of the regression analysis to be obtained. For the simulation process, the parameters was entered into PLAXIS 2D and the stress strain curve was then obtained.

The simulation method is differentiated into two types. Triaxial test and pressuremeter test were simulated using the simplified axisymmetric geometry. The triaxial test was simulated for the soils found at shallow layers typically 0 – 10 m depth which are the sand and sandy clay layer. Although pressuremeter is said to be more reliable than triaxial test and the specimen are considered less disturbed, due to the limitation of pressuremeter test data in shallow layer, triaxial test simulation is chosen. However, for gravel, silty gravel and silty sand type of soils, the pressuremeter test simulation was done. The HS Model as implemented on the Finite element program PLAXIS 2D was used to study the Young's modulus of the residual soil from Kenny Hill Formation. Unlike Mohr Coulomb Model, HS Model consists of several stiffness parameters, the oedometer stiffness and unloading-reloading stiffness were set equal to $1.0E^{ref}_{50}$ and $3.0E^{ref}_{50}$ respectively.

Triaxial test and pressuremeter test modelling

The triaxial tests simulation was done on sand and sandy clay layers. The triaxial tests was modelled in PLAXIS finite element software by means of an axisymmetric geometry of 1m x 1m unit dimensions. This unrealistically huge dimension of the model will not affect the results as the soil samples are set as a weightless material. The simplified geometry in the triaxial model will represent one quarter of the soil sample. The deformations along the boundaries were kept free to allow for a smooth movement along the axes of symmetry, while the deformations perpendicular to the boundaries were fixed. In triaxial simulations, both sand and sandy clay layers were simulated and compared to the reference triaxial test. For sand and sandy clay layers, the soil was simulated as drained and undrained respectively.

The pressuremeter tests simulation was done on gravel, silty gravel and silty sand layers and were modelled in PLAXIS finite element by the means of an axisymmetric. Each pressuremeter test was simulated to the one carried out in the field which comprises of loading, unloading and reloading the soil to a specific pressure. Borehole data was studied and modelled in PLAXIS 2D, the borehole is assumed to be of 0.06 m radius which the soil had been cut and deactivated for 0.06 m followed by the lateral load applied at the centre of loading probe. The node and stress point defined in the mesh were chosen to be at the centre of the loading probe or the one closest to it. The simulated result was compared to the reference pressuremeter test result.

Regression analysis

Inverse analysis procedure in this study combines a finite element analysis and a parameter optimization algorithm to efficiently calibrate a soil model by minimizing the errors between computed responses and experimental observations. However, identifying the vital parameters to be included in the inverse analysis can be challenging. It is not possible to use the regression analysis to guess every input parameter of a given simulation. The number and type of input parameters that one can expect to estimate at the same time depend upon many factors, including the characteristics of the selected soil model, the features of the simulated system, and computational time issues. Therefore, in our study, only 5 basic parameters are subjected to optimization for regression analysis, these are the cohesion, friction angle, secant stiffness in standard triaxial test, tangent stiffness for primary oedometer loading and stiffness for unloading and reloading. The calibration process was repeated until the simulated stress strain curve matches with the reference curve.

RESULTS AND DISCUSSION

Nonlinear behaviour of soil and stress dependent stiffness

As illustrated in Figure 5, the real soil behaviour resulted from triaxial test has shown the nonlinearity attribute of the sand in Kenny Hill Formation. The real soil behaviour was observed from triaxial test and was used to compare the simulation from Mohr Coulomb and Hardening Soil Model. As shown in Figure 5, the real soil behaviour was much more complicated to be simulated by a Mohr Coulomb Model. Moreover, Mohr Coulomb Model often underestimate the soil strength at low stress level while overestimating the soil stress limit at high stress level. However, this problem can be solved by using Hardening Soil Model. Hardening Soil Model features the nonlinear stress strain relationship and this nonlinearity attribute can be important in many practical problems. From Figure 5, the real soil behaviour resulted from triaxial test has shown the nonlinearity attribute of the stress-strain relationship. This behaviour is influenced by the stiffness associated with the soil. However, the prevalent Mohr Coulomb Model features only one stiffness which describes the soil properties as elastic for stress level below the yield point. This has led to underestimation or even overestimation of the soil strength. Unlike Hardening Soil Model, the usage of few stiffness parameters such as tangent stiffness for primary oedometer loading, secant stiffness of triaxial test, unloading and reloading stiffness as well as the power for stress level dependency.

Hardening soil model parameter calibration

As shown in Figure 6, the initial estimation of the Hardening Soil Model's parameters through test results could not represent the real soil behaviour (*in situ* pressuremeter test and laboratory test triaxial test data). It showed poor agreements among all the stress-strain and stress path relationships and therefore, a series of data calibration processes was carried out. The simulated test data was compared with the field and laboratory test data, followed by the parameters optimization to produce the best fit results to the matching of stress-strain and stress path relationships.

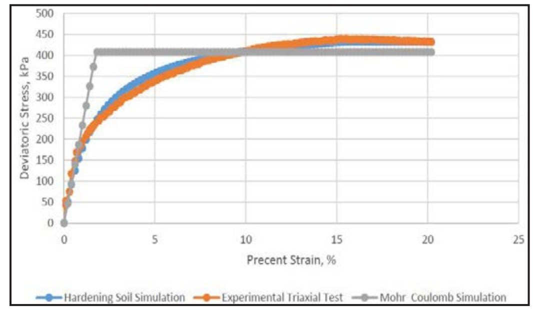

Figure 5: Real soil behaviour of Kenny Hill Formation (sand layer).

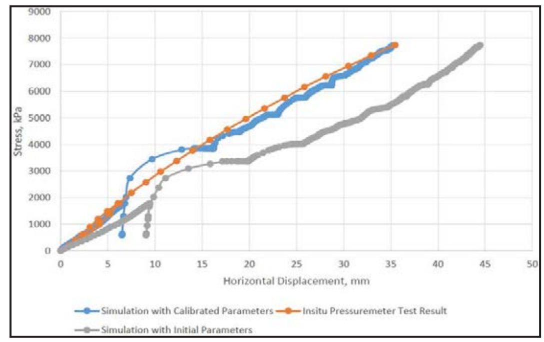

Figure 6: Stress versus horizontal displacement plot.

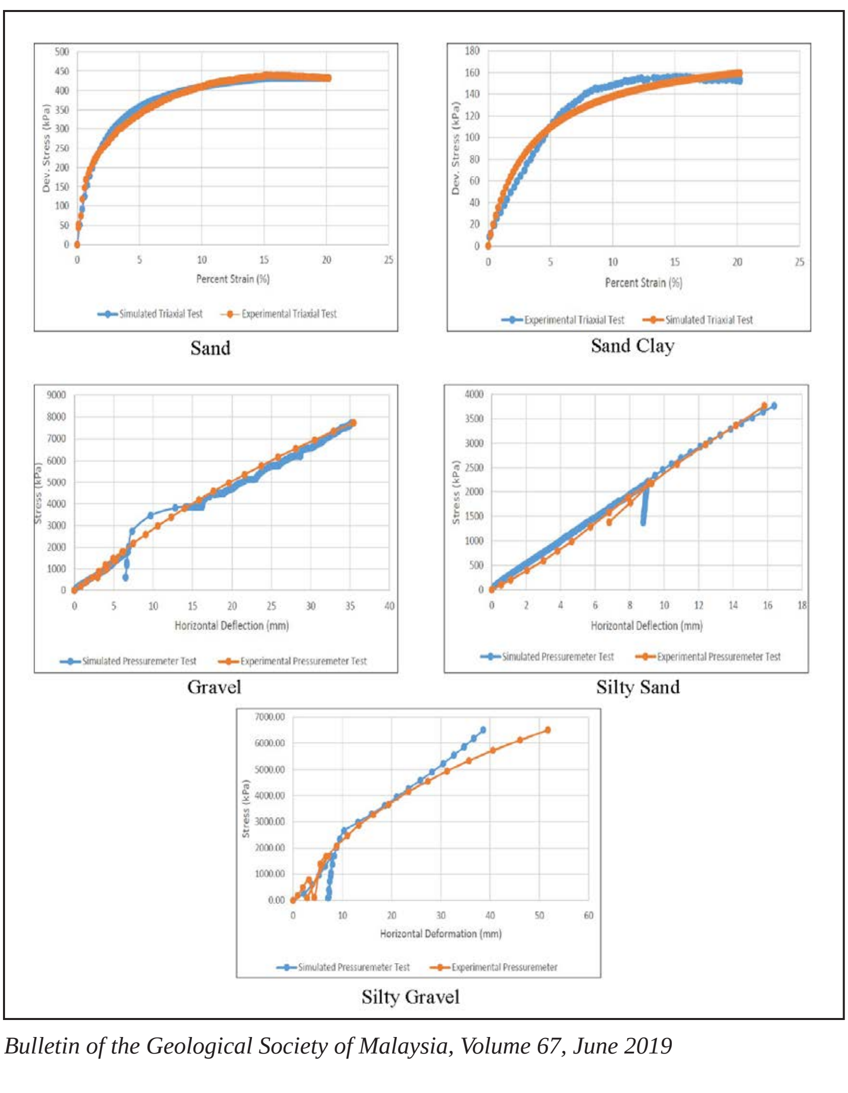

Figure 7: Stress versus horizontal deflection plot for all types of soil.

Table 2: Summary of calibrated hardening soil parameters.

Soil Type	Depth (m)	φ' (deg)	$\emptyset'$ (deg)	c' (kPa)	E^{ref}_{50} (kPa)	E^{ref}_{oed} (kPa)	E^{ref}_{ur} (kPa)	R_f	m	K^{nc}_0	v_{ur}
Sand	0-4	0	37	0	11000	11000	33000	0.9	0.65	0.3982	0.3
Sandy Clay	2.5-8	0	85 ($s_{u,ref}$)		2500	2500	7500	0.9	1.0	0.3982	0.3
Gravel	2.5-10	0	50	10	140000	100000	340000	0.9	0.5	0.234	0.3
Silty Sand	6-36	0	50	39	75000	60000	150000	0.9	0.75	0.3707	0.3
Silty Gravel	30-40	0	33	1	70000	40000	140000	0.9	0.5	0.4701	0.3

The parameter calibration result for all soil types is shown in Figure 7. A summary of calibrated Hardening Soil parameters is presented in Table 2.

CONCLUSIONS

This study covers the residual soil from Kenny Hill Formation typically around the Pasar Seni Station. The Mohr Coulomb Model and the HS Model assume soils behaviour in a different manner and hence giving a different stress strain relationship. These two models were compared and it was found that HS Model can be modelled to represent real soil response in terms of stress-strain relationship, thus eliminating the risk of over or underestimating the soil strength when modelled with the Mohr Coulomb Model. The stress dependent stiffness allows the HS Model to cater to the non-linear stress strain relationship while enabling the simulated soil to react differently under unloading and reloading action. It can be concluded that the HS Model is more suitable to represent real soil behaviour compared to the Mohr Coulomb Model. Specifically, in situation where it involves mobilization of shear strength, or reduction of mean effective stress due to activities such as unloading and reloading as in the case of underground excavation like tunnelling. The modelling procedure described in this paper combines a numerical simulation and a parameter optimization system to efficiently calibrate a soil model by minimizing the difference or errors between computed response and experimental. With this procedure it can increase the database reliability as well as produce a more comprehensive data as compared to the initially calibrated models. The calibration of stiffness parameter is used to establish a relationship between experimental and simulated data. The experimental and simulated data can be used as a guideline or approach in dealing with complex soil formation. A better understanding of the problem is required to define an adequate optimization on which parameter to change when dealing with finite element simulation of a soil test and calibration procedure.

ACKNOWLEDGEMENTS

The author express gratitude to USM Fellowship program for providing financial assistance in the form of scholarship. In addition, this work was supported by the FRGS grant from Ministry of Education Malaysia for the topic on “Establishment of Kenny Hill Small Strain Stiffness Parameter and Stiffness Degradation curve for sustainable urban underground Infrastructure Development in Malaysia” [FRGS 1/2018/TK08/USM/02/2]. Moreover, the authors gratefully acknowledge the lecturers and peers of School of Civil Engineering, Universiti Sains Malaysia for the successful completion of this study.

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Manuscript received 3 July 2018
Revised manuscript received 16 January 2019
Manuscript accepted 27 March 2019