Comparison of Rectangular Tunnel with Shield Jacking Support and Pipe Roof Support in Finite Element Method

M. Y. M. Nasir, H. Mohamad, and H. Alarifi

Abstract Methods of the Gaussian distribution curve and Finite Element Method (FEM) were applied in predicting ground settlement however, those equations are still incomplete with a trough width parameter, *K* of soil condition that has evolved from the developing of Kenny Hills tunnel in Malaysia. Therefore, this paper of research analyses pipe roofing and shield support of rectangular tunnel using FEM by PLAXIS 2D software to estimate in occurrences of ground deformations. Charts of maximum ground surface settlement and trough width parameter are developed to show the difference between both lining supports through parametric study comprises variation of soil properties. Results show that pipe roofing support is suitable to be adopted in weak soil condition while shield support is suitable in soil condition with higher stiffness value. *K* can be concluded with value equal to 0.6 for the rectangular pipe roofing support and 0.7 for rectangular shield support in Kenny Hills soil formation.

Keywords Rectangular · Tunnel · Shield · Pipe · Support

1 Introduction

Rectangular tunnel is becoming popular and has been used in constructions especially by developed country. Hence, for the past few decades improvements have been done on its support systems in order to prevent deformation of ground especially on a weak ground condition. Generally, shield and pipe roofing support were used for constructing rectangular shaped tunnel.

Fang et al. [1] have go through on shield support and Koyama [2] has discussed further on the benefits of the shield support. Koyama [2] found shield support can be applied in different type of soil condition [2] due to rigid structure of shield while pipe roofing support can prevent the settlement of ground above the tunnel using a

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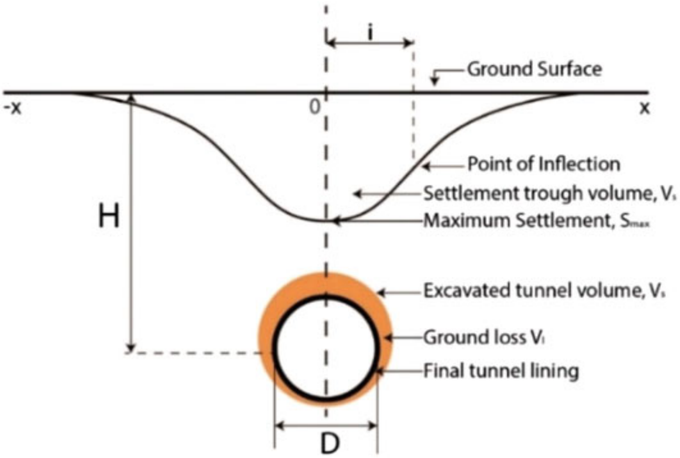

Fig. 1 Settlement trough of Gaussian form

series of steel pipe by consolidate the ground stress and disperse the ground stress to reduce the excavation stress during the tunnel excavation work [3]. The design of the pipe roof support may vary between the project because it solely based on experience [4].

Ground deformation is a major problem that crucial to be solved prior to develop the underground systems which is not able to be seen directly through underground layout. Furthermore, different properties and different characteristics of underground soil at different coordinate makes prediction on ground deformation hardly to be calculated manually. Therefore, simulation will be done to predict amount of risk and to identify the affected surrounding and structure constructed in underground space.

In order to determine the settlement above the tunnel, Peck [5] proposed an equation to develop transverse settlement above the tunnel known as Gaussian distribution curve as shows in Fig. 1.

Equation 1 give a settlement at various point of the trough,

$$S_x = S_{\max} e^{-\frac{x^2}{2ix^2}} \tag{1}$$

where:

S_x the settlement profile at the surface
S_{max} the maximum vertical settlement
i_x the trough width parameter which, physically, is the distance from the tunnel axis to the point of inflection of the curve.

Volume of the surface settlement profile is given by,

$$V_s = \sqrt{2\pi} i_x S_{\max} \tag{2}$$

$$i_x = Kz_0 \tag{3}$$

where

K constant value
z_0 depth of the tunnel axis.

The width through parameter, K, varies with the type of soil. Kimura and Mair [6] suggested that K values must be equal to 0.5 for clay soil. Meanwhile, O'Reilly and New [7] recommend that K values must be between 0.2 and 0.3 for granular soil with condition of tunnel depth less than 10 m, 0.4–0.5 for stiff fissured clay, 0.5–0.6 for Glacial deposits and 0.6–0.7 for silty clay deposits. O'Reilly and New [8] also had suggested K values must be 0.4 for stiff clays, 0.7 for soft silty clays. In contrast, Mair and Taylor [9] suggested differently in K values where K values that they emphasized were 0.5 for all clay soil and 0.35 for granular soils. Khoo et al. [10] stated that an appropriate K to be used was 0.5 for soil type encountered in Klang Valley of Malaysia. On the other hand, Yeates [11] suggested that K value should be from 0.2 to 0.3 for granular material above the water table. Moreover, Rankin [12] had proposed K value which were 0.4–0.5 for stiff fissured clay, 0.5–0.6 for glacial deposits, 0.6–0.7 for silty clay. Overall K is depending on soil properties that significant to consider even though K value does not include in the Gaussian curve distribution that mostly used by researchers, due to none of the research had found K value that specifically use for rectangular or box tunnel. In addition, all trough width parameter is produced by analyze the circular tunnel cross-section. Hence, this research study aims at producing charts for the tunnel designer in estimating the maximum settlement and searching tough width parameter value for the rectangular tunnel with either shield support or pipe roof support located at Kenny Hill soil condition.

2 Kenny Hills Soil Formation

Mostly, Kuala Lumpur, Malaysia covers Kenny Hill soil formation. This type of soil consisting of interbedded shales, mudstone, siltstone, and sandstones. Kenny Hills soil has undergone some metamorphic events resulting in changes of sandstone/siltstone to quartzite and schist/phyllite respectively. As stated by Ooi [13], the depth of Kenny Hills soil layer will be more than 10 m below the existing ground level and the soil formation becomes very hard with SPT greater than $N = 50$.

The investigation of the Kenny Hills engineering properties has been done by Refs. [14, 15]. From their study, the measured bulk unit weight mostly ranged from 15.8 to 21.9 kN/m^3 for residual soil and for highly weathered rock (Grade IV) is 24.0 kN/m^3.

For the effective shear strength parameters, [15] has stated that for the residual soil with SPT $\leq$ 100, the range for cohesion, c' is from 5 to 10 kN/m^2 and for angle of friction, φ' is 28° while for the soil which has SPT greater than 100, the cohesion, c' is 15 kN/m^2 and angle of friction, φ' is 29°. For highly weathered rock (Grade IV), the equivalent Mohr–Coulomb strength parameters are 30 kN/m^2 for cohesion, c' and 34° for an angle of friction, φ' [16].

3 Method of Analyses

The simulation is based on greenfield model with setting as follows:

Model Dimension = 40 m × 40 m
Surcharge Load = 0 kPa
Soil Layer = Homogenous Soil
Tunnel Depth = 15 m.

The boundary condition is fixed by standard fixities, where the side vertical boundaries are fixed in horizontal x-direction but free to move vertically, while the bottom boundary is restrained from any movement in all directions.

For lining support, the steel pipe will be used in the simulation of pipe roof support with an outer diameter of 813 mm with 16 mm thickness. The steel pipe will be used as a pipe roof with grade S275. The tunnel shield support specification will set as in Table 1.

3.1 Parametric Study

Each simulation in PLAXIS 2D software will have one variable parameter and constants for other parameters by Hardening Soil method in as in Table 2.

Table 1 Shield support properties

Parameter	Value
Behavior type	Elastic
Thickness (m)	0.35
Stiffness (MPa)	21,000
Specific weight (kN/m^3)	38
Poisson's ratio	0.3

Table 2 A typical range of Kenny Hill soil for simulation

Soil parameters	Study case	Constant value	Variable value
General properties	y_{unsat} (kN/m^3)	$y_{sat} = 20$ kN/m^3 $c' = 5$ kPa $\varphi' = 28$ $E = 25$ MPa $v = 0.3$	$y_{unsat} = 15, 15.5, 16, 16.5, 17, 17.5, 18$
	y_{sat} (kN/m^3)	$y_{\text{unsat}} = 19$ kN/m^3 $c' = 5$ kPa $\varphi' = 28$ $E = 25$ MPa $v = 0.3$	$y_{sat} = 20, 20.5, 21, 21.5, 22$
Strength parameter	c' (kPa)	$y_{sat} = 20$ kN/m^3 $y_{unsat} = 19$ kN/m^3 $\varphi' = 28$ $E = 25$ MPa $v = 0.3$	$c' = 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25$
	φ' (°)	$y_{sat} = 20$ kN/m^3 $y_{unsat} = 19$ kN/m^3 $c' = 5$ kPa $E = 25$ MPa $v = 0.3$	$\varphi' = 20, 22, 23, 25, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 38, 40$
Stiffness	E (MPa)	$y_{sat} = 20$ kN/m^3 $y_{unsat} = 19$ kN/m^3 $c' = 5$ kPa $\varphi' = 28$ $v = 0.3$	$E = 20, 30, 50, 75, 100, 150, 200, 250$
	v	$y_{sat} = 20$ kN/m^3 $y_{unsat} = 19$ kN/m^3 $c' = 5$ kPa $\varphi' = 28$ E = 25 MPa	$v = 0.1, 0.15, 0.2, 0.25, 0.3$

4 Result

4.1 Relationship Between Maximum Settlement and Soil Parameter

The amount of soil settlements affects the degree damage of the ground surface. Therefore, factors of settlement need to be identified at first in order to ensure least ground deformation. Water content within the soil is one of the factors that determine the level of settlement. Figure 2 proven a higher level of water in soil properties that cause greater settlement from applying for rectangular shield supports. However, rectangular pipe roof supports show a striking effect of constant settlement although water content level is increasing. This condition occurs because pipe roof support provide advance protection for soil deformation caused by tunnel excavation work

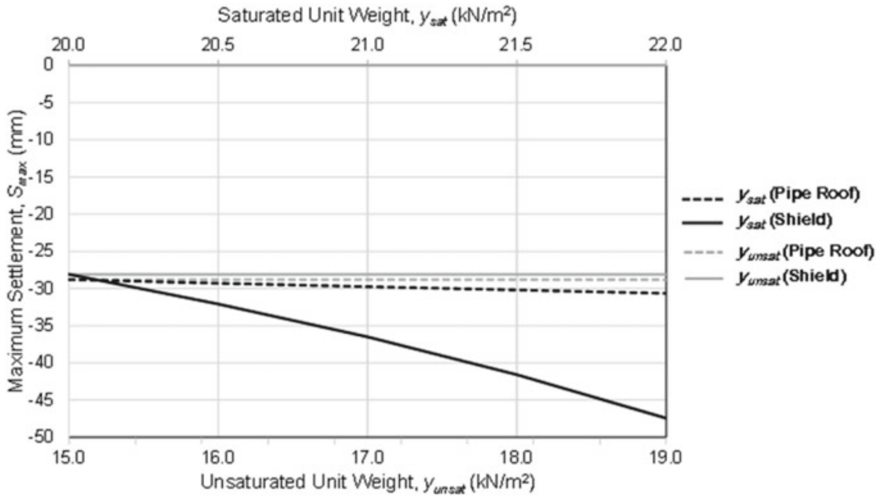

Fig. 2 Relationship between maximum settlement and general properties

while shield support provide soil protection just before the excavation. Next, cohesion and angle of friction as illustrated in Fig. 3 also affecting soil interaction when the pattern of settlement is decreasing inversely to cohesion and angle of friction of the soil with rectangular shield support. On the other side, rectangular pipe roofing support will be maintaining a constant settlement with increasing value of cohesion and angle of friction. Hence, constructing a rectangular pipe roofing support can

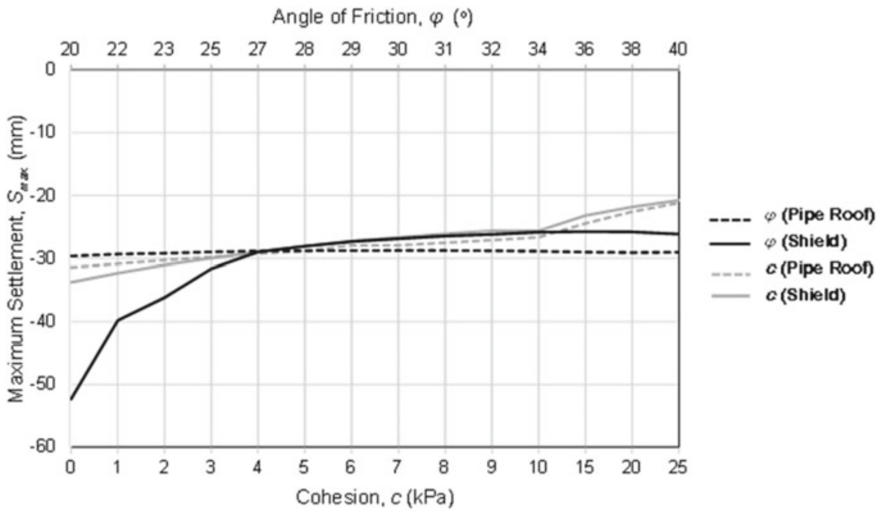

Fig. 3 Relationship between maximum settlement and shear strength properties

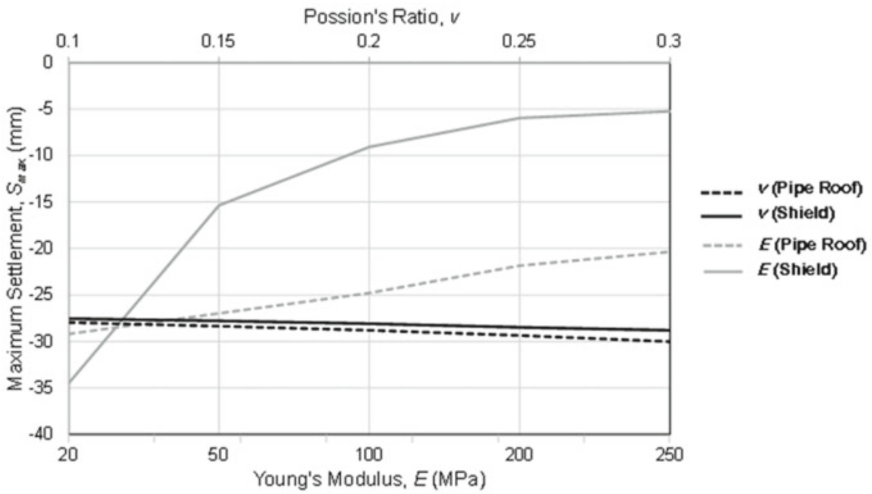

Fig. 4 Relationship between maximum settlement and stiffness properties

minimize the soil interaction thus reduce soil deformation at any degree of cohesion and angle of friction. Figure 4 illustrated a comparison between Young's modulus and Poisson's ratio towards soil settlement and results show reducing settlement with increasing Young's Modulus value on rectangular pipe roofing support which similar to the result of rectangular shield support. However, pipe roof supports produce less settlement reduction compared to shield support because of steel pipe installation for pipe roof support has disturbed the soil stiffness around the support's perimeter. Poison's ratio shows no effect toward the ground surface settlement for both supports.

4.2 Relationship Between Trough Width Parameter and Soil Parameter

By fitting the Gaussian distribution curve graph into the FEM graph, the value of the trough width parameter can be produced as a reference to estimate ground surface settlement in constructing any rectangular tunnel project which has approximate similar soil condition. Hence, investigations to determine a trough width parameter, *K* were done and mostly *K* value for rectangular pipe roofing support is 0.6 and *K* value for rectangular shield support is 0.7. In this study, the range of the trough width parameters are between 0.4 and 0.7 effected by saturated unit weight, angle of friction, cohesion and Young's modulus values used. Figure 5 illustrated the increment of water level within soil due to lesser in *K* value for rectangular shield support, while Fig. 6 resulted in inconsistent *K* value which between 0.6 and 0.7 for both angle of friction and cohesion properties. Hence, it is significant to further study in angle of friction and cohesion properties of soil that affected the *K* value inn understanding

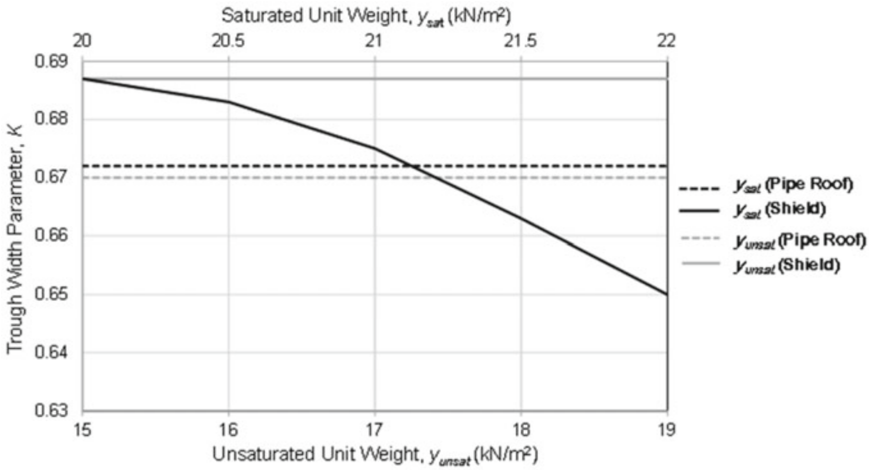

Fig. 5 Relationship between trough width parameter and general properties

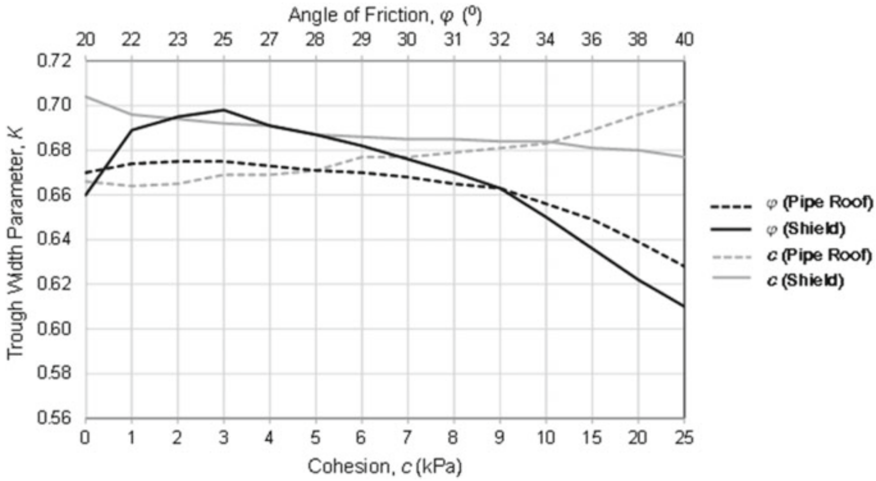

Fig. 6 Relationship between trough width parameter and shear strength properties

the stress of soil. Meanwhile, Fig. 7 illustrated reduction on K value from 0.7 to 0.4 when the value of Young's modulus increases for both types of supports with approximately constant K value on Possion's ratio properties. It can be concluded that unsaturated unit weight and Poisson's ratio properties give no effect to K value for rectangular tunnel with shield of pipe roof support.

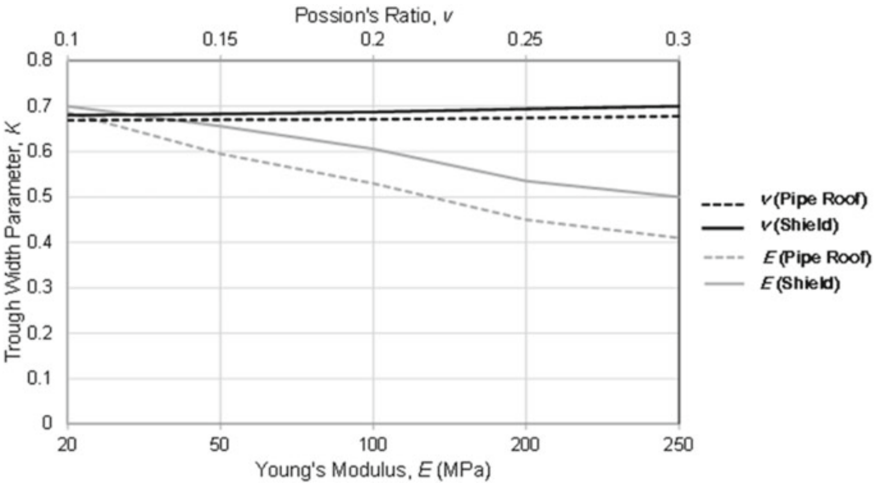

Fig. 7 Relationship between trough width parameter and stiffness properties

5 Conclusion

Previous literatures are yet discovering the trough width parameter use in constructing a rectangular tunnel cross-section. Hence, this simulation and analyses were done to investigate on the maximum settlement and trough width parameter for rectangular pipe roofing and shield support using Kenny Hill soil condition. The outcome of applying rectangular pipe roofing resulted in the suitability of constructing this type of support within the soil with properties of high-water content can still ensure the reduction of ground surface settlement. Furthermore, the result obtains also shows that by constructing a rectangular tunnel with pipe roof support, it is only suitable to be applied for low soil stiffness because the affected area by the pipe excavation in higher soil stiffness will increase soil plasticity area, hence reduction of ground surface settlement is lower. Meanwhile, a rectangular tunnel with shield support gives better respond in reducing the ground surface settlement in soil with high stiffness as shield support only involves with jacking process. Besides that, stiffness of soil is important to be considered prior to all construction works because it will affect the soil deformation during the excavation either rectangular pipe roofing or shield support. Finally, the trough width parameter value can be concluded with K equal to 0.6 for the rectangular pipe roofing support and 0.7 for rectangular shield support in Kenny Hills soil formation.

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