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Soil Settlement and Tunnel Deformations Pattern Analysis of Underground Single Tunnel MRT Putrajaya Line Using Finite Element Method

Syaibatul Nur Eizzaniq Azhar[1], Muhamad Faiz Abd Latif[1], Ahmad Syazwan Mohd Sukarno[2], Thanath Gopalan[2]

[1]Department of Transportation Engineering Technology, Faculty of Engineering Technology,
Universiti Tun Hussein Onn Malaysia, 84600, Pagoh, Johor, MALAYSIA

[2]Department Putrajaya Line Planning and Design, Mass Rapid Transit Corporation Wisma MRT (Project Headquarters), Jalan Gelenggang, Bukit Damansara, 50490 Kuala Lumpur, MALAYSIA

*Corresponding Author Designation

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Abstract: As the growth of Kuala Lumpur conurbation expands, traffic congestion is one of a major issue in many urban areas. By integrating many existing rail networks, MRTC had increase rail transportation opportunities by providing a premium quality service at a reasonable fare. The Putrajaya Line is the second line of the KVMRT Project after Kajang Line operated. The underground alignment of the PY line traversed through Kuala Lumpur Limestone, Granite and Kenny Hills Formation. The process of tunnel excavation will cause a disturbance to the surrounding soil, which is unavoidable. An engineer must observe the behaviour of soil that would cause ground movement during tunnel excavation. To predict the ground behaviour, the development of the Finite Element Method comes as an alternative solution. To design the tunnel and soil modelling using PLAXIS 2D version 2022 to see the output of settlement and tunnel deformed. There are three key parameters to see the effect of surface settlement and tunnel deflection: (1) tunnel depth, (2) groundwater level and (3) soil stiffness. The result analysis of surface settlement will be compared with real settlement on site with the design settlement. As for the analysis result, changing the three key parameters give impact to the surface settlement and tunnel deflection. On first parameter shows that the surface settlement and tunnel deformation decreasing by increasing the depth of tunnel, meanwhile the second parameter shows the surface settlement increasing and tunnel deflection decreasing as the groundwater level increase at below ground level. The final parameter determine the surface settlement produced decreasing, at the time the tunnel deformation increase as the soil stiffness increase from the original. However, at certain level, the settlement and tunnel deflection are at average because the sensitivity of soil are decreasing for the three

*Corresponding author: mfaiz@uthm.edu.my

parameter. This research is necessary for understanding the impact of surface settlement due to ground movement on the underground tunnel.

Keywords: Settlement, Tunnel Deformation, PLAXIS 2D, MRTC, Putrajaya Line

1. Introduction

The Putrajaya Line is the second line of the KVMRT Project developed after MRT Kajang Line operated. The alignment has a length if 57.7 km, with 44.2 km elevated tracks and 13.5 km running through underground tunnels. Putrajaya Line underground tunnel were traverse through Kuala Lumpur Limestone, Granite and Kenny Hill Formation [2]. A lot of excavation have been performed to complete the project.

The disturbance of surrounding soil that caused by tunnel excavation due to the construction of subway, this process is unavoidable. The excessive ground settlement and deformation effects from disturbance of surrounding medium may give a major impact to the ground structure and underground pipelines [1]. Tunnel design and construction require suitable technologies and techniques throughout all stages [6].

As a result, how to estimate the ground surface movement is concerned by engineers. Finite Element Method (FEM) or Finite Element Analysis (FEA) is the best method to approach the ground settlement and deformation due to the tunnel design. The FEA is a mathematical equation used in conjunction with the FEM to simulate how a particular model or design would react in the real world when stressed. Engineers utilize simulation to evaluate how different design elements interact and function under simulated pressures—using numerical solutions when a mathematical problem is too difficult to solve using standard methods [1].

PLAXIS is one of geotechnical finite element program that simulates soil behavior using soil models. This software contains capabilities for dealing with a variety of complex construction aspects. A finite element software includes the two-dimensional or three-dimensional study of deformation, stability, dynamics, and groundwater flow in geotechnical engineering, as well as tools to deal with various aspects of complex geotechnical constructions, are also included in this software [5].

As an engineer concerned, during design phase commonly faces such issues including complex boundary conditions that may change during construction and inelastic materials that cause deformations especially in MRTC project. Hence, the aim of this study is to:

1. To observe the effect of ground settlement during tunnel excavation
2. To analyse the ground settlement and tunnel deformation patterns of soil using Finite Element Method via PLAXIS 2D software.
3. To compare the analysed ground settlement with the actual real site data from MAXWELL.

To analyse the ground settlement and tunnel deflection, this study has select chainage at CH 26+620.000 in report Project MRTC-SSP Line-Final Design Stage: Geotechnical Interpretative Report Tunneling between ESC1 and TTWS [2].

1.1 The Factor of Ground Movement due to Tunnel Excavation

The tunnel excavation procedure involves removing large volume of underground geomaterials, which may cause in the relaxation of in-situ stresses within the vicinity of the tunnel, makes a displacement and local deformation inevitable. As the geometrical around the opening starts to move, the changing stresses within the vicinity of the tunnel directly affect the ground movement. It is very difficult to perfectly fit the lining instantly at the excavation opening event though tunnel linings are placed to reduce such movement resulting in some ground deformation, commonly known as the tunneling gap [3].

Tunneling through soils might cause ground losses due to many consequences such as face relaxation, radial take as the soil tightens around the permanent liner behind the shield, or ovalling of the excavation, causing surface settlement and transverse movement. It is important to estimate the effects upon the structure when the tunnel drive passes below an existing structure but the free ground deformations are not simply to be imposed upon a structure because the structure contributes to stiffening of the ground [4].

In case of groundwater, the groundwater level always remains at its initial level during tunnel excavation. However, if the excavations operates below water level it will affects the facility's operation and design, as well as the cost of construction [7]. To make a proper judgements, engineer must be aware of groundwater's potential consequences.

Understanding how the soil or rock surrounding a tunnel deform elastically in response to changes in stress is critical for solving subsurface engineering issues. Especially at opening tunnel excavation, the rock will not deform if the stress around the opening is not high enough which will cause the soil or rock deform elastically at very least [8]. The determination of soil stiffness during design phase is crucial for predicting the tunnel behavior induced by excavation.

During tunnel excavations can produced surface settlement which is significant issues in urban areas [9]. The settlement generated by cut's excavation that limit the distance equal to the depth of the cut. If a structure is erected near an excavation in sandy soil, the structure will be damaged and produced more settlement [10]. The result can be more disastrous when wrong type of foundations is installed on the wrong type of soil.

There are two requirements in the design and construction of tunnels and underground excavations: stability and serviceability. Due to the variable ground conditions, selecting an acceptable method is primarly based on experience in field rather than calculations based on theoretical knowledge; however there are no legitimate rule for it. It depends on a complex interplay between schedule considerations, cost and safety elements.

2. Materials and Methods

The methodology consists of the operation of PLAXIS 2D software for data input of tunnel and soil properties, calculation and processing result (Output) of ground settlement and deformation pattern of tunnel. A parametric study had been performed to analyse the several input parameter of material properties by using the material model of Hardening Soil Elastoplastic and Mohr-Coulomb; and Tunnel Lining as shown in Table 1 and 2.

2.1 Materials

Table 1 shows four layers of different formation modelled based on the Final Design Stage of Geotechnical Interpretive Report for Tunneling (between ESC1 and TTWS). The First 15m below the ground level are Alluvium Formations. A 5 m depth of Kenny Hills Formations with SPYT-N value 50<N<75, 20 m thick of Kenny Hills Formations with SPT-N value higher than 150 lies beneath 10 m depth of Granite Layer. Meanwhile for tunnel lining properties was taken from MRTC Final Design: Bored Tunnel Design Report (between TTWS and ESC1) as shown in Table 2.

Table 1: Soil Properties

Material	**Soil Behaviour**	γ_{unsat}	γ_{sat}	E_{50}^{ref} (kN/m^2)	E_{oed}^{ref} (kN/m^2)	E_{ur}^{ref} (kN/m^2)	v'	c'_{ref} (kN/m^2)	φ'(°)	$K_{0,x}$
Alluvium Formation										
Hardening Soil	Drained	19	19	3478	3478	10.43×10^3	0.3	1.0	30	0.5
Kenny Hills Formations (50<N<75)										
Hardening Soil	Drained	20	20	111.3	111.3	333.91	0.3	8.0	33	0.46
Kenny Hills Formations (SPT-N>150)										
Hardening Soil	Drained	20	20	309.57	309.57	928.7	0.3	12	35	0.43
Granite Formations										
Mohr-Coulomb	Drained	24	24		4000		0.2	1760	40	0.35

Table 2: Tunnel Lining Properties

Parameter	**Lining**
Material Behavior	Elastic
EA_I **(kN/m)**	10.175×10^6
EI (**kNm^2/m**)	5.8×10^3
w **(kN)**	27.81
v	0.2
Radius (m)	2.9
Thickness (mm)	275

2.2 Methods

In this parametric study, PLAXIS 2D was used to simulate the soil and tunnel behavior and determine the influence of surface settlement based on three key parameters; the depth tunnel, groundwater level and soil stiffness. By implement the material properties of soil and tunnel lining, the researcher able to determine the surface settlement and tunnel deflection.

To achieve the second objective, two phase of calculation was set; the initial phase and Volume Loss 1.00 % for three parameters. As a result of the second calculation phase at Volume Loss 1.00 % (removing soil and water out of the tunnel) there will be settlement of the soil at ground surface and the tunnel lining also will shows some deformation. In this phase the axial force in the lining is the maximum axial force that will be reached.

3. Results and Discussion

As a result, the parameters of water level and soil stiffness description and assumption during tunnel excavation were investigated. There will be three hypothesis expected from the model.

- Anticipation of more ground settlement when tunneling close to the ground surface.
- Anticipation on tunnel deformed when depth increasing.
- Anticipation of decreasing surface settlement when soil stiffness increase

3.1 Results and Discussion

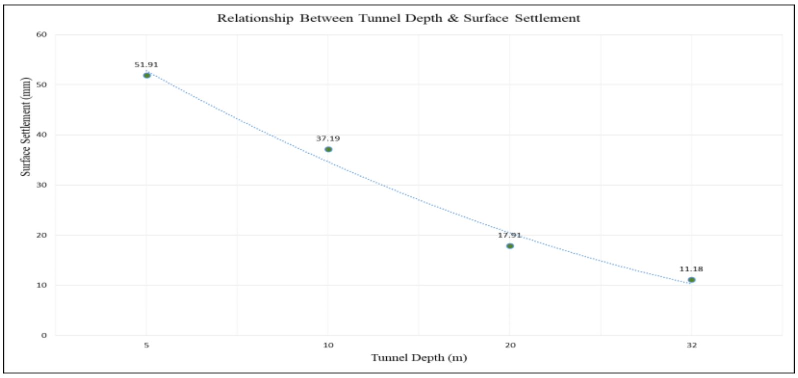


Figure 1: Relationship Graph between Tunnel Depth and Surface Settlement

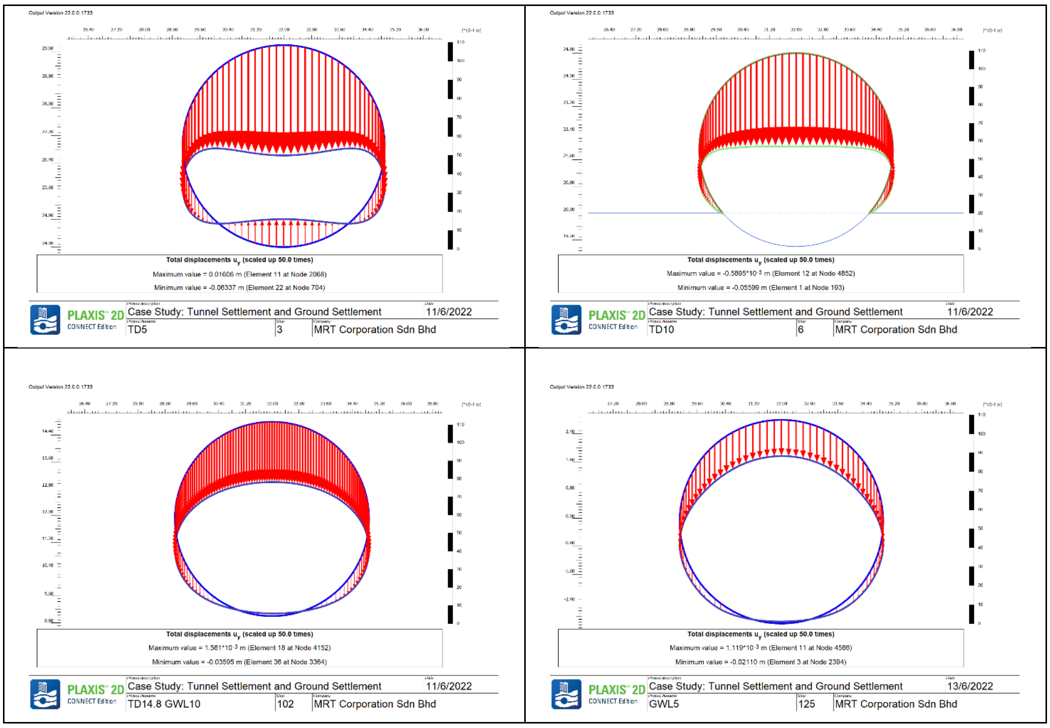


Figure 2: Tunnel Deflection when Tunnel Depth Change

By using PLAXIS 2D, able to see the effect of the surface settlement and tunnel deformation based on the three-parameter which are changing the tunnel depth, changing the groundwater level, and changing the soil stiffness. Based on Figure 1 shows an analysis surface settlement by changing the tunnel depth. Tunnel depth at 5.00 m below ground level shows the maximum settlement is 51.91 mm. For case tunnel depth at 10.00 m, the highest settlement shown based on the analysis is 37.19 mm while, at a depth of 20.00 m below ground level, it shows that to the analysis, the maximum settlement for this case is 17.91mm. For the final parameter, the researcher used a 32m depth tunnel where the actual tunnel was located and it shows that the maximum settlement produced based on the analysis is 11.18 mm. The analysis result shows that the lowest settlement produced for this case is the tunnel located at 32.00 m depth below ground level with a settlement of 11.18 mm. In this case, the researcher could conclude with one hypothesis: the deeper tunnel was located, the lower surface settlement produced. Meanwhile, in tunnel deflections as shown in Figure 2, the tunnel deformed decreasing as the depth increased. Shield tunneling will caused a ground movement and generate surface settlement at different level.

Next parameter shows the result of surface settlement when changing the groundwater level at a certain depth in Figure 3. At a fixed 32m depth of the tunnel, the graph shows that when the groundwater level at 5m below ground level where the actual depth on-site, the highest settlement produced, 11.18 mm. The analysis shows that the maximum settlement produced at a 10m groundwater level is 11.76 mm while, when the water level change to a 20m level, it shows that the maximum settlement produced is 12.17 mm. Lastly, at a 30.00 m water level, the highest surface settlement produced based on the result analysis is 12.41 mm. The analysis above shows that when the water level increases, the surface settlement also produces increases. However, based on the result, the distance value between four cases is not too big even though the water level changes by 10.00 m in each case. There are changes in value settlement for water level, but it does not impact the result. For tunnel deflection case in Figure 4 shows that by lowering the groundwater level still produce a surface settlement; however, the result for four water level only shows a narrow range of value. Even though the groundwater level dropped at different soil properties, it still displayed an approximate result for four cases.

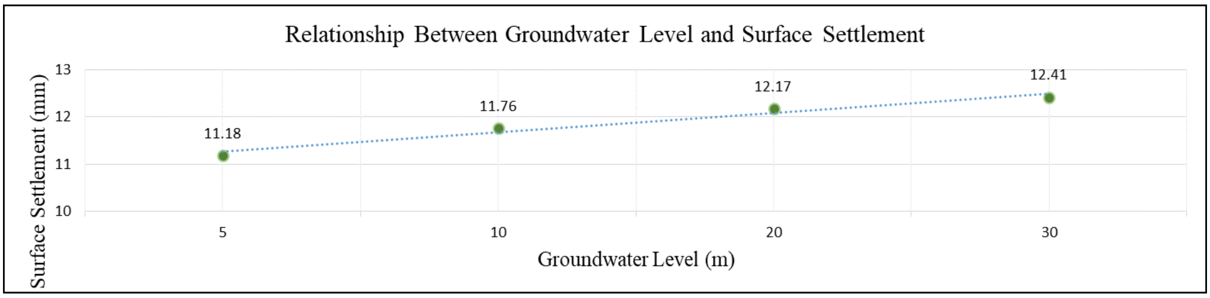


Figure 3: Relationship Graph between Groundwater Level and Surface Settlement

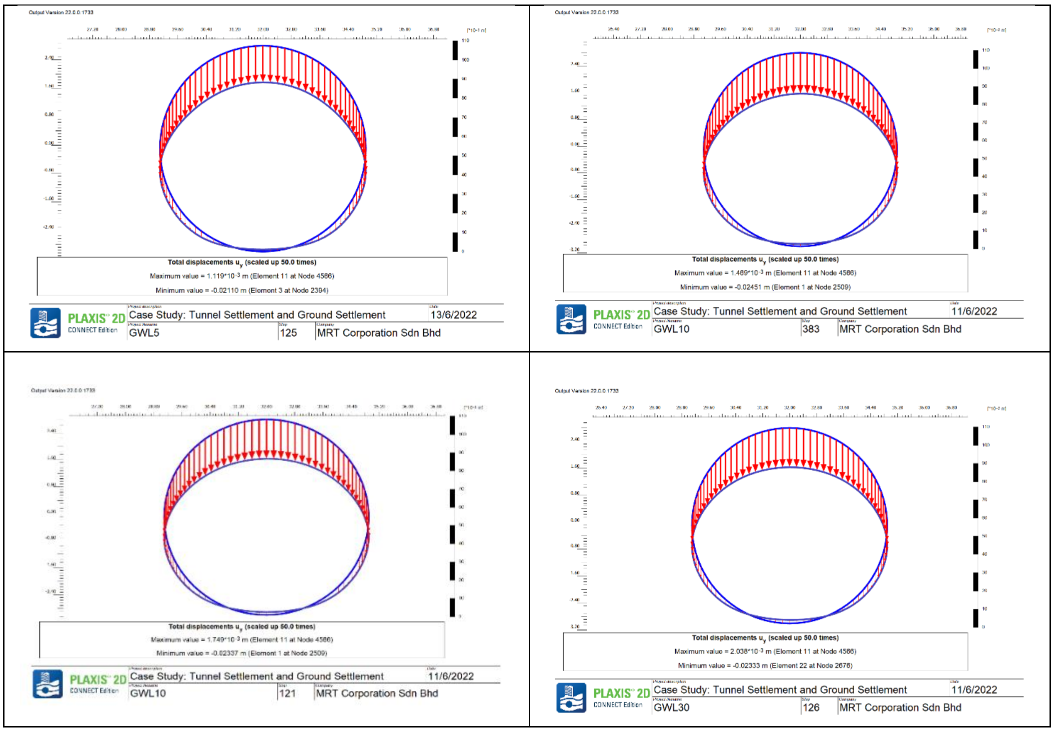


Figure 4: Tunnel Deflection when Groundwater Level Change

For the final parameter in Figure 5 shows the result analysis of settlement affected by changing the soil stiffness in every soil formation at a fixed 32.00 m tunnel depth and 5.00 m groundwater level. When the stiffness is multiple to 0.5 from the original, it produced 13.05 mm of surface settlement. The second parameter is the actual stiffness based on the MRTC G.I report, showing that the maximum settlement produced is 11.18 mm. For the third parameter, the soil stiffness multiple 1.5 from the original value, and the result shows that the highest settlement produced is 9.789 mm. By multiply twice from the original value, it shows that the highest settlement produce is 9.789 mm. When the soil stiffness multiple to 2.5, the maximum settlement is 9.607 mm. Lastly, when the soil stiffness multiple three from the original case for the last case shows the maximum settlement produced is 9.574mm. The result also shows that the settlement decreases when the soil stiffness increase. In this case shows that the settlement decreases when the soil stiffness increase. However, when the stiffness at 2.5 times the original, it shows no significant. The settlement produced by stress applied to the surface depends on the rigidity of the material soil. In Figure 6 shows the tunnel deformation when increasing the soil stiffness. However, the value range between the six parameters is not too extensive.

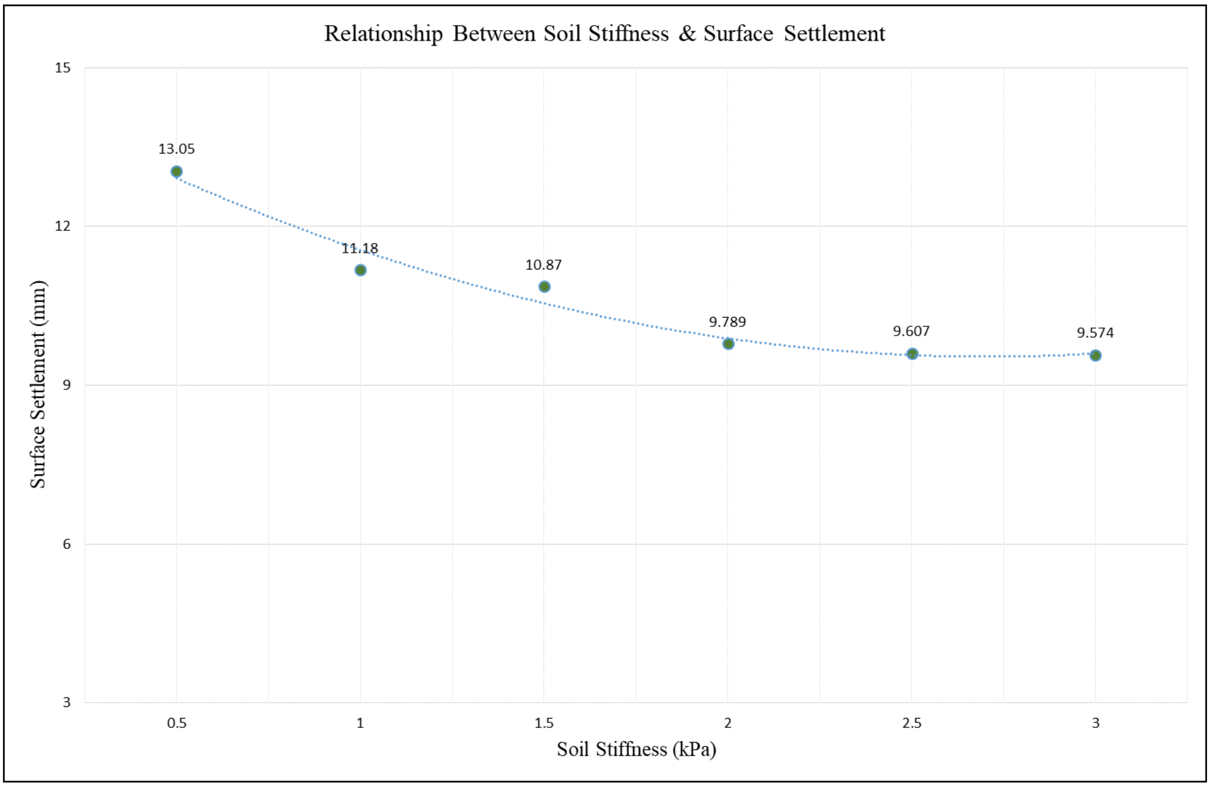
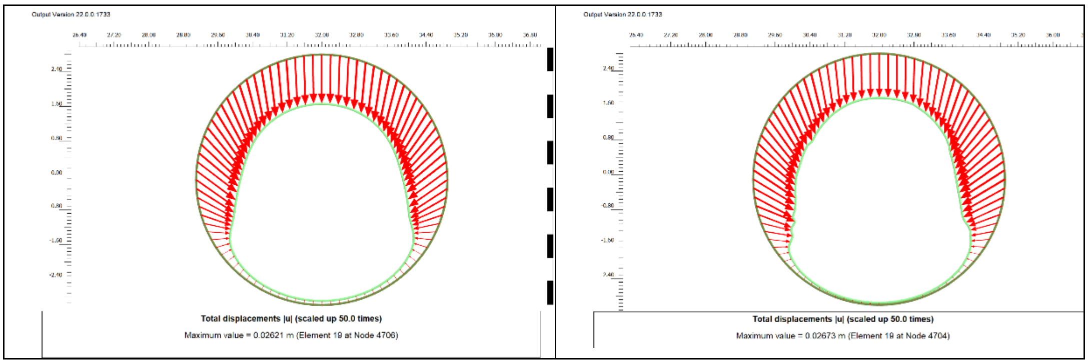


Figure 5: Relationship Graph between Soil Stiffness and Surface Settlement



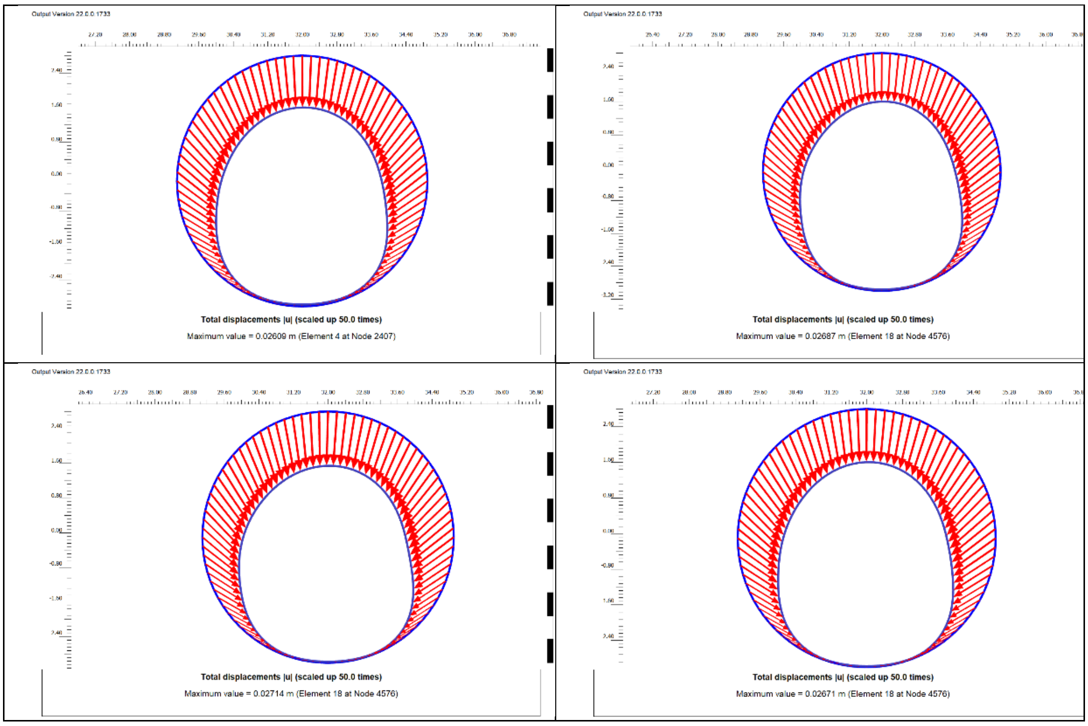


Figure 6: Tunnel Deflection when Soil Stiffness Changes

4. Conclusion

An engineer is concerned about designing geotechnical projects, which are commonly faced because of the complex boundary conditions that might change during construction and the inelastic materials that can cause deformations. Observing the effect of settlement change during tunnel excavation is one of the objectives that have been achieved. From the study, the researchers found that changing tunnel depth, groundwater level, and soil stiffness will effecting the surface settlement.

After finding the cause of surface settlement, the researchers used the Finite Element Method to analyse the ground settlement and deformations patterns of soil and tunnel based on three key parameters. This case study used the actual properties from the MRTC G.I report:

1. For the first parameters, the results show that the depth of settlement and tunnel deformations were affected by the position of tunnel depth. It shows that the surface settlement decrease when the tunnel depth increase; meanwhile, as the depth of the tunnel increase, the tunnel lining deforms also decrease. However, the range of results between the cases is not extensive.

2. The following parameter changed the groundwater level, showing that the surface settlement increase as the water level increase. Meanwhile, the tunnel deformed as the water level near the tunnel decrease. The range result for surface settlement and tunnel deformations also is not significant.

3. The final parameter shows that the surface settlement decrease when the soil stiffness increase. However, when the soil stiffness is three times the original, the result shows no significant difference because the sensitivity to the settlement has low.

After analyzing the result, the researchers able to compare the actual settlement on site with the design analysis settlement where the actual site is lesser settlement than the design. It shows that the final objective has been achieved. Even so, this study did not represent the actual on-site case where many considerations, such as surcharge, soil conditions, and others, must be considered.

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