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To cite this article: Noor Iman Safiya Mohd Muhtar *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **527** 012009

IOP Conf. Series: Materials Science and Engineering **527** (2019) 012009 doi:10.1088/1757-899X/527/1/012009

Assessment on tunnel lining to ensure stability in soft ground

Noor Iman Safiya Mohd Muhtar[1], Siti Norafida Jusoh[2], Dedy Yusufiansyah[1], Asmawisham Alel[2], Nor Zurairahetty Mohd Yunus[2], Rini Asnida Abdullah[2], and Nordiana Mashros[2]

[1] Postgraduate Student, Department of Geotechnics and Transportation, School of Civil Engineering, Universiti Teknologi Malaysia, Malaysia
[2] Lecturer, Department of Geotechnics and Transportation, School of Civil Engineering, Universiti Teknologi Malaysia, Malaysia

*Corresponding author e-mail: snorafida@utm.my

Abstract. Soft ground tunnelling describes as additional measures that are needed to be taken as it has been associated with settlement due to changes of stress and strength of the soil induced by tunnelling. Segmental tunnel lining is a structure used to support the ground and to have allowable movement due to soil stress redistribution. The research will be focusing on the type of modelling, structure parameter of the tunnel, pressure upon the tunnel lining and relationship with the induced ground settlement. Tunnel modelling was done in three dimensional (3D) modelling using ABAQUS software; of tunnel as parameter. This paper will discuss the effect of jack forces to the global behavior of the tunnel in order to support the surrounding load, thus be able to handle the tunnel-soil reaction without any visible or critical deformation, so that the tunnel can be used in the stable condition. A stand- alone ring method together with all-in-once method was used to simulate the Singapore MRT Circle Line 3 (CCL3). In the findings, when the tunnel lining thickness is reduced, the settlement of the ground surface is increased. Jack forces is also one of the reason of the tunnel to distort and the effect is more visible on the rings with reduced thickness compared to original thickness of the tunnel lining.

1. Introduction

Soft ground often described as a soil that can be dug out but not self-supporting for more than a brief of time, and most of soft ground tunnelling is at relatively short depth, at least in urban situations [1]. Construction of a tunnel in a soft ground largely stimulates short term and long term settlements above the tunnel. The short term settlements largely affected by the release of in situ ground settlements, and for long term settlement, existing studies interpreting the settlement in terms of consolidation theory, which the soft ground is considered as elastoplastic materials [2]. Urban tunnelling is aimed to reduce the ground deformation to a minimum, but toleration of the deformation will be significantly bigger due to loading and unloading when the excavation of the tunnel takes place. [3].

For a single tunnel, the volume of surface settlement for individual settlement can be assumed to be equivalent to the volume of the lost ground. Shown in Figure 1, the shape of resultant settlement trough at the ground surface resembles that of the bell-shaped probability curve. The width of the settlement trough is measured by an *i* value, which is the horizontal distance from the location of maximum settlement to the point of inflection of the settlement curve [4].

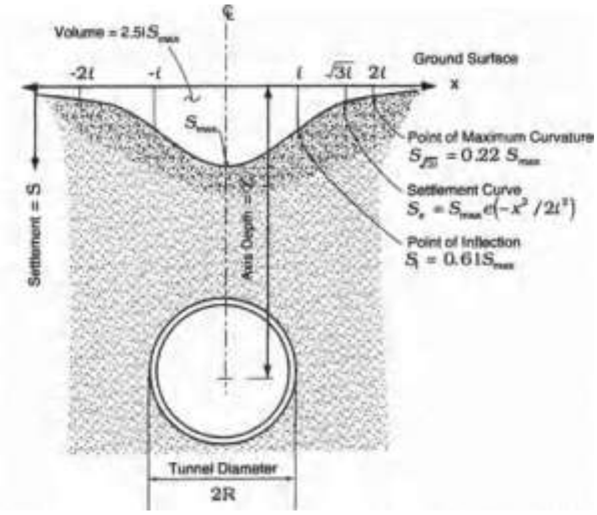


Figure 1. Probability curve used to represent cross section of settlement trough above the tunnel [4].

The thickness of tunnel lining is designed to withstand the load around the tunnel, and to lower the settlement of the ground above the tunnel. A large deformation can cause cracks around the bolt holes of the segmental lining by rotation or shear [5], thus the tunnel lining need to have optimum thickness to withstand the bending moment. This is also to ensure that the tunnel lining is stable enough during tunnel construction.

Jack forces for tunnelling has been used in urban areas underneath busy roads or railways [6]. As jack forces can cause crack at tunnel lining, mainly at concrete reduced areas, it is obviously analysis did not involve these area explicitly. The jack forces applied to the tunnel lining needs to be designed effectively, because if the force is too large, the tunnel lining may failure and heave may occur; but if the forces is too small then the TBM speed may be reduces considerably along with the collapse of the face pressure[7]. To increase the bearing capacity, the high jack forces always introduced in a zone far from the longitudinal joints [8].

This paper focused relationship on effect of the jack force and the thickness of the tunnel lining reduced. Problem tends to occur when modelling a tunnel in a soft ground, as when the lining is constructed during the tunnel excavation, the following unloading within the lining resulting the need of the complete tunnel to move upwards, and leads to the reduction in ground surface settlement.. The research was done by using 3D Finite Element Software ABAQUS, with series of numerical model with various thickness of the tunnel lining, as the research is requires the solution to boundary value problems for partial differential equations as well as to determine the settlement after the tunnelling, both transverse and longitudinal behaviour. Therefore, due to complicated and nonlinear response of tunnel-soil interaction, a three-dimensional finite element model for soft ground and water saturated soil should be taken into account for all the relevant components and models[9].

2. Methodology

The case study is Singapore Circle Line Stage 3 (CCL3), Singapore. Major underlying geological formations for the site consists of Bukit Timah Granite, formed by intrusion into existing rock[10] . The tunnel were constructed in the residual soil and dominated by completely weathered granite of Bukit Timah Granite Formation (GV and GVI) and Old Alluvium, as shown in Table 1 [11]. The parameters of the soil used to develop the model is elastic perfectly-plastic constitutive relation based on Mohr-Coulomb criterion with 5 input parameters (Drained or Undrained Analysis). The water table of the soil model is introduced at 2.5 m from the soil surface, based on the real situation at site.

Table 1. Soil parameters for every later of the soil model in Serangoon Interchange Station, MRT Singapore [12].

Soil Layer	Soil Type	Young Modulus E_s (kPa)	Bulk Density, (kN/m^3)	Poisson's Ratio, v_s	Angle of Friction, ϕ (°)	Cohesion, c (kPa)
L1	Fill	7000	19	0.333	30	0.3
L2	Estuarine	3000	15	0.35	20	0.3
L3	Fluvial Clay	3000	19	0.35	22	0.3
L4	Fluvial Sand	7000	20	0.32	32	0.3
L5	Bukit Timah Granite Formation, G4 (vi)	59200	20	0.333	30	2
L6	Bukit Timah Granite Formation , G4 (v)	86400	20	0.3	35	2
L7	Bukit Timah Granite Formation (v)	3500000	23	0.32	35	400

The soil-tunnel model developed appropriate boundary condition and meshing, as shown in Figure 2. The soil model provides a fundamental basis for a detailed analysis of the entire excavation process of a tunnel. The tunnel that was constructed having a diameter of 50 m by 63 m, and46 m depth from the soil surface. Then, the tunnel lining were installed with two methods which are 1.4 m width and as a full ring. In order to examine the effect of jack forces to the ring lining, a series of lining were developed that are consists of nine (9) rings with 1.4 m width with addition of full lining shaped in cylinder that equals to ten (10) rings with the length of 14 m, shown in Figure 3.

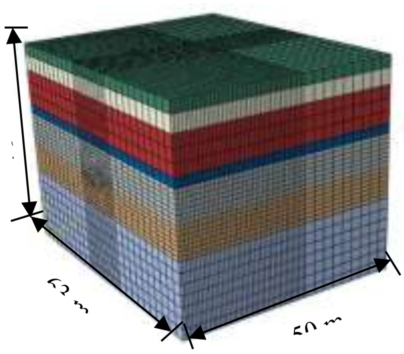


Figure 2. 3D model of soil-tunnel model with its boundary condition and meshing.

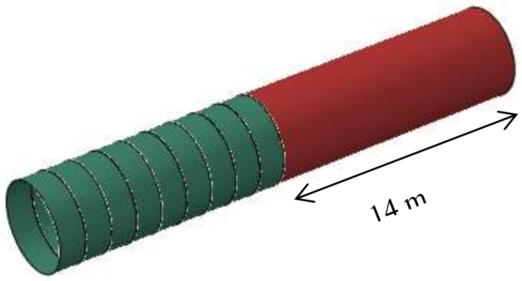


Figure 3. 1.4 m width individual ring (green), and long ring equivalent to 10 rings (red).

2.1 Boundary Condition

To avoid boundary effects, the dimension of the model is drawn 46 m x 63 m x 50 m. Boundary condition is assigned at the bottom of the model, to restrict movement from x, y and z direction, and also assigned to all sides of the model to restrict movement of x and y direction. The boundary condition is also used for assumption of the tunnel moving forward, whilst restricting any movement from the sides while installing the lining and movement from the face of the TBM, shown in Figure 4.

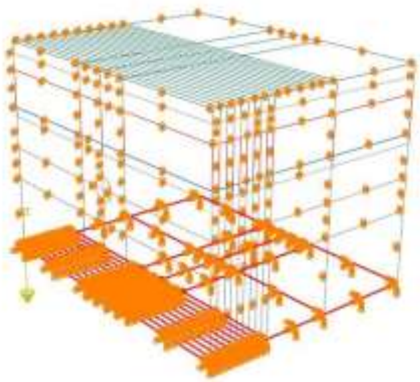


Figure 4. Boundary condition assigned at the bottom of the model.

2.2 Interaction of Soil and Lining

There are few types of interaction available in ABAQUS, but only two type of interaction used in this research, that is general contact and surface-to-surface contact. General contact interaction allows defining contact between regions of the model with a single interaction. The contact is described as an all-inclusive surface, such as rigid surface and edges. The interaction can be used to activate or deactivate the region element, as deactivate can be defined as excavation step of the region, and activating the lining can be defined as installation of the lining after excavation, shown in Figure 5. Surface-to-surface contact interaction can be describes as a contact between two deformable surfaces or between a deformable surface and a rigid one. To optimize stress accuracy, surface-to-surface discretization considers shape of both slave and master surfaces in the region of contact restraints, shown in Figure 6. In this research, a surface-to-surface contacts was used to establish the connection between the lining and the soil surround the tunnel lining.

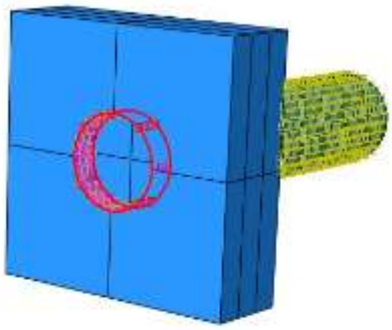


Figure 5. Example for interaction in Ring 1, installation step.

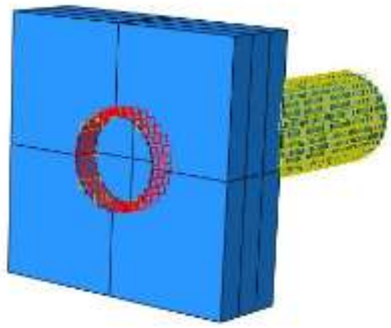


Figure 6. Surface-to-surface contact between soil and tunnel lining for Ring 1.

2.3 Jack Forces on the Tunnel Lining

To let the TBM advance, a distributed loading is appointed to the lining to imitate the jack forces to push the lining to the ones that already been mounted and holding the lining in position with the help of the tie. When the lining is fully installed, the TBM is moved against the face pressure at the tunnel face [13]. The loading appointed to the lining is 10MN, loading that is obtained from previous study by Cho, 2017[14] and Kasper [9], as shown in Figure 7.

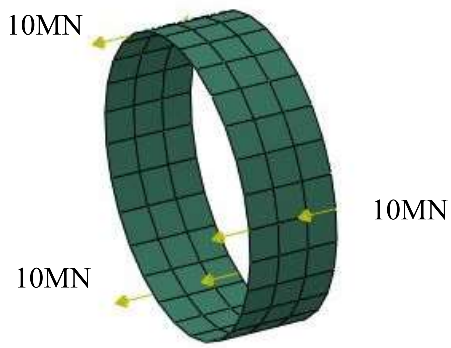


Figure 7. Jack forces (i.e., body forces) applied to a meshed ring of tunnel lining.

2.4 Lining Thickness
Changing the thickness of the tunnel lining, ranging from the original thickness of 0.275 m to half of the original thickness, that is 137.5 mm. The thickness of the model is modified by changing the shell thickness of the lining. To be able to obtain results for deformation of the tunnel lining, path must be defined by specifying a series of points through the lining model, shown in Figure 8.

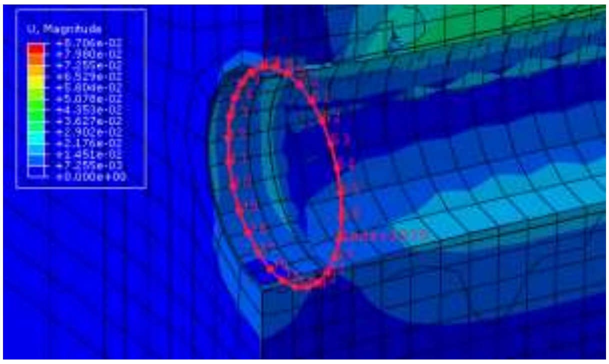


Figure 8. Path for Ring 1.

3. Results
By using ABAQUS, reaction of tunnel lining in different thickness after loading of jack forces can be obtained. This method is also used in order to inspect the ability of the lining to handle the tunnel-soil reaction without visible or critical deformation. The lining thickness varies from the original thickness from the case study which is 0.275 m to half of the original thickness, which is 0.1375 m thick. A model with no tunnel lining installation after the excavation carried out for comparing purposes. As mention previously in Methodology, rings was modelled in combine methods, a stand-alone ring (*i.e.,* Ring 1 until Ring 9) and all-at-once model [15] for Ring 10. As the all-at-once model is a continuous tunnel model, results discuss here in only involved Ring 1 until Ring 9, and jack forces is applied on the tunnel lining to all model.

3.1 Longitudinal Settlement
Longitudinal settlement profile is derived by considering the tunnel as a number of point sources in longitudinal direction, also by overlaying the settlement craters caused by each point source. From the graph in Figure 9, it is safe to say that longitudinal settlement for the tunnel model with the lining thickness of 0.1375 m happens less than 20% difference than the original thickness of 0.275 m. 0.1375 m depicts maximum settlement of 0.0059 m and for 0.275 m it depicts of 0.0051 m of maximum settlement. When the excavation reaches to Ring 9, which the last stand alone ring installed (before commence with all-in-once method lining), the settlement of the model with 0.1375 m lining thickness has only 6% difference than the original thickness. By using the empirical equations to calculate the longitudinal settlement, the settlement calculated for Ring 9 with thickness of 0.275 m is 0.00374 m, as compared to the standard form [16].

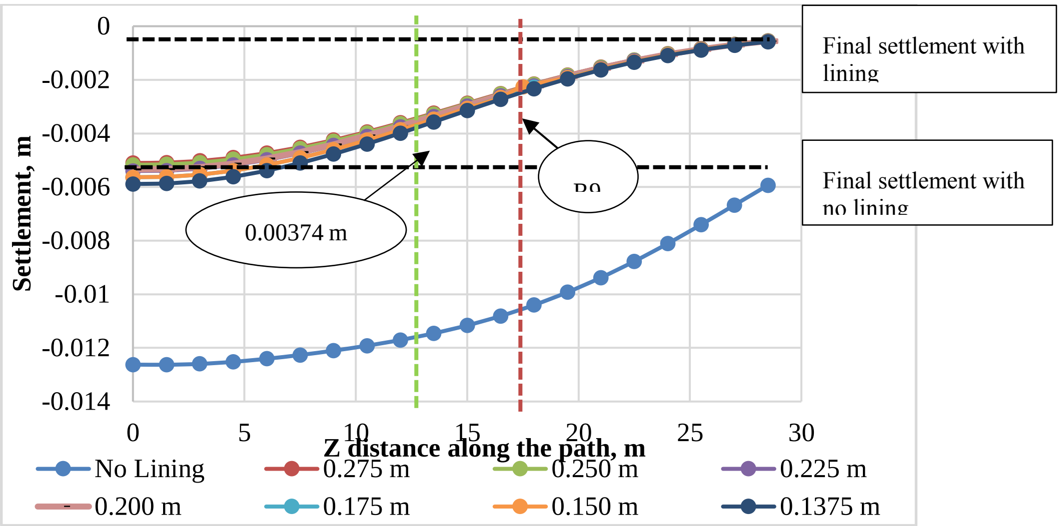


Figure 9. Longitudinal settlement of different tunnel lining thickness compared to excavation with no lining.

The settlement along the ground surface may varies due to the soil around the lining, as the measurements taken above the driven tunnel indicate that the tunnel movement were rarely stabilized at the tail skin, and the response time of the surrounding ground tends to decrease as the cover increases [17]. The reduced thickness of the tunnel lining also the cause of longitudinal settlement increases [14] (i.e., the smaller the thickness, the bigger the settlement). Even though the settlement of the lining is similar to each other after the changes of the lining thickness, the reaction of the loading from the ground to the ring itself may be quite different.

3.2 Crown Tunnel Reaction due to Tunnelling

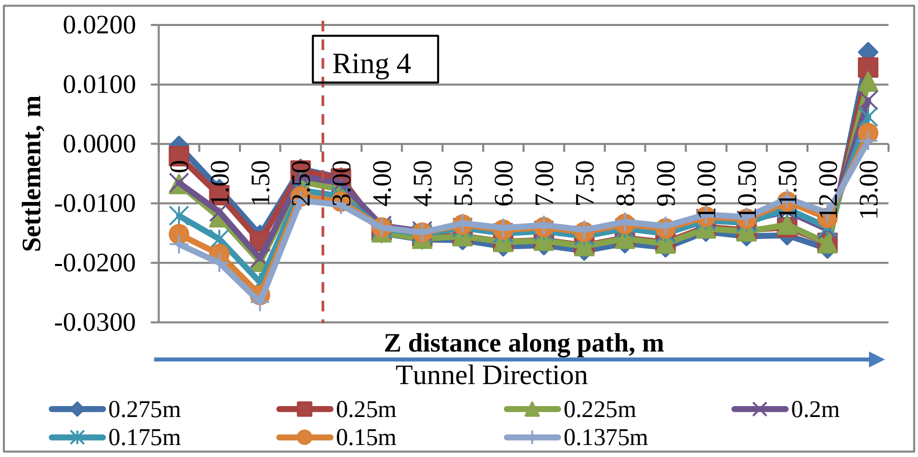
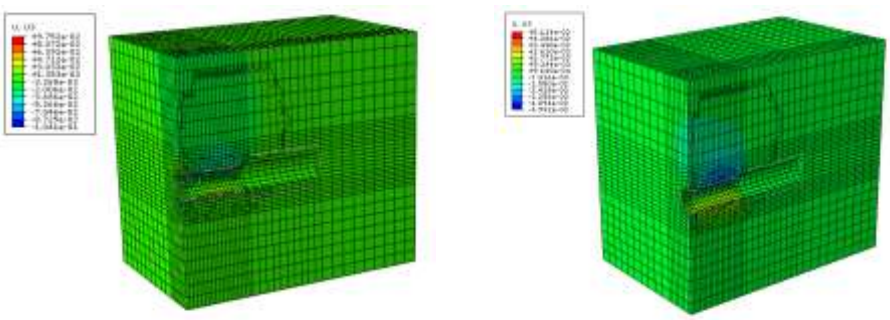


Figure 10. Crown tunnel reaction due to variation of tunnel lining thickness.

Figure 10 shows the crown of the tunnel reaction due to ground settlement because of the lining thickness. Changes in front of the tunnel excavation at initial tunnel crown path, a zigzag pattern can be seen. This occurred due to fully mobilization of ground at the crown of the tunnel. By assuming the distribution of the vertical stress between the ground surface and the crown is in spherical cavity, as shown in Figure 11, can be assumed that the material strength is moving thus creating the pattern.



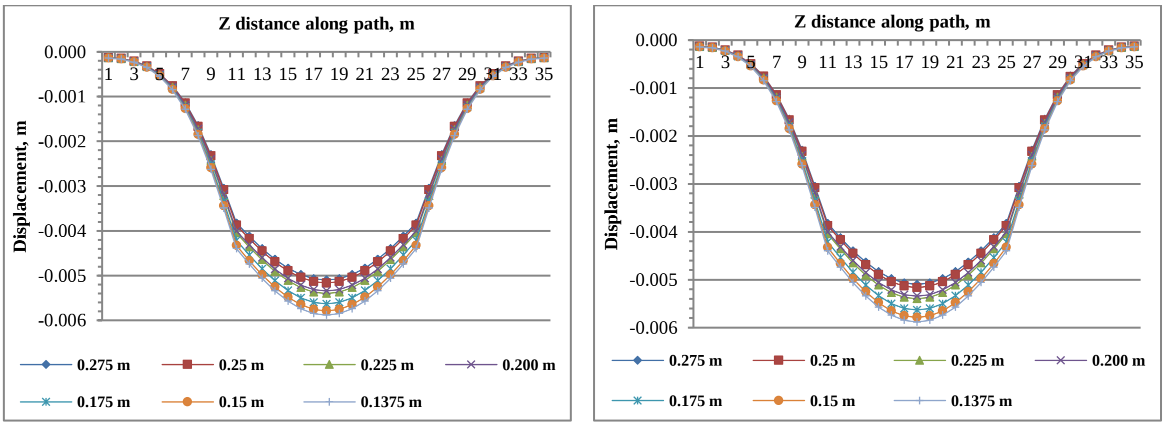
(a) (b)

Figure 11. Crown tunnel reaction for different lining thickness, (a) 0.275 m and (b) 0.1375 m.

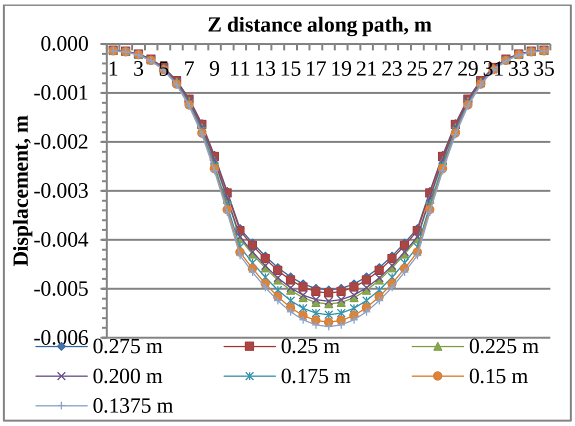
After installation of Ring 4 shown in Figure 10, the crown reaction showing consistent settlement until Ring 8. However Ring 9 starts to reacts differently due to installation of all-in-once model, as the model implies the installation of 10 rings. Based in3w Figure 11, the reaction of the crown tunnel is showing difference in response, due to changes in thickness from the original thickness from the case study, to half of the original thickness. For 0.1375 m thickness model, it shows that the reduced thickness affect the surface ground more than 0.275 m model. This may be due to the bending strength and stiffness of 0.1375 m is lower compared to the original thickness, causing the deformation to the lining and settlement[18].

3.3 Transverse Settlement of Same Ring with Different Thickness

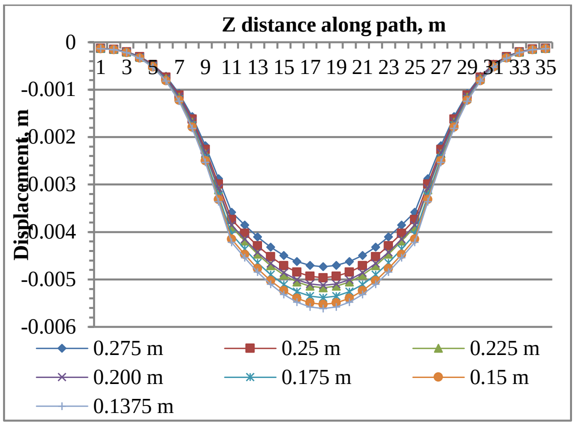
In figure 12, same ring sequence but with different thickness were compared to each other, and the comparison of the crown ring reaction was done for the critical ring sequences, which are Ring 1, 2, 3, 4, 5, 6 and Ring 9 representing the all-in-once model. In general, the transverse settlement obtained was indicated similar pattern too [19].



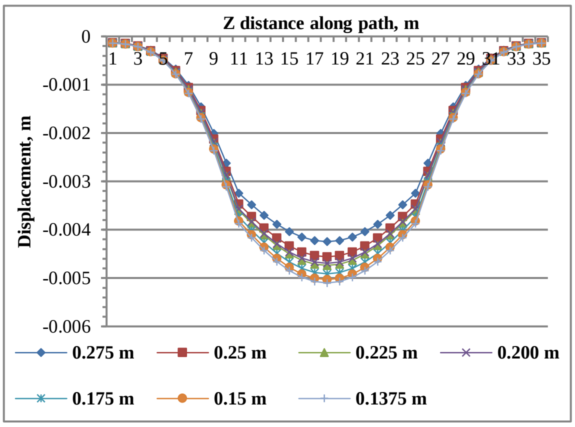
(a) (b)



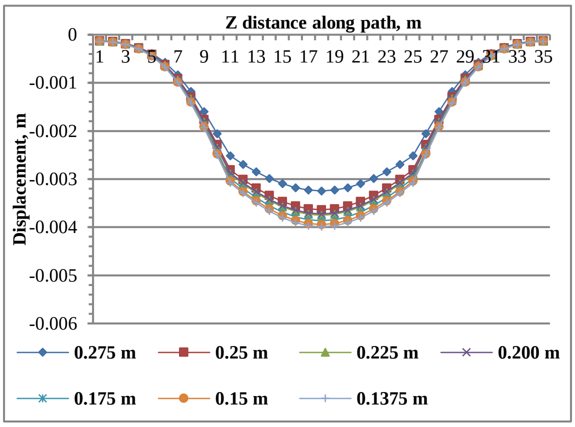
(c)



(d)



(e)



(f)

Figure 12. Transverse settlement of ring sequence with different tunnel lining thickness, compared to excavation of tunnel (a) Ring 1, (b) Ring 2, (c) Ring 3, (d) Ring 4, (e) Ring 6, (f) Ring 9.

Based on Figure 12, the maximum transverse settlement for Ring 1, 2 and 3 of every thickness observed from the figure ranged with minimum settlement of 0.01 mm and 5.9 mm. In general, the development of transverse settlement of the ground surface for tunnel lining with thickness range from 0.275 m to 0.2 m has similar maximum settlement, compared to tunnel lining with thickness ranging from 0.175 m to 0.1375 m. However, the transverse settlement starts to stabilize from sequence of Ring 4 to Ring 7, as it shows that 0.275 m tunnel lining thickness is more stable than the other thickness. This can be concluded that 0.275 m tunnel lining thickness is strong enough to stabilize the ground surface loading, in addition to jack forces acting upon it. The settlement of ground surface is stabilized at Ring 8 and 9, as it shows the lesser settlement throughout its sequence predecessor. This may be due to both of the sequence is the last sequence of lining installation, thus loading from the jack forces is spread.

3.4 Individual Tunnel Lining Reaction Due to Thickness Reduction

Previously, rings were modelled in combined methods, i) as a stand-alone ring (Ring 1 to Ring 9), then the rest of the tunnel was modeled as a continuous tunnel model, but in this section, only the stand-alone ring results will be discussed.

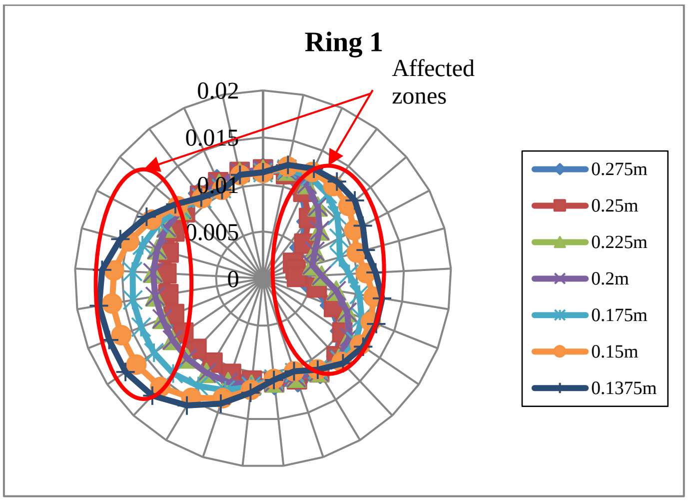


Figure 13. Comparison of thickness reduction for Ring 1.

The distribution of bending moment in Ring 1 shows in Figure 13, and is subjected to concentrated loads at crown. Due to the concentrated loading, the tunnel lining bulges inwards and outward at the spring lines. As seen on the figure, the tunnel lining with thickness range from 0.275 m to 0.2 m distorts into the shape of a bean, and prone to the left side due to initial effect of excavation. Tunnel lining with the range of 0.175 m to 0.1375 m deformed bigger than the predecessor, as the thickness could not endure the effect of the excavation and the loading of the ground. These deformation are considered large compared to other rings with uniform load.

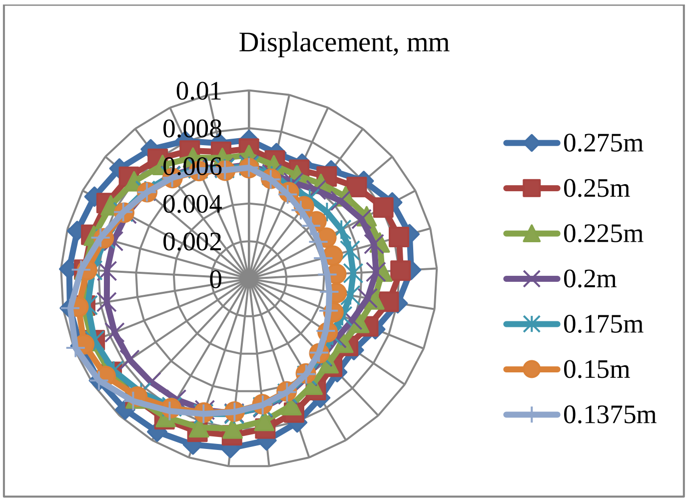


Figure 14. Comparison of thickness reduction for Ring 2.

Ring 2 in Figure 14 deformed after changing of the thickness starting to look quite similar, compared to Ring 1. This may be due to the loading started to transfers to Ring 1. Even though Ring 2 deformed less than Ring 1, From Ring 3, and the deformation of the rings starting to become more similar to each other. Based on Figure 15, the inward and outward bulges are reduced, due to passive pressure developed only at the spring line. In addition, both inward and outward bulging is further reduced in Ring 3 onwards.

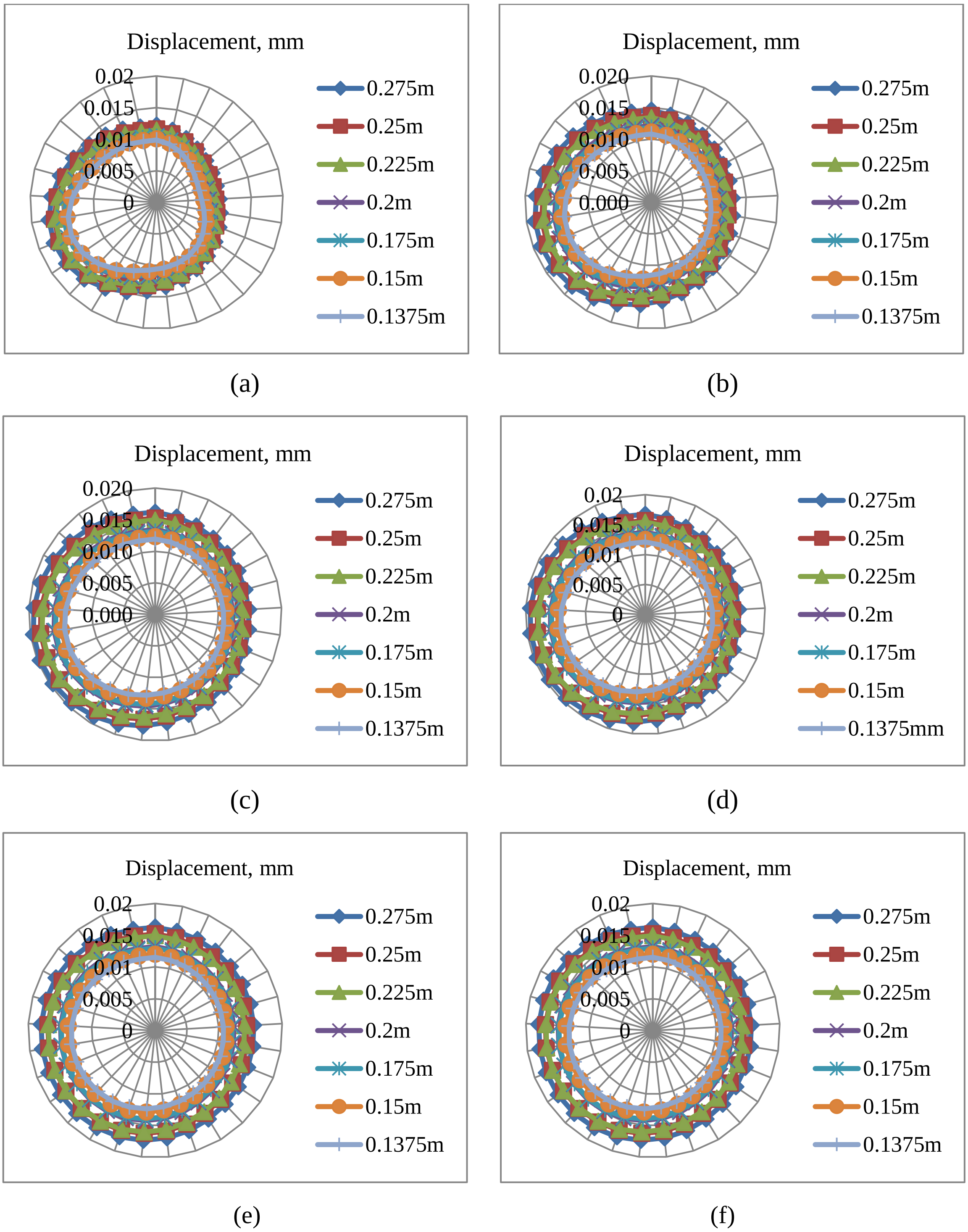


Figure 15. Comparison of thickness reduction for (a) Ring 3, (b) Ring 4, (c) Ring 5, (d) Ring 6, (e) Ring 7 and (f) Ring 8.

The deformation of Ring 3 to Ring 8 in Figure 15 is quite similar, and it may be due to the stabilisation of the ground settlement and uniform loading distribution from soil stress to jack forces itself. For this sequences, the thickness of the tunnel lining is sufficient that buckling is not a problem. This may be due to uniform radial load, and it will remain circular and shrink slightly than the original diameter that are induced by the uniform compression stress [20]. Compared to the predecessor sequence, these sequences looks like not much deformation happened to it, but the case is different for Ring 9.

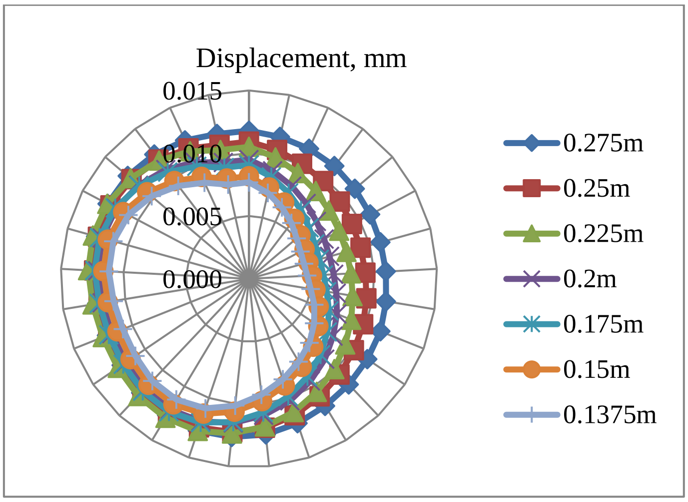


Figure 16. Comparison of thickness reduction for Ring 9.

Although Ring 9 in Figure 16 looked similar to the Ring 4, 5, 6, 7 and 8, the deformation of the ring 9 is different to one another is maybe because of less space for the Ring to settle after the jack forces load is applied to it, compared to other ring. The deformation of 0.275 m lining thickness is quite stable compared to 0.1375 m lining thickness, and this maybe because of the smaller thickness unable to handle the jack forces applied onto it. Ring 9 shows the general case of a fully confined ring that are subjected to random distributed active pressure loading, which passive pressure is distributed relatively, and the deformation and curvature changes of the ring are smoothly distributed.

4. Conclusion

This research aimed to determine the effect of reducing the thickness of tunnel lining, positioning at the settlement of ground surface and reaction of the crown of the tunnel using numerical modelling method. Overall, the tunnel lining thickness does effect the ground surface settlement and crown of the tunnel. The reduction of the tunnel lining thickness affected the ground settlement, but not as severe in thickness range from 0.275 m to 0.2 m.

The reaction of the crown of the tunnel lining of reduced thickness shows major difference, as this is due to jack forces0 applied to the lining and the ground settlement happened upon it. Overall, the reaction of the crown tunnel is quite similar to each other in Y direction.

The tunnel lining by installation sequence shows the settlement of the rings are is quite similar to each other after the changes of the thickness. This is due to the tunnel lining is not independent structure acted upon by well-defined loads, and the deformation of the lining is not governed by its own internal elastic resistance. The properties of the ground controls the deformation of the lining, thus the lining will not significantly deformed. Therefore, the maximum settlement of the ground surface is an indicator of which size of the tunnel lining that is compatible to the ground condition. From the observations and results obtained, it is safe to say that thickness of the tunnel could be reduced to a certain thickness.

5. Recommendation

Further analysis should explore the effects of lining distortion during erection, ring expansion due to dimension changes such as different tunnel diameter and segmental lining, and grouting as this analysis only uses one diameter and the ring is constructed as full ring.

Further analysis can be done to closely parallel, diverging or intersecting tunnel, and 3D FEM should be able to give some qualitative understanding into the ground behavior in such complex geometries.

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Acknowledgement
The authors would like to acknowledge the support of the Universiti Teknologi Malaysia and the Ministry of Higher Education Malaysia through the awarded Research University Grant (RUG), vote number Q.J1300000.2722.09K91 are highly appreciated.