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## 3-D numerical model of jack force interaction to segmental tunnel lining in soft soil

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**Abstract.** The construction process of a bored tunnel is a complicated process. During tunnelling, loads were acting on tunnel and tunnel lining were installed to support excavation. Simultaneously, soil redistribution induced by tunnel excavation leads to lining to deform. One of the parameters that affect global soil-tunnel behaviour is the jack forces. Jack force is exerted during the tunnel advancement to install the lining and the same time to enhance tunnel face stability. The complexity of jack force application to ensure the overall tunnel stability is not fully studied yet. Hence, the impact of jacking force on segmental tunnel lining and surrounding soil during the tunnel advance is still unclear. This paper presents a numerical simulation by using ABAQUS/Standard 3D FE software to determine and investigate the lining deformations/jacking force relationship. The behaviour of different tunnel lining thickness applied with a variation of jack forces in the tunnel-boring machine (TBM) were examined. The result based on the numerical model explained that the jacking force required to advance is related to the cross section area of segments. Finally, a relation has been established between the segment's thickness and the jacking force that required advancing through a certain soil block with specific loads cases. The findings showed that the complex geological features and loads case applied to cause great stress on the tunnel face which have to be encountered by a certain thrust magnitude to advance the tunnel. The model analyses the contact reaction and radial reaction to the segment as a result of the axial force that is exerted by jack thrust and bending moment due to strata load, respectively. However, a proposed model that suggests a certain step to investigate and analyse the magnitude of jack forces is required.

**Keywords:** Segmental tunnel lining; Jack force; TBM; segment's thickness; Numerical Modelling; ABAQUS 3D.

### 1. Introduction

As it is known, during the advance of Tunnel Boring Machine (TBM), the segmental tunnel lining and its joints are imposed for many different kinds of load. The overburden pressure, groundwater pressure and the bending stress due to the arbitrary percentage distortion of the tunnelling diameter are represented as an axial thrust due to Jacking force on segments, which comes from installation process of tunnelling. In



the case of TBM process analysis, modelling methods for various components, such as face pressure, the shield, grout and hydraulic jack, as well as the simulation of the construction procedure, affect the numerical results. Specifically, excavation advances are achieved by applying the thrust force of hydraulic jacks to the installed tunnel linings, which act as reaction wall during TBM tunnel construction; therefore, the stresses of the tunnel lining are affected by thrust forces in addition to earth pressure, water pressure and the dead load of segments in each construction step. The effect on ground movement on lining force is studied and represented by many researchers like Ri-Han *et al.*, Ercelebi *et al.* and Shen *et al.* [1-3], also the structure behaviour and response of segments and its joints is deeply investigated by Wood, Blom, C. and Molins [4-6], yet, a relatively small effort has been made regarding the relationship between the jacking force and the stresses on lining in different ground parameters.

Tunnel codes guidelines from the Land Transport Authority (LTA, 2007) that is reviewed by Bakhshi *et al.* [7], assumed the design of the segments in the permanent condition can be adopted as a short columns design that subjected to the combination of hoop thrust and bending moment. Both ultimate limit state (ULS) and serviceability limit state (SLS) need to be checked. Most of the previous research focused on the loads exerted on the segments during the tunnel advance. Cho, W.H. *et al.* [8] found that maximum axial stress to the converged axial stress was different in each lining and the ratio of the maximum axial stress to the applied jack force increase as the jack force increase. Besides that, the results revealed that the soil elastic modulus has a strong effect on the relationship between the axial stress and jack force. Based on the load and resistance factor design (LRFD) method, one should design the segments for serviceability limit state (SLS) and ultimate limit state (ULS), which the jacking force is considered as a load case should be observed as an element in segment design based on ULS [9].

Bakker and Bloom [10] investigated the lining thickness as a constant ratio to the diameter. They proposed a new design, which considers the lining thicknesses used to analyse many structure mechanism of the lining included the axial jack force. This consists of compressive strength of the concrete, splitting strength under and beside jacks and eccentricity analysis. Also, Saberi *et al.* [11] showed the bursting and spalling stresses on the area of jacking pad and the segments joints due to jacking force. The application of the numerical method in tunnel lining design enhances the design parameters and predicts precisely the response of the segments during the tunnel advance [12-15]. As a three-dimension model, the interaction between the segments in the same ring should be clarified so that the behaviour of lining will not act as a separate ring or rigid pipe [6].

Bloom [5] explained that jack forces can reach high values and cause high-stress levels in the concrete segment. The introduction of the jack forces will cause splitting forces in the concrete (segment). In the segment design (geometry and material), it is often assumed that the jack forces are introduced purely centred in the segments. Many cases had shown the deformation of the rings or rolling of the tunnel boring machine (TBM) that occurred due to the eccentric introduction of the jack forces. Eccentric is produced during the tunnel advance as a result of jack forces that not acting in the axial neutral area of adjoining segments in the deformed rings. Second order deformations and stresses will also produce. All these are the causes for outline introduction of TBM jack forces. It is sometimes necessary that jack forces exceed limitation protocols to be able to continue excavation [5]. Tensile stress areas will appear in-between the introduction areas of the jacking force. Excessive high jack-forces cause high tensile stress levels. Lateral contraction due to jack forces is additional to tangential stresses in segments. Locally tangential stress levels will increase or decrease. Unexpected deformations and stress levels might occur. Seung *et al.* [16] studied numerically the face stability of a tunnel derived by TBM. Based on the result analysis, the soil parameter besides the presence of the pore pressure is considering the main parameters for face stability and the pressure need to stabilize the face.

The main challenge of this study is to determine a robust numerical simulation of the structural behaviour of the segments subject to the jacking force, in different soil parameters, which will lead in-depth understanding of the relation of the segment's thickness to jack force and soil elastic.

**2. Theoretical Principles**

The calculation procedure based on International Tunnel Association (ITA) Working Group No. 2 [17] is used in this research to explain the theoretical solution for the proposed three-dimensional (3D) model in figure 1. Based on that, all active loading that applying on the tunnel lining can be predicted through an analytical or empirical formula. The vertical weight, for an instant, is calculated based on Terzaghi's formula (equation 1) or equal to the total overburden of weight. The main parameter in vertical weight; besides the overburden and unit weight of soil is the ring diameter. Therefore, the ring diameter is fixed in various proposed 3D models in this paper. The active loading on tunnel lining,  $P_{el}$  is can be calculated as follows:

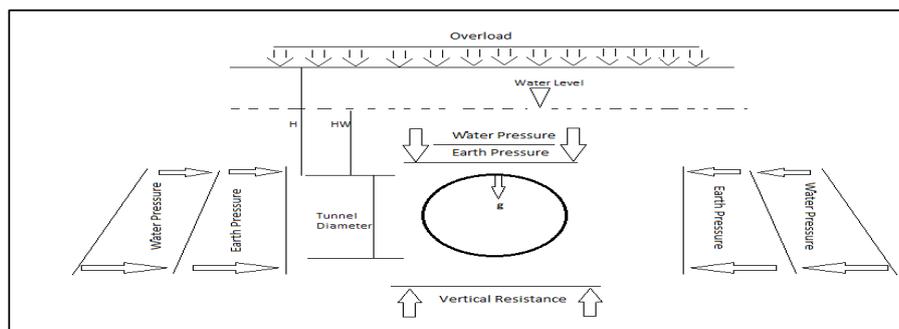
$$P_{el} = P_0 + \sum \gamma_i H_i + \sum \gamma_j H_j \quad (1)$$

Meanwhile, the horizontal earth pressure on the tunnel crown and bottom ( $q_{e1}$  and  $q_{e2}$ ) is predicted by equation 2 and equation 3, respectively. It directly affects the segment thickness beside the segment diameter. The lining resistance for the lateral pressure estimated in equation 4 that shows the relation between the load reaction and the segment thickness. Equation 2 to 4 is as follows:

$$q_{e1} = \lambda \gamma' (2D + \frac{t}{2}) \quad (2)$$

$$q_{e2} = \lambda \gamma' (2D + D - \frac{t}{2}) \quad (3)$$

$$\delta = (2P_1 - q_1 - q_2) / \{24(EI + 0.0454kR_c^4)\} \quad (4)$$



**Figure 1.** Load case diagram (ITA).

On the other hand, Bakker and Bloom [10] argued the relation between segment thickness ( $t$ ) and the tunnel diameter ( $D$ ), which as is shown in equation 5 this relation controlled by soil characteristics and the tunnel depth. All the parameter used in Equation 1 to 5 is listed in table 1.

$$\frac{t}{D} = 1/2 \left( \left( \frac{4\gamma_u \gamma_w}{E_c} \right) \left( \frac{h}{d} \right) D \right)^{1/3} \quad (5)$$

Based on the presented equations, it can be summarized that the geotechnical load case depends on the

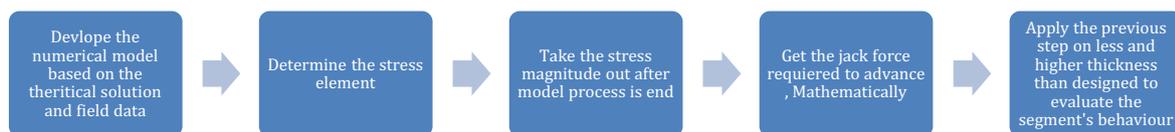
earth condition, each soil layer thickness above the lining, water saturation, density for each soil layer, soil's angle of friction, soil's cohesion, tunnel diameter and segment thickness. From this, the suitable segment thickness can be identified theoretically and it can be considered as the minimum thickness that will be imposed on the other load case, specifically jack force load case in this research. Besides that, the literature shows that the jacking force is predicted through calculation the face pressure and the skin friction of shield with the soil.

Finally, all the equations mentioned above can determine the most suitable thickness of the segment used at a certain depth for a certain length. This segment geometry is used to build a tunnel lining model to simulate the construction process in a specific geological feature that is collected from the field (table 2), to predict the stress on the segments that is exerted from the face pressure and shield skin friction. Next, the following 3D soil–tunnel model was built based on this hypothesis in order to find out numerically: i) the stress is exerted on the tunnel face due to face pressure that as a result of soil parameters, ii) the jacking force needed to advance the tunnel through the geological feature.

**Table 1.** The parameters used in the theoretical solution of equation 1 to equation

Parameter	Symbol	Unit	Parameter	Symbol	Unit
Earth vertical pressure on tunnel crown	$P_{e1}$	kN/m <sup>2</sup>	The thickness of the submerged soil layer	$H_j$	m
Surcharge	$P_0$	kPa	Earth lateral pressure on tunnel crown	$q_{e1}$	kN/m <sup>2</sup>
Unit weight of dry soil layer	$\gamma_i$	kN/m <sup>3</sup>	The coefficient of lateral pressure	$\lambda$	-
The thickness of the dry soil layer	$H_i$	m	Unit weight of submerged soil	$\gamma'$	kN/m <sup>3</sup>
Unit weight of submerged soil	$\gamma_j$	kN/m <sup>3</sup>	Sum of vertical pressure at tunnel crown	$P_1$	kN/m <sup>2</sup>
Earth lateral pressure at tunnel bottom	$q_{e2}$	kN/m <sup>2</sup>	Sum of lateral pressure at tunnel bottom	$q_2$	kN/m <sup>2</sup>
Displacement of lining	$\delta$	m	Moment of inertia of area of the segment	$I$	m <sup>4</sup> /m
Sum of lateral pressure at tunnel crown	$q_1$	kN/m <sup>2</sup>	The radius of the centroid of segment lining	$R_c^4$	mm
Segment modulus of elasticity	$E$	kN/m <sup>2</sup>	Average wet soil weight	$\gamma_w$	
Coefficient of reaction	k	MN/cm <sup>3</sup>	Relative depth ratio	$(\frac{h}{d})$	-
The safety factor of buckling	$\gamma_u$	-	Concrete young's modulus	$E_c$	Mpa

### 3. Model development



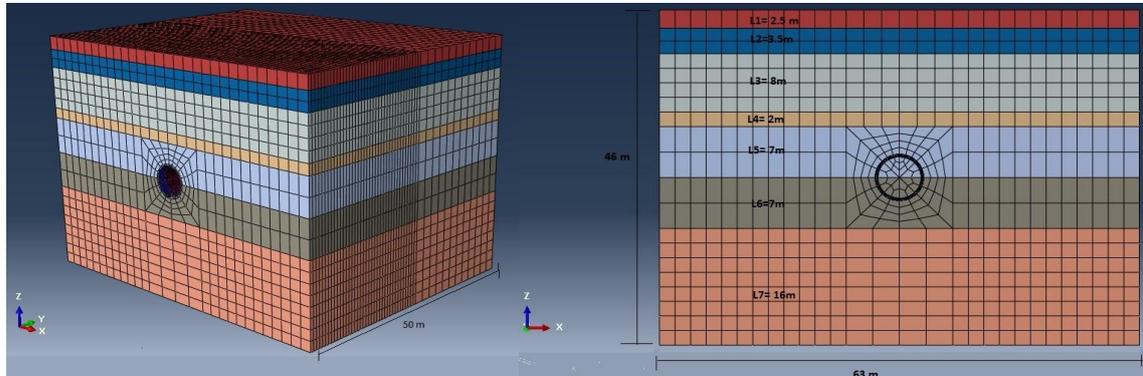
**Figure 2.** The operational flow chart of the model.

This study includes two research methods, which are i) theoretical solution and ii) numerical modelling in ABAQUS 6.14. For numerical simulation is shown in this paper, it consists of two models generated in 3D, the first model identify the soil-tunnel interaction by using the tunnel lining thickness that comes out as a result of theoretical solution, merged with the soil block model. The second model represents the segments tunnel lining with hinged segments joints, which will apply the jacking force derived from the first model (figure 2).

The mesh properties for soil block used in this model, the mesh consists of 33000 solid linear hexahedral stress elements of type (C3D8P). 36210 nodes are ENCASTRE at the bottom of the soil block (fixed in all direction) and zero displacements in X, Y direction for the four sides. For the soil model, this study used of the secondary soil data from tunnel construction of Circle Line Stage 3 (C852), Serangoon Interchange Station, and Singapore (table 2). The same soil data is used in previous research to build a full 3D Finite Element model in ABAQUS by Jusoh *et al.* [18] as to measure the settlement along the surface during the advance of TBM. Other parameters, namely, the angle of longitudinal joints, its distribution and the hinged segments principle that used in this paper is based on the analysis and investigation done by Jusoh *et al.* [19-20]. Figure 3 presents the soil-tunnel modelling in the first phase.

The first phase of the tunnel model presents the reaction of tunnel lining against the different load cases. The load case of this model includes the tail void grouting pressure, pore pressure, geostatic load and earth pressure. The stress element of excavated tunnel face is measured at the end of this model to identify the magnitude of face pressure. The contact between the shield and soil set as a frictionless, to eliminate the friction force and its impact on the segments and on the rate of advance. The lining with the thickness of 0.275 was modelled in soil block and the behaviour of lining radial reaction toward the force is investigated. Grout pressure was modelled by adding a grout layer between lining and soil with the thickness equal to the difference in thickness of lining and the shield. The depth of the tunnel is 25 m from the tunnel crown to the surface of the soil model. Besides that, the geostatic load and the underground water level is identified to be on the surface of the soil model to apply the maximum allowable pore pressure with the corresponding degree of soil saturation. The contact between all the surfaces in the model (*i.e.*, a contact soil layer, grout layer, and the shield) with the lining is defined to be hard contact in this case to avoid any uncalculated layer penetration or water leakage inside the lining. Besides the previously mentioned load case, the jacking force is applied to measure the developing of RF on the lining in presence of affected loads on lining radial direction.

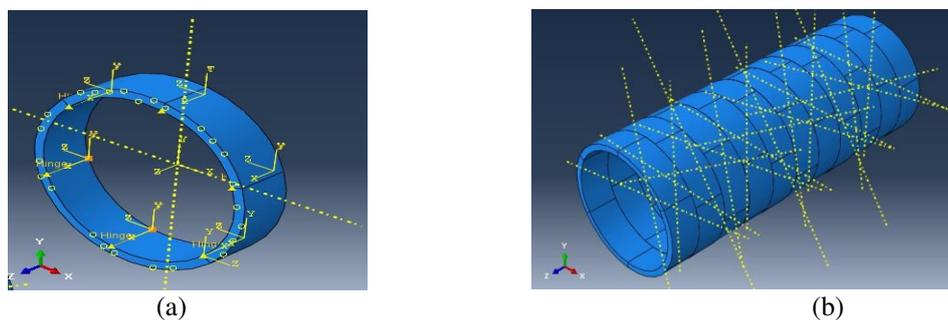
For the tunnel model, the tunnel lining considered in the analysis includes eleven rings; each ring consists of five segments, which are staggered alignment along the tunnel axis. The segments are coupled with the segment joints in longitudinal directions. These joints are considered as a connector element (hinge joints). The joints direction is clockwise with staggered angle interval of  $11.25^\circ$  for each ring. In addition, the total tunnel lining length is 15.4 m; the external diameter of each segment is 6 m and 1.4 m width as in figure 4. Tunnel lining is modelled by means of the linearly elastic model. The isotropic linear elastic model was used with Young's Modulus as 28.7 GPa, density as  $2400 \text{ kg/m}^3$  and Poisson's ratio as 0.2.



**Figure 3.** Soil-tunnel model assigned dimension with mesh developed in ABAQUS 6.14.

The longitudinal stress resulted after the model is ending on the tunnel face, is used to inversely calculated the magnitude of jack force need to overcome this stress and advance the tunnel. The stress element represents the whole face is measured and integrated with the segment edge cross-section. The number of segments and the stiffness of the longitudinal joints affect the jacking forces calculated. The result of mathematical procedures of the stress integration is a force that exerted from face pressure, the jacking force proposed in this numerical model is equal to this force but in the opposite direction.

The second phase of the tunnel model is developed upon the thrust load on the segments with different thickness. The lining was analysed stand alone, with no any loads imposed on radial direction. Segmental tunnel lining with the hinged joint is presented in Figure 4(a). On the other hand, circumferential joints were represented as a face to face interaction along the segment faces to simulate the distribution of the jacking force (Figure 4b). The boundary condition of the tunnel lining model is set to avoid the displacement when different load cases are applied. By other words, the boundary condition of lining in the model is pinned by setting zero displacement value in all three directions ( $U_x=U_y=U_z=0$ ). The element used in lining model is quadratic hexahedron, type C3D20RH, solid, hybrid formulation and reduced integration to decrease the cost of calculation. The density of mesh is controlled by the approximate global size of seeds but the number of elements is different among the three models of lining due to change in thickness



**Figure 4.** (a) Segmental tunnel lining with the hinged joint and (b) Assembly model of rings with a staggered angle of 11.25° interval assigned with face to face circumferential joints.

Figure 5 presents a schematic diagram of a uniformly applied jack force with circumferential joints. It can be seen, the jack forces were applied as a uniform axial pressure on the segments face and the joints represented as F-to-F interaction along the edge of the segment, in order to avoid the eccentricity effect in the model.

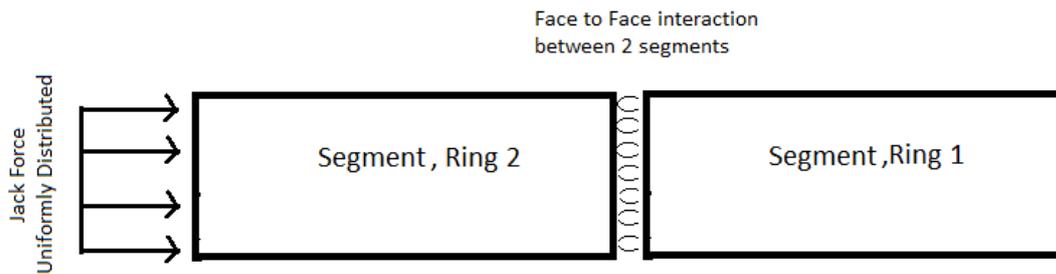


Figure 5. Schematic diagram of a uniform applied jack force and the circumferential.

Table 2. Details of the ground properties for every layer of soil model in MRT Singapore [21; 18].

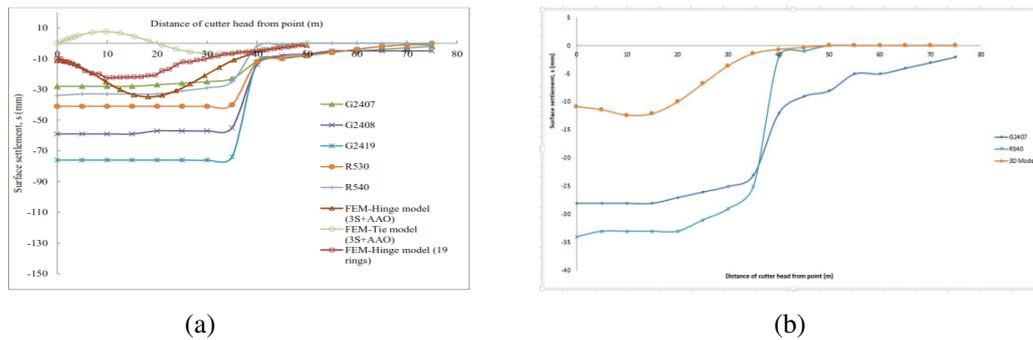
Soil Layer	Thickness (m)	Soil condition	Young Modulus (Pa)	Bulk Density (Kg/m <sup>3</sup> )	Poisson's ratio,	Angle of friction	Cohesion (Pa)
F1	2.5	Fill	7000000	1937.5	0.333	30	300
F2	3.5	Estuarine	3000000	1529.6	0.35	20	300
F3	8	Fluvial clay	3000000	1937.5	0.35	22	300
F4	2	Fluvial sand	7000000	2039.4	0.32	32	300
F5	7	Bukit Timah Granite formation	59200000	2039.4	0.333	30	2000
F6	7	Bukit Timah Granite formation	86400000	2039.4	0.3	35	2000
F7	16	Bukit Timah Granite formation	3500000000	2345.3	0.32	35	400000

The second model, the lining then assembled under the shield cover and followed by application of jack force (Figure 4a). After constructing the first four (4) rings, the shield then advancing and the grout layer then applied on the first ring (Figure 4b). The process is repeated until eleven rings are constructed and imposed to the grout pressure and soil loads.

4. Results and Analysis

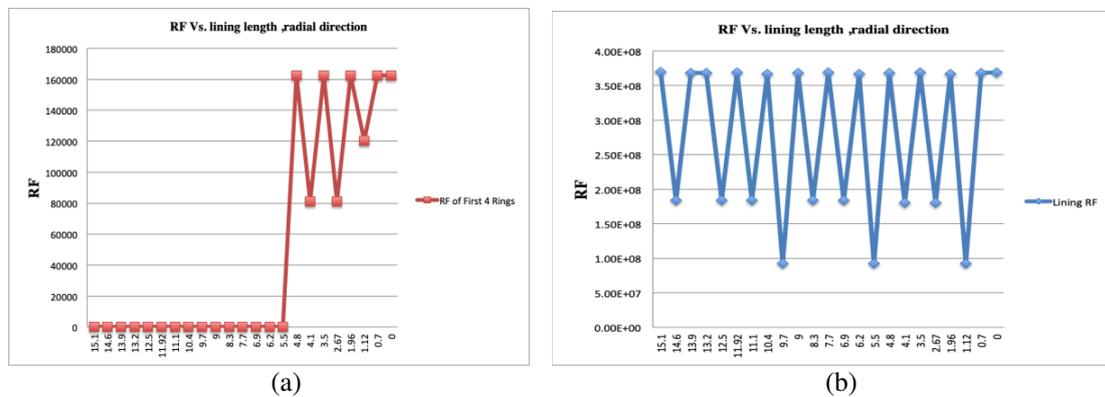
Prior to the start, the constitutive relation that is used to model the soil is verified. The settlement result is compared by the result obtained from 3D FEM of Jusoh *et al.* [18] and the case study that studied by Mohamed *et al.* [22]. The settlement result that is obtained from the soil model showed a great matching with the result of the mentioned sources. The longitudinal settlement trough that occurred and obtained from the 3D FE model based on Moher Coulomb constitutive model validated and compared with the

settlement data of previous mentioned model [18]. Besides that, that model [18] is referred to the actual result of the case study (table 2) and [22], that is obtained by Optical Fiber Strain analyser of the tunnel ring R540 and surface settlement observed from settlement marker of G2407.



**Figure 6.** Result validation by case study data [18] (a) , the validation of 3D model settlement data by case study data (b).

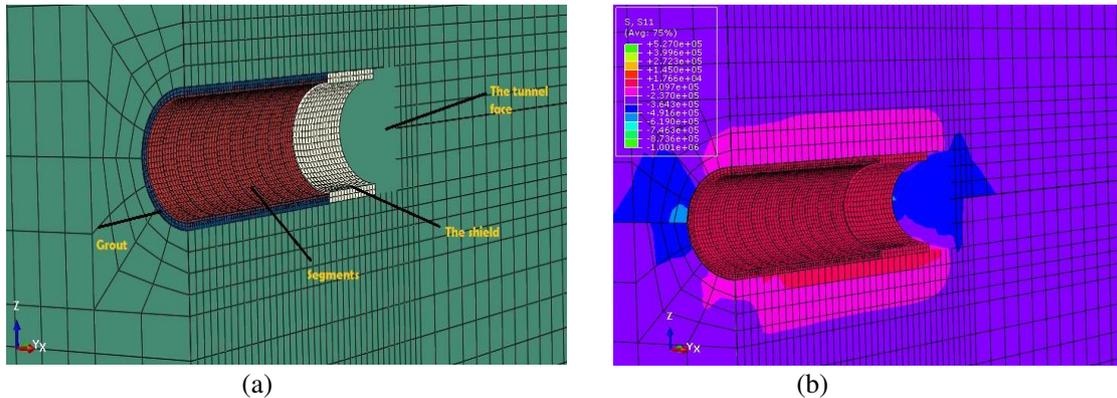
In the first phase of modelling, the lining with a selected thickness of 0.275 was modelled in soil block and the behaviour of lining radial reaction toward the force is investigated. The excavation procedure is modelled by applying all the loads related to the soil block (geostatic, pore pressure, saturation, surcharge and the different soil layer effect) at the initial step before the tunnel construction start. The construction of the tunnel then starts by advancing the shield and excavate the soil by 1.4 m of step rate. The lining is assembled under the shield cover then the shield start move toward the tunnel face.



**Figure 7.** (a) RF of first 4 rings are imposed on the construction load only under the shield only and (b) RF of the whole lining after imposed to the radial loads.

The lining imposed to the radial load ring by ring till the whole lining is assembled and uncovered by the shield. Figure 7(a) and 7(b) present lining with radial loads along the tunnel axis with partially interacted with the soil and fully interacted with the soil, respectively. Figure 7(a) shows the reaction of segment toward the assembly loads under the shield which is not imposed on the soil load and grout pressure. Figure 7(b) shows the result of lining reaction toward the moment developed by loads of soil block and the pressure of grout after the whole lining is constructed. The clear fluctuation in RF because of circumferential joints, which is modelled as face contact. It's a function to connect the segment and

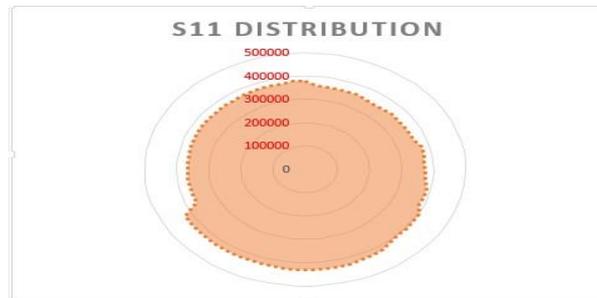
transfer the load along the axial direction. Definitely, its reaction toward the loads will not simulate the segment's reaction, but it resembles the behaviour of ring joints.



**Figure 8.** The position of each Element after the simulation ends (a). The distribution of stress upper and lower the tunnel and the face pressure at the end of the process (b).

As it's mentioned in the previous section based on measurement procedures that is mentioned in Abaqus documentation [23], after the simulation ends, the stress element of the tunnel face is measured as is shown in figure 8(b) and integrated to get the jacking force. The measured stress value represents the stress distributed on the tunnel face as is shown in figure 8. By integrated these value with the total ring cross section, a force is obtained. The resulted force represents the total force magnitude required to make the shield thrust the segments to advance the tunnel, figure 8(a), dividing it on the number of segment to obtain the force is exerted on each segment. Table 3 showed the various magnitude of jacking force applied on different line geometries.

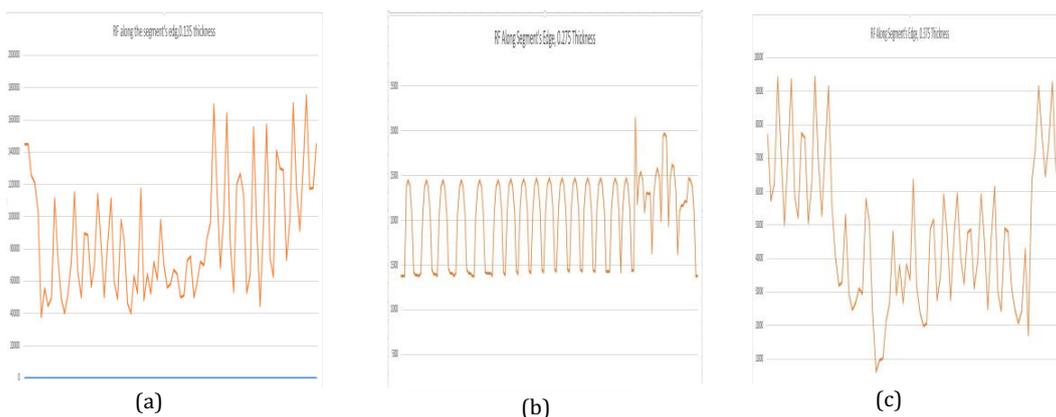
In the second phase, analyses of the segments model in different thickness are presented. Table 3 presents the proposed thickness for segments that used in this study based on thickness,  $d$  to diameter,  $D$  relation of equation 5. The result of the second phase model shows the behaviour of the segments in term of the angle of the tunnel. Figure 10 illustrates the distribution of reaction force on the segment's face by comparing the RF for different three segments in thickness against the circumferential face angle. The contact reaction force (RF) is analysed and presented to explain the segment reaction toward the jacking force. Once the uniform jack force applied the segments face develop a reaction against the exerted force and this reaction transfer along the segment face through the longitudinal joints. Due to change in the Young modulus and moment inertia between the segments and the joints, the reaction of segment against the force was changed. The sudden drops of reaction force are shown when the segment's thickness increase occurred repeatedly near or on the longitudinal joint.



**Figure 9.** The magnitude of stress component that is measured from tunnel excavated phase.

**Table 3.** Segment’s model.

Model	1	2	3
Thickness, $d$ (m)	0.135	0.275	0.375
$d/D$ ratio	0.0225	0.0458	0.0625
S11 (N/m <sup>2</sup> )	387343	387343	387343
Cross section area of the excavated face(m <sup>2</sup> )	28.3	28.3	28.3
Cross section area of segment edge(m <sup>2</sup> )	2.5447	5.1836	7.0686
Jack force applied (kN)	4308	2115	1551



**Figure 10.** Reaction force results of segments due to the exerted jack force for, (a) 0.135 segment’s thickness, (b) 0.275 segment’s thickness and (c) 0.375 segment’s thickness

## 5. Conclusion

A three dimensional numerical model of soil-tunnel has been presented with different tunnel thickness and jack forces. The model was developed to investigate the behaviour of different thickness segment against the jacking force in presence of relevant loads and interactions; the segment behaviour is studied in only jack forces environment and in the complex loads' environment. Conclusions that can be drawn for this study, as are follows:

- The low thickness of the segment can encounter the jacking force required as almost the same the higher thickness segments.
- The proposed model sequences show a method to estimate the jacking force required numerically.
- The reaction of segments toward jack force is non-uniform and the pattern of its behaviour changes with thickness changes.
- The presence of hinged longitudinal joints that are staggered by  $11.25^\circ$  has a greater effect to distribute the loads on the segment's edge and enhance the uniformity of the segment's behaviour.
- The elimination of eccentricity by replacing the ring joints by face-to-face interaction algorithm, enhance the distribution of the load along the tunnel length and decrease the linking reaction.
- The complex load case due to the variation in soil formation properties, pore pressure and presence of surcharge lead to a great radial effect on the tunnel lining.
- The higher reaction comes from the first rings imposed to soil load and grout pressure then the reaction distributed gradually.

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