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Numerical Modelling of Tunnel-Ground Interaction with Building Existence

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Abstract: Tunnel is complex and risky construction. When excavation of tunnel take place, the original ground equilibrium will affected thus lead to the stress redistribution and ground movement. Tunnel construction in the urban city is in concerned as tunnel will passes under a lot of existing building. Therefore, in this study, a series of simulation of tunnel construction with and without external building was conducted. Numerical model by means ABAQUS Software was conducted based on tunnel-soil-load model was developed. From the result, it can be concluded that soil stress redistributed when excavation of soil occurs especially near to the tunnel periphery. The ground settlement trough depicts a significant maximum settlement for the model with high external load and producing flat u-shape in the middle of settlement trough pattern.

Keywords: Tunnel excavation, tunnel mining, ground movement

1. Introduction

In recent years, there has been a rapid population growth in urban areas, leading to effective transportation. However, limited surface area makes underground transportation become an alternative. Therefore, underground tunnels are constructed to support the demand of transportation. In many cities, the amount of tunnel construction is increasing for many purposes such as providing underground roadways and effective utilities [1].

To build a tunnel, several methods are available including the mechanized tunnel method (using a tunnel boring machine), cut and cover method, clay kicking method, shaft method, pipe jacking method, box jacking method, and underwater tunnels. However, the tunnel excavation will affect the surrounding environment, especially the building. The ground movement induced by tunnel construction will give a bad effect on infrastructure and building above the ground [2]. As the tunnel is a complex and risky construction, concerns about the stability of nearby buildings and the ground need to be checked. Many researchers have carried out investigations into the matter. For example, Franzius *et al.* [3] study the damage of the building when tunnel construction happens becomes the major concern in the planning and construction of the tunnel. Franza *et al.* [4] conducted investigation on the effect of the excavations on buildings with shallow foundation or pile. Based on one research conducted by Mayoral and Mosqueda [5], it is stated that underground facilities, such as tunnels construction can result in the seismic vibration to the structures located in urban areas, thus the midrise buildings significantly affected. Settlement might occur. Shahin *et al.* [6] presented their findings on the effect of tunneling on the existing structures. They concluded that the structures was affected mainly depending on the distance between the tunnel and the foundation.The tunnel-building interaction is considered based on the distance of the building and the axis line of the tunnel. When the distance of the building and the axis line of the tunnel increase, the settlement will decrease. The maximum settlement always occurs in the middle of tunnel [7]. This can be illustrated in Fig. 1.

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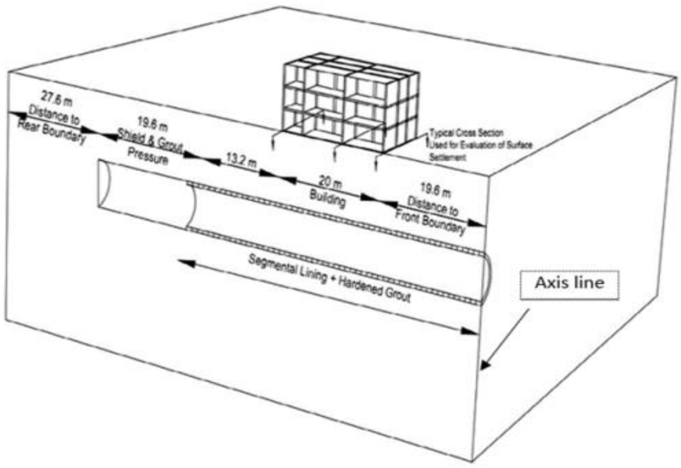


Fig. 1 - Building and tunnel [7]

The focus of this research is to investigate the ground behavior induced by the ground excavation for tunnel in with and without the external building structure (*i.e.*, with load and no-load condition).

2. Numerical Model Development: Tunnel-Soil-Building Development

Three different models were developed for this study, one is a greenfield model, the excavation in the soil block without any external load, other two model is the similar model but with the existence of external loads of 10 kN and 1000 kN to imitating the load of building. The building is located at the starting part of tunnel, i.e., the first to third ring of tunnel excavation and distributed evenly from the center crown of tunnel. In this process of developing the model, there were four important parts in the model development, explained in section 2.1 to 2.4.

2.1 Geometry and Properties

The soil dimensions are 63 m length with 50 m width and 46 m height. The tunnel is 6.35 m in diameter with 1.4 m width and 0.275 m thickness. The soil property was followed Table 1. The property of the tunnel was used with the Young Modulus, E_L of 33GPa and the Poisson's ratio of 0.2.

Table 1 - Details of the soil properties [8]

Soil layer	Soil type	Young Modulus, E_s (kPa)	Bulk density, γ (kN/m^3)	Poison's ratio, v_s	Angle of friction, ϕ (^{o})	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 G4 (VI)	59200	20	0.3333	30	2
L6	Bukit Timah granite G4 (V)	86400	20	0.3	35	2
L7	Bukit Timah granite G2 (III)	3500000	25	0.32	35	400

The tunnel was located at the center of the soil at a depth of 23 m. The tunnel was located exactly between two layers that were layer 4 and layer 5. The model of soil block with the proposed excavation tunnel diameter is presented in Fig. 2.

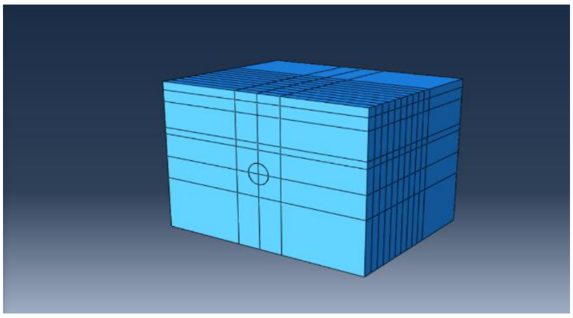


Fig. 2 - 3D model of the soil tunnel with the proposed tunnel diameter in ABAQUS software

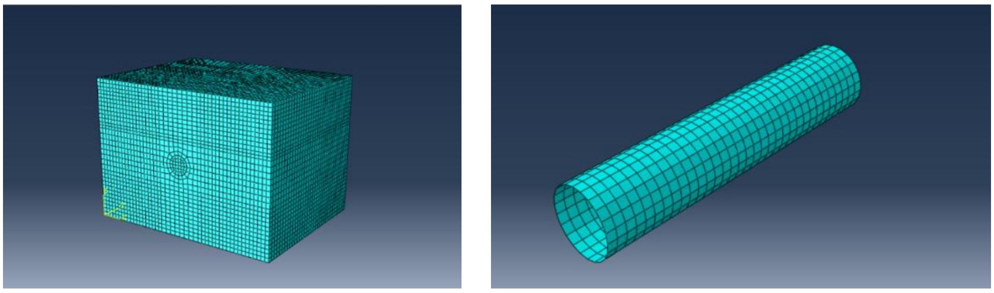
2.2 Boundary Conditions and Load Design

The boundary size of model was carefully considered to ensure it will not affect the results at the end of modelling. The boundary condition and load were applied to imitate the field case study condition. The gravity assigned in this model in the vertical axis of model. The boundary for the model was assigned at the bottom (i.e., fixed in all movements) and sides of the ground model (*i.e*., which allows to move in z-axis only).

In this model, a building load was also applied to represent urban conditions. The pressure load model was applied on the ground surface at the beginning of tunnel construction with the magnitude of 10kN/m^2 and 1000kN/m^2.

2.3 Meshing

The soil and the tunnel were meshed sufficiently to allow for numerical modelling analyses. This process is very important in ABAQUS to allow for the analyses. The meshing used was seed globally with ratio of 1.3 for the soil block model and 0.9 for tunnel model. The meshing of the soil is presented in Fig. 3 (a) and the meshing of tunnel is presented in Figure 3 (b).



(a) (b)

Fig. 1 - Meshing of : (a) soil block model and (b) tunnel model

2.4 Steps

The model had 4 steps which start with the geostatic that apply the properties for the soil. In geostatic condition, stress layer of soil was calculated and assigned as prescribed bearing capacity. To simplify the modelling, the pore pressure and saturation were applied was zero, *i.e*., considering the ground water table is far below the modelling area and model the ground as the undrained condition. The void ratio is adopted as 1 to ensure convergence in modelling.

The second step then is the activation of load above the surface of soil, *i.e.*, the building. Then, the third step is excavating the soil follow the size of proposed build of tunnel, 6.35 m in diameter. Due to complex interaction model and limited of computer capacity, the modelling only considers excavation of tunnel without installation of tunnel lining for model convergence.

3. Result and Discussion

The results from the modelling were compared between the tunnel excavation in the greenfield condition and the tunnel excavation with the existence of building. In order to do so, a series of node path calling was set first in the ABAQUS software to retrieve the results. Fig. 4 presents the stress reaction due to excavation of soil for tunneling with 3 different paths for calling the results of simulations. Node 1 is path created at the ground surface along the x-axis, while Node 2 is comparison path to see the ground distribution parallel to the excavation depth. Node 3 presents the path taken to see the behavior of ground in the longitudinal section (along the excavation of tunnel alignment).

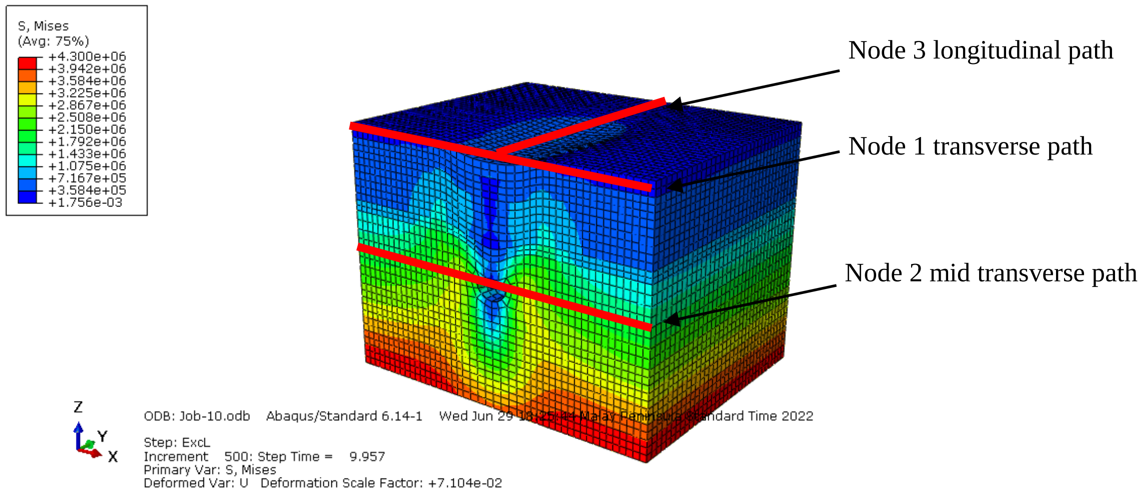


Fig. 2 - Stress reaction due to mining and path of the node series taken to retrieve the results

3.1 Stress Redistribution Due to Soil Mining for Tunneling

After excavation of soil for tunnelling, ground lost it original equilibrium and stress redistribution occurs to find for new stability. Fig.4 and 5 present the stress behavior induced by the excavation activity. From Fig. 4, one can see the stress contour of the stress redistribution due to predefined soil bearing capacity and the redistribution effects due to the soil mining. One can see the behavior of ground is almost symmetrically for left and right sides. Therefore, only half of the behavior of the model presented discusses the stress behavior in Fig. 5.

Fig. 5 shows the result of the stress at the mid depth of soil mining. From the edge of soil block, stress starts at 2 MN/m^2 and increases slowly towards the tunnel position, hitting the high peaks in the range of 2.5 to 3 MN/m^2 then suddenly decreases when it is approaching the diameter of tunnel soil excavation area. The higher the external load applied; the higher stress induces proportionally.

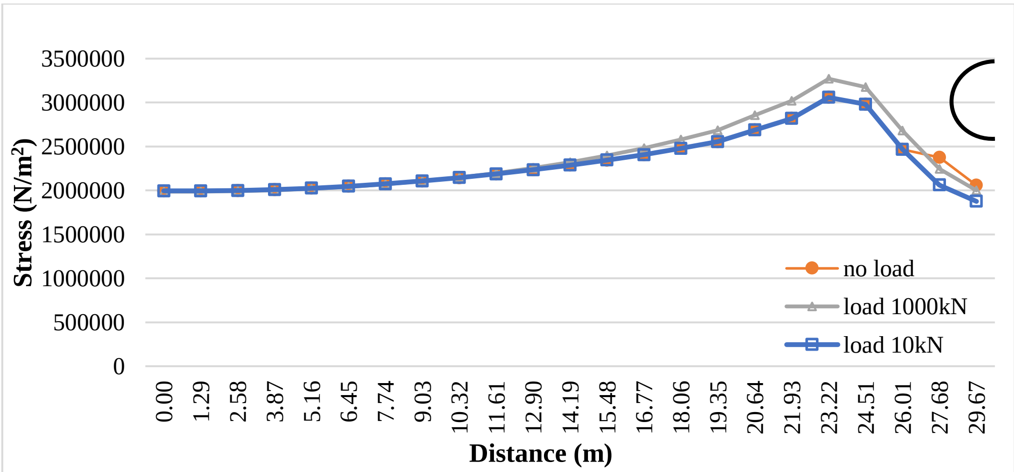


Fig. 5 - The stress induced due to ground excavation

3.2 Tunnel Induced Ground Movement

The mining activity induced ground particle movement until it is supported by the tunnel lining. Hence, the maximum ground settlement can be depicted in both transverse and longitudinal axis of ground surface. Fig. 6 presents the ground movement in the transverse direction. For greenfield condition, a bell shape transverse settlement plotted which is similar to the Gaussian Distribution curve. In addition, small loads did not capture any significant load effect and plotted like the greenfield condition. In opposite, the 1000 kN load anticipating the width of building model and led to a flat u-shape in the maximum settlement reading.

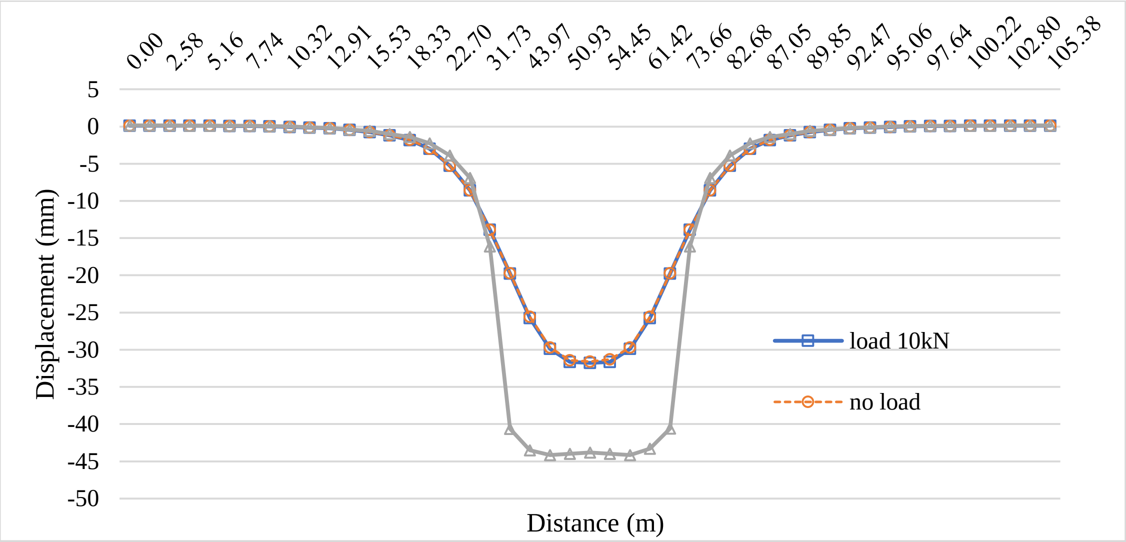


Fig. 6 - Ground settlement in the transverse axis direction

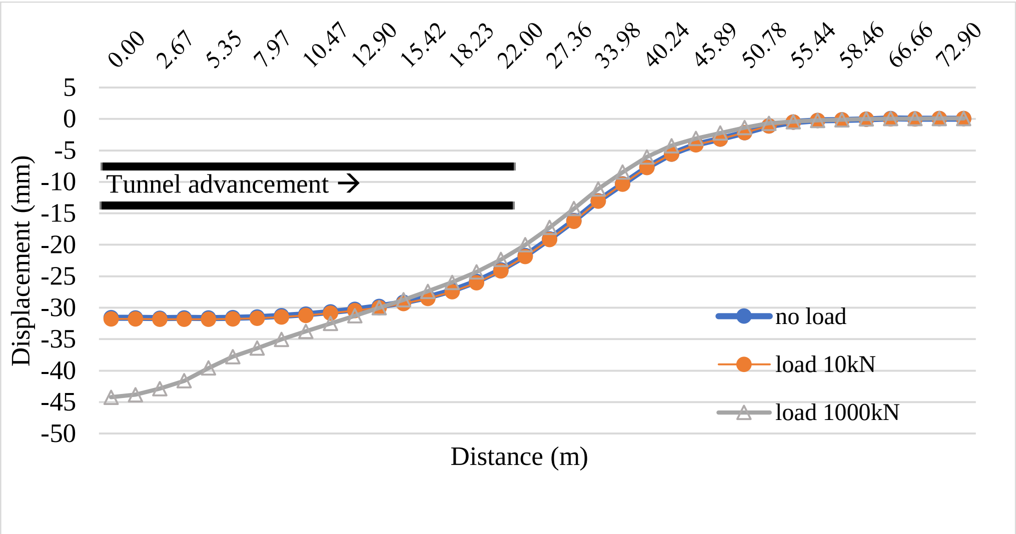


Fig. 7 - Ground settlement in the transverse axis direction

Next, Fig. 7 shows the displacement of the soil in a longitudinal direction. With the tunnel advancement, in the greenfield condition (without load) and 10 kN load, similar surface settlement depicted starts with 32 mm maximum settlement at the tunnel starts point. In opposite, with external load of 1000 kN, the settlement is significant as the building lies at the beginning of tunnel part, it then reduces towards then end of the tunnel advancement.

4. Conclusion

To understand the ground reaction after tunnel mining with and without external loading at the ground surface, a series of simulation was conducted here in. From the result, it can be concluded that:

- The soil mining or ground excavation led to soil stress redistribution as the ground look for new equilibrium. When checked for the tunnel depth level, the stress nearby the tunnel diameter was affected with increment and decrement of stress near to tunnel periphery.
- The tunnel excavation led to ground movement and produced maximum settlement near the tunnel position. For greenfield condition and small external load, the settlement depicted a bell shape which similar to the Gaussian Distribution curve. However, for the simulation with the high external load, significant flat maximum surface settlement can be seen at the tunnel position following the width of the building.

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