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Numerical Analysis for Prediction of Optimum Deformation of Long Tunnel Crown Stability with Respect to Excavation Depth

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ABSTRACT

Optimum stability of tunnel structures and ground movements are influenced by excavation, and these are issues of greater concern as far as the stability of any underground structure is concerned. The critical area of concern is the stability of the tunnel crown which requires special attention to ensure the stability of the tunnel structures and the safety of both man powers and the equipment used. Before the advent of powerful design aids tools such as numerical analysis software, the tunnel's design was primarily based on experience. The use of numerical analysis software has made it possible to model and predict the actual site conditions to achieve safer and more economical designs. This study aims to understand and predict the stability of the tunnel crown with respect to excavation depth by using Plaxis 2D v8 finite element analysis software and East Coast Railway, Malaysia tunnel project as a case study. The site condition was modeled and excavated at various tunnel depths of 0.5D,1.0D,1.5D,2.0D,2.5D to 3.0D which are around 7 m to 42 m depths, where D is the tunnel diameter. Based on the output results, both vertical and horizontal displacements show appreciable increases as the tunnel depths get deeper due to overburden. The result confirmed that there is a clear relationship between the tunnel excavation depth and the stability of the tunnel crown.

Keywords: Underground Structure; Tunnel Crown Stability; Excavation; East Coast Railway

1. INTRODUCTION

Tunnel infrastructures are possible and innovative alternatives to bridge the physical barriers such as rivers, roads, mountains, or facilities. The rail tunnels are important logistic infrastructure to cater for the ever-increasing urban populations such as we are witnessing today across the globe. It reduces environmental impact such as air quality, noise pollution, protection of historical or cultural sites, and for also sustainability purposes.

Tunnels can be defined as underground civil and mining engineering structures with a longitudinal span greater than two times the tunnel diameter, in some cases, it could be twice both the diameter and that of vertical dimension of the tunnel structure combined, [1,2]. According to its method of construction and functionality, the tunnel is regarded as an underground structure that can be constructed mostly by ground excavation, especially where there is a land constraint. The construction is not limited to the underground space alone, it could be immersed or floating tunnels as any of these methods could be used for crossing water under the surface [3].

The rapid development of cities coupled with accelerated urbanization and the need for industrialization made the world embrace the use of underground space since it has limited interference with existing structures [4]. The various method used in the construction of tunnels can be categorized as conventional and machine excavation, the use of Tunnel boring machine (TBM) is a typical example of machinery method, while the New Australian Tunneling Method (NATM) on the other hand is a typical example of a conventional method. NATM is popular due to its flexibility and suitability in variable ground conditions and tunnel shapes [5,6]

The NATM is characterized using the self-support capacity of a rock to ensure stability and to be able to control the forces in the readjustment process which occurs in the surrounding rock mass geological stress after the cavity has been made and to adapt to the selected support accordingly [7]. The type of excavation method, sequence of excavation, primary support, and auxiliary construction measures are the pivots of the conventional tunneling method [1,6]. The excavation methods are either drill and blast (D&B) for hard rock or mechanically supported excavation for weak rock and soft ground on the full-face or partial excavation of the tunnel cross-section. Full-face is suitable for smaller sections while partial excavation is ideal for wider sections and difficult ground [6]. The excavation work in NATM is usually carried out in two phases such as (a) Top-heading and (b) Bench-heading, as shown in figure 1.1 below.

Figure 1.1 NATM excavation method use in ECRL project Malaysia

The use of a Tunnel Boring Machine is also a popular choice among different methods of tunnel construction because of its efficiency in excavation and suitability for circular tunnels [8]. Its mode of operation is through the use of the rotation of the cutter head to cuts the rock into smaller pieces, there are other useful components of the machine such as disk cutters and blade pressure which also play a vital role in cutting the rock [9]. Figures 1.2 and 1.3 below show a typical Rock TBM face and the classification of Tunnel excavation Machines respectively.

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Fig 1.2 Rock Tunnel Boring Machine face, with disc cutters fro hard rock Australia [10]

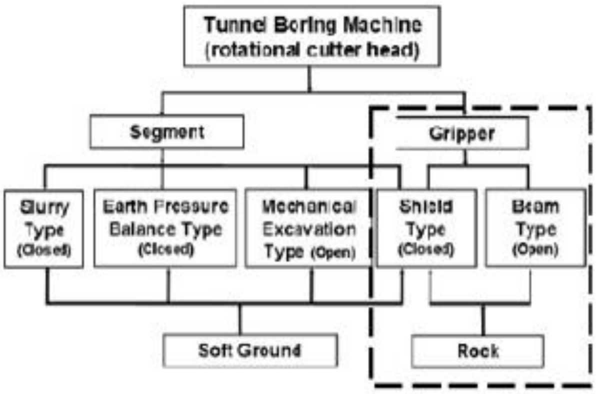

Fig 1.3 Classification of Tunnel excavation machine [11]

Underground excavation such as tunneling structures can result in a ground surface settlement with greater implications on existing structures, especially in urban areas. To avoid the destruction of existing structures during tunneling work, there is a greater need for an effective method to assess the safety of the tunnel structures [12]. The existing methods for tunnel safety assessment are (a) experimental, (b) analytical, and (c) numerical methods. The application of both experimental and analytical methods is appropriate only in specific geological conditions [13].

2. PROJECT BACKGROUND

This study considered the East Coast Rail Link (ECRL) project which is a 640km railway link connecting different parts of the east coast region with the west coast region in Malaysia. Construction on the ECRL project began in August 2017, but the work was suspended in 2018 due to financial reasons. Construction resumed in July 2019, with the completion scheduled for December 2026.The new rail link will pass through the states of Kelantan, Terengganu, Pahang, Negeri Sembilan, WP Putrajaya, and Selangor. It will originate at Kota Bharu, the state capital of Kelantan, and terminate at Port Klang in Selangor. The case study is that of chainage (CH376+709) of Gambang Tunnel, which is part of the ECRL project package. It is a 13.72-m-diameter horseshoe-shaped tunnel in highly weathered sandstone ground condition through which the tunnel is excavated. The construction technique is the New Austrian tunneling method (NATM). Primary support such as rock bolts is usually considered in this type of tunneling work, but for the sake of simplicity in the modeling, no rock bolts would be considered [14].

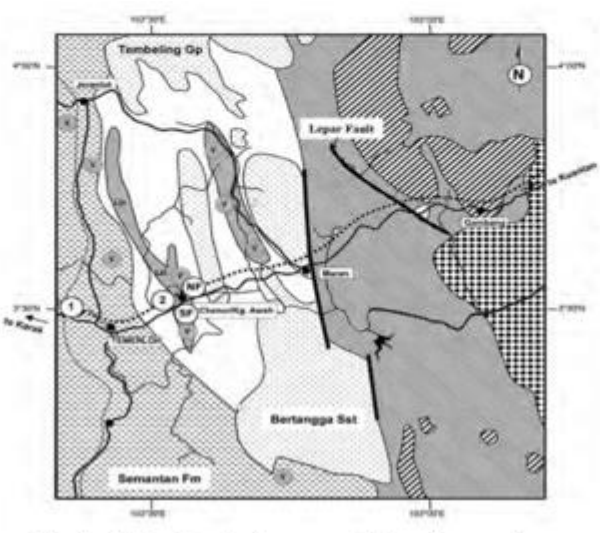

Fig 1.4 Geological map of the Central Belt, Temerloh and Gambang

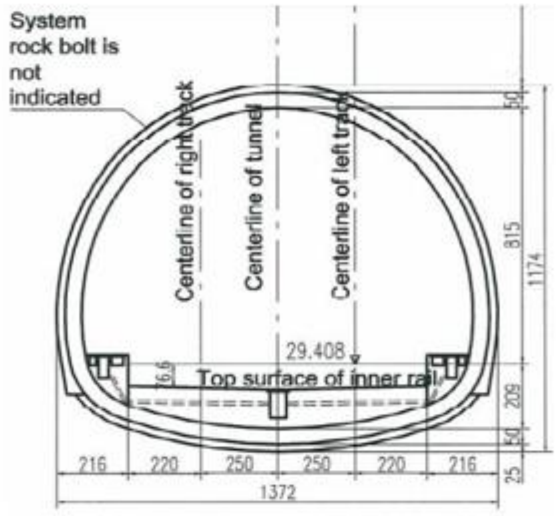

Fig 1.5 Cross section of Tunnel (CH376+709)

3. MATERIALS AND METHOD

To carry out this study, PLAXIS 2D v8 software was used. The excavation depths were divided into six different depths, (m) for the purposed of this study.The table 1.1 below shows the tunnel depths at 0.5D,1.0D,1.5D,2.0D,2.5D and 3.0D which are around 7 m to 42 m depth.This was done in order to have a conservative approach so that finite element analysis can be carried out at a reasonable depth of 0.5D increment. The finite element geometry model was fixed at 50 m in width and 60 m in height, this was sufficiently large to allow for any possible collapse mechanism to develop and to avoid any influence from the model boundaries. Both vertical and horizontal boundaries were also fixed and the FEM model was a plane strain model. The two clusters inside the tunnel contour have a refined coarseness mesh as shown in Fig. 1.6 below.

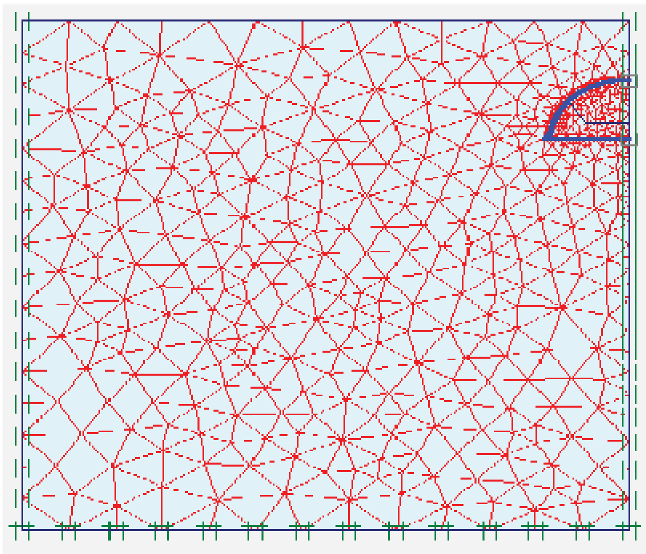

Fig 1. 6 FEM Mesh

Table 1.1 Tunnel Depths

Depth	(m)
0.5D	7
1.0D	14
1.5D	21
2.0D	28
2.5D	35
3.0D	42

Table 1.2 Highly Weathered Sandstone Material Properties [15]

Parameters	Name	Highly Weathered Sandstone	Unit
Material Model	Model	Mohr-Coulomb	-
Type of Material Behaviour	Type	Drained	-
Soil Unit Weight	γ_{unsat}	22	kN/m^3
Young's Modulus	E_{ref}	$7.1*10^6$	kN/m^3
Poisson's Ratio	V	0.35	-
Cohesion	C'_{ref}	50.8	kN/m^3
Friction Angle	φ	47.8	°

Table 1.3 Shotcrete Properties

Parameters	Name	Value	Unit
Type of Behaviour	Material Type	Elastic	-
Normal Stiffness	EA	9.00E+6	kN/m
Flexural Rigidity	EI	6.75E+6	kNm^2/m
Equivalent Thickness	D	0.3	M
Weight	W	7.2	kN/m/m
Poisson's Ratio	v	0.2	-

4. RESULTS AND DISCUSSION

Fig 1.7 (a-f) below shows all the output excavations for vertical displacement from 0.5D to 3.0D, while figure 1.8 (a-f) shows all the output excavations for horizontal displacement from 0.5D to 3.0D. Table 1.1 above shows the tunnel depths at various stages. 'D' is the depth of the excavation.

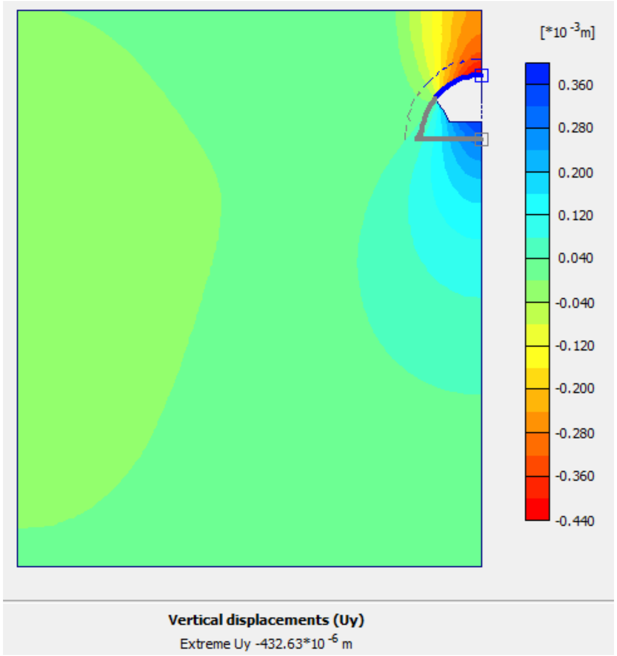

Fig 1.7 (a) Vertical dislacement exavation at 0.5D

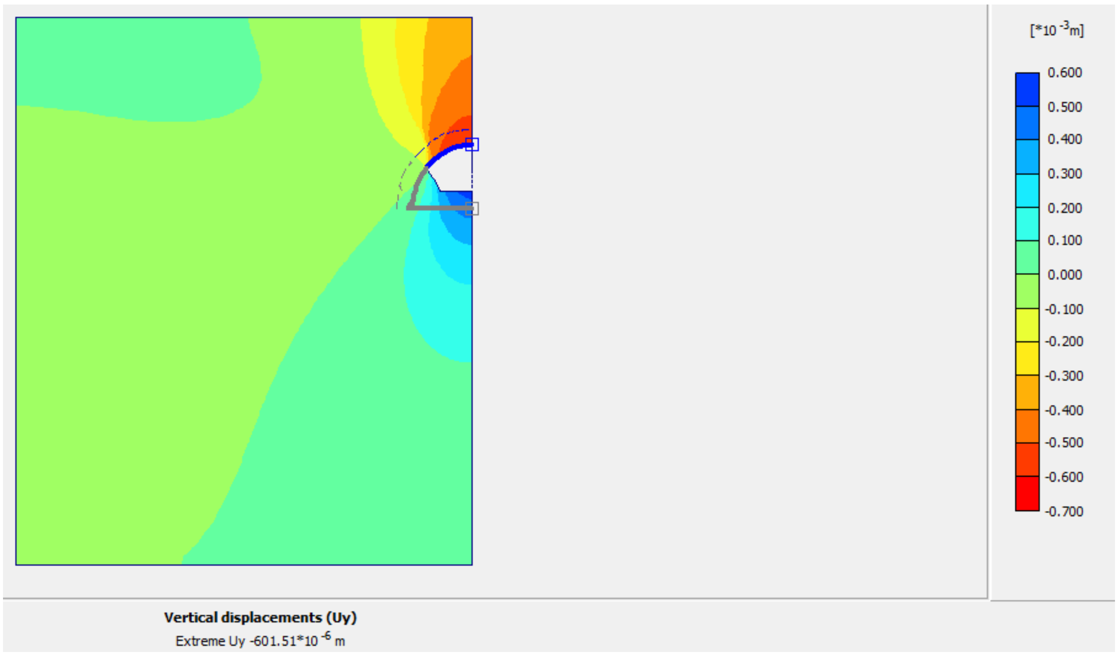

Fig 1.7 (b) Vertical displacement excavation at 1.0D

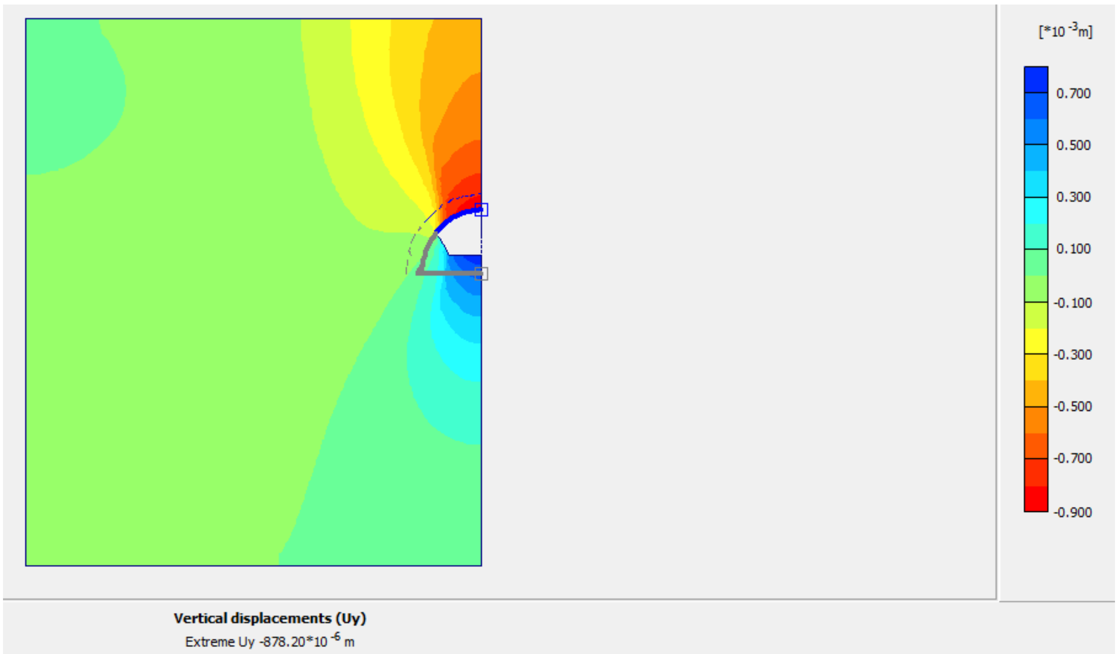

Fig 1.7 (c) Vertical displacement excavation at 1.5D

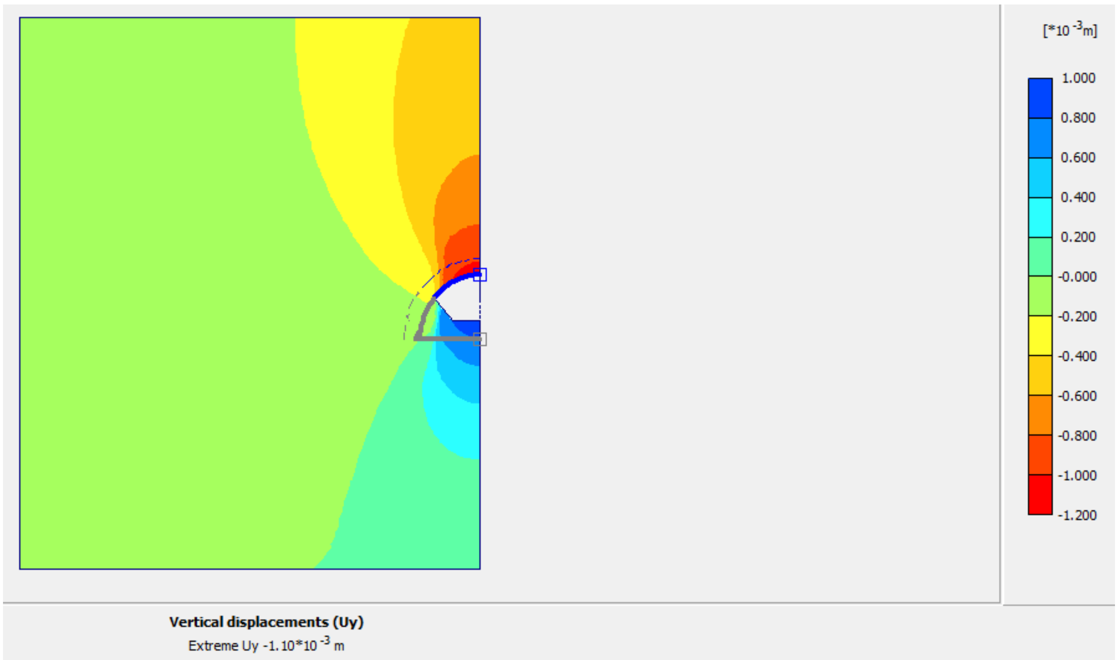

Fig 1.7 (d) Vertical displacement excavation at 2.0D

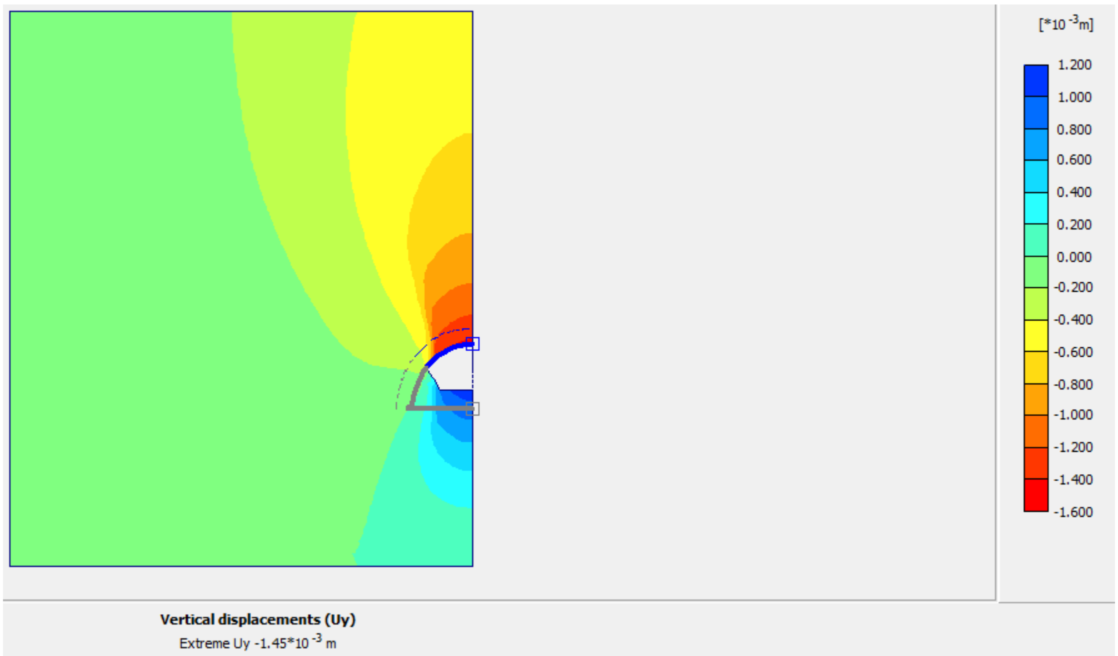

Fig 1.7 (e) Vertical displacement excavation at 2.5D

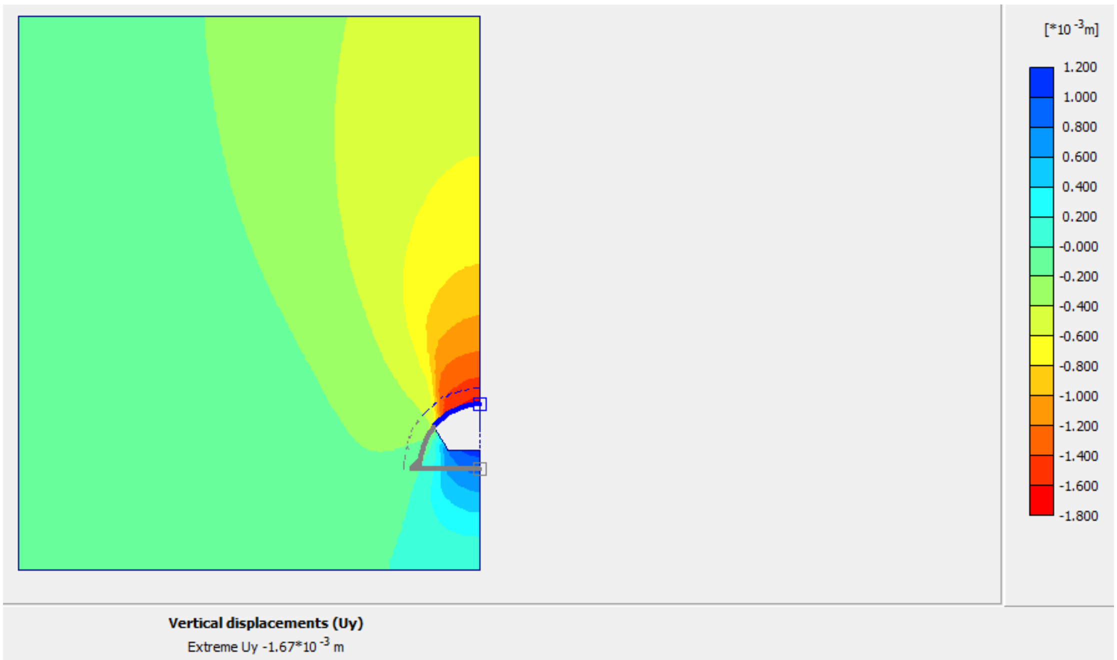

Fig 1.7 (f) Vertical displacement excavation at 3.0D

Figure 1.7 (a-f) Vertical displacement at various excavation depths.

Figure 1.7 (a-f) above shows the vertical displacement output of the tunnel excavation from 0.5D to 3.0D. This shows the vertical displacement of the tunnel crown at the specified excavation depth.

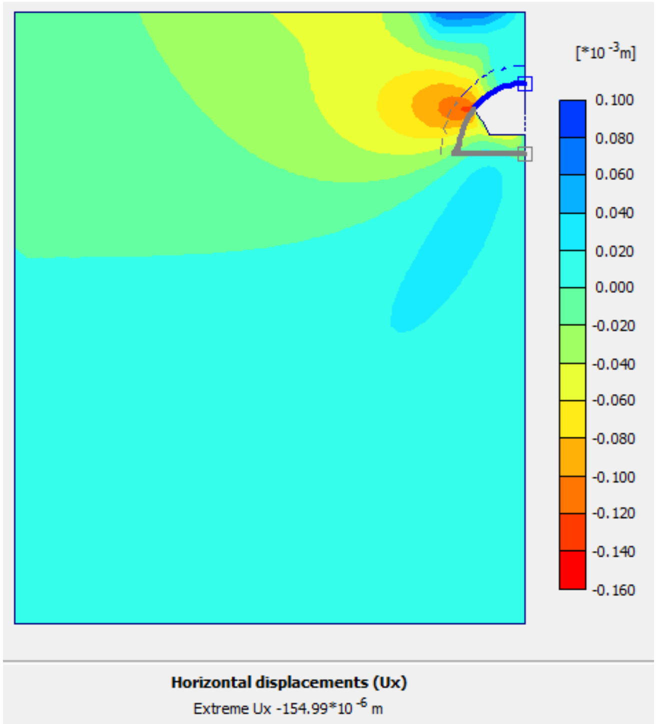

Fig 1.8 (a) Horizontal displacement at excavation depth of 0.5D

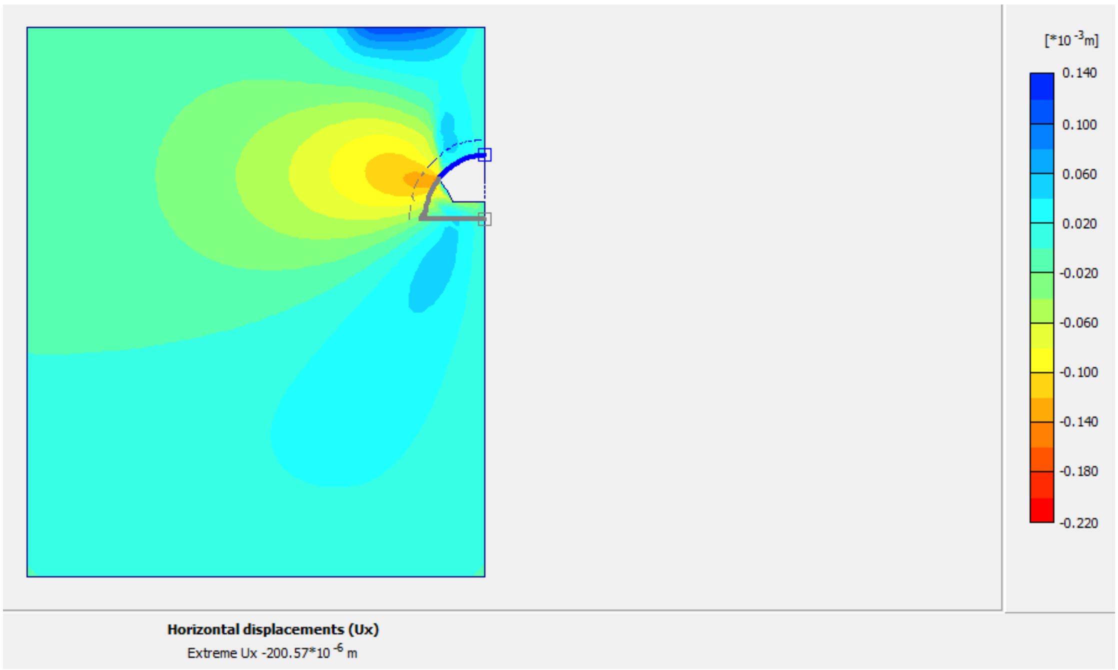

Fig 1.8 (b) Horizontal displacement at excavation depth of 1.0D

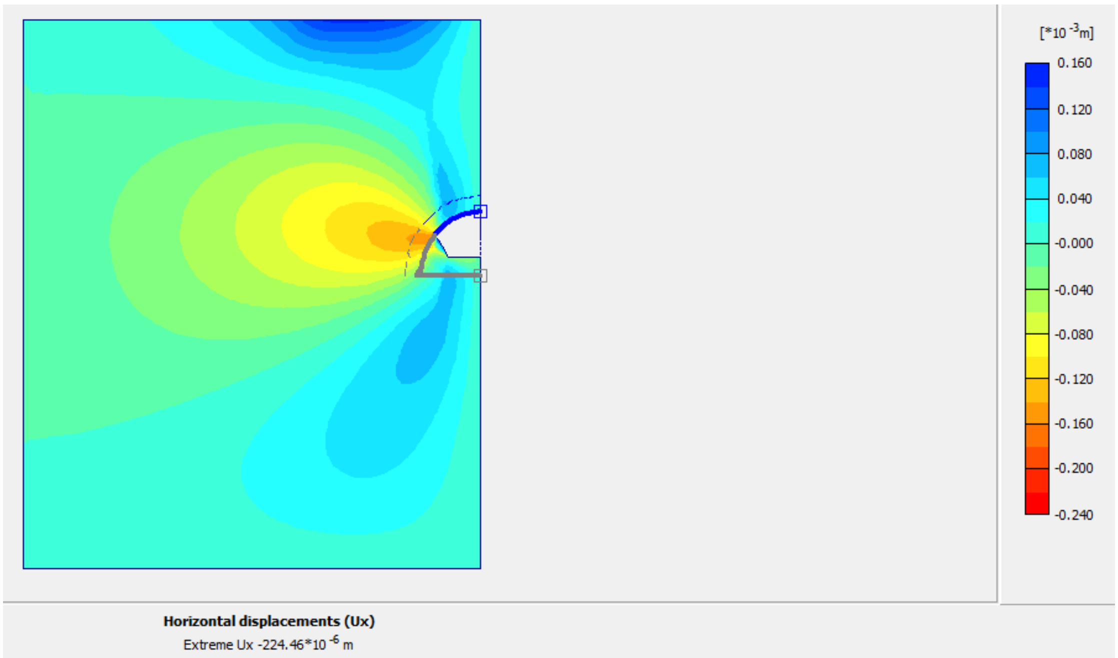

Fig 1.8 (c) Horizontal displacement at excavation depth of 1.5D

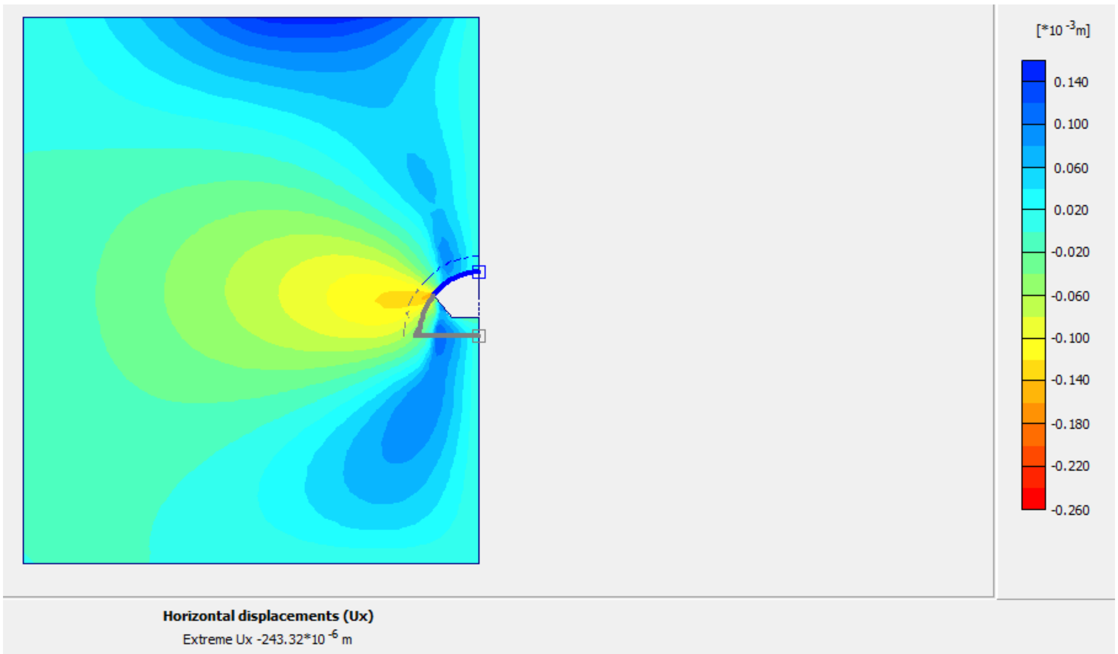

Fig 1.8 (d) Horizontal displacement at excavation depth of 2.0D

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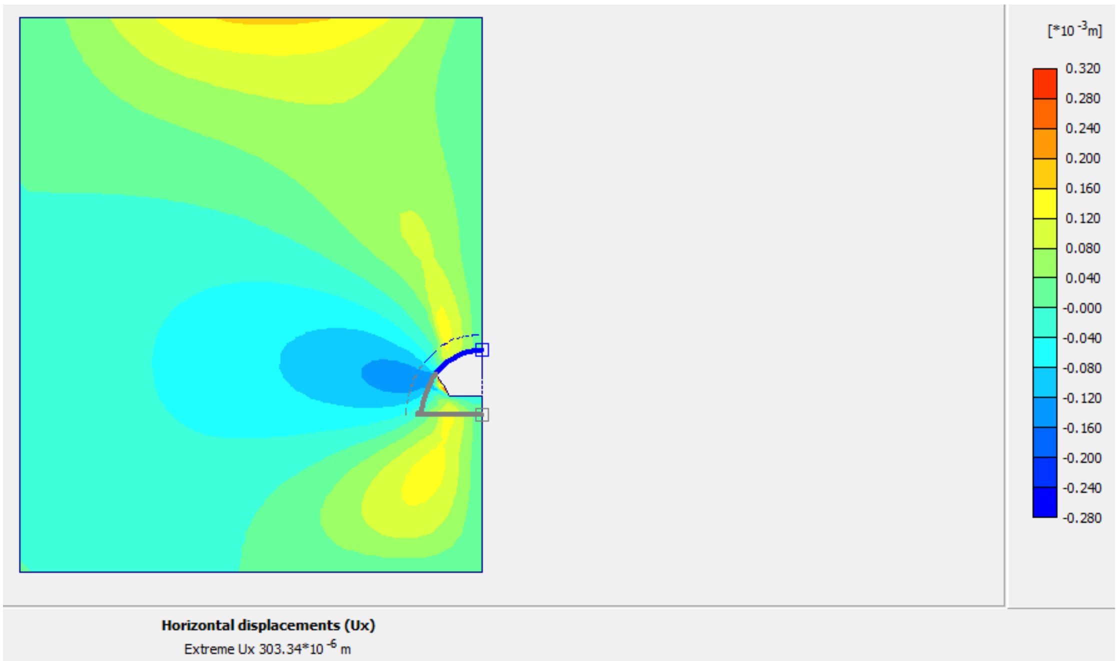

Fig 1.8 (e) Horizontal displacement at excavation depth of 2.5D

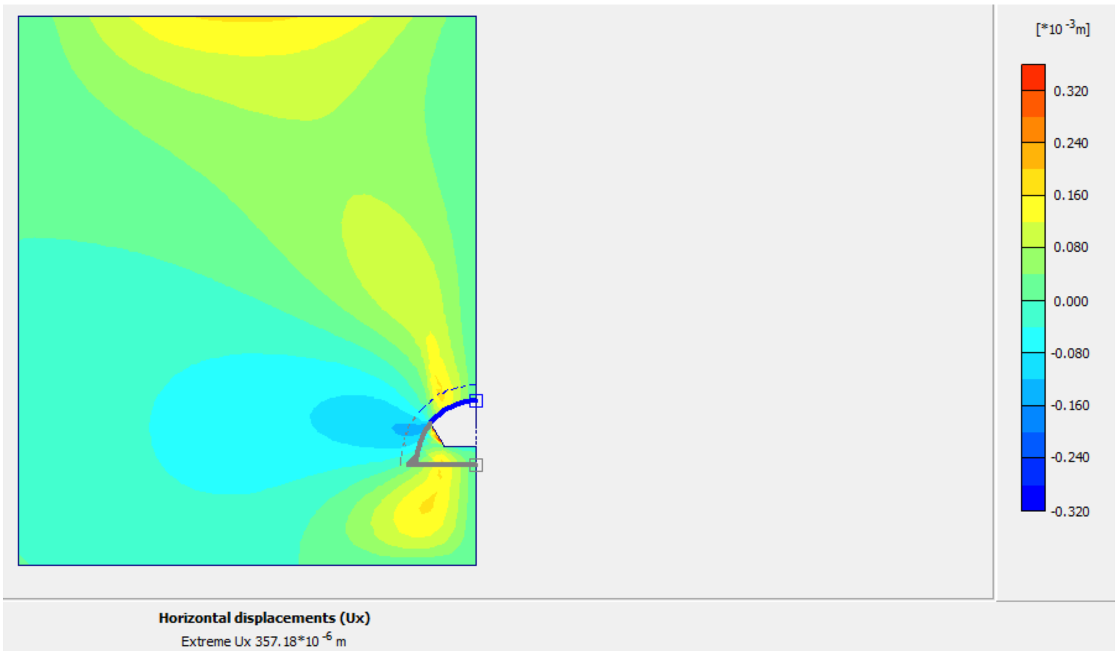

Fig 1.8 (f) Horizontal displacement at excavation depth of 3.0D

Figure 1.8 (a-f) Horizontal displacement at various excavation depths.

Figure 1.8 (a-f) above shows the horizontal displacement output of the tunnel excavation at various depths. This shows the horizontal displacement of the tunnel crown at the specified excavation depth.

5. CONCLUSION

Table 1.4 below shows the FEM results output of various excavation depths from 0.5D to 3.0D, depths.

Table 1.4 FEM Results for vertical displacement and horizontal displacement at excavation depths of 0.5D to 3.0D.

Depth, D (m)	Vertical displacement (m)	Horizontal displacement (m)
0.5D	$432.63*10^{-6}$	$154.99*10^{-6}$
1.0D	$601.51*10^{-6}$	$200.57*10^{-6}$
1.5D	$878.20*10^{-6}$	$224.46*10^{-6}$
2.0D	$1.10*10^{-3}$	$243.32*10^{-6}$
2.5D	$1.45*10^{-3}$	$303.34*10^{-6}$
3.0D	$1.67*10^{-3}$	$357.18*10^{-6}$

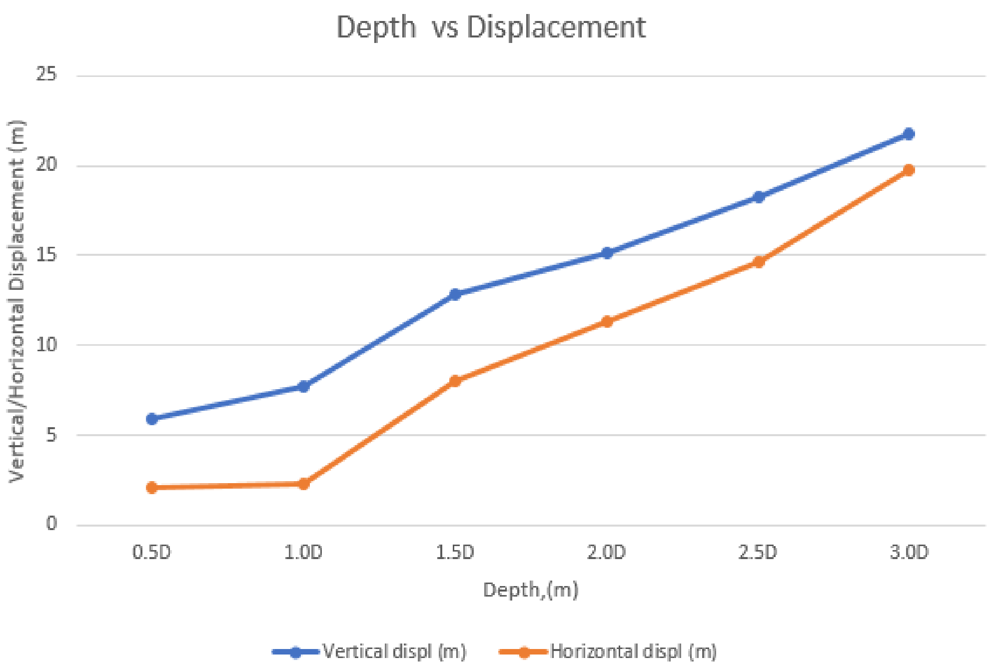

Figure 1.9 Tunnel depths vs displacements

The results obtained in table 1.4 were analyzed in Figure 1.9 above, which shows depth-displacements at corresponding tunnel excavation depths. Figure 1.9 visibly shows the effects of tunnel excavation depths on the safety of the tunnel crown as it related to both vertical and horizontal displacements. Both vertical and horizontal displacements increased as the tunnel excavation gets deeper thereby, evidently affecting the stability of the tunnel crown. This confirmed that there is a clear relationship between the tunnel depth and the ground deformation. The depth of the tunnel excavation is critical to the ground deformation due to the overburden, since the ground deformation is responsible for the failures of tunnels crowns in tunnel works, as a result of this, the stability of the tunnel crown can be said to be influenced by the excavation depth of the tunnel as the tunnel depth get deeper.

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