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Soil-structure interaction of two different configurations of a cut and cover tunnel

Interaction sol-structure de deux configurations différentes d'un tunnel en tranchée couverte

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ABSTRACT: This paper investigates soil-structure interactions for a short/shallow cut and cover tunnel will be constructed in Erbil using Plaxis-2D software. In the analysis, different cross-sectional shapes, triangle cut and cover tunnel (TCCT) and horseshoe cut and cover tunnel (HCCT) shapes, were suggested. These two shapes were simulated for a tunnel having a total height of 5.2m, a width of 8m, and a 0.9m permanent lining. The maximum overburden soil above the tunnel's roof or crown was approximately 7.8m. The simulation of the interaction was performed between a coarse-grained soil and the 0.9m concrete lining. The soil parameters were selected under the worst case to provide the safest scenario. The simulation results showed that the horseshoe cross-sectional configuration produced less shear force and bending moment on different parts of the tunnel components, indicating that less concrete and steel bars could be used for the same cross-sectional area of the tunnel, resulting in reduced carbon dioxide emissions into the air.

RÉSUMÉ: Cet article étudie les interactions sol-structure pour un tunnel en tranchée couverte court/peu profond construit à Erbil à l'aide du logiciel Plaxis-2D. Lors de l'analyse, différentes formes de section transversale, en forme de triangle et de fer à cheval, ont été suggérées. Ces deux formes ont été simulées pour un tunnel ayant une hauteur totale de 5.2m, une largeur de 8m et un revêtement permanent de 0.9m. La hauteur maximale des morts-terrains au-dessus de la couronne du tunnel était d'environ 7.8m. La simulation de l'interaction a été réalisée entre un sol à gros grains entièrement saturé et le revêtement en béton de 0.9m. Les paramètres du sol ont été sélectionnés dans le pire des cas (conditions non drainées) afin de fournir le scénario le plus sûr. Les résultats de la simulation ont montré que la configuration transversale en fer à cheval produisait moins de force de cisaillement et de moment de flexion sur différentes parties des composants du tunnel, ce qui indique que moins de béton et de barres d'acier pourraient être utilisées pour la même section transversale du tunnel, ce qui entraînerait une réduction émissions de dioxyde de carbone dans l'air.

Keywords: Tunnel shape; soil-structure interaction; plaxis-2D; numerical analysis; shear force.

1 INTRODUCTION

The shape of the cross-section of an underground tunnel usually is a consequence of the proposed construction method, function of tunnel and geotechnical conditions (Nguyen et al., 2021). For a cut and cover construction method, tunnels are usually made with different cross-sectional shapes such as rectangular (Di et al., 2016), horseshoe (Abdellah et al., 2022) and arch shaped (Li et al., 2020). The influence of the cross-sectional tunnel shapes has been investigated by a number of researchers, for example, in terms of the stability of a shallow tunnel (Abdellah et al., 2022) and soil settlements under dynamic loads (Di et al., 2016). Triangle shaped tunnels have not been thoroughly studied in terms of the lining thickness and the distribution of the shear force and bending moment. Tunnel shape selection has a significant effect on the mechanical performance of the lining. Reasonable tunnel shapes minimize excessive bending moment on the lining under the self-weight of soil and surcharges. Thus, designing of tunnels requires shape optimization. Therefore, in this research, a comparative numerical study between triangle shaped and horseshoe shaped tunnel was performed using Plaxis 2D software to determine their influences on the soil deformation around the tunnels and the distribution of the amount of the shear force and bending moment on the tunnel lining. In addition, a comparison was made in terms of the volume of the reinforced concrete per meter length in each shape to know which shape will use less reinforced concrete resulting in reduced carbon dioxide emissions into the atmosphere.

2 NUMERICAL MODELLING

2.1 Material parameters

Three materials were considered in the numerical analysis using Plaxis 2D: backfill soil, bed rock and reinforced concrete tunnel lining. The physical and geotechnical properties of the proposed soil backfill were determined in laboratory by Hasan et al. (2023) as shown in Table 1. From a site visit and visual inspection, the rock type was considered as weak and its properties were assumed shown in Table 1. The tunnel lining is made from reinforced concrete (RC). The input parameters of the RC lining are shown in in Table 2. Note that EA is Young's modulus times the area of the lining and EI is Young's modulus times the moment of inertia of the linings cross section, required parameters in the software.

2.2 Ground profile

The proposed cut and cover tunnel located in Erbil governorate. The total length of the tunnel is approximately 170 m with a width of 8 m. The maximum height of the soil over the roof/crown of the tunnel is approximately 7.8 m (see Figure 1). The tunnel is located in a valley, whose topography was surveyed. The client requested and emphasized the triangle shape of the tunnel having a cross sectional area of 38.25m^2 (see Figure 2). Therefore, a comparison was made to confirm to the client the lower cost of the horseshoe cross-sectional tunnel having an area of 27.2m^2 (see Figure 3) compared to the triangular one.

2.3 Finite element analysis

Plaxis 2D software was utilised to perform the numerical analysis because the cross-sectional dimensions are much smaller than the longitudinal length of the tunnel. Thus, plane-strain element type is used in the FE model for all materials. Figure 1 shows the mapped mesh of the 2D FE analysis for the worst case. The bedrock and tunnel lining were considered as linear elastic materials. However, the was soil modelled under Mohr-Coulomb failure criteria. The interface between the soil and the tunnel lining was also considered.

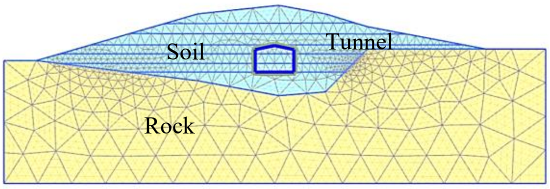

Figure 1. Meshed model for the worst scenario of the tunnel soil profile and construction phases.

Table 1. Physical and geotechnical properties of the used dense sand and rock in the numerical analysis.

Property	Soil	Rock
Void ratio, *e*	0.65	0.40
Dry unit weight, γ_d (kN/m^3)	16.2	21.0
Angle of internal friction, φ°	40	25
Cohesion, c′ (kPa)	1	100
Young's Modulus, E′ (MPa)	52	200
Poisson's ratio, *v'*	0.4	0.15
Specific gravity, G_s	2.73	-
Degree of saturation, S_r (%)	78	-

Table 2. Tunnel lining numerical analysis parameter.

Parameters	RC lining
EA (kN/m)	18 000 000
EI (kN.m^2/m)	1 220 000
Thickness, d (cm)	90
Poisson's ratio, *v*'	0.15

3 NUMERICAL ANALYSIS RESULTS

3.1 Soil deformations above and around the tunnel

Figures 4 and 5 show the total soil deformation of TCCT and HCCT, respectively. Inspection of Figures 4 and 5 shows that the maximum amount of total deformation of the soil above the TCCT is much wider and has a different shape compared to the one of HCCT. This is also true in terms of the soil deformation distributed directly below the foundation of the TCCT. However, the soil deformation above and below the HCCT is uniformly distributed, confirming that the horseshoe shape gives an almost uniform and smooth soil stress distribution around the tunnel and thus uniform shear force (SF) and bending moments (BM). This in turn leads to usage of less lining thickness and reinforcement steel, as confirmed in the next subsection. In addition, this also proves that the different tunnel shapes induce different patterns of soil pressure, which in turns greatly influences the structural design of tunnel members (i.e., soil-structure interaction).

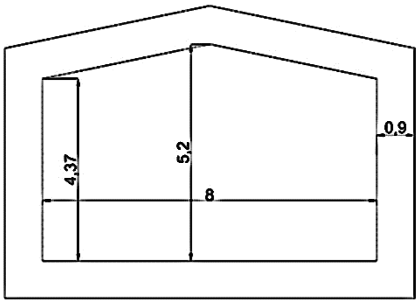

Figure 2. Triangle cross-section of the tunnel.

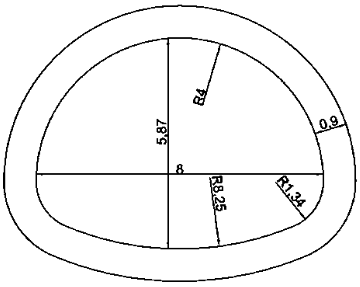

Figure 3. Horseshoe cross-section of the tunnel.

Inspection of Figures 4 and 5 also shows that the deformation in the rock is negligible (the boundary was covered by the blue colour), which only occurred in the soil.

3.2 Influence of tunnel shapes on the lining thickness

To investigate the effect of the tunnel shapes on the lining thickness, shear force (SF) and bending moment (BM) distributions on the roof/crown and footing/invert members of the TCCT and the HCCT are presented in Figure 6, respectively, from the output of Plaxis 2D. The numerical analysis output values of the SF and BM for both shapes are organized in Table 3. It can be noted from Table 3 and Figure 6 that the maximum SF on the roof of TCCT tripled compared to the SF on the crown of HCCT. In addition, the maximum SF on the footing of TCCT is 1.7 times greater than the SF on the invert of HCCT.

Inspection of Figure 6 and table 3 also shows that the BM on the roof and footing of TCCT is 1.1 and 1.37 times greater than BM on crown and invert of HCCT, respectively. From the numerical results in Table 3, it is observed that the SF on the tunnel members significantly changed compared to the slight change of the BM.

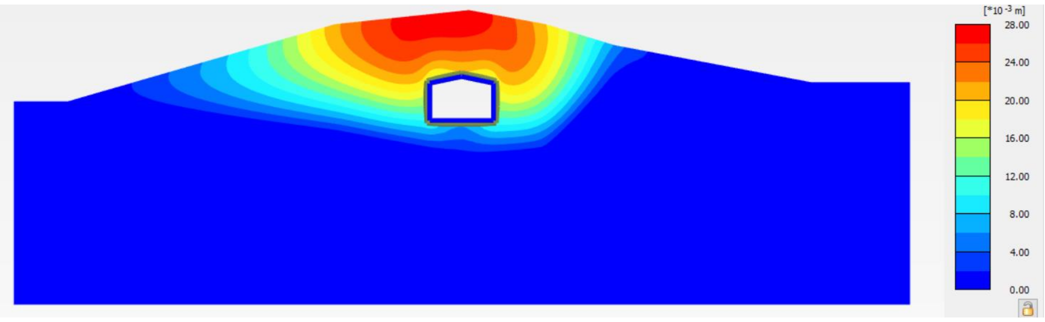

Figure 4. Total displacement of the soil and the rock around the TCCT.

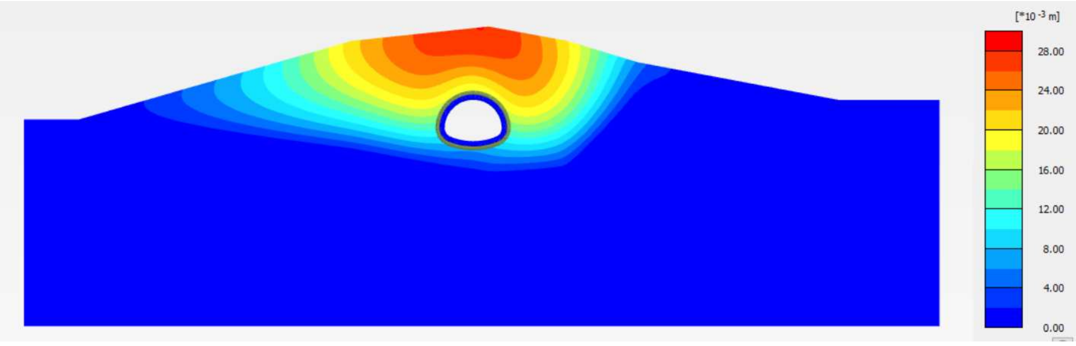

Figure 5. Total displacement of the soil and the rock around the HCCT.

It is obvious from the principles of structural engineering design that the change in the SF and BM greatly affects the lining thickness and the reinforcement steel, respectively. In the numerical analysis, the thickness of the lining in each shape and members (see Figures 2 and 3) of the tunnels was 90cm.This value was increased to 110cm and reduced to 40cm after structural design of the lining of tunnels considering the SF on the roof and crown in TCCT and HCCT, respectively, see Table 4. The 90cm lining thickness was also increased to 140cm and reduced to 85cm in the footing and invert for the TCCT and HCCT, respectively. This significant change in the lining thickness greatly changes the cost per meter length of the cross-sectional area. The total extra cost per meter length of the cross-sectional area of RC lining is 2590.42 US$ (considering 140US$/m of RC) if the TCCT was used instead of HCCT. This is a huge difference in cost which can be induced by changing the tunnel's shape and thickness. Using HCCT not only reduces cost in the engineering projects but also reduces carbon dioxide emissions into the air when less reinforced concrete amounts are used.

4 CONCLUSIONS

Based on the numerical analyses, the following conclusions could be drawn:

1- It seems that the SF is much more sensitive than the BM when the shape of the tunnels is changed due to change in soil pressure distribution.

2- Due to cross-sectional shape change, a great reduction in tunnel thickness lining from 1100mm (roof) to 400mm (crown) occurred, which it is a great promising in minimizing amount of cement and carbon dioxide emissions into the atmosphre.

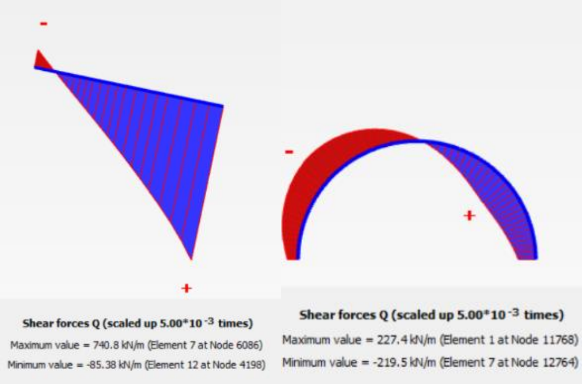

Figure 6. Shear force and bending moment diagrams of the roof right side of the TCCT and the crown of the HCCT.

Table 3. Shear force and bending moment numerical results.

Tunnel shape	**Roof / Crown**		**Footing/Invert**	
	SF	BM	SF	BM
	kN	kN.m	kN	kN.m
Triangle	704.8	-734.2	886.0	901.6
Horseshoe	227.4	-660.2	521.8	656.1

Table 4. Tunnel lining thickness based on the produced shear force on the members.

Item	**Roof or Crown**	**Footing or Invert**
	Thickness **(mm)**	Thickness **(mm)**
Triangle shape	1100	1400
Horseshoe shape	400	850
Extra lining Thickness	700	550
Total Extra cost (US$)/m	2590.42	

REFERENCES

Abdellah, W. R., Haridy, A. K. A., Mohamed, A. K., Kim, J. G., & Ali, M. A. M. (2022). Behaviour of Horseshoe-Shaped Tunnel Subjected to Different In Situ Stress Fields. *Applied Sciences (Switzerland)*, *12*(11). https://doi.org/10.3390/app12115399.

Di, H., Zhou, S., Xiao, J., Gong, Q., & Luo, Z. (2016). Investigation of the long-term settlement of a cut-and-cover metro tunnel in a soft deposit. *Engineering Geology*, *204*, 33–40. https://doi.org/10.1016/j.enggeo.2016.01.016.

Hasan, A., Hummadi, R., & Azeez, O. (2023). The performance of laterally loaded piles in layered sandy soils under variable degree of saturation. *E3S Web of Conferences*, *382*. https://doi.org/10.1051/e3sconf/202338207002.

Li, S., Han, G., Ho, I.-H., Ma, L., Wang, Q., & Yu, B. (2020). *Coupled Effect of Cross-Sectional Shape and Load Reduction on High-Filled Cut-and-Cover Tunnels Considering Soil-Structure Interaction*. https://doi.org/10.1061/(ASCE).

Nguyen, T. T., Do, N. A., Karasev, M. A., Kien, D. Van, & Dias, D. (2021). Influence of tunnel shape on tunnel lining behaviour. *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering*, *174*(4), 355–371. https://doi.org/10.1680/jgeen.20.00057.