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RESEARCH ON THE BEHAVIOR OF METRO TUNNEL SUB-RECTANGULAR CROSS SECTION IN HETEROGENEOUS SOIL CONDITION AT HANOI

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ABSTRACT

The Hanoi Metro Pilot Light Line 3 is part of the new metro tunnel project for Hanoi capital. The construction works in this contract include a twin bored tunnel running parallel, with a distance ranging from 12 to 35 m. The 2.6 km twin tunnels will be bored by two 6.3 m diameters. Even though a lot of works have been done to develop tunnel lining design methods with circular cross-section tunnel, it can be found that most of the analyses assumed that the tunnels are excavated in only one homogeneous soil. However, in real scenarios, it is very rare to meet tunnels built in only one layered soil. In most cases, layered soils are encountered which induces variations in terms of geomechanical properties (soil unit weight, Young modulus, cohesion, and friction angle) for each sub-layer. Moreover, the Hanoi aquifer system and groundwater extraction make the soil subject to land subsidence during tunneling. Therefore, an accurate study of tunnel behavior is needed. This paper presents the behavior of metro tunnel sub-rectangular cross section in heterogeneous soil condition at Hanoi under static pressure, which is the most accurate representation of Hanoi Metro Pilot Light Line 3 actual soil by numerical simulation by Rocscience -RS2- Phase2 software.

Keywords: Four or five keywords (The first characters of each keyword are in uppercase letters), Italic

INTRODUCTION

The Hanoi metro project, currently in construction, plans to solve traffic congestion in one of the most growing cities of the world. Even though a lot of works have been done to develop tunnel lining design methods, it can be found that most of the analyses assumed that the tunnels are excavated in only one homogeneous soil. However, in real scenarios, it is very rare to meet tunnels built in only one layered soil. In most of the cases, layered soils are encountered which induces variations in terms of geomechanically properties (soil unit weight, Young modulus, cohesion and friction angle) for in each sub-layer. Moreover, the Hanoi aquifer system and groundwater extraction makes the soil subject to land subsidence. Therefore, an accurate study of the tunnel behaviour is needed. This paper presents the tunnel behaviour under static pressure in a six layers soil, which is the most accurate representation of the Hanoi actual soil.

GEOLOGY CONDITION

The soil considered refers to results of geological investigation realized on the path of the Hanoi metro line 3 (Figure 1). According to the investigated geological conditions, the tunnel located in the stratum, mainly stiffer clay, sand, or silty sand. The upper soil layers over the twin tunnels are organic, backfill, and soft to firm loam clay (in Table 1).

Fig. 1 Description of UMRT Line 3 (Urbanist Hanoi 2018)

Table 1. Input parameters of the upper soil layers over

Soil layer	H (m)	ρ (kg/m^3)	E (MPa)	υ	φ (^{0})	c (kPa)	K_0
Backfill	6.5	1900	-	0.3	23	-	0.47
GU3&4	5.5	2000	8	0.3	20	5	0.66
GU1_s1	2.5	1850	12	0.3	25	10	0.58
GU1_s2	2.5	1900	50	0.3	25	25	0.58
GU5a	10.5	2000	55	0.3	34	25	0.44
GU7&8	72.5	2100	75	0.25	38	25	0.36

H- Thickness; ρ -Density; E -Young's modulus; υ-Poisson's ratio; φ -Friction angle; c- Cohesion; K_0- The coefficient of lateral earthpressure coefficient.

TUNNEL SHAPE

Several tunnel shapes exist, and one may wonder what shape would then be the more appropriate. The most common shape is the basic circle shape as it presents the great advantage to distribute the stress very homogeneously thanks to his corners-free shape (Figure 2).

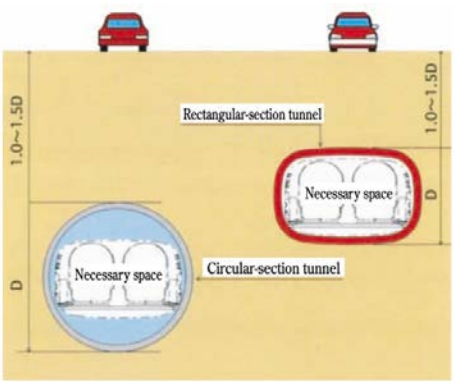


Fig. 2 Comparison between circular and rectangular shapes (Kawai and Minami, 2001)

However, knowing the Hanoi soil complexity and possibility of land subsidence due to the aquifer system and groundwater extraction it became a necessity to optimize the excavation work. It is in this process that the sub-rectangular shape looks appropriate. Compared with round section, the effective utility of area of rectangular section is larger by over 20%. Moreover, a sub-rectangular shape offers a cost-reduction in term of excavation. For example, the sub-rectangular shape allows to reduce the necessary depth of the tunnel but also the minimum width which is very useful as the underground space became rarer in biggest cities. Note that the sub-rectangular shape can be defined by three circular rayons as illustrated, it allows to avoid stress concentration in the corners by offering a smoother design and to limit the impact on surface. Those results highlight the higher efficiency of sub-rectangular shape tunnel as the area available is larger while the tunnel height is lower at the same time. Then, the minimal depth needed can be reduced as well as the minimal width of two circular tunnels.

THE ACTIVE PRESSURES

In the cases when the overburden thickness is 2 times greater than the tunnel width (B), the active vertical pressure σ_V can be determined through Terzaghi's formula (Takano, 2000). On the basis of the assumption of the maximum possible sliding surface, which made an angle of $(\pi/4+\phi/2)$ measured counter-clockwise from horizontal line, an effective overburden thickness h is estimated for different cases of tunnel shapes by the following formula (Figure 3 and Figure 4) (Takano, 2000):

$$B_1 = \frac{B}{2} + H_t \cot\left(\frac{(\pi/4)+(\phi/2)}{2}\right)$$

where B_1 is the trapdoor width half, c is the soil cohesion, ϕ is the internal friction angle of soil, γ is the unit weight of soil; K_0 is the lateral earth pressure coefficient, B and H_t are the width and height of sub-rectangular tunnels, H is the overburden, R is the radius of circular tunnels, R_c is the radius of crown of horse-shoe tunnels, P_0 is the surface load.

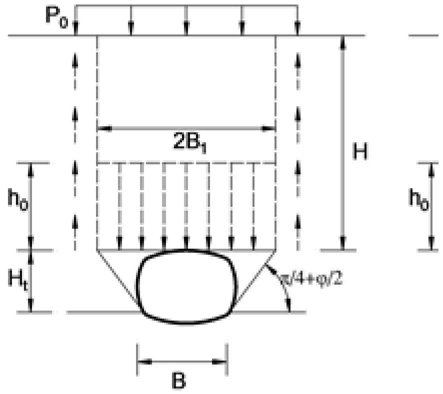


Fig. 3 Reduced earth pressure calculated by the Terzaghi's formula (based on Takano, 2000).

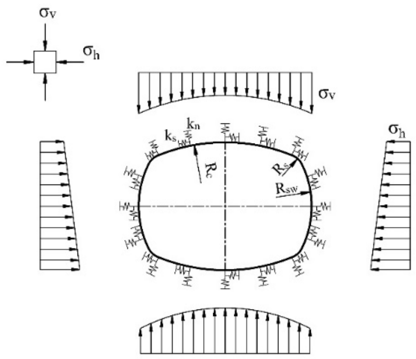


Fig. 4 Calculation scheme of sub-rectangular tunnels support structures; the active vertical loads, σ_v, and the active horizontal loads, σ_h; k_n and k_s are, respectively, normal and tangential stiffness of the interaction springs; R_c is the crown radius, R_s is the shoulder radius, R_{iv} is the radius of the invert part; EJ and EA are bending and normal stiffness of the tunnel structure.

FINITE ELEMENT METHOD

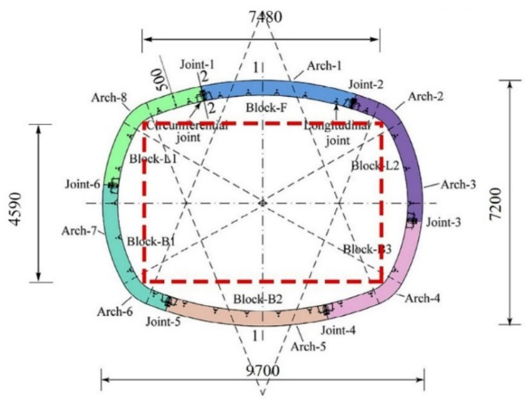
The simulations have been computed on Rocscience Phase2 software. RS2 is a 2D finite element program for calculating stresses and estimating support around underground structure. This software has been chosen as it supports multiple layers soil model and was then very appropriate to this case.

A useful feature provide by Phase2 is the possibility of load split between two stages or more which correspond to the excavation work before the set-up of the shell, with a 30% load and add the last 70% on the final stage when the shell is set-up.

The soil parameters are taken from the silty clay soil of the Shanghai metro line 4 (Do, et al., 2020). These parameters shown in Table 1 and Figure 5 were used for this evaluation. A 2D (plane strain) model was established using Rocscience Phase2 software.

For the sake of simplicity, the soil was modeled using a linear-elastic perfectly plastic constitutive Mohr Coulomb (MC) model (Do & Dias, 2018). The linear elastic perfectly plastic (Mohr Coulomb shear failure criteria) constitutive model named MC is used for the numerical part of this paper. The MC model was therefore applied in many finite-element calculations (Abdellah et al., 2018; Rostami et al., 2016; Vinod & Khabbaz, 2019; Do et al., 2020; Do et al., 2015: Do et al., 2014b; Nguyen Tai Tien el al, 2021). The tunnel lining behavior is presumed to be linear elastic.

In this study, parameters of a tunnel in Shanghai, China (Huang, et al., 2018) are applied as a reference case (Figure 4). The parameters for sub-rectangular tunnels are taken from the Shanghai project, the circular and horseshoe tunnels with the minimum cross-sectional area able to cover the construction tunnel clearance (red dotted line in Figure 5) are considered (Figure 5 and Table 2).



Fi.5 Sub-rectangular tunnel shape (Huang, et al., 2018)

Table 2. Geometrical features of tunnel shapes

Width (B) (m)	Height (H_t) (m)	B/H_t ratio	R_1 (m)	R_2 (m)	R_3 (m)	Area (m^2)
9.70	7.20	1.347	9.95	1.00	5.35	59.786

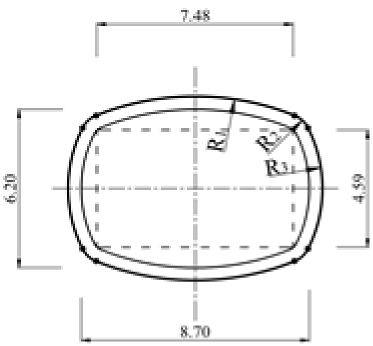


Fig.6 Dimensions of sub-rectangular tunnel

Table 3. Input parameters for Phase2 model

Parameter	Symbol	Value	Unit
Soil's properties			
Young's modulus	E_s	-	MPa
Unit weight	γ_s	-	kN/m^3
Internal friction angle	ϕ	-	degree
Poisson's ratio	νs	-	-
Cohesion	c	-	MPa
The coefficient of lateral earthpressure	K_0	-	–
Overburden	H	10	m
Lining's properties			
Lining thickness	m	0.5	m
Young's modulus	E	35,000	MPa
Poisson's ratio	ν	0.15	-

MULTIPLE LAYERS INFLUENCE

The aim this paper is to study the influence of the multiple layers soil on the tunnel behaviour. For that, the following simulations has been computed (Table 4):

Table 4. Input parameters of the multiple layers

Simulation 1	Simulation 2	Simulation 3
Single layer soil : GU7&8	Double layer soil: GU5a above GU7&8 until 23,5m	Triple layer soil: Backfill (poor quality soil) above GU5a until 21m GU7&8 until 26m
Tunnel depth: 20m K = 0,6 Water line depth : 5m Liner thickness 40cm of C35	Tunnel depth: 20m K = 0,6 Water line depth : 5m Liner thickness 40cm of C35	Tunnel depth: 20m K = 0,6 Water line depth : 5m Liner thickness 40cm of C35

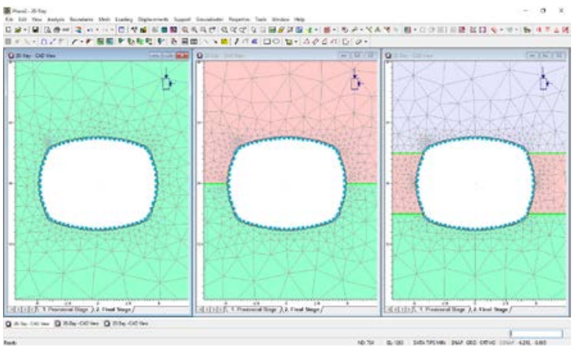


Fig.7 Models of the influence of the multiple layers soil

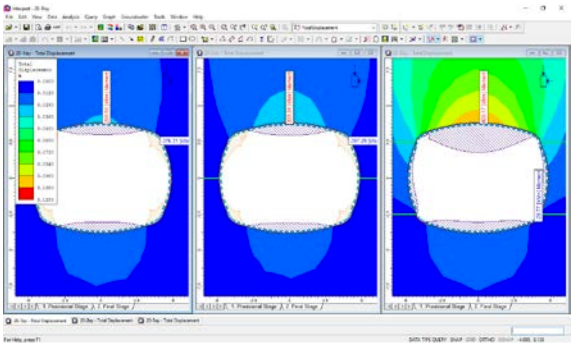


Fig.8 Displacement of multiple layers soil models

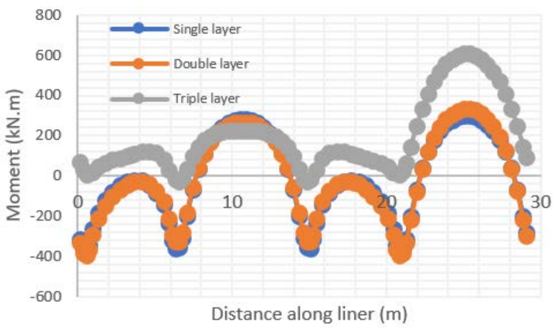


Fig.9 Bending moments at the tunnel

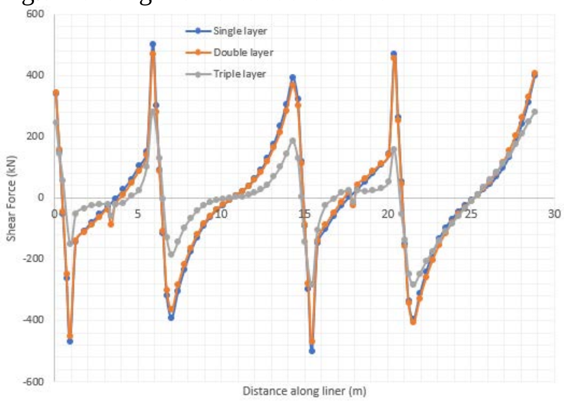


Fig.10 Shear forces at the tunnel

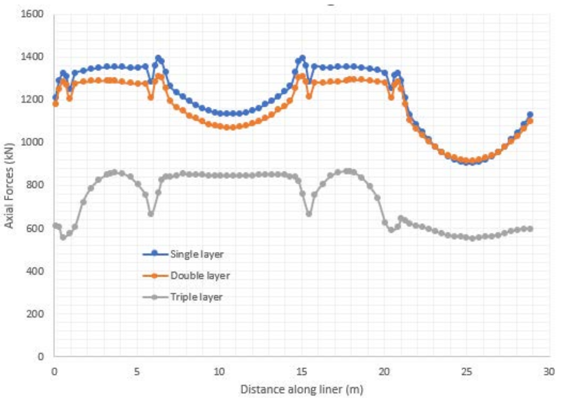


Fig.10 Axial forces at the tunnel

TUNNEL BEHAVIOUR NEAR EXCAVATION WORK

The aim in this section is to study the behaviour of the tunnel near an excavation work and with a fool layer of poor-quality soil above the tunnel. The soil parameter of the fool layer is a density of 18kN/m3, a Poisson ratio of 0.3 and a friction angle of 20□.

TUNNEL BEHAVIOUR NEXT HANOI DAEWOO HOTEL

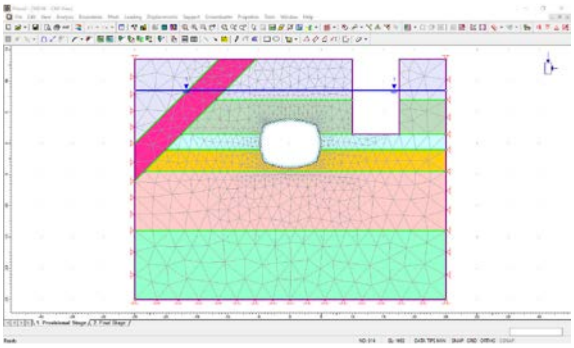


Fig.11 Model of tunnel behaviour near excavation work

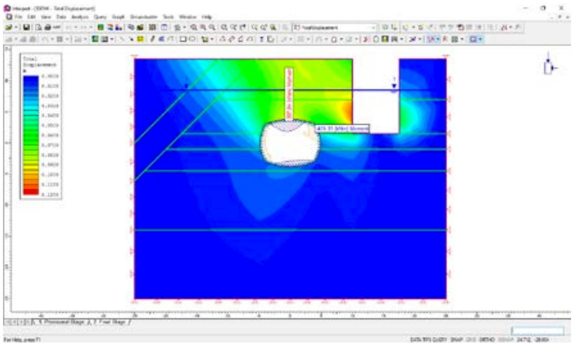
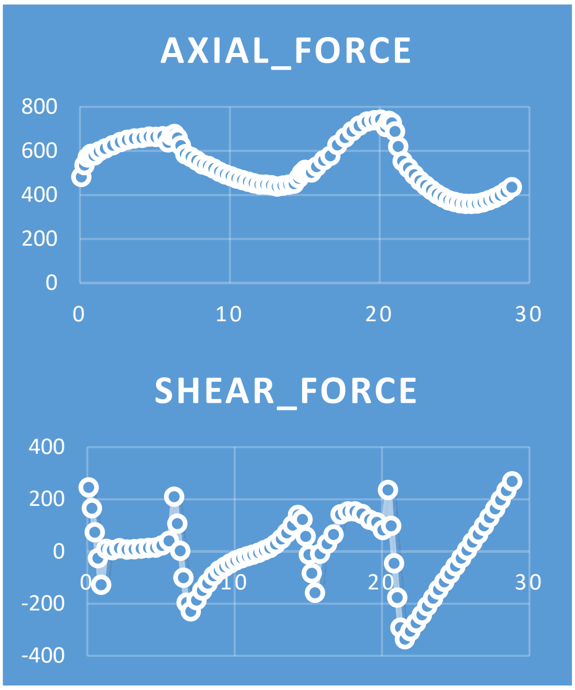


Fig.12 Displacement of behaviour near excavation work



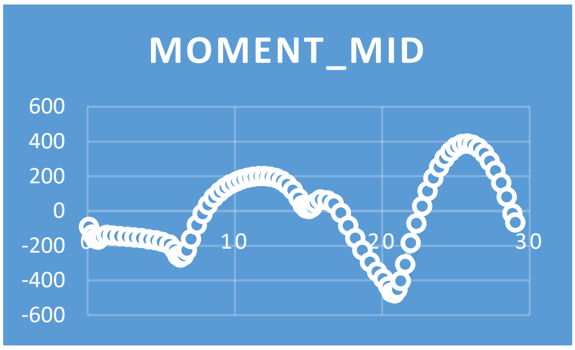


Fig.12 Bending moments, Shear forces , Axial forces in lining

The total displacement for this model are 13,2 cm (4,5 cm in the provisional stage then 8,7 cm in the final stage) which are lower than 20 cm the admissible total displacement.

TUNNEL BEHAVIOUR NEXT HANOI DAEWOO HOTEL

The location of Daewoo hotel is presented on Fig 13. The distance from the hotel to metro line is 25 m.

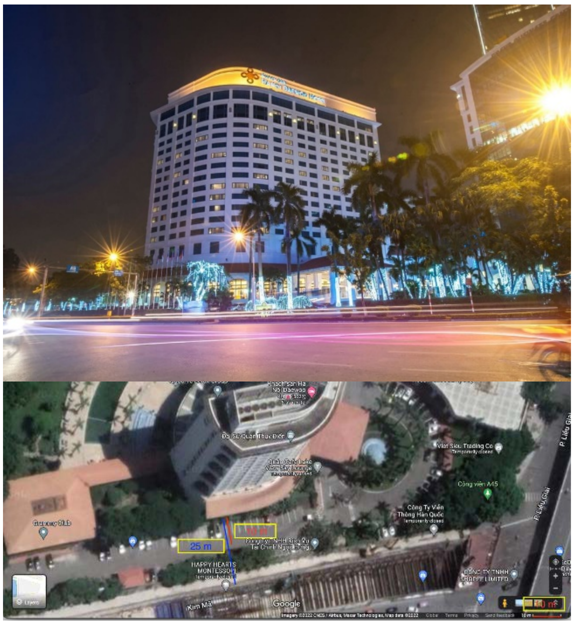


Fig. 13 The location of Daewoo hotel

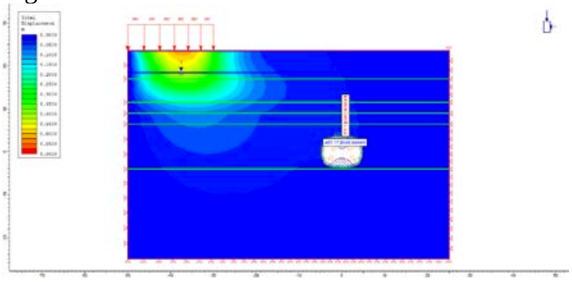


Fig.14 Displacement of behaviour next Hanoi Daewoo hotel

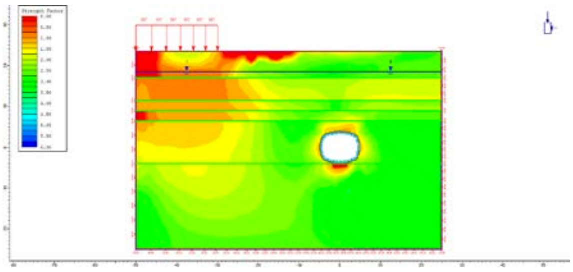


Fig.15 Strenght factor of behaviour next Hanoi Daewoo hotel

The results obtained are the quite the same between the Daewoo Hotel ELU model and the reference model, the maximum moment is 417kN.m in the Daewoo model and 414kN.m in the reference model. Therefore, the influence of the hotel on the metro tunnel behavior is limited and may be neglected. This might be explained by the presence of very clayey soil of Hanoi which absorb the pressure of the hotel within the distance between the tunnel and the hotel.

CONCLUSIONS

The results show an increase of bending moments as well as a diminution of the axial forces and shear forces with the raise of soil layers. Note that the results of the single layer model and the double layer are very near which is explained by the fact that the GU7&8 and the GU5a have quite near properties while the backfill representing poor quality soil has lower characteristics.

The soil pressure increases sharply when moving from one layer to another, mostly when the layers have large properties differences as it is the case in the triple layer model between the backfill layer and the GU5a layer. The rock pressure is therefore less important in the triple layer model. The joint between the materials has the consequence to reduce the shear force on the tunnel liner as shown on the shear force graph and especially for the triple layer model. Therefore, joints between materials in multiple layer soil influence the tunnel behaviour by impacting the spread of soil pressure on the shell.

The research on tunnel behaviour next hanoi daewoo ho Daewoo Hotel model shows that the influence of the hotel on the metro tunnel behavior is is negligible.

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