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Corresponding Author	FamilyName	**Dias**
	Particle	
	Given Name	**Daniel**
	Suffix	
	Division	Laboratory 3SR
	Organization	CNRS UMR 5521, Grenoble Alpes University
	Address	38000, Grenoble, France
	Phone	
	Fax	
	Email	daniel.dias@3sr-grenoble.fr
	URL	
	ORCID	http://orcid.org/0000-0003-2238-7827
Author	FamilyName	**Pham**
	Particle	
	Given Name	**Van Vi**
	Suffix	
	Division	Faculty of Civil Engineering
	Organization	Hanoi University of Mining and Geology
	Address	Bắc Từ Liêm, Vietnam
	Phone	
	Fax	
	Email	
	URL	
	ORCID	http://orcid.org/0000-0001-9586-0406
Author	FamilyName	**Do**
	Particle	
	Given Name	**Ngoc Anh**
	Suffix	
	Division	Department of Underground and Mining Construction, Faculty of Civil Engineering
	Organization	Hanoi University of Mining and Geology
	Address	Bắc Từ Liêm, Vietnam
	Phone	
	Fax	
	Email	
	URL	
	ORCID	http://orcid.org/0000-0002-4862-1688
Author	FamilyName	**Nguyen**
	Particle	
	Given Name	**Chi Thanh**
	Suffix	

	Division	Faculty of Civil Engineering
	Organization	Hanoi University of Mining and Geology
	Address	Bắc Từ Liêm, Vietnam
	Phone	
	Fax	
	Email	
	URL	
	ORCID	
Author	FamilyName	**Dang**
	Particle	
	Given Name	**Van Kien**
	Suffix	
	Division	Faculty of Civil Engineering
	Organization	Hanoi University of Mining and Geology
	Address	Bắc Từ Liêm, Vietnam
	Phone	
	Fax	
	Email	
	URL	
	ORCID	http://orcid.org/0000-0001-8821-9178
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Abstract	Circular- and rectangular-shaped tunnels are usually utilized when excavating at shallow depths in urban areas. Nevertheless, special-shaped tunnels such as sub-rectangular tunnels were recently considered to be used for overcoming some drawbacks of circular and rectangular tunnels in terms of low utilization space ratio and stress concentration at the corners, respectively. Using numerical analyses, this paper focuses on indicating the different behaviour of sub-rectangular tunnels under static loading in comparison with circular and rectangular ones having the same utilization space. It allows designers to decide the appropriate tunnel shape solution that should be used. The influence of parameters, including soil deformability, lateral earth pressure coefficient, and lining thickness, on the behaviour of different tunnel shapes under static loadings is also investigated. The results indicated a significant difference in the behaviour of sub-rectangular tunnels in comparison with the circular and rectangular ones when considering no-slip and full-slip conditions for the soil–lining interaction.

Keywords (separated by '-')	Sub-rectangular tunnel - Static load - Tunnel lining - Numerical analysis

Footnote Information	- Behaviour of differently shaped tunnel linings subjected to static loading was highlighted;- Sub-rectangular tunnels can be an effective solution replacing circular and rectangular tunnel.

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TECHNICAL PAPER

Sub-rectangular Tunnel Behaviour under Static Loading

Van Vi Pham[1] · Ngoc Anh Do[2] · Daniel Dias[3] · Chi Thanh Nguyen[1] · Van Kien Dang[1]

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Abstract
Circular- and rectangular-shaped tunnels are usually utilized when excavating at shallow depths in urban areas. Nevertheless, special-shaped tunnels such as sub-rectangular tunnels were recently considered to be used for overcoming some drawbacks of circular and rectangular tunnels in terms of low utilization space ratio and stress concentration at the corners, respectively. Using numerical analyses, this paper focuses on indicating the different behaviour of sub-rectangular tunnels under static loading in comparison with circular and rectangular ones having the same utilization space. It allows designers to decide the appropriate tunnel shape solution that should be used. The influence of parameters, including soil deformability, lateral earth pressure coefficient, and lining thickness, on the behaviour of different tunnel shapes under static loadings is also investigated. The results indicated a significant difference in the behaviour of sub-rectangular tunnels in comparison with the circular and rectangular ones when considering no-slip and full-slip conditions for the soil–lining interaction.

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Highlights AQ3
- Behaviour of differently shaped tunnel linings subjected to static loading was highlighted;
- Sub-rectangular tunnels can be an effective solution replacing circular and rectangular tunnel.

✉ Daniel Dias
daniel.dias@3sr-grenoble.fr

[1] Faculty of Civil Engineering, Hanoi University of Mining and Geology, Bắc Từ Liêm, Vietnam

[2] Department of Underground and Mining Construction, Faculty of Civil Engineering, Hanoi University of Mining and Geology, Bắc Từ Liêm, Vietnam

[3] Laboratory 3SR, CNRS UMR 5521, Grenoble Alpes University, 38000 Grenoble, France

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1 1. Introduction

The rapid development of urban infrastructures and rising population density is the cause of the serious shortage of urban land and therefore traffic congestion. In dense urban areas, one of the solutions is to develop underground works to solve these difficulties.

Urban traffic often requires the connection of different routes such as terrestrial roads and overhead roads and is connected to tunnel routes. Tunnels are usually located at shallow depth. Optimization of the tunnel shape is important to increase the cross-section utilization as well as the tunnel stability. Until now, circular tunnels (for mechanized tunnelling) or U-shapes (for conventional tunnelling) are usually designed due to their advantage in terms of lining stability and also for circular shapes due to the tunnelling boring machines (TBMs) technology. Circular shape has, however, a low space utilization ratio. On the contrary, square and rectangular tunnels allow a high capacity of using cross-section, but their main disadvantage is the stresses concentration at the tunnel corners (Nakamura et al. 2003). Recently, a special cross-section tunnel named sub-rectangular has been developed (Liu et al. 2018; Zhang et al. 2017; Konstantin and Mikhail 2017; Zhu et al. 2017; Zhang et al. 2019). Sub-rectangular tunnels solve the shortcomings of both the circular and rectangular tunnels while keeping the advantages of a high space utilization ratio and general stability.

The influence of tunnel shapes on the tunnel's stability was studied in the literature (Abdellah et al. 2018; Vinod and Khabbaz 2019; Do et al. 2020). Abdellah et al. (Abdellah et al. 2018) studied the stability of differently shaped tunnels, i.e. circular, square, and horseshoe tunnels, located at shallow depth. Vinod and Khabbaz. (Vinod and Khabbaz 2019) studied the effect of the tunnel shape on lining internal forces induced by twin circular tunnels and twin rectangular tunnels. Do et al. (Do et al. 2020) investigated the influence of the parameters on the lining internal forces of squared or sub-rectangular tunnels. The results obtained by these researches illustrated a significant effect of the tunnel shape on tunnel lining behaviour. Unfortunately, the influence of circular, rectangular, and sub-rectangular tunnels on internal lining forces induced has not been yet thoroughly and simultaneously evaluated.

In this study, a numerical analysis is conducted to investigate the behaviour of sub-rectangular tunnels under static loading compared with circular and rectangular ones having the same utilization space. It allows designers to decide the appropriate tunnel shape solution that should be used. The effects of Young's modulus, E_S, the lateral earth pressure coefficient, K_0, and the lining thickness, t, are highlighted.

2 2. Numerical Simulations of Tunnels under Static Loading

2.1 Reference Sub-Rectangular Tunnel Case—Shanghai Tunnel Metro

The parameters of the sub-rectangular tunnel cross-section in this study were adopted from a constructed tunnel in Shanghai, China (Do et al. 2020). The

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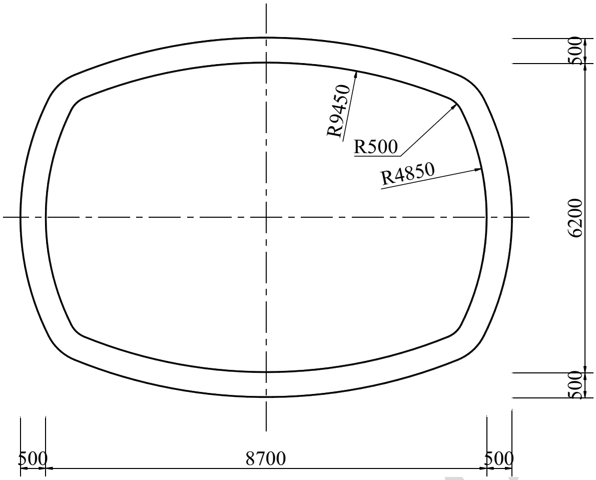

Fig. 1. Sub-rectangular express tunnel in Shanghai (Do et al. 2020), Distances in millimetres

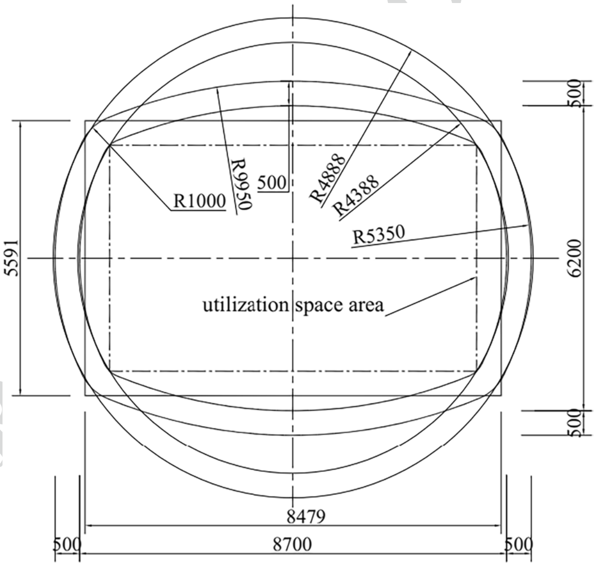

Fig. 2. Circular and Rectangular Tunnel with the Same Utilization Space Area, Distances in Millimetres

dimensions of the sub-rectangular tunnel are 9.7m in width and 7.2m in height and an excavation area of 60 m^2 as shown in Fig. 1. The tunnel is supported by segmental concrete linings of 0.5m in thickness. In this study, a continuous lining was adopted without considering the joint effect. Based on this sub-rectangular tunnel cross-section, a circular tunnel with a radius of 4.89m and a rectangular tunnel with dimensions of 8.48m in width and 5.59m in height are built. They have the same utilization space area as the sub-rectangular tunnel. The cross-section excavation areas of the circular and rectangular tunnels are 75m^2 and 47m^2, respectively (Fig. 2).

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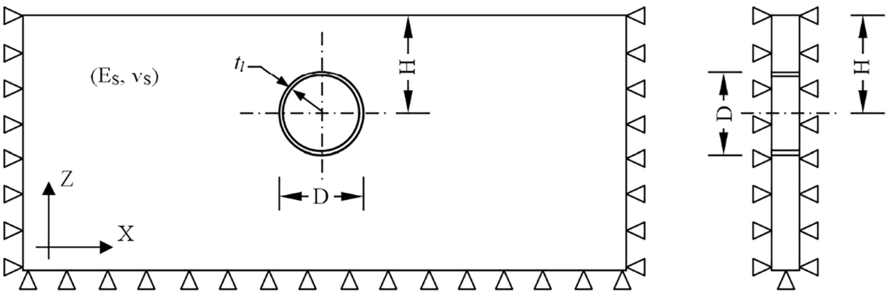

Fig. 3. Plane Strain Model under Consideration

Table 1. Input parameters of the soil and tunnel lining for the reference case

Parameter	Symbol	Unit	Value
Soil properties			
Unit weight	γ	kN/m^3	18
Young's modulus	E_s	MPa	100
Poisson's ratio	ν_s	-	0.34
Internal friction angle	ϕ	degrees	33
Cohesion	c	kPa	0
Lateral earth pressure coefficient	K_0	-	0.5
Depth of tunnel	H	m	20
Tunnel lining properties			
Young's modulus	E_l	GPa	35
Poisson's ratio	ν_l	-	0.15
Lining thickness	t	m	0.5
External diameter of circular tunnel	D	m	9.76
Dimensions of the sub-rectangular tunnel	W x H	m	9.7 x7 .2
Dimensions of the rectangular tunnel	W x H	m	8.48 x 5.95

2.2 Tunnels Numerical Model

2D numerical models of different tunnel shapes, i.e. circular, rectangular, and sub-rectangular ones, are simulated. Figure 3 shows a typical 2D numerical model in plane strain conditions in the case of a circular tunnel. These models were considered to quantify the behaviour of tunnel linings under static loading. It is assumed that the tunnel structure's behaviour and soil mass are linear elastic. The properties of soil and different tunnel lining shapes are given in Table 1.

In this study, numerical simulations are performed employing the Flac^{3D} finite difference program (Itasca Consulting Group,FLAC Fast Lagrangian Analysis of Continua, 2012,Version 5.0. User's manual, Available: ⟨http.itascacg.com⟩ 2012). Hexahedral zones are used for discretizing the volume under study. The tunnel linings are modelled using embedded liner elements. Embedded liner elements are linked to the

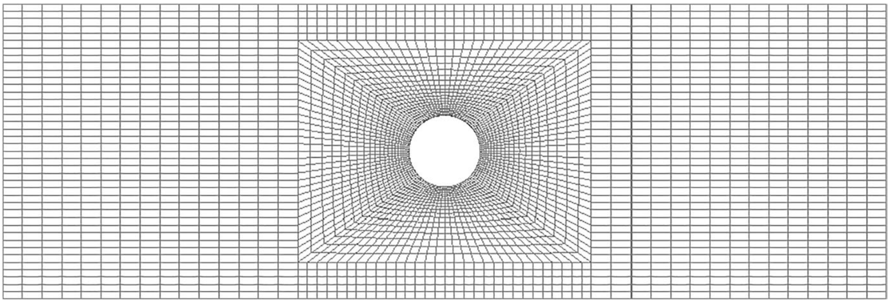

Fig. 4. Geometry and Mesh for the Circular Tunnel Model

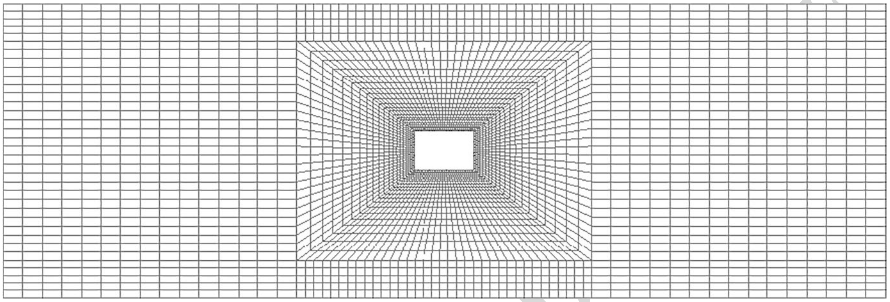

Fig. 5. Geometry and Mesh for the Rectangular Tunnel Model

zone faces along the tunnel boundary through interface stiffness (normal stiffness k_n and tangential stiffness k_S). The values of k_n and k_S are set to one hundred times the equivalent stiffness of the stiffest neighbouring zone (Itasca Consulting Group,FLAC Fast Lagrangian Analysis of Continua, 2012,Version 5.0. User's manual, Available: ⟨http.itascacg.com⟩ 2012) for the no-slip condition case. When considering the full-slip condition, k_S is assigned to be equal to zero. The apparent stiffness (expressed in stress-per-distance units) of a mesh zone in the direction normal to the surface can be calculated by using the following formula:

$$\max\left[\frac{\left(K+\frac{4}{3}G\right)}{\Delta z_{min}}\right] \tag{1}$$

where K and G are the bulk and shear modulus, respectively.

Δz_{min} is the smallest dimension in the normal zones direction that enters in contact with the liner elements.

The mesh consisted of a single layer of zones in the y-direction, and the size of the elements increases as one moves away from the tunnel (Figs. 4, 5, and 6 corresponding to, respectively, the circular, rectangular, and sub-rectangular tunnels). The numerical model is 120 m wide in the x-direction. The two vertical boundaries

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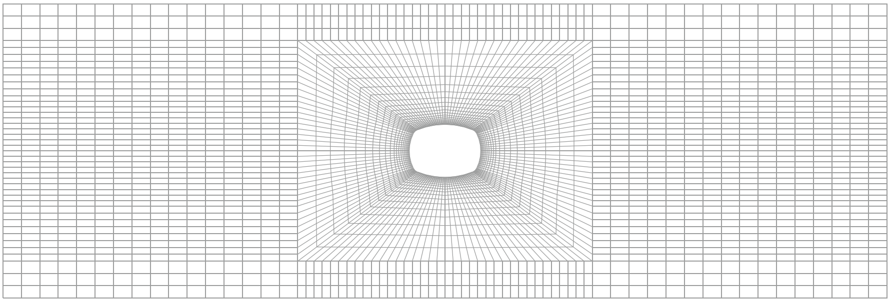

Fig. 6. Geometry and Mesh for the Sub-rectangular Tunnel Model

are fixed in the horizontal direction. (40 m high in the z-direction). The surface of the model is free, and the bottom was blocked in all directions. It consists of approximately 4,800 zones and 9,802 nodes for the circular tunnel, 4,675 zones, and 9,552 nodes for the rectangular tunnel, and the sub-rectangular is 5,816 zones and 11,870 nodes.

The first step of the numerical excavation process is to set up the model and assign the plane strain boundary conditions and the initial stress state taking into consideration the gravity field. Then, the tunnel is excavated and the lining is assigned in the second step. Relaxation of the ground between the excavation boundary and the lining setup was not considered. This case corresponds to the worst one for the lining stress state.

2.3 Comparison of Different Shaped Tunnel Linings under Static Loading

Figure 7a illustrates the bending moments in the tunnel lining for the three types of tunnels: circular, rectangular, and sub-rectangular. Firstly, in comparison with the rectangular and sub-rectangular tunnel, the bending moments in the circular tunnel are the smallest for both the no-slip and full-slip cases. The extreme bending

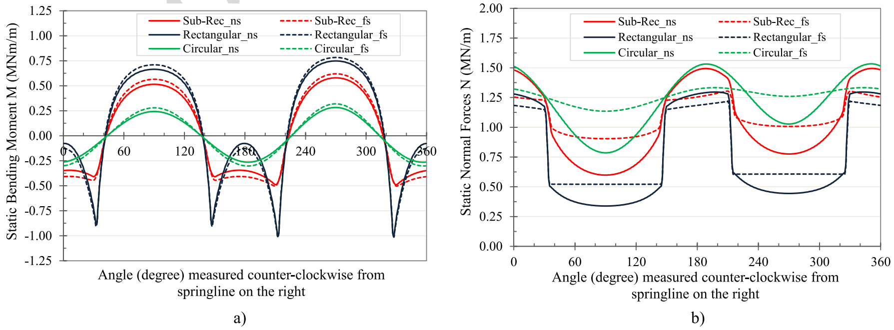

Fig. 7. Internal Forces Induced in Circular, Sub-rectangular, and Rectangular Tunnels **a**) Bending Moment **b**) Normal Forces AQ4

moments are observed at the crown, bottom and two sides of the tunnel. In the rectangular tunnel, while the smallest bending moments are obtained in the corners of the rectangular tunnel, the maximum positive bending moments are observed at the tunnel crown and bottom. As for the sub-rectangular tunnel, the bending moment values are in between those obtained in the two other tunnel cross-sections. The bending moments are not concentrated at the four corners as can be seen for the rectangular tunnel. The bending moments distribution in the tunnel linings is concerned by the fact that corners or sharp positions with small radius cause stress concentrations and prevent the forces redistribution along the tunnel boundaries. The tunnel boundaries should therefore be designed as much curves as possible.

Considering the lining–soil interaction influence, the bending moments in the full-slip case are slightly larger than the ones in the no-slip case. The discrepancy of the maximum bending moments induced in circular, sub-rectangular, and rectangular tunnels considering the two cases of no-slip and full-slip conditions is 13%, 7 %, and 5%, respectively. Those of the minimum bending moments in circular and sub-rectangular tunnels are 14% and 3%. However, there is almost no difference for the minimum bending moments between no-slip and full-slip conditions for rectangular tunnels. The lining–soil interaction influence on the tunnel lining's bending moments is of main importance for circular tunnels. It decreases for sub-rectangular and rectangular tunnels. Circumferential movements of circular tunnel linings do not present corners and sharp positions as they can be seen in rectangular and sub-rectangular tunnels, respectively.

As shown in Fig. 7b, while the smallest minimum normal forces are observed for rectangular tunnels, the largest maximum normal forces are obtained for the circular tunnel, for both no-slip and full-slip conditions. The minimum normal forces for the rectangular tunnel are significantly smaller than those of the two other tunnels shapes (circular and sub-rectangular). This could be explained by the lower transmission effect of the lateral loading from the two tunnel sides to the crown and bottom parts in the case of a rectangular tunnel. It should be mentioned that for small normal forces induced in the tunnel lining, the maximum allowable bending moments will be reduced. That is why small normal forces can be considered as unfavourable for structure stability.

Figure 7b shows a great influence of soil–lining interaction, i.e. full-slip and no-slip conditions, on the normal forces developed in the tunnel lining. The most important change is observed at the crown and bottom area of tunnels. For all three tunnel shapes, while maximum normal forces are seen at the sidewall, minimum values are observed at the top or bottom. It could be related to the low lateral earth pressure factor, K_0, used in this study. It causes greater vertical loadings principally transiting into structures at the sidewalls. For higher K_0 values, the loading will mainly transfer to the tunnel top and bottom. In general, the maximum normal forces obtained at the tunnel sidewalls in the full-slip condition are significantly smaller than for the no-slip condition. However, the minimum normal forces observed at the tunnel's top and bottom in the full-slip condition are greater than the ones in the no-slip case, 45%, 51%, and 54% with the circular tunnel, sub-rectangular, and rectangular tunnel, respectively. The lining–soil interaction influence on the lining normal forces could be explained by the tight

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connection in the no-slip condition. It helps to better distribute the ground loading between tunnel parts, i.e. from the top and bottom to the sidewalls and vice versa. This load redistribution is less effective for the full-slip condition. It causes smaller differences between maximum normal forces at the tunnel's top and minimum one at the sidewalls in the full-slip condition case compared with the no-slip one as indicated in Fig. 7b. It is also interesting to note that the internal forces in the sub-rectangular tunnel are in between the circular and rectangular tunnels ones.

Based on the combined evaluation of the bending moments and normal forces induced in the tunnel lining of the three above shapes, the rectangular tunnel is the worst case in terms of stability and the circular tunnel is the most stable one. In addition, the tunnel will be more efficiently supported in no-slip conditions compared to the full-slip ones.

Normal displacements induced in circular, sub-rectangular, and rectangular tunnels are introduced in Fig. 8. While the smallest displacement is observed in circular tunnels, the largest ones occurred in rectangular tunnels. Due to the low lateral earth pressure factor, K_0 of 0.5, maximum displacements are seen at the top and bottom of the tunnel for both no-slip and full-slip cases. It should be also noted that the full-slip interaction between the soil and tunnel lining is followed by a slightly greater displacement. It is in good agreement with the larger bending moment in full-slip conditions as indicated in Fig. 7a.

3 Parametric Study

The results in Figs. 7 and 8 give a clear understanding of the behaviour of circular, rectangular, and sub-rectangular tunnel linings considering both no-slip and full-slip conditions. In the next sections, a parametric study is conducted to highlight the behaviour of sub-rectangular tunnels compared with circular and rectangular ones. The effect of parameters, like the lateral pressure coefficient, K_0, Young's

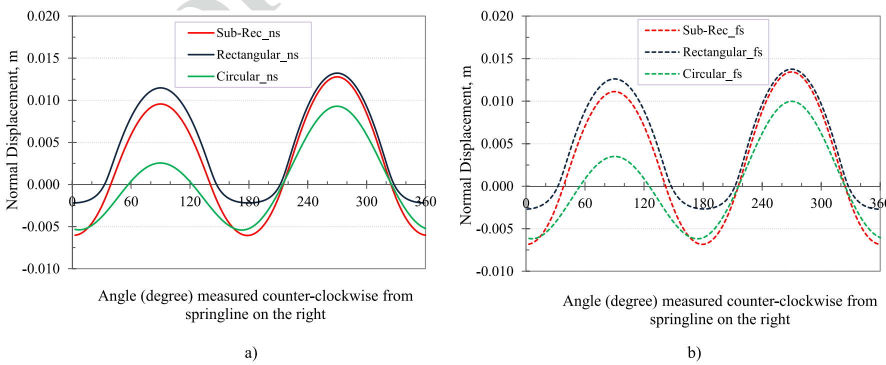

Fig. 8. Normal Displacements Induced in Circular, Sub-rectangular, and Rectangular Tunnels **a**) Normal displacement in no-slip case **b**) Normal displacement in full-slip case

modulus, E_S, and lining thickness, t, considering the soil–lining interface conditions is investigated.

3.1 Effect of the Young's Modulus, E_S

The Young's modulus values are assumed to vary in a wide range from 25 to 350 MPa. The other parameters based on the reference case are considered (Table 1). Results of internal forces in circular, rectangular, and sub-rectangular tunnel linings for both no-slip and full-slip conditions are shown in Fig. 9.

Figure 9a and b shows that when E_S value increases from 25 to 50 MPa, the absolute extreme bending moments decrease sharply. When the E_S value is larger than 50 MPa, an increase in the E_S value causes a slight reduction in the absolute extreme bending moments. This variable trend is seen in all three cross-sections of tunnel linings. The extreme bending moments in the full-slip condition are always greater than the ones in the no-slip condition. It should be noted that the minimum bending

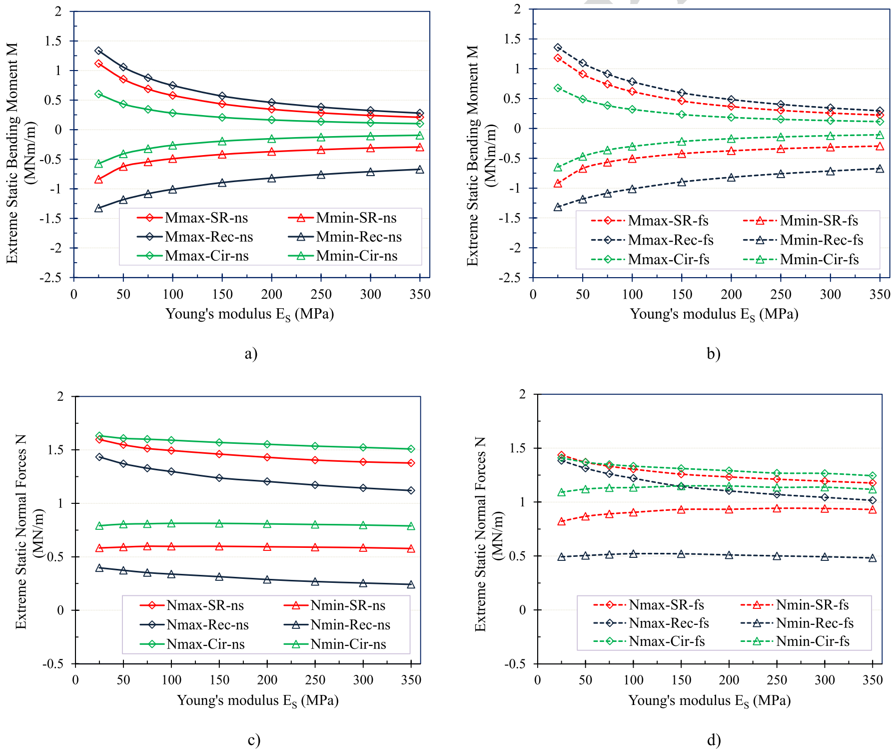

Fig. 9. Effect of Young's Modulus on the Internal Forces in the Tunnel Linings **a**) Extreme bending moments in no-slip case **b**) Extreme bending moments in full-slip case **c**) Extreme normal forces in no-slip case **d**) Extreme normal forces in full-slip case

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moments in the rectangular tunnel are smaller than the ones in circular and sub-rectangular tunnels and both for the no-slip and full-slip conditions.

For the no-slip condition, Fig. 9c indicates a slight decrease in the maximum normal forces (<10%). The minimum normal forces in both sub-rectangular and circular tunnels stayed more less constant when the E_S value increases, while the absolute extreme normal forces in rectangular tunnels tend to decrease gradually (25%). Figure 9d shows that the maximum normal tunnel lining forces in full-slip condition are smaller than the ones in no-slip condition when the E_S increases from 25 to 350 MPa. It should be noted that the extreme normal forces in the rectangular tunnel are strongly affected by the E_S value compared to the sub-rectangular and circular tunnels (steeper lines in Fig. 9d). The dependency of the normal forces in the sub-rectangular and circular tunnels on the E_S value is more or less similar.

Figure 10 introduces the dependency of the normal displacements on the E_S value. The variation in the maximum inward displacements induced at the bottom of rectangular and sub-rectangular tunnels is nearly similar and greater than in circular tunnels. Meanwhile, outward displacements occurred at the sidewalls of the circular and sub-rectangular tunnels are relatively the same and larger than the rectangular tunnel ones (Fig. 10a, b). This could be concerned with the curve radius effect in circular and sub-rectangular tunnels compared with the straight lining parts of rectangular tunnels. Indeed, the curved lining is more efficient in preventing the inward displacements at the top and bottom of the tunnel. On the other hand, straight lining parts and corners in rectangular tunnels cause a smaller forces redistribution from the top and bottom to the sidewall. It, therefore, induces smaller bending forces developed in the lining at the sidewalls. As a consequence, outward displacements in rectangular tunnels are small as indicated in Fig. 10b.

3.2 Effect of the lateral earth pressure, K_0

Lateral earth pressure values are assumed to vary in a range from 0.3 to 2.0 while the other parameters of the reference case in Table 1 are used. The results presented in Fig. 11 indicate that the K_0 has a great effect on the internal forces of

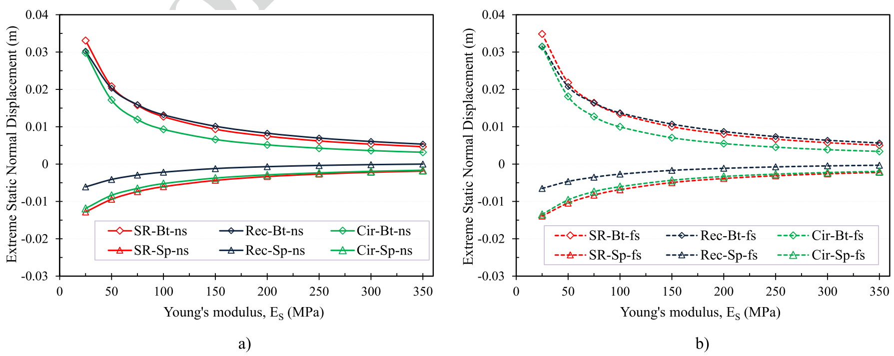


Fig. 10. Effect of Young's Modulus on the Normal Displacement in the Tunnel Linings **a**) Extreme static normal displacement for no-slip case **b**) Extreme static normal displacement for full-slip case

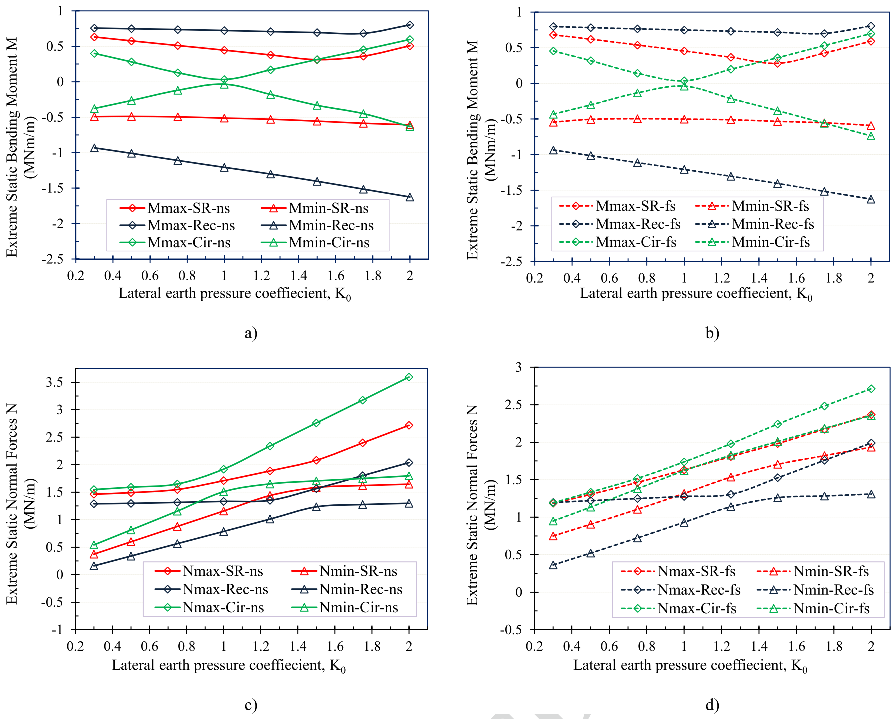


Fig. 11. Effect of the Lateral Earth Pressure Coefficient on the Internal Forces in the Tunnel Linings **a**) Extreme bending moment for no-slip case **b**) Extreme bending moment for full-slip case **c**) Extreme normal forces for no-slip case **d**) Extreme normal forces for full-slip case

the three tunnels and in both no-slip and full-slip conditions. It is also noted that there is a great influence of the tunnel shapes on the tunnel lining's internal forces induced when the K_0 values change.

Figure 11a, b illustrates that the absolute extreme bending moments in the circular tunnel greatly change depending on the K_0 values. They reach the minimum values when the K_0 value is equal to the unity. When the K_0 value is smaller than unity, positive bending moments are observed at the top and bottom of the tunnel. When K_0 value increases, positive bending moments occurred at the sidewalls. In other words, positive bending moments appeared at lining parts being perpendicular with the maximum stress direction (Fig. 11a, b).

Different from the circular tunnel, these figures show a slight influence of the K_0 value on the maximum bending moments for the rectangular tunnels. However, the absolute value of the minimum bending moments in the rectangular tunnels increases linearly when the K_0 value increases from 0.3 to 2.0. It is one of the main drawbacks of rectangular tunnels. The lower influence of the K_0 value on the bending moments in rectangular tunnels is related to the small redistribution effect of the lining forces from the sidewall to the top and bottom parts as mentioned in section 2.3. Consequently, greater horizontal forces from the sidewall caused by the increase in K_0 value cause insignificant forces changes preventing again inward vertical movements at the top and bottom parts of the tunnel lining.

Sub-rectangular tunnels seem to overcome this drawback. Indeed, the minimum bending moments at the 4 shoulders are almost constant when K_0 increases from 0.3 to 2.0 for both full-slip and no-slip conditions. The maximum bending moments induced in sub-rectangular tunnels tend to decrease and reach the minimum value at K_0 values of approximately 1.6.

Considering the interaction between the lining and soil, the absolute extreme bending moments in the circular tunnels in the full-slip condition are 15% greater than the ones in the no-slip condition (Fig. 11a, b). For the rectangular tunnels, there is no clear difference in the minimum extreme bending moments at the four tunnel lining corners between the full-slip and no-slip conditions. It is due to the rectangular tunnel corners which decrease the soil–lining interaction effect on the internal forces.

Particular attention should then be paid to sub-rectangular tunnels; the maximum bending moments in the full-slip conditions are lower than the ones in the no-slip condition when the K_0 value changes from 1.25 to 1.5. It is similar; at the 4 shoulders, the absolute minimum bending moments in the no-slip condition are higher than the ones in the full-slip condition, corresponding to K_0 values from 1 to 2.

Figure 11c and d indicates that the extreme normal forces in the tunnel linings increase in all the tunnel shape cases when the K_0 increases. The maximum and minimum normal forces in circular tunnels are always greater than the corresponding sub-rectangular and rectangular ones

Figure 12 indicates that a K_0 value increase causes a decrease in the inward displacements at the top and bottom of the tunnel. It is then followed by outward displacements for larger K_0 values. Meanwhile, outward displacements induced at the sidewalls observed at low K_0 values are modified to inward displacements for large K_0 values. The extreme displacements variation in rectangular tunnels depending on the K_0 values is lower than those on sub-rectangular and circular tunnels.

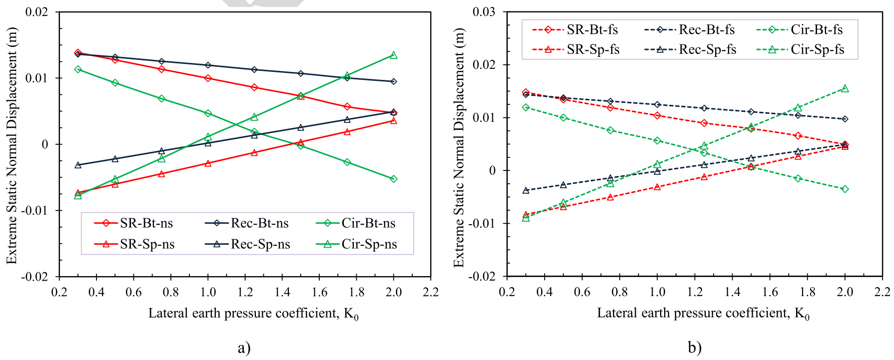


Fig. 12. Effect of the Lateral Earth Pressure Coefficient on the Normal Displacement in the Tunnel Linings **a**) Extreme static normal displacement for no-slip case **b**) Extreme static normal displacement for full-slip case

3.3 Effect of the Lining Thickness

The lining thickness *t* is assumed to vary in the range from 0.2 to 0.8 m, and the other parameters are taken as shown in Table 1. The results presented in Fig. 13 indicate that the *t* value has a great effect on the extreme internal forces for all cases of tunnel shapes for both no-slip and full-slip conditions. The relationship between the absolute extreme internal forces and the lining thickness for the considered cases is quite linear.

Figure 13a, b shows that the absolute extreme bending moments in circular tunnel linings are always the smallest and in rectangular tunnels are the biggest when the lining thickness increases from 0.2 to 0.8 m. The absolute extreme bending moments in the full-slip condition are larger than the ones in the no-slip condition as indicated in section 2.3. The greatest and smallest dependency of the maximum bending moments on the lining thickness is, respectively, observed in rectangular and circular tunnels. It means that rectangular tunnels are more sensitive to the lining thickness change in terms of the bending moments.

As for the extreme normal forces in the circular and sub-rectangular tunnels, they vary less in no-slip conditions. Generally, slight increases in the maximum

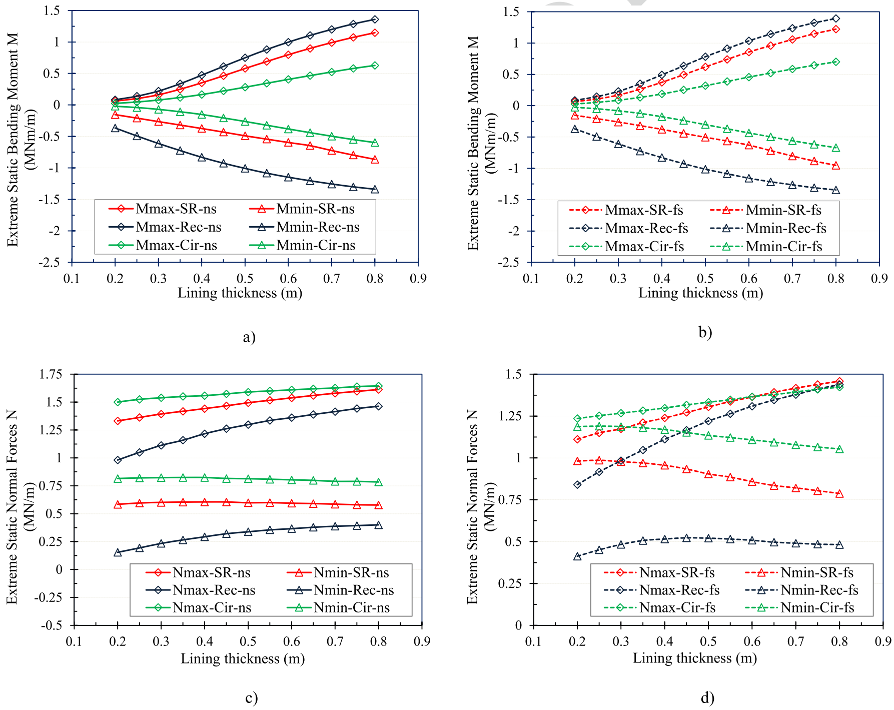


Fig. 13. Effect of the Lining Thickness on the Tunnel Lining Internal Forces **a**) Extreme bending moment for no-slip case **b**) Extreme bending moment for full-slip case **c**) Extreme normal forces for no-slip case **d**) Extreme normal forces for full-slip case

normal forces are observed when the lining thickness increases from 0.2 to 0.8m. In contrast, a greater variation in the normal forces is seen for rectangular tunnels (Fig. 13c). In the full-slip case, an increase in the lining thickness causes a slight decrease in the minimum normal forces and an increase in the maximum normal forces for all three tunnel shapes (Fig. 13d). It should be noted that smaller maximum normal forces in the three kinds of tunnels are observed when the lining is thicker (Fig. 13c, d). In other words, thicker linings will decrease the tunnel shape effect on the maximum normal forces.

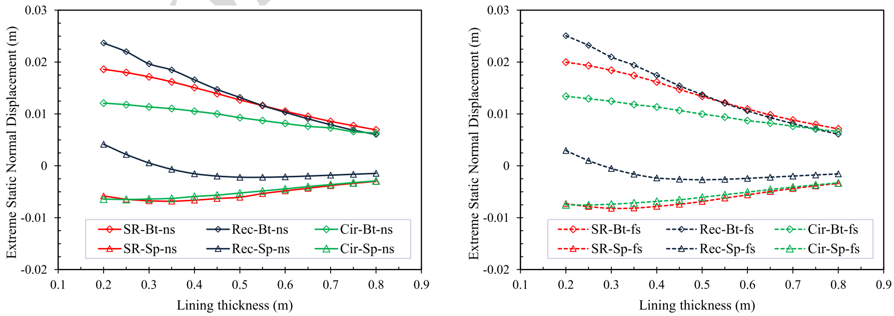
Figure 14 presents extreme normal displacements with the lining thickness variation. The biggest and smallest dependency occurred in rectangular and circular tunnels, respectively. Displacements in the tunnel lining decrease when the lining thickness increases. Similar to the normal forces, the thicker lining causes a lower tunnel shape influence on the lining displacements.

4 4. Conclusions

A 2D numerical parametric study is conducted to highlight the behaviour of circular, rectangular, and sub-rectangular tunnels under static loading. Parameters, like Young's modulus, lateral earth pressure, lining thickness, were investigated. Based on the research results, there are some conclusions as follows:

- In terms of space utilization ratio efficiency, the circular tunnel gives the worst performance compared to the two other cross-sections. By contrast, there is not much difference in the space utilization ratio when comparing the sub-rectangular and rectangular tunnels,

- Investigating the E_S, K_0, and t parameters effect on the tunnel lining shows that the circular tunnel is the most stable tunnel shape and the rectangular tunnel is the worst shape in terms of stability. The high-stress concentration at the four corners of the rectangular tunnel can be minimized when using the sub-rectangular tunnel, and its stability is relatively good when compared to the circular tunnel. It should be



a) b)

Fig. 14. Effect of the Lining Thickness on the Normal Displacement in Tunnel Lining **a**) Extreme static normal displacement for no-slip case **b**) Extreme static normal displacement for full-slip case

noted that the sub-rectangular is more efficient when the lateral earth pressure coefficient gradually increases, specifically for $K_0 > 1.5$. The maximum bending moments in the sub-rectangular tunnels are even smaller than the circular tunnel ones with the same utilization space area. In addition, the tunnel will be more efficiently supported in no-slip conditions compared to the full-slip ones.

Based on the obtained results, it is reasonable to conclude that sub-rectangular shaped tunnels should be considered as a potential solution to replace circular and rectangular tunnels due to their high utilization space ratio, and especially good stability by avoiding the stress concentration at the four corners.

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Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics Approval and Consent to Participate Not applicable

Consent for Publication Not applicable

Competing Interests The authors have no competing interests to declare that are relevant to the content of this article.

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