Journal of Mining and Earth Sciences

Website: http://jmes.humg.edu.vn

Influence of Interior Column on the Behaviour of Quasi-Rectangular Tunnel

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ARTICLE INFO

Article history:
Received 19th Dec. 2023
Revised 15th Mar. 2024
Accepted 20th Mar. 2024

Keywords:
Interior column,
Internal forces,
Quasi-rectangular tunnel,
Sub-rectangular tunnel.

ABSTRACT

The growing population in major cities around the world requires significant development of transportation infrastructure, especially underground system. It requires the construction of more subway lines, and larger tunnel cross-sections. In underground construction, a cross-sectional shape which is a combination of circular and rectangular tunnels is an advanced trend. This shape incorporates the advantages of both forms. There are two terminologies used to classify these shapes, including sub-rectangular and quasi-rectangular tunnels. While the sub-rectangular tunnel lacks an interior column, the quasi-rectangular tunnel includes an interior column located at the center of tunnel. Recent studies focus on separately investigating the behavior of sub-rectangular and quasi-rectangular tunnels using various methods such as numerical methods, analytical methods, and experimental methods. The present study conducted a numerical comparison of these two types of tunnels. The results indicated that the presence of an interior column help to increase the stability of the lining structure. The internal forces within the quasi-rectangular tunnel with an interior column are smaller than those of the sub-rectangular tunnel and quasi-rectangular tunnel without an interior column.

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DOI: 10.46326/JMES.2024.65(2).01

1. Introduction

The population growth in major cities around the world demands significant development in transportation infrastructure, while the available surface areas in urban continue to shrink. Hence, the development of metro lines is essential in large cities. Twin circular tunnels with one-way traffic in each single tunnel are usually the typical metro line solution. Compared to a large single circular tunnel, twin tunnels have technical advantages such as less surface settlement and smaller internal forces induced in the tunnel lining (Li et al., 2019). However, the twin tunnels solution causes a greater surface settlement trough. Double-O-tube (DOT) shield tunnel is a cross-section type that is optimized to minimize the cross-sectional area by increasing the efficiency of underground space utilization and reducing the impacted area on the surface caused by the tunnel construction. On the other hand, a DOT tunnel could eliminate the cross-passages between two circular tunnels, thus avoiding construction risks. However, DOT tunnels also have disadvantages such as difficulty in selecting the location of grouting holes, large soil disturbance, difficulty in adjustment, and significant resistance at the junction between two tubes.

The quasi-rectangular tunnel, which was first used in the Ningbo Metro Line 03 in China, is a combination of the DOT and rectangular tunnels. Compared with a large circular tunnel, a quasi-rectangular tunnel allows for increasing the efficiency of underground space utilization by around 20% (Liu et al., 2018c; Zhang et al., 2020), and the tunnel depth can also be reduced by a corresponding proportion. Studies on the behavior of quasi-rectangular tunnel linings can be conducted using experimental methods (Liu et al., 2018a; 2018b), analytical methods (Yuhang et al., 2019; Zhang et al., 2020; 2022), and numerical methods (Liu et al., 2018a; Huang et al., 2018; Zhu et al., 2018; Nguyen et al., 2021; Zhang et al., 2021).

Liu et al. (2018a, 2018b) conducted a 1:1 scale structural experiment to investigate the mechanical behavior of the segmental lining for quasi-rectangular tunnels (Figure 1). The experimental results revealed the failure state, convergence deformation of the structure, deformation of reinforcing bars, rotation angle of joints, and bolt deformations. From the experimental findings, two analytical methods were employed to assess the mechanical behavior of the tunnel structure. The results indicated that the weakest point of the quasi-rectangular tunnel lining is the position of block T2 (the connection between the interior column and the bottom of the invert part). Zhang et al. (2020) studied the influence of rotational stiffness on the joint behavior of the segmental lining of the quasi-rectangular tunnel. The authors used the beam-spring method (BSM) to study the internal forces and deformations generated in the tunnel lining. The joint's stiffness changes with the change of moment and axial force in the joint. The behavior of the joints is nonlinear, through the relationship between bending moment, axial force, and shear force in the joints. The errors in internal forces

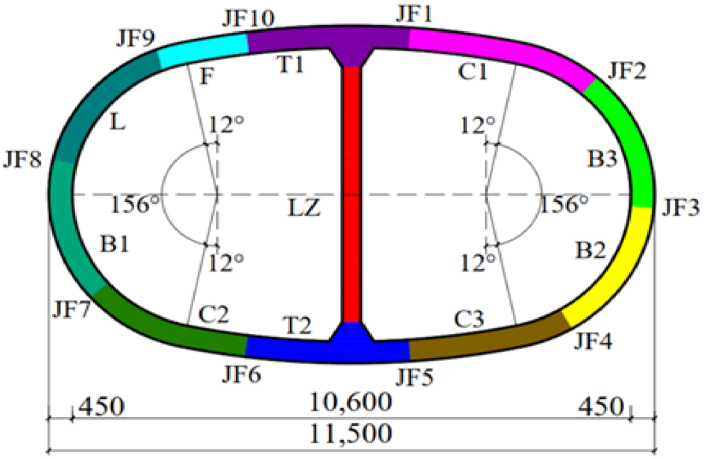

Figure 1. Quasi-rectangular tunnel with interior column of Ningbo Metro line 3 (Liu et al., 2018a).

and deformation in most monitoring points are less than 10% between the results obtained by the BSM method and the experimental results. Zhang et al. (2021) studied the optimization of longitudinal joints in segmental quasi-rectangular tunnel lining using numerical methods. In this study, the internal forces in the area surrounding the joints, the influence of the bolt properties, and the strength of the concrete were considered. The results showed that optimizing the joint section to increase the lever arm between the bolts and the compression zone can effectively improve the performance of the joints.

Huang et al. (2018) conducted a study on the behavior of sub-rectangular tunnel linings (Figure 2) through a full-scale test considering the self-weight of the structure. A new loading configuration was developed to experimentally load the full-scale sub-rectangular tunnel lining, enabling the comprehensive assessment of the mechanical properties of the segmental tunnel lining under full loading conditions for the first time. The experimental results were compared with numerical simulations using the Abaqus program. The findings from the laboratory tests align closely with the numerical simulation data. The results indicated that the maximum positive moment was observed near the crown and the bottom part of the tunnel lining, while the maximum negative moment was observed at the shoulder parts. Zhu et al. (2018) conducted numerical simulations to study the mechanical behavior of sub-rectangular tunnel linings. In the study, the behavior of circular, sub-rectangular, and rectangular tunnel lining with the same external dimensions were clarified. The results indicated that circular tunnels exhibited high load-bearing capabilities but were less economically efficient compared to sub-rectangular tunnels. Meanwhile, rectangular tunnels proved to be unfavorable for load transfer and required additional reinforcement at the corners.

None of the studies mentioned above compared the behavior of quasi-rectangular tunnel lining (with and without an interior column) and sub-rectangular tunnel lining. Although these two types of tunnels serve different purposes, quasi-rectangular tunnels with an interior column are typically used for two-way tunnels. The interior column increases the stability of the tunnel structure, separates the tracks, and improves ventilation efficiency. Sub-rectangular tunnels are used for one-way tunnels

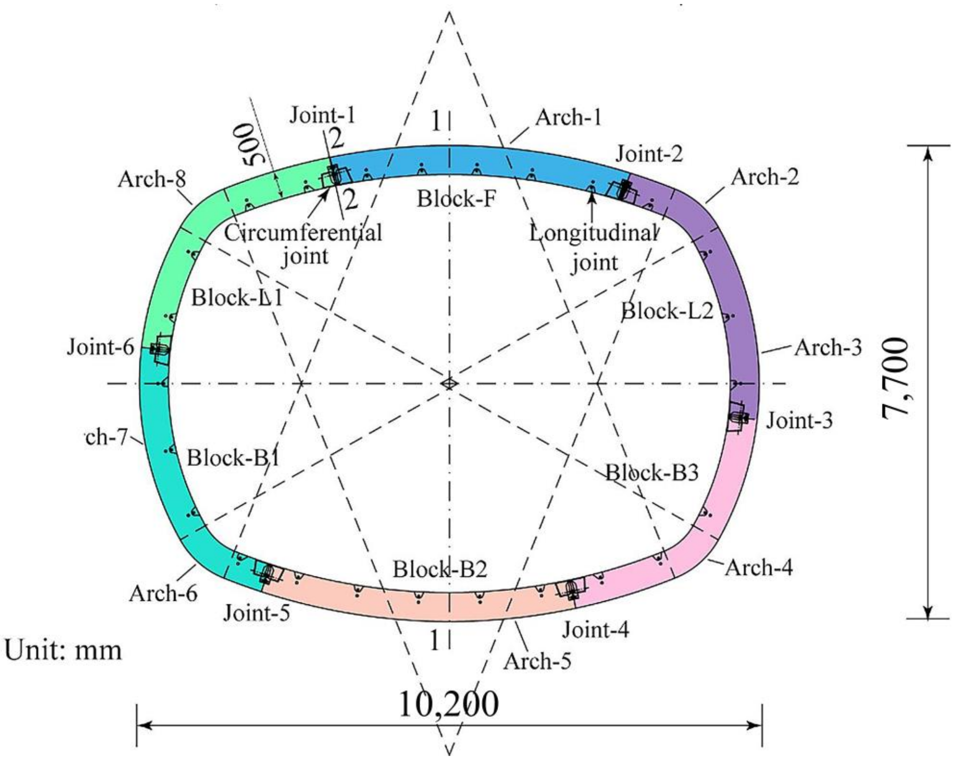

Figure 2. Sub-rectangular tunnel lining (Do et al., 2020; Nguyen et al., 2021).

with two lines. The mentioned studies using experimental methods are often complex, time-consuming, and costly. Analytical methods often rely on simplifications in calculations, making it difficult to simulate the real interaction between the surrounding ground and the tunnel lining. In this study, the behavior of quasi-rectangular tunnel linings with and without an interior column is investigated using numerical methods. This approach allows for a more detailed analysis of the structural behavior and can provide valuable insights into the differences between the two types of tunnels.

2. Numerical simulations

2.1. Geometric dimensions of the tunnel cross-section

The quasi-rectangular tunnel (with an interior column) first used in China on Metro Line 3 Ningbo has an outer dimension of 11.5m x 6.937m. The tunnel lining is composed of 10 segments (B, C, T, L, F) and an interior column (LZ) (Figure 1). The thickness of the tunnel lining is 450mm, while the column has a thickness of 350mm. The quasi-rectangular tunnel structure is formed by four arches, including 2 arches on the sides with an angle of 156 degrees, and arches on the crown and bottom have an angle of 24 degrees (Figure 1).

The sub-rectangular tunnel is described in the studies by Huang et al. (2018), Do et al. (2020), Dang et al. (2021) and Nguyen et al. (2021). The assembled tunnel lining is made up of 6 segments (B, L, and F block). The external dimensions of the tunnel lining are 10.2m x 7.7m with a lining thickness of 500mm. The geometric shape of the quasi-rectangular structure is formed by eight arches, including 2 arcs on the sides with an angle of 54 degrees, 4 arches on the shoulders with an angle of 41 degrees, arches on the crown and bottom with an angle of 44 degrees (Figure 2).

2.2. Numerical simulation using FEM model.

To investigate the behavior of quasi-rectangular (with and without interior columns) and sub-rectangular lining tunnels, the Plaxis 2D program, based on the Finite Element Method (FEM), was employed. The soil parameters were obtained from the silt clay layer of the Shanghai Metro Line 4 tunnel project (Zhu et al., 2018; Nguyen et al., 2021). The parameters of the tunnels were sourced from the Shanghai Metro Line 4 project (Huang et al., 2018) and the Ningbo Metro Line 3 project in Zhejiang, China (Liu et al., 2018a; 2018b).

The input parameters listed in Tables 1 and 2 were utilized. The numerical model has dimensions of 150 meters in width and 50 meters in height, divided into approximately 8900 elements and 72300 nodes (Figure 3). The boundary conditions of the model are as follows: 1) The bottom of the model is fixed in both the vertical and horizontal directions. 2) The two sides of the model are fixed in the horizontal direction. 3) The top of the model is free.

For simplicity, the soil is modeled using the linear elastic-perfect plastic material model following Mohr-Coulomb (MC) criteria. Although the soil behavior in the MC model is less accurate than the Hardening soil model when studying settlement (Çelik, 2017), it is still widely used in many studies on structural behavior (Abdellah et al., 2018; Vinod & Khabbaz, 2019) due to its simplicity in input parameters and reduced computational time.

Table 1. Geometrical features of tunnel shapes.

Parameters	Sub-rectangular	Quasi-rectangular	Note
Tunnel Width, W (m)	10.200	11.500	
Tunnel Height, H (m)	7.700	6.937	
W/H ratio	1.325	1.658	
Outer Perimeter	29.795	30.381	
Internal Perimeter	26.654	27.554	
Internal Area (m^2)	52.926	51.733	With interior column
		53.846	Without interior column
Outer Area (m^2)	67.038	66.881	

Table 2. Input parameters.

Parameter	Symbol	Value	Unit
Properties of soil			
Density	γ_s	18	kN/m^3
Young's modulus	E_s	3.6	MPa
Poisson's ratio	ν_s	0.495	-
Internal friction angle	φ	16.5	degree
Cohesion	c	0.0256	MPa
The lateral earth pressure coefficient	K_0	1-sin(φ)	–
Overburden	H	10	m
Properties of tunnel lining			
Material Model	Linear elastic		
Young's modulus	E	31,000	MPa
Density	γ_c	24	kN/m^3
Lining thickness	Sub-rectangular (t)	0.50	m
	Quasi-rectangular (t)	0.45	m

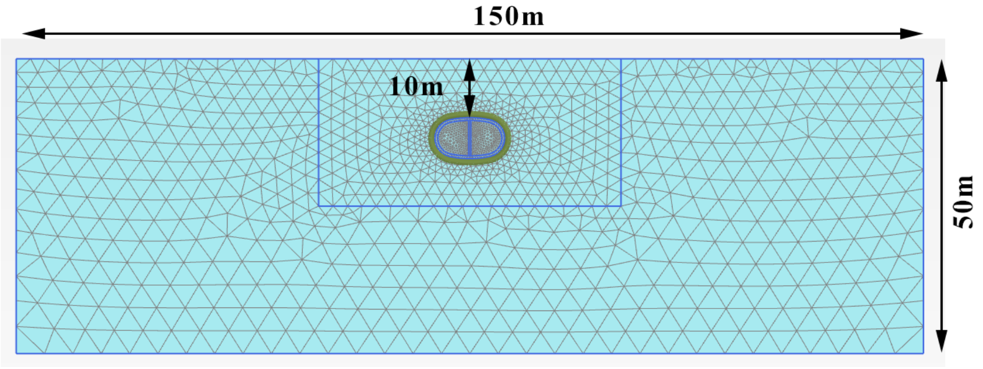

Figure 3. Geometry and finite element mesh of the tunnel model.

3. Results and discussion

Figures 4 and 5, as well as Table 3, depict the results of internal forces generated in the quasi-rectangular with interior column (QRCT), quasi-rectangular without interior column (QRT), and sub-rectangular tunnel (SRT) linings using the FEM models.

The numerical model results show that the maximum absolute bending moment and normal force developed in the QRT tunnel are greater than those induced in the QRCT tunnel by 149.2% and 24.2%, respectively. Obviously, the presence of an interior column increases the overall stiffness of the tunnel structure and therefore reduces the bending deflection of the load-bearing beams at the tunnel crown. As a result, the internal forces generated in the quasi-rectangular tunnel lining with an interior column are smaller.

When comparing the internal forces in the QRT tunnel and SRT tunnel lining, the maximum absolute bending moment in the QRT tunnel is greater by 29.6%, while the difference in the maximum normal force of the two tunnels is negligible, approximately 2.5%. It should be noted that the thickness of the sub-rectangular tunnel lining is greater than the one of the quasi-rectangular tunnel lining, resulting in smaller internal forces within the quasi-rectangular tunnel lining. On the other hand, the W/H ratio of the SRT is also smaller than the one of the QRT tunnel (Table 2). According to the research on sub-rectangular tunnel behavior conducted by Do et al., 2020, the smaller the W/H ratio, the smaller the maximum bending moment generated in the lining.

Figure 4 also indicated that the maximum absolute bending moment and normal forces

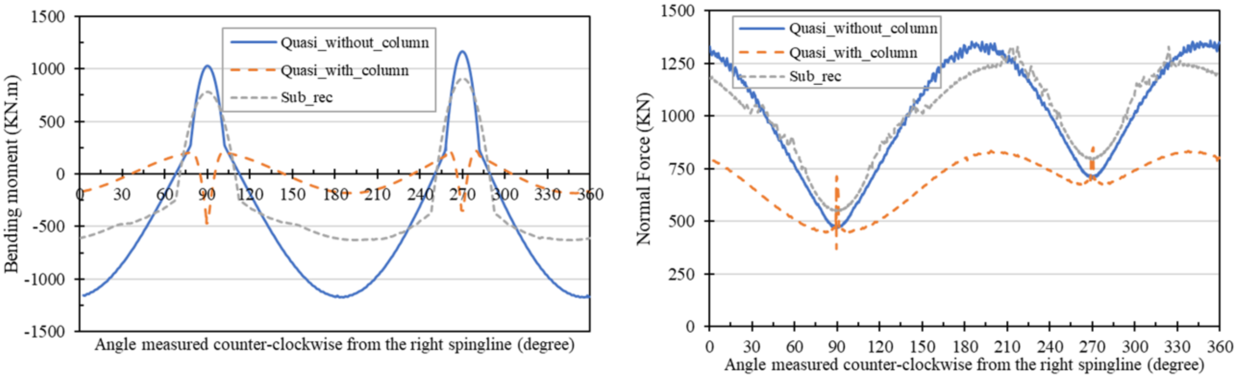

Figure 4. Internal forces in tunnel lining.

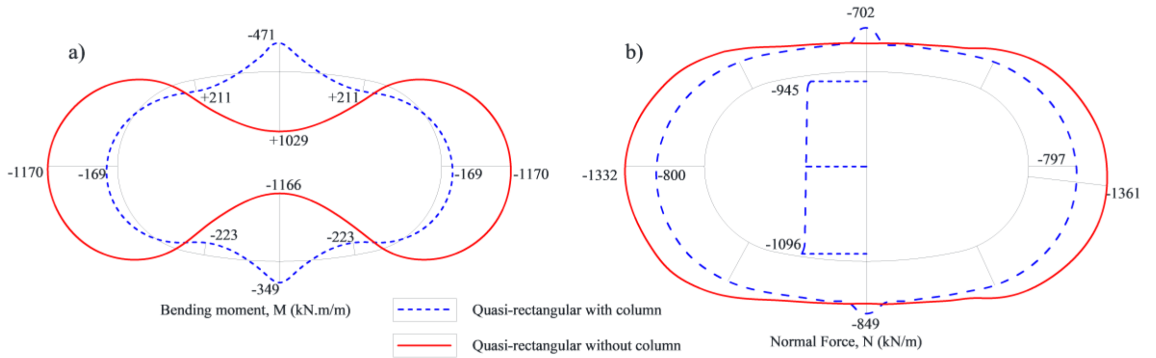

Figure 5. Bending moment and normal force diagrams in the quasi-rectangular tunnel lining. Note: the bending moments within the interior column are exceedingly minimal, they are not described in the figure.

Table 3. Comparison of structural forces induced tunnel lining determined by FEM model.

Case of the tunnel shape	SRT	QRT	QRCT
Maximum bending moments (MN-m/m)	0.906	1.166	0.223
Minimum bending moments (MNm/m)	-0.631	-1.174	-0.471
Maximum normal forces (MN/m)	1.327	1.361	1.096
Minimum normal forces (MN/m)	0.547	0.465	0.367
Maximum shear forces (MN/m)	0.625	0.587	0.567
Minimum shear forces (MN/m)	-0.628	-0.583	-0.604

within the QRCT tunnel lining are reduced by 48% and 17.4%, respectively, compared to those of the SRT tunnel. The presence of the central column results in a negative bending moment induced at the crown and bottom of the lining. It also causes a decrease in positive bending moments along the QRCT tunnel lining. Figure 4 also reveals that negative bending moments primarily occur at the crown, bottom, and sides of the QRCT tunnel. The smallest negative moment is observed at the tunnel crown.

The central column acts as a structure primarily subjected to axial compression. The maximum normal force within the column is the highest value along the entire structure, Nmax = 1.096 MN (Figure 5). These results are consistent with findings obtained through analytical methods (Nakamura et al., 2003) and other numerical approaches (Zhang et al., 2020; Liu el al., 2018).

4. Conclusion

This study investigated the behavior of tunnel lining considering the influence of tunnel shape and interior column. From the analyses mentioned above, it can be concluded that:

- In the quasi-rectangular tunnel, the presence of the central column increases the stability of the tunnel in term of internal forces.

- In all three cross-sections-shaped tunnels mentioned above, the QRCT tunnel proves the highest stability concerning internal forces, the QRT tunnel has the less stability, meanwhile, that of SRT tunnel is in between.

The conclusions drawn above demonstrate the applicability of using quasi-rectangular tunnels in metro line construction as an effective alternative solution to the traditional method of using two parallel circular tunnels. Further studies and engineering assessments would be necessary to fully evaluate its feasibility and benefits in specific locations.

5. Acknowledgement

This research was funded by the Hanoi University of Mining and Geology under grant T23-44. This funding is greatly appreciated.

6. Contributions of authors

Nguyen Tai Tien - conceptualization, funding acquisition, investigation, methodology, writing - original draft; Do Ngoc Anh - writing, review & editing, supervision.

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