Structural Design and Construction Methods of Long-span
Three-lane Quasi-ellipse Shield Tunnel without Columns

Y T Zhu*

Shanghai Tunnel Engineering Co. Ltd., Shanghai 200232, China

Abstract: Compared with the influence of open cut method during the construction of shallow-buried three-lane underground expressway on the surrounding pipelines, urban greenery and traffic organization, as a fully-mechanized construction method, shield tunnelling has much smaller disturbance to the surrounding environment. A long-span three-lane quasi-ellipse shield tunnel was proposed and the inner contour was sketched according to the functional requirements of its internal space. To ensure the enough bearing capacity and the anti-deform ability of the segmental lining, the structural design was finally determined after the sensitive analysis of certain key parameters. Then, a new type of segment lining with inner and outer surface pasted with thin steel plates was created, which made full use of the strong tensile strength of steel, and the mechanical behaviors of the lining were explored through the modified routine method. Given with the special shape, a corresponding segment casting method was chosen taking both of operability and structural integrity into account. To fulfil full face cutting, a quasi-ellipse shield machine equipped with a combined cutter head was designed, which could provide enough thrust force and minimize the disturbance to the surrounding environment in the working state.

1 Introduction

Due to the serious shortage of the urban land resources, the traffic congestions and jams have been widespread in the mega-cities. Although the construction cost of viaducts is relatively lower and can improve the traffic condition in a short time, a great deal of urban space is still occupied, and the noise, vibrations and exhaust gas test the limit of the residents in big cities all the time. Underground expressway system connecting urban center and fringes is undoubtedly the best choice to ensure the driving speed without occupying the land resources, and the centralized control on the exhaust emission can effectively prevent the environmental pollution.

To satisfy the necessary space for a super-large urban three-lane shallow-buried highway tunnel in the soft soil strata, a rectangular clear cross-section with the width of 12.5m and height of 4.5m has to be provided, and the following question is how to choose an optimal construction method. As we know, open-cut method[1] is usually the preferred one for the underground expressway in the condition of shallow overburden if the ground traffic and surrounding environment permit, which has been widely adopted because of its short construction period and low cost. However, the urban ground traffic and the normal life of the residents will be also disturbed unavoidably, the pollutions of the noise, the dust and the waste mud are easily produced by the engineering constructions. Shield method[2] is a fully mechanized construction method to form a tunnel structure, using the shield machine to excavate the stratum and support the surrounding soil through the shield shell and segments to prevent the collapse, but consuming more capital investment and having higher construction difficulty compared with the
open-cut method. Drilling and blasting method[3] or shallow tunnelling method[4] is always employed in the long-span tunnel projects, but no construction conditions are available for both of them in the shallow soft soil stratum. If open-cut method combined with the cast-in-site technology of the tunnel structure is abandoned owing to the influence on the road traffic and surrounding environment, the shield method is finally the only way. Up to now, several representative three-lane highway circular tunnel projects have been built with the diameter of 15m, including Nanjing Yangtze river tunnel (14.96m)[5], Yangtze river cross tunnel in Shanghai (15.0m)[6], Maliuzhou subsea tunnel in Zhuhai (14.5m)[7], etc. Nevertheless, the buried-depth of the circular tunnel has to be increased due to the condition of shallow burden, and compared with the quasi-rectangular[8] shield tunnel, the space utilization rate of the circular tunnel is too low, and the range of the disturbance to the stratum induced by the soil excavation is too large. Although the quasi-rectangular shield tunnel is a good choice after the balance between the space utilization and structural bearing capacity, the existence of the middle column can not achieve the three-lane traffic function.

Finally, a long-span three-lane quasi-ellipse shield tunnel with internal and external surface pasted with thin steel plates was proposed, and the structural behaviors of the lining structure were discussed. A corresponding segment casting method and the design of the quasi-ellipse shield machine were illustrated to fulfil both the feasibility and operability. The design and research results in this paper will provide a complete set of feasible construction methods for the super-large three-lane quasi-ellipse shield tunnel.

2 Detailed design of the quasi-ellipse segmental lining

2.1 Construction clearance of the three-lane highway tunnel

The design of the construction clearance of the quasi-ellipse three-lane highway tunnel was exhibited in Figure 1, and a rectangular cross-section with the width of 12.5m and height of 4.5m was suggested to satisfy the normal functional requirement according to the designed driving speed of 80 km/h.

![Figure 1 Construction clearance of the quasi-ellipse three-lane highway tunnel](image)

Then, the internal dimension of the quasi-ellipse segmental lining with the width of 14.59m and height of 7.2m was sketched, which was composed of four curves: top and bottom curves with a radius of 13.95m, left and right curves with a radius of 2.57m. The vehicles were arranged in the middle of the cross-section, and a width of 0.5m was reserved on both two sides for the necessary equipment pipelines and boxes which were protected by the decorative plates. In addition, a height of 1.23m was retained on the top of the section for the lighting and signal lamps, loudspeakers and the ventilation system, etc., another height of 0.87 was set on the bottom as a necessary passageway for the later maintenance.
Seen from two circles drawn in Figure 1 (a) and (b), it should be noted that the area of the clear space of the quasi-ellipse tunnel was 83.98 m², which was only 50.2% of the circular tunnel with the same span, and the excavation area of the quasi-ellipse tunnel (107.38 m²) was only 54.2% of that of the circular tunnel (198.20 m²) if the thickness was set to be 0.65m. The calculated data fully proved the obvious advantages on the space utilization and economy of this new tunnel section.

2.2 Parameter sensitivity analysis of structural deformations
The structural design of the segmental lining was conducted according to the properties of the No. 4 stratum (silt clay soil) of Shanghai in the operation period, and the main design parameters were present in Figure 2. The width of the segments was selected to be 1.2m, while the strength grade of the concrete, the thickness of the segments and the steel plates should be determined after a series of sensitivity analysis through the FEM calculation. The traverse effective rigidity ratio and the Poisson's ratio were suggested to be 0.7 and 0.167 respectively based on the existing research [9]. Full-circle soil springs were employed to take the interaction between structure and soil into account.

![Figure 2 The geological condition and the design of the segments](image)

Considering the total soil excavation volume, the self-weight of one lining ring, and the lifting capacity of the segment assembling machine, the segment thickness of 650mm were firstly chosen to discussed the influence of the strength grades of the concrete (C55~C80) on the overall deformation of the lining structure (see Figure 3). Ellipticity of the segmental lining was defined by the following formula.

\[
\text{Ellipticity} = \frac{\max \left\{ HE, VC \right\}}{\max \left\{ \text{width}, \text{height} \right\}} \times 100\% \quad (1)
\]

Where, HE was short for horizontal expansion, the relative displacement between the two waists in the horizontal central axis; VC was short for vertical closure, the relative displacement between the crown and the invert along the vertical central axis; the width and the height were derived from the maximum outer dimension in the horizontal and vertical direction of the segmental lining ring respectively.

As shown in Figure 3, both the horizontal expansion and vertical closure decreased linearly with the increasing of the concrete strength grades ranged from C55 to C80, as the concrete elastic modulus increased linearly with the concrete strength grades. However, the ellipticity reached 7.49‰ when the concrete strength grade was C80, which was far more than the limit value of 3‰ [11]. The calculation results proved that the improvement of the concrete strength grade had no obvious promotion on the
anti-deformation ability of the segmental structure, and it was also uneconomical to choose the high grade meantime.

![Figure 3 Variation of the deformations with the strength grades of concrete](image)

In view of the above-mentioned conclusion, the strength grade of C60 was stabilized to continue exploring the influence of the segment thickness on the lining deformation. Then, structural deformations adopting the segment thicknesses ranged from 650mm to 1000mm were calculated and shown in Figure 4. Which could be intuitively found that either the horizontal expansions or the vertical closures were obviously decreased in the form of the quadratic function curve when the segment thickness increased linearly. The main reason was the increase of the segment thickness significantly improved the structural rigidity of the whole lining ring, and the ellipticity reached 2.93% when the thickness increased to be 950mm. Despite all these, the thickness of 950mm was still undesirable since the calculated maximum weight of a single block would exceed 17 tons, which would possibly lead to the collapse of the segment assembling machine. In addition, too large segment thickness directly increased the construction cost and the casting difficulty. Therefore, 650mm was determined to be the final thickness given the above considerations.

![Figure 4 Variation of the deformations with the thicknesses of the segment](image)

To significantly improve the whole structural rigidity, a new type of segment with internal and external surface pasted with thin steel plates was proposed making full use of the tensile strength of steel. $\eta$ was defined to be the rigidity reduced factor for this ‘sandwich’ combination in the following formula.

$$\eta = \frac{(EI)_{eq}}{E_{c}I_{c}}$$

Where, $E_{c}$ and $I_{c}$ represented the elasticity modulus and the inertia moment of the concrete, $(EI)_{eq}$
was equivalent bending stiffness of this new type of transverse section.

Similar to the segment thickness, both the horizontal expansion and vertical closure rapidly declined in the trend of quadratic curve as the steel plate thicknesses increased, and the ellipticity of 3% was achieved with the steel plate thickness of 50mm. In addition, the ribbed steel bars would be inserted into concrete to realize the bonding between the steel plates and concrete.

![Figure 5 Variation of the deformations with the thicknesses of the steel plate](image)

According the above sensitive analysis, excessive concrete grade and segmental thickness were not suggested which not only failed to meeting the design requirement, but also may lead to the waste of the construction cost and resource utilization, this new ‘sandwich’ segmental lining structure was considered to be the optimal scheme to solve the anti-deformation problem of long-span shield tunnels. Ultimately, the cross section of the three-lane quasi-ellipse segmental lining was obtained with the outer dimension of 15.89m × 8.70m (see Figure 2). A single full ring with a width of 1.2m and a thickness of 0.65m was composed of 7 blocks, including one seal roof segment (F), two adjacent segments (L1 and L2), three standard segments (B1, B2 and B3) and one key segment (C), which were hinged circumferentially by four M33 straight bolts. The neighboring rings were stagger-fabricated in the longitudinal direction through 32 M33 bent bolts.

### 2.3 Mechanical behaviors of the quasi-ellipse lining structure

Comparison of the geometric dimensions among three kinds of noncircular shield tunnel was presented in Figure 6. Special-shaped shield tunnel[7] is municipally universal, which can be applied in the projects of subway stations, city underpasses, highway or railway tunnels, etc., and quasi-rectangular shield tunnel[5] is mainly employed in the single-hole double-line metro projects.

![Figure 6 Comparison of the ratios of length to width](image)

Whether the stress state of the segmental structure was good or not was directly related to the ratio of the length to width, the greater the ratio, the worse the force state. Although the ratio of the
quasi-rectangular shield tunnel was bigger than that of the special-shaped shield tunnel, the force state of the former was better than that of the latter, as the existing of the middle column improved the bearing capacity of quasi-rectangular shield tunnel to a great extent. what could be intuitively found was that the ratio of the length to width calculated from the quasi-ellipse tunnel was much bigger than the rest two, and the force state of the quasi-ellipse tunnel was doubtlessly worst among them. Then, the distributions of internal forces and structural deformation of the quasi-ellipse ring in the design buried-depth were shown in Figure 7. It was noted that since the rotational stiffness of the segmental joints was not obtained, the modified routine method, as a general segment design method in the world was adopted firstly to explore the mechanical behaviors of the quasi-ellipse shield tunnel, the results of which were almost consistent with those obtained by beam-spring model, shell-spring model, etc.[12]

![Figure 7 Distributions of internal forces and structural deformation](image)

As figured out in Figure 7(a), both of the vault and the invert of the lining ring were trapped in the positive moment region, while two sides were subjected to the negative moment, the transitions from positive bending moment to negative bending moment were close to the arch shoulders and arch feet. The largest positive bending moments were at the middle of the vault and the invert, and the largest negative bending moments were present at both two waists. The whole lining structure was in compression (see Figure 7b), and the minimum axial force located at the middle of the vault, which led it to be most unfavorable and the control section of the whole. Four largest shear forces occurred at the connecting points between two curves with different radiuses, and the transitions from positive shear force to the negative were in the middles of four sides.

Illustrated in Figure 7(d) and (e), the quasi-ellipse lining ring deformed in a pattern of ‘expansion in the horizontal direction and closure in the vertical direction’. Moreover, the vertical closure was bigger than the horizontal expansion, as the horizontal dimension was much larger than that in the vertical direction, while the lateral soil pressure was not large enough to confine the lateral deformation.

### 3 Comparison and selection of the segment casting method

Since the design scheme of the segmental lining was determined, a corresponding casting method should be thought out taking the both the operability and structural integrity into account. Compared with the traditional segment casting method, the core technological problem needed to be solved was the installation of the embedded steel plates on the outer surface. Then, three schemes were proposed and illustrated in Figure 7.

To the first scheme, after the concrete was poured and tamped, a special mechanical equipment had to be created to grasp the steel plate owing to its large volume and weight. Then, the steel plate would be pressed into the concrete in the condition of the vibration, which mean additional measurements were needed to control the deformation of the steel plate during pressing, and the contact between the steel plate and concrete could not be guaranteed completely.

In the second scheme, after three strip steel plates were installed, the positions of which could be
adjusted to ensure the accuracy, and then the concrete was poured through the gaps between two strip steel plates and then tamped. Although the installation of the strip steel plates was relatively simple, the appearance of the outer surface was so incomplete that the stress concentration phenomenon and cracks would appear in the positions where the concrete and the steel plates contacted, and the width and the thickness of the steel plates needed to be further calculated and optimized.

In the third scheme, three holes were reserved to facilitate the pouring and tamping of the concrete. Then, three small steel plates with the same size with the holes were welded to form a whole, which would consume the extra time caused by the welding, but operability and the structural integrity could be ensured.

In summary, the third scheme was selected to the feasible casting method for this special kind of segments.

Figure 8 Segment production process

4 Design of the quasi-ellipse shield machine
The design of the super-large quasi-ellipse shield machine was exhibited in Figure 8 with the outer dimension of 16.06m × 8.67m, which was mainly composed of the cutter head, cutterhead driving system, shield shell, double-section screw conveyor, crawling segment assembling machine and propulsion system seen from the front to the back.

Figure 9 Illustration of the quasi-ellipse shield machine

The cutter head fixed in the front of the shield machine consisted of one Φ8670 big cutter head, two Φ6000 medium cutter heads and four eccentric small cutter heads, and 100% full-face cutting
could be realized through this kind of combination. The rear ends of the big cutter head and the two middle cutter heads were connected by the brackets with the cutter head driving system, which was equipped with several motors at its rear end and installed in the shield shell. One eccentric cutter head was driven by three eccentric drives, so a total of 12 eccentric drives were prepared.

The shield shell was divided into two parts including the front shell and shield tail, which were welded together. The front end of the double-section screw conveyor was connected and fixed with the front shield shell by the flange surfaces, and the rear end of which was anchored with the front shell by a pull rod. The crawling segment assembling machine mainly consisted of the guide rail and the crawling component. The former was arranged along the inner circumference of the shield shell. Then, the 6-DOF segment assembly could be conducted when the crawling component moved along the guide rail.

The propulsion system equipped with 48 hydro-cylinders could provide enough thrust force (maximum of 144000kN) to make the shield machine drive, which were arranged at the rear end of the front shield shell and divided into 8 adjusting zones. The minimum turning radiiuses in the horizontal and vertical direction were 900m and 500m respectively, and the quasi-ellipse shield machine could effectively control the ground settlement and minimize the disturbance to the surrounding soil.

5 Conclusions

(1) A quasi-ellipse cross section was sketched to satisfy the functional requirement of the long-span three-lane highway tunnel, the clear and excavation area were only 50.2% and 54.2% of those of the circular tunnel respectively, which fully proved the obvious advantages on the space utilization and economy of this new tunnel section.

(2) Both the horizontal expansion and vertical closure of the quasi-ellipse tunnel decreased linearly with the concrete strength grades, and declined in the form of quadratic function curve both with the segment and steel plates thicknesses, finally an optimal design scheme was obtained with the segment thickness of 0.6m, the concrete strength grade of C60 and the steel plate thickness of 50mm.

(3) The vault and the invert of the lining ring were trapped in the positive moment region, and both two sides were subjected to the negative moment, the transitions from positive bending moment to negative bending moment were close to the arch shoulders and arch feet. The maximum positive bending moment and the minimum axial force made the middle of vault the control section of the whole lining.

(4) the quasi-ellipse lining ring deformed in a pattern of ‘expansion in the horizontal direction and closure in the vertical direction’, the vertical closure was bigger than the horizontal expansion, since the horizontal dimension was much larger than that in the vertical direction, the lateral soil pressure was not large enough to confine the lateral deformation.

(5) A special segment casting was selected after the comparison of the operability and structural integrity, and a super-large quasi-ellipse shield machine was designed to fulfil the full-face excavation.

References

[1]. Zhang G Y, Xie W, Yang Q G, et al. (2021). Research on open cut blasting technology of reservoir diversion tunnel. International Journal of Critical Infrastructures, 17(1), pp21-37.

[2]. Zhou S, Ye G L, Han L, et al. (2021). Key Construction Technologies for Large River-Crossing Slurry Shield Tunnel: Case Study. Journal of Aerospace Engineering, 34(2), pp04020118.

[3]. Li R, Zhang D, Fang Q, et al. (2019). Geotechnical monitoring and safety assessment of large-span triple tunnels using drilling and blasting method. Journal of Vibroengineering, 21(5), pp1373-1387.

[4]. Shen G, Zhang D. (2016). Analysis of tunnel deformation under highly weathered sandstone strata by shallow tunneling method. Electronic Journal of Geotechnical Engineering, 21(10), pp3773-83.

[5]. Min F L, Zhu W, Lin C, et al. (2015). Opening the excavation chamber of the large-diameter size slurry shield: A case study in Nanjing Yangtze River Tunnel in China. Tunnelling and
Underground Space Technology, 46(1), pp18-27.

[6]. Talmon A M, Bezuijen A. (2013). Calculation of longitudinal bending moment and shear force for Shanghai Yangtze River Tunnel: Application of lessons from Dutch research. *Tunnelling and Underground Space Technology*, 35(4), pp161-71.

[7]. Huang P, Wang H, Wu T. (2019). Study on Limit Scouring of Maliuzhou Waterway: A Case Study of the Cross Gate Tunnel Project. *IOP Conference Series: Earth and Environmental Science*, 330, pp022123.

[8]. Ding W, Duan C, Zhu Y, et al. (2019). The behavior of synchronous grouting in a quasi-rectangular shield tunnel based on a large visualized model test. *Tunnelling and Underground Space Technology*, 83, pp409-24.

[9]. Zhu Y T, Zhu Y F, Zhang Z X, et al. (2018). Computational model and mechanical characteristics of linings of special-shaped shield tunnels. *Chinese Journal of Geotechnical Engineering*, 40(7), pp1230-36.

[10]. Zhang Z X, Zhu Y T, Huang X, et al. (2019). 'Standing' full-scale loading tests on the mechanical behavior of a special-shape shield lining under shallowly-buried conditions. *Tunnelling and underground space technology*, 86, pp34-50.

[11]. Ministry of Housing and Urban Rural Development of the People's Republic of China. (2017). Code for construction and acceptance of shield tunnel (GB50446-2017). Beijing: China Construction Industry Press, pp50-51.

[12]. Zhu Y T, Zhu Y F, Zhang Z X, et al. (2018). Computational model and mechanical characteristics of linings of specially-shaped shield tunnels. *Chinese Journal of Geotechnical Engineering*, 40(7), pp1230-36.

**Acknowledgments**

The research was funded by Shanghai Rising-Star Program (20QB1405000).