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Design and Finite Element Analysis of a New Type of Skeleton-Free, Traversing Secondary Lining Trolley

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Abstract: To effectively address the challenge where the speed of tunnel lining construction struggles to match that of tunnel face and inverted arch construction, and to enhance the quality of secondary lining, a new type of skeleton-free, traversing secondary lining trolley has been developed. This trolley features a set of gantries paired with two sets of formwork. The formwork adopts a multi-segment hinged and strengthened design, ensuring its own strength can meet the requirements of secondary lining concrete pouring without relying on the support of the gantries. When retracted, the formwork can be transported by the gantries through another set of formwork in the supporting state, enabling early formwork support, effectively accelerating the construction progress of the tunnel's secondary lining, and extending the maintenance time of the secondary lining with the formwork. Finite element software modeling was used for simulation calculations, and the results indicate that the structural strength, stiffness, and other performance parameters of the new secondary lining trolley meet the design requirements, verifying the rationality of the design.

Keywords: Tunnel; Secondary lining trolley; Skeleton-free; Traversing; Finite element analysis

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1. Introduction

With China's increased investment in infrastructure construction and the development of urban transportation, tunnel projects such as subways, railway tunnels, highway tunnels, and urban utility tunnels have developed rapidly [1–5]. As the main equipment for tunnel lining construction using the drilling and blasting method, the technical level of the secondary lining trolley directly restricts the construction quality and progress of the tunnel [6, 7].

Traditional secondary lining trolleys basically use a gantry to support the formwork and bear the load of secondary lining concrete pouring [8]. The supporting rods are densely distributed, resulting in high work intensity and limited vehicle access space [9]. The ideal monthly construction efficiency of the secondary lining can only reach about 180m. In the case of long tunnel construction, it is difficult to keep up with the excavation efficiency of the tunnel face and inverted arch, affecting the overall construction progress of the tunnel [10].

Given the mismatch between the tunnel lining construction line, the excavation line of the tunnel face, and the inverted arch construction line, traditional secondary lining trolleys cannot meet the comprehensive efficiency of tunnel construction [11]. Through improvements to the traditional secondary lining trolley structure, based on the 350km/h high-speed railway tunnel section, this article studies a new type of traversing skeleton-free secondary lining trolley. Innovatively, the supporting role of the gantry during the secondary lining pouring process is eliminated, and the formwork structure is strengthened.

The stability of the structure during secondary lining concrete pouring can be ensured by using the internal rod support of the formwork, expanding the internal access space. The gantry structure and function have been improved, and the gantry function has been changed from bearing the secondary lining concrete load to bearing the formwork's own weight. The gantry carries the formwork forward and allows two sets of formwork to pass through each other, which can effectively accelerate the construction progress of the tunnel's secondary lining, increase the maintenance time of the secondary lining concrete with the formwork, and improve the quality of the secondary lining concrete in alpine regions.

2. Design proposal and key technologies

2.1. Design proposal

The traversing skeleton-free secondary lining trolley mainly consists of traversing formwork (two sets), a carrying gantry, a traveling mechanism, a screw rod assembly, auxiliary structures, a hydraulic system, and an electrical system, as shown in **Figure 1**. The trolley adopts a skeleton-free design, and the traversing formwork can meet the strength and rigidity requirements of secondary lining concrete pouring without additional supporting skeletons. The formwork in the retracted state can be carried by the gantry to pass through another set of formwork in the supporting state, achieving alternating lining construction. The advantage is that the second board lining construction can be carried out without removing the formwork of the first board lining, realizing continuous construction of the secondary lining concrete and improving construction efficiency.

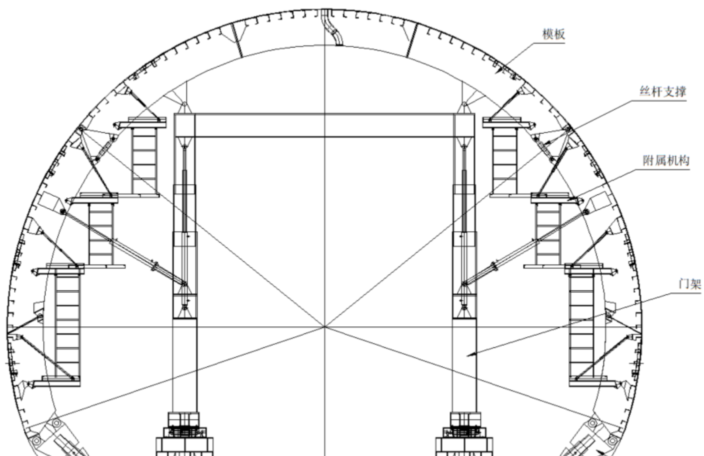

Figure 1. Overall scheme of the traversing type secondary lining trolley without framework (Translation from left to right: Template; Screw support; Auxiliary support; Door frame; Foot support)

2.1.1. Design of the traversing formwork

Compared with traditional formwork, the traversing formwork can bear the load of secondary lining concrete pouring without relying on the gantry, and its internal clearance can allow another formwork in the retracted state to pass through.

There are two sets of traversing formwork with the same structure, which is arched. Each set of formwork includes a top formwork, two shoulder formworks connected at both ends of the top formwork, two side formworks connected below the shoulder formwork, a flipping formwork connected to the side formwork, and bottom foot supports. The shoulder formwork and side formwork are connected in a way that allows the formwork to be extended and retracted. Through the gantry, foot supports, and auxiliary devices, the formwork can be extended and retracted, allowing it to alternately traverse between the formwork and achieve continuous secondary lining construction.

The bottom foot supports are supported on the inverted arch fill layer. During the secondary lining pouring process, it is necessary to strictly control the pouring speed and height difference of concrete on both sides to balance the lateral pressure on both sides of the formwork. The formwork itself has relatively high rigidity, which can transmit the lateral force at the arch waist positions on both sides to the inside, ultimately canceling each other out. The vertical concrete pressure at the arch top position is transferred through the formwork to the bottom screw rod supporting the ground, maintaining the overall stability and rigidity of the structure during the secondary lining pouring process. The schematic diagram of the formwork structure in the working state is shown in **Figure 2**.

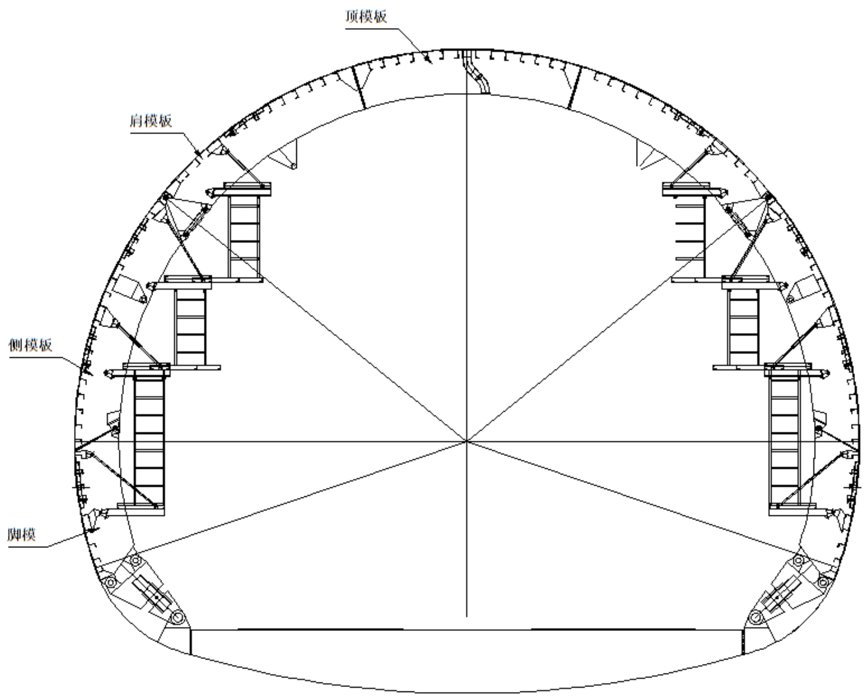

Figure 2. Schematic diagram of traversing formwork structure (Translation from left to right: Foot mold; Side mold; Shoulder mold; Top mold)

2.1.2. Design of the carrying gantry

Compared to traditional trolley gantries, the carrying gantry only bears the weight of the trolley itself and no longer assists the formwork in bearing the casting load. At the same time, it adopts a flexible connection with the formwork, allowing for quick installation and removal.

The carrying gantry employs a large gantry structure that can be raised and lowered separately. It consists of two sets of front and rear columns equipped with large-stroke lifting mechanisms that can operate in tandem or independently. The top of the gantry is equipped with hinged ear seats to support the formwork. The columns are connected by longitudinal beams and truss beams to form an integrated structure, enhancing the overall stability and rigidity of the structure. The lower end of the gantry is equipped with a transverse lifting mechanism and a traveling mechanism, along with a self-feeding track function. The customized track is suspended on the traveling mechanism through supporting wheels. The carrying gantry can be adjusted in the transverse, longitudinal, and height directions, assisting the traversing formwork in actions such as formwork support, formwork removal, and movement. When the formwork deviates from the centerline or during curved tunnel construction, the formwork can be adjusted to the correct position with the help of the gantry's transverse shifting mechanism. The schematic diagram of the gantry structure is shown in **Figure 3**.

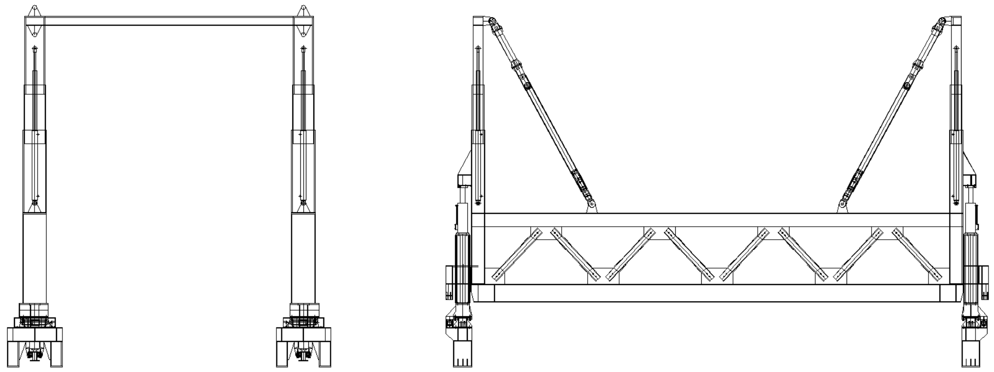

Figure 3. Schematic diagram of the structure of the carrying gantry

2.2. Key technologies

2.2.1. Formwork under-passing technology

Formwork under-passing refers to the process where the formwork in the retracted state passes through and advances under the formwork in the supported state, enabling alternating construction. The main challenge lies in spatial limitations. The external formwork structure of the traversing formwork is divided into three sections: the top form, side form, and flipping form. The formwork adopts foldable platforms and ladders. During formwork support and casting, workers operate on the ladder platform. During the solidification period after casting is completed, the ladder and platform are folded and stored inside the waistboard of the formwork, not occupying internal space. When the other formwork is retracted, the flipping form rotates 160 degrees around the hinged ear, the side form rotates 20 degrees around the hinged ear, and the top form descends 1.8 meters. At this time, the minimum clearance between the outer contour of the retracted formwork and the supported formwork is 21cm, enabling traversal under the carrying of the gantry, as shown in **Figure 4** and **Figure 5**.

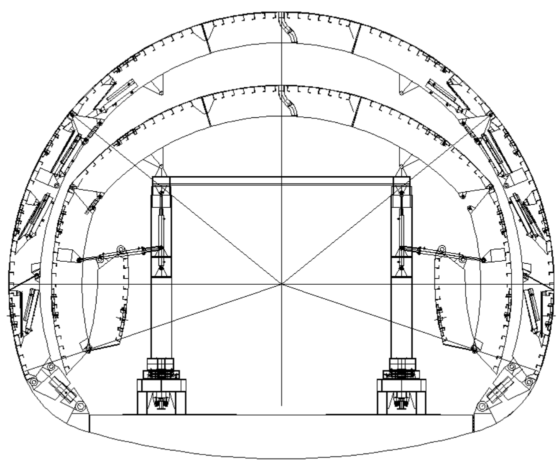

Figure 4. Front view of the gantry carrying formwork passing through

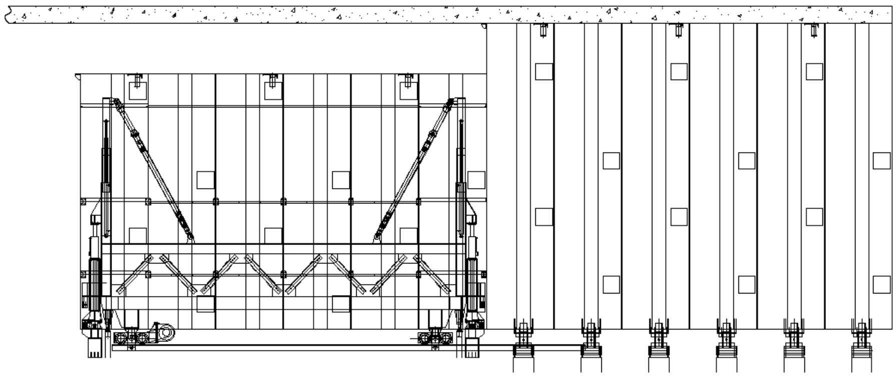

Figure 5. Side view of the gantry carrying formwork passing through

2.2.2. Rapid construction technology

The traversing skeleton-free secondary lining trolley solves the problem of traditional secondary lining trolleys being unable to remove the formwork for the next board lining construction before the concrete strength reaches the standard through continuous construction with two sets of formwork. This greatly improves construction efficiency. The process follows a cyclic sequence: support of formwork 1, concrete casting, retraction and under-passing of formwork 2, support of formwork 2, casting, retraction and under-passing of formwork 1, followed by the next support of formwork 1. The specific steps are as follows:

(1) Formwork 1 forms a stable overall structure through screw rods and hydraulic cylinders, and the connection between the gantry and formwork 1 is released.

(2) Concrete pouring operations for formwork 1 begin.

(3) The gantry travels to the underside of formwork 2 and connects with it.

(4) The side forms of formwork 2 are retracted, and the top form is lowered, reducing the outer contour size to allow traversal within formwork 1.

(5) The gantry carries formwork 2 through formwork 1 to the next secondary lining construction position. The gantry assists in completing the formwork support for formwork 2, as shown in **Figure 6**. After formwork support, the connection between the gantry and formwork 2 is released.

(6) Concrete pouring operations for formwork 2 begin.

(7) After formwork 2 completes the pouring, the gantry travels to the underside of formwork 1 and connects with it, assisting in formwork removal.

(8) The gantry carries formwork 1 through formwork 2 to the next secondary lining construction position. After the gantry assists in completing the formwork support for formwork 1, the connection between the gantry and formwork 1 is released.

By repeating the above operations, the two formworks alternate in traversal, working continuously until the tunnel secondary lining construction is completed.

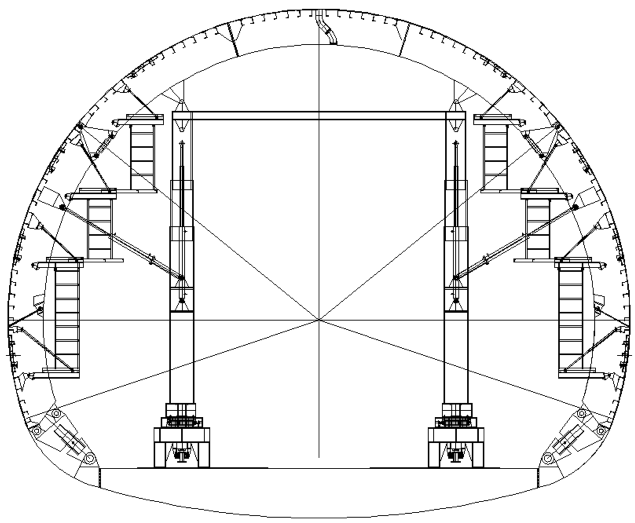

Figure 6. Front view of gantry auxiliary formwork

3. Finite element calculation

3.1. Calculation of mechanical parameters

The design effective lining length of the traversing skeleton-free trolley is 12m, and the thickness of the formwork panel is 12mm. The strength and rigidity of the main stressed components of the trolley are checked to verify whether the mechanical properties of the trolley can meet the requirements of use [12, 13].

(1) Calculate the pressure generated by the concrete on the top formwork. The pressure on the top formwork is mainly lateral pressure, and the effective pressure head height is calculated as shown in Formula (1).

$h = 1.53 + 3.8\, v/T$ (1)

Calculate the maximum lateral pressure generated by the concrete on the top formwork as shown in Formula (2).

$P_1 = \gamma h$ (2)

In the formulas: P_1- The maximum lateral pressure on the top formwork caused by the freshly poured concrete; γ- The volumetric weight of concrete (KN/m^3), γ =24 KN/m^3; T- The temperature of the concrete when poured into the formwork (°C), where T = 20°C in the formula; v- is the concrete pouring speed (m/h). Due to the reduced arc slope during top formwork pouring, the pouring speed is taken as 1m/h. When calculating the side formwork, the concrete pouring speed is taken as 2m/h.

Using Formula (2), the maximum lateral pressure on the top formwork caused by concrete is calculated as P_1 = 41.28 KN/m^2.

(2) The pressure exerted by concrete on the side formwork is shown in Formula (3).

$P_2 = 0.22\, \gamma T \beta_1 \beta_2 v^{1/2}$ (3)

In the formula: P_2-The lateral pressure on the side formwork caused by freshly poured concrete; β_1-Correction coefficient for the influence of admixtures. When no admixture is added, it is taken as 1.0. When adding a retarder admixture, it is taken as 1.2. The influence of admixtures is considered in the calculation; β_2-Correction coefficient for the influence of concrete slump speed. When the slump is less than 30mm, it is taken as 0.85; 50–90mm, taken as 1.0; 110–150mm, taken as 1.15. For calculation purposes, it is taken as 1.15.

When calculating the side formwork load, the impact load P_3 generated by pouring concrete should also be considered, taking P_3 = 4 KN/m^2.

(3) The maximum lateral pressure on the side formwork of the trolley during pouring is calculated as shown

in Formula (4).

$$P_4 = P_2 + P_3 \qquad (4)$$

Using Formula (4), the maximum lateral pressure on the side formwork during pouring is calculated as P_4 =64.4 KN/m^2. The calculated loads are applied as uniformly distributed pressure to the corresponding top and side formwork.

3.2. Analysis of simulation calculation results

When the skeleton-free secondary lining trolley is operating, the formwork relies on its own structure to bear the load of the secondary lining concrete, while the gantry does not bear any load and is therefore not involved in the calculation. **Figure 7** shows the finite element model of the trolley in working condition. The finite element calculation results are shown in **Figure 8** and **Figure 9**, with a maximum stress of 114 MPa and a maximum deformation of 2.5 mm.

The main structural steel of the secondary lining trolley is Q235B carbon structural steel, with a gravity density of 78.5 KN/m^3 and an elastic modulus of 206 GPa. Referring to the "Steel Structure Design Standards" (GB5017-2017), the structural strength safety factor is taken as 1.5, and the allowable stress [σ] is 156 MPa. According to the finite element calculation results, the maximum stress of 114 MPa during the trolley's working state is less than the allowable stress [σ], indicating that the strength meets the design requirements. The maximum deformation of 2.5 mm also satisfies the design specifications.

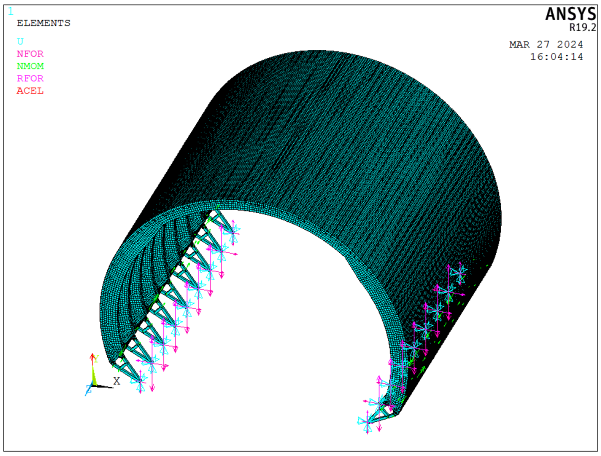

Figure 7. Finite element model of trolley without framework

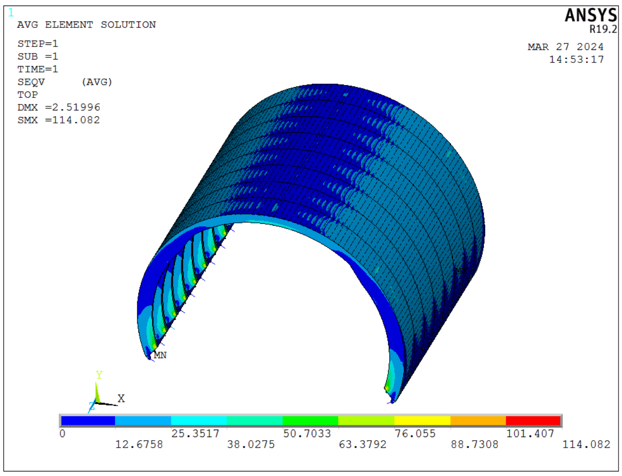

Figure 8. Stress calculation results

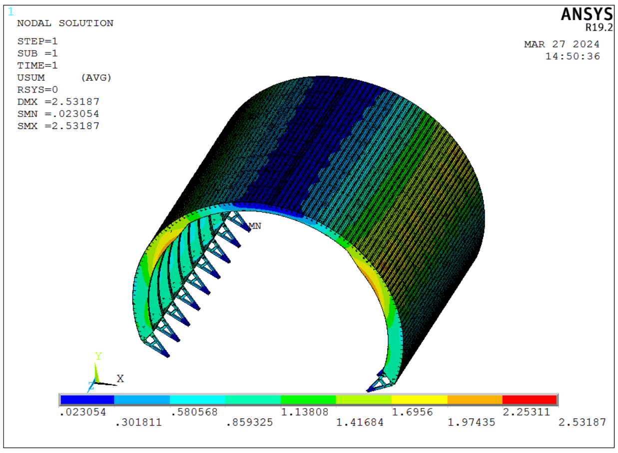

Figure 9. Deformation calculation results

The force models used in the above mechanical analysis process are calculated using simplified methods that tend to be safe. After analysis, each component can meet the force and deformation requirements.

4. Conclusion

Through the application of the traversing skeleton-free secondary lining trolley, continuous operation of the secondary lining can be achieved, enabling dynamic support construction. The efficiency of secondary lining construction has been improved from one form (12m) every two days to one form per day, accelerating the progress of tunnel construction.

By using one set of gantries to transport two sets of formwork for interchangeable and alternating construction, the curing time of the secondary lining concrete with the form can be increased, significantly improving the forming quality of the secondary lining concrete in alpine regions.

The new traversing skeleton-free secondary lining trolley can accelerate the efficiency of tunnel secondary lining construction, help improve the efficiency and quality of tunnel construction, ensure safe step distances during tunnel construction, reduce variable costs, and enhance economic and social benefits.

Disclosure statement

The author declares no conflict of interest.

References

[1] Huang G, 2015, Research on the Application of Arch Wall Separated Trolley in the Second Lining Construction of Large Section Tunnels in Metro Intervals. Railway Construction Technology, 2015(6): 36–39+62.

[2] Yan X, Wu X, Peng W, et al., 2014, Construction Technology of Full-Section Secondary Lining Steel Formwork Trolley for Tunnels. Construction Technology, 2014(13): 114–117.

[3] Luo D, Gao B, Sun T, 2008, Application of Integral Lining Trolley in Railway Passenger Dedicated Line Tunnels. Modern Tunnelling Technology, 2008(06): 88–91.

[4] Lou C, 2022, Research and Application of Construction Technology for Integrated Pipe Corridor Traversing Steel Formwork Trolley. China High-Tech Industries, 2022(24): 34–36+51.

[5] Zhang J, Han G, 2007, Application of Full-Section Lining Trolley in Water Conveyance Tunnel Construction.

Construction Technology, 2007(S1): 191–194.
[6] Chen J, Zhao P, Luo Y, et al., 2023, Field Test on Heat Transfer Characteristics and Temperature Field Evolution Law of Tunnels in Cold Regions. China Journal of Highway and Transport, 2023(8): 190–203.
[7] Xu P, Wu Y, Yan X, et al., 2022, Analysis of Temperature Field and Effectiveness of Insulation Layer in High-Speed Railway Tunnels in Severe Cold Regions. China Railway Science, 2022(04): 64–73.
[8] Lin Q, 2020, Design Concept and Application of Triangular Articulated Tunnel Lining Trolley. Railway Construction Technology, 2020(08): 64–66+75.
[9] Sheng J, 2008, Development of a New Fully Hydraulic Self-Propelled Tunnel Lining Trolley. Journal of Shijiazhuang Tiedao University (Natural Science Edition), 2008(03): 86–89.
[10] Zhang G, Tang B, Chen Z, et al., 2024, Research on Key Technologies of New Digital-Intelligent Integrated Tunnel Lining Trolley. China Water Transport (Second Half Month), 2024(1): 131–133.
[11] Li L, Wang P, Yang J, 2022, Design and Optimization Analysis of Large-Span Variable Cross-Section Tunnel Lining Trolley. Railway Construction Technology, 2022(02): 48–52.
[12] Liu S, Zhang H, Zhu F, et al., 2021, Load Calculation and Numerical Simulation of Secondary Lining Trolley. Journal of Hunan University of Technology, 2021(02): 7–14.
[13] Liu X, Huang G, Cheng C, 2019, Optimization Analysis of Tunnel Lining Trolley Formwork Structure. Construction Machinery, 2019(10): 37–39+4.