

Numerical Simulation Study of Midas-Based Tunnel Section Structural Forces and Deformations

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Abstract. The burial depth significantly influences the structural forces and deformations of tunnel sections, playing a crucial role in the safe operation of tunnels. This study focuses on the structural design and deformation analysis in underground tunnel engineering. Utilizing Midas modeling techniques, tunnel models were designed for experimentation to comprehensively explore the impact of tunnel burial depth and key design parameters on structural deformations and safety.(1) The research reveals that design parameters such as tunnel diameter are the dominant factors affecting deformation, lining pressure, and structural displacement.(2) With an increase in tunnel diameter, substantial deformation occurs, and the lining pressure distribution evolves from a "fan-shaped" pattern to a "peach-shaped" pattern. The bottom structure transitions from uplift to slight settlement. (3) The study results provide a rational range of parameter values for tunnel design. Simulation outcomes highlight areas with higher deformation, offering insights for proposing corresponding remedial measures.

Keywords: Tunnel Engineering, Railway Tunnel, Tunnel Bottom Uplift, Midas Modeling Techniques, Virtual Simulation Model Testing.

1. Introduction

The study of the force and deformation of tunnel structures is of great significance for the sustainable development and safe operation of underground tunnel engineering in China. With the flourishing development of China's high-speed infrastructure construction, underground tunnel engineering, as a crucial component, faces diverse geological conditions, hydrological characteristics, and traffic operation demands. In light of various challenges such as different rock types, periodic fluctuations in groundwater levels, ecosystem protection, and traffic operation factors, in-depth research on the force characteristics of tunnel structures becomes crucial. This research aims to provide theoretical and practical support for engineers to adapt to the complex geological conditions and changing environmental requirements of tunnel design. Through a comprehensive exploration of tunnel force characteristics, we hope to offer effective technical solutions for tunnel engineering, ensuring stable operation under various conditions and promoting advancements in the field of underground tunnel engineering in China. Lu [1] used Midas modeling and FLAC3D numerical simulation software to simulate the tunnel stress and strain characteristics under the excavation methods of three benches and reserved core soil in order to comprehensively evaluate the applicability of the bench method and reserved core soil method for the construction of the Xigeda Tunnel. It was determined that the reserved core soil method is more favorable for tunnel construction. Ji [2], based on examples of shallow-buried tunnel engineering, established a finite element model to analyze the force situation of the tunnel and proposed deformation and failure handling measures. Teng [3] conducted research on the lining internal force and seepage pressure under the conditions of drainage and seepage prevention in hidden water-rich karst tunnels. Using the Midas finite element software, the tunnel's fluid-structure coupling model was simulated under different drainage conditions, analyzing the variation patterns of the internal forces in the second lining and the external water pressure on the lining. Ruan [4] established a three-dimensional refined numerical calculation model for subway shield tunnel structures and explored the force evolution mechanism of subway shield tunnel segment structures under the action of surface loading. The correctness of the simulation

results was validated by analytical theory, and the relevant research can further support the clarification of the mechanical response characteristics of subway shield tunnel structures under temporary and sudden surface loading. Wang [5], based on the Yangcheng Tunnel of the Haoji Railway, analyzed the force characteristics of support structures and safety of tunnel structures in fully weathered red sandstone formations. Using a combination of field measurements and numerical simulation methods, the internal force characteristics of the tunnel structure were studied. The research results can provide reference for the construction of tunnels in fully weathered red sandstone and similar formations. Ramón Argüelles-Fraga [6] employed ground laser scanning and optimized the method of scanning cross-sections of the tunnel. Representing objects in the form of point clouds, this method quickly, reasonably, and accurately captures the three-dimensional surface within a range of tens to hundreds of meters. The study determined the maximum scanning distance and angular sampling interval to achieve the predetermined tunnel geometric accuracy level while minimizing working time.

Tunnel structure research has made significant progress both internationally and domestically. Domestically, the focus is on engineering practices and regulatory adaptability due to the complex and diverse geological conditions. Finite element analysis combined with specific examples is commonly used to comprehensively analyze and verify the structural strength and stiffness [1-3], with a specific focus on the deformation [4, 7-8] and safety [5, 9-10] of support structures. International research emphasizes simulation analysis [11], utilizing simulation software combined with on-site data collection techniques to recreate tunnel conditions [6, 12]. Simulation analysis of models focuses on optimizing the design of tunnel support structures to enhance construction safety and reliability [13-14]. In summary, both domestic and international research directions play important roles. Internationally, there is a focus on the electronic simulation of tunnel research [15], while domestically, the emphasis is more on adapting solutions to address practical engineering problems in local conditions.

This study focuses on the in-depth analysis of tunnel cross-section structures during the process of force application, utilizing MIDAS software for the first time. By establishing accurate numerical models, the research investigates the impact of external factors such as surface loads, fluctuations in groundwater levels, and seismic events on tunnel structures. The findings of this study will provide a scientific basis for tunnel design and construction, enabling the optimization of structural design and enhancing the safety and stability of engineering projects. Ultimately, this research aims to contribute to the advancement of the tunnel engineering field.

2. Model establishment

2.1. Model size

This is a horseshoe-shaped tunnel with an excavation span of 14.58 meters and a height of 12.24 meters. A composite lining support scheme is employed, with the initial support structure consisting of a 28 cm thick C25 shotcrete to ensure the stability of the structure.

The cross-sectional shape of the tunnel is horseshoe-shaped, and the initial support structure, through shotcrete, provides the necessary support Figure 1.

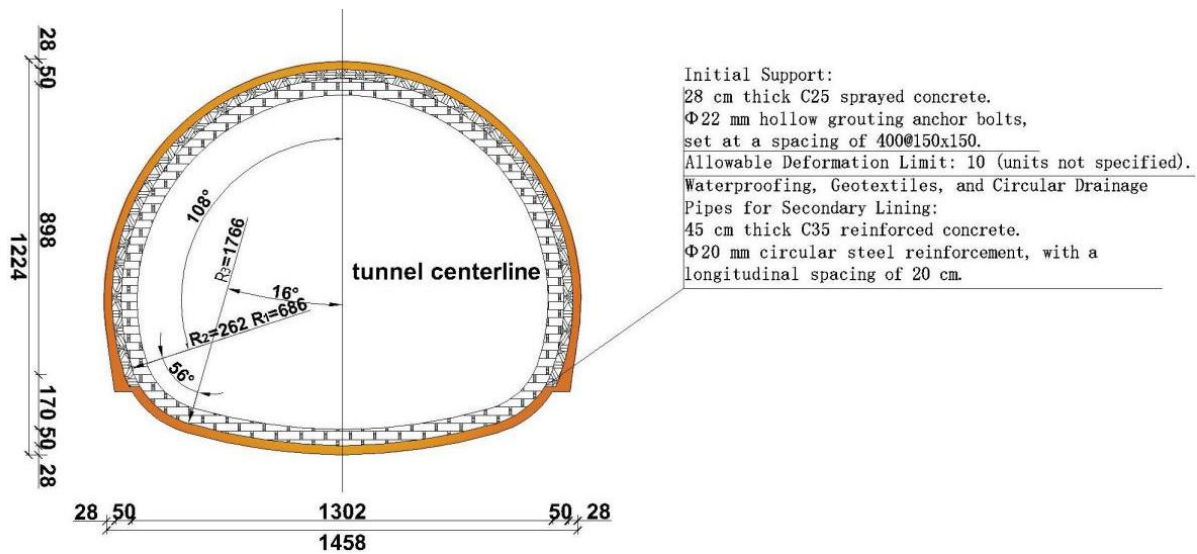


Figure 1. Schematic Diagram of Tunnel Cross-Section Dimensions

Through multiple engineering cases, it has been found that in the stability analysis of tunnel cross-sectional structures, the drainage system and the rail system do not significantly influence the deformation of the tunnel cross-section. Therefore, the model is simplified during the modeling process. A tunnel cross-section is created with a unit length of 50 cm along the y-axis.

Research results indicate that establishing the model with the boundary condition at the bottom of the center of the tunnel arch in the tunnel cross-section yields relatively accurate simulation results. The schematic representation of the model boundary range is shown in Figure 2.

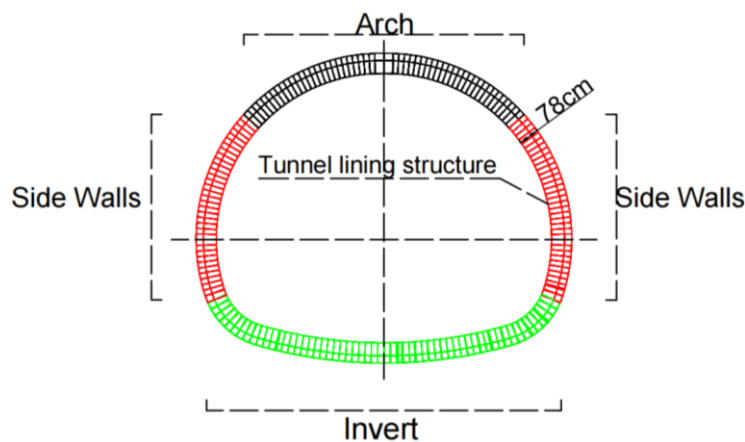


Figure 2. Model Structure diagram

The article adopts a spatial finite element analysis model, which is a three-dimensional finite element model.

(1) Import the pre-processed tunnel cross-section lines from the CAD program, ensuring that all geometric model segments are continuously closed.

(2) Define materials based on the actual tunnel initial lining and concrete structure as C25 and C30 strength concrete, respectively.

(3) Define the initial lining cross-section as 50cm × 50cm, and the concrete frame section as 28cm × 50cm.

(4) Set boundary conditions, determining the lowest point of the arch as the only support.

(5) Since the tunnel cross-section forces have been simplified to uniformly distributed loads in the upward, downward, left, and right directions, establish a pre-loading model for each direction to assign different load values.

(6) After assigning loads for each condition, run finite element analysis to obtain results for the model's stress analysis. Isolate deformation results and force results to obtain two separate analyses.

(7) Add new uniformly distributed load conditions, update the analysis results, and solve.

2.2. Model Loads

In terms of loading conditions, equivalent fixed uniformly distributed loads were applied to simulate external loading conditions at different depths. The load magnitudes were 40, 80, 120, and 160 kPa, uniformly distributed in all four directions of the tunnel, to simulate surface loads at different depths.

Finally, a static analysis was conducted on the tunnel to assess the structural static response under various loading conditions. This helps evaluate whether the structure is robust enough to withstand different external loading conditions. Overall, the tunnel structure has been carefully designed and analyzed to ensure its stability and reliability under various operational conditions.

3. Results Analysis

3.1. Deformation Analysis of the Tunnel

Through numerical simulations, the deformation behavior of the tunnel cross-section model was investigated under loading conditions of 40, 80, 120, and 160 kPa. The simulation results reveal that, with increasing loads, the deformation in the central portion of the tunnel becomes progressively significant, primarily influenced by structural loading factors.

Under a 40 kPa load, the tunnel structure may exhibit relatively small deformations. However, as the load increases to 80 kPa, the tunnel cross-section begins to deform noticeably, manifesting as slight compression or displacement. At 120 kPa, the deformations further increase, leading to significant changes in the cross-sectional shape. Under the maximum load of 160 kPa, the tunnel cross-section experiences pronounced deformation, including compression or other forms of damage.

The main cause of these deformations lies in the fact that the applied loads exceed the structural bearing capacity, resulting in various deformation forms such as compression and damage. Therefore, in tunnel design, it is essential to thoroughly consider structural loading factors, including load-bearing capacity and structural strength, to ensure the stability and safety of the tunnel structure under different loading conditions.

As illustrated in Figure 3, during the numerical simulation of deformation, the overall external framework of the tunnel evolves gradually from a 'peach' shape to an 'elliptical' shape, with stress concentrating in the upper-middle portion. As the load increases, the structure exhibits a progressively enlarging trend of deformation. Under a 40 kPa load, the deformation of the tunnel cross-section is relatively small. However, when the load increases to 80 kPa, the structure begins to show noticeable deformation, including slight compression and displacement. Under high loads of 120 kPa and 160 kPa, the deformation further increases, potentially leading to significant changes in the structural shape, and even compression, distortion, and damage may occur.

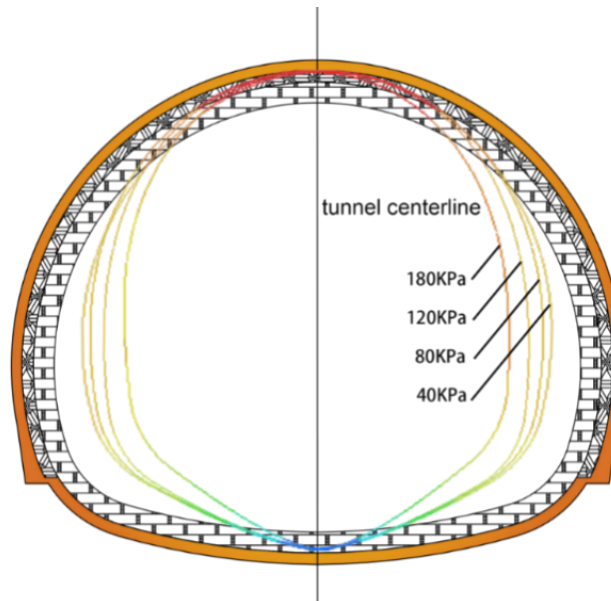


Figure 3. Tunnel Cross-Section Deformation Profile

3.2. Tunnel stress

In the simulation experiment, four different external load values were selected, namely 40, 80, 120, and 160 kPa, to simulate the stress conditions of the tunnel structure at different depths corresponding to different loads. A typical tunnel structure model with baffles and walls was used in the experiment to observe the variation of stress concentration points.

During the 40 kPa load stage, the primary stress concentration point was observed on the baffles, indicating locally higher stresses on the baffles. Subsequently, as the load increased to 80, 120, and 160 kPa, it was notable that the stress concentration points gradually spread from the baffles to both sidewalls. This led to a relatively uniform stress distribution, with stress values on the sidewalls gradually increasing.

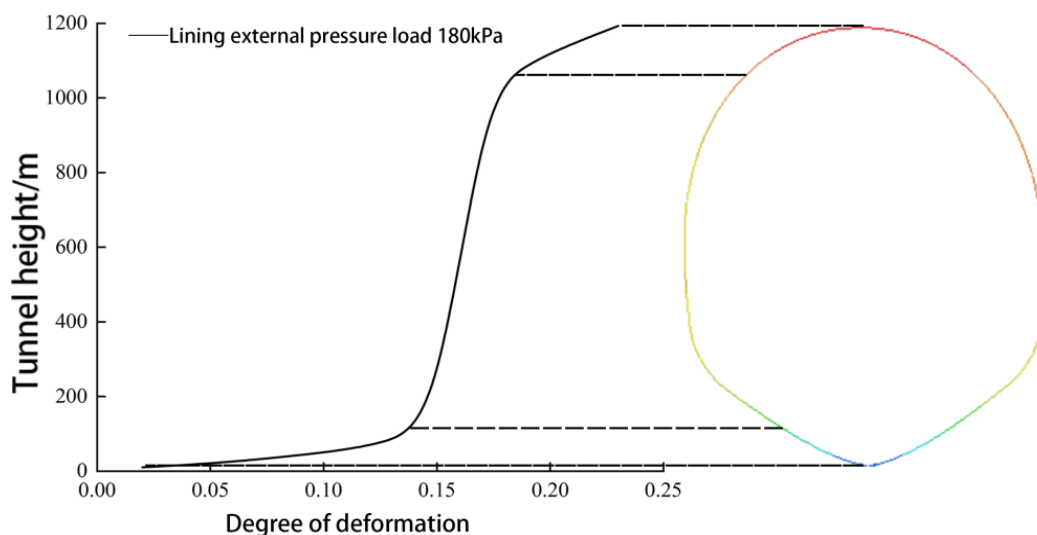


Figure 4. At 160 kPa, simulate the deformation results and its corresponding deformation profile.

As the load gradually increased, the stress concentration points, originally confined to the baffles, began to spread gradually to both sidewalls. Under a 40 kPa load, the stress was primarily localized on the baffles. However, as the load increased to 80 kPa, we observed stress spreading gradually to both sidewalls, as shown in Figure 5, forming a relatively uniform stress distribution. When the load reached 120 and 160 kPa, this phenomenon became more pronounced, with stress concentration

points not only highlighted on the baffles but also rapidly spreading to both sidewalls, resulting in a noticeable increase in stress values on the walls.

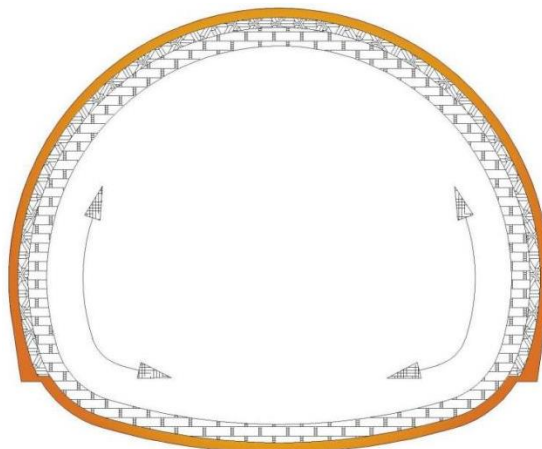


Figure 5. Phenomenon of Side Wall Stress Concentration and Dispersion

In the simulation experiment, during the initial 40 kPa load stage, the primary stress concentration was observed on the baffles, leading to locally higher stresses on the baffles. In the subsequent 80, 120, and 160 kPa load stages, it was observed that the stress concentration gradually spread from the baffles to both sidewalls, forming a relatively uniform stress distribution, with stress values on the sidewalls gradually increasing.

4. Conclusion

Simplifying the tunnel as an elastic foundation beam and representing the load as a trapezoidal load simplifies the complex underground structural problem into a more manageable elastic mechanics problem. This approach reduces the complexity of theoretical analysis.

Simulation experiments indicate that, with an increase in external load, stress concentration points in the tunnel structure gradually shift from the baffles to both sidewalls. This phenomenon suggests a significant alteration in stress distribution under high load conditions, impacting the overall stability and safety of the structure. Therefore, when designing tunnel structures, it is crucial to consider stress distribution under different load conditions and optimize the design of structurally vulnerable areas prone to stress concentration, aiming for a rational stress distribution.

Numerical simulations reveal that the primary deformation trend of the tunnel cross-section is significantly influenced by structural loading factors. As the load increases, the structure may surpass its bearing capacity, leading to pronounced compression, distortion, and damage. Therefore, prioritizing an understanding of structural loading characteristics is paramount in tunnel design, ensuring stability and safety under various loading conditions.

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