Journal of Architectural Research and Development, 2025, Volume 9, Issue 3
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Design Strategies for Roadbed and Pavement Based on the Goal of Green Highway Construction

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Abstract: This article takes the reconstruction and expansion project of the Tianjin section of the Beijing-Tianjin-Tanggu Expressway as an example to systematically explore the design strategies for roadbed and pavement under the goal of green highway construction. During the research, after discussing the goals and policies of green highway construction in Beijing, in-depth research was conducted around the design of protective support engineering, soft foundation treatment, comprehensive utilization of earthwork, drainage systems, and pavement design to explore how the case project can achieve high-quality design based on the goal of green highway construction. It is hoped that this article can provide technical reference and value for China's road and bridge engineering design and construction units, providing a low-carbon practice paradigm for the integration of Beijing-Tianjin-Hebei transportation, while promoting the sustainable development of China's green highway concept.

Keywords: Green highway; Roadbed and pavement design; Protective retaining engineering; Comprehensive utilization of earth and stone

Online publication: May 30, 2025

1. Introduction

The application of green construction technology in highway engineering has two main benefits. Firstly, it contributes to environmental protection by reducing carbon emissions, noise pollution, and water wastage during construction and operation, thereby protecting the ecological environment and biodiversity [1]. Secondly, green highway technology can improve resource utilization efficiency during the construction phase, such as adopting renewable materials and energy-saving technologies to reduce resource consumption and energy costs. Therefore, overall, exploring green highway construction in highway engineering and conducting roadbed and pavement design guided by the goal of green highway construction has significant implications for promoting sustainable development in China's road and bridge engineering [2].

2. Goals and policy background of green highway construction

2.1. Construction goals

2.1.1. Incorporating ecological concepts

The primary goal of green highway construction is to incorporate ecological concepts into the project, minimizing the negative impact on the natural environment. For example, using permeable pavement and low-fill, shallow-excavation techniques to enhance rainwater infiltration and groundwater recharge capabilities, while effectively reducing the amount of earthwork and minimizing changes to the terrain and landforms caused by highway construction. This approach also protects soil structure and existing vegetation [3].

2.1.2. Resource intensification and recycling

In addition to reducing environmental damage, green highway construction emphasizes the efficient utilization of resources [4]. For example, during the design phase, it is essential to specify the use of recycled aggregates and industrial waste residues as substitutes for traditional materials in the construction stage. This approach effectively reduces energy consumption and pollution associated with material production while enabling the utilization of waste resources.

2.1.3. Energy conservation, emission reduction, and low carbonization

The third objective of green highway construction is energy conservation, emission reduction, and low carbonization. This involves actively applying advanced energy-saving design techniques, dust control measures at construction sites, and other related technologies during the design and construction processes. These efforts aim to reduce energy consumption while effectively controlling various types of pollution generated during construction, thereby minimizing negative impacts on the lives of surrounding residents. Simultaneously, improving the overall carbon sequestration capacity of highways through measures such as planting carbon-absorbing vegetation in green belts effectively improves air quality and reduces greenhouse gas emissions [5].

2.2. Policy background

In September 2019, the Central Committee of the Communist Party of China and the State Council issued the “Outline for Building a Strong Transportation Country,” which clearly proposed the establishment of a safe, convenient, efficient, green, and economical modern integrated transportation system. With the promulgation of policies in Beijing, green highways have become a crucial aspect of achieving “green transportation” in China. In 2020, the “dual carbon” goals were introduced, setting requirements for accelerating the low-carbon transformation in the transportation sector, specifically focusing on reducing emissions and energy consumption through green technologies. In 2021, the State Council issued the “Development Plan for the 14th Five-Year Modern Integrated Transportation System,” urging highway construction enterprises to actively promote green highway construction technologies and enhance resource recycling levels. Additionally, the plan set a target for newly built expressway projects to have a green highway proportion of at least 80%. In the context of these policies, national transportation authorities and local governments across the country have issued technical guidelines for green highway construction, such as the “Technical Guidelines for Green Highway Construction” and the “Guidelines for Carbon Emission Accounting in Expressway Construction,” further advancing the progress of green highway development.

3. Research on roadbed and pavement design based on the goal of green highway construction

3.1. Project overview

The Beijing-Tianjin-Tanggu Expressway, as the first highway in China approved for construction by the State

Council, is also the first inter-provincial highway in the country, with a total length of 142.69km. It starts at Shibalidian in Chaoyang District, Beijing, and ends at Hebei Road, Binhai District, Tianjin, spanning 35.075km in Beijing, 6.707km in Hebei Province, and 100.908km in Tianjin. According to predictions by relevant departments, the long-term traffic volume of the Beijing-Tianjin-Tanggu Expressway will reach 220,000 pcu/d by 2045, which will require at least 3 expressways (including the existing Beijing-Tianjin-Tanggu Expressway) to share the load, with each expressway requiring a design of 8 lanes or more. To cater to the increase in highway traffic volume in the future and further implement the Beijing-Tianjin-Hebei coordinated planning, promoting the integration process of Beijing-Tianjin-Hebei, it has been decided to expand and renovate the Beijing-Tianjin-Tanggu Expressway. This article takes the green highway design project of the Beijing-Tianjin-Tanggu Expressway (Tianjin Section) reconstruction and expansion project (hereinafter referred to as the Tianjin Section Reconstruction and Expansion Project) as an example to conduct in-depth research on the roadbed and pavement design under the goal of green highway construction.

3.2. Protective retaining engineering design

During the design of the protective retaining works for the Tianjin Section Reconstruction and Expansion Project, the design unit adhered to the four principles of safety, economy, environmental protection, and aesthetics. By actively combining biological and engineering techniques during the design process, the goal was to create a green highway that integrates engineering functionality and ecological visuals. The slope protection design of the project emphasizes the synergy between biological and engineering measures. Based on the project requirements and environmental characteristics, the design unit adopted the following innovative protection scheme [6].

Firstly, the roadbed protection design mainly focuses on vegetation cover, selecting drought-tolerant and pollution-absorbing plants suitable for the local climate and soil, such as clover. Using these plants to build a biological protection system not only has strong economic and environmental benefits but also enables the roadbed to have good soil and water conservation capabilities and landscape beautification effects. For the design of engineering protection, when the slope height exceeds 5m, a prefabricated, diamond-shaped, frame vegetation structure is used. The diamond-shaped frame is assembled from prefabricated parts, and then the soil and vegetation are filled into the frame to improve slope stability and promote ecological effects.

Secondly, for the protection of filled sections with large water ponds and pits, M10 mortar masonry technology with a thickness of 35cm is adopted, aiming to provide superior drainage and anti-scouring capabilities for the slopes [7]. The overall height of the slope protection requires the sum of wave attack, backwater height, and safety height to be greater than or equal to 0.5 meters, ensuring that the protection strategy meets the protection needs under different hydrological conditions.

Finally, for land-constrained road segments, the project adopts balanced weight retaining walls, cantilever retaining walls, and lightweight soil panel solutions for the retaining design. The balanced weight retaining wall can resist external pressure with its own weight. During the design process, the main consideration is the depth and bearing capacity of the pile foundation, and a design standard of 20KN/m² is used to ensure the stability of the structure. The cantilever retaining wall adopts a reinforced concrete frame structure, which utilizes the cantilever principle to provide good deformation resistance and strength in a limited space. The lightweight soil panel scheme uses special materials to meet strength requirements, improve construction convenience, and promote the improvement of the overall lightweight level [8].

3.3. Soft foundation treatment and comprehensive utilization design of earthwork

3.3.1. Soft foundation treatment design

The reconstruction and expansion project of the Tianjin section features numerous soft soil foundation segments from the starting point to the K112 segment. Specifically, the K41 + 840 to K91 + 700 segment includes 7 sections of soft soil foundation, the K99 + 400 to K103 + 100 segment has 3 sections of soft soil foundation, the entire K107 + 231 to K122 + 731 segment is composed of soft soil foundation, and the entire K112 + 731 to K138 + 600 segment is also soft soil foundation. **Table 1** below outlines the distribution of soft soil in the reconstruction and expansion project of the Tianjin section:

Table 1. Distribution of soft soil in the reconstruction and expansion project of the Tianjin Section of the Beijing-Tianjin-Tanggu Expressway

Pile number	Distribution quantity	Total length	Characteristics of soft soil distribution
K41 + 840 – K91 + 700	7 sections	37.08km	(5) Layer 1 is widely distributed; (6) Layer1-1 clay has high compressibility, large void ratio, long consolidation time, and low bearing capacity
K99 + 400 – K103 + 100	3 sections	2.1km	(6) Layer14 muddy soil has a diamond-shaped distribution, large void ratio, high compressibility, a long consolidation time, and low bearing capacity
K107 + 231 – K122 + 731	1 sections	5.5km	(3) Layers 3 and (6)12u muddy soil are sporadically distributed
K112 + 731 – K138 + 600	1 sections	25.95km	(6) Layer 2 muddy soil is continuously distributed; (3) Layers 3 and (6) 12 muddy soil are sporadically distributed

Meanwhile, the project team proposed clear settlement control standards for the reconstruction and expansion project of the Tianjin section, namely, within the 15-year designed service life of the pavement, the post-construction settlement standards should meet the requirements of ≤ 15 cm for general road segments, ≤ 5 cm for bridge embankments, and ≤ 10 cm for passageways and culverts.

For soft foundation treatment, after joint research with the design unit, the project team decided that for general widening sections, when the subgrade fill height does not exceed the treatment limit, no control measures would be taken. The old subgrade would be excavated and cleared, and a 50 cm-thick crushed stone cushion would be set within the widening range. A layer of geocell would be used to isolate groundwater and achieve ground consolidation and drainage. When the subgrade fill height exceeds the treatment limit, CFG piles would be used. For noise-sensitive areas and space-limited areas, high-pressure jet grouting piles would be used, and the pile spacing and length would be determined based on the working conditions, adopting a rectangular arrangement [9].

In addition, for positions with higher subgrade fill heights in general widening sections, such as high-fill subgrades, bridgeheads, or areas with deep soft soil, PHC high-strength prestressed concrete pipe piles would be used with a pile diameter of 40 cm. The piles would also be arranged in a rectangular pattern. A 50 cm-thick graded crushed stone cushion would be set at the pile top, and a layer of geocell would be installed in the middle. For the treatment of soft soil foundations at bridgehead transition sections and culvert passageways, the spacing of piles at the culvert location would be densified, and the pile length would be appropriately increased. For bridgehead transition sections, it is required to maintain the same height as adjacent subgrades, and lightweight soil would be used for backfilling at the bridgehead to form a variable stiffness road-bridge transition. For newly built bridgeheads and culvert passageways in the interchange area, the pipe piles within 50 m of the newly built bridgehead and 30 m of the culvert would be treated with variable pile lengths in two sections.

3.3.2. Comprehensive utilization design of earth and stone

During the design phase of the Beijing-Tianjin-Tanggu Expressway Tianjin Section Reconstruction and Expansion Project, the design unit and the project unit jointly planned a reasonable earthwork extraction and transportation scheme for the comprehensive utilization of earth and stone. Regarding the selection of earthwork extraction sites, based on the "Tianjin Land Remediation Planning (2021–2035)", they chose to extract earth from non-farmland areas such as low-efficiency farmland and wasteland, strictly avoiding ecological red lines such as wetlands and water conservation areas. For earth transportation routes, GIS and BIM technologies were utilized to maximize the shortening of transportation routes, effectively reducing carbon emissions. For inferior soil, the design required lime mixing improvement, utilizing indoor geotechnical tests to determine soil properties. The improvement targeted clay and silty soil with insufficient bearing capacity and high water content. Subsequently, the lime content was determined based on the soil test results, and a forced mixer was used for dry mixing to effectively control the uniformity of the lime and soil mixture. After improvement, it was expected that the CBR value of the original soil could be increased from 3%~5% to 8%~10%, meeting the requirements specified in the roadbed filling specifications. Additionally, for the comprehensive utilization of earth and stone, the project team prioritized the use of construction waste such as demolished abutments and beam slabs from the reconstruction and expansion phase. After crushing treatment, these materials were used as roadbed filling and blind ditch materials, implementing the goal of low-carbon roadbed construction [10].

3.4. Drainage system design

During the early design phase of the drainage system for the Beijing-Tianjin-Tanggu Expressway Tianjin Section Reconstruction and Expansion Project, trapezoidal soil drainage ditches were used for the old road, with a depth and bottom width of 1.0 m and a slope ratio of 1: 1.5 for the ditch walls on both sides. Through investigation, it was found that the drainage ditches on both sides of the old road had issues of interruption and discontinuity, resulting in a significantly fragmented drainage system. Additionally, many road segments did not have drainage outlets, and the main form of drainage was concentrated on infiltration and evaporation. Some road segments also had problems of external water intrusion into the drainage ditches. Based on these existing issues, a reconstruction plan for the old road drainage system was designed. Firstly, for surface water on the road, a 2% cross slope was utilized to converge the water to both shoulders. Then, a drainage system integrating water barriers, chutes, and drainage ditches was adopted to transport the surface runoff to the outlets. Secondly, a 2-in-1 discharge strategy was implemented for the outlets, utilizing both external drainage channels and pump houses set up at channel locations for pumping and drainage. The first scheme was primarily used during the construction phase, with a requirement that the spacing between each outlet of the drainage ditches along the highway should be ≤ 500 m. Finally, for general road segments with a longitudinal slope of < 0.5 %, chutes were set every 25 m, and for those with a longitudinal slope of ≥ 0.5 %, chutes were set every 35 m. For the bottom of concave vertical curves, a chute was set at the lowest point, and additional chutes were set 3 m to 5 m away on both sides.

Regarding roadside drainage, after comparing three schemes: decentralized drainage, shoulder water barrier + chute, and shoulder drainage ditch + chute, the water barrier + chute scheme was finally selected. For the drainage design of the median strip, the original greenery was removed and the median strip was fully enclosed and retrofitted with an anti-glare net to achieve anti-glare.

3.5. Pavement design

In terms of pavement design, the theoretical program of the multi-layer elastic system (under the action of double-circle vertical uniform load) was used to calculate the mechanical response of design indexes for both the West and East sections of Tianjin in this project. Control parameters such as low-temperature cracking of seasonally frozen soil pavement, vertical compressive strain at the top of the subgrade, and fatigue cracking of the asphalt mixture layer were considered. A comprehensive design was carried out for the thickness, materials, and subgrade improvement of the asphalt pavement structure. For asphalt concrete pavement, a biaxial load design axle load (single axle 100KN) was used, while a single-axle load was used as the standard axle load (single axle 100KN) for cement concrete pavement. The newly built asphalt concrete widening sections of the main highway were designed for a service life of 30 years, and the original pavement was designed for a service life of 15 years. Cement concrete pavement was designed based on a 30-year design benchmark. Additionally, during the pavement design phase, the project team attached great importance to the utilization of the old pavement, fully leveraging the remaining value of the existing old pavement. They emphasized the recycling of old materials and ecological protection, striving to minimize longitudinal reflection cracks at the joint between new and old pavement while eliminating existing diseases of the old pavement.

4. Conclusion

Based on the research on the subgrade and pavement design of the Beijing-Tianjin-Tanggu Expressway Tianjin Section Reconstruction and Expansion Project, this article summarizes a green highway design paradigm that integrates "ecological priority, resource conservation, and technological innovation". This paradigm includes multi-dimensional designs such as protective retaining works, soft foundation treatment, and comprehensive utilization of earth and stone. Road and bridge engineering design and construction units can refer to the design ideas and achievements of the Tianjin Section Reconstruction and Expansion Project to actively promote the achievement of green highway construction goals. This not only aligns with social and national development requirements but also establishes a green corporate image, effectively promoting the sustainable development of enterprises and the industry.

Disclosure statement

The author declares no conflict of interest.

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