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Design Strategies for Complex Mountain Highway Bridge

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Abstract: This article discusses the design strategy of complex mountain highway bridges. During the research phase, details were obtained based on prior literature review and analysis of engineering materials from mountainous area bridges. After analyzing the design characteristics of complex mountainous area road and bridge projects, the principles for the design of bridges on complex mountainous area expressways were proposed. The research on bridge design was carried out from five dimensions: bridge type selection, foundation design, superstructure design, connection part design, and material and technological innovation. Eventually, a relatively complete design system was formed. It is expected that this paper can provide technical references and value for road and bridge projects in China and promote the sustainable development of China's road traffic system from a macro perspective.

Keywords: Complex mountainous area; Bridge design; Bridge type selection; Superstructure

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1. Introduction

Driven by the development of economic construction, the scale of China's transportation routes continues to expand, effectively realizing the resource interoperability of urban and rural areas, and the mileage of highways constructed in complex mountainous areas is also expanding [1]. However, during the design of highway bridges in complex mountainous areas, design units often need to face the challenges of complex terrain, geological conditions and ecological protection. Therefore, exploring the design strategy of highway bridges in complex mountainous areas is a high-value study to further improve the design level of highway bridges, meet the demand for resource exchange between mountainous areas and towns, and ensure the durability of bridges [2].

2. Design characteristics of road and bridge engineering in complex mountainous areas

Due to a series of special factors such as geological conditions, topography, landforms and climate environment, the road and bridge projects in complex mountainous areas have three distinct features during the design period: emphasizing terrain adaptability, geological complexity and ecological protection design.

2.1. Emphasize terrain adaptability

The terrain in complex mountainous areas is highly undulating and has significant elevation differences. In the design of road and bridge projects, great importance must be attached to the adaptability to the terrain. During the route planning stage, it is necessary to fully consider the trend of the mountains, the distribution of the valleys and the course of the rivers. Meanwhile, to effectively overcome terrain obstacles, reasonable measures such as line extension design should be adopted. By extending the line length and other forms, the slope of the longitudinal slope can be effectively reduced to ensure the safe passage of pedestrians and vehicles.

2.2. Emphasize geological complexity

Complex mountainous areas are characterized by variable and complex geological conditions, which pose huge challenges to the design of road and bridge projects. For example, the geological features of caves and dark rivers under the karst geomorphology area may lead to the instability of bridge foundations, roadbed collapse or even cause landslides and mudslides. Therefore, detailed ground investigation and risk assessment should be carried out during the design period, and reasonable reinforcement and support measures should be selected based on the ground investigation materials and risk assessment results to improve the stability [3].

3. Design principles for expressway bridges in complex mountainous areas

3.1. Safety

When conducting the design stage of expressway bridges in complex mountainous areas, safety is the primary consideration. The mountainous terrain is complex and geologically variable, and natural disasters such as earthquakes, mudslides and landslides may exist in some areas. The complex mountainous environment requires that the structural design of expressway bridges must have sufficient strength, rigidity and stability. Based on detailed geological exploration materials, the underlying structure and geotechnical mechanics parameters should be mastered.

3.2. Balancing economy and environmental protection

In the design of highway bridges in complex mountainous areas, while ensuring design quality, economic and environmental considerations must also be taken into account. Efforts should be made to optimize the design plan and reduce construction costs by rationally selecting building materials and construction techniques.

Meanwhile, during the bridge design phase, the requirements for environmental protection in mountainous areas should be fully considered. The impact of site selection and design on natural vegetation and wildlife habitats should be minimized as much as possible. Moreover, construction techniques such as retaining walls should be reasonably utilized to prevent soil erosion, achieving a balance between engineering economic benefits and environmental protection benefits [4].

3.3. Adequate consideration of accessibility for post-maintenance and reinforcement

The environment where complex mountainous highway bridges are located is extremely harsh, and the accessibility of subsequent maintenance and reinforcement work is of vital importance. Therefore, during the design of the bridge, sufficient space should be reserved for later maintenance and reinforcement to ensure that the maintenance and inspection teams can easily reach the key maintenance areas such as the bridge piers, beams, and fabrication processes of the bridge during the later maintenance and repair stages [5].

4. Research on design strategies of expressway bridges in complex mountainous areas

The design of highway bridges in complex mountainous areas focuses on the selection of bridge types, foundation design, upper structure design, connection part design, as well as the innovation of similar materials and technologies to enhance economic benefits and construction quality.

4.1. Bridge type selection

When conducting highway bridge design in complex mountainous areas, the selection of bridge type is of vital importance. To meet the requirements of safety, economy and environmental protection, multiple factors such as topography, geology, hydrology and climate need to be comprehensively considered, and specific forms such as beam bridges and cable-stayed bridges should be reasonably chosen. **Table 1** presents the characteristics and applicable environmental parameters of different bridge types.

Table 1. Characteristics of Different Bridge Types and Applicable Environmental Parameters

Bridge type	Characteristics	Applied environment
Rigid bridge	It has a simple structure, mature construction technology and low cost. It has stable mechanical properties and mainly bears the bending moment caused by vertical loads. The spanning capacity is limited, and it is generally more suitable for small and medium spans.	It is suitable for mountainous sections with relatively flat terrain and good geological condition.
Suspension bridge	It has strong spanning capacity, elegant structural shape and reasonable force-bearing system. The stay cables transfer the load of the main beam to the tower, reducing the burden on the main beam and enhancing the stiffness of the bridge. There are various construction methods, and techniques such as cantilever pouring and cantilever assembly can be selected according to the actual situation.	It is often used in complex mountainous areas spanning large valleys and rivers.
Arch bridge	It has an attractive design and can fully utilize the compressive strength of the masonry materials, thus having a relatively large spanning capacity. Arch Bridges have high requirements for foundations and complex construction techniques.	It is suitable for construction in canyon areas with solid rock foundations in mountainous regions.
Suspension bridge	It has an extremely strong spanning capacity, relies on suspension cables to bear loads, and has unique force characteristics. Suspension Bridges have relatively low stiffness and are prone to vibration under wind loads, thus having high requirements for the wind environment.	It is suitable for mountainous canyons that require extremely large spans.

During the selection of bridge types, the actual conditions of mountainous areas should be fully considered. Seismic performance of bridges should be prioritized in earthquake-prone mountainous areas. In areas with strong winds, special attention should be paid to the wind resistance stability of the bridge structure. In addition, the selection phase needs to weigh the pros and cons in relation to construction conditions and maintenance costs.

4.2. Basic design

During the foundation design period, the geological conditions of the complex mountainous area are extremely complicated, and the geological investigation work needs to be carried out strictly before the design, so as to obtain comprehensive information on the stratum structure, geotechnical parameters, and groundwater level, and provide a solid basis for the foundation design.

4.2.1. Rock foundation

For rocky foundations in mountainous areas, if the investigation results show that the rocks have high strength and good integrity, it is advisable to reasonably expand the foundation to directly transfer the bridge load to the foundation rocks. This form of foundation is easy to construct and less expensive. For example, for hard granite foundations in mountainous areas, open excavation can be used to expand the foundation form, combined with the scientific design of the foundation size and depth to ensure that the foundation is in a highly stable state for a long time [6].

4.2.2. Soft soil foundation

For soft land foundation in mountainous areas, the use of pile foundation is recommended. Pile foundation can transfer the load to the deep stable soil layer and rock, and improve the bearing capacity and stability of the foundation. Under the background of different geological conditions and engineering demands, the injection pile and prefabricated pile can be reasonably selected according to the demand. Among them, the grouted pile technology allows flexible adjustment of the pile diameter and length according to the actual situation on site during the later construction period. Prefabricated piles can improve the construction speed and have the advantage of easy quality control.

4.2.3. Karst areas

For karst areas in mountainous regions, detailed investigation of the distribution of cavities and erosion fissures should be carried out before foundation design, followed by the rational use of treatment measures for traversing cavities, avoiding cavities and filling cavities. For example, long piles can be used to penetrate through the cave, with the pile ends resting on stable bedrock. For smaller caves, the form of grouting and filling can be used to improve foundation stability [7].

4.3. Superstructure design

During the design stage of the upper structure of a complex mountainous highway bridge, designers need to comprehensively consider the span of the bridge, load level, site topography conditions, and the difficulty of subsequent construction, in order to ensure that the structure has good applicability, economy, and safety.

4.3.1. Superstructure design of small and medium-span bridges

For the design of the upper structure of medium and small-span bridges, a prestressed concrete beam bridge form can be adopted. The prestressing technology not only enhances the crack resistance and load-bearing capacity of the beams, but also effectively reduces the cross-sectional size and weight of the beams. For example, “pre-tensioning” or “post-tensioning” can be adopted to produce prestressed concrete hollow core slab girders or T-beams, which are prefabricated in factories and then transported to the site, where construction teams are organized to carry out installation. This structural form not only has mature construction techniques but also enables large-scale production of prefabricated components, effectively reducing construction costs. During the design process, it is necessary to rationally arrange the prestressed tendons and optimize the mechanical performance of the components through precise mechanical calculations.

4.3.2. Design of the upper structure of long-span bridges

For long-span bridges, steel-concrete composite beam bridges can be adopted [8]. The steel-concrete composite beam form combines the tensile strength of steel and the compressive strength of concrete. It features light weight, large spanning capacity, and fast construction speed in the later stage. In complex mountainous areas, steel-concrete composite beam bridges can reduce the number of bridge piers and lower the difficulty of foundation construction. For example, in the design of bridges spanning deep valleys, a combination of steel beams and concrete bridge decks is used. Through shear connectors, the two components can work together to bear the loads from both themselves and vehicle traffic. During the design process, it is necessary to accurately calculate the shear force transfer between the steel beams and the concrete bridge deck, ensuring that the overall performance of the combined structure meets the design requirements. At the same time, the possible impacts of the shrinkage and creep characteristics of different materials on the upper structure should be fully considered.

4.3.3. Consideration of influencing factors

During the design of the superstructure of bridges in mountainous areas, designers need to take into account the impacts brought by various special loads such as temperature changes, seismic actions, and wind loads. On this basis, expansion joints and supports should be reasonably set for the superstructure to ensure that the superstructure can freely adapt to the deformation caused by temperature changes. Meanwhile, designers can conduct wind tunnel tests to conduct in-depth analysis of the impact of wind loads on the bridge structure. Based on the test results, they can optimize the cross-sectional form of the bridge or implement measures such as setting up wind barriers.

In addition, for earthquake-prone areas, seismic isolation and damping techniques should be reasonably added during the design period, such as setting lead-core rubber bearings and dampers for the superstructure to improve the seismic performance of bridges.

4.4. Design of connection parts

As a key node of a bridge, the design quality of the connection part directly affects the overall performance, safety and stability of the bridge. Connection parts usually cover the connections between beams, between beams and piers, and between piers and foundations. The connection methods and technical key points for different parts can be referred to **Table 2**

Table 2. Key points for design of bridge connection parts in complex mountainous areas

Connection points	Technical points
Between beams	Install the prefabricated beams, pour concrete into the reserved grooves of adjacent beams, and make the beams form a whole.
Between beams	Prestressed tendons connect components and beams
Between beam and pier	Select suitable bearings, such as the height of higher piers, the use of vibration isolation bearings (lead rubber, high damping rubber)
Between pier and foundation	Pour the bridge piers and foundations as a whole into one structure
Between pier and foundation	Consider pile arrangement, pile top reaction force and abutment load in the design stage of bearing platform, and reasonably design the size and reinforcement of bearing platform

As shown in **Table 2**, during the wet joint connection stage between beams, considering the inconvenience of transportation, it can be appropriately and reasonably adjusted to a dry joint form. However, the dry joint connection has extremely high precision requirements. During the construction design period, it is necessary to require the construction unit to adopt advanced measuring equipment and provide technical guarantee measures. For the connection between the beam and the pier, the selection of the appropriate bearing is of vital importance. During the design stage, the type of bearing should be reasonably selected based on the specific conditions of the bridge.

At the same time, regular inspection and maintenance are necessary to ensure that the performance of the bearing is good. The connection between the bridge piers and the foundation, whether it is achieved through overall pouring or via the use of a transfer slab, must undergo a thorough technical briefing. This ensures that the construction unit operates strictly according to the drawings, thereby guaranteeing the strength and stability of the connection area.

4.5. Innovation in materials and technologies

In the design of complex mountainous highway bridges, material and technological innovations aim to enhance the performance of the bridges, reduce engineering costs, and ensure that the bridges are better adapted to the complex environment.

4.5.1. Material innovation

In terms of material innovation, at present, the application of high-performance concrete in road and bridge engineering is becoming increasingly widespread. High-performance concrete not only possesses technical advantages such as high strength, excellent working performance and good durability, but also can significantly enhance the service life and load-bearing capacity of bridge structures. In complex mountainous areas, bridges are constantly exposed to harsh conditions over a long period of time, and they have higher requirements for the durability of concrete compared to urban bridges [9]. Therefore, during the design stage, the impermeability, erosion resistance, frost resistance and other properties of concrete can be improved by optimizing the concrete mix ratio and rationally designing the addition schemes of mineral admixtures and additives. For example, in the design of bridges near mountainous rivers, sulfate-resistant high-performance concrete can be used to resist long-term erosion by river water and extend service life.

4.5.2. Technological innovation

In the field of technological innovation, at present, bridge health monitoring technology has been widely applied in the safe operation of bridges both at home and abroad. During the design of complex mountainous highway bridges, this technical system can also be applied to enhance the management level of the bridges during their subsequent operation. During the specific implementation phase, sensors can be installed within the bridge structure to monitor the stress, strain, vibration, displacement and parameters of the bridge during operation.

At the same time, by leveraging the big data and artificial intelligence technologies of the central control platform, the monitoring data can be analyzed and processed to ensure that the operation unit can promptly identify potential diseases and safety hazards of the bridge structure. For example, fiber-optic sensors can be used to monitor the stress changes in bridges, and after the sensors complete data collection, the data can be transmitted remotely and shared in real time based on Internet of Things technology.

In addition, industrialized construction technology has already demonstrated broad prospects in bridge construction projects. During the bridge design using prefabricated assembly technology, 3D printing and intelligent construction technology can be integrated to further improve the efficiency and accuracy of bridge construction in complex mountainous areas, promote the construction of highway bridges in complex mountainous areas to break through to the field of "intelligent construction", and reduce the damage to the ecological environment of mountainous areas caused by the traditional construction forms while improving the economic benefits [10].

5. Conclusion

This research focuses on the design of highways' bridges in complex mountainous areas, deeply analyzing the design characteristics and principles of highway and bridge projects in such areas. At the same time, it proposes design strategies for the selection of highways' bridges in complex mountainous regions, ensuring that the design level of highways' bridges in complex mountainous areas can be comprehensively improved by making reasonable choices of bridge types, optimizing the design of foundations, optimizing the design of upper structures and connection parts, and applying new materials and new technologies.

In the future, for the design of complex mountainous highway bridges, further research can be conducted focusing on the design of highway bridges in complex mountainous areas. In-depth analysis of the design characteristics and principles of highway and bridge projects in complex mountainous regions should be carried out. At the same time, design strategies for the selection of highway bridges in complex mountainous areas should be proposed. To ensure this, the design level of complex mountainous highway bridges can be comprehensively improved through the reasonable selection of bridge types, the optimization design of foundations, the optimization design of the superstructure and connection parts, as well as the application of new materials and new technologies.

In the future, for the design of highway bridges in complex mountainous areas, we can try to further study the design of highway bridges focusing on complex mountainous areas, deeply analyze the design characteristics and principles of road and bridge projects in complex mountainous areas, and at the same time, put forward the design strategy of highway bridges in complex mountainous areas, to ensure that the design level of complex mountainous expressway bridges can be comprehensively enhanced through the reasonable selection of bridge types, the optimized design of foundations, the optimized design of superstructures and connection parts, as well as the application of new materials and new technologies.

We can further integrate emerging technologies, such as smart materials and new construction techniques, to effectively explore new ideas for further enhancing the performance and safety of bridges, and to better achieve ecological protection, thereby promoting the construction of mountainous area transportation facilities to a new level.

Disclosure statement

The author declares no conflict of interest.

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