

# Review on Hydrodynamic Stability, Structural Performance, and Cost Efficiency in Submersible and Short-Span Bridge Design

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**Abstract**—Submersible and short-span bridges present unique challenges in structural engineering due to the combined demands of hydrodynamic stability, efficient material usage, and life-cycle cost optimization. This review synthesizes recent research focusing on three key aspects of bridge design: structural performance of superstructures, hydrodynamic behavior of submerged components, and economic evaluation through life-cycle cost analysis. Prestressed concrete girders and box girder superstructures demonstrate superior structural efficiency and reduced deflections under varying span conditions, as highlighted in finite element studies. Experimental investigations into the stability of submerged deck slabs reveal the critical influence of deck shape, base width, and flow-induced forces, with rectangular box girders showing enhanced resistance under critical submergence. Furthermore, dynamic analyses of bridge piers under combined seismic and wave loading underscore the amplified effects of hydrodynamic forces in deep or fast-flowing waters. Life-cycle cost analysis frameworks indicate that although prestressed systems may involve higher initial investment, they offer long-term economic benefits through reduced maintenance and rehabilitation costs. This paper integrates these findings to offer a comprehensive perspective on the structural and economic considerations vital for the safe and sustainable design of submersible and short-span bridges.

**Index Terms**—Submersible bridge, Hydrodynamic forces, Prestressed girders, Life-cycle cost analysis, Structural performance, Deck slab stability

## 1. INTRODUCTION

Bridges serve as critical infrastructural components, enabling seamless transportation across challenging terrains such as rivers, valleys, and flood-prone zones. Among various bridge types, submersible and short-span bridges play a vital role in rural and semi-urban regions where economic constraints and hydraulic considerations guide their adoption. These bridges are typically designed to be overtopped during floods while maintaining structural integrity and stability during submergence. Hence, the performance of both superstructure and substructure components under diverse environmental and load conditions becomes paramount.

The structural design of bridges has evolved with advancements in materials, construction techniques, and analytical tools. For short- and medium-span bridges, superstructure selection significantly influences not only initial construction cost but also long-term durability and maintenance demands. Prestressed concrete girders and reinforced concrete T-beams are widely used due to their adaptability and strength characteristics. However, their behavior under varying span conditions, including deflection, bending stress, and material optimization, requires detailed evaluation.

Submersible bridge substructures face additional complexity due to exposure to hydrodynamic forces, such as drag, lift, and wave-induced pressures. These forces become more critical under flood or seismic conditions, demanding robust stability in pier and deck design. Physical modeling and numerical simulation methods have been developed to analyze

these dynamic effects and ensure that overturning, sliding, and scour risks are minimized.



Fig. 1.1: Submersible Bridge

(<https://im.whatshot.in/img/2022/Feb/baba-bhide-bridge-1-cropped-1643869493.jpg>)

Moreover, the economic efficiency of bridge systems must be assessed holistically through life-cycle cost analysis (LCCA), encompassing construction, maintenance, and rehabilitation costs. Recent research indicates that despite higher initial investment, some superstructure configurations, such as prestressed concrete girders, offer significant savings over the lifespan of a bridge due to lower upkeep and greater longevity.

This review consolidates key findings from recent literature on the structural performance, hydrodynamic behavior, and cost-effectiveness of submersible and short-span bridge components. It aims to highlight the engineering challenges and propose design strategies that balance structural safety, hydraulic performance, and economic viability.

## 2 LITERATURE REVIEW

The design and performance evaluation of bridge superstructures has evolved considerably in recent decades, with a growing emphasis on life-cycle cost efficiency, dynamic behavior under various loads, and resilience in extreme environmental conditions. The selected body of literature provides comprehensive insights into these aspects, spanning both theoretical models and experimental validation. Leiva-Maldonado, S. L., & Bowman, M. D. (2023), "Superstructure bridge selection based on life-cycle

cost analysis for short and medium-span bridges," *Engineering Structures*, ELSEVIER.

This paper presents a life-cycle cost analysis framework for selecting the optimal superstructure type for short- and medium-span bridges. The study considers construction, maintenance, and rehabilitation costs for various bridge designs. The results suggest that prestressed concrete girders are cost-effective over their lifespan, despite higher initial construction costs. While the study does not focus on submersible bridge substructures, it provides essential knowledge on cost-benefit evaluation, which is a major component of this research.

Hemalatha, K., James, C., Natrayan, L., & Swamynadh, V. (2021), "Analysis of RCC T-beam and prestressed concrete box girder bridge superstructure under different span conditions," *Materials Today: Proceedings*, ELSEVIER.

This study focuses on the structural performance of RCC T-beam and prestressed concrete box girder superstructures under varying span conditions. The research investigates bending moments, deflections, and material consumption using finite element modelling. The findings suggest that prestressed concrete box girders exhibit superior load-carrying capacity and reduced deflection compared to RCC T-beams. While insightful for superstructure behavior, the study does not evaluate substructure performance. Li, Z.-X., et al. (2024), "Experimental research on dynamic responses and hydrodynamic pressures of

deep-water bridge piers under seismic and wave actions," *Engineering Structures*, ELSEVIER.

This research examines the hydrodynamic effects on bridge piers in deep-water conditions, considering seismic loads and wave interactions. Using physical model testing and numerical simulations, the study evaluates pressure distributions, pier responses, and failure mechanisms under varying water depths and earthquake intensities. Although focused on deep-water bridges, the findings are relevant to submersible bridge substructures, as hydrodynamic forces are a key design consideration.

Vaidyaraman, P. P., & Khatsuria, R. M. (1995), "Investigations on the Stability of Deck Slabs of Submersible Bridges," *ISH Journal of Hydraulic Engineering*, Taylor & Francis.

This experimental study investigates the hydrodynamic stability of deck slabs in submersible bridges. Conducted at CWPRS Pune, the research evaluates drag and lift forces on hydrofoil and rectangular box slab shapes. Although hydrofoils show better coefficients, rectangular box slabs provide superior overall stability under critical submergence. The study emphasizes the significance of base width, self-weight, and flow characteristics for optimal design.

### 3 SUMMARIES OF LITERATURE AND GAP

From the reviewed literature, it is evident that extensive research has been conducted on the structural behavior and cost implications of various bridge superstructures and substructures. While studies have addressed performance under different span conditions and the effects of seismic and hydrodynamic forces on piers, there is limited integration of these factors for submersible bridges. Specifically, the hydrodynamic stability of substructure elements under combined seismic and wave forces has not been sufficiently correlated with superstructure selection and economic performance. Likewise, studies focusing on deck slab hydrodynamics often omit foundation and pier design under variable flow conditions. There is also a lack of life-cycle-based evaluations that simultaneously consider hydraulic safety and cost optimization. This review aims to bridge this gap by presenting a holistic understanding of superstructure performance, hydrodynamic response, and life-cycle cost

effectiveness in submersible and short-span bridge systems.

## 4 RESULTS AND DISCUSSION

The reviewed studies collectively offer significant insights into the structural, hydraulic, and economic aspects of submersible and short-span bridge design. The findings are discussed below in three thematic areas:

### 4.1 Structural Performance of Superstructures

Hemalatha et al. (2021) compared RCC T-beams and prestressed box girders under variable spans using finite element analysis. Prestressed systems demonstrated lower deflections and better material efficiency, making them preferable for medium spans. However, their performance under submerged conditions was not addressed.

### 4.2 Hydrodynamic Stability of Substructures

Li et al. (2024) emphasized the combined impact of wave and seismic forces on piers, which can significantly amplify displacements. Vaidyaraman & Khatsuria (1995) showed that rectangular box slab decks, due to their shape and weight, offer greater resistance to overturning and uplift during submergence. These insights are crucial for substructure design in flood-prone areas.

### 4.3 Economic Considerations: Life-Cycle Cost Analysis

Leiva-Maldonado & Bowman (2023) highlighted those prestressed concrete girders, despite higher upfront cost, result in lower life-cycle expenditures. Their study supports the idea that selection of superstructure type has a lasting impact on bridge economics, especially where maintenance logistics are challenging.

### 4.4 Integrated Perspective

Although the studies individually address structural behavior, hydrodynamic forces, or cost analysis, there is a need for a comprehensive model combining all three. Integrated frameworks would enhance the accuracy of design decisions, ensuring safer and more cost-effective submersible bridge systems.

## 5 CONCLUSIONS

This review highlights the multifaceted considerations required in the design of submersible and short-span bridges, particularly focusing on

structural performance, hydrodynamic stability, and cost efficiency. Key insights from the reviewed literature are summarized as follows:

- Prestressed concrete superstructures demonstrate superior load-carrying capacity and reduced deflection compared to traditional RCC systems, making them structurally efficient for short and medium spans.
- Hydrodynamic forces significantly influence the stability of substructures. Design parameters such as deck shape, base width, and self-weight are vital to resist overturning and uplift.
- Seismic and wave-induced dynamic loads can amplify displacements and stresses in submerged piers, emphasizing the need for robust substructure designs.
- Life-cycle cost analysis supports the use of prestressed systems for long-term economic efficiency, especially where maintenance is difficult or costly.

To design resilient and cost-effective submersible bridges, future work should develop integrated frameworks that simultaneously evaluate superstructure performance, substructure hydrodynamics, and life-cycle economics.

## 6. DECLARATIONS

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## REFERENCES

- [1] Leiva-Maldonado, S. L., & Bowman, M. D. (2023). *Superstructure bridge selection based on life-cycle cost analysis for short and medium span bridges*. *Engineering Structures*, 285, 116031. <https://doi.org/10.1016/j.engstruct.2023.116031>
- [2] Yun, G., & Liu, C. (2022). *Nonlinear dynamic analysis of the deep-water bridge piers under combined earthquakes and wave actions*. *Ocean Engineering*, 261, 112076. <https://doi.org/10.1016/j.oceaneng.2022.112076>
- [3] Leiva-Maldonado, S., Bowman, M. D., & Gomez, D. (2023). *Life-cycle cost profiles selection for different superstructure bridge types*. *Structures*, 54, 1–13. <https://doi.org/10.1016/j.istruc.2023.04.105>
- [4] Vaidyaraman, P. P., & Khatsuria, R. M. (1995). *Investigations on the stability of deck slabs of submersible bridges*. *ISH Journal of Hydraulic Engineering*, 1(1), 29–36. <https://doi.org/10.1080/09715010.1995.10514568>
- [5] Chen, Y., Huang, X., Wu, K., & Li, Z.-X. (2024). *Experimental research on dynamic responses and hydrodynamic pressures of deep-water bridge piers under seismic and wave actions*. *Engineering Structures*, 313, 118276. <https://doi.org/10.1016/j.engstruct.2024.118276>
- [6] Liu, X., Tao, S., Zhao, X., Liu, X., Lu, Z., & Liu, F. (2024). *Dynamic response analysis for bridges subjected to moving vehicle loads by using the analytical dynamic stiffness method*. *Computers and Structures*, 292, 107240. <https://doi.org/10.1016/j.compstruc.2023.107240>
- [7] Hemalatha, K., James, C., Natrayan, L., & Swamynadh, V. (2020). *Analysis of RCC T-beam and prestressed concrete box girder bridge's super structure under different span conditions*. *Materials Today: Proceedings*. <https://doi.org/10.1016/j.matpr.2020.07.119>