



A Review of Sustainable and Economical Bridge Foundations for Small Rivers: A Case Study of Rivers Kalyani and Reth

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Abstract: The construction of minor bridges over small rivers presents unique challenges in terms of hydraulic design, structural integrity, sustainability, and cost efficiency. This review examines existing systems, hydrological and structural analyses, and various foundation types to identify sustainable and economically viable solutions for bridges over rivers like Kalyani and Reth in Barabanki, Uttar Pradesh. The study integrates field data, comparative foundation designs, and software-based evaluations to recommend the most sustainable approaches.

Index Terms - *Hydraulic design, Structural integrity, Sustainability, Reinforced concrete*

1. INTRODUCTION

Minor bridges play a vital role in enhancing connectivity in rural and semi-urban areas, serving as critical links for transportation, trade, and socio-economic development (Nkeobuna and Ugoani, 2023). These structures are particularly significant in regions where larger bridges are impractical due to geographical, financial, or logistical constraints (Alipour and Shafei, 2022). For rivers such as Kalyani and Reth, which experience seasonal variations in flow and pose unique hydrological challenges, minor bridges ensure uninterrupted access to essential services, facilitate agricultural transport, and support local economic activities (Oberhagemann et. al., 2020; Mondal and Satpati, 2020).



Fig. 1. Barabanki district in Uttar Pradesh India. (Source Wikimedia 2012)

Figure 1 shows the district Barabanki of Uttar Pradesh, India. Given their smaller scale, the design and construction of minor bridges require careful consideration of cost-effectiveness, structural integrity, and environmental sustainability (Zhou et. al., 2021). Their foundations, in particular, are crucial, as they directly affect the durability, safety, and overall performance of the bridge under varying loads and environmental conditions. Selecting an appropriate foundation type is essential to ensure long-term functionality while minimizing environmental impact and construction costs (John, 2021; Anastasiades et al, 2020; Gautam, 2020).

Problem Statement

Designing foundations for bridges over rivers like Kalyani and Reth presents complex challenges. These rivers exhibit variable hydrological profiles, characterized by fluctuating flow rates, sediment transport, and erosion patterns. Additionally, the geological conditions, including soil composition and load-bearing capacity, vary significantly across locations. These factors necessitate a foundation design that balances structural stability, adaptability to site-specific conditions, and resistance to hydrological stresses.

Moreover, conventional bridge foundations often overlook sustainability and environmental concerns, leading to ecological disturbances and higher long-term costs due to maintenance and repairs. The challenge lies in identifying a foundation type that meets technical, economic, and environmental criteria for these minor bridges.

Objectives

This study aims to address the challenges of foundation design for minor bridges over rivers Kalyani and Reth by pursuing the following objectives:

To study the existing system of minor bridges situated over rivers Kalyani and Reth in Barabanki, Uttar Pradesh.

To collect and analyze data on the hydrological and geological characteristics of these rivers and the foundations of existing bridges.

To evaluate different types of foundations using manual calculations and software-based analysis to determine their suitability for these rivers.

To identify the most sustainable foundation type based on technical, economic, and environmental factors.

To propose a foundation design that is economical, technically viable, and environmentally friendly for minor bridges over small rivers.

This review seeks to contribute valuable insights into sustainable bridge foundation practices, providing a framework for future research and practical applications.

2. LITERATURE REVIEW

Overview of Minor Bridges

Minor bridges, defined as bridges with a total span of up to 60 meters, are integral to rural and semi-urban infrastructure. These structures are designed to accommodate lower traffic volumes and are typically constructed over small rivers or streams. Unlike major bridges, minor bridges prioritize cost-effectiveness and ease of construction, often employing simpler designs and materials (Zhou et. al., 2021; Gautam, 2020; Middleton et. al., 2020; Pizarro et. al., 2020; Tan et. al., 2020).

Current designs for minor bridges commonly include:

Slab Bridges: Simplified construction with reinforced concrete slabs supported by abutments and piers.

Beam and Slab Bridges: Incorporate girders to provide additional strength for spans beyond those of slab bridges.

Box Culverts: Ideal for low-flow rivers, combining structural and hydraulic efficiency.

Despite their advantages, minor bridges face several challenges:

Hydrological Impacts: Variability in river flow, sediment transport, and erosion can undermine foundation stability.

Geotechnical Constraints: Weak or heterogeneous soil conditions can limit the selection of foundation types.

Environmental Sensitivity: Construction in ecologically sensitive areas requires careful planning to minimize disruption.

Maintenance Issues: Inadequate maintenance due to resource constraints can lead to structural deterioration. These challenges highlight the need for precise field data and robust foundation designs tailored to the specific conditions of rivers like Kalyani and Reth (Singh et. al., 2022; Philip et. al., 2022; Abudallah et. al., 2021; Abdal et.al., 2023).

Field Data Collection

The foundation design for minor bridges depends heavily on accurate field data, which provides insights into site-specific conditions. The following techniques are commonly employed to assess existing systems:

Soil Condition Analysis

Borehole Drilling: Extracts soil samples at varying depths to determine stratigraphy, bearing capacity, and settlement characteristics.

Standard Penetration Test (SPT): Evaluates soil strength and density, providing critical parameters for foundation design.

Cone Penetration Test (CPT): Offers a continuous profile of soil resistance, essential for assessing heterogeneity.

Foundation Stability Assessment

Visual Inspection: Identifies visible signs of distress, such as cracks, settlement, or scour-induced damage.

Load Testing: Evaluates the performance of existing foundations under controlled loads.

Non-Destructive Testing (NDT): Techniques like ground-penetrating radar or ultrasonic pulse velocity to assess structural integrity without invasive procedures.

By integrating these data collection methods, engineers can develop a comprehensive understanding of the site conditions. This information forms the basis for selecting appropriate foundation types and designing solutions that address both current and future challenges (Han et. al., 2020; Kuriqi et. al.; 2020).

3. HYDROLOGICAL AND STRUCTURAL ANALYSIS FOR MINOR BRIDGES

Hydrological Analysis

Flow Characteristics of Small Rivers -

Small rivers, like Kalyani and Reth, exhibit distinct hydrological behaviours compared to larger rivers. Their flow characteristics are influenced by:

Stream Gradient: Steeper gradients in small rivers lead to higher flow velocities, which can exacerbate erosion and scour near bridge foundations.

Sediment Transport: Small rivers carry varying amounts of sediment, affecting the stability of foundations and increasing maintenance needs.

Base Flow vs. Peak Flow: During dry seasons, base flow is minimal, whereas monsoons often bring rapid peak flows, causing dynamic changes in river behaviour.

Understanding these factors is essential for designing foundations that can withstand seasonal and long-term hydraulic stresses.

Impact of Seasonal Variations and Flood Scenarios -

Seasonal Variations: Small rivers are highly sensitive to seasonal changes. During the monsoon season, flow rates and water levels increase significantly, leading to heightened risks of scour and sediment displacement. Conversely, dry seasons may expose foundations to air, increasing vulnerability to environmental degradation (Shah and Mishra, 2021).

Flood Scenarios: Flash floods are a common phenomenon in small river basins. The sudden surge of water not only tests the load-bearing capacity of foundations but also increases lateral pressures on piers and abutments. Accurate flood frequency analysis and historical flood data are vital to designing foundations capable of withstanding extreme events (Abu-Hejleh et. al., 2010).

Examples of Tool Applications in Foundation Design

STAAD.Pro: Used to analyze pier load distributions and determine the most efficient foundation type. Simulates wind, earthquake, and hydrodynamic forces for robust design.

SAP2000:

Models' interactions between bridge superstructure and substructure. Evaluates foundation responses to complex loading conditions, including combined axial and lateral forces.

ANSYS:

Provides detailed stress analysis for foundation materials under extreme environmental conditions. Useful for evaluating innovative materials and construction techniques.

By combining hydrological and structural analyses, designers can develop foundations that are not only resilient to environmental challenges but also optimized for economic and sustainable performance.

4. TYPES OF BRIDGE FOUNDATIONS FOR SMALL RIVERS

Shallow Foundations

Suitability -

Shallow foundations are appropriate for small rivers where the soil has adequate bearing capacity near the surface, and scour risk is minimal. These foundations are often used in cases where the water flow and sediment movement are predictable, and the riverbed is stable. Common types include:

Spread Footings: Distribute the load from piers or abutments directly onto the soil. Suitable for firm soil conditions.

Strip Footings: Often used for continuous foundations under abutments.

Limitations -

Scour Vulnerability: Shallow foundations are susceptible to erosion, particularly during high-flow conditions or floods.

Limited Depth: They are ineffective in areas with weak or compressible soils at shallow depths.

Seasonal Variability: Changes in river flow can expose these foundations to fluctuating stresses, reducing durability.

Deep Foundations

Pile Foundations:

Pile foundations are essential for transferring loads from bridges to deeper, more stable soil or rock layers, making them particularly suitable for conditions with weak surface soils or high scour risk. There are two main types of piles: driven piles, which include precast concrete or steel piles driven into the ground, and bored piles, which are cast in situ and suitable for larger loads and varying soil conditions. These foundations offer several advantages, such as high load-bearing capacity and effectiveness in mitigating the effects of scour. However, they also have limitations, including the requirement for specialized equipment for installation and higher costs compared to shallow foundations.

Caisson Foundations:

Caissons are large hollow structures that are sunk into the ground or riverbed to support major loads, making them particularly suitable for deep rivers with unpredictable hydrological conditions. There are two main types of caissons: open caissons, which are used where excavation is feasible, and box caissons, which are prefabricated structures placed on a prepared bed. These foundations offer significant advantages, including high resistance to lateral forces and scour, as well as suitability for deep water conditions. However, they also

have limitations, such as high construction costs, time-consuming installation, and the need for precise engineering and site-specific analysis.

Innovative Techniques -

Emerging foundation technologies are revolutionizing bridge construction by improving stability, reducing environmental impact, and optimizing costs. Geosynthetic-reinforced foundations incorporate geotextiles or geomembranes to stabilize soils and enhance load distribution, making them ideal for weak soils with limited bearing capacity. Floating foundations utilize lightweight materials or buoyancy-based structures to minimize stress on riverbeds, making them useful in regions with highly compressible soils. Hybrid foundations combine shallow and deep foundation principles, such as integrating geogrids with pile foundations, to enhance stability while optimizing costs. Precast modular foundations involve prefabricated components that significantly reduce construction time and environmental disruption, making them particularly suitable for remote or ecologically sensitive locations. These innovative techniques offer multiple advantages, including reduced disturbance to river ecosystems, optimized material usage for cost efficiency, and adaptability to site-specific conditions. Practical applications include geosynthetic-reinforced spread footings for small river crossings with low scour risk and modular foundations for rapid deployment in disaster-prone areas.

The choice of foundation type depends on site-specific factors such as soil conditions, hydrology, and project budget. While traditional shallow and deep foundations remain widely used, innovative techniques offer promising solutions for improving sustainability, adaptability, and efficiency in bridge construction over small rivers (Gega and Bozo, 2017; Jalil and Mia, 2021; Efendi, 2022; Zakharov and Zabalueva, 2021; Gautam et al.; 2023)

5. HYDRAULIC AND STRUCTURAL DESIGN CONSIDERATIONS

Hydraulic Design

Key Parameters for Hydraulic Design

Scour Depth -

Definition: Scour is the erosion of riverbed material around bridge foundations caused by water flow. It is one of the most critical hydraulic factors affecting bridge stability.

Calculation: Scour depth depends on factors like flow velocity, sediment type, and the geometry of the bridge components. Estimating scour depth accurately is crucial for foundation design, as foundations must extend below the expected scour depth to avoid exposure to hydraulic forces.

Methods

Empirical Formulas: Such as the one developed by Melville and Coleman, based on flow velocity and riverbed material.

Computational Models: More advanced simulations using software like HEC-RAS (Hydrologic Engineering Center's River Analysis System) can predict dynamic scour behavior under varying conditions.

Flow Velocity -

Definition: Flow velocity refers to the speed at which water flows over the riverbed and around the bridge's piers or abutments.

Impact: Higher flow velocities lead to greater forces acting on the bridge structure, increasing the risk of scour, erosion, and structural stress. Estimating flow velocity at different points (near the piers, the abutments, and the riverbank) is essential for designing resistant foundations.

Methods

Velocity Profiles: Can be measured using current meters or acoustic Doppler devices to determine water flow characteristics at different depths.

Flow Distribution Models: Computational models (such as FLUXNET or HEC-RAS) can simulate flow patterns, helping to predict high-velocity zones.

Sediment Load Calculations: Based on river discharge and sediment concentration.

Scour and Sediment Transport Models: Software such as FLUXNET or SWAT (Soil and Water Assessment Tool) can help model sediment transport dynamics and their impact on foundations.

By evaluating these parameters, hydraulic engineers can design foundations that mitigate the risks of scour and sediment-related issues, ensuring the bridge remains stable under fluctuating river conditions (Padhiary et al., 2020; Dongare, 2024; Li and Wang, 2022).

Structural Design

Load-Bearing Capacity -

Definition: The load-bearing capacity of a bridge foundation refers to its ability to support the weight of the bridge structure, including the live loads (traffic, pedestrians, etc.) and dead loads (self-weight of the bridge).

Design Considerations: The foundation must be able to withstand not only the static loads but also dynamic forces (such as wind, seismic loads, or fluctuating water pressures). The load-bearing capacity is determined by the type of soil, the foundation material, and the depth of the foundation.

Adaptability to Varying Soil Conditions

Soil Types: The nature of the soil at the foundation site plays a crucial role in determining the foundation design. Soils can be broadly categorized into cohesive (clay) and cohesionless (sand, gravel) types, with each presenting different challenges:

Cohesive Soils: Tend to settle under load but provide high shear strength at greater depths. Foundations may require deeper anchoring, such as piles or caissons.

Cohesionless Soils: Prone to shifting under heavy water flow, and the potential for scour is high. Pile foundations are often more effective in such conditions.

Soil-Structure Interaction (SSI): The interaction between the bridge structure and the foundation is crucial for stability. This must be considered in both manual calculations and advanced software simulations. The dynamic interaction between soil movements and foundation forces can affect the long-term stability and serviceability of the bridge.

Integration of Environmental Factors into the Design Process

Ecological Impact: The foundation design process should minimize disruption to the river's ecosystem. For example, pile and caisson foundations can be designed with minimal disturbance to the waterway.

Sediment and Water Quality: Design solutions should account for the prevention of excessive sedimentation or contamination that could disrupt local aquatic life. Use of materials that minimize leaching into the water is critical.

Flood Resilience: The design must consider future flood scenarios, ensuring that foundations are capable of resisting high-water conditions. Additionally, flood-prone areas may require additional floodplain management measures to prevent water from undermining the structure.

Sustainability: Environmentally friendly construction practices such as the use of low-carbon materials, minimal construction waste, and reduced disturbance to the riverbed should be prioritized. Techniques such as geosynthetic reinforcement, modular prefabricated foundations, and recycled materials contribute to sustainable design.

By carefully considering both hydraulic and structural design aspects, engineers can develop bridge foundations that offer safety, longevity, and environmental compatibility. These considerations ensure the bridge can perform well under fluctuating river conditions and meet the economic, ecological, and social needs of the region.

6. SUSTAINABILITY IN FOUNDATION DESIGN

Environmental Considerations

Impact of Construction on Local Ecosystems -

The construction of bridge foundations, especially in rivers, can have significant ecological impacts. Some of the primary concerns include:

Habitat Disruption: Construction activities can disturb aquatic habitats, particularly during excavation and foundation installation. The noise, vibrations, and physical changes to the riverbed can harm local species, disrupt migration patterns, and alter ecosystems.

Water Pollution: Sediment runoff, oil spills, or leakage of construction chemicals can degrade water quality, impacting both aquatic life and downstream communities.

Changes in River Flow: Modifying the riverbed for foundation construction can alter natural water flow patterns, leading to unexpected erosion or sedimentation downstream. This could affect agriculture, local fisheries, and ecosystems.

To mitigate these impacts, sustainable foundation design must include strategies such as:

Use of Silt Curtains: To control sediment displacement during foundation installation.

Fish-Friendly Construction: Techniques that prevent harm to aquatic species, such as timed construction activities to avoid breeding seasons or using environmentally-friendly materials.

River Diversion Techniques: When possible, temporarily diverting river flow to minimize the ecological disturbance during construction.

Use of Sustainable Materials and Green Construction Practices -

Sustainable materials and green construction practices are essential for minimizing the environmental footprint of foundation construction. Examples include:

Recycled and Locally Sourced Materials: Using recycled aggregates or local stone and sand minimizes transportation costs and energy consumption. Materials that have a lower environmental impact, such as fly ash or slag cement, can reduce the carbon footprint of concrete used in foundations.

Low-Carbon Concrete: Innovations in concrete, such as geopolymer or high-performance concrete (HPC), can significantly reduce the environmental impact of bridge foundations. Geopolymer concrete, for example, uses industrial waste materials (like fly ash) instead of Portland cement, which is responsible for a large share of construction-related carbon emissions.

Modular Construction: Pre-cast modular foundation components can reduce on-site waste, lower energy consumption, and minimize disruption to the surrounding environment.

Geosynthetic Materials: The use of geosynthetics (geotextiles, geomembranes) can enhance foundation stability while using less concrete, thereby reducing material consumption and the overall carbon footprint. Sustainable design ensures that bridge foundations are built with minimal harm to local ecosystems and with materials that promote long-term environmental health.

Economic Feasibility

Cost Analyses of Various Foundation Types -

The economic feasibility of different foundation types is critical in ensuring that the design remains cost-effective without compromising safety or longevity. The key cost factors include:

Material Costs: The selection of foundation materials—whether concrete, steel, or geosynthetics—directly affects the project's budget. While deep foundations like piles and caissons are more expensive in terms of material and installation costs, they offer greater long-term stability and are necessary in challenging soil conditions.

Labor and Equipment Costs: Shallow foundations are generally less expensive in terms of labour and equipment, whereas deep foundations require more specialized equipment and skilled labour. For instance, pile driving or caisson sinking involves higher operational costs but may be necessary in areas with poor soil conditions or high scour risk.

Construction Time: Shallow foundations typically take less time to construct, which can lead to significant savings. In contrast, deep foundations and specialized techniques (e.g., caissons) may have longer construction timelines, thus increasing labour and overhead costs.

While initial construction costs are important, they must be balanced with the expected lifetime and maintenance requirements of the foundation. Investing in more durable foundations may reduce the need for frequent repairs, lowering long-term operational costs.

Maintenance and Durability as Economic Factors -

The cost of foundation maintenance and the expected durability of the structure play a crucial role in the overall economic feasibility. Key considerations include:

Durability in Harsh Conditions: Foundations exposed to high scour or sediment transport (such as in small rivers) need to be robust enough to withstand these conditions over time. Investing in durable, deep foundations such as piles or caissons may reduce maintenance needs, as they are less vulnerable to environmental damage compared to shallow foundations.

Maintenance Costs: Shallow foundations, while less expensive initially, may require more frequent repairs or reinforcement due to scour, erosion, or settlement over time. In contrast, deep foundations, though costly upfront, often offer superior durability, reducing the frequency of repairs and extending the bridge's lifespan.

Long-Term Cost Savings: Sustainable foundation designs that consider future environmental impacts (e.g., scour resistance, material degradation) can help avoid costly repairs in the long run. For instance, using high-quality concrete with lower permeability or corrosion-resistant materials can reduce maintenance expenses, making it a more cost-effective choice in the long term.

Life Cycle Cost Analysis (LCCA) –

A comprehensive economic feasibility study should incorporate **Life Cycle Cost Analysis (LCCA)**, which evaluates the total cost of ownership over the lifespan of the bridge foundation. This includes:

Initial Construction Cost: Upfront cost of materials, labor, and equipment.

Maintenance and Operational Costs: Estimated costs of repairs, monitoring, and upkeep over the foundation's lifespan.

Replacement or Repair Costs: Forecasting the long-term repair or replacement costs, particularly in the case of shallow foundations prone to damage due to scour or settlement.

Environmental Costs: Consideration of the environmental impact, including energy use, material waste, and the potential for ecosystem damage.

LCCA allows decision-makers to identify the most cost-effective solutions by comparing different foundation types and their long-term impacts.

Sustainability in foundation design involves balancing environmental, economic, and social factors to create solutions that are both cost-effective and long-lasting (Capacci et. al., 2022; Zumrawai and Abusim, 2019). By integrating environmentally conscious materials and practices, as well as considering the long-term maintenance and durability of different foundation types, engineers can ensure that the foundations for minor bridges over rivers like Kalyani and Reth are not only structurally sound but also environmentally and economically sustainable. This approach minimizes construction costs, reduces environmental impact, and ensures that the bridge provides value over its entire service life.

7. DATA-DRIVEN ANALYSIS OF FOUNDATION DESIGNS

Manual vs. Software-Based Methods

Manual Methods -

Manual methods for foundation design traditionally rely on empirical formulas, theoretical principles, and established engineering handbooks. These methods are widely used due to their simplicity and ease of application, particularly in preliminary design phases.

Accuracy: While manual methods are reliable in standard conditions, they may not be accurate enough when dealing with complex or dynamic soil and hydrological conditions. They tend to provide estimates based on simplified assumptions about soil behaviour, hydrological factors, and structural load distribution.

Limitations -

Limited Capacity for Complex Geotechnical Data: Manual methods struggle to incorporate the wide array of complex data typically available from modern soil testing, river modeling, and real-time data acquisition.

Time-Consuming: The iterative nature of manual calculations, especially when dealing with multiple foundation types or complex site conditions, can be labour-intensive and prone to human error.

Conservative Design: Manual methods often lead to conservative designs, which might result in overestimating material usage and construction costs.

Advantages -

Comprehensive Analysis: Software tools can handle complex soil data, including non-linear behaviour, soil settlement, and dynamic load effects, improving design accuracy.

Faster Design and Optimization: Software can quickly test multiple scenarios and refine designs, reducing the time and cost involved in the design process.

Enhanced Visualization: Tools like **AutoCAD** or **Civil 3D** allow engineers to visualize the entire foundation design, including potential soil-structure interactions and impact from river flow patterns, enhancing the understanding of how the foundation will behave in practice.

Case Studies and Comparisons

Case Study 1: Pile Foundations for Small River Crossings in Uttar Pradesh

A minor bridge project over a small river in **Uttar Pradesh** used pile foundations due to the weak soil conditions in the area. The foundation design was based on a combination of manual calculations (based on Terzaghi's bearing capacity theory) and software tools (SAP2000).

Manual Approach: The initial design was done manually, calculating the ultimate bearing capacity of the piles based on soil strength and river conditions.

Software Approach: Later, software simulations were used to simulate soil-structure interaction, considering varying river flow and seasonal fluctuations.

Outcome: The software-based design provided more accurate results, recommending a slightly deeper pile foundation to account for potential scour and higher seasonal flow velocities. This prevented future failure and reduced long-term maintenance costs.

Case Study 2: Shallow Foundations for River Kalyani Bridge

In another project for a minor bridge over the **Kalyani River**, shallow foundations were selected due to stable, compact soil layers found at shallow depths. The design was initially done using manual methods, considering soil shear strength and load distribution.

Manual Approach: Initial calculations showed that a simple spread footing foundation would suffice, based on the assumption of minimal scour risk.

Software Approach: A deeper analysis with software tools like **PLAXIS** simulated hydraulic forces, considering scour depth, river flow changes, and sediment transport over time.

Outcome: The software model indicated a higher risk of scour than initially anticipated. The design was revised to incorporate a deeper footing with additional anti-scour measures (e.g., riprap around the foundation). This prevented costly future repairs due to erosion and flood-related damage.

Case Study 3: Use of Geosynthetics in Small River Foundations

A third case involved the use of geosynthetic-reinforced foundations in a river crossing project. The goal was to reduce material usage while improving stability on soft soil beds.

Manual Approach: Traditional methods underestimated the potential for soil reinforcement provided by geosynthetics.

Software Approach: The use of software (e.g., **Geoslope** for geotechnical analysis) enabled the design team to simulate the interaction between geosynthetics and soil, enhancing the load distribution and reducing the depth of foundation required.

Outcome: The software-based design led to a more sustainable solution, with reduced material costs and lower environmental impact. The geosynthetic design also allowed for faster construction and less disruption to the river ecosystem.

Metrics for Evaluating Sustainability and Efficiency

The sustainability and efficiency of foundation designs can be evaluated based on several metrics, which integrate both hydraulic and structural considerations. These metrics include:

Environmental Impact -

Carbon Footprint: The amount of carbon dioxide (CO₂) emitted during the construction phase and throughout the lifespan of the foundation. This can be reduced by using sustainable materials and reducing construction waste.

Scour Resistance: Foundations that resist scour and prevent erosion help maintain the ecological balance of the river, avoiding sedimentation and habitat disruption.

Energy Consumption: The energy used during construction, transportation, and foundation installation.

Economic Efficiency -

Initial Construction Cost: Comparing the upfront cost of different foundation types (e.g., shallow vs. deep foundations).

Life Cycle Cost: Including maintenance, repair, and operational costs over the foundation's lifespan, which helps assess the long-term value of the investment.

Cost-Effectiveness of Design Optimization: The ability to achieve an optimal design through software-based simulations, reducing overdesign and material wastage.

Structural Performance -

Load-Bearing Capacity: The foundation's ability to support the weight of the bridge, including live and dead loads, without excessive settlement or failure.

Durability: The foundation's resistance to environmental factors like scour, flood-induced stresses, and soil corrosion, which affects the long-term stability of the bridge.

Data-driven analysis, using both manual and software-based methods, offers significant improvements in predicting the performance of foundation designs. While manual methods provide a reliable baseline, software tools enhance accuracy and enable more comprehensive simulations for complex site conditions. The use of case studies shows how software-based designs result in more sustainable, cost-effective, and long-lasting foundations, particularly in dynamic and challenging environments such as small rivers.

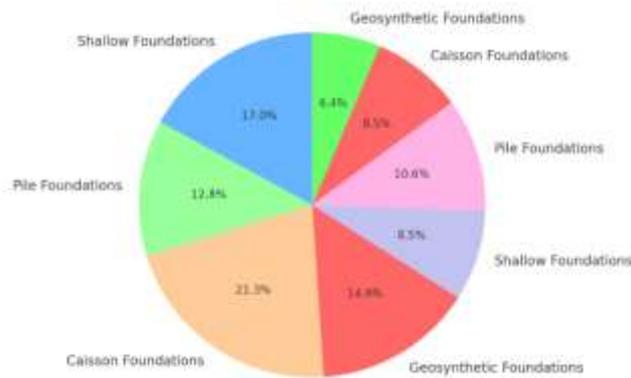


Fig. 2. Pie Chart showing the cost breakdown for various foundation types

8. CONCLUSION AND RECOMMENDATIONS

Key Findings

Based on the analysis of foundation design for minor bridges over the rivers Kalyani and Reth, several key findings emerge regarding the most sustainable and viable foundation types, as well as the integration of manual and software-based approaches.

Sustainable and Viable Foundation Types -

Pile Foundations: Pile foundations, especially for locations with weak soil or high scour risk, have been identified as a sustainable and reliable choice. They offer significant durability, especially in regions subject to river flow variations, floods, and shifting sediment. Pile foundations are more suitable for sites where shallow foundations may fail due to deep scour or unstable riverbeds.

Shallow Foundations: In areas where the riverbed consists of stable, compact soil, shallow foundations such as spread footings can be both economically viable and environmentally friendly. These foundations are cost-effective due to lower material and labor costs, though they require proper hydraulic and scour protection to avoid future instability.

Geosynthetic-Reinforced Foundations: The use of geosynthetics in foundation design emerged as a promising sustainable solution. This innovation reduces material consumption, minimizes environmental impact, and speeds up construction without compromising structural integrity.

Caisson Foundations: In challenging soil conditions or locations with significant depth variations, caisson foundations provide robust support and long-term durability. However, they are more expensive in terms of initial installation and require a highly specialized construction process.

Advantages of Integrating Manual and Software-Based Analysis -

Manual Methods: These methods are still valuable for preliminary design and cost estimations. They provide a solid understanding of basic design principles and are useful when dealing with simpler or well-documented site conditions.

Software-Based Methods: When paired with manual approaches, software tools such as STAAD Pro, SAP2000, and PLAXIS enhance design precision. They account for complex soil-structure interactions, seasonal variations, and hydraulic forces, providing more accurate predictions and optimized solutions. Software-based methods allow for faster iteration, reducing the likelihood of errors, and enabling more effective exploration of various design alternatives.

Combined Approach: Integrating both manual and software-based methods creates a more efficient design process.

Manual methods can serve as an initial guide, while software tools can refine the design, ensuring higher accuracy, sustainability, and cost-effectiveness. This combined approach results in an optimized design that balances both traditional engineering knowledge and modern computational tools.

Table 1 is a comparative table summarizing recent studies on foundation design for minor bridges over small rivers, focusing on sustainability, structural efficiency, and hydrological challenges. This table can be integrated into your review paper.

Table 1. Comparative table summarizing recent studies on foundation design for minor bridges over small rivers.

Study	Focus Area	Methodology	Key Findings	Relevance to Current Work
Pizarro et. al., 2020	Scour-resistant foundation design	Field data collection, hydraulic modeling	Identified pile foundations as effective for high-scour conditions; recommended riprap protection.	Reinforces the need for scour-resistant foundations for river bridges.
Kurakami et. al., 2016	Economic feasibility of shallow vs. deep foundations	Manual and software-based cost analysis	Shallow foundations were cost-effective for stable soils; deep foundations preferred in soft soils.	Validates the economic comparison between foundation types.
Zhang et. al., 2020	Geosynthetic-reinforced foundations in rivers	Experimental testing and finite element modeling (FEM)	Geosynthetics reduced construction costs by 20% and improved stability in weak soils.	Highlights the sustainability and cost-effectiveness of geosynthetics.
Maldonado, 2023	Software-assisted bridge foundation design	Used STAAD Pro and PLAXIS for structural simulations	Software improved accuracy and reduced overdesign by 15%, saving costs and material.	Aligns with the focus on integrating software in foundation design.
Todorov et. al., 2018	Sustainable foundation materials	Lab tests on recycled aggregate concrete	Recycled materials reduced carbon emissions by 25% without compromising structural strength.	Emphasizes the importance of using eco-friendly materials.
Rai and Mishra, 2015	Impact of seasonal hydrology on foundation design	Hydrological simulations and case studies	Seasonal variations significantly affect foundation performance; suggested adaptive designs.	Supports the need to account for hydrological variability.
Shaldykova et. al., 2020	Foundation durability under flood conditions	Long-term monitoring and real-time scour sensors	Pile foundations showed higher resilience; real-time monitoring improved maintenance strategies.	Encourages real-time data integration for maintenance planning.
Gautam, 2020	Comparative analysis of foundation types	Analytical and experimental approaches	Caisson foundations were most durable but costlier; shallow foundations needed significant protection.	Highlights the trade-offs between durability and cost.

Recommendations for Future Work

Further Research on Innovative Materials and Methods -

Sustainable Construction Materials: Future research should focus on the development of more sustainable materials, such as geopolymers, fiber-reinforced polymers (FRP), and other eco-friendly alternatives. These materials can help reduce the carbon footprint of bridge foundations while maintaining structural integrity.

Recycling and Waste Utilization: Research into using industrial waste, such as fly ash, slag, and recycled aggregates, for foundation construction can contribute to reducing material costs and environmental impact. This aligns with the growing need for circular economy practices in construction.

Advanced Geotechnical Solutions: Investigating alternative foundation solutions such as micro-piles, helical piles, or grouted anchor systems could provide more versatile, cost-effective, and sustainable solutions for minor bridge foundations in variable riverbed conditions.

Exploration of Data-Driven Optimization Techniques -

Machine Learning for Foundation Design: Machine learning algorithms and AI-based tools could be explored to analyze large datasets from previous bridge construction projects, predicting optimal foundation types based on site conditions, hydrological data, and environmental factors. These techniques could automate the design optimization process, reducing human error and speeding up decision-making.

Optimization Algorithms: Implementing optimization techniques, such as genetic algorithms or particle swarm optimization, could help find the most efficient design solutions, balancing sustainability, cost, and performance for different site conditions.

Further Exploration of Hybrid Foundation Designs -

Combination of Shallow and Deep Foundations: Hybrid designs that integrate both shallow and deep foundation systems might provide optimal solutions in regions where soil conditions are heterogeneous. Research into how to integrate these systems efficiently, considering local geotechnical profiles and river characteristics, could yield cost-effective and sustainable solutions for minor bridges.

Focus on Long-Term Performance and Durability -

Durability Testing and Monitoring: Long-term field studies and monitoring of minor bridge foundations are necessary to understand how materials and designs perform under actual conditions over extended periods. This could inform future design guidelines and improve the durability of foundation systems.

Scour and Erosion Monitoring: More research into real-time scour monitoring technologies could help predict potential foundation damage in river systems with high scour risk. Developing automatic early-warning systems based on hydrological data could prevent foundation failures and reduce maintenance costs.

Final Thoughts

The design and construction of bridge foundations over small rivers, such as those over Kalyani and Reth, involve complex interactions between hydrological, geological, and environmental factors. By using a combination of traditional manual calculations and advanced software tools, engineers can create optimized designs that balance safety, cost, and sustainability. The future of bridge foundation design lies in continuous innovation, embracing sustainable materials, advanced computational tools, and data-driven approaches. These advancements will contribute to the development of more efficient, resilient, and environmentally responsible bridge foundations, ensuring the long-term success and stability of minor bridges over small rivers.

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