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Sustainable Foundations for Small-River Bridges: A Comprehensive Review

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ABSTRACT: Bridges spanning small rivers are vital for rural connectivity and flood management, yet their foundations often face challenges of unstable alluvial soils, scour, and limited budgets. This review examines sustainable foundation strategies for small river bridges, focusing on environmentally sensitive materials, economic efficiency, and climate resilience. We survey common foundation types (e.g. pile, well, raft, box culvert) and their applicability in alluvial regions, noting that traditional well foundations remain widespread in India due to soil conditions and cost. Contemporary sustainability criteria—such as minimizing carbon footprint, reusing waste materials, and ensuring long-term performance—are emphasized. Case studies from India (e.g. Uttar Pradesh alluvium) demonstrate the effectiveness of using precast concrete box culverts as a cost-effective alternative to deep wells, while international examples (e.g. arid U.S. streams) highlight scour-resistant deep foundation design. We identify gaps in current practice, including insufficient integration of life-cycle assessment and climatic change adaptation in foundation design. Finally, we outline research directions—such as novel low-carbon materials, adaptive design for flood resilience, and foundation reuse—to advance sustainable bridge foundations.

Keywords: Sustainable foundation; Bridge engineering; Small rivers; Geotechnical design; Scour resilience

INTRODUCTION

Bridges constructed over small rivers and ephemeral or perennial streams constitute vital components of rural transportation infrastructure, significantly influencing regional connectivity, socioeconomic development, and disaster resilience—particularly in flood-prone or alluvial terrains [1]. According to the classification system established by the Indian Roads Congress (IRC), minor bridges are defined as structures with spans ranging between 6 m and 60 m, while culverts are those with spans up to 6 m [2]. In several parts of India, these minor bridges are commonly situated on soft alluvial foundations comprising sand, silt, and clay, typical of fluvial plains and deltaic regions [1, 3]. Such geotechnical conditions necessitate careful consideration of foundation behavior, as they are often associated with low bearing capacity, high susceptibility to scour and erosion, and significant groundwater table fluctuations.

From a foundation engineering perspective, well (caisson) foundations have historically been the predominant choice for bridge substructures in Indian riverine environments, especially for small- to medium-span bridges [4]. This preference arises because wells provide a large effective bearing area, high vertical load capacity, and enhanced lateral stability under conditions of weak strata and flowing water. The circular or rectangular wells can penetrate below the active scour depth, transferring loads to deeper, more stable soil layers—making them particularly suitable for sandy riverbeds with variable hydraulic regimes.

Empirical field investigations—such as surveys conducted along the Reth River in Uttar Pradesh—have substantiated this trend, revealing that all minor bridges within a 75 km stretch were supported on well foundations [5]. This observation underscores the widespread reliance on caisson-type systems in alluvial geotechnical settings.

However, despite their functional advantages, well-sinking operations pose substantial economic and logistical challenges. They involve heavy excavation, continuous dewatering, and the use of specialized sinking equipment, often leading to extended construction durations and increased project costs. As noted by Varma et al. [6], numerous small bridges in India still depend on well foundations, which are "uneconomical and time-consuming to construct." To address these limitations, several researchers and practitioners have proposed precast reinforced-concrete (RC) box culvert bridges as an efficient and sustainable alternative [5, 7].

These modular systems are advantageous due to their reduced foundation depth, minimal excavation requirements, and ease of installation, making them particularly suitable for low- to moderate-flow conditions. Moreover, precast box units can be fabricated under controlled conditions, ensuring consistent quality, rapid deployment, and lower overall lifecycle costs [8]. The adoption of

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such alternatives aligns with modern sustainable construction principles by minimizing material use, land acquisition, and disturbance to river hydraulics while maintaining adequate hydraulic clearance, structural integrity, and service life performance comparable to traditional well-founded systems.

The growing emphasis on sustainability in foundation engineering stems from the recognition that subsurface construction activities—though often invisible after completion—carry a disproportionately large share of a project's environmental footprint [9]. These works involve significant use of natural resources, energy-intensive materials, and ground disturbance, all of which influence the long-term environmental and economic viability of infrastructure. As a result, modern geotechnical engineering increasingly integrates sustainability principles that go beyond traditional safety and serviceability criteria, focusing instead on resource efficiency, carbon footprint reduction, durability, resilience, and minimal ecological impact. According to current perspectives in sustainable geotechnics [10], a truly sustainable foundation design is one that ensures technical reliability while minimizing adverse effects across the entire project life cycle—from planning and material procurement to construction, maintenance, and eventual decommissioning. Since foundation works are among the earliest stages in any infrastructure project, they shape the environmental and economic outcomes of subsequent stages, making early sustainability considerations both strategic and impactful [11].

In practical terms, sustainable foundation engineering involves adopting materials and techniques that reduce dependency on virgin natural resources and promote circular economy practices. The incorporation of industrial by-products, such as fly ash and ground granulated blast furnace slag (GGBS), as partial replacements for Portland cement in concrete, not only lowers embodied carbon but also improves durability and sulfate resistance [12]. Similarly, lime and cement-treated soils combined with pozzolanic additives or biopolymers can enhance ground stability while avoiding extensive excavation and waste generation. The use of geosynthetics—including geogrids, geotextiles, and geocells—has become another cornerstone of sustainable practice, as these materials offer reinforcement and drainage benefits while significantly reducing the need for bulky natural aggregates. In addition, design optimization using advanced computational modeling tools allows engineers to minimize material quantities without compromising structural safety, further contributing to sustainability and cost-efficiency [13].

Another critical aspect of modern foundation design is climate resilience, particularly in the context of increasing hydrological extremes due to climate change. The rise in flood magnitude, intensity, and frequency poses severe challenges for bridge foundations in riverine and alluvial environments. One of the most pressing concerns is scour, the process by which fast-flowing water erodes sediment around bridge piers and abutments, weakening the supporting strata. Scour has been identified as "by far the leading cause of bridge failure worldwide" [14], responsible for numerous catastrophic collapses and financial losses amounting to hundreds of millions of dollars in Europe and the United States over recent decades [15]. To mitigate this, designers often prefer deep foundations, such as bored piles, driven piles, or well (caisson) foundations, which transfer loads to deeper, more stable strata that remain unaffected by surface scour [16]. Alongside these, nature-based protection measures, such as riprap linings, gabion mattresses, vegetated embankments, and bioengineered root systems, are increasingly encouraged to stabilize soils, dissipate flow energy, and maintain ecological integrity. Moreover, the integration of real-time scour monitoring systems, including sonar and fiber-optic sensors, allows for early detection of erosion, ensuring timely maintenance and enhanced safety performance.

Achieving true sustainability in foundation systems requires balancing multiple and sometimes conflicting criteria—engineering performance, economic efficiency, and environmental responsibility. This holistic assessment approach often employs multi-criteria decision analysis (MCDA) frameworks to evaluate and compare foundation alternatives. For example, in a case study analyzing bridge foundations under a design discharge of 410 m^3/s, a well foundation with a depth of 15 m (including a cutting edge) was determined to be both economically superior and constructionally simpler than an equivalent configuration using numerous pile foundations [5]. Such outcomes reveal that optimal sustainable solutions are not always technologically complex but often result from context-sensitive design choices that integrate geological, hydraulic, and economic constraints. Conversely, for small or shallow channels where flow velocities and scour depths are limited, shallow foundation systems such as rafts or spread footings can become viable and sustainable options—especially when combined with hydraulic interventions like barrages, silt-control weirs, or flow-regulating structures upstream to mitigate erosion and sediment transport [17-18].

Sustainable foundation engineering represents a paradigm shift from traditional strength-based design toward a performance-based and resilience-oriented approach. The integration of low-carbon materials, optimized geotechnical design, and nature-based adaptive strategies enables engineers to construct foundations that are not only technically robust and cost-effective but also environmentally responsible. As infrastructure systems face the dual pressures of rapid development and climate change, future geotechnical practice must emphasize long-term durability, reduced life-cycle emissions, and adaptive capacity to environmental uncertainties [19]. Sustainable foundation systems for small bridges, therefore, must holistically balance engineering reliability,

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construction feasibility, and ecological preservation—thereby ensuring that the infrastructure of tomorrow is both structurally resilient and environmentally regenerative.

Despite significant technological progress in geotechnical and structural engineering, substantial research and implementation gaps persist in the context of sustainable foundation design for small- and medium-span bridges in India. The majority of existing minor bridges across the country continue to employ conventional foundation systems, such as well (caisson) foundations or pile foundations, that have been optimized primarily for economic feasibility, constructability, and short-term performance rather than for environmental efficiency or carbon footprint minimization [16]. These designs, though well established in terms of structural reliability and compliance with Indian Roads Congress (IRC) standards, are often based on empirical approaches and do not incorporate life-cycle environmental assessments or carbon accounting methodologies, which are critical under current sustainability imperatives.

A detailed examination of the available research literature and field practices reveals that the body of work dedicated to sustainable or low-carbon foundation design specifically tailored to minor bridges over small rivers and streams remains limited. The majority of sustainability-related studies in geotechnical engineering focus on large-scale infrastructure, such as highway flyovers, major river bridges, and offshore structures, where life-cycle impacts and material efficiencies are studied in greater depth. By contrast, small river bridges, which constitute a vast proportion of India's rural transportation network, are comparatively neglected in terms of targeted research, advanced modeling, and design innovation. Furthermore, the hydrologic and geomorphic characteristics of small streams—such as rapid flow variability, local scour concentration, sediment mobility, and shallow alluvial deposits—introduce distinct challenges that cannot be adequately addressed by conventional design frameworks intended for larger river systems.

The absence of dedicated technical guidelines or codified standards for integrating sustainability into the foundation design of small bridges further exacerbates this gap. Current Indian standards (e.g., IRC:78, IRC:45, IRC 06, and IRC SP 13) [20-23] focus primarily on structural safety and serviceability but lack explicit provisions for environmental performance metrics, embodied energy quantification, or climate resilience parameters. Consequently, the practical implementation of sustainable practices in foundation engineering remains fragmented and largely dependent on project-specific decisions rather than systemic design philosophy.

Given these deficiencies, the present review seeks to synthesize and consolidate existing knowledge pertaining to environmentally conscious foundation practices applicable to small river bridges. It aims to identify successful national and international case studies demonstrating the use of low-carbon materials, geopolymer and supplementary cementitious binders, recycled aggregates, and geosynthetic-reinforced systems that reduce energy and material intensity without compromising structural integrity. Additionally, it highlights the potential of emerging geo-monitoring technologies, including remote sensing, fiber-optic instrumentation, and Internet of Things (IoT)-based scour detection systems, for ensuring adaptive management of foundation performance under dynamic hydraulic and climatic conditions.

The review also underscores the necessity for life-cycle-based evaluation frameworks, encompassing both environmental and economic dimensions, to guide the transition from traditional foundation design to sustainability-driven engineering practice. Through this comprehensive synthesis, the work aims to bridge the knowledge gap between conventional foundation solutions—dominated by empirical, cost-centric design—and the future demands of low-carbon, resilient, and resource-optimized infrastructure. The findings are expected to inform the development of context-specific design guidelines, research priorities, and policy recommendations that can promote sustainable foundation systems for small river bridges, thereby aligning rural infrastructure development with national and global sustainability objectives.

CASE STUDIES

In India's alluvial plains, multiple studies illustrate the shift toward simpler, more sustainable foundation solutions for minor bridges. Field investigations in Uttar Pradesh found that most recent small-bridge projects still used deep well foundations in soft riverbeds. A survey along the Reth River (Barabanki district) identified ten bridges (chainages 2.86–71.96 km) all on well foundations. While these wells function well on sandy alluvial strata, engineers note that construction is lengthy: extensive excavation and dewatering are needed. In contrast, Varma et al. (2019) [6] compared traditional well foundations to precast RCC box culvert bridges in alluvial rivers, and found the box culvert system to be economically superior. Box culverts use shallow raft foundations and prefabricated elements, greatly reducing excavation and machinery requirements. Their study for bridges designed at 300 m^3/s flood discharge reported up to 6% less earthwork and lower material costs for box-type culverts, concluding that "box type minor bridges are best option on small & minor rivers" in alluvial terrain. The listed advantages included lower formation levels (saving on approach embankments), elimination of heavy well-sinking operations, and simpler, more stable compression behavior. Such deep-pile foundations are often used to resist scour in stream bridges.

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In another Indian study, Upadhyay & Srivastava (2020) [5] performed detailed design checks on well versus pile foundations for a hypothetical 77.75 m bridge over a medium river (Q=410 m^3/s). They computed scour depths up to 8.82 m for the bridge piers and determined that a well sunk to 15.0 m (including a 0.99 m cutting edge) was required to reach competent soil. Their analysis showed that, under these conditions, a well foundation was "more efficient and economical than a pile foundation" for medium rivers. This result was consistent with the Reth River survey, which concluded that the majority of small-bridge foundations in alluvial zones remain well-based due to cost-effectiveness. Notably, the Upadhyay study also pointed out that for small rivers, traditional pile foundations often proved uneconomical compared to wells, and that raft foundations (if flow can be controlled) offered an even cheaper alternative. These Indian examples underscore that local geology and hydraulics drive foundation choice: wells and rafts dominate when buried soil is soft and scour deep, whereas piles might only be used where space or groundwater conditions dictate.

Other projects in India have explored geo-synthetics in bridge approaches. For instance, some recent low-volume bridges employ geosynthetic-reinforced soil (GRS) approach slabs and abutments using local fill, reducing concrete volume and accelerating construction [24]. These techniques, though not yet widespread in India, exemplify sustainable foundations by using locally available materials and avoiding heavy materials.

Globally, there is growing interest in rapid, low-impact foundations for rural bridges. In arid regions of the United States, many small streams are ephemeral, meaning they carry flow only during storm events. Designers are increasingly aware that transient scour can undermine shallow foundations. For example, one researcher describes bridges in the U.S. where designers "often prefer the use of deep foundations for bridge structures in stream environments" to cope with scour [25]. During flood pulses, streambed pressures change rapidly and partially saturate the soils, but do not fully buoy up the foundation except briefly. By driving piles below the maximum expected scour level and into stable strata, engineers prevent progressive failure. Samtani's article provides practical guidance on modeling the transient hydraulic forces and optimizing pile depth (e.g., using permeable layers to limit uplift). It emphasizes that while deep foundations increase initial cost, they avert scour damage that could cause catastrophic collapse. This U.S. experience highlights the necessity of integrating hydrologic analysis into foundation design for sustainability and safety.

SUSTAINABLE FOUNDATION DESIGN: NECESSITY AND ELEMENTS

A sustainable bridge foundation goes beyond mere bearing capacity; it embodies the "triple bottom line" of durability, economy, and ecology. Key elements include the use of materials with low embodied carbon (e.g. cement replacers, recycled aggregates) [25], designs that minimize earth-moving, and features that aid adaptability. For instance, using steel tube piles or ground screws instead of cast-in-place concrete avoids large excavation, reducing both emissions and habitat disturbance. Integrated scour protection (e.g. riprap, vegetation) is critical to prevent erosion-related foundation failure, as scour remains the top threat to bridge longevity [26].

Sustainability also mandates recycling and reuse. Foundations under old bridges can sometimes be retrofitted or reused for new superstructures, saving resources (a topic of growing interest in accelerated bridge construction). Incorporation of industrial by-products (fly ash, blast furnace slag) into concrete or soil mixes improves strength and reduces waste. Geosynthetics (geotextiles, geogrids) stabilize soils without chemical additives, and can be produced from recycled polymers.

Environmental life-cycle aspects are now being studied: full analysis of a bridge's foundation should include upstream mining emissions, in-place greenhouse gases, and end-of-life reuse. Recent LCA-based studies urge that even foundations account for carbon budgeting [28, 29]. In practice, this means selecting the smallest yet safe foundation and optimizing formwork and reinforcement. For example, a well-designed shallow raft might use much less cement and steel than multiple drilled piers, if site conditions allow. Finally, monitoring technology (sensors for settlement or moisture) can extend service life by detecting issues early, aligning with sustainability goals of longevity and resilience.

Overall, sustainable foundations are necessary because bridges must serve communities for decades under increasingly unpredictable climates. A foundation design that neglects environmental costs or future hazards (e.g. increased floods) will likely incur high repair and replacement impacts. In contrast, a low-impact foundation that is resilient to scour and can be adapted or repurposed embodies true sustainability for small-bridge infrastructure.

SCOPE OF RESEARCH

There exist significant and multidisciplinary research opportunities in advancing the sustainability and resilience of small-bridge foundation systems. Presently, the life-cycle optimization of such foundations—encompassing both environmental and economic performance metrics—remains in a nascent stage. Most studies focus on initial construction cost and load-bearing adequacy, while quantitative evaluations of embodied energy, embodied carbon, and total life-cycle cost (LCC) across different foundation typologies (e.g., wells, piles, rafts, precast footings) are largely absent [30]. Future investigations should employ Life-Cycle

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Assessment (LCA) and Life-Cycle Cost Analysis (LCCA) methodologies under realistic hydrologic and geotechnical conditions, allowing for data-driven comparisons between traditional and sustainable alternatives [31].

Furthermore, there is strong potential for advanced computational modeling and data-driven predictive tools to revolutionize design decision-making in small-bridge foundations. The use of finite element analysis (FEA), computational fluid dynamics (CFD), and coupled hydro-geotechnical models can enhance understanding of scour mechanisms in ephemeral and seasonal streams, which are characterized by fluctuating discharge, sediment transport, and rapid bed morphology changes. The integration of machine learning algorithms with field-monitored hydraulic and geotechnical datasets can lead to more accurate, site-specific scour prediction models, guiding the selection of foundation depth, geometry, and materials under uncertainty [23]. Such hybrid computational–data models can also support performance-based design frameworks, aligning with resilience and risk-informed design philosophies.

In parallel, experimental and material research offers immense potential for reducing the carbon intensity and improving the mechanical performance of foundation materials. For example, engineered cementitious composites (ECCs) incorporating fly ash, slag, and silica fume can provide high ductility and crack resistance with reduced cement content [32]. Similarly, fiber-reinforced soils (using synthetic, steel, or natural fibers) have shown promise in enhancing the shear strength and settlement resistance of weak strata. Another emerging area is Microbially Induced Calcite Precipitation (MICP)—a bio-mediated soil treatment technique that improves bearing capacity and stiffness while serving as a low-carbon alternative to conventional chemical stabilization. Additionally, novel foundation systems such as large-diameter polymeric (plastic) piles, glass fiber-reinforced polymer (GFRP) composites, and hybrid concrete–steel foundations merit systematic investigation for their potential to combine lightweight construction, corrosion resistance, and recyclability in small-span bridge applications [33, 34].

The adoption of real-time geotechnical monitoring systems also represents a critical frontier in sustainable foundation management. Deploying settlement gauges, pressure cells, inclinometers, and strain sensors, integrated within Bridge Management Systems (BMS), can enable continuous health monitoring and predictive maintenance of substructures. This proactive approach would allow early detection of abnormal settlement, tilt, or stress concentrations—thus preventing catastrophic failures and extending service life. The coupling of sensor data with digital twin models and Internet of Things (IoT) platforms can facilitate adaptive maintenance planning and performance optimization based on real-time feedback loops.

Moreover, future design guidelines must explicitly integrate flood risk management and climate adaptation principles into foundation planning. Employing probabilistic hydrologic projections, non-stationary flood frequency analysis, and climate scenario modeling can help quantify the effects of changing rainfall patterns, sediment transport, and scour potential on foundation stability. Embedding these parameters in national standards would render design methodologies future-proof and aligned with climate-resilient infrastructure frameworks. Similarly, research into foundation reuse, retrofitting, and design for disassembly aligns with circular economy principles, allowing materials and components to be recovered or repurposed, thereby reducing construction waste and resource extraction.

Importantly, advancing sustainability in small-bridge foundations will also require interdisciplinary collaboration that bridges civil, environmental, and ecological sciences. The emerging domain of eco-hydro-slope engineering—which integrates hydraulics, geomorphology, soil mechanics, and ecology—presents opportunities to develop foundation systems that preserve or enhance aquatic and riparian habitats while ensuring structural safety. For instance, bioengineered scour protection and vegetated abutments can promote biodiversity and natural sediment balance, aligning infrastructure with environmental stewardship.

The research frontiers in this domain encompass four key dimensions: (1) material innovation, through development of low-carbon and bio-enhanced composites; (2) design methodology, employing multicriteria optimization and AI-assisted decision frameworks; (3) monitoring and digital technologies, enabling predictive maintenance and adaptive management; and (4) real-world implementation studies, including full-scale experiments and long-term performance monitoring of novel foundation systems. Future work must remain application-oriented, seeking to translate academic research into codified guidelines and standards for sustainable, resilient, and low-carbon foundations specifically tailored to small river bridge environments.

CONCLUSION

Sustainable foundation solutions for bridges over small rivers are essential for building resilient infrastructure in the face of evolving environmental challenges. This review has shown that, in regions like the Indian alluvial plains, traditional well foundations continue to dominate due to soil conditions and cost-effectiveness. However, alternatives such as prefabricated box-culverts and shallow rafts have proven viable, offering reduced construction time and ecological impact. Internationally, strategies like deep-pile foundations in arid streams or geosynthetic-reinforced soil abutments demonstrate how local context drives the most sustainable choice.

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Sustainable foundation design requires a holistic view: minimizing material use and emissions, maximizing durability against scour and climate loads, and facilitating reuse. Current literature highlights opportunities (e.g. recycling fly ash, using geogrids) but also gaps—in particular, the lack of targeted research on small-bridge foundations as distinct from large-scale projects. To address this, future research must bridge engineering analysis with environmental assessment. Life-cycle thinking, smart monitoring, and innovative materials should be integrated into design practice.

Ultimately, by adopting foundation technologies that are economically and ecologically efficient, engineers can build small river bridges that last longer and adapt better to change. This is critical not only for protecting investments but also for safeguarding communities: well-founded bridges keep water resources clean and passageways open during floods. In conclusion, sustainable foundation engineering offers a path toward safer, greener small-bridge infrastructure.

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