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Thematic Articles on

Sustainability of Civil Infrastructure

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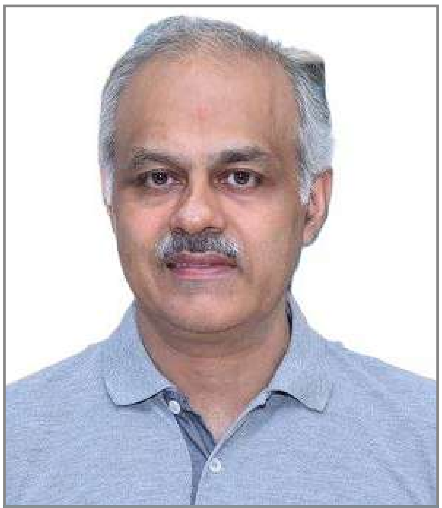
Featured Articles



Prof. Sanjay Mittal
Vice-President (Publications),
INAE

From the Editorial Desk

We are pleased to share with you the latest edition of *INAE TechFrontier*, the quarterly e-magazine launched on April 20, 2025, during the INAE Foundation Day of the Indian National Academy of Engineering (INAE).

The initial issues of Volume 1 of *INAE TechFrontier* include *Quantum Technology: India-centric Policy Perspectives* (Issue I), focusing on policy frameworks guiding the growth of quantum technologies in India; Manufacturing (Issue II), highlighting India's drive towards technological self-reliance and global competitiveness; and *Cyber-Physical Systems* (Issue III), exploring the integration of computation, communication, and control across key sectors. The magazine continues to serve as a platform for showcasing recent advancements and innovations across the engineering and technology landscape.

This edition focuses on the theme of *Sustainability of Civil Infrastructure*, a domain of critical importance in the context of rapid urbanization, climate change, and resource constraints, emphasizing resilient, environmentally responsible, and future-ready engineering practices.

The articles in this issue collectively explore innovative design approaches, climate-responsive strategies, advanced foundation systems, and low-carbon materials, offering valuable insights into building sustainable and durable infrastructure for the future.

We are grateful to the Guest Editors for their valuable efforts in curating this edition and ensuring the quality and relevance of the contributions.

The next issue shall focus on ***Artificial Intelligence*** and is scheduled for June–July 2026. We are actively inviting engaging and original articles from interested contributors.

Submissions may be sent to publications@inae.in.

Building for Better Tomorrow: Sustainability and Infrastructure

Dr. N. Anandavalli, FNAE, Director, CSIR-Structural Engineering Research Centre, Chennai

Dr. N. Anandavalli

Dr. N. Anandavalli, FNAE, Director of CSIR-Structural Engineering Research Centre, Chennai, graduated in 1991 from University of Madras earning the Rao Bahadur S. Subbarayachariyar Gold Medal. She completed postgraduate studies at PSG College of Technology as top ranker and earned a Ph.D. from Anna University on laced composite elements. She holds INAE and IEI fellowships and is member of ASCE. She is life member of "Indian Concrete Institute" and "Computer Society of India". She is selected as a Member of INSA Women Associates (IWA). She has US and Indian patents on Laced Composite System, and received the Sir Arthur Cotton Memorial Prize and John C Gammon Prize. Her research interests are structural blast response, sustainable materials, and composite modelling.

Abstract

Sustainability embodies the balance of the five fundamental elements—earth, fire, water, air, and space—reflecting harmony between nature and human activity. Resource sustainability calls for reducing pressure on natural systems while minimising environmental risks. In this context, the transition from fossil fuels to renewable energy is crucial, alongside the development of future-ready offshore renewable infrastructure. Water security is addressed through efficient usage in construction and the advancement of air-curing materials that significantly reduce water demand. Clean air and climate-smart construction are promoted through low-carbon building materials, climate-resilient demonstration structures, and CO_2-cured, carbon-sequestering concrete. These innovations illustrate the convergence of technology and nature in shaping a climate-equilibrium framework.

The discussion further extends to sustainable civil infrastructure, highlighting the importance of life cycle assessment, resource-efficient design, durable and advanced materials, structural health monitoring, retrofitting, and disaster resilience. Ultimately, sustainability is not merely a technical pursuit but an ethical, cultural, and systemic responsibility. It requires collective action from researchers, industry, policymakers, and citizens. The enduring principle of living in harmony with the five elements—now increasingly supported by modern scientific understanding—remains central to achieving resilient development and a thriving future.

Introduction

நிலம் தீ நீர் வளி
விசும்போடு ஐந்தும்
கலந்து மயக்கம் உலகம்

(Tholkappiyam, the oldest extant work of Tamil literature and the earliest Tamil grammar text)

which says that the world is nothing but a delicate balance of 5 basic elements, namely, earth, fire, water, air and space.

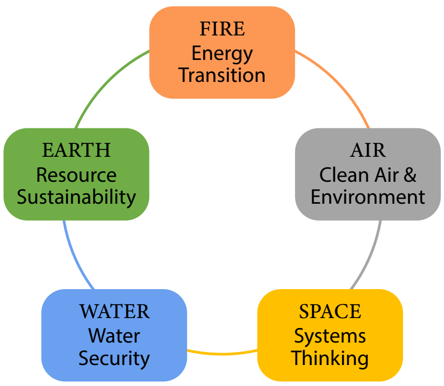


Fig. 1 - Sustainability: Balance of Basic Five Elements

This has sustained life for millennia. Sustainability, at its core, is maintaining this balance (Fig. 1).

Sustainability: Balance of Basic Five Elements

Earth represents the resource sustainability. Our soils and land resources are under pressure from urbanisation, mining, and deforestation. Waste occupies more space than ever. As our cities grow taller, we need to develop low carbon construction materials. The use of recycled materials addresses two aspects of sustainability: depletion of natural materials as well as environmental hazard caused by used materials. CSIR-SERC is developing technologies using Construction and Demolition (C&D) wastes. The development is not restricted to non-structural components, but extends to the utilisation of these C&D wastes in structural applications.

Fire represents the energy transition from fossil fuels to renewables. In this direction, we need to create a road map for repurposing existing thermal power plant structures, even though not in near future. Challenges of renewable energy infrastructures such as floating platforms for wind turbines and solar farms needs to be addressed. This is even more necessary in the case of offshore renewable energy infrastructure. Keeping this in view, CSIR-SERC has developed the know-how on the design of offshore floating platforms to support renewable energy structures such as wind turbines and solar farms (Fig. 2). The solution focusses not only on design and analysis, but also structural health monitoring of these structures.

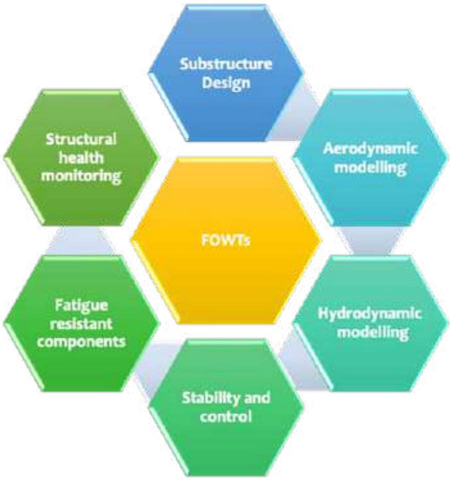


Fig. 2 - Floating Offshore Platform for Wind Turbine

Fig. 3 - Climate Resilient Demo Building at CSIR-SERC

Water in terms of sustainability is represented as water security. Efficient use and storage of water is essential for survival of life. Construction industry is one of the largest utilisers of water, both for production of materials as well as for curing of concrete structures. Some of the advanced materials, where the concept of air curing is adopted, are already being researched into. CSIR-SERC has developed the know-how and technologies in this direction.

Air is represented by means of clean air and environment. Climate change mitigation strategies are essential to be adopted in construction in addition to the use of carbon sink materials. CSIR-SERC has developed two types of building blocks, one is by using Expanded Polystyrene (EPS) blocks whereby thermal comfort is taken care and the other is by using stabilised blocks. The efficacy of these blocks is demonstrated through the construction of a climate resilient demo building (Fig. 3). Towards carbon sink materials, efforts are being taken for carbon capturing through CO_2 curing of concrete blocks which is an accelerated, sustainable, and eco-friendly technology. By making materials more durable, sustainability aspect is addressed by reducing the emissions.

Element Space can be idealised as Systems thinking, where in the climate equilibrium is ensured by global view of the whole process. A disturbance in one element cascades into others, thereby disturbing the whole eco system. Technology and nature are not two different things. Nature provides us with best optimised solutions. CSIR-SERC is developing bio-inspired functionally graded composite panels for enhanced impact resistance.

Sustainability in Civil Infrastructure

The economic value of building stock including infrastructure is often among the largest assets in national economies. As people tend to spend more than 90% of their time in buildings or in transportation, it is easily understood that all three dimensions of sustainability (namely, social, environmental and economical), are highly significant for consideration in the building and construction sector. Sustainability implies that the needs of the present generation are met without wasting, polluting or damaging/destroying the environment and without compromising the ability of the future generations to meet their needs.

Sustainability of civil infrastructure involves designing, constructing, and maintaining structures—such as roads, bridges, and buildings—to minimise environmental impact, enhance durability, and ensure long-term economic and social benefits for future generations. It focuses on resource efficiency, using eco-friendly materials like recycled steel and low-carbon concrete, and integrating climate resilience to withstand extreme weather events.

Sustainability in infrastructure focuses on creating long-lasting, environmentally friendly systems that support economic growth while minimizing ecological harm. Sustainable construction prioritises energy efficiency via insulation, solar integration, and low-carbon materials like recycled or locally sourced options. Technologies such as Building Information Modeling (BIM) and IoT optimise designs and monitor usage to cut waste. Prefabricated materials and fleet monitoring further lower on-site emissions (1,2). India aims to reach net-zero emissions by 2070 through the "Panchamrit" pledge announced at COP26, focusing on renewable energy expansion, efficiency improvements, and resilient infrastructure (3).

In essence, sustainability in infrastructure development can be looked into various aspects as follows:

Life Cycle Assessment (LCA): Evaluates environmental impacts from material extraction and construction to operation and decommissioning.

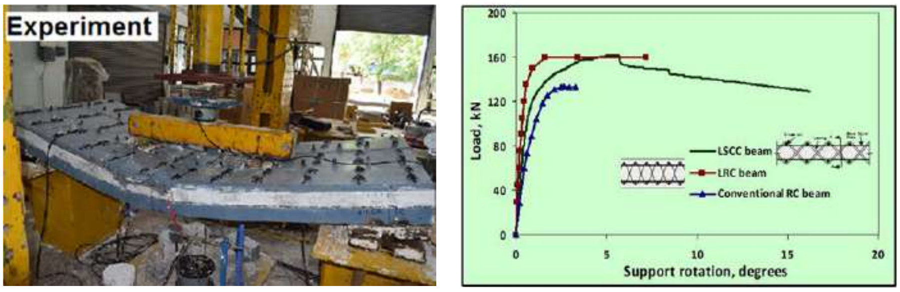


Fig. 4 - Laced Steel-Concrete Composite System

Efficient design optimisation to use less material and energy (e.g., Laced Steel-Concrete Composite System, bio inspired functionally graded composite panels). CSIR-SERC has developed Laced Steel-Concrete Composite System which effectively utilises the material (Fig. 4). As seen from Fig. 4, for the same quantity of material, the simple innovation has led to enhanced performance nearly 4 times that of conventional material.

Durability: Long life reduces resource use over time (e.g. Textile Reinforced Concrete, FRP, Steel-FRP Composites etc.).

Innovation: Use of advanced materials (e.g., geopolymer, recycled aggregates, ultra-high performance concrete, engineered

Fig. 5 - 3D Print Pod using Ultra-High Performance concrete with fibres

composites, 3D printed materials).

Monitoring and retrofitting: It is to extend the lifespan of existing structures (e.g. Structural Health Monitoring of bridges) - One of the thrust areas of CSIR-SERC is SHM including sensor development and digital twins for predictive maintenance of structures.

Disaster resilience: Designing for floods, quakes, and climate extremes (cyclone shelter, climate resilient buildings). In addition to natural disasters, man-made disasters also need to be addressed.

This holistic approach transforms the construction industry by balancing ecological responsibility with the necessity of infrastructure development.

Sustainability - A Collective Responsibility

True sustainability is not merely technological - it is ethical, cultural, and systemic. It requires:

- Responsible consumption
- Intergenerational equity
- Circular economy models
- Resilient infrastructure
- Science-policy-industry collaboration

Sustainability is a collective responsibility of researchers, industrialists, policy makers and citizens.

For research: affordable, scalable and sustainable innovations

For industry: adopting clean technologies, circular economy practices, and ESG principles

For policymakers: creating the enabling environment for adoption of sustainable technologies

For society: to rediscover our ancient wisdom: harmony with nature is the only true progress.

Summary

Ancient wisdom understood what modern science now confirms.

When the five elements are in harmony, life flourishes. When they are disturbed, imbalance follows.

Civil infrastructure development, especially in rapidly urbanising contexts, cannot focus solely on growth; it must integrate ecological responsibility, long term durability, and resilience to climate and disaster risks. Ultimately, true sustainability is not merely technological progress but a collective, ethical commitment encompassing responsible consumption, intergenerational equity, circular economy practices, and robust science–policy– industry collaboration. By rediscovering the harmony between nature and technology, and by treating the five elements as a guiding principle, society can build resilient infrastructure that meets present needs without compromising the ability of future generations to thrive.

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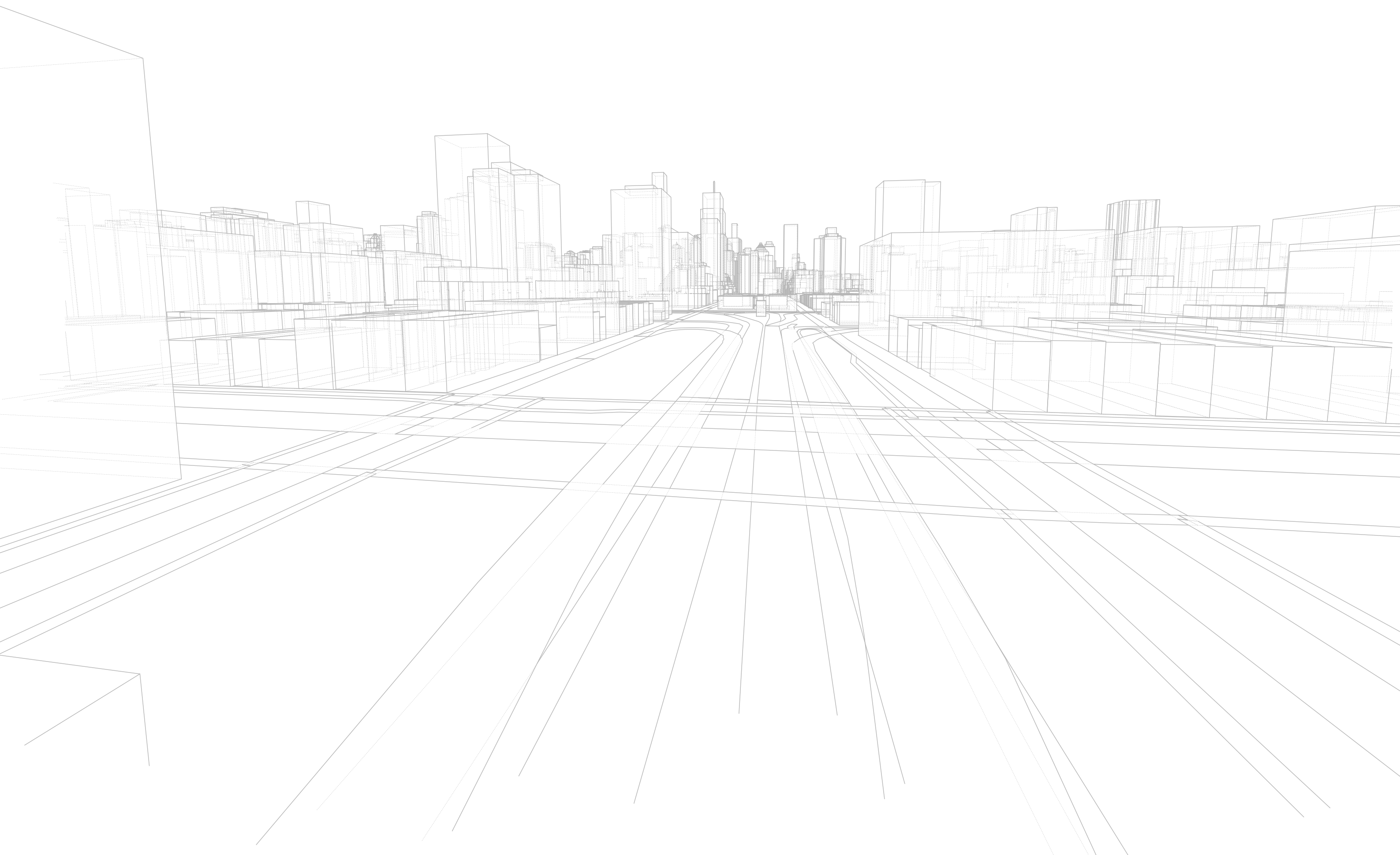

Sustainability of Civil Infrastructure - Is It an Option or Necessity?

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Prof. Sriman Kumar Bhattacharyya

Prof. S. K. Bhattacharyya, FNAE, FNASc currently is the Founding Vice Chancellor of Shiv Nadar University Chennai. He was a senior Professor and former Head of Civil Engineering at IIT Kharagpur. He is the former Deputy Director and Director (Officiating) of IIT Kharagpur. He was the former Director of CSIR-Central Building Research Institute at Roorkee. He also had served as AICTE-INAE distinguished Professor at IIEST, Shibpur. He was the Adjunct Professor of BITS-Pilani and Outstanding Professor of Academy of Scientific and Innovative Research (AcSIR). He was the Chief Editor of the 'Institution of Engineers (India) journal – A'- series.

Abstract

Sustainability of Civil Infrastructure is an important issue today as the civil infrastructure contributes to a large extent to the generation of carbon footprint thereby causing serious concern to the environment. With the changing scenario in the climatic conditions, it has become even more a necessity to adhere to the sustainability issues in terms of utilisation of appropriate materials, cost effective and newer construction technologies, maintenance strategies and reusability. While appropriate policy decisions at different level are important, it is imperative that all the stakeholders of the civil infrastructure projects are made aware of the needs so that sustainability measures can be adopted at different levels as deemed fit. Today, adopting to sustainability measures in civil infrastructure is not an option but a dire necessity.

Introduction

Development of civil infrastructure is considered as the backbone of the modern society. Today the country is investing a large sum of money to develop several infrastructural projects. Infrastructure such as buildings, roads, bridges, water systems, energy grids and digital networks enables economic growth and social well-being. However, development of infrastructure in a traditional way has often come at a significant environmental and social expense – in terms of depletion of natural resources, carbon emissions, ecological imbalances, and inequitable access. Question that arises as, is the traditional way of development of infrastructure the right way to continue to achieve sustainability? Possibly, no, as it comes at the expense of social and environmental impacts. At the same time, today a fundamental question confronts the policymakers, engineers, and the planners alike, is sustainability in infrastructure merely an option or has it become an unavoidable necessity?

Sustainable Infrastructure

Sustainable infrastructure refers to the planning, design, construction, and operation of physical assets in a manner that enhances durability, minimises environmental impact, optimises resource efficiency and enhances social and economic value across the entire life cycle. It is not merely about using eco-friendly materials, it is a holistic approach that integrates environmental responsibility, economic viability, and social inclusiveness. As for example, energy-efficient buildings reduce operational costs, durable materials lower maintenance needs, the resilient systems minimise losses from disasters. Hence, the objective should be to adopt such measures while planning and designing the infrastructural systems to achieve sustainability.

Environmental Aspects

The environmental aspect focuses on reducing carbon footprints, conserving natural resources, and protecting ecosystems. Green building practices, renewable energy integration, efficient waste management and water conservation systems are the key components. For example, energy efficient buildings with solar panels, rainwater harvesting, and smart lighting systems significantly reduce operational emissions and long-term costs. Similarly for other infrastructural systems, several adoptable measures are available to achieve environmental sustainability.

Economic Aspects

In the past it has been experienced that production of earthquake resistant structural system comes at a premium. To avoid that there was a tendency to adopt risk-based design depending on the geological aspects, though it has been proven time and again that if the measures are adopted, the same helps the system in the long run. Similarly, implementation of sustainable infrastructure is often perceived as expensive in the short term, but it yields substantial economic benefits over time. Lower maintenance costs, reduced energy consumption, longer asset life and improved productivity make such investments financially sound. Lifecycle cost analysis demonstrates that sustainable designs frequently outperform conventional alternatives in durability and efficiency. Hence, adoption of strategies for sustainable infrastructure is strongly recommended.

Social Aspects

Infrastructure should serve people equitably. Accessibility, safety, and inclusivity are essential elements of sustainability. Projects that consider local community needs, promote public transport, create green public spaces, and ensure disaster resilience contribute to improved quality of life. Sustainable infrastructure also generates employment opportunities and supports local economies.

Role of Technologies

Today advancement of technologies is happening at a very fast pace. Technological advancement is a powerful enabler of sustainable infrastructure. Smart sensors, Internet of Things (IoT), Building Information Modelling (BIM) and data analytics help monitor performance, predict maintenance needs, and optimise resource use. Digital twins and simulation tools allow engineers and planners to evaluate environmental impacts before construction begins, reducing errors and waste.

Policy and Governance

It has been realised that effective sustainability measures require strong policies, regulatory frameworks, and institutional commitment. Governments, private sectors, and academic institutions must collaborate to establish standards, incentives, and accountability mechanisms. Public-private partnerships and green financing models are increasingly playing a critical role in scaling sustainable projects.

Academic Intervention

It has been realised that the stakeholders to create infrastructural facilities should be educated about the measures that are already available or prevalent to implement sustainability in infrastructural projects. Towards this, it's necessary to create training modules to educate different groups of people in a systematic way. Academic institutions should be advised to incorporate the sustainability strategies in their curricula so that the younger generations are made aware of this concept.

Challenges and the Way Forward

As stated earlier, despite several advantages, sustainable infrastructure faces challenges such as higher initial capital requirements, lack of awareness, limited technical expertise and policy gaps. Overcoming these barriers demands interdisciplinary collaboration, capacity building and a shift in mindset from short-term gains to long-term value creation.

Concluding Remarks

Sustainability of infrastructure is no longer a matter of choice. Sustainability in infrastructure is about building responsibly for future generations. It aligns engineering excellence with environmental stewardship, economic logic, and social responsibility. As urbanisation accelerates and climate concerns intensify, the adoption of sustainable infrastructure practices will define the resilience and prosperity of societies worldwide. The true measure of progress lies not only in what we build but in how wisely and sustainably we build it. Sustainability in infrastructure is, therefore, no longer an option, but it is a necessity for ensuring long-term prosperity and resilience.

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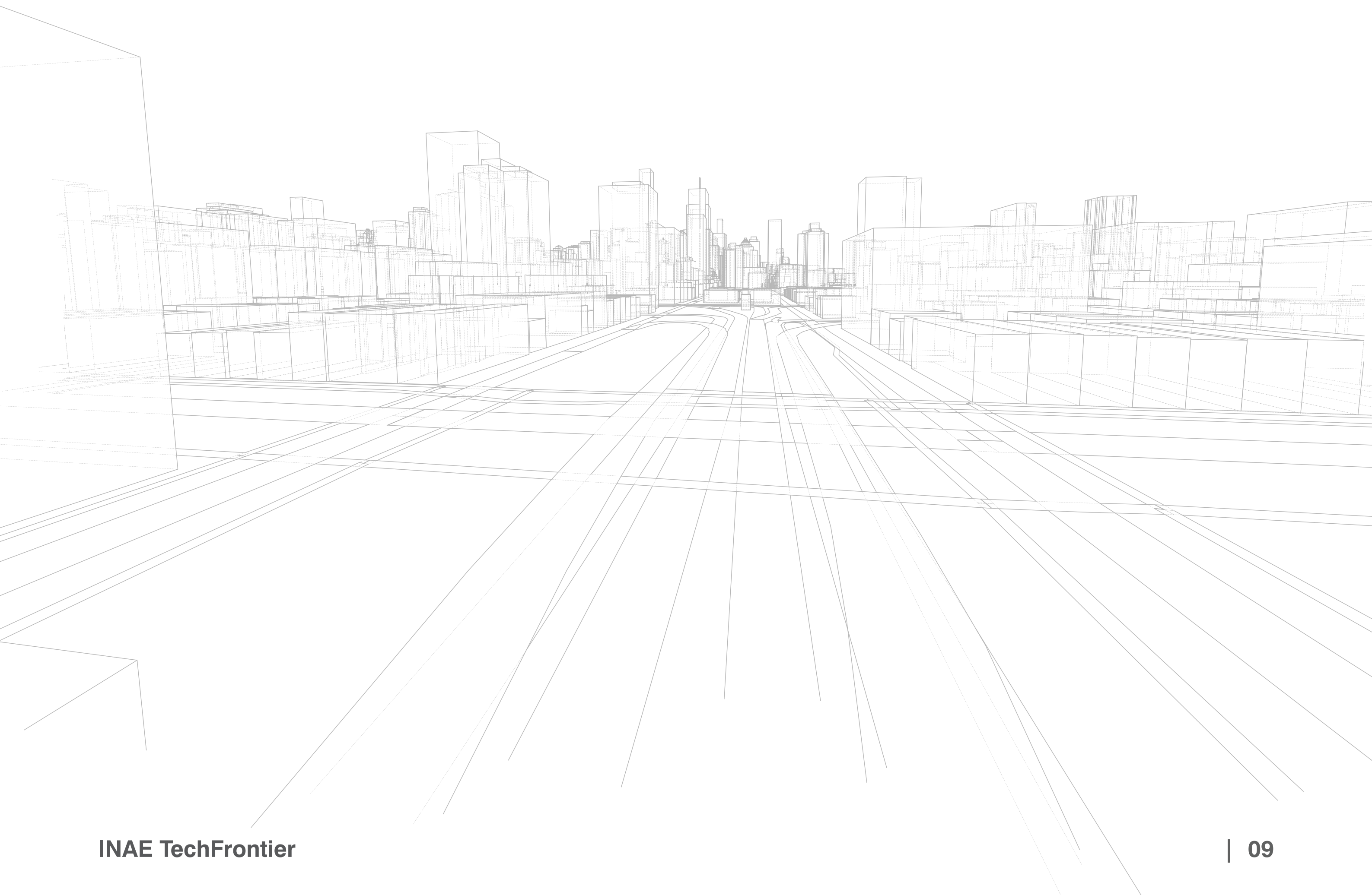

Achieving Sustainability through Combined Pile–Raft Foundation Systems for Mega Infrastructures: Insights from new IS: 19117 (2025)

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Abstract

Smart Cities Mission aims to boost the construction of large infrastructure projects in India where sometimes it faces significant constraints arising from complex subsoil conditions and high consumption of steel and cement, thereby affecting sustainability goal requirements. Since foundation systems supporting these structures play a significant role in governing construction cost, there is an increasing need for adopting rational and performance-based design philosophy. The Combined Piled-Raft Foundation (CPRF) system offers a cost-effective sustainable alternative to conventional pile-group foundations by enabling the load-transfer through both piles and raft components. The publication of new BIS code of practice on Design and Construction of Combined Piled-Raft Foundations (IS: 19117 - 2025) provides a clear direction to the Indian geotechnical community for designing and constructing foundations for megastructures. This article systematically discusses the design philosophy and construction considerations, and shows how this code implicitly considers the sustainability requirements while maintaining safety and serviceability of the structure. The framework provided by this code supports wider adoption of CPRF systems for resilient and sustainable infrastructure development in India.

Introduction

India is entering into an era of mega infrastructure revolution with a focus on large infrastructure projects through various initiative such as Smart-Cities Mission by bringing strategic investment in infrastructure. The sustainable construction of civil engineering mega infrastructure would require a better understanding of the complex subsoil conditions and a more rational and cost-effective foundation design philosophy to support the superstructure by limiting the excessive material usage and enhancing the sustainability. The tall buildings traditionally adopt pile group

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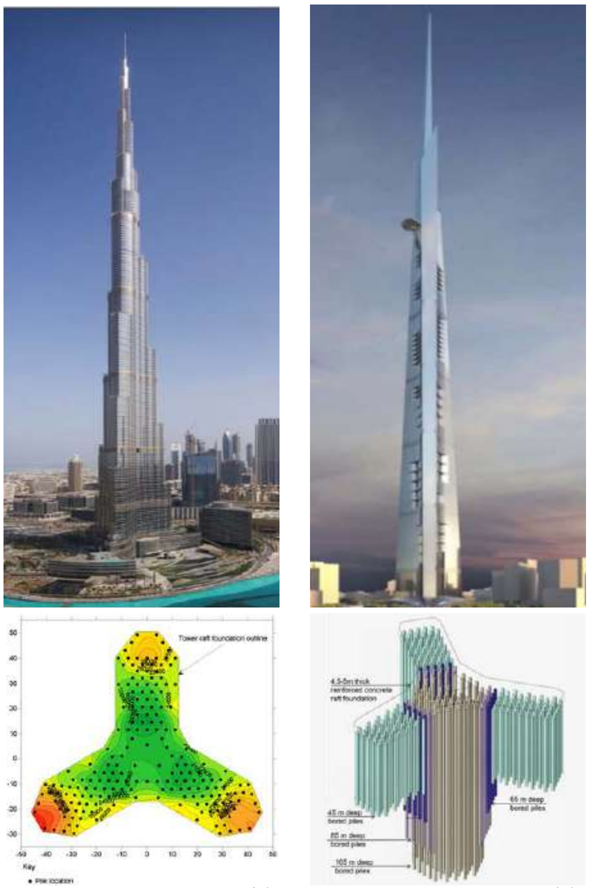
foundations by treating the piles as the sole load-carrying element, while the raft or pile cap is considered a structural connector. This design philosophy often leads to over-conservatism in the design, thereby overlooking the sustainability requirement in the infrastructure planning (Katzenbach et al. 2016).

Combined pile-raft foundation (CPRF) systems offer a sustainable alternative by allowing the raft and pile components to share the superstructure loads. This is achieved by utilising the capacities of subsoil by incorporating complex soil-structure interaction (Kumar and Choudhury 2018). The raft shares the higher portion of the load and redistributes the load while piles act as settlement reducers (Katzenbach and Choudhury 2013). This design philosophy leads to a reduction in the number of piles without compromising the safety and serviceability. The new IS: 19117 (2025), developed under the Convenorship of Prof. Deepankar Choudhury of IIT Bombay with Dr. Ashutsh Kumar as one of the contributing members under WG-17 of CED-43 of BIS and published by the Bureau of Indian standard (BIS) is a major step for achieving sustainability in the geotechnical engineering practice for Indian condition. The standard moves beyond prescriptive design rules and introduces a performance-based framework that places settlement behaviour, soil–structure interaction, and load-sharing at the centre of foundation design. Importantly, it provides engineers with the confidence and clarity needed to adopt CPRF for mega civil engineering projects.



(a) *(b)*

Fig. 1 - Megastructure supported by combined pile raft foundations: (a) Burj Khalifa (828 m) and pile distribution in CPRF (Poulos and Bunce 2008) and (b) Kingdom Tower (1008 m) and pile configuration in CPRF (Poeppel and Konstantinos 2015)

1. Adoption of Combined Pile-Raft Foundations Philosophy: Field Experiences

In recent years, CPRF has successfully been adopted as foundation system in some of the world's tallest and most complex structures. The iconic Burj Khalifa in Dubai provides a landmark example of CPRF application (Fig. 1a). The tower is supported on a thick raft approximately 3.7 m deep, underlain by 194 large-diameter bored piles, each about 1.5 m in diameter and extending 47.45 m into the ground (Poulos and Bunce 2008). Herein, raft carried a substantial portion of the applied load, while piles primarily served to control settlement. A similar philosophy underpins the foundation of the future world's tallest tower over 1 km tall Kingdom Tower (Jeddah Tower) in Saudi Arabia (Fig. 1b). Here, a very thick raft (up to 5m) was provided in conjunction with more than 270 bored piles of varying diameters, with pile lengths reaching over 100 m in the central core region (Poeppel and Konstantinos 2015).

Fig. 2 - Messeturm Tower, Frankfurt, Germany (Kumar et al. 2016)

In Europe, the 256 m tall Messeturm Tower in Frankfurt, Germany, constructed on Frankfurt clay, employed a raft supported by strategically placed piles beneath heavily loaded zones (Fig. 2). The successful use of the CPRF system, having 64 piles beneath the tower, proved it as an alternative and economical foundation system by saving approximately 3.9 million Euro, over a conventional group pile foundation (316 piles) (Katzenbach et al. 2016). The application of CPRF in industrial structures is illustrated by a raw materials storage building in South Bà Rịa–Vũng Tàu Province, Vietnam (Fig. 3). The foundation comprised an 81 m × 55.5 m raft supported by 581 piles, each 20 m long and 400 mm in diameter, and the raft carried about 23 to 31 percent of the total vertical load (Kumar et al. 2017).

The CPRF concept has also been extended to critical infrastructure such as nuclear facilities, where stringent serviceability and safety requirements apply. Advanced three-dimensional soil–foundation– superstructure interaction analyses have demonstrated that CPRFs can meet these demands when complex soil-pile-raft interaction, structural stiffness, and staged construction sequencing are explicitly accounted (Fig. 4) (Choudhury, 2026). Together, these examples show that CPRFs are proven practical solutions for various structures whose success

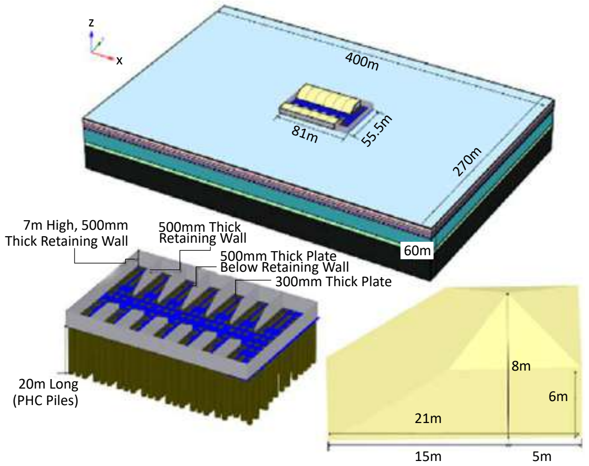


Fig. 3 - Finite element model of industrial structure of Vietnam (Kumar et al. 2017)

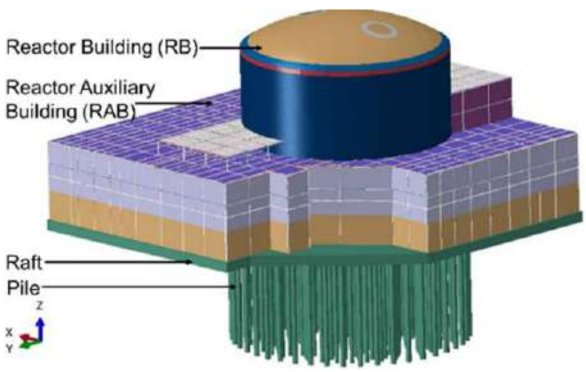


Fig. 4 - Finite Element model of a typical nuclear building supported on combined pile-raft foundation (Choudhury, 2026)

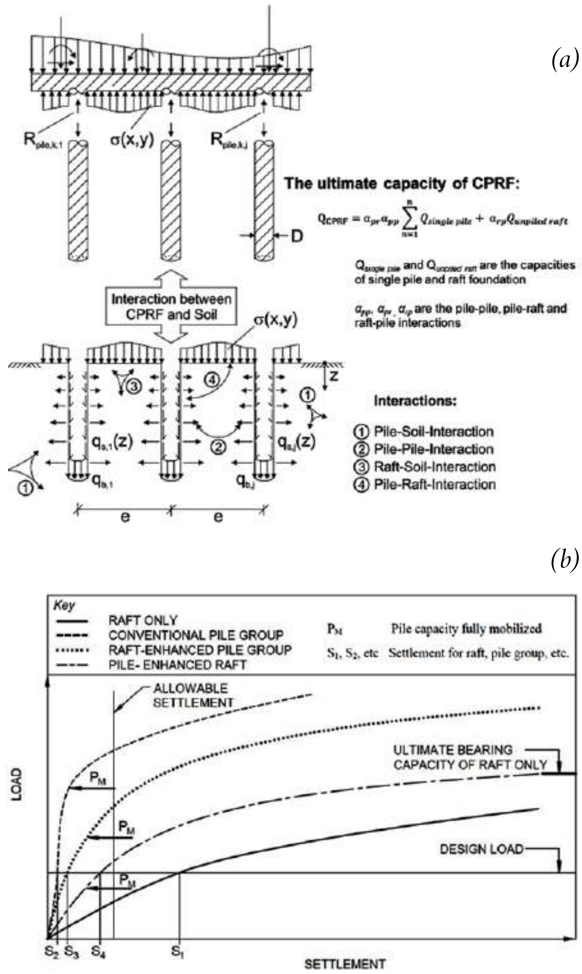


Fig. 5 - Combined pile raft foundation: (a) soil–structure interaction and (b) load–settlement response of raft, pile group, and CPRF. (IS: 19117 - 2025)

under challenging ground conditions offers valuable lessons for India's ambition to construct megastructures.

2. Design Philosophy of Combined Pile-Raft Foundations: What IS 19117:2025 Changes

IS: 19117 (2025) introduces a foundation design philosophy that recognises the combined pile–raft foundation (CPRF) as a hybrid foundation system in which the raft and piles act together to satisfy both strength and serviceability requirements, while explicitly accounting for complex soil–pile–raft interaction, as illustrated in Fig. 5a. By mobilising the combined capacities of the raft and piles, a CPRF can safely support higher loads than an un-piled raft and can achieve improved settlement performance compared with conventional pile group foundations (Fig. 5b).

A central design requirement in IS: 19117 is the explicit evaluation of load-sharing between the raft and the piles. The design is governed not only by ultimate bearing capacity but also by limiting settlement and differential settlement criteria. The code advocates a settlement-based design approach, wherein pile number, length, and spacing are optimised to reduce settlements. Analytical methods and numerical modelling techniques may be adopted depending on the complexity of sub-soil conditions and structural demands of mega civil engineering projects. For large and critical projects, the code recommends advanced soil–structure interaction analysis to realistically capture pile–pile, pile–raft, and raft–pile interaction effects. These interactions govern how the presence of one structural component within the subsoil influences the performance of the others.

The code adopts a three-stage design philosophy. The first stage involves a feasibility assessment, in which the performance of the raft without piles is evaluated and the approximate number of piles required to satisfy the design criteria is estimated. The second stage is a preliminary design stage, where the piles are designed to transfer loads through shaft resistance and end bearing. The final stage comprises a detailed design, which establishes the optimal number, location, and configuration of piles, and evaluates settlements, bending moments and shear forces in the raft, as well as the loads and moments in the piles.

2.1 Construction and Implementation Considerations

The code recognises that the performance of a CPRF system is strongly influenced by sound geotechnical practice. It therefore recommends a critical review of the geotechnical investigation report and emphasises that the input parameters used for design should be derived from both field and laboratory test data. The construction of pile with sound concrete quality while maintaining pile verticality is essential as the performance of CPRF is strongly influenced by construction practices. This is important to achieve a predictable load-settlement response particularly in the Indian context where variability in the ground condition and seismic demand of the foundation could affect the performance of the foundation. Additionally, the proper connections between the piles and raft are also critical to facilitate the effective load-transfer between the components. This is achievable through close coordination between the designer, contractor and the site engineer.

2.2 Monitoring, Observational Method, and Performance

Monitoring the load-settlement behaviour and the load-transfer mechanism within the CPRF components is pivotal for the successful application of this foundation system. IS: 19117 (2025) strongly recommends the geotechnical and geodetic measurements at the proposed and the adjacent buildings using settlement markers, extensometer and inclinometers. The selected piles and raft at strategic locations shall be instrumented with load-cells and strain gauges to monitor the evolution of loads between the foundation components and observe total and differential settlements. Experience from the use of instrumentation within the foundations of various megastructures in Europe has shown that the CPRF exhibited better performance than predicted using design methods (Katzenbach et al. 2016). In addition to validating the analytical and numerical models, this approach would reinforce designers' confidence in reducing the conservatism in future projects and update the design parameters whenever deemed necessary.

3. Achieving Sustainability, Indian Application and the Future Outlook

The building and construction sector is the largest contributor of greenhouse gases due to the use of cement and steel. Therefore, the adoption of CPRF as an alternative foundation provide a sustainable foundation solution by reducing the number of piles (less materials usage), shorter construction duration (pile construction takes a longer duration compared to raft) and lower excavation volume of soil. At the time when Indian infrastructure development moves towards achieving climate-resilience, the application of CPRF is well positioned to become an alternate solution within mega infrastructure projects by conducting a detailed ground investigation, numerical modelling and adopting sound monitoring protocols. Additionally, the CPRF can also offer better performance in seismically active regions as per the experience of its successful performance during the Tohoku earthquake (M_w = 9.0) in Japan (Yamashita et al. 2012).

Conclusions

The adoption of newly published standard IS: 19117 (2025) provides a timely solution for adopting CPRF as cost-effective and sustainable foundation system for megastructures in the Indian practice. The code clearly advocates for performance-based design philosophy while considering soil-structure interaction. The code also offers a tangible solution to reduce the construction time by reducing the pile number within the construction projects thereby reducing material consumption and achieving the long-term sustainability requirements. As India continues to pursue large-scale and climate-resilient infrastructure development, CPRF systems are well positioned to play a central role in delivering safe, economical, and sustainable foundation solutions for mega infrastructure projects.

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Risks and Remediation of Climate Change Effects on Built Environment in India

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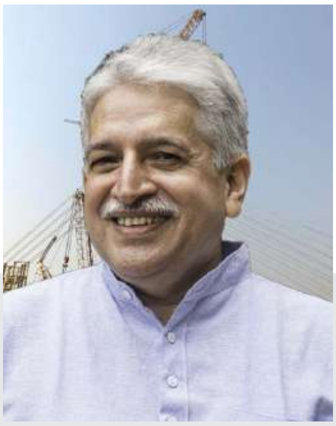

Er. V. N. Heggade

Er. V. N. Heggade, FNAE, is a senior construction professional with nearly four decades of experience across design, technical, site, project, and contract management of highways, bridges, energy, marine, environmental, and hydraulic structures. He is a former CEO of STUP Consultants and former Executive Director of Gammon. A recipient of around 19 national awards and international recognition from IABSE and fib, he has over 240 publications. He serves on IRC and BIS committees and contributes to fib Model Code 2020 (TG 10.1). He convened IRC guidelines on carbon neutrality for steel bridges and is an AICTE Distinguished Professional.

Abstract

India's infrastructure is increasingly exposed to climate change through rising temperatures, erratic monsoons, sea-level rise, and intensifying extreme events. Bridge systems, in particular, face risks from thermal stresses, scour, flooding, material degradation, and foundation instability. Traditional design approaches based on historical climate data are no longer adequate.

This paper highlights key climate-induced risks to the built environment and advocates a shift toward **climate-resilient engineering**, including revised design codes, probabilistic modelling, adaptive design strategies, and data-driven monitoring. Climate change must now be treated as a **dynamic design parameter** to ensure long-term infrastructure safety and sustainability.

Introduction

Climate change is no longer a future concern, it is already altering the design environment for infrastructure in India.

Observed trends include:

- Rising temperatures
- Increasing frequency of extreme events (floods, cyclones, heatwaves)
- Changing rainfall patterns
- Sea-level rise

India has already experienced a temperature rise of about **0.7°C (1901–2018)**, with projections indicating increases of up to **4–4.5°C by 2100** under high-emission scenarios.

These changes are not merely environmental, but they directly affect **structural performance, durability, and safety**, especially for long-life assets such as bridges.

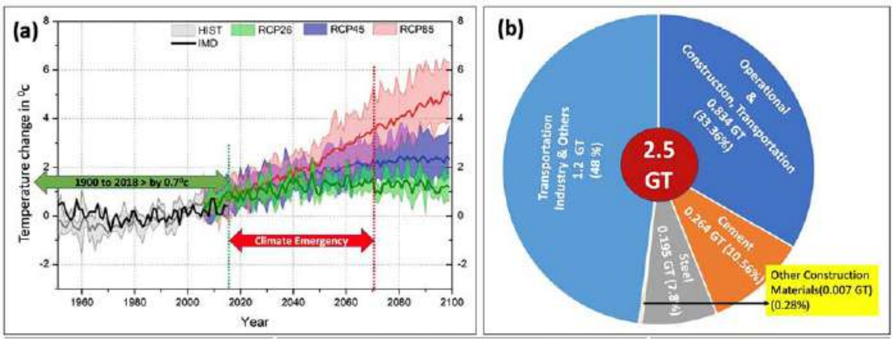

Fig. 1 - (a) Projected temperature trends in India [1], (b) Sector-wise carbon footprint distribution in India [2].

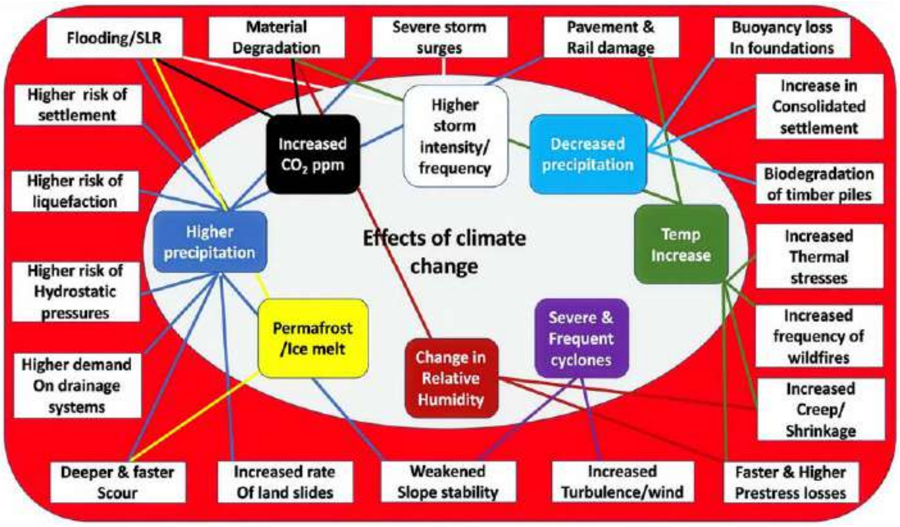

Fig. 2 - The risks of climate change effects on infrastructure

1. Key Climate Change Drivers Affecting Infrastructure [3]

1.1 Temperature Rise

- Increased thermal gradients → expansion, fatigue, and material degradation
- More frequent heatwaves → reduced service life of structural components

1.2 Sea Surface Temperature & Sea-Level Rise

- Indian Ocean warming (~1°C historically)
- Sea levels rising up to 3.3mm/year, with projections of ~300 mm by 2100
- Implications: coastal erosion, storm surge amplification, saline intrusion

1.3 Changing Precipitation Patterns

- Decline in average monsoon rainfall but increase in extreme rainfall events
- Higher flood risks due to short-duration intense storms

1.4 Extreme Events Intensification

- Increase in severe cyclones (especially post-monsoon)
- Glacier melt → higher river flows and flash floods
- Increased droughts and wildfires

1.5 Mountain and Cryosphere Changes

- Glacier retreat and reduced snow cover
- Landslides, avalanches, and glacial lake outburst floods

2. Climate-Induced Risks to Built Environment [4]

Studies indicate that nearly **80% of infrastructure failures in India are linked to natural hazards**, with actual service life far below design expectations.

These risks can be grouped into the following engineering categories (Fig. 2):

2.1 Material Degradation

- Accelerated corrosion in reinforced concrete
- Increased UV and moisture effects
- Biological deterioration

2.2 Thermal and Heat-Induced Effects

- Expansion and buckling of bridge decks
- Reduced fatigue life
- Softening of pavements

2.3 Long-Term Deformation

- Increased creep and shrinkage in concrete
- Prestress losses in PSC bridges
- Increased deflections

2.4 Scour and Hydraulic Risks

- Increased flow velocities and depths
- Enhanced erosion due to higher runoff and sea-level rise
- Major contributor to bridge failures

2.5 Geotechnical Risks

- Foundation settlement due to fluctuating groundwater
- Soil shrink–swell cycles
- Increased loads on foundations

2.6 Landslides and Avalanches

- Slope instability due to rainfall and glacier retreat
- Increased debris flow and rockfall risks

2.7 Drainage and Urban Flooding

- Overloading of existing drainage systems
- Urban flooding (e.g., Mumbai-type events)
- Hydrostatic pressures on structures

2.8 Wind, Wave, and Coastal Risks

- Increased wind speeds affecting long-span bridges
- Higher wave forces and storm surges
- Tsunami amplification under higher sea levels

2.9 Multi-Hazard Events

- Combined effects of floods, cyclones, and wildfires
- Cascading failures in infrastructure system

2.10 Operational Risks

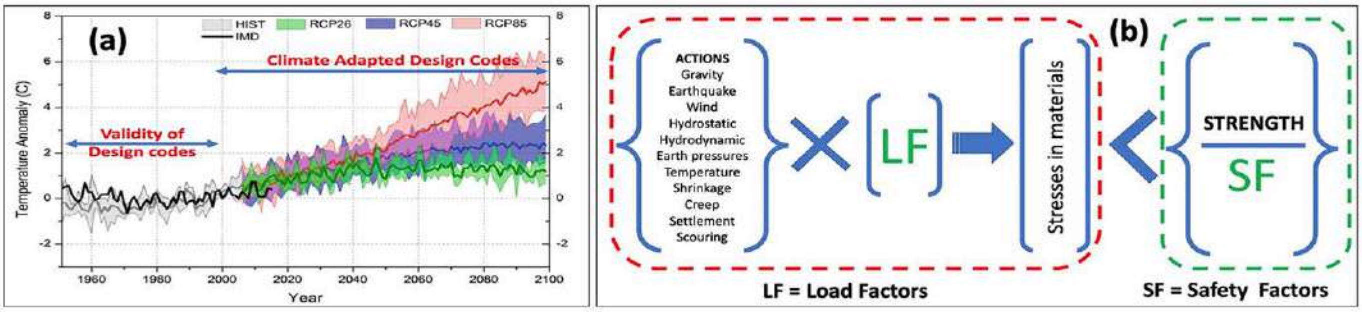

Fig. 3 - (a) Need for climate resilient codes, (b) Need of revised load factors & safety factors for climate change combination [4]

- Increased accidents due to fog, rainfall, and extreme weather
- Railway buckling and derailments
- Ship and vehicular collisions

3. Climate-Resilient Engineering Strategies

3.1 Sectoral Adaptation Measures (Key Themes)

- Integrated water resource and coastal management
- Climate-resilient urban planning
- Strengthened disaster early-warning systems
- Climate-resilient agriculture and livelihoods

3.2 Need for Climate-Adapted Design Codes

Current codes are based on historical climate data, which is no longer representative. A paradigm shift is required in the design approaches(Fig. 3).

Introduce "Climate Change Load Combination"

- Modify **load factors (actions)**
- Revise **partial safety factors (resistance)**
- Incorporate probabilistic future climate scenarios

3.3 Priority Research Areas

1. Revised temperature gradients and thermal loads
2. Climate-dependent creep and shrinkage models
3. Durability under changing environmental exposure
4. Stochastic modelling of floods and wind
5. Sea-level rise and coastal impact studies
6. Climate–seismic interaction
7. Geotechnical parameter variability

3.4 Design Philosophy Shift

- From deterministic → probabilistic
- From static → adaptive design
- From design-only → lifecycle resilience

3.5 Technology Integration

- Structural Health Monitoring (SHM)
- AI-based predictive maintenance
- Real-time risk assessment systems

4. Key Takeaways for Engineers

- Climate change is now a design parameter, not a boundary condition
- Historical data is insufficient for future infrastructure design
- Transportation infrastructure is particularly vulnerable
- Nearly 90% of failures are climate-linked directly or indirectly

Conclusions

India's infrastructure is entering a **new risk regime** driven by climate variability and extremes.

The impacts of thermal stresses, flooding, scour, material degradation, and coastal threats are already visible and will intensify.

To address this:

- Design codes must be **revised for future climate scenarios**
- Infrastructure must be **adaptable and retrofit ready**
- Monitoring must be **continuous and data driven**

The engineering community must transition toward **resilience based design**, where uncertainty is explicitly addressed.

Climate change is redefining engineering practice. The challenge is significant, but with proactive, science based approaches, it also presents an opportunity to build infrastructure that is **safer, smarter, and future-ready.**

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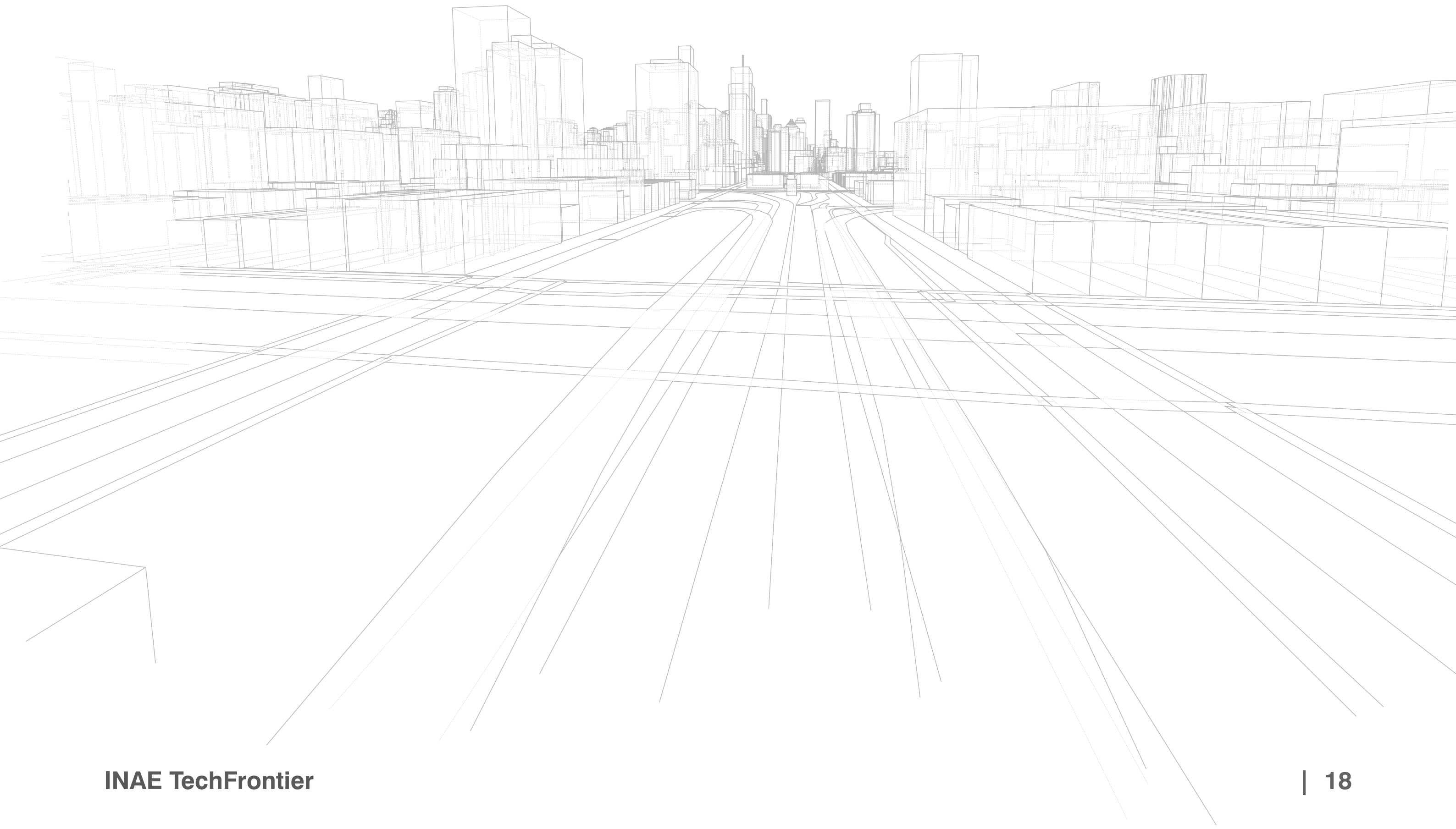

Morphological Evolution of Meandering Rivers and Consequent Risks to Roadway and Bridge Infrastructure

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Abstract

Morphodynamically active meandering alluvial rivers are defined as natural systems with sinuosity index greater than 1.5, active width of the channel, highly asymmetric cross-sections, dominant secondary flow (helicoidal flow) and highly uneven distribution of boundary shear stress. The rivers of Uttarakhand including Bhagirathi River system are high gradient systems with high sediment flux, highly seasonal and periodic behaviour in terms of flow, due to both seasonal monsoon rainfall and periodic glacial runoff. The August 2025 flash flood at Dharali (approximately 45 km upstream of Uttarkashi) dramatically and permanently changed the course and size of the river, leading to large amounts of active lateral shifting and deposition of sediment. The channel underwent significant bank erosion and changes in floodplain dynamics. Due to construction constraints, the effective conveyance capacity of the river has been reduced, leading to increased flood levels. The critical Gangotri National Highway (74), which runs along both sides of the river, has suffered severe scouring, bank failure and road blockage on numerous occasions due to high sediment load in the river and resultant debris flows. This article emphasizes that consideration of fluvial geomorphology should be included in river floodplain management, and shows how it is interlinked with more conventional design from a hydraulic and geotechnical perspective to develop long term, sustainable and resilient structures in dynamic environments.

Prof. Chandra Shekhar Prasad Ojha

Prof. Chandra Shekhar Prasad Ojha, FNAE, Ph.D. (Imperial College, London) is Professor since 2004 in Civil Engineering Department at IIT Roorkee. He has more than 40 years of teaching and research experience at University of Roorkee /IIT Roorkee. He has been Curtis Visiting Professor at Purdue University, USA in 2012; Adjunct Prof. at University of Missouri, Columbia, USA in 2018-2020, IIT Roorkee Institute Chair Professor for six years between 2018-2024. He is Fellow ASCE since 2017, and INAE Chair Professor since 2026.

Er. Ashish Kumar Singh

Er. Ashish Kumar Singh (M.Tech), is a PhD. Student of Prof. CSP Ojha in the Department of Civil Engineering, Madan Mohan Malaviya University of Technology, Gorakhpur, U.P. He also possesses approximately six years of professional experience in engineering works. He has received Uttar Pradesh State Gold Medal in Technical Research by Dr. A.P.J. Abdul Kalam Technical University, Lucknow, and Uttar Pradesh State Winner in Technical Research by U.P Council of Science and Technology. He has published few patents in the area of river bank stabilisation.

Introduction

This study examines processes, controls and resultant landforms in mature alluvial reaches with high sinuosity of 'Meandering Rivers'. Such channels have an asymmetric depth and width and, whilst there is considerable control over processes acting within the channel (flow and sediment transport), there is relatively little control over the final shape of the channel (Leopold et al., 1964; Knighton, 1998). The secondary or helicoidal flow within river bends significantly affects the magnitude and direction of the boundary shear stress. This leads to some reaches experiencing net erosion (e.g. outer banks) while other reaches experience net deposition (e.g. point bars on inner banks) (Bridge, 2003). This net difference in erosion and deposition results in periodic channel change or migration in a downdip direction, as well as bend development that increases in length and migrates in a steady downstream direction. Eventually the neck of bends closes off through a cutoff process - either as a chute cutoff or neck cutoff. These changes in river planform and actively erosion-dominated floodplain evolve over a long period of change (Leopold et al., 1964).

This study summarises current understanding of the channel morpho-dynamics relevant to roads and bridges. The channel meandering morphology poses threats to roads, abutments and approach fills, and bridges: width through lateral migration, and height through degradation or aggradation (Knighton, 1998). In addition to these long-term threats, there is also a short-term risk of local and contraction scour at bridges in floods in non-cohesive alluvial beds with potential for foundation failure (Richardson & Davis, 2001).

Understanding river meandering dynamics is crucial in assessing these risks. In addition, major floods can rapidly alter a channel's morphology resulting in unforeseen avulsion events that may place unanticipated loads on bridges (Bridge, 2003). Modelling the dynamics of meandering rivers using an integrated approach of fluvial geomorphology, hydraulic engineering and geotechnical engineering enables prediction of rates of channel migration and bank-attachment induced scour and calculation of the long-term development of the river channel (Parker et al., 2003). This information can be used by road planners and bridge designers to construct a safe and sustainable river crossing - new or upgraded. Studies on the morphological behaviour of meandering rivers provide a scientific basis for risk avoidance and risk management for roads and bridges in areas of natural hazard, such as dynamic alluvial rivers. Engineering design and management issues to be tackled include: bridge alignment; bridge footing design; stabilisation of potentially unstable river banks; and zoning hazardous reaches within the river corridor.

Case Study:

Morphological Evolution and Infrastructure Risk in Uttarakhand (Bhagirathi River System)

The Bhagirathi River in the Himalayan state of Uttarakhand, India, exemplifies the limits of road and bridge construction as its geomorphology shifts. The Bhagirathi River is a steep, high gradient, high energy river, draining from the Gaumukh Glacier, exhibiting high channel mobility, high sediment loads and rapid changes in planform.

River Morphodynamics and Channel Adjustment:

Extreme hydrological events such as flash floods can cause dramatic geomorphic changes to a channel within a matter of hours. Satellite images show how a flash flood that occurred at Dharali on 5 August 2025 drastically cut away an alluvial fan at the confluence of the 23 km long, 6–35 m wide Kheer Gad tributary and the Bhagirathi River. The channel was displaced to the left of the pre-existing channel, increasing the bank shear stress in the downstream reaches. The changes to the channel plan,

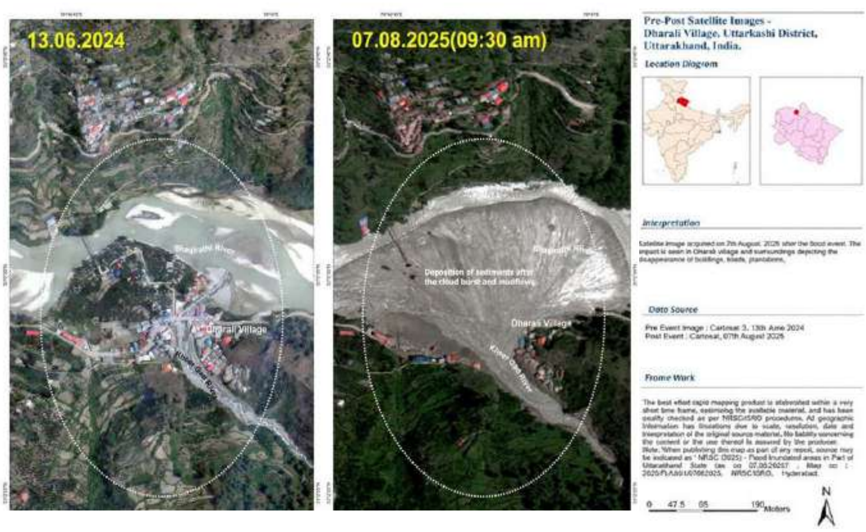

Fig. 1 - ISRO/NRSC used Cartosat-2S data to assess the devastating Aug 5 flash flood in Dharali & Harsil, Uttarakhand.
(Source: https://www.isro.gov.in/indian_satellite_data_based_analysis_of_the_dharali_flash_flood.html)

wider flow paths, increased deposition of sediment and engulfing of critical corridors such as transmission lines and roads are also visible.

Huge sediment build-up of volumes of material deposited upstream by the rivers, under ban due to long-standing guidelines for the eco-sensitive zone under the regulation of Bel Eco-Sensitive Zone (BESZ), has caused the levels of the bed to increase appreciably reducing its carrying capacity. As a result, the increased levels of the bed of the Uttarkashi reach raise the flood stage leading to instability of the banks. The greater degree of overflow and severe undercutting makes the river banks even more unstable, especially during the post-monsoon high discharge and during rapid melting of glaciers.

Impacts on Roadway and Bridge Infrastructure

Gangotri National Highway is backbone of the region for strategic and socio-economic activities. It has suffered greatly from severe geomorphological changes.

1. Lateral river bank cutting, frequent crossing and high velocity of flow caused severe lateral bank erosion and hill-toe undercutting causing damage to pavement and embankment. Slope and landslide stabilization work undertaken on emergency basis at Chinyalisaur, Matli and both sides of pavement at Badethi Chungi.
2. Deals with channel migration and scour including details of breaches to both major flood defence structures and river safety walls and design for rebuild under high shear and hydraulic loading.
3. After the flash flood, the sudden change in the planform of the river, blocked sections of the highway with deposits of sediment and flood borne materials, creating hazardous road conditions as well as problematic access for maintenance personnel.

Changes to the river channel may introduce significant fluvial hazards such as bank erosion (particularly at river bends), severe scour around large structures with high stream power, and channel migration / avulsion following extreme flood events. These hazards expose and weaken bridge foundations which may pose a risk to crossing roads or potentially cause bridge pier failure.

Geomorphic Drivers and Policy Implications:

Uttarakhand is a seismically and geologically sensitive State. The rugged terrain of steep slopes, with its inherent lithological diversity and mass movement hazards, already presents a complex environmental scenario. However, this complexity is further compounded by episodes of landsliding and slope instability, which in conjunction with river undercutting, significantly enhances the vulnerability of the existing infrastructure to debris accumulation in rivers and to changes in sediment load.

However potential risks can be reduced by adopting an integrated approach that considers fluvial geomorphology, hydraulic criteria and geotechnical evaluations.

- Modelling of qualitative and quantitative trends in channel migration, and qualitative and quantitative regimes of sediment transport.
- Estimation of scour depth at piers and abutments under design flow as well as worst case extreme flood conditions.
- An adaptive design comprising deep foundations, erosion resistant articulated revetments and alignment on land to accommodate subsequent changes in planform.

From Uttarakhand experience, it is felt desirable to incorporate such studies in the planning and design codes for major structures

Conclusions

The Bhagirathi River case demonstrates that sustainability of civil infrastructure in river systems can only be achieved when engineering practices work with, rather than against, natural geomorphic processes. In order to become resilient over the long term, we need adaptive designs that take into consideration channel migration, sediment fluxes and hydrological extremes in plenty. Taking the morphological features of rivers into account when planning infrastructure helps in the safety and rational choice of alignments, designing of foundations that can withstand channel migration, and installing of scour protection and erosion control. Moreover, the development of sustainable civil infrastructure in river systems require integration of various policy tools, sediment management options, continued monitoring, etc. Ultimately, a combination of geomorphology, hydraulics and geotechnical engineering will enable win-win situation by eliminating risk.

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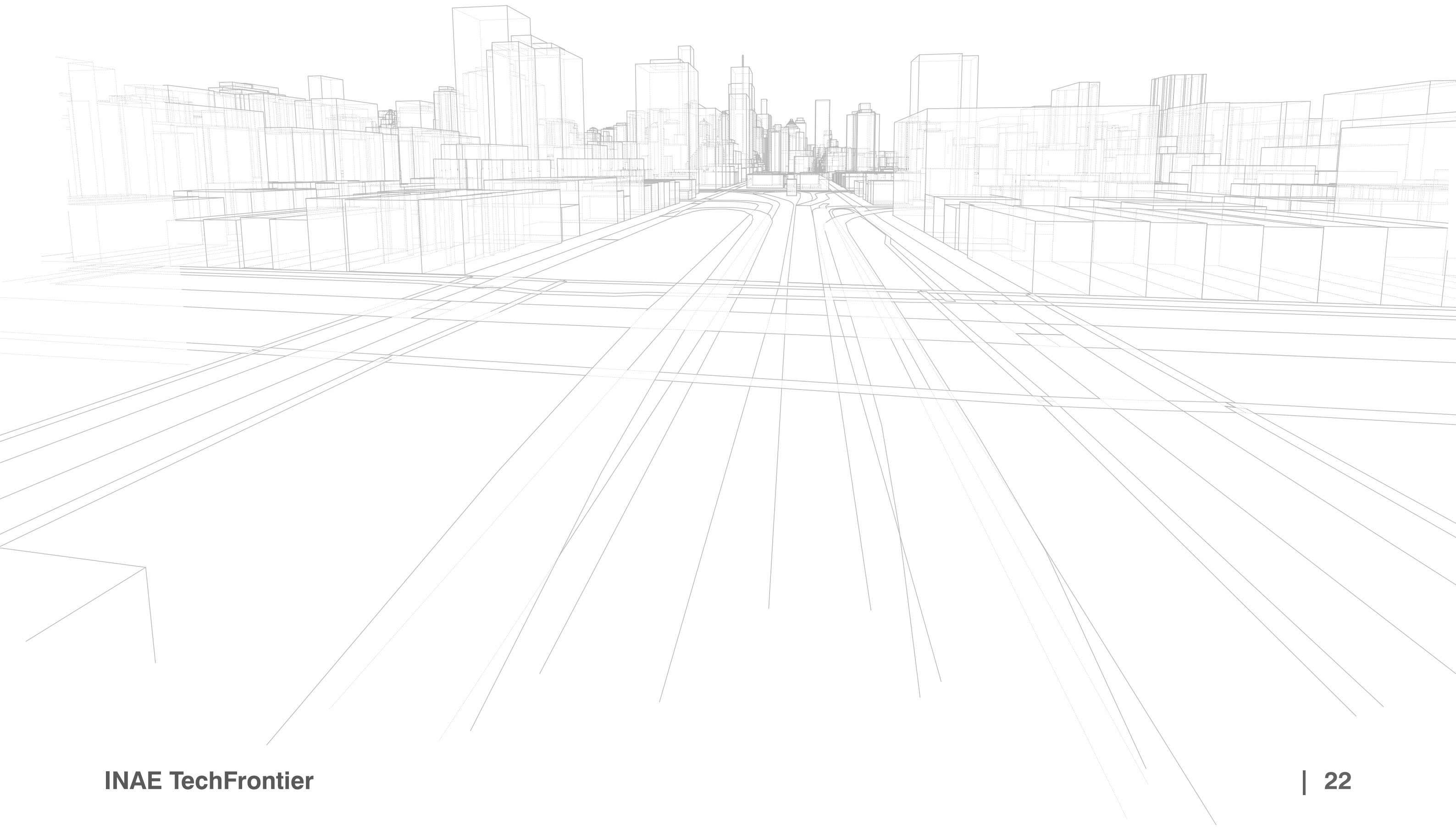

Sustainability of Civil Structures of Metro Railways

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Prof. B.C. Roy

Dr. B.C. Roy, FNAE, possesses over three decades of multi-faceted experience across project planning, design, and implementation, including Build-Operate-Transfer (BOT) models. His career spans more than 300 projects characterized by technological innovation and the development of national standards and codes. Dr. Roy has led landmark "signature" projects—including MRTS, high-speed corridors (elevated and underground), expressways, and specialized industrial structures—with a consistent focus on fast-track construction and resource optimization.

A Fellow of premier global institutions, including the National Academy of Engineering, his work integrates structural resilience with environmental stewardship. His research and field applications address critical challenges in sustainability, climate change, and poverty alleviation. Dr. Roy is a prolific contributor to engineering literature, having authored four books and over 120 technical papers.

Abstract

Sustainability necessitates the responsible utilisation of resources to preserve ecological and social systems without compromising future generational needs. This paper examines the integration of core sustainability principles—resource efficiency, regeneration, and circular economy strategies—within large-scale infrastructure. Specifically, it highlights the strategic framework of Indian Railways' mandate to achieve Net-Zero Carbon Emissions by 2030.

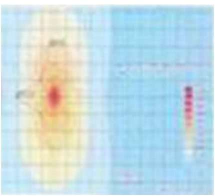
The paper evaluates the implementation of sustainability protocols in Indian Metro Rail systems, focusing on durability and reduced environmental footprints. It categorises essential measures into several key pillars: network optimization, green building initiatives, sustainable construction methodologies, and water/waste management systems. By analysing technological and infrastructural innovations, this paper provides a concise roadmap for achieving energy-efficient and resilient urban transportation networks.

Introduction

Sustainability is the capacity to maintain long-term ecological, economic, and social systems through the efficient and responsible utilisation of resources, ensuring intergenerational equity. It seeks to preserve essential environmental functions and quality of life while meeting current demands without compromising the ability of future generations to meet their own needs. Core principles of sustainability include resource efficiency, system continuity, regeneration, and the reduction of negative environmental impacts. Strategies such as the circular economy, in which waste streams are transformed into valuable resources, and the transition to renewable energy systems are fundamental to sustainable development. In the context of climate change—driven primarily by anthropogenic greenhouse gas emissions—sustainability plays a critical role in mitigating global risks by supporting systemic transformations aimed at limiting global warming to 1.5 °C through energy transition, conservation, and structural change.

Indian Railways has set a target to achieve **Net-Zero Carbon Emissions by 2030**, supported by a comprehensive energy efficiency policy aimed at rapid and effective implementation. The policy addresses multiple dimensions of energy optimisation, including sustainable and green buildings, energy-efficient equipment and appliances, and improved power quality management. As part of these initiatives, conventional electrical systems are being replaced with high-efficiency technologies; notably, the Kolkata Metro has envisaged the large-scale adoption of Brushless Direct Current (BLDC) fans, offering energy efficiency improvements of up to 114% compared to conventional fans.

Sustainability objectives in construction include: (i) reduction of carbon footprint through decreased reliance on diesel-powered heavy machinery; (ii) efficient resource utilisation by minimising concrete and steel waste using precise, high-efficiency production and fabrication technologies; (iii) enhanced material performance, where improved mixing and placement quality extend structural lifespan and reduce repair and replacement requirements; and (iv) reduced energy demand through the adoption of advanced equipment and construction methods that lower energy consumption during construction and erection activities.



Use of FEM

Precast Elements Using Heavy Machinery

Modern Batching Plant

Precast Concrete Tunnel Segments

Indian Metros: Planning, engineering, system design, construction, procurement, and operation of Indian metro rail systems are increasingly guided by sustainability principles, emphasizing durability, energy efficiency, and reduced environmental impact. Metro systems provide low-emission urban mobility by shifting commuters from road-based private transport to rail, thereby reducing fossil fuel consumption, traffic congestion, and associated air and noise pollution. The Kolkata North–South Metro, India's first metro corridor, started operation in 1984, and represents an early example of sustainable mass transit in the country.

Subsequently, the Delhi Metro, which commenced operations in 2002, rapidly emerged as a benchmark for sustainable metro development through innovations in energy efficiency and large-scale adoption of renewable energy, positioning the Delhi Metro Rail Corporation (DMRC) as a global leader in sustainable urban transport. Further advancements include the East–West Metro in Kolkata, featuring India's first underwater tunnel beneath a major river, designed to enhance connectivity across a river and connecting two major Rail terminals, while mitigating urban congestion and carbon emissions. Currently, most metro systems in India integrate renewable energy sources, particularly solar power, reinforcing their role in sustainable urban infrastructure. Metro projects incorporate Environmental Management Plans (EMP) which include, pollution control and managing environmental risks, ensuring a cleaner, more sustainable urban transport network. Sustainable measures for Metros, include - Network, Environmental measures, Infrastructure & Technology, Energy, Emission & Renewable Energy, Green Building Initiatives, Sustainable Design & Construction, Water Recycling & Conservation, Waste Management & Others.

Design and Construction

Network: Networks planned and being planned are both for present and future needs. Alignments are designed with minimum encroachment, particularly in built-up areas and adhering to land use as far as practicable. Affected properties and people, are being rehabilitated, with better environment and improved living condition, number of them with sustainable construction and energy efficient facilities.

Sustainable Design & Construction Practices: Quality of design & construction and sustainability are intrinsically linked, focusing on high-quality, sustainable construction utilising effective and modern equipment, sustainable materials, reduction in waste, optimising resource consumption, and ensuring long-term structural integrity to provide economic and social benefits. Metro projects, use advanced technology for construction and operation, including, automatic train operations, signalling, and safety systems. Energy-Efficient Design and Planning incorporate natural lighting, smart ventilation systems, and reflective roofing reducing energy demand for lighting & cooling, and operational costs.

Material selection forms a critical component of sustainable structural design, as it directly influences durability, service life, and life-cycle performance. In metro infrastructure, the structures are exposed to aggressive conditions such as corrosion—particularly in marine or high-humidity environments—and fatigue due to repetitive cyclic loading. These challenges are addressed using technically advanced materials, including weathering steel or stainless steel, dense and high-grade concrete, and protective systems such as epoxy coatings to mitigate corrosion. Fatigue performance is enhanced through the adoption of high-performance concrete, engineered to provide superior mechanical properties and improved resistance to cyclic loading, thereby significantly extending structural durability. Metro design and construction typically employ reinforced and prestressed concrete systems, both in situ and precast, structural steel, and steel–concrete composite construction. The use of high-grade concrete enables a reduction in the size and quantity of structural elements, resulting in lower self-weight, improved constructability of precast components in terms of size and erection height, reduced seismic demand, and an overall increase in structural service life. By selecting materials that are technically robust and appropriate for current and future operational demands, sustainability is achieved through enhanced durability, reduced maintenance requirements, and extended design life of the metro infrastructure.

Metro infrastructure design employs advanced analytical tools such as the Finite Element Method (FEM) and project-specific, performance-based approaches to optimise structural behaviour, reduce material usage, and minimise self-weight without compromising safety. These efficiencies directly contribute to sustainability by lowering embodied energy and carbon emissions. Building Information Modelling (BIM) enables integrated, multidisciplinary coordination, early identification of clashes, and improved constructability, thereby reducing rework, material wastage, and construction risks. Together, FEM-based optimization and BIM-enabled coordination enhance resource efficiency and support circular economy principles across the project lifecycle.

Modern concrete construction equipment enhances sustainability by increasing precision, reducing waste, and enabling the use of eco-friendly materials. Electrification of machinery decreases carbon emissions, while automated, precision-based equipment, RMC plants, slipform forms, optimises material usage and improves durability. Key technologies include advanced batching systems, robotic, and energy-efficient, and battery-powered, machinery. At the early stage of metro construction, grades of concrete used was M20/M25 in north-south metro, and increased to higher grades, including M50 for tunnel segments. In Indian metros, the grade of concrete used depends heavily on the specific structural application, ranging from **M20 to M60+**. In general, the grade of concrete used is **M35 and M40.**

Green Materials and Hybrid Construction Techniques: The advent of green concrete is an eco-friendly alternative incorporating recycled materials like fly ash, slag, and recycled aggregates, reducing the carbon footprint associated with concrete production and include optimising the mix design to use less cement, employing alternative and low-carbon cementitious materials, and harnessing renewable energy sources in production processes. Enhancing the durability of concrete extends the lifespan of structures, reducing the need for frequent repairs and rebuilds, thereby conserving resources.

Recyclable and Reusable Steel Materials: The advantage of steel is its recyclability without loss in strength or quality, and can be reused at the end of their lifecycle supporting a circular economy. Reduced Carbon Footprint through efficient fabrication facilities, energy-efficient machinery and optimised production planning minimise waste and emissions. Hybrid Construction Techniques combining steel with other eco-friendly materials like concrete, enhance both performance and sustainability.

Lifecycle Management

Water, Waste, and Lifecycle Management in Metro Infrastructure: Sustainable metro infrastructure extends beyond material selection to encompass responsible resource management throughout construction and operation.

Practices such as rainwater harvesting, wastewater recycling, and eco-efficient fabrication technologies reduce water consumption, minimise waste generation, and ensure compliance with green manufacturing standards. The adoption of prefabrication techniques enables off-site, precision fabrication, significantly reducing on-site waste and construction time. Material durability further enhances sustainability, as long-life, low-maintenance systems reduce resource demand over the asset lifecycle. Steel structures, owing to their resistance to corrosion, pests, and weathering, offer extended service life with reduced maintenance requirements. During operations, metro stations generate large amount of solid waste per station per day, across the network, underscoring the need for systematic waste segregation and disposal strategies.

Indian metro rail systems are increasingly adopting integrated water management strategies to enhance resource efficiency and reduce freshwater demand. These measures include the deployment of Effluent Treatment Plants (ETPs), Sewage Treatment Plants (STPs), and Water Recycling Plants (WRPs) for non-potable applications such as coach washing, station cleaning, and landscape irrigation. Key initiatives include Automatic Coach Washing Plants (ACWPs) and widespread implementation of rainwater harvesting for groundwater recharge. The Delhi Metro recycles approximately 140 kilolitres of water per day through STP/ETP systems, while the Mumbai Metro operates a dedicated water treatment facility that recycles for train washing. Similarly, metro stations in Pune and Secunderabad utilise advanced treatment systems capable of recycling. Collectively, these practices demonstrate a systematic shift toward sustainable water use across Indian metro networks.

Sustainable Energy Use

Environmental Sustainability: In a significant advancement toward energy efficiency and environmental sustainability, Kolkata Metro has initiated the replacement of conventional steel third rails with aluminium third rails on the North–South corridor. The transition is expected to substantially reduce traction power losses and achieve substantial reduction in carbon emissions. Aluminium third rails have already been commissioned on the East–West Metro and the Joka–Taratala Corridor and are planned for deployment across all future Kolkata Metro corridors. Pune Metro Line 3 has also proposed the adoption of aluminium third rail technology. Owing to its lower electrical resistance, the aluminium third rail minimises system voltage drops and associated energy losses, thereby improving traction performance. The reduced voltage drop enables higher acceleration rates and supports shorter headways, resulting in enhanced operational efficiency and reduced operation and maintenance costs. Additionally, the aluminium third rail contributes to improved tunnel air quality by limiting heat generation. In recognition of similar environmentally sustainable practices, the Delhi Metro has received international certifications and awards from the United Nations, RINA, and the International Organisation for Standardisation.

Energy, Emissions and Renewable Energy Initiatives: The Delhi Metro Rail Corporation (DMRC) has incorporated sustainability as a core design and operational principle through the large-scale adoption of energy-efficient technologies, regenerative braking, and renewable energy integration. Regenerative braking systems deployed across the rolling stock enable the recovery of large percentage of traction energy during deceleration, which is fed back into the power network for reuse. In 2024 alone, this system resulted in electricity savings exceeding 112 million kWh. DMRC is the world's first railway project to have earned big credits through the application of regenerative braking technology. With a network spanning over 390 km, the Delhi Metro contributes significantly to carbon emission reduction by replacing a substantial number of road-based vehicle trips. Complementing these measures, DMRC pioneered the installation of rooftop solar power plants within the metro sector. With an installed solar capacity exceeding 28 MW across stations and depots, Delhi Metro has emerged as one of the largest metro rail operators globally in terms of solar power generation.

Solar Infrastructure Development: The deployment of solar photovoltaic systems across metro

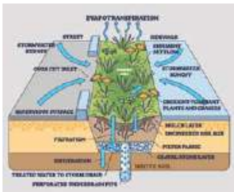
Rooftop Solar Power-Chennai Metro

Delhi Metro

Green Depot-Central Park Kolkata

infrastructure has become a key strategy for enhancing energy security and reducing emissions. Kolkata Metro Rail Corporation (KMRC) commissioned its first solar power plants in 2018, while Mumbai Metro has installed solar panels on stations, depots, and selected corridors to meet auxiliary power requirements. The electricity generated is primarily utilised for non-traction applications such as station and depot lighting, air-conditioning, and maintenance facilities. Maha Metro has proposed the installation of solar panels on station rooftops and along boundary walls in at-grade sections, while Nagpur Metro adopted solar power integration from the project's inception. Chennai Metro Rail Limited (CMRL) has implemented a diversified solar strategy, including rooftop, ground-mounted, and parking-area installations across depots and stations, both elevated and underground. At present, solar energy is being utilised by most Indian metro systems, underscoring the sector's transition toward low-carbon and energy-efficient urban transportation.

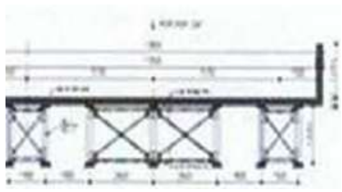
Sustainability of System: System sustainability in electrified metro rail networks is achieved through advanced energy-efficient technologies and sustainable rolling stock design. Electrification substantially reduces direct emissions, while regenerative braking systems recover up to 50% of traction energy and feed it back into the power network, improving overall energy efficiency. Contemporary metro rolling stock in India reflects a strong shift toward electrification, energy optimisation, and indigenization. Although the initial capital investment for advanced, sustainable technologies is high, these systems significantly lower lifecycle costs through reduced energy consumption and maintenance requirements, with reported maintenance cost reductions. Modern metro trains incorporate recyclable materials—achieving recyclability and lightweight components that enhance performance and efficiency. In parallel, the installation of solar power systems across stations and depots further supports low-carbon operations and long-term system sustainability.



Depot-Swales

Precast Concrete Segments

Formwork Factory Made



Reusable Prefabricated Steel Structure

Green Buildings

Green Building Initiatives: Green buildings in Indian metros are rapidly increasing, driven by certifications like IGBC, LEED, and GRIHA to minimise environmental impact through energy efficiency, solar power, and water conservation. Bengaluru, Hyderabad, Kochi, Lucknow, Mumbai, Nagpur, and other metro rails have received IGBC Certification for using sustainable designs and the use of green material. Kolkata Metro, India's first rapid transit system, is actively enhancing its green credentials by incorporating solar power and improved waste management, including the underwater Green Line.

The Central Park Depot of the Kolkata East–West Metro is envisaged as one of the first "green depots" among Indian metro systems. At the initiative of the client, KMRCL, green design strategies were customised for the open areas with an emphasis on maximising rainwater harvesting and temporary ponding to facilitate groundwater recharge. The landscape was contoured accordingly, and native plant species were selected as part of an enhanced greening strategy. The built-up areas incorporated multiple sustainability measures. Daylight availability was evaluated through daylight analysis, and internal spatial planning and partitioning were optimised based on material properties and surface reflectance. High-performance glazing, including double-layer and spectrum-selective glass, was adopted to improve thermal performance, reduce operational energy demand, and minimise overall embodied energy, achieving an optimal balance between energy efficiency and material use. In addition, sun-path analysis was conducted to inform the design of solar laminations and shading devices, ensuring effective control of solar gains throughout the year.

Green Cover Development for Metros are adhered by extensive tree plantation and have more than compensated for the trees affected during construction. For every tree removed, multiple saplings are planted and maintained, resulting in a net increase in green cover.

Conclusions

Indian Railways and Metro Rail Corporations are progressively transforming metro networks into environmentally sustainable transport systems through the integration of energy-efficient technologies, renewable energy adoption, water conservation measures, and resource-optimised infrastructure design. These initiatives collectively contribute to reduced carbon emissions, improved operational efficiency, and enhanced environmental performance across the transport sector. The continued advancement of sustainable planning, system design, and lifecycle-based management positions India's rail-based urban mobility as a critical component of the country's low-carbon and resilient transportation future.

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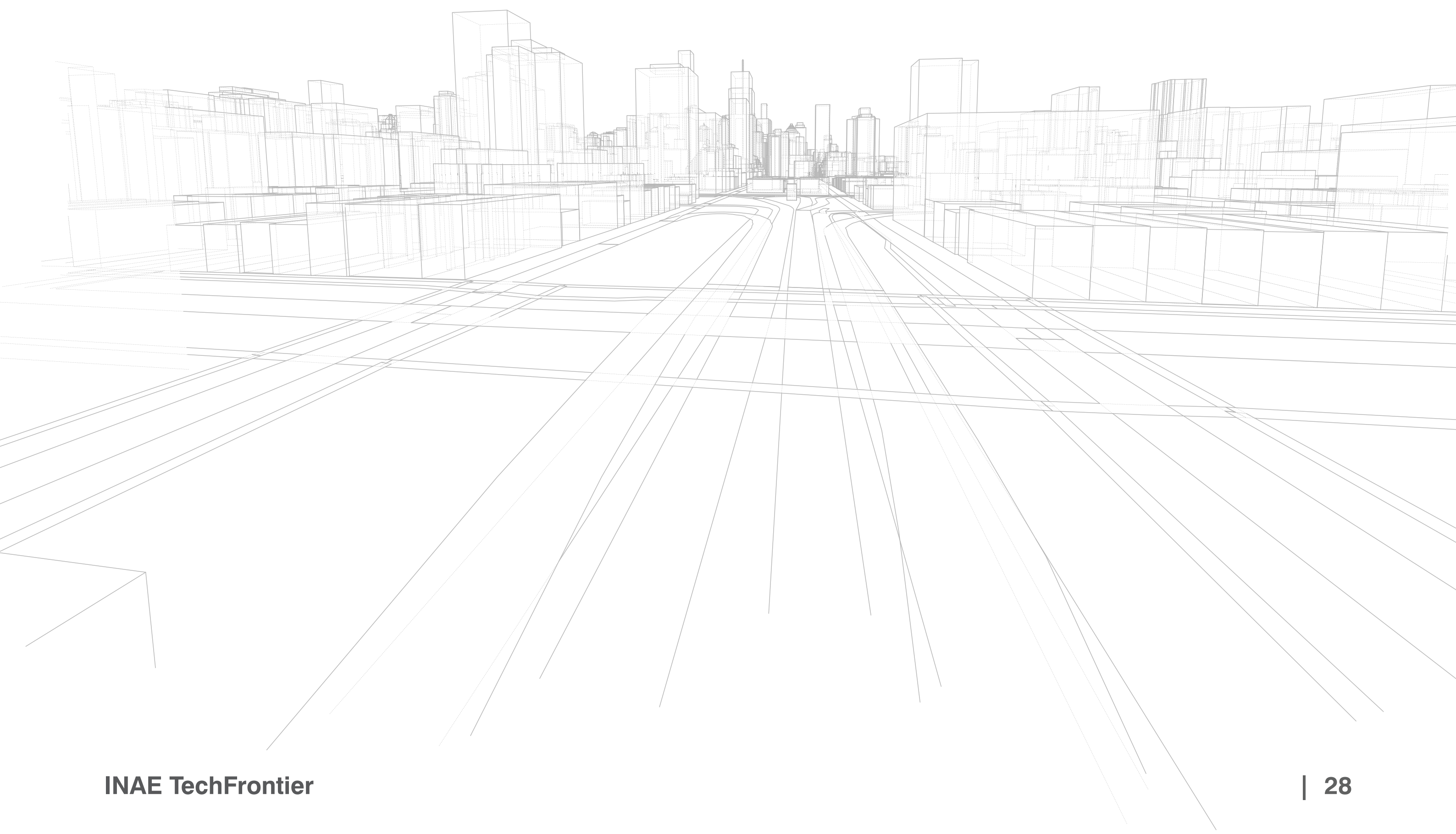

Dr. Abhishek Rajput

Dr. Abhishek Rajput has obtained his B.E. degree in Civil Engineering from Govt. Engineering College Jabalpur in 2009, and his M.Tech and Ph.D. in Structural Engineering in 2011 and 2017 from Indian Institute of Technology Roorkee respectively. He has also worked as postdoctoral researcher at Korean Ships and Offshore Research Institute, Pusan National University, Busan in 2017-18. He joined IIT Indore in 2018 as an Assistant Professor and is currently working as an Associate Professor at Department of Civil Engineering IIT Indore. He has also served as Head, Department of Civil Engineering IIT Indore 2022-2025. His research interests include performance of structural material such as concrete, steel, composite under low, medium and high rate of loading. He is also working in the area of sustainable construction and practices in which recently patented a technology on "High Strength Geopolymer Composition" which could be an alternative to cement and concrete.

Low Carbon and Earth Friendly Alternative to Cement

Dr. Abhishek Rajput, Associate Professor, Department of Civil Engineering, IIT Indore

Abstract

Concrete has been widely used in the construction of buildings, bridges, roads, and other critical infrastructure. It has shaped the modern world and serves as the backbone of global development. Yet behind its strength and reliability lies an uncomfortable truth: the production of conventional cement-concrete contributes nearly 8% of worldwide CO_2 emissions, creating an environmental burden that is too significant to overlook. So, the construction industry has been constantly looking out for a sustainable and eco-friendly alternative. One promising development in this direction is geopolymer concrete. It has emerged as a transformative alternative, offering substantial reductions in carbon footprint. At the same time, its strength and durability performance often outperform traditional concrete. This article presents practical insights, technological innovations, and forward-looking perspectives on geopolymer concrete. Also, the properties, composition, and applications of geopolymer concrete have been discussed. With emerging technologies and evolving policy frameworks, the geopolymer system can reshape every phase of construction towards a more resilient and sustainable future. However, a strong and coordinated collaboration between government agencies, construction industries, and academic research institutions is required for scaling up geopolymer concrete to a national level. Such collective efforts can help India accelerate low-carbon infrastructure development, strengthen climate resilience, and move closer to its long-term sustainability goals.

Introduction

Civil infrastructure is widely recognised as the foundation of modern society. Rapid urbanisation, large-scale transportation networks, energy facilities, and housing projects demand enormous volumes of concrete, making the cement industry one of the largest industrial sources of greenhouse gas emissions. Atmospheric CO_2 concentrations have increased from approximately 280 ppm in the pre-industrial era to about 417 ppm in recent years, with projections indicating a continued rise if current trends persist [1,2]. Among industrial sectors, the cement industry plays a major role in global greenhouse gas emissions. Ordinary Portland Cement (OPC) production exceeds 4 billion tons annually and is responsible for approximately

5-8% of total anthropogenic CO_2 emissions, generating about 0.7-1.0 tons of CO_2 per ton of cement produced [3-5]. Without effective mitigation strategies, emissions from the cement sector are expected to further increase, posing serious challenges to achieving the net-zero targets outlined in the Paris Agreement [6]. Consequently, the development of sustainable alternatives to OPC-based construction materials has become imperative.

Geopolymer concrete has gained recognition as a promising low-carbon substitution due to its substantially reduced environmental footprint and favourable engineering performance. Geopolymers are synthesised through the alkaline activation of aluminosilicate precursors such as fly ash, ground granulated blast-furnace slag (GGBS), metakaolin, and red mud, typically using sodium hydroxide and sodium silicate solutions, and cured under ambient or elevated temperature conditions [7-9]. Compared with OPC-based concrete, geopolymer systems have been reported to reduce CO_2 emissions by approximately 22-72%, primarily by eliminating energy-intensive clinker production and enabling the beneficial utilisation of industrial by-products [10]. In addition to their environmental advantages, geopolymer concretes exhibit excellent mechanical and durability properties, including high compressive strength, resistance to elevated temperatures, chemical stability, and reduced permeability.

1. A New Generation Binder System

Sustainability in civil infrastructure is no longer an aspirational concept; it is a necessity. Beyond reducing emissions, sustainable infrastructure must address durability, resilience to climate extremes, efficient resource utilisation, and long-term socio-economic benefits. Among the emerging material technologies responding to this challenge, geopolymer concrete represents one of the most promising pathways.

Geopolymer concrete replaces Ordinary Portland Cement (OPC) with Aluminosilicate source materials such as fly ash, ground granulated blast furnace slag (GGBS), metakaolin, and other industrial by-products. These materials are activated using alkaline solutions to form a polymeric network that binds aggregates into a hardened matrix. Unlike traditional Portland cement, geopolymer concrete does not require the calcination process, thereby significantly reducing carbon emissions. Life-cycle assessments consistently report CO_2 reductions of 40-80% compared to traditional concrete, depending on material sourcing and processing routes. Beyond environmental benefits, geopolymer concrete exhibits attractive engineering properties: high early strength, superior resistance to chemical attack, excellent fire performance, and enhanced durability in aggressive environments. Fig. 1 & 2 represents the components and the applications of Geopolymer Concrete respectively.

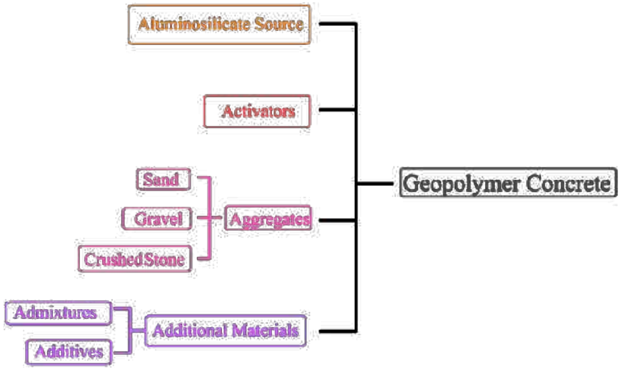

Fig. 1 - Components of Geopolymer Concrete

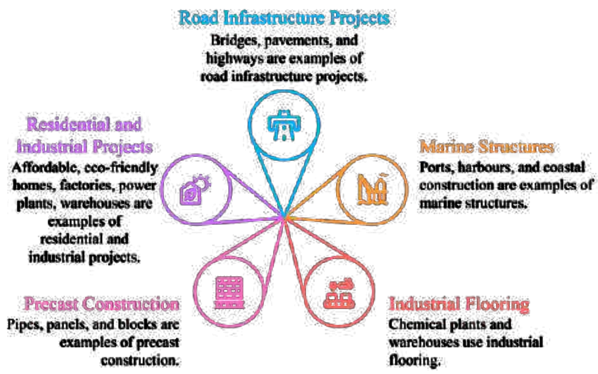

Fig. 2 - Applications of Geopolymer Concrete

2. Practical Insights from Field Applications and Case Studies

The transition from laboratory research to field implementation is a critical step for any sustainable technology. Over the past decade, geopolymer concrete has moved steadily into real-world infrastructure.

Transportation Infrastructure

Several bridge decks, pavements, and precast railway sleepers in Australia, and parts of Europe have successfully employed geopolymer concrete. These projects demonstrated not only comparable structural performance but also improved resistance to sulphate and chloride penetration.

Precast and Modular Construction:

This sector is most suitable for geopolymer concrete due to its controlled curing conditions. Industrial adoption has been observed in precast beams, panels, pipes, and retaining walls, where rapid strength gain and dimensional stability are advantageous.

Waste Utilisation in Urban Projects:

Municipal solid waste incineration ash and mining tailings are being used as precursor materials in geopolymer. This helps in recycling resources, reducing environmental pollution, and supporting the circular economy, where waste is reused rather than thrown away.

Geopolymer concrete is no longer experimental. It is a deployable solution capable of meeting structural and durability requirements in severe environmental conditions.

3. Recent advancements in Geopolymer Concrete

Recent advancements are accelerating the practical viability of geopolymer concrete. Better production techniques, improved mix designs, and advanced testing tools are helping geopolymer concrete become more practical and widely accepted.

Ambient-Cured Systems:

Early geopolymer formulations required heat curing, limiting field applications. New ambient cured blends based on slag-fly ash hybrids now allow in-situ casting under normal site conditions, removing a major barrier to adoption.

Geopolymers Binder:

The development of geopolymers binders ready to mix ("just-add-water") could be a potential alternative of cement. The author has developed some of the binder material which is ready to mix and could be a replacement of cement as well as concrete.

Digital Design and Performance-Based Mix Optimisation:

It refers to data driven and computational approach for the development of high-performance concrete with optimised mix proportions. This approach can significantly reduce the extensive trial-error experiments and material wastage. Currently, machine learning and multi-objective optimisation techniques are being used to design geopolymer mixes tailored for strength, durability, workability, and sustainability.

Hybrid and Fiber-Reinforced Systems:

The incorporation of fibers, recycled aggregates, and nano-materials further enhances toughness, crack resistance, and functional performance, opening new opportunities in seismic, impact-resistant, and marine infrastructure.

4. Policy Perspectives

Despite its technical maturity, widespread adoption of geopolymer concrete remains constrained by regulatory and institutional barriers.

Standardisation and Codes:

Most national design codes remain cement centric. The development of performance-based concrete standards and inclusion of geopolymer binders in material specifications are essential for mainstream acceptance.

Public Procurement and Green Mandates:

Government-led infrastructure programs can act as powerful catalysts by mandating low-carbon materials and life-cycle-based performance criteria in tender documents.

Carbon Pricing and Incentives:

Charging extra costs for high carbon materials and providing benefits for low carbon alternatives can improve the competitiveness of geopolymer concrete relative to conventional cement.

Skill Development and Knowledge Transfer:

Training engineers, contractors, and quality-control personnel, along with proper guidance on mixing, handling, and quality checking is required to ensure consistent field performance.

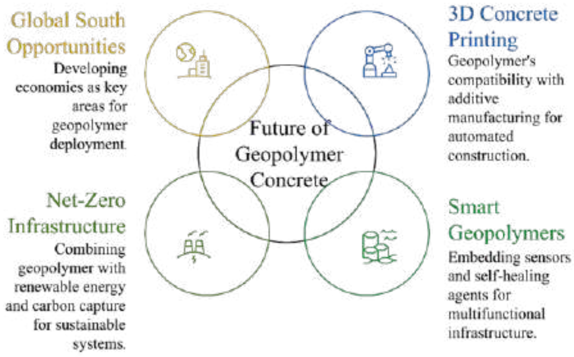

Fig. 3 - Future of Geopolymer Concrete

5. Future Directions: Toward Smart, Net-Zero, and Resilient Infrastructure

The future of geopolymer concrete lies at the intersection of sustainability, digitalisation, advanced manufacturing, and is illustrated in Fig. 3.

Conclusions

Geopolymer concrete is a low carbon material and Earth friendly alternative to cement, as well as concrete representing a significant step towards sustainable future. By combining industrial waste, advanced binder chemistry, emerging digital technologies, and supportive policy frameworks, geopolymer systems would be capable to offer a practical pathway toward low-carbon, durable, and resilient infrastructure.

However, despite its strong potential, large-scale adoption in India remains limited. The conventional cement production is supported by a well-established industrial ecosystem, taxation structure, and supply chain network, making it economically and logistically easier to continue with traditional materials. In contrast, geopolymer concrete lacks clear approval mechanisms, and large-scale pilot implementation frameworks, which discourages public agencies from adopting it in major infrastructure projects. As a result, geopolymer concrete remains largely confined to academic research and small-scale trials, rather than becoming a mainstream construction material.

With coordinated efforts of researchers, industry stakeholders, and policymakers, geopolymer technology can become mainstream construction material and could play a defining role towards sustainable and resilient infrastructure.

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INAE's membership structure is designed to build a vibrant, interconnected community of institutions, companies, and individuals who are committed to advancing engineering and technology for national development. Through its diverse membership base, INAE fosters interdisciplinary collaboration, provides a platform for dialogue on critical technological issues and promotes excellence in engineering practice and education across India and beyond.

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A significant new initiative launched by INAE is the quarterly e-Magazine TechFrontier, conceived to showcase emerging trends, impactful research, and technological innovations in engineering and technology. The magazine was successfully launched on April 20, 2025, during the INAE Foundation Day.

This digital publication is envisioned as a platform to highlight cutting-edge advancements from India and across the globe. Its objective is to create awareness about engineering and technology by publishing articles on futuristic, emerging, and high-impact technologies that appeal not only to the engineering community but also to readers outside the field who have an interest in science and technology.

Volume I, Issue I of INAE TechFrontier, centred on the theme "Quantum Technology: India-centric Policy Perspectives", was successfully launched on April 20, 2025, during the INAE Foundation Day function held at IIT Delhi. The inaugural issue received an encouraging response and set a strong precedent for future editions. The issue features invited articles highlighting indigenous products, technological breakthroughs, and conceptual or review contributions that collectively reflect the cutting-edge advancements taking place in the country in the field of quantum technology.

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This edition features a thoughtfully curated collection of insightful articles that showcase the diversity, depth, and transformative potential of manufacturing-related research and development underway across the country.

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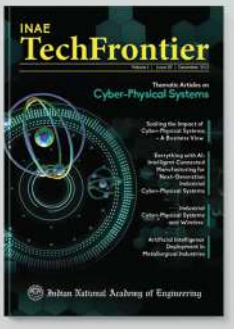

Volume I, Issue III, of INAE TechFrontier focuses on the theme "Cyber-Physical Systems", a rapidly evolving domain that integrates computation, communication, and control to transform sectors ranging from manufacturing and healthcare to transportation and industrial automation. The curated articles in this issue offer diverse perspectives on how Cyber-Physical Systems are reshaping industries, enabling intelligent and interconnected systems, and driving next-generation engineering solutions.

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