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Crisil Intelligence



Engineering Connectivity:

Innovations in Tunnel and Bridge Development

by S&P Global

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Acronyms and abbreviations

AI	Artificial intelligence	J&K	Jammu and Kashmir
AIMC	Automated and intelligent machine-aided construction	ML	Machine learning
BRO	Border Roads organisation	MoU	Memorandum of understanding
BIM	Building information modelling	MoRTH	Ministry of Road Transport and Highways
CAGR	Compound Annual Growth Rate	MoSPI	Ministry of Statistics and Program Implementation
DMRC	Delhi Metro Rail Corporation	MMRDA	Mumbai Metropolitan Region Development Authority
DPR	Detailed project report	NHIDCL	National Highways and Infrastructure Development Corporation Ltd
DTS	Digital Thermal Sensing	NHAI	National Highways Authority of India
DT	Digital Twins	NIP	National Infrastructure Pipeline
FIDIC	Fédération Internationale des Ingénieurs-Conseils	NATM	New Austrian tunnelling method
FOB	Foot over bridge	NPA	Non-performing asset
GIS	Geographic Information Systems	PPP	Public-private partnership
GSI	Geological Survey of India	RFI	Request for information
SGFRP	Glass Fibre Reinforced Polymer	RFP	Request for Proposal
GBS	Gross budgetary support	SHM	Structural Health Monitoring
GGBS	Ground granulated blast furnace slag	SCMs	Supplementary cementitious materials
HSR	High-speed rail	TBM	Tunnel Boring Machine
InvIT	Infrastructure investment trust	TEM	Tunnel excavation material
IDEP	integrated digital engineering platforms	USBRL	Udhampur-Srinagar-Baramulla Rail Link
IoT	Internet of things	UHPC	Ultra-high-performance concrete

Message from FICCI



Mr S Paramasivan
Co-Chairman, FICCI Committee on Transport Infrastructure and Managing Director, Afcons Infrastructure

I am pleased to present the **FICCI-CRISIL Knowledge Report on '*Engineering Connectivity: Innovations in Tunnel and Bridge Development*'**, unveiled at the **3rd Edition of the Tunnels & Bridges Conference 2025**, organized by the Federation of Indian Chambers of Commerce and Industry (FICCI).

India's tunnel and bridge construction sector stands at an inflection point of extraordinary growth, driven by the nation's vision to transform infrastructure. Over the last decade, landmark tunnel projects have been completed across challenging mountainous regions and dense urban areas. Simultaneously, major bridge projects, including record-breaking railway and sea crossings, now stretch from the Himalayas to vast rivers and coastal regions, significantly enhancing logistics and regional connectivity.

The industry continues to advance through innovation and resilience. While complex engineering challenges in geologically sensitive terrains persist, emerging technologies like AI, machine learning, digital twins, and BIM are transforming construction. The use of advanced safety systems, sustainable materials, waste recycling, and green financing is boosting project viability and reducing environmental impact. Supported by strong policies and government investment, the sector is poised to enhance efficiency, quality, and resilience while unlocking new opportunities.

This report provides a comprehensive examination of India's tunnelling and bridge landscape, analyzing emerging trends and identifying opportunities and challenges. It explores technological innovations and addresses sustainability imperatives while proposing a framework for strategic advancement through enhanced construction and maintenance practices, optimized project execution, and advanced safety and risk management approaches.

As representatives of an industry engaged in building the backbone of India's economic transformation, we believe this report will serve as a valuable resource for all stakeholders committed to advancing infrastructure development. We welcome your perspectives and invite constructive dialogue that can further strengthen our collective efforts.

Message from Crisil



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India is spearheading ambitious projects to rapidly augment its infrastructure landscape to enhance connectivity and boost economic growth. Tunnels and bridges play a critical role in this infrastructure development by overcoming geographical barriers, reducing travel time and improving logistics efficiency, all of which pave the path for integrated economic development. These structures are vital for achieving the vision of a connected, competitive and developed India by 2047, and ensuring seamless flow of goods and people across diverse terrains.

On the eve of the release of FICCI's third edition of the **Tunnels & Bridges Conference 2025**, our knowledge report, titled 'Towards light–Bridging the gap between technology and construction of tunnels', gives an in-depth view on the latest systems and processes being used to improve the construction and maintenance of these structures. It highlights the importance of artificial intelligence (AI), the increasing importance of using sustainable materials and advanced project modelling techniques such as digital twins (DT), structural health monitoring (SHM) and predictive maintenance systems. The report also explores the various aspects of safety considerations, improvements in award mechanism of detailed project report (DPR) consultancy works, the tightened selection criteria in request for proposal (RFP) framework, and certain revisions in processes. All these factors aim at better control and consistency during construction and maintenance of projects undertaken by the National Highways Authority of India (NHAI) and the Ministry of Road Transport and Highways (MoRTH).

The report explains how the aspects mentioned above are being used effectively as a tool to reshape the way India builds and maintains its tunnels and bridges, which aren't just civil structures, but arteries that take various ideas and practices of commerce, safety and sustainability to all corners of the country.

Preface

Tunnels and Bridges: Forging India's path to prosperity

Tunnels and Bridges are critical for connectivity, economic growth and technological progress. This report explores innovations transforming their construction, management and sustainability.

The infrastructure emerging in India, particularly the tunnels and bridges, demonstrate a narrative of progress and connectivity not seen until now. This preface explores how these monumental engineering achievements are not merely structures, but catalysts for comprehensive growth, transforming the economic and social landscape of the nation.

A vision for a connected India and national policies supporting this view have in recent years led to an unprecedented acceleration in the construction of world-class infrastructure. Bridges now ensure connectivity across vast river systems, and tunnels pierce through hitherto impassable mountain terrains. These structures also help us go over or under dense urban spaces, offering vital vehicular and mass transit connectivity. The Atal Tunnel in Himachal Pradesh and the Sela Tunnel in Arunachal Pradesh are testaments to how advanced tunnelling techniques are conquering formidable geological obstacles, slashing travel time and enhancing accessibility. Metro rail and high-speed rail tunnels that go deep beneath waterbodies, too, exemplify engineering proficiencies.

These developments have a direct impact on connectivity and economic activity. The reduction in travel time between major economic centres—such as the Delhi-Mumbai Expressway—translates into reduced logistics costs and increased opportunities for industries and businesses. This enhanced connectivity fosters greater integration between urban centres and remote regions, unlocking new avenues for real estate development and rural prosperity.

The ongoing construction of the national highways, border roads and strategic railway networks, including the ambitious projects in the Himalayas, shows the significant interest and investment going into infrastructure development.

The report also explores the advancements in technologies such as the use of DTs and Building Information Modelling (BIM) during the planning and designing stages, and the integration of AI/ML within the construction and maintenance monitoring practices. It highlights the adoption of sustainable practices, including the use of innovative and advanced materials across the construction lifecycle. The report discusses the innovative use of AI/ML tools to monitor safety during construction and maintenance.

The narrative of India's growth is increasingly being written through these engineering feats. As we witness the continuous expansion of road, railway and metro rail networks, and the increasing application of sophisticated technology, the country is laying the foundation for a more efficient, integrated and prosperous future. This work delves into the remarkable journey of Indian infrastructure, highlighting how tunnels and bridges are not just symbols of progress but the lifelines for India's growth.

Purpose and Scope of the report

The purpose of this report is to assess and propose a framework for the strategic advancement of India's bridge and tunnel infrastructure by leveraging technological innovations, sustainable practices and advanced management techniques, with a focus on integrating AI, green finance, DT and BIM to enhance construction and maintenance, ensure safety and promote the development of tunnels and bridges for improved national connectivity and sustainable development.

This report aims to:

- Foster technological advancements and integration in construction and maintenance
- Promote sustainability and green finance
- Discuss advanced tools and techniques and optimise project execution
- Initiate ideas on advanced safety and risk management
- Support national connectivity and economic growth



1 Introduction

Tunnels and Bridges are the backbone of infrastructure, enabling reliable transport, reducing travel time and improving access for millions. Based on India's ambitious infrastructure development goals and diverse topography, bridges and tunnels are crucial instruments of economic and social transformation. They play a pivotal role in connecting remote regions, decongesting urban centres, facilitating trade and ensuring national security. This report delves into the vital significance of the country's bridge and tunnel infrastructure, examining its historical evolution, recent advancements and the potential.

- **Historical context and modern achievements**

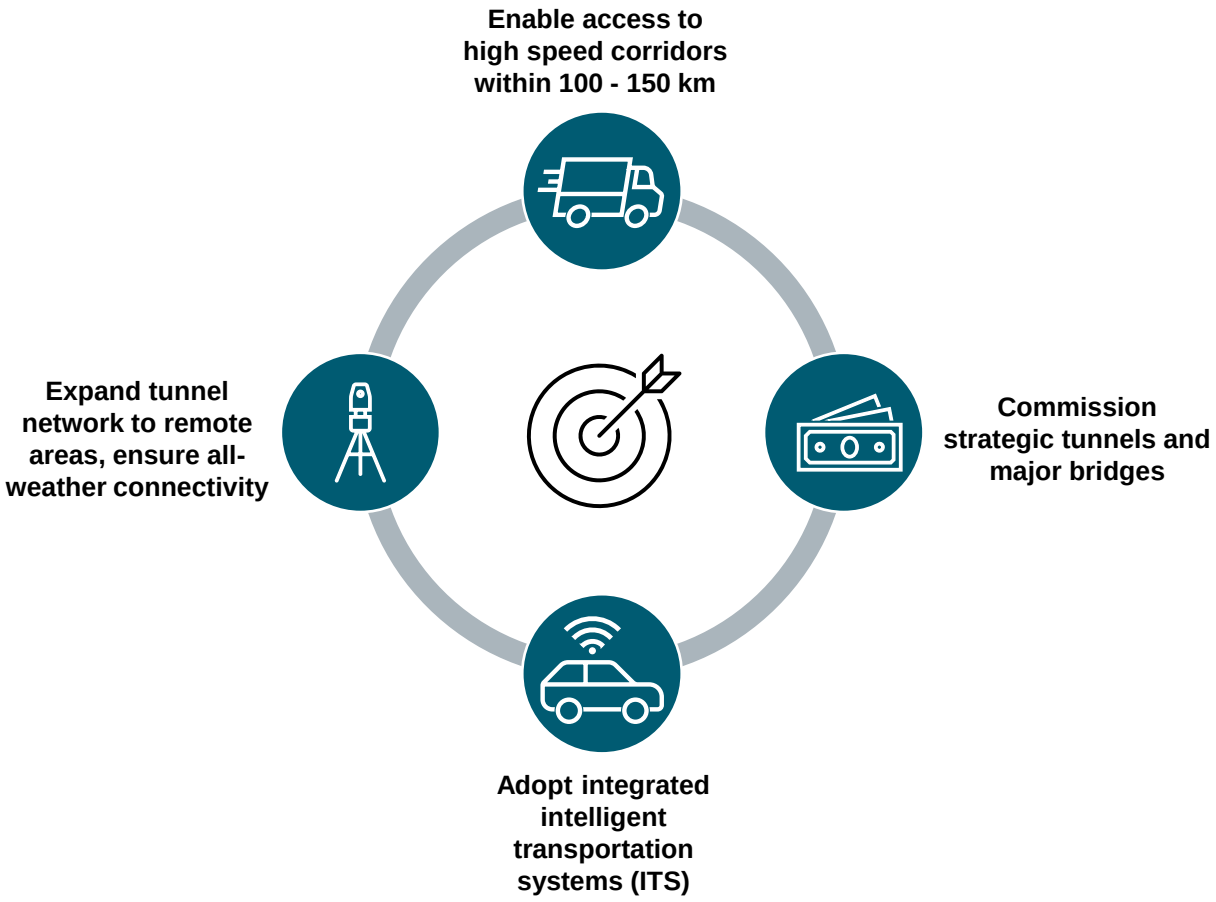
  Historically, India's diverse geography—including the formidable Himalayas, dense urban areas and numerous rivers—has presented significant challenges to the transportation sector. In recent decades, however, modern engineering has eased the challenges. Until 2000, the country exhibited modest achievements in bridges and tunnels. The Howrah Bridge, Vivekananda Setu, the old Pamban Bridge and the old Gandhi Setu were some of the noteworthy bridge projects. Tunnels were largely limited to the Kolkata Metro project and, to some extent, in roads, railways and hydro projects.

  The turn of the new millennium saw the Delhi Metro being commissioned with complex tunnels and elevated structures, the cable-stayed New Yamuna Bridge in Prayagraj (then Allahabad), the Sister Nivedita Setu in Kolkata, and the Bandra-Worli Sea Link in Mumbai. The next decade and a half saw more complex and cutting-edge projects, such as the Dhola Sadiya bridge in Assam, the Dr Syama Prasad Mookerjee Tunnel (Chenani-Nashri) and the Chenab Railway Bridge in Jammu and Kashmir, the Atal Tunnel in Himachal Pradesh, the Aunta-Simaria Bridge in Bihar, the Mumbai Metro Line 3 (Aqua line), the Atal Setu (Mumbai Trans Harbour Sea Link) in Mumbai. These and other landmark projects showcase India's capacity to overcome formidable natural barriers. These projects have redefined connectivity and set new benchmarks in construction.

- **India Vision 2047: Tunnel and bridge infrastructure**

  India aims to transform its infrastructure by 2047, focusing on connectivity, sustainability and economic growth. The government's vision includes building a world-class transportation network, strengthening connectivity and promoting regional development.

Key objectives



Landmark initiatives include

- Bharat Mala Pariyojana, 2015
- Setu Bharatam, 2016
- PM Gati Shakti, 2020
- Metro Rail Policy, 2017
- PM DevINE, 2022
- North Eastern Railway Connectivity
- National High Speed Corridor

1.1 Infra investments in India

- **Emphasis on capital expenditure**

  Investments have expanded in recent years, reflecting a strong push towards infrastructure augmentation. This includes the National Infrastructure Pipeline (NIP) (fiscals 2024 to 2030) which projects infrastructure investments of Rs 143 trillion higher than the previous cycle. This expanded pipeline, following the initial NIP for fiscals 2019 to 2025, seeks to boost economic growth, create jobs and improve the quality of life by funding projects in sectors such as roads, railways and renewable energy[1]. In line with this, the Union Budget for fiscal 2026 allocates Rs 11.21 trillion for capital expenditure, forming a core part of the Viksit Bharat 2047 vision[2].

- **Construction investments to grow at 6-8% CAGR between fiscals 2026 and 2030**

  India's construction industry is projected to grow, logging a compound annual growth rate (CAGR) of 6-8% between fiscals 2026 and 2030. This growth is expected to be driven by an increase in investments in infrastructure projects, particularly roads and railways, supported by both the central and state government spending[3].

Infrastructure investments to drive growth in the medium term

Sector	FY21-FY25 CAGR	FY25E Rs lakh crore	FY26P % y-o-y	FY26-30P/ FY21-25	Estimated source of funds (FY25E-30P)
Roads	13%	4.1	5-7%	1.8x	70% 21% 9% FY25E; 60% 21% 19% FY26-30P
Power	17%	0.5	13-15%	1.4x	35% 24% 41%; 18% 29% 53%
Railways	14%	1.2	0-2%	1.3x	97% 3%; ~1%; 96%
Urban infra	30%	1.4	4-6%	1.6x	43% 53% 4%; 41% 53% 8%
Irrigation	6%	0.9	8-10%	1.3x	10% 50% 40%; 18% 47% 35%
Other infra	16%	0.4	6-8%	1.0x	Center Center; State State; Private Private; FY25E FY26-30P
Total Infrastructure	15%	8.5	6-8%	1.6x	

(Source: Crisil Research)

[1] https://www.financialexpress.com/business/infrastructure-infra-investments-to-double-to-rs-143-trn-in-fy24-fy30-3275708/

[2] https://www.india.gov.in/spotlight/union-budget-2025-2026#:~:text=The%20net%20tax%20receipts%20are,Expansion%20of%20Capacity%20in%20IITs

[3] https://www.crisilresearch.com/#/home/industry/construction

Construction capex growth to stabilise at 6-8%



Note: A: Actual, P - Projected

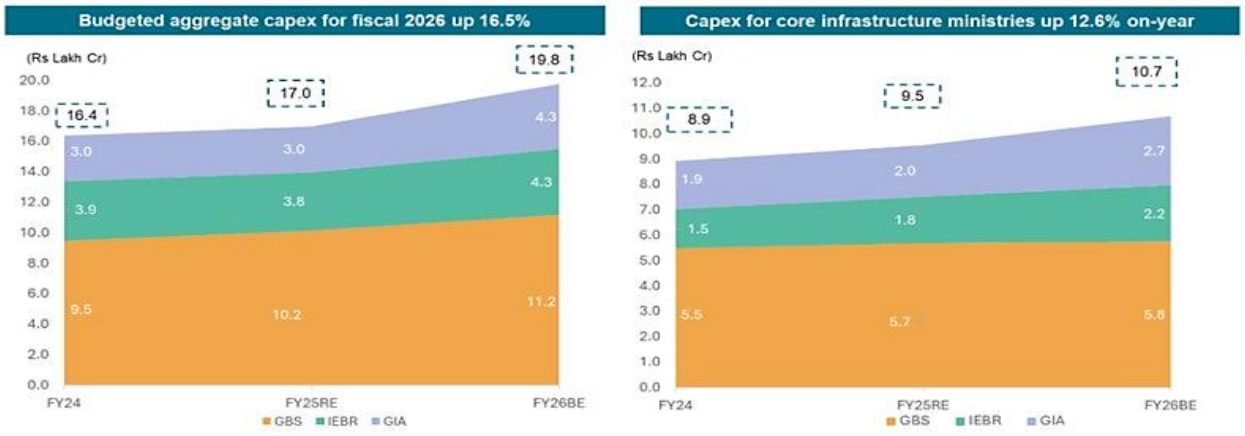
(Source: Crisil Research)

Construction capital expenditure (capex) experienced a steady 7% annual growth rate from Fiscals 2018 to 2022, driven by moderate increases in infrastructure spending. However, this trend was disrupted in fiscals 2023 and 2024 when the government significantly boosted infrastructure investments, resulting in double-digit capex growth. This surge was fuelled by large-scale projects in roads, railways and urban development. As the government scales back its spending, rapid capex growth is expected to slow and return to its pre- Fiscal 2022 pace, stabilising at a CAGR of 6-8% by Fiscal 2026. To sustain this growth trajectory in the long term, private investments in infrastructure will play a crucial role.

- **Centre budget allocations for infrastructure in fiscal 2026**

  The budgetary capital expenditure allocated to infrastructure ministries has increased to Rs 10.7 trillion, representing an 12.6% rise from fiscal 2025RE of Rs 9.5 trillion.

Core infra sector allocation of Rs 10.7 lakh crores further sets the stage for private participation



10 infra ministries include: Road Transport and Highways, Housing and Urban Affairs, Civil Aviation, Power, Railways, Shipping, Rural Development, Water Resources, New and Renewable Energy, Department of Atomic Energy

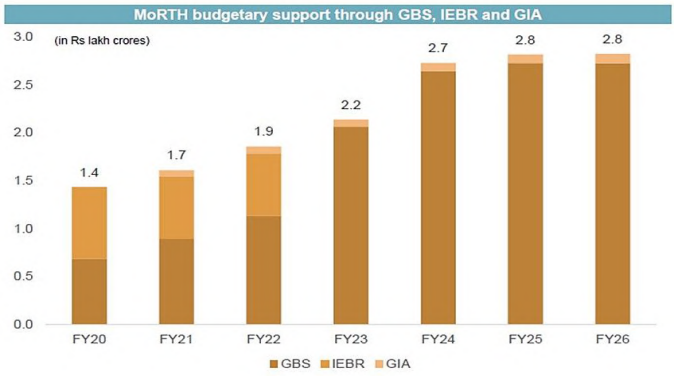
RE – Revised estimate; BE – Budget estimate , value for FY23 is actuals
GBS: Gross Budgetary Support; IEBR: Internal and Extra Budgetary Resources; GIA : Grants allocated for capital creation

For Ministry of power GIA calculated as per Crisil Intelligence
Source: Budget Documents, Crisil Intelligence

(Source: Crisil Research)

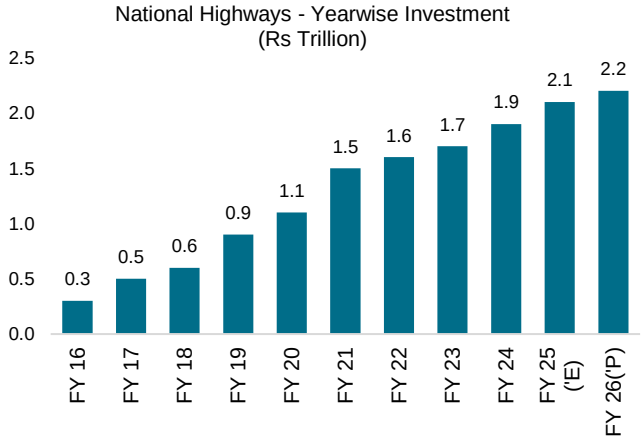
- **MoRTH allocations over the years**

Overall budgetary support doubled from Rs 1.4 trillion in fiscal 2020 to Rs 2.8 trillion in fiscal 2025 with Gross budgetary support (GBS) as the main source. However, allocation growth remains muted in fiscal 2026 compared with fiscal 2025, marking the second consecutive year of steady growth. Grant in aid (GIA) is primarily sourced from the Central Road and Infrastructure Fund, the Consolidated Fund of India and various centrally sponsored schemes. Budget allocation through internal and external borrowings (IEBR) were phased out after fiscal 2022 to curb rising debt of National Highways Authority of India (NHAI). Overall support has clocked a CAGR of 12.25% from fiscal 2020 to fiscal 2026.



(E: Estimated, P: Projected) (Source: Crisil Research)

On similar lines, investments in National Highways also saw a steep rise over the decade from Rs 0.3 trillion in fiscal 16 to Rs 2.2 trillion in fiscal 26 (Projected).



1.2 Milestone projects

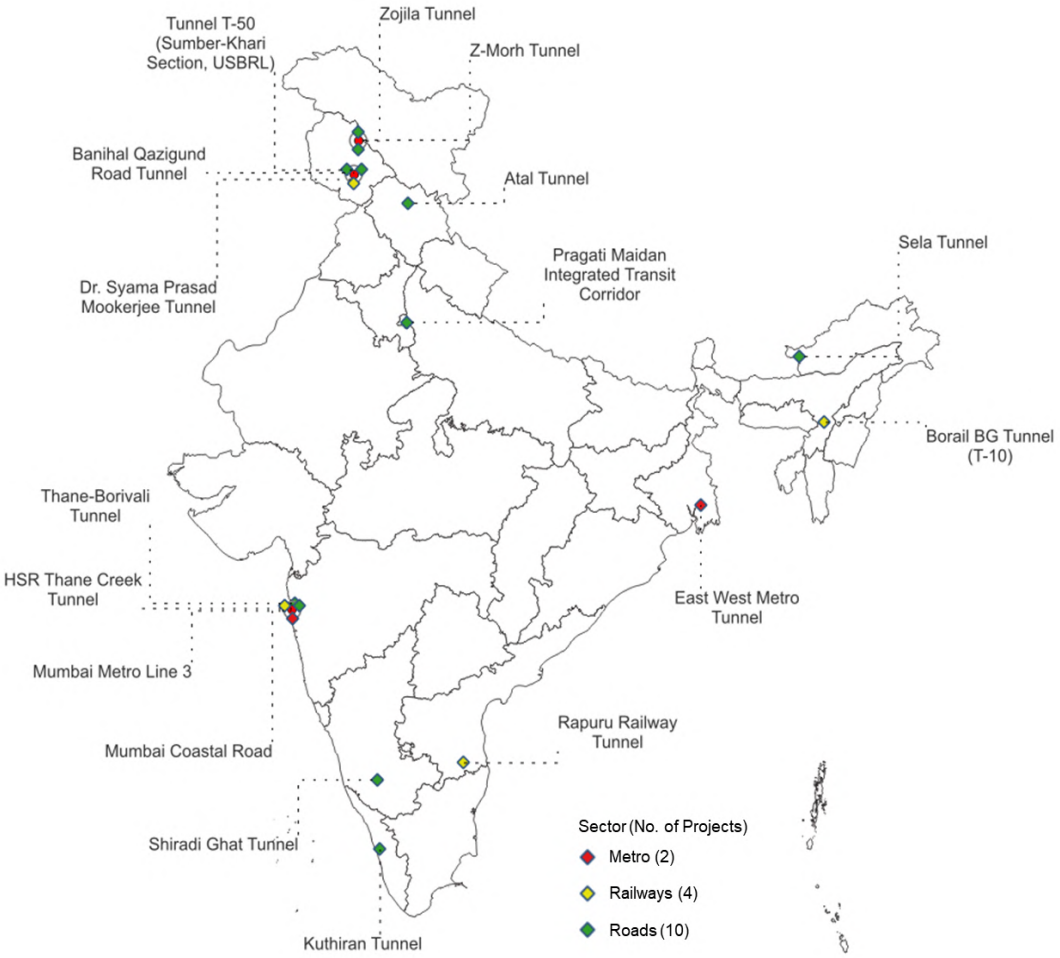
Key tunnels and bridges over the last decade

Tunnel construction in India has evolved from ancient shelter-digging to complex post-independence hydro and rail projects. Bridge construction expanded significantly during the British rule, with projects such as the Howrah Bridge and accelerated after fiscal 2014, particularly in national highways with major undertakings like the Mumbai Trans Harbour Link and numerous modern railway and road bridges.

Tunnels

Over the last 10 years, India has implemented several landmark tunnel projects across its road, railway and metro sectors, especially in challenging mountainous regions and dense urban areas. Key projects include strategic tunnels in the Himalayas, new railway lines and the country's first underwater metro line. Prominent tunnels that have commenced or are under construction over the last decade are showcased below.

Figure: Prominent Tunnel projects in India over last decade



These projects have been selected based on their unique characteristics such as geographic conditions, strategic importance, adoption of complex engineering techniques for construction, large ticket size in terms of cost and schedule/time construction period and widespread media coverage gathered during construction and inauguration.

Prominent road tunnels opened/under construction since 2010

- **Dr. Syama Prasad Mookerjee Tunnel (Chenani-Nashri, J&K), 2017**: This 9.2-km tunnel on NH 44 is India's longest road tunnel bypassing the treacherous terrain of Patni top and reducing the travel distance between Jammu and Srinagar by 31 km
- **Atal Tunnel (Rohtang Pass, Himachal Pradesh), 2020**: Constructed at an altitude of above 10,000 feet, Atal Tunnel is the world's longest highway tunnel (9.02 km). It provides year-round connectivity between Manali and the Lahaul-Spiti Valley, which would earlier be cut off during winter due to heavy snowfall.



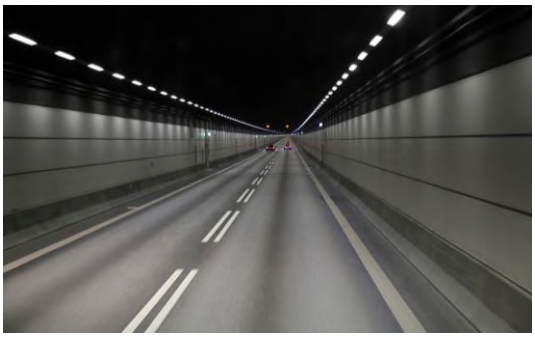
(Illustrative Picture)

- **Banihal Qazigund Road Tunnel (J&K), 2021**: This 8.45-km twin-tube tunnel provides an all-weather route on NH 44, reducing the road distance between Banihal and Qazigund by 16 km
- **Kuthiran Tunnel (Kerala), 2021:** This 1.6 km tunnel which eases traffic congestion on the Thrissur-Palakkad stretch of NH 544, is Kerala's first and south India's longest six-lane road tunnel

- **Pragati Maidan Integrated Transit Corridor (Delhi), 2022:** This project, includes a 1.3-km main tunnel beneath Pragati Maidan, which helps decongest traffic in central Delhi
- **Z-Morh Tunnel (J&K), 2023:** This 6.5-km road tunnel on the Srinagar-Leh highway provides all-weather connectivity to Sonamarg, which is prone to avalanches
- **Mumbai Coastal Road (Dharamveer Swarajya Rakshak Chatrapati Sambhaji Maharaj Marg, Maharashtra), 2024:** Completed sections of this project include a 2.07 km long undersea twin tunnel which provides high-speed connectivity to suburbs along the coastline of Mumbai
- **Sela Tunnel (Arunachal Pradesh), 2024:** This project consists of two tunnels and a link road that provide all-weather connectivity to Tawang, located near the Line of Actual Control. This tunnel avoids the need to cross the high-altitude Sela Pass
- **Thane-Borivali Tunnel (Mumbai, Maharashtra), 2028 (under construction):** This 11.8 km twin tunnel project by the MMRDA under the Sanjay Gandhi National Park, is designed SSto connect Ghodbunder Road in Thane to the Western Express Highway in Borivali



(Illustrative Picture)



(Illustrative Picture)

- **Shiradi Ghat Tunnel (Karnataka), 2030 (under construction):** The Shiradi Ghat is a mountain pass in Karnataka's Western Ghats on the NH-75 (formerly NH-48), connecting the coastal city of Mangalore with Bangalore via Hassan and Sakleshpur. While the Shiradi Ghat currently does not have a tunnel, a long-planned tunnel project has been proposed to bypass the difficult terrain and reduce travel time on this route through the forests of the Western Ghats, a UNESCO World Heritage Site. The proposed tunnel, along with the realignment, is expected to be completed within five years.[4]

Railway tunnels

- **Borail BG Tunnel (T-10, Assam), 2015:** This 3.23 km tunnel is a part of the gauge conversion project in the Northeast
- **Rapuru Railway Tunnel (Andhra Pradesh), 2019:** This 6.64-km tunnel is on the Obulavaripalli–Krishnapatnam railway line
- **Udhampur-Srinagar-Baramulla Rail Link (USBRL, J&K), 2025:** Numerous tunnels on the Udhampur-Srinagar-Baramulla Rail Link (USBRL) have been completed or are nearing completion
  - Pir Panjal Railway Tunnel (T-80): At 11.2 km, this was India's longest railway tunnel when it opened in 2013
  - Tunnel T-50: Completed in 2024, this 12.7-km tunnel between Sumber and Khari is a part of the USBRL
  - Tunnel T-49: Completed in 2024, this 10.17-km tunnel is located between Sangaldan and Sumber
  - USBRL Tunnel 44 (T-44): The trial run for this 11.13-km tunnel between Katra and Banihal was conducted in 2024
- **Mumbai-Ahmedabad high-speed rail (HSR), 2029 (under construction** A 4.88 km tunnel was achieved in Ghansoli and Shilphata in Thane region in September 2025 for the bullet train project which has a total length of ~21 km, including a 7 km section under the Thane Creek[5] [6].

[4] https://www.thehindu.com/news/cities/Mangalore/realigned-highway-to-bengaluru-via-shiradi-ghat-will-be-ready-in-five-years-says-nhai-official/article69851377.ece
[5] https://www.pib.gov.in/PressReleasePage.aspx?PRID=2168979
[6] https://www.nhsrcl.in/en/media/press-release/media-brief-5-km-tunnel-completed-between-ghansoli-and-shilphata-mumbai

Metro rail and other tunnels

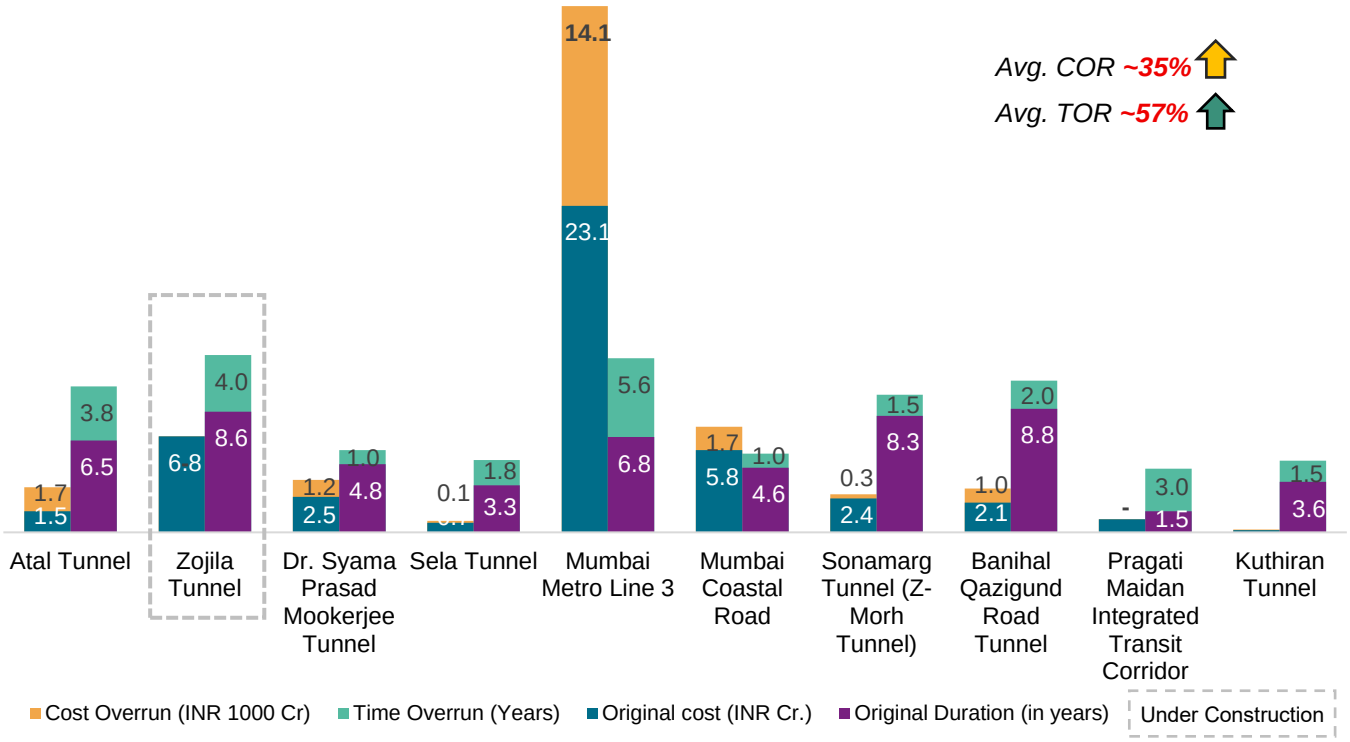
- **East-West Metro Corridor (Kolkata), 2024:** The East-West Metro corridor launched India's first underwater metro line, with tunnels running beneath the Hooghly River
- **Aqua Line (Mumbai Metro line 3, Maharashtra), 2024:** Several underground sections have been constructed as part of Mumbai's metro expansion, including tunnels on Line 3 (Aqua Line)

Cost and Time Overrun Comparison for Prominent Projects with tunnels over the last decade

Tunnel projects in India have consistently faced challenges. An analysis of the selected key tunnel projects shows an average cost overrun of ~35% and a time overrun of ~57% compared with their originally budgeted costs and timelines.

Source: Annexure 1 (refer page 42)

Time Overrun (TOR) and Cost Overruns (COR) in Select Tunnel Projects

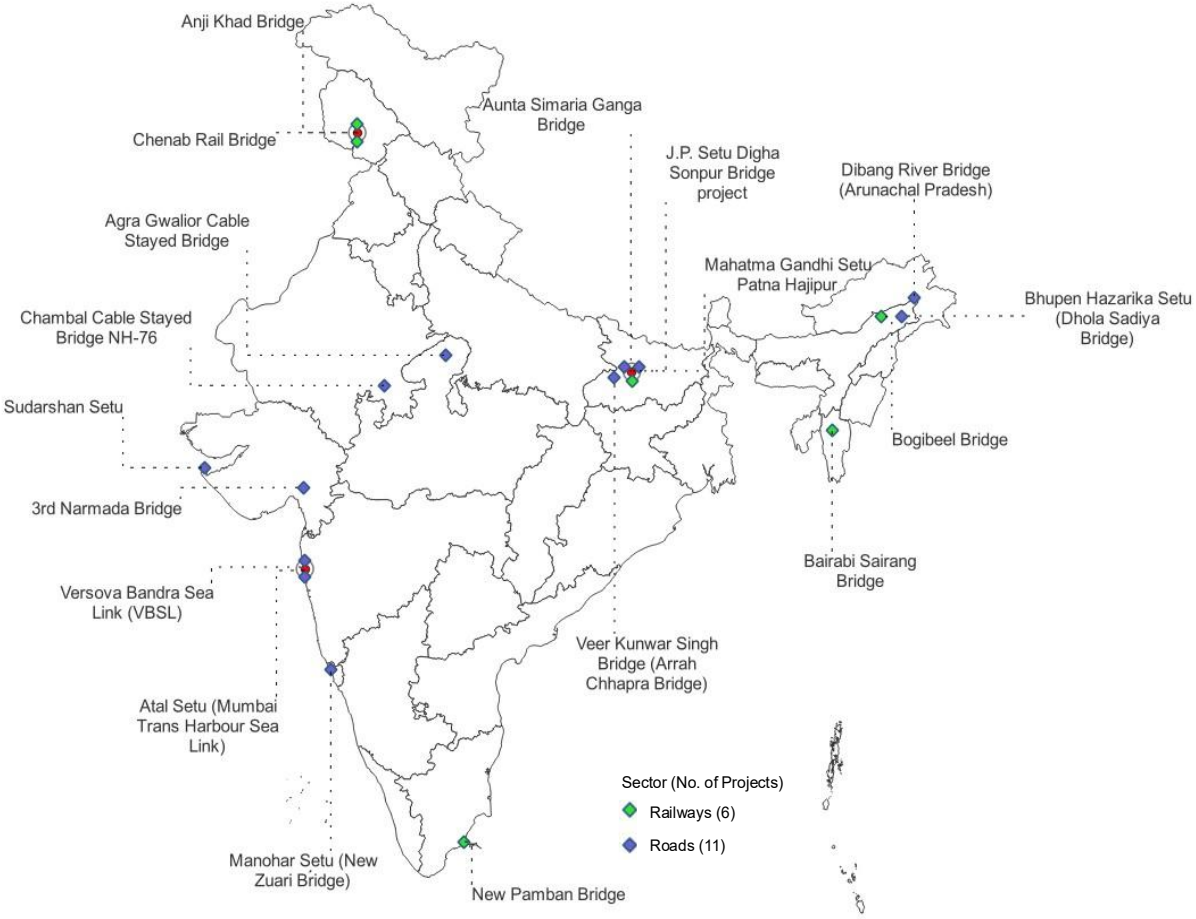


Disclaimer: The information presented has been compiled from publicly available sources, news articles, and other referenced materials, as detailed in the annex. Crisil has not independently verified the accuracy or completeness of this information. The purpose is to provide general perspective on the nature of delays and cost overruns typically observed in complex infrastructure projects. The examples cited represent a selective sample from the past decade

1.3 Overview of Bridges

Over the last decade, India has completed several major bridge projects ranging from the challenging terrains of the Himalayas to expansive rivers and coastal areas. These projects include record-breaking railway and sea bridges, as well as crucial links that improve connectivity and strengthen defense logistics.

Figure: Prominent bridge projects in India over last decade



These projects have been selected based on their unique characteristics such as geographic conditions, strategic importance, adoption of complex engineering techniques for construction, large ticket size in terms of cost and schedule/time construction period and widespread media coverage gathered during construction and inauguration.

Prominent road bridges commenced/under construction over the last decade

- **Bhupen Hazarika Setu (Dhola Sadiya Bridge, Assam), 2017:** This 9.15 km bridge, is India's longest over water bridge, spanning the Lohit River. It provides connectivity between Assam and Arunachal Pradesh, benefitting civilian and defense logistics
- **Arrah-Chhapra Bridge (Veer Kunwar Singh Bridge, Bihar), 2017:** This 4.35-kilometer road bridge across the Ganga, significantly reduced the travel distance between Arrah and Chhapra
- **Third Narmada Bridge (New Narmada Bridge, Gujarat), 2017:** This cable-stayed bridge near Bharuch was built to relieve traffic congestion on the Ahmedabad-Mumbai NH 8
- **Dibang River Bridge (Arunachal Pradesh), 2018:** This 6.2-kilometer bridge improves road connectivity in remote regions of Arunachal Pradesh and is also strategically important for national security

- **Manohar Setu (New Zuari Bridge, Goa), 2022:** This is India's second-longest cable-stayed bridge, which improves connectivity on the Mumbai-Goa highway
- **Mahatma Gandhi Setu (Bihar), 2022:** Completed in 2022, the rehabilitation involved dismantling the original balanced cantilever concrete bridge and replacing it with a new steel framework, making it India's first and longest steel-supported river bridge
- **Mumbai Trans Harbour Sea Link (Atal Setu, Mumbai), 2024:** This 21.8-kilometer sea bridge is India's longest, connecting Sewri in Mumbai to Nhava Sheva in Navi Mumbai, reducing travel time to and from Mumbai.
- **Sudarshan Setu (Okha-Beyt Dwarka Signature Bridge, Gujarat), 2024:** This cable-stayed bridge connects mainland Okha to Beyt Dwarka island, improving access to a major pilgrimage site



(Illustrative Picture)

- **Aunta–Simaria Bridge (Bihar), 2025:** This 6-lane, 1.86 km long extra dosed bridge over the Ganga in Bihar, inaugurated in 22nd August 2025, connects Patna and Begusarai
- **Swatantrya Veer Savarkar Sea Link (Versova–Bandra Sea Link, Mumbai), 2028 (Under Construction):** The construction of the **17-km** bridge in Mumbai, connecting the Bandra-Worli Sea Link t Versova, is to alleviate traffic congestion. The project, which is scheduled to be completed in 2028, involves cable-stayed bridge technology
- **Chambal River Bridge (Madhya Pradesh), 2028 (Under Construction):** This **1.2-km** cable stayed structure being built on the Agra-Gwalior Greenfield Expressway section, will be one of the longest in the country upon completion, which is scheduled for 2028



(Illustrative Picture)

Prominent Rail Bridges that commenced / are under construction over the past decade

- **J P Setu (Digha–Sonpur Bridge Bihar), 2016:** This 4.55 km rail-cum-road bridge crosses the Ganga links Digha Ghat in Patna to Pahleja Ghat in Sonpur.
- **Bogibeel Bridge (Assam), 2018:** Opened in 2018, the 4.94-km rail-cum-road bridge spans the Brahmaputra River. It links Dibrugarh and Dhemaji, providing a crucial transport link for India's northeastern region as well as significantly reducing travel times.
- **Chenab Rail Bridge (J&K), 2025:** Inaugurated in June 2025, this is the world's highest railway arch bridge. At 359 meters above the Chenab River, the 1,315-meter-long steel arch structure is engineered to withstand high wind and seismic conditions. It is a key part of the USBRL



- **Anji Khad Bridge (J&K), 2025:** Opened in June 2025, this is India's first cable-stayed railway bridge. It provides critical rail connectivity in challenging hilly terrain.
- **New Pamban Bridge (Tamil Nadu), 2025:** This is India's first vertical-lift railway sea bridge, which was completed in 2024 and inaugurated in April 2025. The 2.07-km bridge connects mainland India with Rameswaram, replacing a century-old bridge to accommodate higher vehicular speeds and more traffic.
- **Bairabi-Sairang Rail Line (Mizoram), 2025:** As part of a new railway line inaugurated in September 2025, an 114-meter-tall railway bridge (Bridge No. 144) was built near Sairang. It is the tallest pier railway bridge in India.



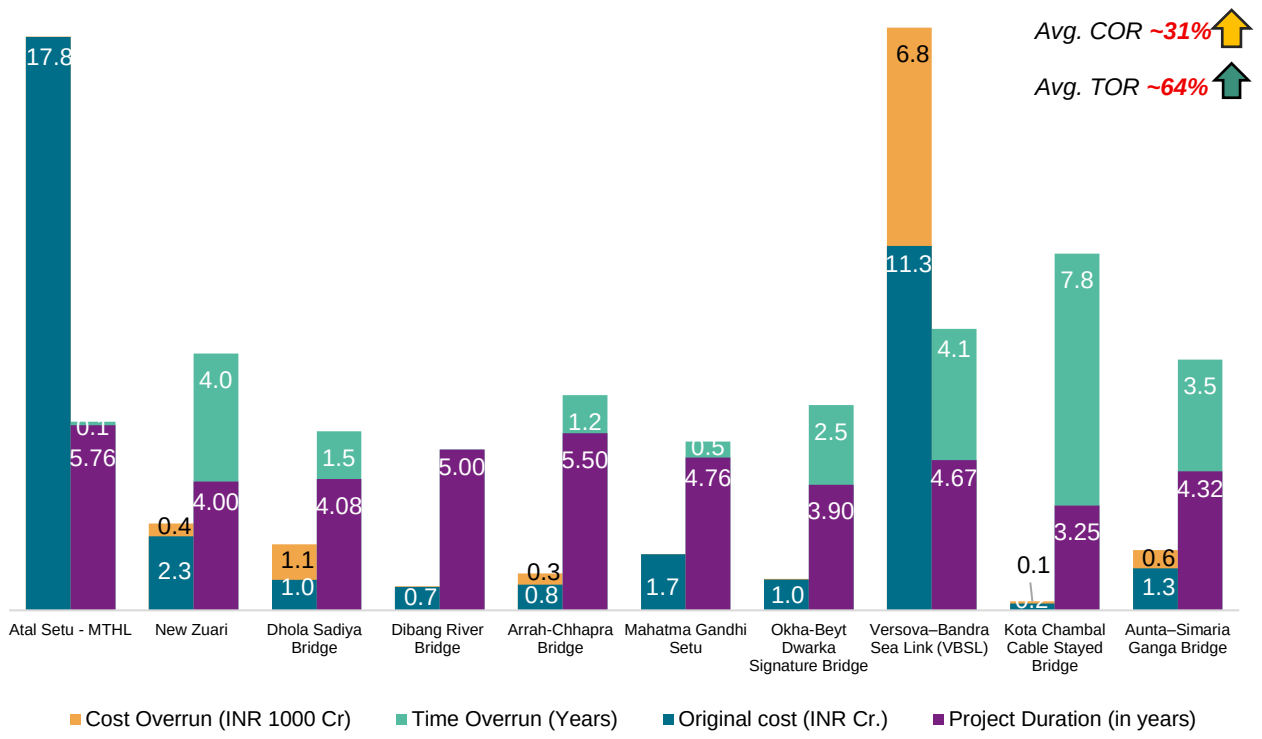
(Illustrative Picture)

Cost and Time Overrun Comparison for Prominent Bridge Projects over the last decade

The bridge projects in India have experienced considerable challenges. An analysis of the selected key bridge projects shown below, stare at an *average cost overrun of ~31% and a time overrun of ~64% from their originally budgeted costs and timelines*

Source: Annexure 1 (refer page 44)

Time Overrun (TOR) and Cost Overruns (COR) in Select Bridge Projects



Disclaimer: The information presented has been compiled from publicly available sources, news articles, and other referenced materials, as detailed in the annex. Crisil has not independently verified the accuracy or completeness of this information. The purpose is to provide general perspective on the nature of delays and cost overruns typically observed in complex infrastructure projects. The examples cited represent a selective sample from the past decade

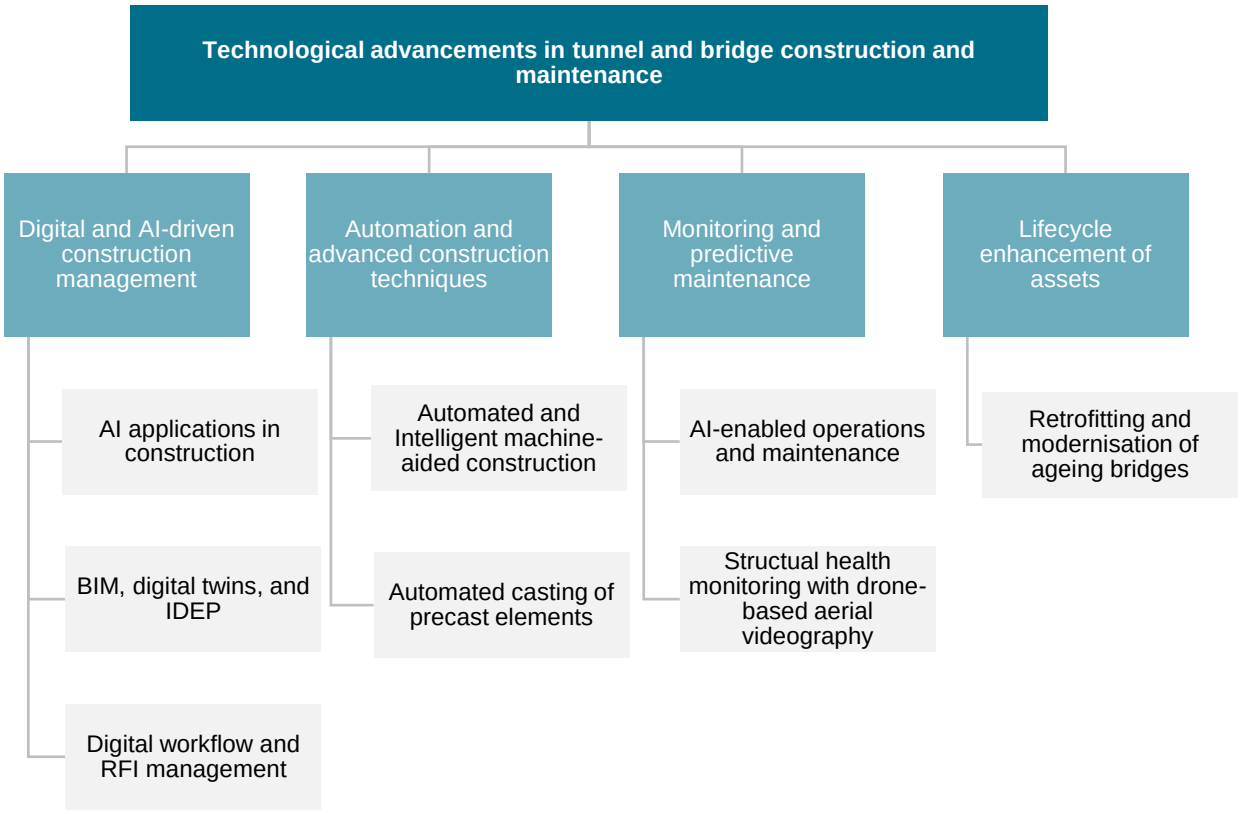


2 New-age technologies

The construction of modern bridges and tunnels is increasingly being shaped by technological innovations that enhance efficiency, precision and asset performance. From the adoption of digital platforms and AI-driven tools to the automation in the construction processes, these technologies are transforming the way infrastructure is built, monitored and maintained. **Advanced sensing systems, drone-assisted inspections and predictive maintenance** enable real-time insights into structural health; while retrofitting and modernisation techniques extend the life of existing assets.

The following sections explore digital management, automation in construction, monitoring and maintenance, and lifecycle enhancement of an infrastructure project.

BIM – Building Information Modelling; IDEP – Integrated Digital Engineering Platforms; RFI - Request for Information



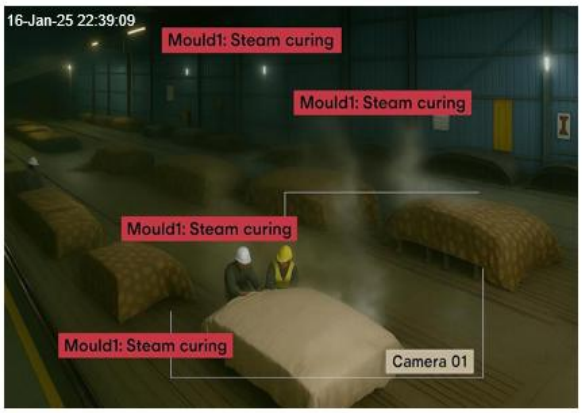
2.1 AI applications in construction

AI is increasingly transforming construction practices by providing data-driven insights that enhance efficiency, safety and operational control. In bridge and tunnel projects, AI can be leveraged to monitor site operations, optimise resources and support data-driven decision-making throughout the project lifecycle.

The key applications include:

- **Productivity analysis:** AI systems, by integrating computer vision (through CCTV or drone footage) and machine learning, enable a comprehensive assessment of construction productivity through time and motion studies (TMS). This includes activity-level time tracking, idle time detection, bottleneck identification, workforce monitoring and equipment utilisation. By objectively quantifying performance, AI helps project teams allocate labour and machinery more efficiently, reduce project delays and improve overall execution efficiency

Figure: Activity-wise time and labour movement tracking





- **Automated safety compliance monitoring:** AI-powered cameras, drones and sensors allow continuous surveillance of construction sites. These systems can detect unsafe practices, unauthorised zone entries and potential hazards, ensuring compliance with safety protocols. Real-time monitoring can also provide accurate progress updates, reducing reliance on manual inspections and enhancing site supervision, particularly in complex or high-risk construction environments such as tunnels and elevated bridge segments

Figure: AI-based safety (personal protective equipment) compliance monitoring





- **Predictive equipment maintenance:** Machine learning algorithms analyse sensor and operational data from construction machinery to predict wear, faults or failures. This enables proactive maintenance planning, reduces equipment downtime, improves asset utilisation and ensures critical machinery is available when required. Predictive maintenance contributes to smoother project execution, cost efficiency and longevity of high-value construction equipment

Hence, integrating AI across productivity monitoring, site surveillance and predictive maintenance allows construction projects to enhance operational efficiency, improve safety compliance and optimise resource deployment. Beyond these applications, AI can support broader construction management objectives, including design and schedule optimisation, demonstrating its potential to drive smarter, data-driven decision-making throughout the project lifecycle.

2.2 BIM, Digital Twins and integrated digital engineering platforms

The adoption of digital technologies has transformed the planning, construction and management of complex infrastructure, such as bridges and tunnels. Among these, BIM, DT and IDEP are enabling data-driven decision-making, enhancing collaboration and improving lifecycle performance.

Building Information Modelling: BIM has evolved into a cornerstone of modern engineering practice. It offers a model-based, data-rich environment, where multidisciplinary inputs are integrated into a central digital framework. For bridges and tunnels, BIM supports:

- Visualisation of complex geometries and design alternatives
- Early clash/conflict detection and error reduction
- Optimised resource allocation and interdisciplinary coordination
- Improved stakeholder communication and risk management

Digital Twins: DTs extend the capabilities of BIM by creating a dynamic, continuously updated virtual replica of physical assets. Enabled by sensors, internet of things (IoT) networks and real-time data acquisition systems, DTs provide actionable intelligence during the construction as well as operations phases. Key applications include:

- Predictive maintenance and structural health monitoring
- Lifecycle asset management across all phases

- Enhanced safety through real-time monitoring and early warning systems

Integrated Digital Engineering Platforms: IDEPs bring together BIM, DT, geographic information systems (GIS) and specialised domain models (e.g., bridge information modelling) into a coordinated digital ecosystem. For bridge and tunnel projects, IDEPs are particularly valuable because of their complexity, multi-stakeholder nature and long asset lifespans. Their applications include:

- Coordinated design and early clash detection across disciplines
- Spatially contextualised planning by integrating BIM with GIS
- Unified data management across the construction and operation phases
- Predictive analytics for asset performance, durability and risk management

A notable example of an IDEP application is the Sydney Metro project in Australia, which deployed a common data environment approach, combining BIM, GIS and DT, for underground tunnelling works. This approach ensured data and information management consistency and efficiency across stakeholders during the project lifecycle[7]. Despite the transformative potential of these digital technologies, several constraints limit widespread adoption, such as:

- High upfront investment in sensors, IoT and data infrastructure
- Technical complexity and interoperability limitations
- Workforce skill gaps and training requirements
- Lack of standardised protocols across organisations and geographies

Still, the integration of BIM, DT and IDEP represents a significant step toward digitalised infrastructure delivery. While the benefits for efficiency, safety and resilience in bridges and tunnels are significant, their successful adoption depends on sustained investments and capacity building, and development of uniform standards to ensure interoperability and industry-wide acceptance.

The continued progress of international standards (e.g., ISO 19650 for BIM) and government-led digital push are expected to accelerate adoption, particularly in large-scale national infrastructure projects.

2.3 Digital workflow and RFI management

The digitisation of workflows and information exchange has become integral to managing large-scale infrastructure projects such as bridges and tunnels. Owing to multiple stakeholders and high technical complexity, digital platforms are being deployed to standardise processes, reduce delays and improve accountability across the project's lifecycle.

Workflow automation

Digital workflow management systems ensure that approvals, document submissions and technical reviews follow predefined, transparent pathways. This minimises the risk of information loss, improves compliance with contractual requirements, and provides stakeholders with real-time visibility into project decisions and deliverables.

Request for information management

RFI serves as a key mechanism for addressing design clarifications, site conditions and technical queries. Digital RFI platforms centralise submissions, tracking and resolutions, thereby reducing response times and strengthening accountability. Integration with BIM further enhances precision by linking RFIs to specific model elements or drawings. Notably, metro rail clients such as Maharashtra Metro Rail Corporation Ltd are now mandating that contractors manage RFIs through their integrated enterprise resource planning (ERP) systems, underscoring the shift towards centralised and digital information management.

Advantages of digital workflow and RFI systems

- Improved coordination: Streamlines communication between contractors, consultants and clients
- Transparency and accountability: Centralises records with clear audit trails
- Reduced delays: Ensures faster resolution of queries and avoids rework
- Integration with models: Provides direct linkage of RFIs to BIM elements for contextual issue resolution

[7] https://www.infrastructure.nsw.gov.au/media/yimawfr3/insw_sydney-metro-csw_harnessing-cde_case-study.pdf

The adoption of workflow automation and ERP-enabled RFI management represents an important step in advancing Construction 4.0, where data-driven systems enhance efficiency, compliance and quality in the delivery of critical infrastructure.

2.4 Automated and intelligent machine-aided construction

Automated and intelligent machine-aided construction (AIMC) refers to the use of advanced, GPS-guided machinery such as intelligent compactors and motor graders in road construction to improve quality and efficiency and reduce delays.

Specifically for compaction, AIMC involves using intelligent compaction rollers to achieve consistent density and prevent damage by minimising air pockets, ensuring roads meet design specifications and have a longer lifespan.

This technology enables real-time monitoring, digital data collection for DT applications, reduced wastage and improved transparency on national highway projects, including the approaches of bridges and tunnels. The Ministry of Road Transport & Highways (MoRTH), vide a circular in December 2024, encouraged the use of AIMC in national highway (NH) projects and sought suggestions/clarification in this regard from stakeholders[8].

Uses of AIMC

- **Intelligent compaction rollers:** These machines are equipped with sensors and GPS technology to monitor soil density in real-time
- **Real-time compaction mapping:** The technology generates continuous compaction maps, allowing operators to see exactly where more work is needed
- **Consistent density:** This real-time feedback helps to avoid over- or under-compaction, ensuring consistent density across the entire area
- **Reduced air pockets:** By achieving optimal compaction, AIMC minimises air voids, preventing future damage and increasing the road's durability and longevity

Benefits of AIMC compaction

- **Higher quality:** Ensures the soil and base layers meet design specifications, leading to more durable roads
- **Improved project efficiency:** Reduces project cycle times by eliminating guesswork and ensuring the job is done right the first time
- **Cost saving:** Prevents wastage of materials and reduces rework, which can lead to delays and cost overruns
- **Increased productivity:** Allows faster and more accurate compaction compared with traditional methods

2.5 Automated casting for precast elements

Automation in precast construction has become increasingly relevant for large-scale tunnel and bridge projects, where **innumerable repetitive concrete elements** must be produced with the same standards. Automated casting systems integrate batching, concrete transport and hydraulically operated moulds to streamline this process. The main objectives are to improve consistency, reduce manual intervention and accelerate the production cycle.

The key features of automated casting for precast elements include:

- **Automated batching and feeding:** Centralised batching plants coupled with computerised dosing ensure precise control of mix proportions
- **Concrete transport systems:** Shuttles, conveyors, or bucket systems deliver concrete directly to moulds, reducing handling losses and variability
- **Hydraulic mould operations:** Hydraulics support vibration, compaction, alignment and demoulding, minimising defects and labour requirements
- **Carousel or battery mould setup:** Enable simultaneous casting of multiple elements such as tunnel ring segments, girders, slabs and barriers
- **Curing chambers:** Controlled curing (often steam or hot air) improves strength gain and uniformity

[8] https://morth.nic.in/sites/default/files/Adoption-of-Automated-Intelligent-Machine-aided-Construction%28AIMC%29-16122024%20-hoisted.pdf

Automated casting methods hold considerable potential for application in tunnel segments, bridge girders, noise barriers and parapets. For instance, the Mumbai-Ahmedabad High-Speed Rail (MAHSR) project has used automated casting machines for noise barrier panels, deploying shuttle-fed concrete systems and multi-segment moulds[9].

However, these systems have certain limitations. The high initial capital investment required for moulds, hydraulics and handling equipment can be substantial. Additionally, automated casting systems are most efficient for repetitive, standardised elements and less adaptable to unique or complex geometries.

Despite these challenges, automated casting represents a significant step towards industrialised construction in transport infrastructure, offering improved productivity, consistent quality control and enhanced efficiency in the fabrication of tunnel and bridge components.

2.6 AI-enabled O&M and traffic management

For operations and maintenance

Predictive maintenance and advanced surveillance technologies are transforming infrastructure management by leveraging AI, IoT devices, sensors, data analytics and BIM. AI-powered sensors monitor parameters to detect anomalies early, enabling timely interventions. Advanced surveillance and mapping tools, such as DT, drones and Light Detection and Ranging (LiDAR) strengthen infrastructure monitoring.

In tunnels, they deliver high-resolution insights for rock bolt monitoring and optimisation of drilling and blasting operations. **Integrated tunnel control systems (ITCS)** include advanced safety features such as fire detection and alarm systems, which are crucial for the safety and efficient operation of long tunnel, digital thermal sensing (DTS) technology, fibreoptic networks and public address/voice alarm (PA/VA) systems, which provide critical, real-time monitoring for the tunnel.

A notable example is **Boston's Big Dig:** The Central Artery/Tunnel Project, popularly known as the Big Dig, is one of the largest infrastructure undertakings in the US, involving the construction of an extensive tunnel system beneath downtown Boston. To ensure structural safety and operational efficiency, the project integrated advanced tunnel monitoring systems equipped with sensors to track critical parameters such as temperature, stress, load, pressure, pore water pressure, deformation and strain. These systems provided real-time data on potential issues such as cracks or mass displacements in the rock strata. The continuous monitoring and data-driven analysis enabled early detection of anomalies, improved decision-making and optimised tunnel safety and performance throughout the project's lifecycle[10].

Another notable case was noticed in Mumbai September 2025, when a car travelling through the Mumbai Coastal Road underground tunnel caught fire, which was sensed by **linear hear detector cables** that alerted the control room and the installed **video incident detection system (VIDS)** helped locate the vehicle to initiate immediate fire extinguishing action within 10 minutes. Regular traffic resumed within 30 minutes with no casualties.[11].

For traffic monitoring

The integration of AI in traffic control has revolutionised the way cities manage their transportation infrastructure, enabling real-time monitoring, dynamic signal adjustments, and predictive analytics. Intelligent traffic management systems (ITMS) leverage AI technologies such as ML, computer vision and IoT devices to optimise traffic flow, reduce congestion and improve safety. These systems analyse vast amounts of traffic data to identify patterns, predict bottlenecks and implement proactive measures to manage vehicle movement efficiently, ultimately reducing travel times and minimising the risk of accidents. By providing valuable insights and data analytics, AI-powered ITMS enable urban planners and traffic authorities to make informed decisions about transportation infrastructure development and optimisation, and the technologies used in these systems, including ML, computer vision and IoT devices, collaborate to create a more efficient, safe and sustainable transportation network.

Overall, the integration of AI in traffic control has the potential to significantly improve the efficiency, safety and sustainability of urban transportation systems, making cities more liveable and reducing the environmental impact of transportation. Resultantly, AI-powered ITMS has become a crucial tool for urban

[9] https://blogs.lntecc.com/mumbai-ahmedabad-high-speed-railway-corridor-mahsr-the-first-bullet-train-of-india/
[10] https://www.encardio.com/blog/how-smart-tunnel-monitoring-systems-are-transforming-infrastructure-management
[11] https://timesofindia.indiatimes.com/city/mumbai/horrific-car-blaze-traps-motorists-at-mumbai-coastal-road-tunnel-disrupts-traffic/articleshow/124106916.cms

planners and traffic authorities to create a better transportation experience for India.

- Take the **urban intelligent traffic systems,** for instance**.** Bengaluru has implemented the **Bengaluru Adaptive Traffic Control System (BATCS)**, which uses AI-driven adaptive signal technology, vehicle detectors and real-time traffic data to optimise signal timings across key junctions, thereby reducing congestion and travel delays. Similarly, the **Integrated Traffic Management System (ITMS)** on the Pune-Mumbai Expressway leverages AI-enabled surveillance cameras, automatic number plate recognition (ANPR), speed detection systems and incident management tools to enhance traffic flow, ensure road safety, and enable quick emergency response on one of India's busiest expressways[12].

Safety and security

Digital Twin Models and drone-based LiDAR have been used for underground tunnel mapping and post-accident rescue operations. A notable example for safety and security is AI-enabled surveillance systems that enhance security through vehicle identification, licence plate recognition and facial detection. They also monitor attendance and helmet compliance checks, ensuring a safer working environment. For instance, the J&K Police deployed an AI-based facial recognition system to bolster tunnel safety and security. This system uses high-resolution CCTV cameras along the Jammu-Srinagar National Highway. By leveraging these technologies, construction and infrastructure projects can improve safety, reduce risks and enhance efficiency.

2.7 Structural health monitoring with aerial videography

The integration of structural health monitoring (SHM), unmanned aerial vehicles (UAV)/drones and AI/ML tools is a revolutionary approach to asset management, transforming the way inspections are conducted, maintenance is planned, and asset performance is optimised. This comprehensive system offers numerous benefits, including optimised inspections, reduced downtime, extended asset life, improved cost efficiency and enhanced decision-making. Here's a detailed breakdown of how these technologies work together and their advantages.

SHM	• SHM systems are equipped with **sensors that continuously monitor** the condition of physical assets by collecting data on parameters such as **temperature, pressure, vibration and strain** • This real-time data provides critical insights into an asset's condition, enabling early detection of potential issues before they escalate into major problems
UAV	• UAVs (drones) are equipped with **high-resolution cameras and sensors** to conduct detailed inspections of hard-to-reach areas. They capture visual and thermal data, which can reveal structural damage, leaks, or other issues that might not be detectable through SHM alone • The use of drones significantly enhances the inspection process by providing detailed, close-up views without the need for manual intervention, thereby reducing risks and increasing the efficiency of inspections
AI/ML tools	• **Data pre-processing:** Cleaning, scaling and transforming raw data into a suitable format for analysis • **Anomaly detection:** AI identifies unusual patterns and deviations from normal behaviour, indicating potential problems • **Predictive modelling:** ML algorithms learn from historical data of equipment performance and failures to predict when future breakdowns are likely to occur

[12] https://indiaai.gov.in/article/ai-and-traffic-control-in-india-revolutionizing-road-management

Key benefits
• **Optimised inspections:** Automated and remote data collection makes inspections faster, more comprehensive and safer • **Reduced downtime**: Predictive maintenance scheduling prevents unexpected breakdown, minimising costly interruptions • **Extended asset life:** Early detection and correction of issues prevent minor problems from escalating, maintaining asset integrity and extending the lifespan • **Improved cost efficiency:** Lower downtime, optimised resource allocation and reduced inventory for spare parts contribute to significant cost savings • **Enhanced decision-making:** Data-driven insights and advanced visualisations empower stakeholders to make informed decisions about maintenance planning and resource allocation

Implementation and future direction

Successful implementation of the integrated system requires careful planning, including the selection of appropriate SHM sensors, drones with suitable payloads, and AI/ML tools tailored to the specific needs of the assets being monitored. Continuous training of AI/ML models with new data is essential to improve their predictive accuracy.

As technology advances, we can expect even more sophisticated SHM systems, drones with enhanced capabilities (such as autonomous navigation and advanced sensor suites), and more powerful AI/ML algorithms capable of handling larger datasets and providing more precise predictions. The future of asset management is moving towards a fully automated, predictive and proactive model, where maintenance is optimised, downtime is minimised and asset performance is maximised, all thanks to the synergy of SHM, drones and AI/ML.

A notable example in this case is the **Chenab Railway Bridge in J&K, India**, which is recognised as the world's highest railway bridge. It has been equipped with a state-of-the-art **Bridge Health Monitoring System (BHMS)** to ensure structural integrity under extreme conditions. Given its location in a high seismic zone and exposure to strong winds, the monitoring framework integrates a wide range of sensors, including accelerometers, strain gauges, anemometers and displacement metres to continuously measure parameters such as wind loads, vibrations, temperature variations and material stresses. The collected data is transmitted in real time to a central monitoring system, enabling engineers to assess structural performance, detect anomalies and implement predictive maintenance strategies. By integrating these systems with digital modelling tools, the Chenab Bridge exemplifies the use of advanced digital and cyber-physical technologies in ensuring the safety, resilience and longevity of critical infrastructure assets[13]. The Chenab Bridge has become operational with a range of advanced safety features, including **120 sensors** and **150 servers**[14].

2.8 Retrofitting and modernising aging bridges

Industry approaches involve a systematic process of structural assessment, strengthening and lifecycle extension to enhance durability and safety.

Structural assessment

- Visual and component-level inspection: Detailed visual inspections identify the existing damage and deterioration
- Advanced technologies: Non-destructive testing methods such as ground penetrating radar (GPR) detect internal defects

Strengthening and retrofitting techniques

- Column jacketing: Columns are encased in jackets to increase strength and ductility
- Adding structural elements: New walls, frames, or bracing elements improve lateral strength and stiffness

Lifecycle extension and modernisation

- Focus on sustainability: Interventions prioritise minimally invasive and sustainable approaches
- Digitalisation: Digital tools enhance reliability and accuracy in structural ratings, leading to better maintenance strategies

[13] https://iricen.gov.in/iricen/ipwe_seminar/2017/IPWE%202018/24%20Warning%20and%20Structural%20Health%20Monitoring%20System%20for%20the%20World%20Highest%20Railway%20Bridge%20across%20the%20Chenab%20River.pdf

[14] https://risingkashmir.com/worlds-tallest-rail-bridge-equipped-with-120-sensors-for-safe-train-operations/



3 Sustainable practices and safety systems

The tunnelling industry is witnessing key developments that are setting new benchmarks in sustainability and efficiency. The use of sustainable materials and the recycling of construction waste are becoming central to reducing environmental impact. This chapter explores these developments.

3.1 New-age materials

The infrastructure sector is undergoing a transformation aided by the adoption of advanced materials that deliver unprecedented performance, sustainability and longevity. Modern bridge and tunnel construction increasingly relies on these innovative materials to address durability, environmental impact, maintenance costs and long-term resilience.



- **Ultra-high-performance concrete (UHPC)**

  UHPC represents a breakthrough in cementitious materials, with compressive strengths exceeding 150 MPa and exceptional durability. Its dense microstructure prevents liquid ingress, while the steel fibre reinforcement provides post-crack tensile strength, reducing the need for secondary reinforcement.

  – **Khambataki Ghat Tunnel (India)**: The tunnel demonstrated the use of ultra-high-performance fibre reinforced concrete (UHPFRC) in tunnel linings through shotcreting, providing enhanced durability. [15]

  – **Langat River Bridge (Malaysia)**: The bridge achieved a world-record 105-metre precast U-girder span using UHPC, eliminating in-river piers, improving sustainability and reducing maintenance costs.[16]

- **Glass fibre reinforced polymer (GFRP)**

  GFRP rebars provide superior corrosion resistance and strength-to-weight ratios, making them ideal for harsh environments that cause a deterioration of steel reinforcement. They are 4–5 times lighter than steel, up to twice as strong in tension, non-conductive and non-magnetic. Their long lifespan reduces maintenance requirements and environmental footprint.

  – **Patna Metro rail project:** GFRP bars were used in viaducts and stations to withstand monsoon conditions.[17]

  – **Dubai Metro viaduct:** Dubai Metro leveraged GFRP's corrosion resistance in a humid, marine environment.

  – **Düsseldorf Wehrhahn line:** It employed GFRP reinforcement in underground stations to provide efficient TBM breakthroughs.

- **Corrosion-resistant steel**

  Advanced stainless-steel grades form a self-healing chromium oxide layer, extending the lifespan of bridges from 15–20 years to more than 100 years, while lowering lifecycle costs, and minimising lifecycle maintenance and environmental impact.

  – **Bhayandar Railway Station FOB, Mumbai (India):** India's first stainless-steel foot overbridge, designed for a 100+-year lifespan, used 170 MT of IRS350CR grade stainless steel. [18]

- **Low-carbon concrete**

  Green and low-carbon concretes reduce CO_2 emissions, while maintaining performance. Supplementary cementitious materials (fly ash, ground granulated blast furnace slag (GGBS) and silica fume) can replace 40–70% of Portland cement. Geopolymer concretes go further, eliminating ordinary portland cement entirely by using aluminosilicate-rich waste materials, offering improved resistance to heat, fire and chemical corrosion.

Limitations

Although advanced materials offer significant advantages, their widespread adoption also faces practical constraints such as:

- **High initial costs:** Materials such as UHPC, GFRP and stainless steel involve higher upfront investment compared with conventional alternatives, which can be a barrier in cost-sensitive projects.

[15] https://uniqueuhpcinfra.com/uhpfrc/
[16] https://www.pci.org/PCI/PCI/Project Resources/Project_Profile/Project_Profile_Details.aspx?ID=259730
[17] Glass Fiber Reinforced Polymer Rebar | GFRP Rebar
[18]https://wr.indianrailways.gov.in/view_detail.jsp?lang=0&id=0,4,268&dcd=6541&did=16541734620610E46D0F721224F42895378624369733A

- **Specialised knowledge and training:** Design, handling and installation often require new skills and familiarity among engineers, contractors and construction workers.
- **Codes and standards:** Formal codes, specifications and design guidelines for some of the advanced materials are still limited in India, leading to challenges in uniform adoption and ensuring confidence in their long-term performance.
- **Construction constraints:** Some materials pose specific challenges — e.g., UHPC requires precise mixing and curing processes, GFRP cannot be bent on-site like steel and high-GGBS concretes can suffer delayed strength gain.

These constraints underline the need for cautious adoption and gradual scale-up, rather than blanket substitution of traditional materials.

3.2 Recycling of tunnel excavation material (TEM)

In parallel with material innovation, sustainable infrastructure requires effective management of waste generated during construction. Tunnelling produces massive volumes of **TEM**, often referred to as muck or spoil. Traditionally disposed of in landfills, this practice creates both environmental and financial challenges.

Key applications of TEM recycling include:

- **Reuse as aggregates:** Processed TEM can replace conventional aggregates in road construction, embankments and base layers. In Croatia's **Istrian Y Motorway**, tunnel excavation material was used to produce a low-carbon concrete, saving more than 200,000 tons of virgin aggregates[19]. In India, around 300,000 cubic metres of tunnel muck was used in the **Udhampur-Srinagar-Baramulla Railway Link (USBRL)** project in retaining the wall to support one of the Chenab bridge abutments[20].
- **Reuse in grouting:** Spoil can be blended with binders to form cost-effective grouting materials in shield tunnelling. The **Vienna S1 Project** successfully reused 14 million cubic metres of TEM for grouting a 19 km tunnel, reducing shrinkage issues and overall costs[21].
- **Soil conditioning:** Spoil from slurry operations can enhance soil conditioning in mechanised tunnelling. The **Yellow River Tunnel (China)** replaced lime with waste sand for slurry dewatering, achieving similar technical performance at lower costs and environmental impact.
- **Refilling abandoned sites:** TEM can be used to backfill exhaust quarries, reducing land disturbance. The **Katzenberg Tunnel (Germany)** reused 2.3 million cubic metres of spoil for quarry rehabilitation, with environmental safeguards to protect groundwater.

Through these applications, TEM recycling not only minimises disposal requirements, but also provides a cost-effective source of construction inputs, reduces carbon emission and aligns with circular economy principles.

Collectively, advanced materials such as UHPC, GFRP, corrosion-resistant steel and low-carbon concrete deliver superior durability, reduced maintenance, enhanced safety and better environmental performance. Although their upfront costs are higher, lifecycle analyses consistently demonstrate significant long-term economic and sustainability benefits.

At the same time, their limitations — including higher initial costs, availability constraints and lack of standardisation — must be carefully weighed before large-scale adoption. A balanced approach that combines selective use of advanced materials with responsible recycling of tunnelling spoil should deliver the most sustainable outcomes.

By reusing excavation materials such as aggregates, grouts, soil conditioners and refilling materials, projects can reduce environmental impact, lower costs and ease the pressure on natural resources. Together, advanced materials and muck recycling represent complementary strategies that can shape resilient, cost-efficient and environmentally responsible bridges and tunnels of the future.

[19] https://www.holcim.com/who-we-are/our-stories/ecopact-saves-co2-croatia-tunnel

[20] Reinforced Soil System for Railways at USBRL Project in Jammu

[21] https://www.mdpi.com/2071-1050/16/12/4889

3.3 Advanced environmental impact assessments

- **Geographic information systems (GIS)**

  GIS-based spatial analysis is used to provide a more detailed understanding of the spatial distribution of environmental impacts, which is crucial in complex terrains and for sensitive projects.

- **Sustainable techniques**

  Adopting energy-efficient building practices and sustainable construction materials can significantly reduce the overall environmental footprint of tunnels and bridges.

- **Satellite-imagery-based assessment/geospatial AI analytics**

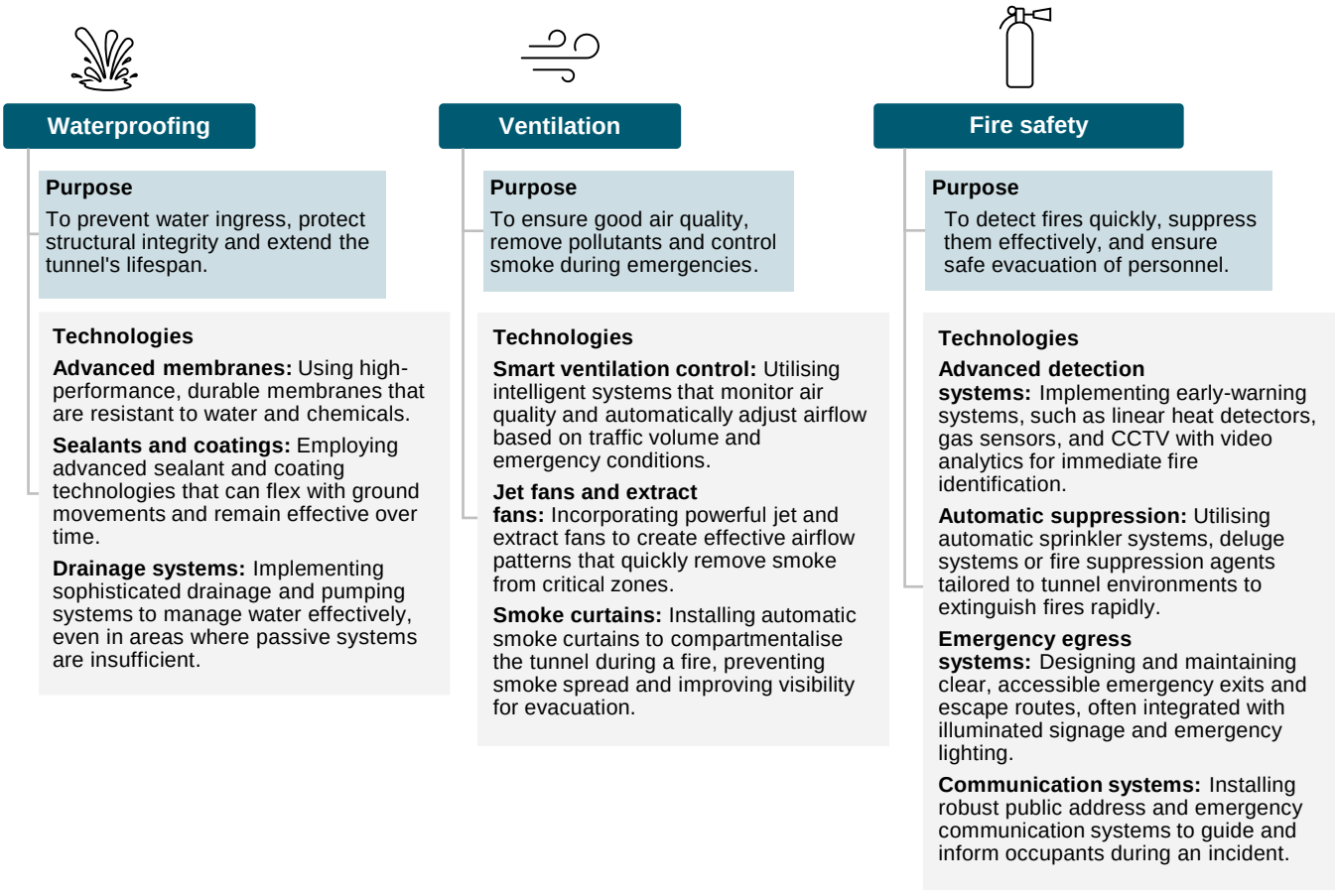
  Managing physical risk, driven by climate change, and compliance risks driven by regulatory shifts, leveraging advance monitoring tools.[22]

These include:

- **Wildfire** risk monitoring and **methane** watching
- **Deforestation** tracker and **vegetation/forest carbon** monitoring
- **Forestry** due diligence

3.4 Tunnel safety systems

Upgrading tunnel safety systems for operational excellence involves integrating advanced waterproofing, ventilation and fire-safety technologies to enhance durability, safety and functionality. Advanced waterproofing systems prevent structural damage and ensure long-term stability. Enhanced ventilation systems provide clean air and control smoke in emergencies, while modern fire-safety systems include early detection, automatic suppression and clear evacuation routes to protect occupants and infrastructure.



[22] https://www.kayrros.com/products-risk-solutions/

3.5 Disaster preparedness in tunnel and bridge construction

Integrated strategies such as robust risk assessment, implementing mitigation measures during design and construction (e.g., earthquake-resistant structures), developing comprehensive emergency plans with clear protocols, establishing early warning systems, conducting regular training and drills, ensuring access to communication and control centres and creating detailed recovery and business continuity plans.

Risk assessment and mitigation

- **Comprehensive risk analysis:** Conduct detailed assessments to identify potential hazards such as seismic activity, flooding, landslides and structural failures specific to the project site.
- **Design for resilience:** Incorporate design features and materials that enhance resistance to anticipated hazards, such as seismic-resistant components for bridges or fire-retardant materials for tunnel linings.
- **Site selection and planning:** Choose construction sites and design them to avoid high-risk areas such as floodplains or unstable geological zones.

Robust safety protocols and preparedness

Emergency response plans	Develop detailed plans outlining actions for various scenarios, including evacuation procedures, rescue operations and coordination with external agencies.
Staff training and capacity building	Provide extensive training to construction personnel on safety procedures, emergency protocols and proper use of safety equipment.
Emergency control centers	Establish and equip command posts or control centres for effective communication, coordination and decision-making during emergencies.
Early warning systems	Implement systems to provide advance notice of potential threats, allowing for proactive measures and timely evacuation or safety actions.
Community engagement	Engage with the local community and emergency services to foster collaboration and integrate construction site safety into broader community emergency plans.
Emergency equipment and supplies	Stockpile essential equipment such as personal protective gear, first-aid supplies, rescue tools and temporary shelter materials.



4 Recent improvements in infrastructure policy

Regulatory mechanisms are pivotal to tunnel and bridge infrastructure development, transforming ambitious engineering plans into tangible assets of national and regional significance. The regulatory ecosystem has evolved over the past decade, integrating government incentives, digital innovations, data analytics and novel policy frameworks to enhance project compliance and sustainability.

4.1 Improvements in DPR awards with MoRTH's new rating system

Raising accountability and quality of DPRs

- The Ministry of Road Transport and Highways (MoRTH), through its office memorandum dated July 7, 2025, has introduced reforms aimed at raising accountability and improving the quality of DPR consultancy across road, tunnel and bridge projects. The reform is anchored on two concept notes: one proposing a structured DPR rating system and the other suggesting amendments to the RFP framework for appointment of consultants for national highways and centrally sponsored road works. Together, these measures mark a decisive shift from cost-driven selection towards performance-based evaluation, where consultants are assessed based on the quality and reliability of their output.
- The DPR rating system is designed to objectively evaluate consultancy firms based on the performance of their past projects. Parameters include the realism of project cost estimation, delays in the declaration of the appointed date caused by incomplete land acquisition or pending statutory clearances, technical deficiencies that result in the change of scope or variation orders, and errors in utility shifting estimates or general arrangement drawings[23].
- In parallel, the revised RFP process introduces fundamental changes in consultant selection. Instead of relying on financial bids, where contracts often go to the lowest bidder, the cost of consultancy

[23][1] MoRTH Proposes Rating Mechanism for DPR Consultancy ... https://foxmandal.in/News/morth-proposes-rating-mechanism-for-dpr-consultancy-firms/

[2] Government Plans New Rating System for DPR Consultants https://infra.tractorjunction.com/en/news/government-plans-new-rating-system-for-dpr-consultants

will now be fixed by the tendering authority. Selection will depend on a combination of technical qualifications, DPR ratings and the **performance bank guarantee (PBG)** quoted by firms. The PBG mechanism makes consultants financially accountable, as the government can encash the guarantee in cases where DPRs are found deficient in quality, safety or execution utility[24]. This raises the stakes for accuracy and thoroughness in DPR preparation, while reducing the risks associated with underbidding.

- The MoRTH's memorandum also solicits public feedback on proposed amendments to the RFP process, with the aim of enhancing transparency and standards in consultancy appointments. These reforms are complemented by requirements of greater technological adoption—such as mandatory AIMC for greenfield projects—and a push to address state-level challenges in land acquisition by ranking states based on the ease and quality of land management for highway projects. By integrating consultant rating, financial guarantees, advanced technology and improved land management coordination, the MoRTH aims to ensure that future road and tunnel projects are not only well-conceived, but also efficiently executed and safer for users.
- Overall, the office memorandum represents a significant step towards institutionalising accountability, technical rigor and innovation in India's highway development process, aligning consultancy incentives with national infrastructure goals.[25]

4.2 Stringent and tightened RFPs for NH project tenders

The NHAI has tightened contract norms in its request for proposal (RFP) document to improve project quality, curb delays and boost financial transparency by increasing the scrutiny of contractors, prohibiting third-party bids and including clauses mandating performance securities. The eligibility criteria has been revised to ensure only technically capable and experienced contractors are selected. It has classified unauthorised subcontracting beyond permissible limits as an "undesirable practice" with penalties and also included clauses to ensure financial accountability[26].

Summary of the key changes and their implications

No.	Change	Description	Impact
1	Stricter contractor qualification	**Tighter eligibility criteria**: The RFP now includes stringent conditions to ensure only technically capable and experienced contractors, who have completed full-fledged highway projects, are qualified to bid for national highway projects	This ensures projects are entrusted to competent companies, improving execution and quality
2	Curbing subcontracting practices	**Penalties for unauthorised work**: Unapproved sub-contracting beyond permitted limits will now be classified as an "undesirable practice" and will attract penalties	This prevents fragmentation of work and ensure that the prime contractor remains fully accountable for the project's quality and timely completion
3	Enhanced financial transparency	**Ban on third-party securities**: Bidders are banned from sourcing their bid and performance securities from third parties	This ensures that financial accountability rests solely with the bidding contractor, promoting greater financial discipline and transparency

[24][3] Road Ministry to rate consultancy firms amid concerns over ... https://infra.economictimes.indiatimes.com/news/roads-highways/road-ministry-introduces-rating-system-for-consultancy-firms-improving-dpr-quality/122324185
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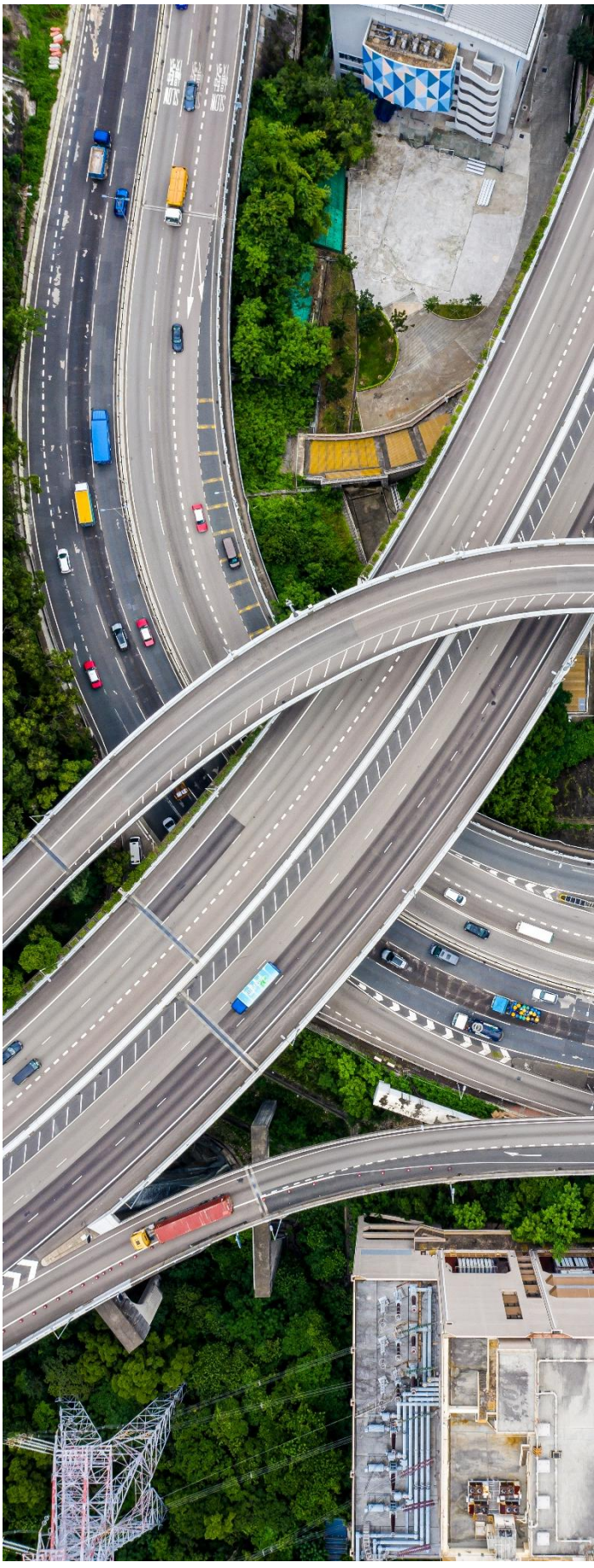
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[26] https://www.livemint.com/news/india/nhal-tightens-rfp-provisions-to-enhance-quality-of-national-highway-projects-11758105488877.html

- **Overall goals**
  - Increase the quality of national highway projects and ensure their timely completion
  - Cut down project lifecycle costs by curbing poor execution practices
  - Enhance accountability of contractors throughout the execution phase

4.3 Implementation process improvements by MoRTH and NHAI

The NHAI has refined its approaches and protocols for construction, operation and maintenance of projects based on the new insights it gained from experiences. These revisions encompass not only technical aspects but also the broader functional aspects of asset management, covering all stages of project development, from construction to maintenance, and incorporating recent market advancements. The key circulars and guidelines issued by MoRTH and NHAI has been annexed. Further, following the collapse of the Silkyara Tunnel in Uttarakhand, the MoRTH has introduced standard operating procedures for tunnel alignments exceeding 1.5 km. They are aimed at minimising social and environmental impacts and reducing construction risks and delays[27].



[27] After Silkyara Collapse, MoRTH Issues SOP for NH Tunnel Alignments Over 1.5 km To Cut Risks, Delays | India News - News18

5 Case studies

5.1 Modern projects (International and Domestic)

There are several projects that demonstrate how digital and sustainability-linked financing improves project viability.

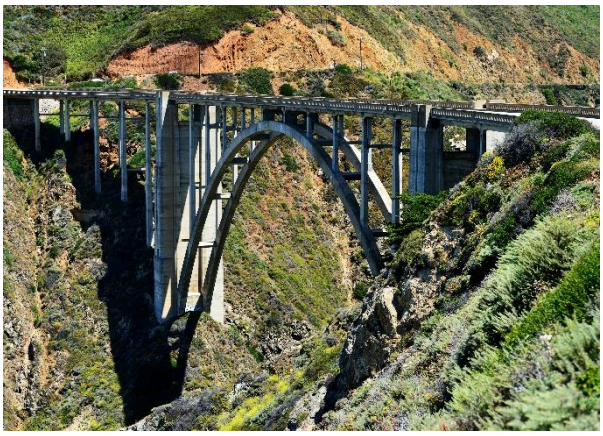
Crossrail, United Kingdom



The Crossrail (Elizabeth Line) in London is one of the most advanced examples of digital adoption in tunnelling. The use of DTs and BIM improved design accuracy, cost predictability and lifecycle planning. This made the project more transparent and enabled it to secure long-term financing at competitive rates from both public and private investors.

Belt & Road Initiative: This is an umbrella project by the Chinese government involving a series of infrastructure projects. By continuously monitoring geological and construction risks, the projects reduced delays and improved bankability, securing large-scale financing from policy banks and international partners.

Chenab Bridge, India



(Illustrative Picture)

The world's highest railway bridge in Jammu & Kashmir used advanced digital design tools and seismic risk mitigation techniques. These innovations improved safety and built confidence among investors and policymakers, ensuring sustained funding for a challenging project.

Table: Case studies

No.	Project	Country	Digital technologies adopted	Outcome
1.	Crossrail (Elizabeth Line)	United Kingdom (UK)	DT, BIM	Increased cost predictability, enabling the project to secure long-term financing at favourable rates
2.	Chenab Bridge	India	Digital seismic design, advanced monitoring	Sustained funding despite high risks



6 The Road Ahead

Outlook, challenges and areas for improvement

While the government's infrastructure thrust opens immense opportunities for construction companies, it also comes with significant challenges, such as hindrances to land acquisition issues, funding constraints and complex geological conditions, especially in seismically active areas. A clear vision, effective governance and the adoption of cutting-edge technology are essential to address these issues. As the country continues to invest in these strategic infrastructure projects, the lessons learned, and innovative solutions deployed will be critical to achieving inclusive growth and enhanced resilience.

The Indian bridge and tunnel sector is witnessing rapid transformation driven by digital technologies, advanced construction methods and evolving policy frameworks. While these have created significant opportunities, several constraints continue to affect efficiency, quality and resilience. Addressing these constraints with forward looking strategies is essential to achieving efficiency and resilience in future projects.

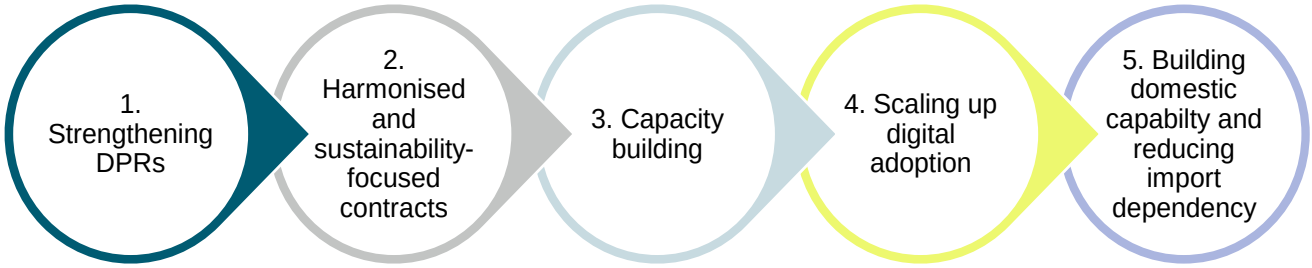
Despite the use of new-age technologies and policy reforms undertaken, the sector continues to face systemic **challenges** as per feedback from stakeholders**:**

- **DPR quality and risk management:** Many DPRs, particularly for tunnelling projects, fail to adequately capture geological and hydrological uncertainties, leading to frequent revisions, delays and cost overruns. Weak accountability and limited quality assurance mechanisms for DPR consultants exacerbate this challenge
- **Governance and contracting practices:** Contracting frameworks for tunnels vary across central and state authorities, resulting in inconsistencies in risk allocation and dispute resolution. Additionally, bidder selection frameworks often prioritise financial capacity over technical competence and project-specific experience, affecting timely, on-budget and quality delivery
- **Skilled workforce:** The sector faces a shortage of engineers and contractors skilled in advanced construction techniques and use of digital engineering tools
- **Limited digital integration and adoption barriers:** While technologies such as DT, IoT-based predictive maintenance and AI-driven monitoring are available, their adoption remains lacklustre. Challenges include

high upfront costs and limited skilled workforce for implementation

- **Equipment and resource self-reliance:** India's tunnel equipment market was valued at around Rs 8,000 crore in 2023–24 and is projected to expand to nearly Rs 11,000 crore by 2029–30. Despite this growth, the country remains heavily dependent on imported tunnelling and mechanised construction equipment.[28] It is one of the largest importers of specialised tunnelling machineries, including tunnel boring machines and trench cutters[29]. This increases project costs and exposes projects to global supply chain disruptions. A recent instance of this was when three tunnel boring machines critical to the Mumbai-Ahmedabad High Speed Rail project got stuck at Chinese ports for more than 10 months, significantly impacting the project schedule.

Addressing the above challenges requires an integrated approach that combines technology adoption, domestic capability building, governance reform and skill development. **The following measures outline a structured path forward:**



1. **Strengthening DPRs**
   - The recently introduced DPR rating framework and revised RFP guidelines by MoRTH are a welcome step towards raising accountability. The Quality-based selection and with strict enforcement will be essential to ensure consultants are held responsible for accuracy and completeness
   - Other infrastructure sectors can also adopt similar accountability-driven systems, creating uniform practices that raise quality across the board
2. **Harmonised and sustainability-focused contracts**
   - Standardising contract frameworks across central and state authorities, clearly defining risk allocation and dispute resolution
   - Embedding sustainability and safety criteria (low-carbon materials, reuse of excavation material, tunnel safety systems) as mandatory evaluation and compliance parameters in contracts
   - Aligning Indian contracting practices with international standards to attract competent domestic and global bidders
   - Refining bidder evaluation frameworks to balance financial capacity with technical competence, project-specific experience and past performance
3. **Capacity building**
   - Imparting specialised training and certification programmes for engineers, consultants and contractors on new-age technologies, digital engineering and sustainable practices
   - Creating inter-agency knowledge-sharing platforms to disseminate lessons from pilot projects and global best practices
4. **Scaling up digital adoption**
   - Promoting the use of AI, DT, SHM and drone-based monitoring for large-scale bridge and tunnel projects
   - Establishing a national digital repository to centralise geotech data and project performance data for benchmarking and predictive analytics
   - Providing fiscal incentives to encourage adoption of advanced technologies
   - Standardising protocols for digital data collection, storage and sharing across agencies and contractors to ensure interoperability

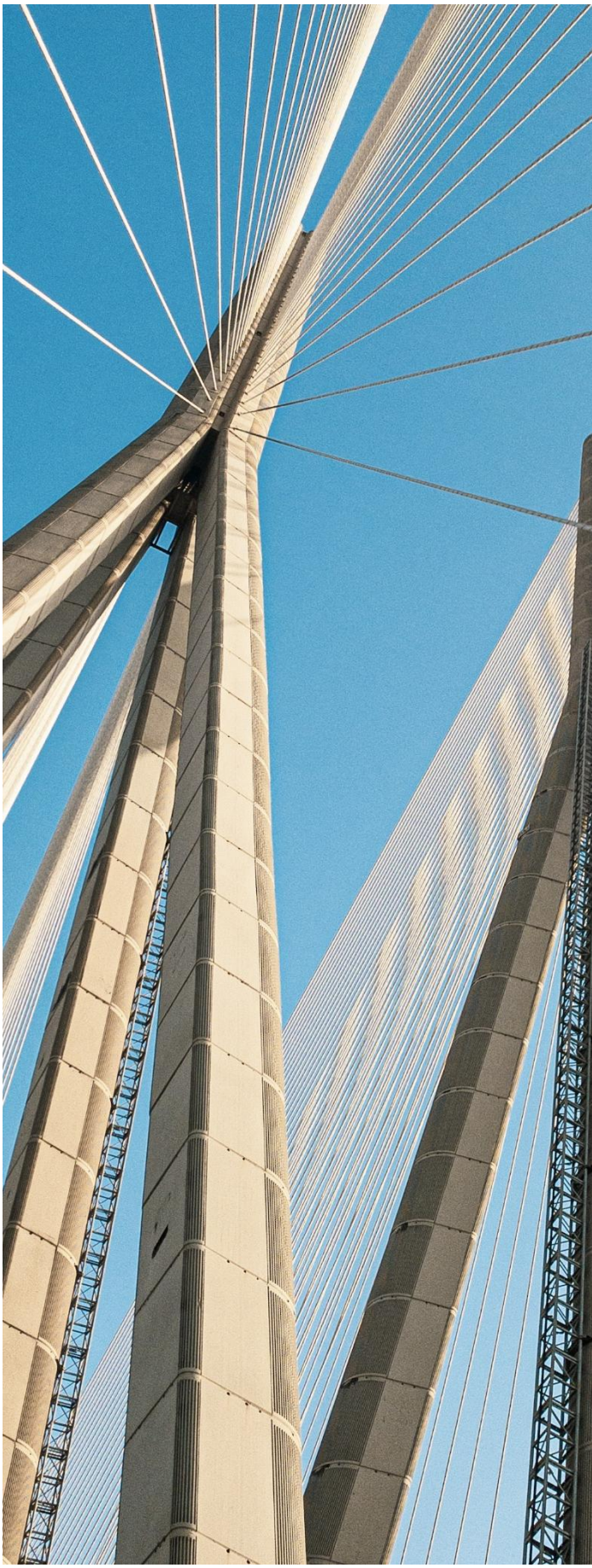
[28] https://www.livemint.com/opinion/online-views/tbm-indigenisation-make-in-india-china-supply-chains-infrastructure-tunnel-boring-machine-urban-himalayan-geopolitics/amp-11759312943956.html

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5. Building domestic capability and reducing import dependency

- Introducing a Production Linked Incentive (PLI) scheme to promote domestic manufacturing of tunnelling equipment. The recent acquisition of 12.4 acres of land in Chennai by Herrenknecht to expand its operations by setting up a new manufacturing plant, underscores the growing confidence in India's tunnelling equipment market[30].
- Adopting a phased indigenization strategy, beginning with assembly and servicing of imported machines and progressing towards domestic production of critical subsystems such as cutterheads, gears, hydraulics, and controls.
- Developing supplier clusters, workforce skilling programmes, and harmonized technical standards to support a competitive domestic ecosystem.
- Promoting industry–academia collaboration to advance research on terrain-specific and cost-effective tunnelling technologies.

The future of bridge and tunnel engineering in India depends on a **holistic approach** that integrates digital technologies, domestic manufacturing, governance reform, sustainability and skill development. By addressing import dependency, standardising contracts, strengthening DPR quality and building a skilled workforce, the sector can deliver projects that are **efficient, safe, sustainable and resilient**. Implementing these recommendations will position India to meet the growing demand for world-class bridges and tunnels while adhering to global benchmarks in quality, safety and environmental responsibility.



[30] https://www.thehindubusinessline.com/companies/tunnel-boring-machine-maker-herrenknecht-to-expand-chennai-operations-with-new-plant/article70127766.ece

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8 Annexure 2: Key circulars issued by NHAI/MoRTH in recent years

No	Circular	Date of issuance	Subject
1	RW/NH - 24036/27/2010- PPP	February 4, 2019	Clarifications with respect to provision of boundary wall and toe wall to be constructed along NH projects
2	NHAI/Bharatmala/EC/DPR/2016/143430	October 30, 2019	Policy for development of highways under Bharatmala Pariyojana
3	RW/NH- 29023/02/2019-S&R(P&B)	January 1, 2020	Guidelines for providing type of median on national highways network and guidelines for metal crash barrier (semi-rigid) to be installed on the highways
4	8.3.36/2020	July 10, 2020	Guidelines for determination of cost of change of scope/reduction in scope/withdrawal and alteration of works in DBFOT projects
5	RW/NH/Tunnel zone/01 /2020-21	February 4, 2021	Constitution of expert committee on tunnels by MoRTH
6	NHAI/Policy Guidelines/Management of Toll Plaza/2021	May 24, 2021	Policy circular number 17.5.82
7	RW/NH-33044/10/2021-S&R(P&B)	March 15, 2023	Reuse of materials reclaimed from pavement layers
8	NHAI/Policy Guidelines/Standard Documents/2023	October 10, 2023	Advanced traffic management system
9	IHMCL/Manual Transactions/FASTag/123819/269	May 25, 2024	Two-stage validation of manual FASTag transactions
10	RW/NH-33044/22/2020-S&R	June 4, 2024	Width of shoulder (paved and earthen) for national highways
11	NH- 12037/8/2024 / Tunnel/Misc/ North-I	September 6, 2024	Constitution of panel of experts for tunnel projects
12	12.36/2024	December 12, 2024	Strengthening of incident management services (amendment to circular 12.19, dated March 20, 2018)
13	RT-25035/07/2023-RS	December 24, 2024	Guidelines for provision of signages on expressways and national highways
14	RW/BNG/GENL/ROADSAFTY/112/2021	July 4, 2025	Inspection and maintenance of bridges/structures falling on national highways and expressways
15	NH-12037/3/2025/Tunnel/Zone-1	September 2, 2025	Standard operating procedure for NH tunnel alignment studies and approval
16	Policy Guidelines/O&M/2025/Policy Circular 9.4.31/2025	September 25, 2025	Maintenance manual of NHAI projects

Notes

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