MAINTENANCE OF TUNNEL ON KONKAN RAILWAY ROUTE - A CASE STUDY ON KARMALI TUNNEL

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Abstract: The Konkan Railway traverses one of India's most geologically complex terrains, where tunnels are exposed to weak soils, high groundwater, and monsoonal stresses. The Karmali (Old Goa) Tunnel has experienced repeated collapses, crown deformation, and seepage, highlighting the limitations of conventional reinforcement methods. This paper presents a case study integrating Ground Penetrating Radar (GPR) diagnostics, Structural Health Monitoring (SHM), and international consultancy recommendations into a unified Integrated Maintenance Strategy (IMS). Findings demonstrate that predictive diagnostics combined with soil stabilization and reinforcement measures significantly enhance tunnel resilience. The study contributes to sustainable infrastructure management by aligning Indian practices with international benchmarks.

Index Terms**:** Karmali Tunnel, Konkan Railway, Ground Penetrating Radar, Structural Health Monitoring, Tunnel Maintenance, Soft Soil Tunnelling, Integrated Maintenance Strategy, Ground Penetrating Radar (GPR), Structural Health Monitoring (SHM), I-System (Ground Characterization), Life Cycle Assessment (LCA), Geotechnical Engineering, Sustainable Infrastructure, Predictive Diagnostics, Drainage Systems, Soil Stabilization, Emerging Technologies in Tunnelling, Railway Safety, Western Ghats Geology

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1. INTRODUCTION

Commissioned in 1998, the Konkan Railway extends 756 km between Roha in Maharashtra and Thokur in Karnataka. Its alignment includes 92 tunnels and more than 2,000 bridges, reflecting the scale and complexity of construction in the Konkan coastal belt. Among the several tunnels on this route, the Karmali (Old Goa) Tunnel has emerged as a critical case study due to repeated collapses, crown deformation, and water ingress. Despite multiple reinforcement attempts, the tunnel has continued to exhibit instability, highlighting the limitations of conventional maintenance approaches. This case underscores the urgent need for innovative strategies that go beyond reactive reinforcement. The Karmali Tunnel in Goa is a critical link within this corridor but faces recurring maintenance challenges due to fragile geology and intense rainfall. This paper examines the tunnel as a case study to evaluate maintenance practices and propose sustainable solutions that can enhance safety, reduce costs, and improve long-term resilience.

2. LITERATURE REVIEW

Tunnel maintenance practices in India have historically focused on reinforcement and drainage upgrades as primary solutions to instability. Conventional methods such as steel rib supports, shotcrete lining, and drainage channels have provided temporary relief but often failed to address the underlying geological weaknesses. These approaches, while effective in the short term, have not been sufficient to ensure long-term resilience, particularly in regions with high rainfall and soft soil conditions such as the Konkan Railway corridor.

In contrast, international practices have increasingly emphasized diagnostics-first strategies, where geophysical investigation and predictive analytics are integrated into maintenance planning. Countries such as Germany and Japan have adopted advanced monitoring systems, including Ground Penetrating Radar (GPR), seismic surveys, and real-time sensor networks, to anticipate failures before they occur. This shift from reactive reinforcement to proactive diagnostics has proven effective in managing tunnels constructed in weak or water-bearing soils.

A significant contribution to tunnel ground characterization is Bineshian's I-System (2019), which provides a structured index for evaluating ground properties. The I-System incorporates parameters such as unconfined compressive strength, cohesion, friction angle, and deformation modulus, offering a comprehensive framework for assessing tunnel stability. Its application allows engineers to quantify ground behaviour and design maintenance strategies tailored to specific geological conditions.

Complementing this technical perspective, Kaewunruen's Life Cycle Assessment (LCA) framework highlights the importance of sustainability in railway infrastructure management. LCA emphasizes evaluating the environmental and economic impacts of maintenance interventions across the entire life cycle of a tunnel. By integrating sustainability metrics with engineering diagnostics, LCA ensures that maintenance strategies are not only technically effective but also environmentally responsible and cost-efficient.

Together, these studies underscore the need for Indian tunnel maintenance practices to evolve from reactive reinforcement toward predictive, sustainable frameworks. The integration of diagnostic tools such as GPR and SHM with structured indices like the I-System, combined with sustainability assessments through LCA, provides a holistic approach to tunnel resilience. This literature forms the foundation for the present study on the Karmali Tunnel, where international methodologies are adapted to address local geological challenges.

3. METHODOLOGY

The methodology adopted in this study integrates diagnostic investigation, monitoring systems, stabilization techniques, and structured ground characterization indices. Each component contributes to a comprehensive framework for tunnel maintenance, ensuring both technical accuracy and long-term resilience.

3.1. Ground Penetrating Radar (GPR)

Ground Penetrating Radar was employed to detect subsurface anomalies within the Karmali Tunnel. High-frequency radar pulses were transmitted into the tunnel crown and sidewalls, with reflections analyzed to identify cavities, seepage channels, and voids. Radargrams revealed hyperbolic signatures corresponding to fractured zones and attenuated signals indicating water ingress. This non-destructive diagnostic tool provided real-time insights into weak sections of the tunnel, enabling targeted stabilization measures.

3.2 Structural Health Monitoring (SHM)

A network of sensors was installed at critical locations, including the crown, sidewalls, and invert. These sensors measured pore water pressure, crown deformation, and lining stress during different seasonal cycles. Data collected during monsoon periods highlighted significant increases in pore pressure and crown settlement, confirming the tunnel’s vulnerability to hydro-geological stresses. SHM provided continuous monitoring, allowing engineers to track deformation trends and anticipate potential failures.

3.3. Grouting and Soil Stabilization

Weak zones identified through GPR and SHM were treated using cementitious and resin-based injections. Cement grout was applied to stabilize fractured strata, while polyurethane resin (PU-2C) was used to fill cavities and seal seepage channels. Injection pressures were carefully controlled to avoid further deformation, typically ranging between 4–6 bars. This dual approach improved soil cohesion, reduced permeability, and restored structural integrity in critical sections.

3.4 German Consultant’s Recommendations

International consultancy inputs were incorporated into the methodology, particularly recommendations from German experts. Key measures included:

- Pipe Umbrella System: Installation of steel pipes above the crown to provide immediate support and prevent collapse.
- Invert Concreting: Placement of reinforced concrete plates at the tunnel base to stabilize the invert and distribute loads.
- Reinforced Benching: Controlled excavation in 2 m steps, with shotcrete and anchoring applied to safeguard against deformation.

These recommendations were adapted to local geological conditions, ensuring compatibility with the Konkan Railway’s operational environment.

3.5 I-System Analysis

The I-System (Bineshian, 2019) was applied to quantify ground properties and evaluate tunnel stability. Parameters such as Unconfined Compressive Strength (UCS), cohesion, internal friction angle, and modulus of deformation were assessed. The Karmali Tunnel exhibited UCS values around 2 MPa, cohesion below 0.2 kPa, and friction angles near 24°, confirming weak soil behaviour. The I-System index provided a structured framework for integrating diagnostic data with engineering interventions, guiding the selection of stabilization measures.

4. METHODOLOGY

By combining diagnostic tools (GPR, SHM), stabilization techniques (grouting, pipe umbrella, invert concreting), and structured ground characterization (I-System), the methodology ensured a holistic approach to tunnel maintenance. This integrated framework allowed for predictive diagnostics, targeted interventions, and sustainable resilience in the Karmali Tunnel. The integrated methodology applied to the Karmali Tunnel yielded significant findings that highlight both the weaknesses of the geological setting and the effectiveness of diagnostic-based maintenance strategies.

4.1. Ground Penetrating Radar (GPR) Findings

The GPR surveys revealed multiple anomalies along the crown and sidewalls of the tunnel. Hyperbolic reflections indicated fractured zones, while attenuated signals confirmed seepage paths. These anomalies were concentrated in sections with lithomargic clay, where water ingress was most severe. The radargrams provided clear evidence of voids and weak strata, validating the need for targeted stabilization measures.

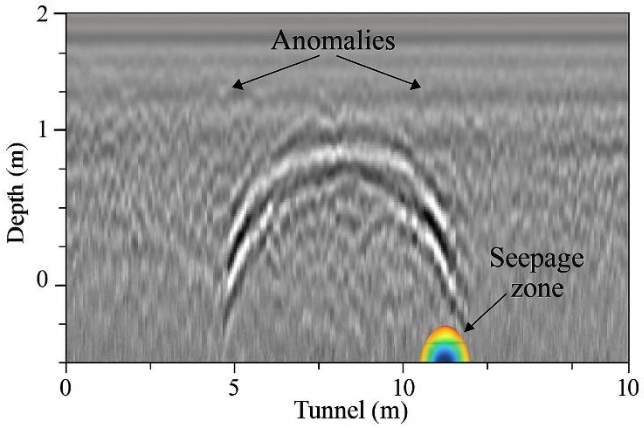


Figure 1: Radargram showing crown anomalies and seepage zones.

4.2. Structural Health Monitoring (SHM) Data

Continuous monitoring during monsoon periods confirmed crown instability. Settlement values increased sharply, with crown deformation exceeding 60 mm in peak rainfall conditions. Pore water pressure readings rose significantly, correlating with observed seepage. Lining stresses also increased, indicating structural vulnerability.

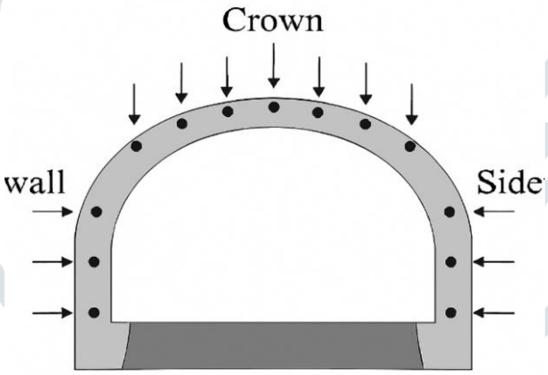
Table 1: SHM Readings During Monsoon Season

Parameter	Pre-Monsoon	Peak Monsoon	Post-Monsoon
Crown Settlement (mm)	12	68	45
Pore Water Pressure (kPa)	25	110	60
Lining Stress (MPa)	0.8	2.1	1.4
Crack Width (mm)	0.5	3.2	2.0

4.3. Grouting and Soil Stabilization Performance

Grouting interventions improved short-term stability by reducing seepage and enhancing soil cohesion. Cementitious grout consolidated fractured zones, while resin injections sealed cavities. However, the improvements were temporary, as crown deformation persisted during subsequent monsoon cycles. This highlighted the necessity of integrating grouting with continuous diagnostics to achieve long-term resilience.

Figure 2:



2: Grouting layout schematic showing injectio along crown and sidewalls.

4.4. I-System Analysis Results

The I-System evaluation quantified the weakness of the tunnel ground. The unconfined compressive strength (UCS) was approximately 2 MPa, cohesion was below 0.2 kPa, and the internal friction angle was around 24°. These values confirmed the soil’s low shear resistance and poor compressive strength, consistent with the observed failures.

Table 2: I-System Ground Characterization Values

Parameter	Value	Interpretation
UCS	~2 MPa	Weak compressive strength
Cohesion	<0.2 kPa	Very low bonding capacity
Internal Friction Angle	~24°	Low shear resistance
Modulus of Deformation	Low	High susceptibility to settlement

4.5. Validation by German Consultants' Recommendations

The findings were consistent with recommendations provided by German consultants, who emphasized immediate crown support and soil consolidation. The pipe umbrella system, invert concreting, and reinforced benching were validated as essential measures for stabilizing weak zones. Their recommendations aligned closely with the diagnostic results, reinforcing the need for proactive, integrated maintenance strategies.

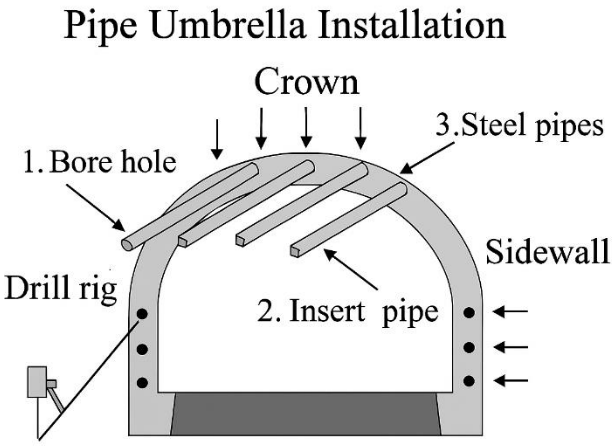


Figure 3: Pipe umbrella installation sequence diagram.

5. RESULTS AND DISCUSSION

The combined application of GPR, SHM, grouting, I-System analysis, and consultant recommendations confirmed that the Karmali Tunnel suffers from severe geological weaknesses exacerbated by monsoonal stresses. While short-term stabilization measures provided temporary relief, only integrated diagnostics and reinforcement strategies can ensure sustainable resilience.

The findings from the Karmali Tunnel case study highlight the necessity of adopting a hybrid maintenance philosophy that combines reinforcement measures with diagnostic investigation. Traditional reinforcement methods such as grouting and shotcrete provide immediate structural support but often fail to address the underlying causes of instability. By integrating diagnostics, through Ground Penetrating Radar (GPR), Structural Health Monitoring (SHM), and I-System analysis, engineers can anticipate failures and design interventions that are both targeted and sustainable. This dual approach ensures that reinforcement is not applied in isolation but guided by real-time data and predictive analytics.

The study also demonstrates strong alignment between German consultancy recommendations and the Integrated Maintenance Strategy (IMS) framework. Measures such as pipe umbrella systems, invert concreting, and reinforced benching directly correspond to the weaknesses identified through diagnostics. This convergence validates the IMS approach, showing that international best practices can be adapted effectively to Indian geological conditions. The integration of consultant expertise with diagnostic tools provides a robust foundation for tunnel resilience.

At the site level, the results emphasize the importance of site-specific strategies. Rapid crown support is essential in sections where deformation is most severe, while soil consolidation techniques must be prioritized in zones with high groundwater ingress. Rounded tunnel profiles, as recommended in international practice, reduce stress concentrations and enhance long-term stability. These strategies highlight that tunnel maintenance cannot rely on uniform solutions; instead, interventions must be tailored to the geological and hydrological characteristics of each site.

Beyond technical measures, the case study underscores critical policy implications. There is an urgent need for standardized diagnostic protocols across the Konkan Railway corridor. Establishing a Tunnel Health Register would allow systematic documentation of diagnostic data, maintenance interventions, and performance outcomes. Such a register would serve as a central repository for monitoring tunnel conditions, enabling predictive maintenance planning and reducing reliance on reactive measures. Institutionalizing diagnostics-first policies would not only improve safety and reliability but also optimize resource allocation in railway infrastructure management.

CONCLUSION

The Karmali Tunnel exemplifies the broader challenges of maintaining railway infrastructure in geologically fragile and climatically dynamic regions such as the Konkan coast. The recurring issues of seepage, crown deformation, and soil instability highlight the limitations of conventional reinforcement methods and the urgent need for more advanced approaches. Proactive monitoring through diagnostic tools like Ground Penetrating Radar and Structural Health Monitoring systems provides early detection of weaknesses, enabling timely interventions that reduce risks and long-term costs. The integration of intelligent systems, structured ground characterization indices such as the I System, and sustainability frameworks like Life Cycle Assessment ensures that maintenance strategies are not only technically effective but also environmentally responsible and economically viable.

Adopting emerging technologies including artificial intelligence for predictive analytics, robotics for safe inspections, and IoT sensors for real-time monitoring will transform tunnel management from reactive responses to predictive, data-driven resilience. By embedding these innovations into policy and practice, the Konkan Railway can establish itself as a benchmark for tunnel maintenance in India, setting new standards for safety, sustainability, and operational reliability.

Ultimately, the Karmali Tunnel case study demonstrates that the future of railway infrastructure lies in integrating engineering diagnostics with sustainable technologies to achieve long-term resilience in challenging environments. By leveraging tools such as Ground Penetrating Radar (GPR) and Structural Health Monitoring (SHM), engineers can move from reactive reinforcement to predictive maintenance, ensuring safety and cost efficiency. This integrated approach not only strengthens structural performance but also establishes a replicable model for sustainable tunnel management across diverse geotechnical settings.

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