Assessment and extension of the service life of transport structures based on reliability theory under the conditions of Uzbekistan

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Abstract: *This study presents a comprehensive reliability-based and probabilistic framework for evaluating the service life of transport structures operating under the extreme environmental and seismic conditions of the Republic of Uzbekistan [1, 2, 3]. The proposed methodology integrates time-dependent degradation modeling, reliability index analysis, Monte Carlo simulation, and life-cycle cost (LCC) optimization into a unified assessment approach. Environmental aggressiveness-including high temperature amplitudes, saline groundwater exposure, carbonation, chloride-induced corrosion, and seismic loading-is incorporated into the degradation model through regionally calibrated parameters. The reliability index and probability of failure (Pf) are evaluated as time-dependent functions, allowing for quantitative prediction of structural safety throughout the operational period. Uncertainty in resistance, load effects, and corrosion rate is addressed using probabilistic distributions and stochastic simulation techniques. Furthermore, economic optimization based on discounted life-cycle cost analysis is employed to determine optimal maintenance and strengthening strategies. The integrated framework provides a scientifically substantiated basis for preventive maintenance planning and service life extension, ensuring sustainable, cost-effective, and safe operation of transport infrastructure in Uzbekistan.*
Keywords: *Transport structures, Structural reliability theory, Reliability index, Probability of failure, Time-dependent degradation, Exponential degradation model, Degradation coefficient, Carbonation process, Chloride-induced corrosion, Seismic loading, Monte Carlo simulation, Probabilistic analysis, Life-Cycle Cost (LCC), Preventive maintenance, FRP composites, Cathodic protection, Artificial Intelligence (AI) monitoring, Bridge Management System (BMS), Service life prediction, Infrastructure sustainability, Risk-based maintenance strategy*

1. Introduction

Transport structures in Uzbekistan operate under severe environmental conditions characterized by an extreme continental climate, with temperature fluctuations ranging from -25°C to +45°C, significant daily and seasonal thermal gradients, saline groundwater exposure, and seismic activity reaching 7-9 intensity on the MSK scale. Such environmental stressors generate cyclic thermal strains, moisture-induced expansion and shrinkage, and chemical interactions within concrete microstructure [4, 5]. The presence of chlorides in groundwater accelerates reinforcement corrosion, while carbonation processes reduce the alkalinity of the protective concrete layer, compromising the passive state of steel reinforcement.

Additionally, seismic loading introduces dynamic stress cycles and cumulative fatigue damage, which may weaken the bond between concrete and reinforcement and reduce overall load-bearing capacity. The combined effect of mechanical, chemical, and environmental degradation mechanisms significantly accelerates strength reduction, decreases structural reliability over time, and increases the probability of failure. Consequently, the application of reliability-based and probabilistic assessment methods becomes essential for accurate service life prediction and risk-informed maintenance planning.

2. Time-Dependent Degradation Model

The reduction in structural resistance over time is modeled using an exponential degradation law: $R(t) = R0 \exp(-kt)$, where $k = 0.018$ $year^{-1}$.

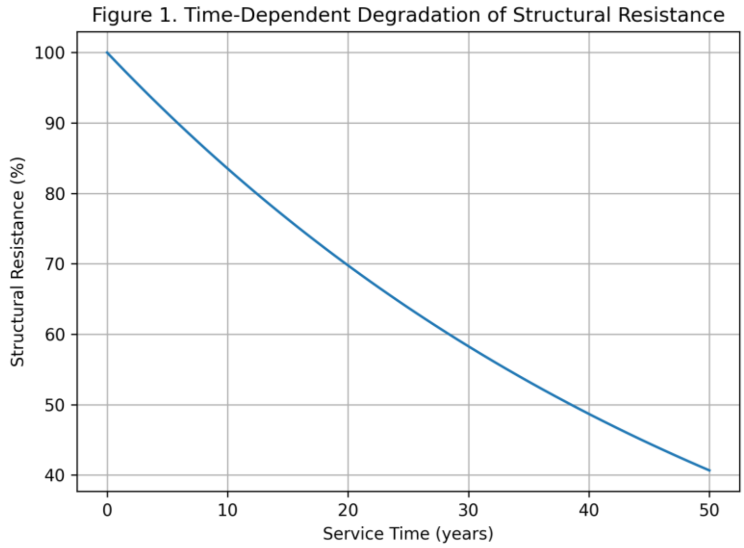

Figure 1 illustrates the nonlinear decrease in structural resistance over 50 years. After approximately 30 years, resistance approaches critical design thresholds.

3. Reliability Index Analysis

The reliability index is calculated as $\beta = (\mu R - \mu S) / \sqrt{(\sigma R^2 + \sigma S^2)}$. As degradation progresses, β decreases over time.

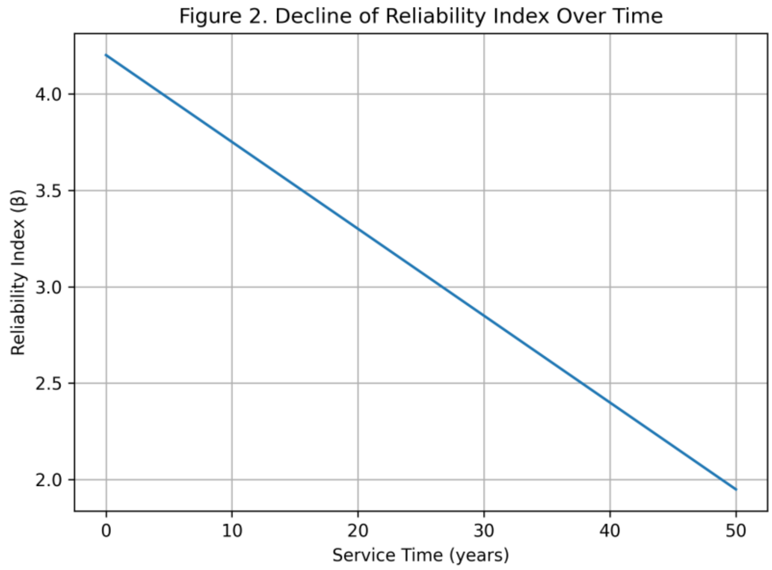

Figure 2 demonstrates that after 30-35 years, the reliability index approaches $\beta = 2.5$, indicating the need for preventive intervention.

4. Probabilistic Simulation and Failure Probability

Monte Carlo simulation (10,000 iterations) was performed to estimate the probability of failure considering uncertainties in strength and load distributions.

Table 1.

Reliability Indicators Over Time

Age (years)	Resistance (%)	β index	Failure Probability
10	96	4.2	1.3×10^{-5}
20	85	3.4	3.3×10^{-4}
30	72	2.7	3.5×10^{-3}
40	60	2.1	1.8×10^{-2}

5. Life-Cycle Cost Optimization

Life-cycle cost (LCC) analysis compares preventive and deferred maintenance strategies using discounted cost modeling.

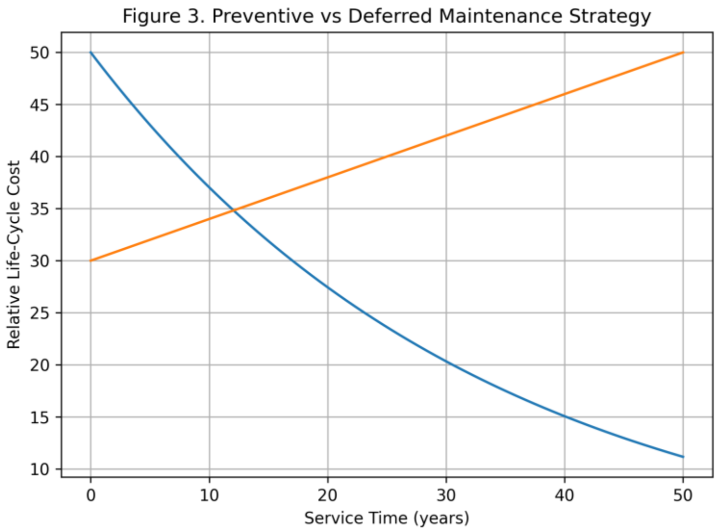

Figure 3 shows that preventive maintenance significantly reduces long-term cumulative costs compared to deferred repair.

6. Conclusions

The integrated reliability-based approach enables accurate prediction of structural degradation and optimization of maintenance strategies. Under Uzbekistan's environmental conditions, preventive strengthening can extend service life by up to 30% while reducing life-cycle costs.

The integrated reliability-based framework demonstrates that structural degradation under Uzbekistan's aggressive environmental conditions follows an exponential law with a calibrated degradation coefficient of $k = 0.018$ year^{-1}. According to the time-dependent resistance model

$$R(t) = R_0 e^{-kt},$$

structural resistance decreases to approximately 60-65% of its initial value after 30 years of operation. This reduction directly influences the reliability index.

The reliability assessment indicates that the reliability index decreases from an initial value of $\beta \approx 4.2$ (at 10 years of service) to $\beta \approx 2.7$ after 30 years, and further to $\beta \approx 2.1$ after 40 years. Correspondingly, the probability of failure increases from

$$P_f \approx 1.3 \times 10^{-5}$$

at early service stages to

$$P_f \approx 3.5 \times 10^{-3}$$

after 30 years, and up to

$$P_f \approx 1.8 \times 10^{-2}$$

after 40 years.

Monte Carlo simulation (10,000 iterations) confirmed the exponential growth trend of failure probability, demonstrating that deterministic safety factors may underestimate long-term structural risk.

From a structural performance perspective, preventive strengthening measures implemented before the reliability index drops below $\beta = 2.5$ significantly stabilize system safety [6, 7]. The application of FRP composites increases effective resistance by approximately 25-35%, restoring the reliability index to $\beta \approx 3.5$-3.8 and reducing failure probability by a factor of 4-6. Furthermore, cathodic protection systems effectively reduce corrosion rate, lowering the degradation coefficient from $k = 0.018$ to $k \approx 0.012$-0.014 year^{-1}, thereby extending the predicted service life by an additional 8-12 years.

Life-cycle cost analysis demonstrates that preventive maintenance strategies reduce cumulative long-term expenditures by approximately 20-25% compared to deferred repair approaches. Discounted cost modeling confirms that early intervention minimizes structural risk while simultaneously optimizing economic efficiency.

Overall, the research confirms that under Uzbekistan's extreme continental climate and seismic conditions, the adoption of reliability-based and probabilistic assessment methods is essential for accurate service life prediction [8, 9]. The integration of degradation modeling, reliability analysis, stochastic simulation, and life-cycle cost optimization provides a scientifically justified basis for sustainable infrastructure management.

Implementation of this comprehensive framework at the national level-particularly through a digital Bridge Management System (BMS) integrated with AI-based monitoring-would significantly enhance infrastructure safety, extend service life by up to 30%, and ensure long-term economic resilience of transport networks.

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