

Cable-Stayed Bridges Maintenance Challenges: Case Studies from Russia

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Abstract: Cable-stayed bridges have become a major component of the Russian highway network over the past 25 years, and many of these structures are now approaching the stage at which long-term operational risks become critical. Experience from inspections, repairs, and monitoring has shown that cable systems are among the most vulnerable bridge components, particularly because corrosion- and fatigue-related defects may develop in zones that are only partially accessible to conventional inspection methods. This paper systematizes the Russian experience of operating highway cable-stayed bridges and presents a preventive, risk-based framework for cable-system operation that was used in the development of GOST R 59629—2021. This study is based on the analysis of 189 national and international regulatory and technical documents, the classification of cable systems relevant to Russian practice, and the structuring of operational measures across the design, construction, and service stages of the bridge life cycle. The proposed framework includes risk analysis at the design stage, formation of threshold and reference databases, integration of structural health monitoring, and condition-based planning of scheduled and unscheduled inspections and maintenance. The results support a transition from passive defect-response practice to preventive operations aimed at the early detection of pre-critical states and timely risk mitigation. However, major technical limitations remain, especially the incomplete non-destructive testing coverage of anchorage and transition zones, which constrains the reliability of condition assessment and should be treated as a priority area for further development.

Keywords: cable-stayed bridge; cable systems; maintenance; risk; reliability; safety

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1 Introduction

The use of cable systems is one of the most successful solutions for constructing bridges with large and extra-large spans. Such schemes have a significantly greater range of rational span lengths compared to classical beam schemes. At the same time, unlike similar cable-stayed suspension bridges, cable-stayed bridges are characterized by significantly greater rigidity.

1.1 History of Cable-Stay Bridge Construction in Russia

Due to geographical and climatic features, historically, beam schemes of bridges were preferred in the territory of Russia, including for large spans. In the 20th century, individual urban cable-stayed bridges were built in major cities of the USSR, largely due to the high architectural expressiveness of this scheme. In such bridges, a single-pylon scheme with rare cable bundles was usually used: the October Bridge in Cherepovets, the Moscow (now: Northern) Bridge in Kyiv (Ukraine), and the Gorky (now: Cable-Stayed) Bridge in Riga (Latvia). Pedestrian cable-stayed bridges were built more frequently.

A new stage in cable-stayed bridge construction began after the 1990s, which was associated, on the one hand, with a significant expansion of available technologies, and on the other hand, with the beginning of implementation of major bridge projects across large water obstacles, where the application of beam schemes was impractical or impossible. Moreover, in the new economic conditions, cable-stayed bridges were often preferred for their enhanced aesthetic characteristics, as a demonstration of industry modernization.

One of the first cable-stayed bridges of the new stage was the Yugorsk Bridge in Surgut (2000), located in the far north of Siberia, across the wide Ob River. Subsequently, bridges were built in Salekhard (2004) and Murom (2009). Cable-stayed bridges were also constructed on freeways and urban highways of major metropolitan areas: the Great Obukhovskiy Bridge on the ring highway of St. Petersburg (2004, 2007), the Aleksandrovskaya Farm overpass in St. Petersburg (2008), and the "Millennium" bridges in Kazan (2005, 2007). In 2012, truly iconic bridges were opened in Vladivostok—the Golden Bridge and the Russian Bridge. The latter held the record for span length among cable-stayed bridges for 14 years until 2025 (1,104 m). In 2016, sea cable-stayed bridges were opened in St. Petersburg on the western bypass of the city (Western High-Speed Diameter Highway). In addition, small classical cable-stayed and low-pylon cable-stayed bridges began to be massively constructed on medium rivers and in urban agglomerations. The low-pylon scheme was also used for the Friendship Border Bridge on the border with China near the cities of Blagoveshchensk and Heihe (opened in 2024). Currently, one of the main challenges of Russian bridge construction is the construction of the Lena Bridge in Yakutia, across a very wide river in permafrost conditions. The bridge will be constructed with three pylons, with a large central pylon and smaller side pylons. The central spans will be 840 m long, and the total length of the bridge will be 4.6 km.

Table 1 Bridges constructed before 2010 and new bridges with spans exceeding 200 m

No.	Bridge Name and Obstacle Crossed	Main span length	Year opened	Age in 2026	Image
1	October Bridge across the Sheksna River	194	1979	47	
2	Yugra Bridge across the Ob River	408	2000	26	
3	Bolshoy Obukhovskiy Bridge across the Neva River	382	2004 (first phase), 2007 (second phase)	22	
4	Fakel Bridge across the Shaitanka River	100	2004	22	
5	Millennium Bridges across the Kazanka River	100	2005 (first phase), 2007 (second phase)	21	

No.	Bridge Name and Obstacle Crossed	Main span length	Year opened	Age in 2026	Image
6	Zhivopisny Bridge across the Moscow River	409.5	2007	19	
7	Aleksandrovsкая Farm Overpass across the October Railway Tracks	182.3	2008	18	
8	Murom Bridge across the Oka River	231	2009	17	
9	Rusky Bridge across the Eastern Bosphorus Strait	1,104	2012	14	
10	Zolotoy Bridge across Golden Horn Bay	737	2012	14	
11	Bridge across the Mzymta River	312	2013	13	
12	Bridge across the Korabelniy Fairway	320	2016	10	
13	Bridge across the Petrovsky Fairway	240	2016	10	
14	Arkhangelsk Bridge across the Sheksna River	220	2022	4	
15	New Murom Bridge across the Oka River	254	2023	3	

1.2 Operational Problems of Cable-Stayed Bridges

As shown in Table 1, some cable-stayed bridges have been in operation for a long time without significant repair work. For example, the October Bridge (Item 1) has a service life of more than 47 years, and a significant portion of bridges have been in operation for 20–30 years. Under severe climatic conditions associated with negative temperatures and the impact of winter de-icing agents, as well as considering the increasing intensity of traffic and total vehicle masses, the safety of

cable-stayed bridge operation in general, and of their cable systems in particular as the most critical element, becomes extremely relevant. Based on the results of periodic inspections of cable systems of various bridges, experts noted significant damage to cables and anchors of a corrosive and fatigue nature (Figure 1).



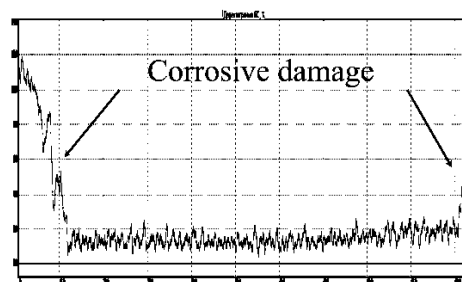
a) Stay cable pipe "waviness"



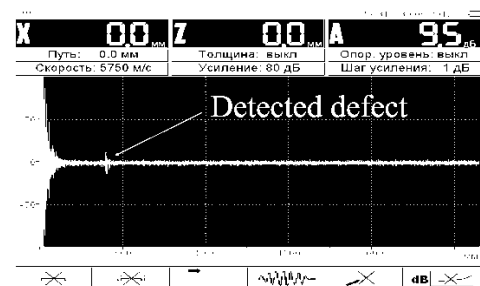
b) Wire breakage of bridge multi-layer strand cable



c) Wire breakage of bridge multi-layer strand cable



d) Defectogram of the free length of a cable with detected areas of corrosive damage to wires



e) Echogram of wires in the end anchor device with detected defects

Figure 1 Typical damage types observed in cable systems of Russian cable-stayed bridges

It should be noted that some damage can be detected in advance in visible and accessible sections of cable systems (Figure 1a), while a significant portion of the structures remains inaccessible for inspection and represents a "black box" during operation (Figure 1e), preventing reliable assessment of the technical condition of the cable system and the structure as a whole. This problem has also been noted in numerous studies devoted to the inspection and operation of cable systems conducted by research teams from around the world [1], which confirms its general nature and points to the need for a universal systematic solution.

1.3 Safety of Bridge and Bridge Operation Strategies

Currently, in most design approaches, proof of safety is proof of strength, durability, rigidity, etc. [2–4] However, the term "safety" means the absence of unacceptable risks, and this term, strictly speaking, should be used only to denote the state of a structure in which the level of risk remains acceptable [3,5]. Risk is the product of the probability of failure multiplied by the damage from it. Sometimes, instead of "risk," the phrase "average probable losses" is used. Consequently, the task of determining cumulative risk reduces to determining the sum of the products of the probabilities of each failure multiplied by the corresponding damage. Damage is generally a probabilistic (random) quantity [3–7].

To analyze the risks associated with the operation of complex technical systems, the following qualitative and quantitative methods can be used [4,8–13]:

- Nature and technical hazards, impacts and associated issues analysis;
- Impact analysis to reliability (dependability) of human aspects (including training and education);
- Event Tree Analysis (ETA);
- Fault Tree Analysis (FTA);
- Failure mode and consequence analysis;
- Calculating the probability/consequence matrix (risk matrix method);
- Risk criticality analysis (prioritization);
- Reliability Block Diagrams (RBD), related to FTA and Markov methods;
- Operational data review (including lessons the past, failures and collapses);
- Hidden processes analysis (for bridges, it is mainly prediction of hidden defects).

Unfortunately, most modern approaches to operation do not involve a deep analysis of probable hazards and risks [13–17]. At the same time, a widespread disadvantage of many existing life cycle systems for bridge structures is not only the underestimation of risks, but also the use of so-called passive risk management strategies, which include responding to already identified damage, which entails significant risks of failure to detect damage and, consequently, failure to take necessary action. The necessary solution in this situation appears to be a transition to preventive operation strategies [11,18–22].

Three typical management strategies can be observed in the diagram: passive, preventive, and pro-active [23,24](Figure 2):

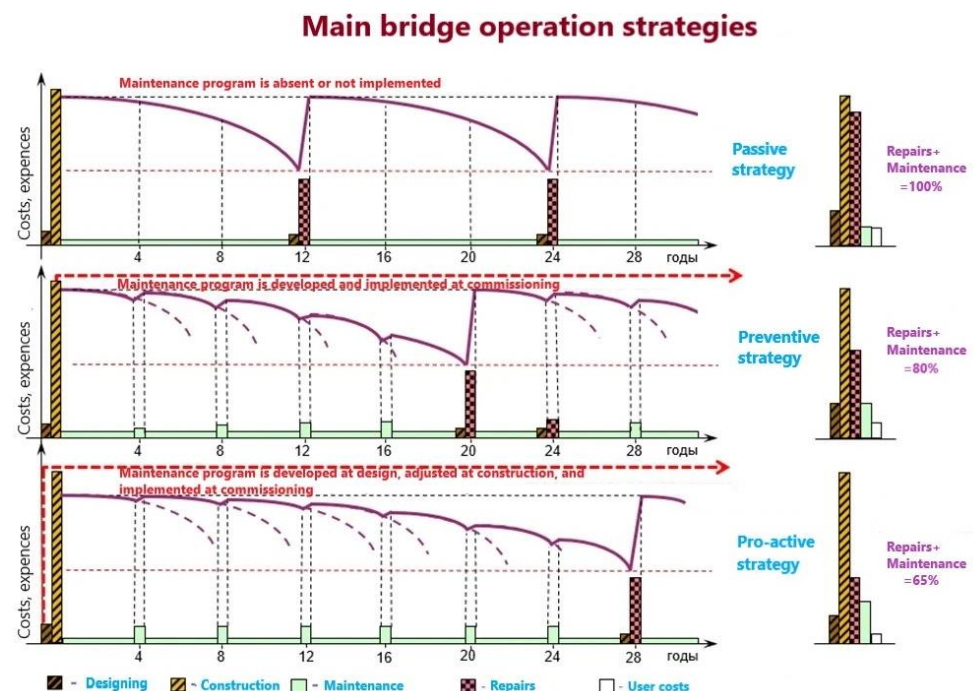


Figure 2 Bridges maintenance strategies

The most effective are the two last, where decisive measures are implemented before any type of critical faults. Nevertheless, despite the significant negative consequences, such as damage to human comfort, life, and health, and huge material and other losses due to the dominance of passive strategies, they are often taken for granted.

However, this approach becomes increasingly unacceptable when applied to critical and unique infrastructure facilities such as bridges. The need to prevent damage at its early stages rather than respond to already developed defects has stimulated the transition toward preventive maintenance and monitoring strategies[18,21].

In such bespoke structures, this progressive strategy adoption in Russia was triggered by the high cost of restoring or complete replacement of the unique structural elements of cable-stayed bridges [25].

1.4 Research Objectives

The objectives of this study were as follows:

- (1) Analyze the accumulated Russian experience in the operation, inspection, repair, and monitoring of highway cable-stayed bridges, with emphasis on typical damage and maintenance challenges affecting cable systems;
- (2) Substantiate the need to replace predominantly passive defect-response practices with a preventive, risk-based operation strategy for safety-critical bridge cable systems;
- (3) Develop and systematize a life-cycle-based organizational framework for cable system operation covering the design, construction, commissioning, and service stages, including risk analysis, threshold and reference data, and SHM integration;
- (4) Define the scope of application and operational requirements of the proposed approach for the cable-system types currently relevant to Russian highway bridges;
- (5) Identify the principal technical limitations that constrain reliable condition assessment in practice, particularly the incomplete non-destructive testing coverage of anchorage and transition zones.

2 Methodological Foundations for Organizing the Operation System of Cable-Stayed Bridges Based on a Preventive Operation Strategy

2.1 Classification of Cables and Cable Systems

During the development of the state standard, an analysis of 189 national and international regulatory and scientific-technical documents was conducted, on the basis of which the need to develop some new terms and definitions was identified [26]. In total, GOST R provided definitions for 53 terms, of which 42 were formulated individually. Thus, the term "cable system" (CS) and its definition are fundamentally new in Russian practice: "A set of elements connecting other load-bearing parts of a building structure (a stiffening beam with an arch or pylon, etc.), including a cable made of flexible straight load-bearing stretched elements (ropes, strands, etc.), anchor devices, additional devices to increase damping, reduce fatigue, corrosive and other hazards." Unlike a "static cable system," this term defines a structural part uniform in the nature of its operation and arrangement, which can be used in various static systems (cable-stayed, combined, etc.), which corresponds to generally accepted international approaches [27–30].

During the research, highway bridges in operation on public highways of the Russian Federation with cable systems in their composition were analyzed. It was

established that this component of the bridge fleet is represented by two types of static schemes: cable-stayed bridges with a stiffening beam suspended on pylons and arches with flexible cable suspensions of the stiffening beam. The cable systems characteristic of these static schemes corresponds to the scope of application of the developed national standard.

Based on an analysis of world experience[27–30], six main types of cables included in the respective cable systems were identified (Figure 3):

- Multi-layer-strand cable stays (cables of closed structure, MLS);
- Cables consisting of a bundle of parallel seven-wire steel strands (parallel strand cable, PSC);
- Cables consisting of a bundle of parallel high-strength steel wires (parallel wire cable, PWC);
- Cables made of rigid steel rolled products;
- Cables made of rigid reinforced concrete elements;
- Cables made of flexible composite elements.

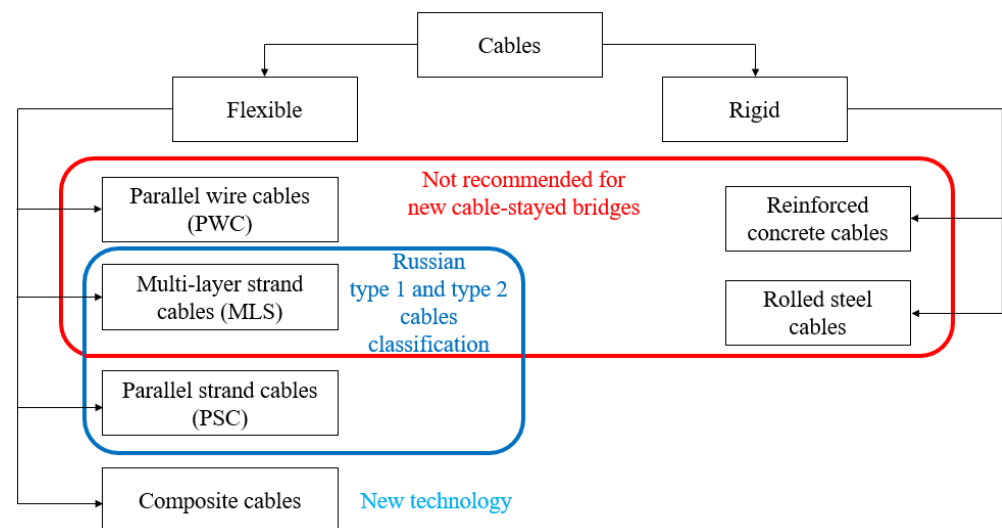


Figure 3 Classification of cables

Among the bridges identified on public highways of the Russian Federation with cable systems in their composition, only the first two types from the above list are present. Moreover, the design of the first type is being used less frequently, giving way to more technologically advanced parallel seven-wire strands.

Types 3, 4, and 5 were widely used during the 1950s–1990s and are currently not recommended for newly constructed bridges, at least in EU countries, owing to the difficulty of regulating forces and the tendency toward fatigue and corrosive damage during long-term operation [29–31]. The design of type 3 is still actively used in the main load-bearing elements of suspension bridges owing to the greater rigidity of parallel wires. Cables made of flexible composite elements have not yet been fully investigated and cannot be considered sufficiently reliable for large-span highway bridges [30].

Considering the results of the above-mentioned analysis, the scope of application of the national standard was limited to types 1 and 2 of cables relevant to the Russian Federation from the above list. Accordingly, terminological articles were introduced into the national standard defining "Type 1 cables" consisting of one main stretched element in the form of a closed rope and "Type 2 cables" consisting of several main stretched elements in the form of parallel seven-wire strands (Figure 4).

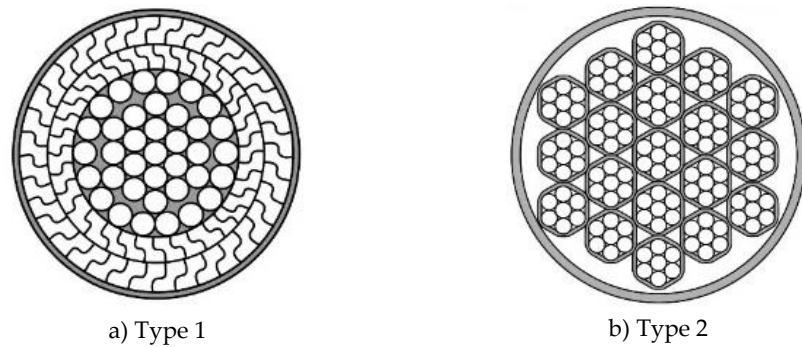


Figure 4 Russian type 1 and type 2 cables classification

2.2 Organization of the Operation System

The main comprehensive results obtained as a result of the research are the standardization of the organizational structure of measures for the preparation and implementation of the operation of cable systems of highway bridges at all stages of its life cycle: the design stage, the construction stage, and the operation stage. This standardized organizational structure of measures for preparation and implementation of the operation of cable systems of highway bridges, which must be provided at the above-mentioned stages of the life cycle of bridge structures, is presented in Figure 5.

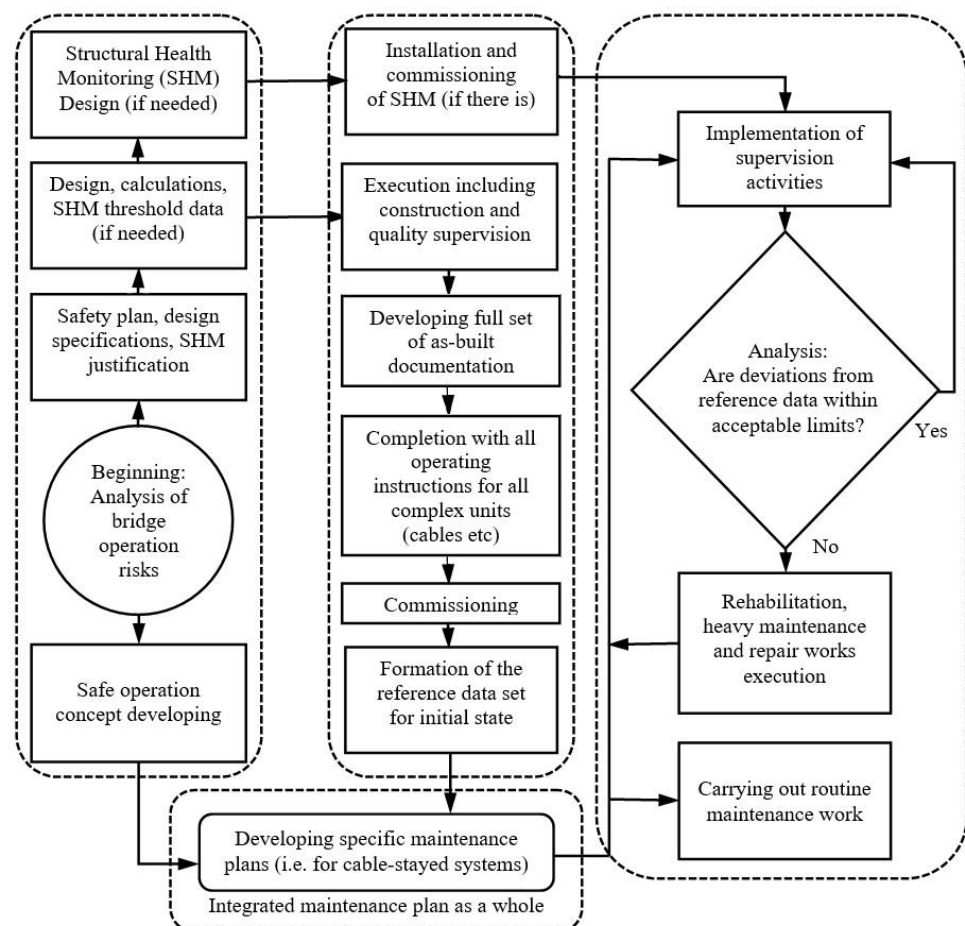


Figure 5 Organizational structure of measures for preparation and implementation of operation of cable systems of highway bridges

The methodology is based on the continuous coverage of all stages of the structure's life cycle, from design to operation. During the development of project documentation, operational risks are analyzed, a concept of safe operation is formed, calculations of load-bearing elements are performed, and controlled parameters are determined. Based on the calculations, a database of threshold values was created, with which the monitoring results were subsequently compared, and a section of the monitoring system for engineering structures and engineering systems (SHM) was developed.

At the stage of preparation of working documentation and construction, provision and supervision of equipment installation, installation of sensors, and adjustment and commissioning of the monitoring system are provided. Simultaneously, an operation manual is developed. Upon completion of construction, an acceptance inspection is conducted, which makes it possible to record its initial technical condition and form a database of reference data.

Continuous monitoring is carried out during the operation period. Data from instrumental measurements are supplemented by the results of supervision, periodic inspections, and surveys, after which actual indicators are compared with reference and threshold values. If there are no deviations, planned regulatory maintenance work on the structure is performed. If exceedances or unfavorable dynamics are detected, unscheduled inspections are assigned with subsequent non-standard work.

Thus, the methodology ensures a transition from responding to existing defects to preventing dangerous conditions. The connection between design calculations, the results of acceptance inspection, and operational monitoring and supervision makes it possible to assess the technical condition of the structure in a timely manner, make informed decisions on risk management, and maintain the required level of safety throughout the service life.

2.3 Operational Risks of Cable Systems of Highway Bridges and Measures to Reduce Them

The main technical requirement in the operation of cable-stayed bridges, guaranteeing their structural safety for users, is to ensure the required level of reliability corresponding to the level of acceptable risk. Given the increased level of responsibility and/or uniqueness of cable-stayed bridge structures, their period of operation is the most dangerous in the presence of critical defects, especially those that are hidden from visual inspection and may manifest themselves at the most unfavorable moment, for example, during periods of intensive traffic on or under the bridge. Analysis of bridge collapses have shown that casualties from large-span failures often exceed 100 per event [32]. For example, when the cable-stayed viaduct in Genoa collapsed on August 14, 2018, 43 people died and dozens suffered serious injuries [33]. In 2019, a bridge with cable suspensions collapsed in eastern Taiwan, China. Six people under the bridge at the time of the collapse died. Twelve individuals were injured.

When designing and operating, one should consider the occurrence of risks in accordance with the provisions [34]. Hazards, hazardous events for cable systems (Figure 6), and measures for managing the main operational risks are presented in Table 2.

To identify and rank the degree of risk criticality, the provisions [34] should be applied. Practice in applying such methodologies shows that a problem often arises with the statistical substantiation of failure probabilities, in which case, it is recommended to rely on expert assessments of these probabilities [2]. However, if necessary to refine the risk analysis, alternative tools can be used, for example, the new "Fault-Screen" methodology based on statistical data of intermediate and primary hazardous events [11,12].

Ranking of risk criticalities obtained using the above-mentioned methodologies [12,34] makes it possible to develop a substantiated concept of safe operation (Figure 6), determine the applicability and/or priority of design and technological solutions and risk management measures, which in turn leads to the formation of an optimal operation strategy for bridge structures and their cable systems [25].

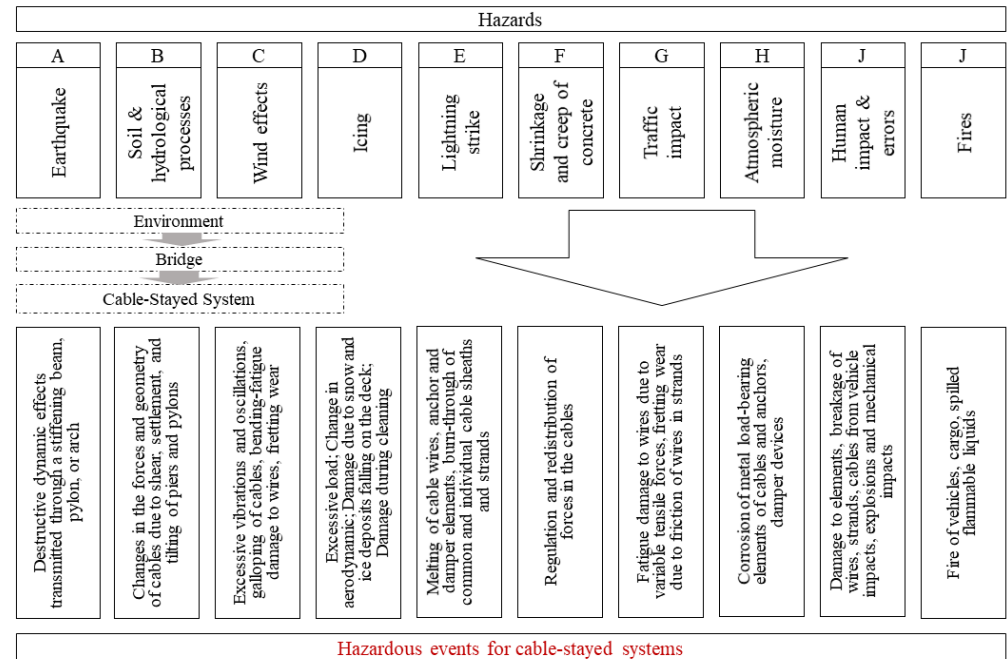


Figure 6 Hazards and hazardous events for cable-stayed systems

Table 2 Final risk screening table

Hazards	Hazardous events for cable-stayed systems	Risk management measures for cable-stayed systems operation:	
		At the design stage:	At the operation stage:
A. Earthquake	Destructive dynamic effects transmitted through a stiffening beam, pylon, or arch	Seismic resistance and seismic isolation measures	Monitoring using seismic monitoring systems, restricting access for temporary loads, finding and assessing damage, repairing, strengthening, or replacing elements
B. Soil and hydrological processes	Changes in the forces and geometry of cables due to shear, settlement, and tilting of piers and pylons	Anti-karst, anti-landslide, etc. measures	Instrumental monitoring, including using seismic monitoring systems, restricting access for temporary loads, assessing damage, repairing, strengthening, or replacing elements
C. Wind effects, including those combined with rain and icing	Excessive vibrations and oscillations, galloping of cables, bending-fatigue damage to wires, fretting wear	Measures to improve damping capacity	Timely detection of deviations and defects through supervisory activities, as well as by means of the SHM, timely maintenance and repair of dampers and cables, installation of additional dampers and ties
D. Icing, formation of snow and ice buildup on cables, main supports (pylons), and arches	Excessive loads for cable-stayed systems, changes in aerodynamic characteristics, damage due to snow and ice deposits falling on the	Forecasting the ice lay thickness in accordance with the Codes, use of cable coatings that reduce ice adhesion, thermal, vibration, electric pulse, chemical, and other preventive devices (e.g. Inclusion of	Timely detection of snow and ice buildup on cable-stayed systems using surveillance and SHM systems, use of mechanical, thermal, chemical and other cleaning methods that minimize damage to cable-stayed systems; if

Hazards	Hazardous events for cable-stayed systems	Risk management measures for cable-stayed systems operation:	
		At the design stage:	At the operation stage:
	bridge deck and underlying structures, damage during cleaning	icing alarms in the SHM, if necessary)	necessary, modernization of cable-stayed systems with the installation of additional preventive devices.
E. Lightning strike	Melting of cable wires, anchor and damper elements, burn-through of common and individual cable sheaths and strands	Installation of lightning protection systems	Monitoring lightning strikes, searching for and assessing damage using supervision tools, SHM, repair and replacement of cables, anchors and dampers
F. Shrinkage and creep of concrete, stress relaxation and creep in the strands and ropes	Regulation and redistribution of forces in the cables	Taking into account the change in the camber of the stiffening beam and the change in the forces in the cables over time	Instrumental control of the geometric position of the stiffening beam and pylons, regulation of forces in the cables (including by means of the SHM)
G. Impact of traffic flow	Fatigue damage to wires due to variable tensile forces, fretting wear due to friction of wires in strands	Application of high fatigue and fretting resistance strands and ropes	Periodic visual and instrumental NDT of cables, collection of information on strands and ropes loading conditions, identification of cases of excessive impact of moving loads using the SHM, replacement of damaged elements
H. Atmospheric moisture, including chlorides dissolved in it	Corrosion of metal load-bearing elements of cables and anchors, damper devices	Application of effective systems for protecting wires and ropes from corrosion, drainage devices	Periodic visual and instrumental inspection, restoration of protective coatings and fillers, cleaning of drains, replacement of damaged elements
I. Human error, negligence, vandalism, terrorism	Damage to elements, breakage of wires, strands, cables from vehicle impacts, explosions and mechanical impacts	Application of vandal-proof systems and video surveillance systems	Prevention of illegal actions, damage assessment, repair, strengthening or replacement of elements
J. Fires	Fire of vehicles, cargo, spilled flammable liquids	Use of built-in fire protection systems, provision of a direct communication channel with fire extinguishing services	Ensuring uninterrupted operation of a direct communication channel with fire-fighting services, ensuring constant video surveillance, and taking immediate measures to eliminate the source of the fire.

3 Requirements for Design Solutions and Construction Process

3.1 Ensuring Access

Regardless of risk criticality, at the design stage, the following design measures must be provided, which are necessary for the effective operation of cable systems:

- Installation of inspection devices for the control and operation of anchor devices and transition zones when located at height;
- Ensuring the possibility of maintenance and replacement of any element of the cable system.
- Ensuring the possibility of installing and operating non-destructive testing (NDT) equipment;
- Ensuring the possibility of installing jacks to regulate forces in cables;
- Installation of built-in geodetic marks for long-term monitoring of the displacements of stiffening beams, pylons, or arches.

3.2 Monitoring Systems

The GOST R 59629—2021 [35] standardizes for the first time the requirement for forming a database of threshold data at the design stage, which is necessary for developing a monitoring system for engineering structures (SHM) because the most accurate values can be provided by the design organization that performed the structure calculations. The development of subsections of the project on SHM, installation, and commissioning of SHM are standardized by national standards [36,37].

Unlike periodic inspections, SHM allows continuous recording of the values of controlled parameters of cable systems and bridge structures under dynamically changing traffic flow conditions.

A typical system includes accelerometers, strain gauges, displacement and inclination sensors (inclinometers), weather stations, GNSS satellite positioning systems, corrosion sensors, and anchor node condition sensors.

3.3 Requirements for the Construction Stage

At the construction stage, in terms of mandatory measures to prepare for operation, the development of an operation manual for cable systems is provided. At the same time, the GOST R 59629—2021 [35] standardizes the requirement for the development of this manual by the cable system supplier, that is, the legal entity carrying out contractual supply, which corresponds to worldwide practice [29,31].

Another new requirement is the formation of a database of reference data. According to a new terminological article [35], reference data are indicators of bridge structures (forces, coordinates, defect parameters, and other quantitative parameters) measured by reliable methods at the time of commissioning after construction, reconstruction, or major repair, which are compared with current indicators measured at the same points and sections during inspections and tests during the operation period. As shown by international practice, effective and reliable operation of cable systems without creating a database of necessary reference data is impossible [27,29].

As shown in Figure 5, the section on cable system operation at the construction stage is supplemented by an operation manual for cable systems developed by the supplier and necessary reference data. Subsequently, during the operation stage, these documents serve as the basis for organizing supervision and maintenance. In the national standard [35], a mandatory condition is established for developing a section on cable system operation as part of the general bridge maintenance project as the main regulator of the cable system operation system, and requirements are defined for its stages, composition, and content of subsections.

4 Peculiarities of Organization of Supervisory Measures

4.1 Required Measures

When developing the GOST R 59629—2021 standard [35], based on the analysis of hazards, hazardous events, and associated risks, the types of required measures for the supervision and maintenance of cable systems of highway bridges were determined. The nomenclature of these measures is presented directly in [35] and is not considered in this study. However, it should be noted that supervisory measures play a special role in forming a preventive system of cable system operation, allowing the analysis of whether deviations from reference data are within acceptable limits (Figure 5), which will determine the need for non-standard maintenance and repair work. In this case, standard maintenance work is carried out regularly throughout the year (season) in accordance with the established frequency, regardless of the condition of the structure elements.

In [35], traditional, largely standard, planned types of comprehensive measures are provided for cable systems: acceptance inspection, continuous supervision, current inspection, periodic inspection, and periodic survey. The frequency of planned supervisory measures is largely consistent with the frequency provided by current standards and methodologies [38,39]. In addition to planned measures, when hazards and hazardous events indicated in Table 2 arise in the area of cable system location, [35] provides unscheduled inspections, based on the results of which a number of specialized works must be carried out that have significant differences from ordinary bridge structures. The list of such works, along with relevant hazards and hazardous events, upon the implementation of which they should be carried out, is presented in Table 3.

Among the works listed in Table 3, non-destructive testing of the free zones and closed zones of cables should be highlighted. The remaining measures, despite their complexity and labor intensity, appear to be fully implementable. However, it is precisely NDT of the integrity of the main stretched elements (wires, strands, ropes) of cables that makes it possible to reliably determine the degree of deviation of controlled cable system parameters (forces, displacements) from reference values.

Table 3 Work ordered based on the results of unscheduled inspections
 ("+" means work is required, "-" means it is not required)

Types of Control Work	Hazardous events						
	Earthquake 7 Points and Above	Lightning Strike to Cable	Breakage of External Cable Wires	Vehicle impact on Cable System	Fire, Explosion in Cable System Area	Shifts, Settlements, and Tilting of Bearings	Hurricane Wind Exceeding 30 m/s
NDT of Free Cable Zone	+	+	+	+	+	-	-
NDT Control of Closed Cable Zones	+	-	+	+	+	-	-
Force Measurement in Cables	+	-	-	-	+	+	-
Geodetic Control of Stiffening Beam	+	-	-	-	-	+	-
Geodetic Control of Pylons or Arches	+	-	-	-	-	+	-
Inspection of Internal Dampers for Type 2 Cables	+	-	-	+	+	-	+
Inspection of External Dampers for Type 1,2 Cables	+	-	-	+	+	-	+
Types of Control Work: Inspection of Deviators for Type 2 Cables	+	-	-	+	+	-	+

4.2 Existing Non-Destructive Testing Methods

During research on the development of the GOST R 59629—2021 standard [35], a detailed analysis of NDT methods and means was performed. Visual, measurement, and optical NDT methods should be applied to assess the outer surface of cable system elements. When diagnosing the working sections of the main stretched elements of cable systems in depth, magnetic, induction, eddy current, and ultrasonic methods can be used [40]. The magnetic NDT method should be applied when diagnosing the working sections of the free length of cables. This method has been successfully mastered in the Russian Federation using domestic equipment, the reliability of which has been confirmed [41]. For this reason, the use of other listed methods for free-length cable sections appears unnecessary. Figure 7 shows examples of NDT on Russian bridges.



a) Bolshoy Obukhovskiy Bridge across the Neva River



b) October Bridge across the Sheksna River



c) Fakel Bridge across the Shaitanka River



d) Russky Bridge across the Eastern Bosphorus Strait

Figure 7 Examples of NDT on Russian bridges

The magnetic NDT method can be used to diagnose the working sections of the free length of both Type 1 and Type 2 cables. The ultrasonic method (echo method) NDT [42] is possible only when diagnosing wires of the main stretched element of a cable system located in the anchor device zone and the transition zone of Type 2 cables. This method, as applied to cable systems, has not yet found widespread use in the Russian Federation, but is successfully used abroad [43]. The length of the main stretched element of a cable system diagnosed by the ultrasonic method, located in the anchor device zone and the transition zone of Type 2 cables, can range from 300 to 500 mm from its end, depending on the design of the anchor device. However, neither magnetic nor ultrasonic methods allow for complete NDT of the entire length of both Type 1 and Type 2 cables (Figure 8).

Thus, there are the following problems concerning the NDT of cable systems:

- Absence of world NDT methodologies for diagnosing Type 1 cables within the anchor bushing and the portion of the cable directly adjacent to it at the entrance to the bushing.

- Need to develop and certify a Russian methodology and instrumental equipment for NDT by the ultrasonic method for confident diagnosis of anchor and transition zones of Type 2 cables;
- Absence of global NDT methodologies for diagnosing Type 2 cables within the anchor tube and the portion of the cable directly adjacent to it at the entrance to the anchor tube.

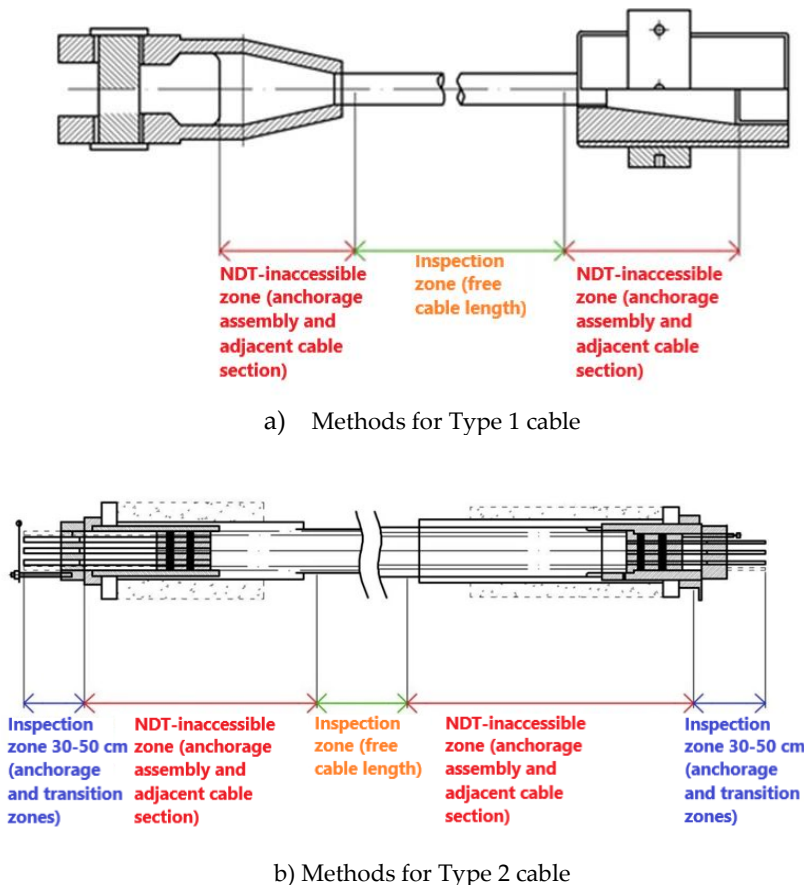


Figure 8 Zones of possibility of investigation of cable working sections by NDT

5 Discussion

The vast majority of cable-stayed bridges in Russia are less than 26 years old (Table 1), significantly shorter than the minimum design service life established by current standards. However, due to the lack of pre-developed preventive maintenance programs based on risk analysis at all stages of the life cycle, some elements of these structures have developed significant defects during operation, failing to reach their minimum design life, requiring maintenance and repair work beyond the scope of current standards.

The GOST R 59629—2021 standard discussed in this paper was successfully put into effect in 2021 and is mandatory for application throughout the territory of Russia. Nevertheless, even with its implementation, the following problems are observed and have even become more evident:

- (1) The transition to preventative and proactive maintenance systems should be supported by macroeconomic reforms in financing, particularly for the most expensive transport infrastructure assets, such as cable-stayed bridges. Financing should be justified based on risk analysis and reliability at all stages of the lifecycle. Such approaches allow for the adoption of often more expensive design solutions that ensure adequate accessibility and monitoring, reduce operating costs and risks, but thereby reduce overall lifecycle costs. Illustrative examples from practice show cases where the assessment of defects in a cable

system becomes a subject of prolonged debate among the owner, the operator, and experts regarding the feasibility of urgent repair of such damage because of its high cost.

- (2) The issue of quantitative risk assessment methods is critical, as it enables the economic justification for more expensive design and operational solutions. At present, the methods of this theory are rarely used in engineering practice, since they require substantial multidisciplinary scientific substantiation. The development of engineering methodologies based on these methods, in particular using modern digital technologies for analysis and event prediction, will significantly expand their field of application. A good example of such an “engineering” transition on the scale of the global engineering community is the work of the Joint Committee of Structural Safety, which resulted in the development of guidelines for the application of probabilistic methods to assess reliability and safety [44].
- (3) In addition to the assessment of structures and, in particular, their risks, from the standpoint of national regulation, the issue of setting target indicators is important. In this matter, an effective step would be a transition from the existing non-mandatory principles of individual scientific justifications to direct standardization. Furthermore, as a fairly simple but effective measure, the concept of “attention indices” implemented within some BMS can be mentioned. A similar solution could also be applied within a single bridge, where each component part is characterized by an “index of attention” that actually reflects the level of consequences (risk) of failure of that element [45].
- (4) There is a conservatism in the current approach to building monitoring systems, which places significant emphasis on collecting gigabytes of data and their elementary “snapshot” interpretation using fixed threshold values without taking into account long-term processes and the actual behavior of the structure [46]. A promising development is a transition from monitoring systems based on static data comparison to systems that compare the performance characteristics of the structure over time using a self-updating digital twin [47,48].
- (5) A natural outcome of the synergetic development of bridge asset management methods, risk and reliability assessment methods, and digital twin and monitoring technologies could be a unified system for condition assessment and decision-making for particularly important bridges. Figure 9 presents the concept of this system, which can be integrated with minimal changes into existing approaches to bridge operation management [49].

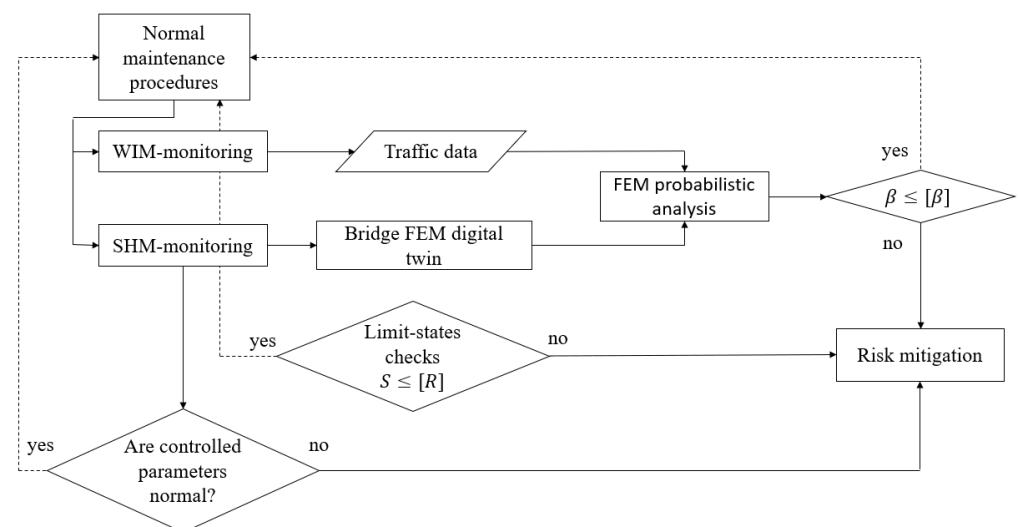


Figure 9 Proposed framework for risk analysis using SHM data [49]

- (6) In addition to the above, it is also important to note technical problems that significantly constrain the above concepts in terms of data reliability. Currently, there are significant limitations in non-destructive testing methods for cable systems, which, as a rule, can be applied only to sections of the free length of the cable, while one of the most vulnerable parts is the anchorage zones. This technical problem should be one of the priorities to be addressed.

6 Conclusions

The main contribution of the study is the formalization of a preventive and proactive, risk-based operational framework for cable systems of highway bridges that links design decisions, commissioning data, monitoring, inspections, and maintenance actions across the full life cycle of the structure. This framework shifts bridge operation away from passive response to already developed defects and toward earlier detection of pre-critical conditions supported by threshold values, reference data, and SHM integration. For Russian practice, this is a meaningful step because cable systems are safety-critical elements that are exposed to corrosion, fatigue, climatic actions, and traffic effects, while some of their most vulnerable zones remain difficult to inspect directly. The most important unresolved issue is the lack of reliable non-destructive testing methodologies for anchorage and transition zones of both major cable types, which limits the completeness of technical diagnostics and therefore the robustness of risk-informed decisions. Further work should therefore focus on validating quantitative risk-assessment tools and developing inspection technologies that can close the current diagnostic blind spots and make preventive operation fully evidence-based.

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References

1. Mehrabi, A.B. In-Service Evaluation of Cable-Stayed Bridges: Overview of Available Methods and Findings. *Journal of Bridge Engineering* **2006**, *11*, 716–724, doi:10.1061/(ASCE)1084-0702(2006)11:6(716).
2. Syrkov, A.V. New Approach to Creating Bridge Structure Condition Management Systems. *Science and Technology in the Road Industry* **2009**, 14–16.
3. Diamantidis, D. Current Safety Acceptance Criteria in Codes and Standards — A Critical Review. **2012**, 1–8, doi:10.1061/41016(314)76.
4. Mkrtchev, O.; Rayzer, D. *Reliability Theory in the Design of Building Structures (in Russian)*; ASV: Moscow, 2016; ISBN 978-5-4323-0189-5.
5. Sykora, M.; Holicky, M.; Jung, K.; Diamantidis, D. Human Safety Criteria for Risk-Based Structural Design. *Int. J. SAFE* **2018**, *8*, 287–298, doi:10.2495/SAFE-V8-N2-287-298.

6. Sykora, M.; Holicky, M.; Lenner, R.; Manas, P. Target Reliability Levels for Existing Bridges Considering Emergency and Crisis Situations. *Advances in Military Technology* **2014**, *9*, 45–57.
7. Schneider, J.; Vrouwenvelder, T. *Introduction to Safety and Reliability of Structures*; Structural Engineering Documents; 3rd reviewd and extended.; International Association for Bridge and Structural Engineering (IABSE): Zurich, Switzerland, 1997; ISBN 978-3-85748-151-2.
8. Leimeister, M.; Kolios, A. A Review of Reliability-Based Methods for Risk Analysis and Their Application in the Offshore Wind Industry. *Renewable and Sustainable Energy Reviews* **2018**, *91*, 1065–1076, doi:10.1016/j.rser.2018.04.004.
9. Kabir, S.; Papadopoulos, Y. Applications of Bayesian Networks and Petri Nets in Safety, Reliability, and Risk Assessments: A Review. *Safety Science* **2019**, *115*, 154–175, doi:10.1016/j.ssci.2019.02.009.
10. Shafiee, M.; Enjema, E.; Kolios, A. An Integrated FTA-FMEA Model for Risk Analysis of Engineering Systems: A Case Study of Subsea Blowout Preventers. *Applied Sciences* **2019**, *9*, 1192, doi:10.3390/app9061192.
11. Syrkov, A.V.; Hoj, N.P. Bridge Failures Analysis as a Risk Mitigating Tool. In Proceedings of the Proceedings of the IABSE Symposium: Towards a Resilient Built Environment Risk and Asset Management, Guimarães, Portugal, 27–29 March 2019; Guimarães, Portugal., 2019; Vol. 113, pp. 304–310.
12. Syrkov, A.V.; Sizikov, A. Enhancing of Bridge Management given Failures Data. In Proceedings of the Proceedings of the IABSE Symposium: Synergy of Culture and Civil Engineering – History and Challenges, Wrocław, Poland, 7–9 October 2020; Wrocław, Poland, 2020; pp. 1173–1180.
13. Han, X.; Frangopol, D.M. Life-Cycle Risk-Based Optimal Maintenance Strategy for Bridge Networks Subjected to Corrosion and Seismic Hazards. *J. Bridge Eng.* **2023**, *28*, 04022128, doi:10.1061/JBENF2.BEENG-5799.
14. Ariza Flores, V.A.; Zavala Ascaño, G. Quantitative Risk Analysis Framework for Cost and Time Estimation in Road Infrastructure Projects. *Infrastructures* **2025**, *10*, 139, doi:10.3390/infrastructures10060139.
15. Eidsvig, U.; Santamaría, M.; Galvão, N.; Tanasic, N.; Piciullo, L.; Hajdin, R.; Nadim, F.; Sousa, H.S.; Matos, J. Risk Assessment of Terrestrial Transportation Infrastructures Exposed to Extreme Events. *Infrastructures* **2021**, *6*, 163, doi:10.3390/infrastructures6110163.
16. Lotfi, R.; Vaseei, M.; Ali, S.S.; Davoodi, S.M.R.; Bazregar, M.; Sadeghi, S. Budget Allocation Problem for Projects with Considering Risks, Robustness, Resiliency, and Sustainability Requirements. *Results in Engineering* **2024**, *24*, 102828, doi:10.1016/j.rineng.2024.102828.
17. Proske, D.; Papastergiou, D.; Friedl, H. Discussion of Consequence Parameters for Risk Assessment of Bridges and Retaining Structures. In Proceedings of the 20th International Probabilistic Workshop; Matos, J.C., Lourenço, P.B., Oliveira, D.V., Branco, J., Proske, D., Silva, R.A., Sousa, H.S., Eds.; Springer Nature Switzerland: Cham, 2024; pp. 125–136.
18. *Bridge Maintenance, Safety, Management, Digitalization and Sustainability*; Jensen, J.S., Frangopol, D.M., Schmidt, J.W., Eds.; CRC Press: London, 2024; ISBN 978-1-00-348375-5.
19. Frangopol, D.M.; Kim, S. Life-Cycle Probabilistic Multi-Objective Optimum SHM Planning. In Proceedings of the 20th International Probabilistic Workshop; Matos, J.C., Lourenço, P.B., Oliveira, D.V., Branco, J., Proske, D., Silva, R.A., Sousa, H.S., Eds.; Springer Nature Switzerland: Cham, 2024; pp. 3–11.
20. Mahmoud, K.M. *Risk-Based Strategies for Bridge Maintenance: Proceedings of the 11th New York City Bridge Conference, 21–22 August 2023, New York, USA*; 1st ed.; CRC Press: London, 2023; ISBN 978-1-03-263829-4.
21. Xie, H.-B.; Wu, W.-J.; Wang, Y.-F. Life-Time Reliability Based Optimization of Bridge Maintenance Strategy Considering LCA and LCC. *Journal of Cleaner Production* **2018**, *176*, 36–45, doi:10.1016/j.jclepro.2017.12.123.
22. Matos, J.; Fernandes, S.; Tran Quang, M.; Nguyen, Q.; Baron, E.; Dang, S. Developing a Comprehensive Quality Control Framework for Roadway Bridge Management: A Case Study Approach Using Key Performance Indicators. *Applied Sciences* **2023**, *13*, 7985, doi:10.3390/app13137985.
23. Yousof Gholipour; Mohsen Zare; Majid Vaziri Sereshk; Yasser Gholipour A Comprehensive Review of Maintenance Strategies: From Reactive to Proactive Approaches. *CAC* **2025**, *26*, 70–83, doi:10.61841/ca-c.70-83.
24. Cheikh, K.; Boudi, E.M.; Rabi, R.; Mokhliss, H. Balancing the Maintenance Strategies to Making Decisions Using Monte Carlo Method. *MethodsX* **2024**, *13*, 102819, doi:10.1016/j.mex.2024.102819.
25. Syrkov, A.V.; Krutikov, O.V. Optimization of the Life Cycle of the Bridge to Russky Island in Vladivostok by Means of Risk Analysis and Monitoring. *Automation in Industry* **2012**, 45–50.
26. *Research Report: Analysis of National and Interstate Regulatory Documents for the Operation and Technical Diagnostics of Cable-Stayed Systems (in Russian)*; 2020; p. 162;.
27. *Acceptance of Stay Cable Systems Using Prestressing Steels. Recommendations*; fib Bulletin; fib, 2019;
28. *Eurocode 3 – Design of Steel Structures. Part 1-11: Design of Structures with Tension Components*, EN 1993-1-11:2006; **2006**.
29. *Surveillance et Entretien Des Ouvrages d'art. 2ème Partie. Fascicule 34-2. Ponts à Haubans.*; 2008;
30. *Cable Stays. Recommendations of French Inter-Ministerial Commission on Prestressing*; Setra: Service d'Études Techniques des Routes et Autoroutes., 2002;

31. *Inspection and Maintenance of Bridge Stay Cable Systems: A Synthesis of Highway Practice*; National Cooperative Highway Research Program, 2005;
32. Proske, D. *Bridge Collapse Frequencies versus Failure Probabilities*; Springer, 2018;
33. Calvi, G.M.; Moratti, M.; O'Reilly, G.J. Once upon a Time in Italy: The Tale of the Morandi Bridge. *Structural Engineering International* **2019**, *29*, 198–216, doi:10.1080/10168664.2018.1558033.
34. GOST R 58137-2018. *Public Highways. Guide for Risk Assessment During Life Cycle*; **2018**.
35. GOST R 59629-2021. *Public Highways. Cable Systems of Bridge Structures. Requirements for Operation*; **2021**.
36. GOST R 59943-2021. *Public Highways. Bridge Structure Monitoring Systems. Design Rules*; **2021**.
37. SP 274.1325800.2016. *Bridges. Monitoring of Technical Condition*; **2016**.
38. SP 79.13330.2012. *SNiP 3.06.07-86. Bridges and Pipes. Rules for Inspection and Testing*; **2012**.
39. ODM 218.4.001-2008. *Methodological Recommendations for the Organization of Inspection and Testing of Bridge Structures on Highways*; **2008**.
40. GOST R 55612-2013. *Non-Destructive Magnetic Testing. Terms and Definitions*; **2018**.
41. RD 03-348-00. *Methodological Instructions for Magnetic Defectoscopy of Steel Ropes. Basic Provisions* 2015.
42. GOST 20415-82. *Non-Destructive Testing. Acoustic Methods. General Provisions*; **1983**.
43. Wit, M.; Hovhanessian, G. Defect Detection in Strand Wires within the Anchorage Area of High Tensioned Cables. In *Proceedings of the IABSE Conference: Structural Engineering: Providing Solutions to Global Challenges*, Geneva, Switzerland; 2015; pp. 1408–1411.
44. *JCSS Probabilistic Model Code. Part I – Basis of Design*; Joint Committee on Structural Safety, 2001; Vol. 1; ISBN 978-3-909386-79-6.
45. Ormando, C.; Lucaferri, V.; Giocoli, A.; Clemente, P.; Buffarini, G.; Tofani, A. Index of Attention for a Simplified Condition Assessment and Classification of Bridges. *Infrastructures* **2024**, *9*, 125, doi:10.3390/infrastructures9080125.
46. Kozak, N.; Matos, J.C.; Rudakov, I.; Zolotov, V.; Zobova, M. Reliability of Composite Bridge Superstructures with Fatigue-Degraded Shear Connectors. *Structural Engineering International* **2026**, TSEI 2676160, doi:10.1080/10168664.2026.2676160.
47. Pallante, L.; Meriggi, P.; D'Amico, F.; Gagliardi, V.; Napolitano, A.; Paolacci, F.; Quinci, G.; Lorello, M.; Felice, G. de An Integrated Data-Driven System for Digital Bridge Management. *Buildings* **2024**, *14*, doi:10.3390/buildings14010253.
48. Tan, Z.; Gou, H.; Li, W.; Peng, Y.; Wang, J.; Pu, Q.; Bao, Y. Digital Twin-Based Cyber-Physical System for Intelligent Monitoring and Predictive Operation of Long-Span High-Speed Railway Arch Bridges. *Structures* **2025**, *82*, 110609, doi:10.1016/j.istruc.2025.110609.
49. Zorochkin, O. Reliability Assessment Methodology for Steel-Concrete Composite Structures of Road Bridges on Public Highways. Master Thesis, Saint Petersburg State University of Architecture and Civil Engineering: St. Petersburg, Russia, 2026.

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