UDC 624.21 **doi:10.31650/2707-3068-2024-28-35-45**

ANALYTICAL REVIEW OF THE METHODS OF INSPECTION AND PLANNING THE REPAIR OF REINFORCED CONCRETE AND METAL BRIDGES

Talavira G.M., PhD, Associate Professor,
hennadii.talavira@npp.nau.edu.ua, ORCID 0000-0002-5089-1775
Vizir A.S., student
anhelinavizir@gmail.com, ORCID 0000-0002-0763-997X
National Aviation University
Talavira O.G., engineer
tl12man@gmail.com, ORCID 0009-0005-2259-1766
National Aviation University

Abstract. The article analyzes the factors that affect the service life of bridge structures. Based on the practical recommendations of foreign project institutions, the principles of monitoring the state of bridges and their maintenance were determined. The expediency of survey strategies for the expansion of domestic regulatory recommendations for bridge repair and maintenance has been clarified.

General scientific methods are used, such as analysis, systematization, generalization, comparison. The article examines the current norms and standards of Ukraine, the materials of international legislative documents in the field of road infrastructure. Remote analysis of objects: scientific publications and articles became the empirical basis for conducting scientific work.

The article examines the peculiarities of bridge inspection implementation and maintenance planning. The main decisions regarding effective management of the network of bridge structures and control of their operational condition are outlined. A number of Ukrainian and foreign sources dealing with this problem have been studied. In order to create an idea about the procedure of repair work, the world experience of the procedure for carrying out bridge inspections, the systematization of assessing the condition and urgency of repairs, the level of inspection and its periodicity, and also analyzed the methods aimed at increasing the durability of specific elements of bridges were studied. It was found that a rational and systematic inspection of the condition of bridge structures is a cost-effective way to ensure its functionality.

Key words: bridge inspection, maintenance, repair, service life, defect, condition assessment system, road infrastructure.

Introduction. The network of bridge structures plays a critically important role in the transport infrastructure and development of the national economy. Physical wear and tear of the main structures of bridge structures is an inevitable mechanism that mostly occurs under the influence of significant operating loads.

Bridges are a key element of the road network. They are strategically located over natural or other obstacles, so any failure of the bridge can restrict road traffic with further losses to the local community. Although the focus is always on new bridges, it should be determined that the existing bridge network needs to be managed through technical upgrades and repairs.

Bridges are a valuable asset that needs constant, careful maintenance in the most cost-effective way.

Bridge replacement is a more expensive option compared to repair and can lead to economic losses. In addition, it can affect the environment and cause overloading of nearby infrastructure. These factors make the repair and strengthening of bridge structures a topical issue for all states. The main fundamental indicators in evaluating the correct inspection and subsequent repair work are safety, repair time and cost-effectiveness.

In order to preserve the optimal operational characteristics of bridges during their service life, it is necessary to carry out regular inspections in order to monitor the progress of wear.

Analysis of previous research. The main documents in the normative base of Ukraine are DBN V.2.3-22:2009 "Bridges and pipes. Basic design requirements"[1], which establishes the basic requirements for the design of new, reconstruction and overhaul of existing permanent bridges, and DSTU 9181:2022 "Instructions for evaluating and forecasting the technical condition of road bridges" [2], which takes into account the shortcomings of the current model expert assessment and forecasting of the technical condition of bridge elements, as well as the latest model of expert rating assessment of the technical condition of the bridge crossing, taking into account the modern scientific approach to the operation of structures, is proposed.

Methods for evaluating various road bridges in use are covered in "Bridge inspectors reference manual", Washington, U.S. Department of Transportation [3], which presents improved bridge inspection methods and includes modern inspection equipment.

The article [4] highlights a study containing a critical comparative analysis of bridge inspection and maintenance strategies applied in Indonesia, Japan, and the United States of America. The study demonstrates the inspection categories and the bridge condition assessment system.

In the course of the research, a number of other sources were studied, in particular, [5], [6] and [7].

The aim of the research. The purpose of this article is to define practical recommendations regarding the procedure for carrying out technical inspection and repair of bridges based on the experience of domestic and international scientific institutions.

Results and discussion. The success of any bridge inspection and maintenance program depends on the reporting system, as the results of the report are included in the design and estimate documentation and repair work is carried out. Accurate record keeping allows the bridge inspection engineer to:

- develop a service plan;
- check the effect of repairs on the intensity of traffic;
- evaluate the bearing capacity of elements of bridge structures;
- monitor changes in the structural integrity of the bridge.

The records of the report on the state of bridges, as a rule, should become an integral part of the "bridge information system", the purpose of which is to provide the necessary amount of information about each bridge for effective planning of further monitoring of the state of structures. It is important that this documentation is kept for reference throughout the life of the bridge. Therefore, the "information system of bridges" should be developed electronically using VIM technologies [6].

The manual [5] provides detailed information about the data that can be recorded and entered into a single system:

- general information about the bridge;
- executive drawings;
- inspection forms, reports, photos and diagrams (condition history);
- records of repair work and history of maintenance costs.

Inspection, testing and monitoring of bridges is an integral part of the management system and a key factor in achieving the lowest operating cost and ensuring an adequate level of maintenance. As stated in [6], in order for bridge inspections to be effective, it is important to have:

- relevant terms for various types of inspections;
- appropriate equipment and machinery;
- consistency in the management of data and records;
- appropriately trained personnel;
- effective quality control processes.

The types of bridge inspections generally fall into three categories: routine inspection, in-depth inspection, and special inspection.

The structure of data collection during the current inspection includes the recording of defects that affect the functionality of the bridge and the collection of data on the tested elements of the bridge structures. The data collection framework for the in-depth review includes capturing the need for items that have undergone physical wear and tear and require higher-level monitoring and inspection. A special inspection is a type of inspection that is carried out on an as-needed basis. For example, when it is necessary to test the material and evaluate durability, or to collect specific data that were not obtained during previous reviews due to their unavailability [6].

Visual inspection is a common method of determining the condition of the bridge and its elements. Table 1 shows indicative criteria by which the state of the bridge can be assessed.

Table 1

Condition State	**Description**
Concrete components	
1	• The components have minor fine cracking due to corroding reinforcement but there should be no shear cracking or spalling of the concrete. • The component shows only minor scaling or efflorescence having no effect on strength.
2	• The components may have fine flexural and/or shear cracking. • Longitudinal cracking along the bottom of the beams due to reinforcement corrosion may be of fine size with minor spalling • Construction joints opening.
3	• Flexural cracking and shear cracking may be medium sized. • Longitudinal cracking may be medium along the bottom of the beams due to reinforcement corrosion and there may be large spalls with delaminated cover concrete. • Scaling and efflorescence are prevalent.
4	• Flexural and shear cracking may be heavy with medium cracking along joints. • Severe spalling or delamination of the of the beams components is occurring, with heavy corrosion of the reinforcement • The component may be beginning to lose shape due to movement of a footing
Steel components	
1	• The protective coating system is sound with only minor chalking, peeling, or curling of paint. There are no exposed metal surfaces. • All weld, bolts, or rivets are in good condition, with no signs of weld cracks, or movement of plates or sections of the component evident.;
2	• Rust spotting of the protective coating system to 5% of the component surface area is occurring and the protective coating system is no longer effective. No corrosion or section loss has occurred. • All welds or bolts are in good condition with no cracking, corrosion, or loose bolts.
3	• Some surface pitting is present and active corrosion is occurring in isolated areas, but no loss of a whole area is occurring to affect the strength of the component. • Protective coating system has broken down with surface rusting to 10% of component area and pitting present in several locations. • Nuts and bolts may be corroding but are still tight. No cracking of welds has occurred. • Impact damage to component is evident and has minor effect on the component’s stiffness or alignment.
4	• Corrosion is well advanced • Welds cracks are visible. Nuts or bolts are severely corroded, and possibly no longer functioning to full capacity.

Maintenance criteria may trigger either maintenance to correct minor defects or major capital work such as component replacement.

Current inspection is performed for components that are visible and available for inspection from the ground. These checks do not require access to bridges to be restricted or closed. Defects that may be detected during the current inspection include road surface defects, missing bolts, corrosion, erosion, and erosion of embankments.

According to the structure of the display of defects, the following states of technical intervention can be distinguished [7]:

• urgent – non-standard maintenance is required in the short term to prevent further degradation of components;

• high priority – unscheduled maintenance must be completed within 12 months due to severe wear and tear and necessary to maintain component longevity;

• medium priority – non-standard maintenance should be completed within 2 years due to structural elements showing progressive wear;

• low priority - non-standard maintenance must be completed within 4 years due to the fact that structural elements begin to show not so progressive changes in reducing durability;

• monitor – the change in wear rate is minimal and in isolated locations, but has a predictable effect on durability.

An unscheduled routine inspection should be carried out when, for example, a traffic accident has occurred that could alter the structural integrity of the bridge. An in-depth inspection is the inspection that provides the most value from a bridge management perspective. Such checks are carried out by specially trained personnel on a cyclical basis. An in-depth review includes reporting on the condition of major bridge elements, photographs of the structure, and requesting detailed engineering studies of the elements when warranted by accidental damage or apparent rapid changes in structural condition. The results of the in-depth inspection can be used to track the condition of bridge components over time to allow for the appropriate timing of maintenance and to provide recommendations for the next inspection requirements [7].

The advantage of defect mapping is the speed of tracking the deterioration of defects over time, while the disadvantages are the initial cost of mapping and the need for additional training of inspectors.

Special inspections are conducted for complex and unique structures that require special knowledge or equipment to accurately determine the condition of the bridge. This type of inspection includes:

• detailed technical examination;

• underwater inspections;

• inspections of hard-to-reach places.

The need for specialized equipment is usually required for:

1) safe access to the workplace and reducing the risk of injury during the inspection (any activity that affects the roadway must have a traffic management plan);

2) work at height (to gain full access to all components of the bridge, as a rule, you can use ladders, cranes, rigging equipment, scaffolding);

3) work on or under water (a boat or barge may be needed for work on water; underwater inspections are carried out by divers or remotely controlled underwater vehicles);

4) work in a confined space (use unmanned aerial vehicles or ground vehicles that may contain robotic equipment).

If the visual inspection is not enough for complete information about the condition of the bridges, testing is carried out. Testing is one of the main stages of the examination. Testing can be classified into non-destructive and destructive.

Non-destructive testing can include ultrasonic control. Destructive testing includes intrusive tests, such as drilling holes, to determine a condition inside a structure that cannot be detected by normal visual inspection.

Table 2 lists the most common testing methods for assessing the condition of the bridge.

Table 2

Test Name	Principle	Application	Advantages/ Limitations
Integrity and Structural Performance			
Visual Inspection	Observe, classify, and document the appearance of distress and defects on exposed surfaces of the structure. Map distress and defects.	Surface defects such as cracking, spalling, leaching, erosion, or construction defects.	Simplest and least expensive; extensive information can be gathered from visual inspection to give a preliminary indication of the condition of the structure and allow formulation of a subsequent testing program. Does not cover areas not visible.
Delamination Survey	Tap the concrete surface using a light hammer to identify delaminated concrete through a 'hollow' impact sound.	Assessment and location and extent of discontinuity in the cover concrete, which is substantially separated, but not completely detached, from the concrete.	Low cost; quick; no instrumentation needed; easy; portable; can measure large areas; can identify a variety of additional information (hardness, voids, peeling etc.). Indicative only; need access to surface; depths of around 100 mm; non-specific; inconsistent results; requires further tests to confirm results; not good for thin components; cannot define deep voids.
Ground Penetrating Radar (GPR)	Radio frequency waves from radar transmitter are directed into the material. The waves propagate through the material until a boundary of different electrical characteristic is encountered. Then part of the incident energy is reflected and the remainder travels across the boundary at a new velocity. The reflected (echo) wave is picked up by a receiver. The	It can detect several parameters within concrete structures such as the location of reinforcement, the depth of cover, the location of voids, location of cracks, in situ density and moisture content variations.	Good identification of reinforcing bars, prestressing strands, cable ducts, zones of varying moisture content and thickness of slabs, and a fair assessment of delamination and large voids in concrete. Quick; non-disruptive; nondestructive; good coverage. Expensive; cannot see through areas with heavily congested steel; does not differentiate between defect types: reliant upon operator judgement;

	transducer is drawn over a surface and forms a continuous profile of the substrate below		complicated equipment setup; specialist experience in data interpretation. Additional tests needed to confirm results
Concrete Properties Affecting Durability and Deterioration			
Cement Content and Type	Cement content by calcium oxide – analysis for hardened concrete	Assess concrete quality.	Quick; low cost; reliable. Reliability is affected by knowledge of cement chemistry and aggregates related to the structure. Experience and correlation with other test data is needed for interpretation.
Chloride and Sulfate Content	The sample is dissolved in hot nitric acid to provide a solution from which aliquots may be tested for chloride or sulfate content.	Assess susceptibility of concrete to sulfate attack. Provide input data for chloride induced corrosion service life modelling.	Low cost; quick; direct results, reliable; accurate. Interpretation requires experience. Need to drill holes or collect core samples and repair.
Identification of Presence of Alkali Silica Reaction (ASR)	Application of acidic uranyl acetate solution forming a complex with components of ASR gel that fluoresces under UV-C light.	Identification of likely presence of ASR.	Quick and relatively inexpensive. Requires experience in interpretation, especially in structures exposed to marine or other high salinity conditions.
Corrosion of Embedded Steel			
Carbonation Depth	Apply phenolphthalein solution uniformly to freshly exposed concrete surface and measure the depth of carbonation (absence of colour).	Assess corrosion protection value of concrete with depth and susceptibility of steel reinforcement to corrosion due to carbonation. Carbonation depth is used to assess whether the reinforcement is likely to have depassivated leading to corrosion. The results can be used to model concrete carbonation rates to estimate remaining service life.	Low cost; quick; direct results, easy; evaluation; reliable; accurate. Need trained people; need to drill holes or collect core samples and repair; only freshly exposed surface can be tested; powder contamination can affect the results; one location only; not valid for concrete with large aggregate unless a representative area of surface can be tested.
Corrosion Potential (Electrochemical, Half-cell)	Measure the potential difference (voltage) between the steel reinforcement and	Identify region or regions in a reinforced concrete structure where there is	Quick; easy; objective data; relatively low cost; large areas can be measured; strong

	a standard reference electrode; the measured voltage provides an indication of the likelihood that corrosion is occurring in the reinforcement.	a high probability that corrosion is occurring at the time of the measurement.	indicator of corrosion potential; can result in timely intervention; helps to determine type of repair needed; allows quantification of area likely to be corroding. Need trained people; specialist interpretation required; requires complementary testing to verify results; calibration is required before using the results; can only measure potentials on first layer of reinforcement; needs connection to reinforcement, with subsequent repairs required; influenced by humidity in the concrete; cannot be used when it is cold, <5°C;
Steel Structures Deterioration			
Steel Structures Deterioration	Very high frequency sound waves are passed through the metal structure under test. The waves are reflected by either a defect or from the far surface of the member.	Ultrasonic flaw detection methods can detect voids and defects within a metal section and are best viewed as being complementary methods. Identifies most weld discontinuities including cracks, slag, lack of fusion; accurate metal thickness measurements possible.	Most sensitive to planar type defects; immediate results; portable; provides relatively rapid, and cost effective, defect detection; detect defects that are too small, or incorrectly oriented, for detection by radiography; requires access from one surface only; when correctly calibrated and employed, permits the detection of extremely small defects. Irregular, rough, nonhomogeneous, very small or thin components are difficult to test; surface condition should be suitable for coupling of transducer; requires highly skilled operators to use the equipment and to interpret the results.

Availability of qualified and experienced inspectors is of paramount importance for bridge inspections. Determining the condition of the bridge and, in particular, assessing any signs of its deterioration, rely on the reports of inspectors, who are required to describe in detail any deficiencies noted in the structure.

To maintain a high level of reporting, a structured and continuous training program for bridge inspection inspectors is required to learn, maintain and improve fundamental bridge inspection skills.

The benefits of successfully implementing a training and certification program are that it will certify inspectors in specific disciplines and will serve to impart the basic knowledge necessary for accurate reporting.

Also, to improve the work of inspectors, a mandatory vision test is proposed, as well as psychological tests for fear of heights or fear of traffic.

In many countries, separate units deal with the issue of bridge inspection and maintenance. So, for example, in Thailand it is the Department of Highways (TDOH), under the Ministry of Transport; in the USA - the Department of Transportation (DOT), which is in each state, as well as the Federal Highway Administration (FHWA), which is responsible for the national bridge inspection plan [9].

In Ukraine, in 2023, the Bridge Inspection Commission was established by the Ministry of Infrastructure. As a result of their work, it was found that 24% of bridges are in critical condition. In addition, in its report, the Commission proposed to use the Analytical Expert Bridge Management System (AESUM) for the formation of strategic and tactical steps for the restoration of bridges and maintaining their operability through scientifically based recommendations to ensure the maximum efficiency of repair works and optimize the use of financial resources [10].

After the inspection of the condition of the bridge, a repair plan is drawn up, which varies from the removal of minor damage to the replacement of worn components [11].

Repair is a complex of works, the main purpose of which is to maintain the load-bearing capacity and geometric parameters within limits close to the initial state.

In civil construction, depending on the complexity of repair work, current and major repairs are distinguished.

Mainly, current repairs are carried out by operating organizations. At the same time, the movement of vehicles may be partially restricted. Current repair consists of preventive and unforeseen works [12].

Preventive repair work is the basis of normal operation of the bridge structure to ensure project durability and minimize capital repair costs. For such works, a plan is drawn up in advance with defined deadlines, scope of work and cost. Examples of preventive works:

- pothole repair of the coating;
- partial repair of deformation seams;
- sparging and injection of cracks;
- protection of reinforcement and concrete from corrosion;
- cleaning of drainage pipes.

Unpredictable works are works that eliminate accidental damages and defects formed during operation. Such repair consists in the elimination of the consequences of a traffic accident (for example, repair of railings), elimination of washouts due to an unforeseen flood, etc.

Major repairs are carried out according to projects developed by specialized organizations. At the same time, the movement of vehicles may be partially limited or completely blocked. Selective and comprehensive overhaul are distinguished [12].

Selective repair work is work on the replacement of some elements of the bridge structure (for example, replacement of the guard rail, waterproofing of the carriageway). Complex repairs are works with simultaneous performance of all types of selective work (for example, replacement of supporting parts).

In order to prevent physical wear and tear of the main structures of bridge structures and to maintain their normative service life defined in [2], it is necessary to regularly carry out preventive ongoing repairs in the specified terms. The periodicity of their execution is given in the table. 3.

The age of the structure, the state of the environment, and the intensity of traffic of vehicles are factors that affect the actual repair intervals of bridge elements.

To take into account the degree of these factors, it is customary to use correction coefficients: K1 - a coefficient that takes into account the regional location of the bridge structure; K2 is a coefficient, the value of which depends on the actual service life; K3 is a coefficient that depends on the category of the road and takes into account the intensity of vehicle traffic.

The value of the estimated repair period is found by the formula:

$$T=T_n \times K_1 \times K_2 \times K_3$$

where T_n is the normative maintenance period according to the table. 3.

Table 3

The period of repair work on bridges	
Repairs	**Periodicity**
Roadway	
Repair of irregularities, potholes, cracks in the coating	1
Repair of expansion joints of the compensatory type, repair of waterproofing in the area of expansion joints, on sidewalks, along the fence on the roadway with a width of 70 cm	5
Replacement of steel sliding sheets	10
Replacement of the metal barrier fence	20
New surface treatment	2
Replacement of pavements	5
Painting the metal handrail	5
Replacement of asphalt concrete pavement	7
Reinforced concrete span structures	
Sparing of cracks, sinks, chips	1
Restoration of the protective layer (in prestressed beams)	10/20
Repair of transverse union	10
Applying a protective coating	8
Supports and supporting parts	
Filling of cracks in concrete and stone supports	20
Filling of cracks and chips in reinforced concrete supports	25
Repair of undercarriage	25
Painting and lubrication of supporting parts	3
Cementing and shotcrete	40
Connecting the bridge with the embankment	
Replacement of transitional plates	25
Backfilling of embankments and cones	2 years after construction and every 7 years
Restoration of areas of cones	6
Coastal cleaning and restoration	10

When planning repair work, it is necessary to take into account their cost. Analyzing the graph of the dependence of operating costs, which were determined as a percentage of the cost of repair work to the cost of construction of the structure by years of operation (Fig. 1), we can conclude that the costs of repair work range from 1% to 27% and cannot be constant annually [11].

The peak of costs falls on the 30th year of the reinforced concrete bridge's existence. This is explained by the need for significant repair of reinforced concrete beams in these years.

Also, operating costs depend on the length of the runs, i.e. with an increase in the length of the run, the costs attributed to 1 run. m of the running structure are increasing, but the peak costs remain the same over the years [11].

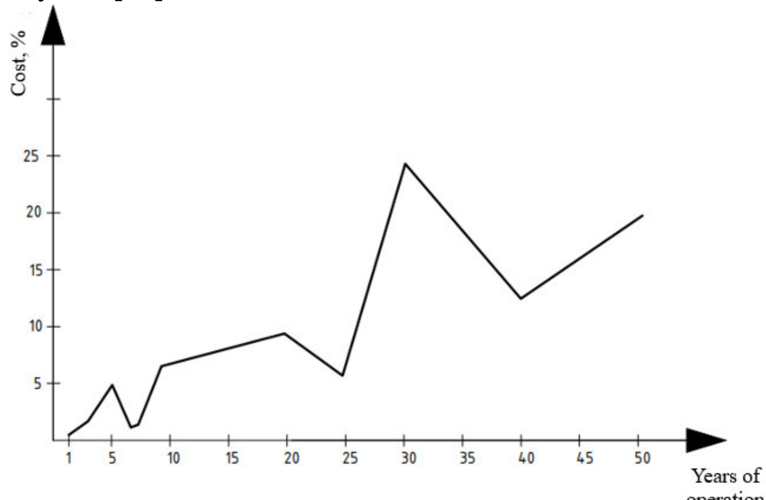

Fig. 1. Schedule of changes in the cost of repair works

Conclusions. It was found that the planning of repair works of existing bridge structures must begin with their survey.

An inspection and maintenance program has been found to provide a better understanding of bridge condition to ensure maximum performance of bridge structures throughout their lifetime.

It should be noted that for a productive inspection of bridges, there is a need to create a single manual on bridge inspection to standardize and simplify the monitoring procedure, which will be applied throughout the country.

It is also determined that the key to successful maintenance is a qualified and experienced inspector, whose reports are used for further planning of repairs.

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АНАЛІТИЧНИЙ ОГЛЯД МЕТОДІВ ОБСТЕЖЕННЯ ТА ПЛАНУВАННЯ РЕМОНТУ ЗАЛІЗОБЕТОННИХ ТА МЕТАЛЕВИХ МОСТІВ

Талавіра Г.М., к.т.н., доцент,
hennadii.talavira@npp.nau.edu.ua, ORCID 0000-0002-5089-1775
Візір А.С., студентка,
anhelinavizir@gmail.com, ORCID 0000-0002-0763-997X
Національний авіаційний університет
Талавіра О.Г., інженер
tl12man@gmail.com, ORCID 0009-0005-2259-1766
Національний авіаційний університет

Анотація. У статті проаналізувано чинники, які впливають на термін служби мостових споруд. Визначено на основі практичних рекомендацій зарубіжних проєктних установ принципи моніторингу стану мостів та їх технічного обслуговування. З'ясувано доцільність стратегій обстеження для розширення вітчизняних нормативних рекомендацій щодо ремонту та утримання мостів.

Використано загально-наукові методи, такі як аналіз, систематизація, узагальнення, порівняння. У статті розглянуто діючі норми та стандарти України, матеріали світових законодавчих документів у галузі дорожньої інфраструктури. Емпіричною базою для проведення наукової роботи став дистанційний аналіз об'єктів: наукових публікацій та статей.

В статті досліджено особливості впровадження інспекції мостів та планування технічного обслуговування. Окреслено основні рішення щодо ефективного управління мережею мостових споруд та контролю їхнього експлуатаційного стану. Опрацьовано низку українських та закордонних джерел, що розглядають дану проблему. Для створення уяви про процедуру ремонтних робіт, було вивчено світовий досвід порядку проведення обстежень мостів, систематизації оцінки стану та терміновості ремонту, рівень перевірки та її періодичність, а також проаналізовано методи, спрямовані на збільшення довговічності конкретних елементів мостів. Виявлено, що раціональний та систематичний огляд стану мостових конструкцій є економічно ефективним способом забезпечення його функціональності.

Ключові слова: обстеження мостів, технічне обслуговування, ремонт, термін служби, дефект, система оцінки стану, дорожня інфраструктура.