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Recent developments in bridge scour monitoring in the UK and Ireland

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Abstract

Scour, the erosion of sediment around bridge foundations caused by water flow, poses a serious threat to structural stability, particularly during high-water events such as floods. Network Rail has identified scour as the leading cause of bridge failures in the UK over the past century, with approximately 4500 structures currently at risk. This paper underscores the urgent need for enhanced scour monitoring, a need that is increasingly important due to the rising frequency of flood events driven by climate change. It critically reviews recent advances in scour monitoring technologies, focusing on systems that measure scour depth or detect structural dynamic changes. The review highlights emerging methods including interferometric synthetic aperture radar, water penetrating radar, electromagnetic probes, underwater sonar scanning, as well as vibration-based techniques such as natural frequency, mode shape and operating deflection shape analysis, and indirect approaches using drive-by monitoring, computer vision, and satellite-based synthetic aperture radar. These advancements are needed for developing more resilient infrastructure management strategies and the paper includes a comparative evaluation of the benefits and limitations of each approach.

Keywords

Bridge Scour Monitoring, Structural Health Monitoring, Climate Change

1 Introduction

Bridge infrastructure plays a crucial role in maintaining connectivity, supporting economic activity, and safeguarding public safety across both urban and rural landscapes [1]. In the UK and Ireland, where thousands of bridges span rivers and estuaries, ensuring the stability and safety of these assets is of paramount importance. However, climate change is presenting new challenges to the durability of transport infrastructure, particularly through increased rainfall intensity and more frequent flooding events. One of the most significant threats arising from these hydrological changes is scour, the erosion of sediment around bridge foundations caused by fast-flowing water. Scour can seriously compromise structural integrity and is recognized as the leading cause of bridge collapse in the UK, with over 4500 structures currently identified by Network Rail as being at risk [2].

As extreme weather events become more frequent, the need for real-time, accurate, and cost-effective scour monitoring solutions is becoming apparent. Traditional visual inspections are often inadequate, especially during or immediately after flood events [3]. This has driven a surge in research into advanced scour monitoring technologies. In recent years, researchers in the UK and Ireland have

investigated a variety of innovative solutions, ranging from instrumentation-based systems, such as sonar sensors, tilt meters, and fibre optic cables, to vibration-based techniques that detect scour by monitoring changes in a bridge's dynamic response.

Although several previous reviews have explored bridge scour monitoring from global or thematic perspectives [4–6], many have concentrated on individual technologies—such as vibration-based methods [7], sensor network architectures [8], or data-driven analytical frameworks [9]—and often generalize findings across international contexts [10–11]. As a result, these reviews frequently overlook region-specific challenges that are unique to the UK and Ireland, including distinct climatic patterns, ageing infrastructure, varied hydrological conditions, and local asset management practices.

This review addresses that gap by synthesising research and case studies specific to the UK and Ireland, offering a contextualised understanding of how both conventional and emerging scour monitoring systems are being applied in practice. It examines recent developments in instrumentation-based and vibration-based monitoring techniques and also explores novel approaches such as drive-by monitoring, which uses vehicle-mounted sensors to

passively assess bridge condition during routine traffic. By consolidating current advancements, this review aims to provide a comprehensive overview of monitoring practices, highlight promising directions for future research, and support the shift towards smarter, more resilient infrastructure management.

2 Methodology

To support this review, a scientometric analysis was conducted to investigate the research landscape of bridge scour monitoring, with a particular focus on developments in the UK and Ireland. The methodology closely follows the approach adopted by Fayyad et al. [12] in their scientometric study on drone-based structural health monitoring. The analysis was carried out using the Scopus database (<https://www.scopus.com/>), with the search restricted to documents containing the phrase “bridge AND scour AND monitoring” search within the “Article title, Abstract, Keywords”.

The initial search returned a total of 551 documents. To narrow the scope to region-specific contributions, the results were filtered to include only studies affiliated with institutions or research projects based in the UK and Ireland, specifically, those with at least one co-author affiliated with an institution in the UK or Ireland, yielding 86 documents. One paper, which focused on scour monitoring for a tidal turbine rather than a bridge structure, was excluded from further analysis.

The final dataset comprised 85 relevant publications. These were reviewed to identify key research trends, methodological advancements, and the emergence of new technologies in scour monitoring. This analysis provided both a quantitative and qualitative foundation for evaluating instrumentation-based and vibration-based approaches, while also highlighting emerging research directions within the UK and Ireland.

3 Instrumentation-based approaches

Instrumentation-based approaches for bridge scour monitoring have attracted considerable attention due to their ability to deliver continuous, real-time, and quantitative assessments of scour depth and progression [13]. In contrast to traditional visual inspections—which are often subjective, time-consuming, and restricted to accessible conditions—these methods employ sensor technologies installed on or near critical bridge components to directly or indirectly detect scour-related changes. A wide range of sensor types are utilised, including electromagnetic probes, sonar systems, fibre optic sensors, and accelerometers. These technologies enable the detection of subsurface erosion, foundation exposure, and structural response variations induced by scour, thereby supporting timely and informed decision-making by asset managers.

The integration of such sensors within advanced data acquisition and processing systems further enhances the reliability and accuracy of scour assessments, particularly during adverse conditions such as flood events, when manual inspections are either impractical or unsafe. Although challenges remain—such as high installation costs, sensor durability, and the complexity of data interpreta-

tion—instrumentation-based monitoring represents a significant step towards proactive and data-driven infrastructure management. This section reviews the current state of instrumentation techniques, outlining their working principles, practical applications, benefits, and limitations. Several representative examples are discussed to illustrate their role in modern scour risk mitigation strategies.

Interferometric Synthetic Aperture Radar (InSAR):

Selvakumaran et al. [14–15] demonstrate the use of InSAR for monitoring scour-prone bridges, using the partial collapse of Tadcaster Bridge in England on 29 December 2015 as a case study. By analysing 48 TerraSAR-X satellite images with the Small Baseline Subset InSAR technique, the study detected significant ground movement at the failure site more than a month prior to the collapse, highlighting InSAR's potential as an early warning tool in scour-related structural health monitoring.

Water Penetrating Radar (WPR):

WPR, a modified form of Ground-Penetrating Radar adapted for underwater use, is a non-destructive technique for detecting subsurface features such as scour holes and sediment layers. Campbell et al. [16] investigate the application of integrated geophysical methods, primarily WPR, complemented by sonar, to assess scour and infill around bridge foundations. While sonar is effective at imaging the water-sediment interface, WPR performs particularly well in shallow freshwater environments, where sonar may be hindered by sediment, vegetation, or gas interference. High-quality WPR data, collected from small vessels, enabled bathymetric mapping and the identification of potential scour-prone areas. The study highlights the benefits of combining WPR and sonar for the accurate assessment of underwater bridge structures.

Electromagnetic probes:

Building on principles similar to those of water-penetrating radar, some researchers, such as Michalis et al. [17] develop custom sensor probes incorporating integrated electromagnetic sensors to detect changes in dielectric permittivity near bridge foundations. Their novel wireless sensor system is designed to measure scour depth and sediment deposition in real time. It can distinguish between in situ and re-deposited sediments, providing valuable insight into the foundation's load-bearing capacity. Validated through laboratory flume experiments and static scour simulations, the sensors demonstrated high sensitivity and cost-effectiveness for real-time monitoring. Maroni et al. [18] present a field-deployed scour monitoring system using smart electromagnetic probes installed at the A76 200 Bridge in Scotland. These sensors continuously recorded scour progression over a period of nearly two years, successfully capturing bed level changes and validating measurements during peak flood events. This method offers a practical and reliable alternative to diver-based inspections, enhancing safety and ensuring more consistent structural monitoring.

Underwater sonar scanning:

Unlike water-penetrating radar, Rogers et al. [19] propose a novel rotating-head sonar profiler mounted on a sliding mechanism to map complex scour hole geometries around vertical cylinders simulating bridge piers. This scanning technique captures high-density elevation data with a precision of approxi-

mately $\pm 1.5\text{--}2$ mm, enabling quasi-non-invasive measurements suitable for clear-water conditions. Experimental trials using cylinders of varying diameters showed that monitoring the entire scour hole over time—rather than focusing solely on maximum depth—provides deeper insights into the development of scour. Notably, the study found that scour volume scales with the cube of the maximum depth, following three distinct linear regimes. The third regime, referred to as the "crossover point," signifies a transition where turbulent energy production plateaus and erosion rates begin to decline. This stage is characterised by a balance between sediment erosion at the pier front and deposition along the sides. Identifying this crossover point may help define key temporal and spatial scales, contributing to more accurate scour modelling and prediction.

Other instrumentation-based techniques: In addition to the core technologies discussed above, a wide range of other instrumentation-based techniques are being explored in both laboratory and field settings to enhance scour monitoring capabilities. Porter et al. [20] evaluate photogrammetry, echosounder profiling, and calibrated piles for measuring scour depth during experiments, introducing an underwater camera system that delivers accurate quantitative results alongside valuable qualitative imagery. Pregnolato et al. [21] assess eight different technologies for railway bridge scour monitoring in the UK, ranging from direct sensors—such as sonar, fibre Bragg grating sensors, and electromagnetic probes—to indirect devices including micro-electro-mechanical systems (MEMS) tilt sensors and ultrasonic water level sensors. Similarly, Xu et al. [22] introduce instrumented particles to detect potential destabilisation of rip-rap protection layers under extreme flows, demonstrating their potential to identify entrainment mechanisms through flume-based studies.

Recent developments also highlight the potential of low-cost or non-contact approaches. Perugini et al. [23] propose an image velocimetry-based method integrated with scour models for critical bridge monitoring, while Koursari et al. [24] present a "Smart Bridge" framework for environmental hazard detection using real-time sensors monitoring water surface levels and scour conditions. Yousefpour et al. [25] advance the integration of artificial intelligence and machine learning with real-time monitoring systems, achieving early scour forecasting through deep learning and ensemble models trained on actual sensor data.

Other studies focus on improving scour resilience through numerical and experimental analyses. Kripakaran et al. [26] employ computational fluid dynamics-based force prediction combined with structural modelling of masonry bridges under flood conditions. Bento et al. [27] carry out long-term inspections of the Doan Hung Bridge in Vietnam to track the evolution of riverbed scour. Ebrahimi et al. [28] examine the influence of debris geometry and elevation on scour at sharp-nosed piers, offering insights into debris-induced scour under shallow flow conditions. Long-standing research by Paice and Hey [29] verifies the effectiveness of scour mitigation schemes through field deployment, while Yaqoobi et al. [30] compare existing scour monitoring rating frameworks, emphasising the need for

bridge-specific structural health monitoring system specifications.

Together, these diverse yet complementary studies enrich the understanding of instrumentation-based approaches to scour monitoring. They underscore the shift from traditional inspections to data-driven, sensor-enhanced, and model-integrated systems that support early warnings, guide mitigation efforts, and strengthen the overall resilience of critical infrastructure facing increasing hydrological pressures.

4 Vibration-based approaches

Vibration-based approaches to bridge scour monitoring are receiving growing attention due to their ability to detect structural changes resulting from foundation erosion [31]. These methods are generally classified into direct and indirect techniques, each offering distinct advantages and practical challenges. This section reviews both direct and indirect vibration-based scour monitoring techniques, outlining their operating principles, benefits, and limitations. Collectively, these methods play a vital role in early scour detection and contribute to more effective risk management in bridge infrastructure.

4.1 Direct methods

Direct vibration-based methods involve installing sensors—such as accelerometers, strain gauges, and displacement transducers—directly onto the bridge structure to measure its dynamic response. These sensors monitor changes in natural frequencies, mode shapes, and damping characteristics resulting from scour-related degradation of the foundation. This sensing approach provides high-resolution, real-time data capable of detecting early signs of scour damage. Examples include the deployment of accelerometer arrays on bridge piers to capture vibration changes during flood events, as well as modal testing conducted before and after scour incidents to quantify alterations in structural behaviour. While these methods offer precise diagnostics, they require on-site installation and regular maintenance. Some classic and notable studies are noted in the following paragraphs.

Prendergast et al. [32–34] are among the first to investigate the influence of scour on the natural frequencies of pile foundations. Both laboratory and field tests demonstrate that increasing scour hole depth results in a clear reduction in a pile's natural frequency. By integrating geotechnical analysis with simplified finite element models, Prendergast et al. propose a method for estimating scour depth based on observed frequency shifts. In a subsequent study, a vehicle–bridge–soil interaction model illustrates that dynamic responses from passing vehicles can capture these frequency changes, enabling scour detection without the need for direct inspection. More recently, Kariyawasam et al. [35–36] at the University of Cambridge develop a centrifuge-based testing programme to investigate how scour affects the natural frequency of various bridge foundation types. The results reveal up to a 40% change in natural frequency with a 30% loss of embedment when testing a scaled integral bridge model and three foundation types: shallow pad, pile bent, and monopile. Frequency is more sensitive to scour in deep foundations than in shallow foundations, and global scour has a

slightly greater impact than local scour. These findings further reinforce the feasibility of using natural frequency as a reliable indicator for both local and global scour in bridges, particularly those supported by deep foundations.

Mode shape-based approaches are also actively explored for scour monitoring. Malekjafarian et al. [37] propose a technique that identifies scour in multi-span bridges with shallow foundations by tracking changes in pier mode shape amplitudes. Using frequency domain decomposition, the first global mode shape is extracted from acceleration data, and mean-normalised mode shapes are calculated to compare individual piers with the average response of the others. Tests on a scaled four-span model demonstrate that increases in mean-normalised mode shape values correlate with reductions in foundation stiffness, enabling both the detection and localisation of scour. Building on this, mode shape ratios provide an even more sensitive indicator of scour progression [38]. Derived from structural vibration data, these ratios show greater responsiveness to scour than natural frequencies alone. Notably, they behave in contrast to temperature effects—rising with heat while frequencies decline—highlighting their potential for isolating thermal influences from scour-related changes. This makes mode shape ratios a more robust tool for reliable scour detection under variable environmental conditions. Khan et al. [39] introduce a re-deployable sensor strategy for estimating mode shapes using a limited number of sensors that are sequentially moved across different sections of a bridge. This approach enables the reconstruction of global mode shapes and the identification of changes in support stiffness. Field trials conducted on a railway bridge in Ireland confirm the effectiveness of the technique, both before and after structural rehabilitation.

Similar to mode shape-based methods, OBrien et al. [40] propose a novel approach that employs wavelet-based operating deflection shapes to detect scour-induced stiffness loss in multi-span bridges. The technique involves simulating a four-span simply supported bridge subjected to excitations from a fleet of half-car model vehicles. Scour is modelled as a reduction in foundation stiffness at one or more piers. Acceleration data collected at each support are averaged over time and transformed into the frequency-spatial domain to estimate the operating deflection shapes. By comparing these shapes between healthy and damaged states, a damage indicator is derived that effectively localises scour sites across a range of natural frequencies.

Other studies investigate natural frequencies and mode shapes in combination. For example, Scozzese et al. [41–43] carry out numerical simulations to examine flood-induced scour of masonry arch bridges, focusing on the collapse of two spans of the Rubbianello Bridge in Central Italy during a flood event in 2013. The study aims to replicate the failure mechanism using a detailed 3D non-linear model, calibrated with data from Operational Modal Analysis of the remaining structure. Simulations assess both the scour depth that triggered the collapse and the sensitivity of the bridge's dynamic properties—namely natural frequencies and mode shapes—to scour progression. The findings highlight the potential of Operational Modal Analysis as an effective tool for scour monitoring in

masonry bridges and offer valuable insight into the structural failure process.

Following this approach, Scozzese et al. [44–47] conduct detailed numerical studies using a refined 3D Abaqus model to investigate how various structural and dynamic parameters respond to different levels of scour in a masonry arch bridge prototype. The analysis considers both kinematic responses—such as displacements, rotations, and diagonal strains—and modal characteristics, including natural frequencies and transverse mode shapes. By simulating progressive scour scenarios, the study identifies the failure mechanisms most commonly associated with piers, spandrel walls, and arches. Key parameters demonstrating high sensitivity to scour are highlighted, along with threshold values relevant to risk assessment. These findings offer valuable guidance for developing effective scour monitoring strategies for masonry arch bridges.

Beyond the core studies outlined above, several additional works have contributed valuable insights into direct vibration-based scour monitoring. Real-time estimation techniques have been developed using vibration data from in-service bridges, enabling probabilistic assessments of scour progression during flood events [48]. Changes in dynamic response before and after repair interventions have also proven effective for diagnosing foundation conditions and verifying the success of rehabilitation measures [49–50]. Advanced modal analysis approaches—including decentralised and re-deployable sensor configurations—have been validated in both laboratory and full-scale settings for detecting stiffness loss caused by scour [51].

Furthermore, novel sensing technologies such as gyroscopes [52], wireless monitoring systems [53], and energy-harvesting devices [54] have broadened the available toolkit for vibration-based monitoring. Field deployments across the UK and Ireland have helped demonstrate the practicality and reliability of these methods under real-world operational conditions [55–56].

Recent efforts have also incorporated coda wave interferometry to monitor changes in the elastic properties of masonry bridges [57], along with dynamic simulation frameworks—such as vehicle-bridge-soil interaction models—to predict the effects of scour [58]. Both full-scale and numerical investigations have examined scour impacts on shallow and deep foundations [59–60], as well as structural performance under combined scour and traffic loading in masonry arch bridges [61]. Collectively, these studies highlight the increasing maturity and versatility of vibration-based scour monitoring, particularly when integrated with advanced modelling and sensor innovations. They reinforce its value as a key component of proactive asset management strategies for safeguarding vulnerable bridge infrastructure.

4.2 Indirect methods

Indirect vibration-based methods infer scour damage using sensors that are not physically attached to the bridge structure. A common approach involves vehicle-mounted accelerometers that capture the dynamic response of vehicles as they cross the bridge—an approach widely known as drive-by monitoring. This technique has recently gained significant interest for bridge structural health monitoring

(SHM) applications [62–63], as it can reveal changes in bridge stiffness associated with scour. In addition, remote sensing technologies—such as satellite-based radar and computer vision systems—are used to analyse surface vibrations or structural displacements from a distance. These non-contact methods enable the monitoring of larger bridge networks while minimising installation requirements. However, while indirect techniques offer broad applicability, they often require advanced data processing to distinguish scour effects from other structural or environmental influences.

Drive-by Techniques for Indirect Scour Monitoring:

With specific regard to the application of drive-by techniques to bridge scour monitoring, Fitzgerald et al. [64] investigate a numerical approach that utilises bogie acceleration data from passing trains to detect scour. In their study, scour is modelled as a localised reduction in pier stiffness. Simulated acceleration signals are processed using continuous wavelet transform, and average wavelet coefficients are calculated over multiple train runs. A scour indicator is then defined based on the difference in average coefficients between healthy and scoured bridge conditions. The method is validated through a blind test, in which only the acceleration data is provided to selected authors, who successfully identify the scour state without prior information. The results demonstrate that the proposed indicator is effective under typical train operating conditions, highlighting the potential of drive-by monitoring for practical scour detection.

Tan et al. [65] propose a drive-by bridge health monitoring approach that utilises mode shapes extracted from the acceleration response of a vehicle-mounted sensor to detect both local and global bridge damage, including scour. Using a simplified vehicle–bridge interaction model with a moving sprung mass, a closed-form solution is derived to estimate the bridge's mode shape from a single on-vehicle accelerometer. A damage index, based on deviations in the extracted mode shape, is introduced to identify both the presence and severity of damage. The method is validated through numerical simulations and two laboratory experiments, demonstrating its effectiveness in detecting foundation scour as well as other forms of structural damage. The study also investigates the influence of vehicle speed and measurement noise on detection accuracy, offering insights into the robustness and potential for practical deployment of the technique.

Zhang et al. [66] address the challenge of detecting scour in bridges with surface foundations, where underwater conditions often hinder the use of direct instrumentation. To overcome this limitation, they propose a drive-by structural health monitoring method that relies on vehicle acceleration data collected at operational speeds. Using wavelet transforms, the study finds that wavelet energy increases with the severity of scour damage. However, environmental factors such as sensor noise can obscure these signals. To enhance robustness, the authors introduce a statistical-wavelet approach capable of identifying both the presence and location of scour. The method is validated through numerical simulations and laboratory experiments, demonstrating strong potential for reliable, indirect scour detection.

McGeown et al. [67] introduce a novel bridge monitoring approach that utilises the pitch (rotational motion) of a passing vehicle as an indicator of foundation scour. The method is evaluated through two-dimensional vehicle–bridge interaction simulations, where scour is modelled as a reduction in pier stiffness. A train comprising multiple carriages with varying masses and speeds is simulated crossing the bridge, and changes in vehicle pitch consistently indicate the presence of scour. The approach is further validated in a scaled laboratory experiment involving a tractor–trailer crossing a four-span bridge, with scour simulated by modifying foundation spring stiffness. In both the numerical simulations and physical tests, clear pitch deviations are observed under scoured conditions, demonstrating the method's potential for practical scour detection.

Tola et al. [68–70] have developed a series of indirect drive-by monitoring techniques for detecting bridge scour using instrumented railway vehicles. In one approach [68], the concept of the bridge's apparent profile is introduced, derived from finite element modelling and Moving Reference Influence Lines. By comparing apparent profiles measured from in-service trains with model predictions, the study estimates changes in foundation stiffness—where reductions indicate potential scour. In a follow-up study [69], displacement data from a six-axle vehicle is used in conjunction with a vehicle–bridge interaction model, to simulate scour conditions. A cross-entropy optimisation algorithm is employed to match measured and simulated responses, with variations in stiffness serving as indicators of damage. This technique is further extended using machine learning to enable network-level monitoring. Most recently, the team [70] utilised the Rail Infrastructure Alignment Acquisition system—a mobile platform mounted on trains—to collect displacement data. By comparing healthy bridge measurements with synthetically generated scour scenarios, the system is shown to be capable of detecting scour and supporting targeted maintenance planning. Collectively, these studies demonstrate scalable, cost-effective solutions for early scour detection in railway infrastructure.

Computer Vision Approaches for Indirect Scour Detection:

Beyond drive-by approaches, computer vision technology also presents a promising solution for indirect vibration-based scour monitoring. Millar et al. [71] introduce a vision-based system, ArchIMEDES, designed to assess scour conditions in real time by analysing structural response patterns under varying support conditions. Laboratory tests on a FlexiArch bridge model subjected to controlled scour scenarios, establish a clear correlation between load-carrying behaviour and foundation degradation, forming the basis of an algorithm used to estimate scour severity. This system facilitates early detection of critical scour developments, thereby enhancing bridge safety. Further investigations by Millar and colleagues [72–73] examine the interaction between bed scour and structural performance, focusing on how load–response characteristics evolve as scour progresses towards failure thresholds. These studies contribute to a more nuanced understanding of the relationship between scour and structural integrity, reinforcing the potential of vision-based monitoring for timely risk assessment.

Satellite-Based Synthetic Aperture Radar (SAR) for Remote Scour Assessment: Satellite-based SAR has also been investigated as an indirect method for structural monitoring. Biondi et al. [74] introduce a novel approach that utilises satellite SAR data to estimate micro-motions of critical infrastructure and extract modal properties—such as natural frequencies and mode shapes—for early damage detection. Applied to the Morandi Bridge in Genoa, Italy, the method identified abnormal vibrational patterns in the period preceding the collapse. This study underscores the potential of remote sensing technologies for large-scale infrastructure monitoring and pre-collapse assessment, offering a non-intrusive alternative to on-site instrumentation.

5 Discussion and Conclusion

Bridge scour remains the leading cause of bridge failures worldwide, posing a significant threat to infrastructure safety, economic resilience, and public welfare. Effective monitoring and early detection are therefore critical for mitigating these risks. This review has examined two primary technological approaches to scour monitoring: instrumentation-based and vibration-based methods, each offering distinct advantages and limitations.

Instrumentation-based techniques deliver accurate, real-time measurements of scour depth or hydraulic conditions through sensors such as sonar, fibre optics, and electromagnetic probes. Although highly precise, these systems often entail substantial installation and maintenance costs and are challenging to deploy at scale. In contrast, vibration-based methods detect changes in a bridge's dynamic response using either installed sensors or indirect systems—such as vehicle-mounted or satellite-based platforms. These techniques offer greater scalability but may lack spatial precision and typically require more complex data interpretation.

Recent advancements in machine learning and probabilistic modelling have the potential to enhance both approaches by improving data interpretation and enabling predictive maintenance strategies. A promising direction for future research lies in the development of integrated, hybrid systems that combine the strengths of both methods—striking a balance between accuracy, scalability, and cost-effectiveness in scour risk management.

Beyond detection, recent research underscores the importance of integrating monitoring data with decision-making frameworks. Approaches such as Bayesian decision analysis and value of information methods are increasingly used to assess whether structural health monitoring systems offer sufficient long-term value to justify their costs [75–78]. These tools enable infrastructure agencies to prioritise interventions and allocate resources more effectively, supporting more informed and economically sound asset management strategies.

Complementary efforts focus on risk-informed, network-level management through the use of decision support systems and Bayesian networks [79–93]. These frameworks extend insights gained from a limited number of instrumented bridges to wider infrastructure networks, accounting for spatial variability, environmental change, and

socio-economic impacts. Such integrated strategies are vital for achieving resilient infrastructure management—an area the author seeks to advance by combining monitoring data with decision analysis under uncertainty.

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