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REVIEW

REVISED Advancing bridge resilience: a review of monitoring technologies for flood-prone infrastructure

[version 2; peer review: 2 approved]

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Abstract

Floods pose a critical threat to bridge infrastructure, which plays an essential role in transportation networks and economic resilience. This review examines state-of-the-art Structural Health Monitoring (SHM) technologies tailored to mitigate flood risks, focusing on their real-world applications in flood-prone bridges. A central feature of this review is the extensive use of case studies, illustrating diverse SHM methods applied globally to monitor challenges such as debris accumulation, hydrodynamic forces, and scour—primary causes of bridge failures. These examples provide detailed insights into technologies like sonar-based devices, scour probes, photographic monitoring, rotation- and vibration-based techniques. By showcasing specific case studies—such as bridges monitored using smart magnetic rocks, Interferometric Synthetic Aperture Radar (InSAR), and fibre optic sensors—the review highlights practical outcomes, demonstrating how SHM systems enhance resilience through early detection and predictive maintenance. It also explores the challenges of implementing these systems, including environmental sensitivity, cost, and data complexity, while identifying gaps in integrating hydraulic and structural data for holistic risk assessments. This review advocates for multidisciplinary collaboration and advanced data-driven solutions, such as AI-based predictive maintenance, to address climate change impacts and increasing flood risks. By bridging cutting-edge research with real-world applications, this article provides actionable insights into scalable, adaptive SHM solutions, inspiring engineers and researchers to develop more resilient infrastructure for a changing world.

Plain Language Summary

Bridges are vital for our daily lives, connecting communities, enabling trade, and supporting emergency responses. However, floods, which are becoming more frequent and severe due to climate change, pose

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a major threat to bridge safety. This review explores how new technologies help monitor and protect bridges from damage caused by floods. It explains why bridges fail during floods, such as when fast-moving water erodes their foundations, debris piles up against them, or powerful water forces overwhelm their structure. The review highlights real-world examples from around the globe, showing how sensors, cameras, and other tools are being used to detect early signs of danger. These technologies, like sonar systems that monitor underwater erosion or cameras that track debris, provide real-time information, allowing engineers to act before a disaster occurs. The article also discusses how combining different monitoring methods with advanced data analysis, including artificial intelligence, can improve bridge safety. By focusing on practical examples and innovative solutions, this review emphasizes the importance of preparing our infrastructure for a changing climate, ensuring that bridges remain safe and reliable for generations to come.

Keywords
Structural Health Monitoring, bridge failures, resilient infrastructure, scour monitoring, hydrodynamic monitoring, debris impact on bridges, flood risk mitigation, climate change

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REVISED **Amendments from Version 1**

In this revised version, several improvements have been made based on reviewers' feedback. The Introduction has been refined for clarity by simplifying lengthy sentences. The Summary section has been revised to enhance conciseness and ensure findings are directly tied to the study's objectives.

The "Debris Impact" section now distinguishes between floating and submerged debris, incorporating findings from experimental studies on how submerged debris alters flow velocity and local scour. Formula 2 in Section 3.2 has been clarified with a comprehensive explanation of the shape factor (k), its empirical basis, and its influence on hydrodynamic force calculations.

We have added a cross-reference in Section 3.2 regarding fibre optic sensors to Table 4, where fibre optic sensing technologies are further detailed. Additionally, Table 4 has been expanded to clarify the differences between Distributed Fibre Optic Sensors (DFOS) and Fibre Bragg Gratings (FBGs) and to include an additional example of Fibre-Optic Distributed Temperature Sensing (DTS).

The discussion on float-out devices has been expanded within Section 3.3, detailing their operational mechanisms, real-world applications (e.g., SR 101 Bridge, California), and a comparison with alternative flood resilience solutions.

Table 6 has been refined to include an economic feasibility assessment. This update enhances the study's practical relevance by providing insights into the affordability and long-term sustainability of different monitoring methods.

Any further responses from the reviewers can be found at the end of the article

1. Introduction

Bridges are vital for transportation, enabling the movement of people, goods, and services while supporting economic stability, social connectivity, and disaster response. Their structural integrity is essential for maintaining these functions, as demonstrated by recent events. On September 11, 2024, the partial collapse of the Carola Bridge in Dresden, Germany, disrupted both car and ship traffic and also caused a citywide hot water outage by bursting two large district heating pipes. Fortunately, there were no victims, which would otherwise greatly increase the damage count.

Floods pose a significant risk to bridges, often causing severe damage or collapse. In the United States, data from 1992 to 2017 show that approximately 55% of bridge collapses, totalling 239 bridges, were caused by hydraulic factors, including flooding, scour, and debris accumulation[1–4]. Scour, the erosion of sediment around bridge foundations by fast-moving water, is the leading cause of hydraulic failures in shallow foundations[5,6]. The risk is not limited to the U.S.; for example, scour is recognised as the leading cause of bridge failure in the UK and Ireland, accounting for 140 railway bridge failures during 65 separate flood events between 1846 and 2013[7]. Projections indicate that due to climate change, 1 in 20 bridges in the United Kingdom will face a high risk of failure within the next 60 years[8]. In China, data from 2007 to 2015 show that floods were responsible for 44 out of 102 bridge collapses, accounting for 43.1% of failures. Of these, 17 were arch bridges (38.6% of the collapsed bridges), and 18 were beam bridges (40.9% of the collapsed bridges)[9].

According to the EM-DAT database, which tracks global natural disasters, 3,977 flood events were recorded worldwide from 2000 to 2023. While not all of these events directly affected bridges, they caused significant damage and loss of life, with 130,379 fatalities recorded over this period[10]. Figure 1b shows that while flooding follows a cyclical pattern, the frequency has increased over the last two decades.

The Paris Agreement of 2015 aims to limit global warming to well below 2°C above pre-industrial levels, keeping the increase to 1.5°C. However, under current national policies, the world is on track for a 2.8°C warming pathway[11].

Studies show a strong correlation between atmospheric warming and increased flood risk on a global scale. At 4°C of global warming, countries representing over 70% of the global

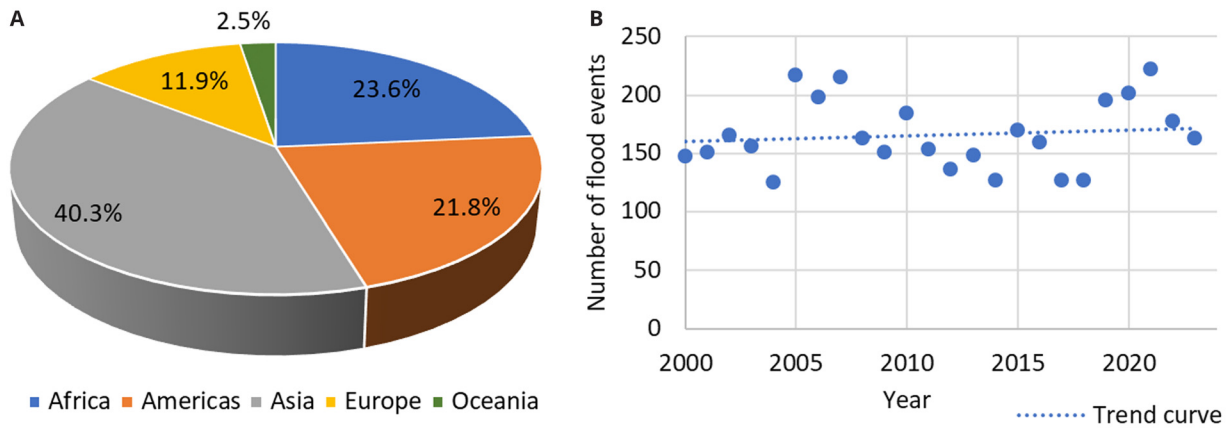

Figure 1. Worldwide flood events from 2000 to 2023, categorised by: **a**) geographic regions; **b**) annual distribution.

population and gross domestic product will face a 500% increase in flood risk. Even at 1.5°C warming, global flood risk is expected to more than double compared to 1976–2005. These changes in flood risk are unevenly distributed, with the largest increases projected for Asia, the U.S., and Europe[12,13].

As climate change leads to more frequent and intense flooding globally, bridges are increasingly at risk of damage or collapse due to hydraulic forces. Moreover, bridges in mountainous regions face particularly high structural failure risks, as steep topography amplifies water-flow intensity during flood events[14]. This escalating threat underscores the need for comprehensive monitoring and assessment of bridge structural health. Effective Structural Health Monitoring (SHM) systems are essential for identifying vulnerabilities early, allowing for timely preventive measures to reduce the likelihood of catastrophic failure. SHM systems with advanced sensors for monitoring structural changes, can offer real-time data for proactive responses during extreme floods[15–19].

The role of SHM is especially important in flood-prone regions, where SHM systems can be a vital tool for protecting infrastructure, reducing maintenance costs, and, most importantly, saving lives[20–22]. Current research on bridge monitoring focuses on the challenges of data capture and interpretation.

This review aims to provide a comprehensive evaluation of SHM technologies applied to flood-prone bridges and related challenges, highlighting their strengths, limitations, and the potential for hybrid integration to enhance infrastructure resilience under extreme conditions. The main focus is on recent advancements in SHM technologies, specifically those published since 2018, to highlight contemporary solutions for monitoring flood-prone bridges. While this approach excludes older methods, it ensures an emphasis on state-of-the-art technologies and their applicability to current and future challenges.

2. Flood-related bridge failures and risks

Floods pose significant bridge risks, causing immediate and long-term structural issues. The primary types of flood-related damage include[23]:

- Debris impacts
- Hydrodynamic forces
- Scour and erosion

While some of these risks can be mitigated through preventive measures, structural monitoring is crucial for detecting and managing vulnerabilities, particularly during extreme flood events. Human factors also contribute to flood-related bridge collapses, including[8,24–26]:

- Insufficient hydrological data for accurately estimating flood magnitudes during design.
- Lack of reliable methods for predicting scour at bridge piers.
- Inability to model and anticipate debris impact and accumulation during floods.

Moreover, inadequate maintenance and poor management practices exacerbate these risks, further heightening the vulnerability of bridges to hydraulic forces. Solutions such as flood-resilient designs, improved scour protection, and foundation reinforcements are crucial to ensure bridge stability during extreme weather events. The implementation of advanced hydrological models, debris control systems, and consistent maintenance protocols can further safeguard these critical infrastructures from failure during floods. Table 1 summarises a few recent flood-related bridge failures, highlighting the diverse impacts of flooding events on bridge infrastructure across different regions.

These incidents underscore the urgent need to account for increasingly severe flood scenarios in future bridge designs and to continuously control the existing ones during floods to prevent such catastrophic failures.

Debris impacts

Floodwaters carrying debris present serious risks to bridges, both by directly impacting the structure and by altering water flow around piers and abutments. Debris and mud flows are often characterised by high velocities, occasionally exceeding 10 m/s, and can have densities up to twice that of water[27]. Debris carried by swift currents, such as trees, rocks, and even vehicles, can collide with bridge components, exerting significant impact forces that compromise the structural integrity of the piers. Studies examining logs as floating objects have shown that their substantial mass, combined with acceleration from floodwaters, results in considerable kinetic energy upon impact. Empirical evidence highlights the dynamic behavior of logs in relation to hydraulic structures, demonstrating their potential to exert strong forces on bridge piers, increasing the risk of structural instability during flood events[28]. Smaller bridges are particularly susceptible to debris-induced damage (see Table 1, cases #8 and #14). In addition to floating debris, submerged objects such as waterlogged logs and cylindrical debris alter flow dynamics and local scour effects. Experimental studies[29] have shown that the position of submerged debris relative to the flow surface has a direct impact on scour depth. Specifically, as debris is positioned deeper in the water column (up to a relative depth of 0.5 of water column), the strength of the down-flow jet increases, leading to intensified scour around bridge piers. However, when debris is placed near the bed, it can act as a protective collar, reducing the strength of the down-flow and mitigating local scour. These findings highlight the complex role of submerged debris, which can either worsen or alleviate scouring effects depending on its position within the flow.

Debris accumulation around piers significantly intensifies hydrodynamic forces[1], which can be estimated using simplified empirical models. These models typically use flow characteristics such as water depth, width, velocity, and the size of the debris pile to calculate a drag coefficient and, consequently, the drag force acting on the debris jam[30]. This drag force on the debris pile translates into an additional load on the bridge pier, increasing the overall hydrodynamic force that the structure must withstand. Moreover, debris acts as a partial blockage, disrupting the flow and creating localised pressure

Table 1. Some recent bridge damages and collapses due to floods.

#	Bridge name, location	Date	Failure cause	Description
1	Misasa Railroad Bridge and 22 out of 94 nearby bridges, Japan[31]	July 2018	Hydrodynamic forces, and scour	Flood-induced forces nearly doubled those used in seismic design[32]. 11 bridges had collapsed, 6 had localised scour, 4 had abutment erosion, and 1 had other damage.
2	Baringin Bridge, Indonesia[33]	November 2018	Debris impact	Large wooden debris damaged the temporary support structure, causing a collapse of the bridge during its construction.
3	Jinshajiang Bridge, China[34]	November 2018	Hydrodynamic forces	Seven out of ten spans were washed away when the water rose 4 meters above the bridge deck.
4	Catalonia Bridges, Spain[2]	October 2019	Debris accumulation	Flash floods clogged bridges with debris, causing collapses and flooding in nearby areas.
5	15 bridges in Thessaly, Greece[14]	September 2020	Overflowing, debris accumulation, scour	Various damages following the Cyclone Ianos.
6	Fitzroy River Bridge, Australia	January 2023	Erosion, debris	Exceptional floods caused by rainfall equalled the past twenty years' worth in 24 hours. Floodwaters with debris washed away one of the piers, causing significant bridge damage.
7	Randklev Railway steel-truss Bridge, Norway	August 2023	Foundation failure caused by hydrodynamic forces	Despite the good condition of the bridge, approved by regular inspections, the foundation failed on the riverbed, sinking two bridge elements into the river. Traffic was suspended because of a storm warning, preventing injuries or fatalities.
8	Malo Bridge, Italy	May 2024	Debris impact	Small viaduct collapsed under debris load in floodwaters.
9	Visletto arch-type Bridge, Switzerland	June 2024	Hydrodynamic overload	River flow increased from 25 to 2,000 cubic meters per second, overwhelming the bridge.
10	Railway bridge, South Dacota, US	June 2024	Hydrodynamic forces	After heavy rainfall, floodwaters surged over the steel bridge, ultimately causing its collapse.
11	Shaanxi Bridge, China	July 2024	Scour	40-meter deck section of just 6-year-old bridge collapsed during flash floods with a maximum inflow of 1,640 cubic meters per second; 38 fatalities were reported.
12	Phong Chau Bridge, Vietnam[35]	September 2024	Scour	Intermediate support scoured during floods; 13 people missing.
13	Kinser Bridge, Tennessee, US	September 2024	Hydrodynamic forces	The bridge was swept away after the water level rose by at least 18 meters.
14	Pedestrian Bridge in Carcare, Italy	October 2024	Debris accumulation	Logs formed a blockage, increasing hydrodynamic forces and leading to damage.
15	Paiporta Bridge, Spain	October 2024	Hydrodynamic forces	Bridge destroyed in seconds; rainfall equalled a year's worth in eight hours.

variations. This blockage raises the upstream water level, increasing pressure on the bridge structure[36,37]. Simultaneously, as shown in Figure 2, the reduced flow area beneath the debris, driven by the principle of continuity, accelerates the water, increasing its erosive power and promoting local scour around the piers. This acceleration and altered flow patterns generate vortices, which further intensify the scouring effect at the bridge foundation[38–41]. The cumulative effect of debris accumulation, increased flow velocities, and intensified scour severely threaten bridge stability. If left unchecked, such conditions can lead to progressive structural damage, potentially resulting in partial or full bridge collapse, especially during extreme flood events[39].

To mitigate these risks, debris deflectors or protective barriers can be installed in front of bridge foundations. These barriers (Figure 3) deflect debris, reduce blockages, and prevent structural damage[42,43]. However, their design and placement must be carefully tailored to specific flood and debris flow conditions.

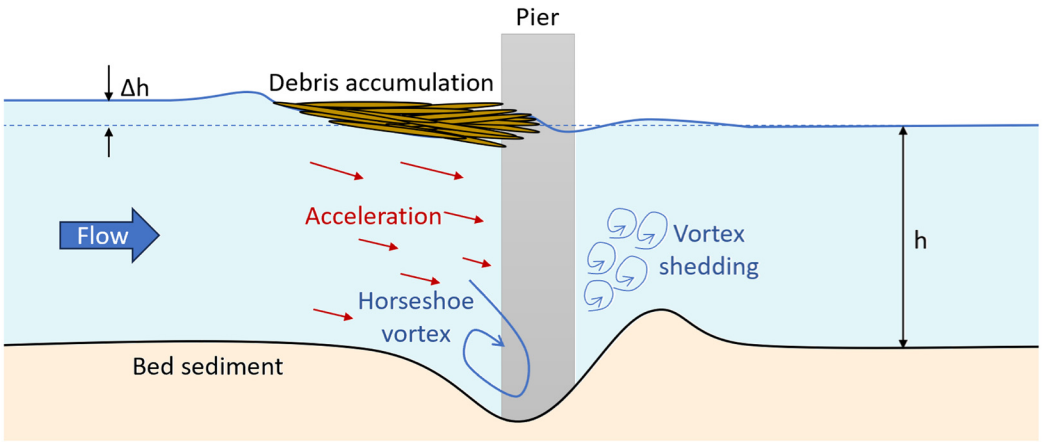

Figure 2. **Scour around bridge piers exacerbated by debris accumulation.**



Figure 3. **An example of protective measure for bridge piers, including barriers to shield against water flow and debris.**

Hydrodynamic forces

The force exerted by fast-moving floodwaters on bridges can cause structural deformations, displacements, and even collapse. This hydrodynamic failure is particularly significant for bridges with foundations such as piers with spread footings on bedrock, where scour might not be the primary failure mode[44].

Stream-crossing bridges are exposed to multiple hydrodynamic effects[45]:

- Hydrostatic forces, caused by differences in water levels on both sides of submerged bridge components (e.g., piers, deck).
- Buoyant forces, equal to the weight of the water displaced by submerged bridge structures.
- Hydrodynamic forces, including drag and lift forces.
- Overturning moments, created by uneven forces applied to the bridge.

Hydrodynamic forces during floods consist of two primary components: drag force and lift force. Drag force acts parallel to the flow, pushing the bridge downstream, while lift force acts perpendicular to the flow, either pushing the structure upward (positive lift) or downward (negative lift). For bridge decks, particularly during submersion, lift forces can threaten to lift the deck off its supports, leading to failure.

The intensity of these forces is influenced by the velocity of the water, with a quadratic relationship between hydrodynamic

forces and water flow velocity[44,46]. Additionally, hydrodynamic pressure is affected by water depth: as the depth increases, the volume of water interacting with the structure grows, increasing the pressure exerted on the bridge.

If the bridge deck becomes submerged during a flood, it faces increased horizontal forces and greater static water pressure. Submerged decks can act like dams, further increasing the load and potentially causing structural failure. Therefore, hydrodynamic deck failure can occur on all bridges, regardless of foundation type[44].

Accurately estimating flood-induced hydrodynamic loads, especially on bridge superstructures, is critical for designing flood-resilient bridges[1,47]. For instance, bridge design standards in various countries, such as the Eurocode (EN 1991-1-6), U.S. AASHTO, and Australian AS 5100 codes, account for similar types of forces[45].

Scour and erosion

Scour is the process of erosion and removal of sediment from around bridge foundations, piers, or abutments caused by the increased velocity of water flow near the structure. It is the leading cause of failures for bridges with shallow foundations during floods, as it undermines the stability of a bridge by removing the supporting material, which weakens the foundations and can potentially lead to collapse. As scour progresses, it increases the unsupported length of the foundation, reducing its lateral stiffness, strength, and buckling resistance, while also lowering the factor of safety against structural instability[48].

Interestingly, both bridges recently damaged by scour (Table 1, cases #11 and #12) featured round-shaped and oblong-shaped piers, respectively. Round-nose designs are generally considered the standard baseline for scour resistance.

Research indicates that pier shape significantly impacts scour depth, with correction factors providing a measurable indicator of a shape's effectiveness against scour[49–51]. Square and rectangular shapes are the least effective, as they increase turbulence and vortex intensity, leading to more severe sediment removal around the foundation. In contrast, shapes with a sharp nose and curved body, such as lenticular piers, reduce turbulence, allowing for smoother water flow around the pier and minimising vortex formation and sediment removal. These designs are typically associated with enhanced scour resistance. Correction factors (CF) for various pier shapes are summarised in Figure 4[52,53].

Despite round-nose optimised designs, piers still experienced significant scour damage, underscoring that even with favourable geometry, bridges can remain vulnerable to extreme flood conditions. So, the use of scour protection systems and continuous monitoring are always recommended.

Scour is particularly dangerous because it often occurs below the waterline, making it difficult to detect without proper monitoring systems. A notable example of this occurred in November 2000 when a major flood, affected a state road bridge crossing the Po River near Borgoforte, Italy. Three months after the flood, a bathymetric survey revealed a 15-meter-deep scour hole near two central piers in the river's main channel. It is believed that the scour depths could have been even greater during the flood event than what was recorded post-event[54].

Traditional deterministic methods provide qualitative indicators of scour risk by combining the likelihood and consequences of failure, but they do not offer precise measures of scour vulnerability[55]. Numerous studies focus on the development of precise predictive models for scour depth estimation. For example, one recent study investigated a prediction method for the temporal evolution of local scour depth at bridge piers during floods, based on the law of conservation of energy[56]. Another approach utilised Bayesian Networks to propagate information from scour probes and gauging stations, updating the probabilistic distribution of scour at unmonitored bridge foundations across a network[57].

High-importance bridges require regular visual inspections, especially after hazards[57,58]. However, the challenge with scour is that it is often only detectable after a flood, and sediment deposition during the event can obscure the extent of damage. This makes visual inspections prone to errors, complicating the accurate assessment of scour and increasing the potential for human error in interpretation[8,59].

Similar to scour but more widespread, erosion involves the gradual loss of soil and sediment surrounding the bridge's structural component foundations. Over time, this can weaken the support structures, leading to instability, misalignment, or collapse. Riverbanks and embankments near bridges are particularly susceptible to erosion during prolonged floods or high-flow events.

Mitigation measures such as pilings, riprap, revetment, gabion mattresses (rock or other material used to protect foundations from erosion)[8,60], scour protection devices, and real-time

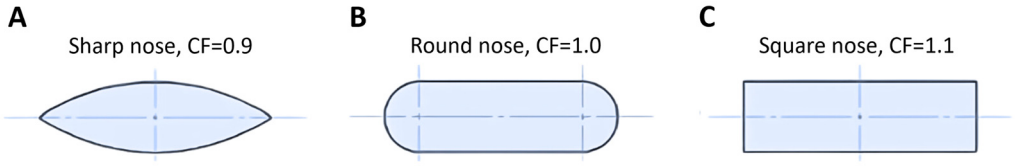

Figure 4. Correction factors (CF) for various pier shapes: **a**) lenticular, **b**) oblong, **c**) rectangular.

monitoring systems are essential for identifying and managing these scour-associated risks. Furthermore, understanding local hydrological conditions and flood patterns is crucial for designing effective protective measures that can withstand the long-term effects of scour and erosion.

3. SHM technologies and methods for remote monitoring bridges during and after floods

SHM plays a vital role in minimising flood risks by providing remote monitoring, enabling early warnings, and supporting structural evaluations during and after floods. While preventive measures, such as barriers, help mitigate debris impact, SHM systems are invaluable for detecting unexpected stress or vibrations from collisions. These systems enable rapid assessments and timely interventions, such as temporarily closing the bridge to prevent further damage. Similarly, real-time monitoring of hydrodynamic forces during extreme weather events allows proactive responses to prevent failures. Due to scour long-term and progressive nature, advanced SHM systems are essential for detecting early signs of scour, the leading cause of flood-related bridge failures. Scour and erosion detection strategies can be classified as direct and indirect, depending on whether detection and measuring are performed directly on scour at a particular location or if they measure the effects of scour on the bridge[61,62]. Technologies like sonar, scour probes, float-out devices and smart rocks provide direct insights into sediment movement, while vibration-based sensors, tiltmeters, and Interferometric Synthetic Aperture Radar (InSAR) offer indirect clues by monitoring the structure's response and environmental conditions. While direct methods can detect the presence or progression of a scour hole, an additional SHM system is required to assess the overall condition of the bridge[63]. The following sections discuss and summarise recent advancements in monitoring technologies, along with illustrative case studies.

3.1. Monitoring of debris accumulation by photographic imagery

Numerous studies investigated the effects of debris accumulation, taking into account the shape and position of the debris accumulation, on both final scour depth and horizontal loads acting on the pier[64–66], evaluating these effects as significant. According to Eurocode (EN 1991-1-6, 2005) the impact of the debris (F_{deb}) can be calculated by the formula (1):

$$F_{deb} = k_{deb} \times A_{deb} \times v_{wa}^2, \qquad (1)$$

where k_{deb} is debris density parameter (kg/m^2), A_{deb} is area of obstruction presented by debris (m^2), and v_{wa} is mean speed of the water (m/s).

In the case of fully submerged abutment of single span arch bridge, floating debris impact loads on the superstructure can be more than 6 times higher than the combination of hydrostatic and hydrodynamic loads for the case of no debris[67].

The most common approach to monitoring debris accumulation upstream of piers is through photographic or video capture, providing a direct and effective method to assess the extent of debris buildup and its timing[68]. This method was implemented in the monitoring of the multi-span brick masonry Candia Bridge over the Sesia River[41] and the Borgoforte Road Bridge over the Po River[48], both located in Italy, using video cameras. For monitoring the Aurence Bridge in France[69], a HIK Vision 4 MP WDR fixed network camera was used to observe the sensors. Following a flood event, the camera confirmed that a dead tree had twisted the sensor setup, which explained the abnormal data readings.

Image processing techniques, such as calculating the average grey level for the region of interest in each video frame, can further enhance debris monitoring capabilities[70]. When paired with Artificial Intelligence (AI), cameras can alert operators to critical levels of debris accumulation that may require intervention. Additionally, high-speed cameras enable high-resolution image analysis, which can be used to measure the velocity of debris flow[71].

3.2. Hydrodynamic force monitoring

Hydrodynamic forces are traditionally considered during the design phase, but monitoring these forces can be essential during operation to provide timely alerts if water levels and forces approach or exceed design thresholds. Such monitoring enables informed decisions regarding bridge closure, evacuation, or urgent maintenance. According to Eurocode (EN 1991-1-6, 2005), the drag force (F_D) on structures such as bridge piers can be calculated by the following formula:

$$F_D = 0.5 \times k \times \rho_{wa} \times h \times b \times v_{wa}^2, \qquad (2)$$

where k is shape factor, which accounts for the influence of the pier's cross-sectional geometry on the hydrodynamic drag force, ρ_{wa} is density of water (kg/m^3), h is water depth, excluding local scour depth (m), b is the width of the object facing the flow (m), and v_{wa} is mean speed of the water, averaged over the depth (m/s).

The shape factor k is an empirical coefficient derived from experimental and analytical studies to reflect how different cross-sectional geometries affect drag forces. According to Eurocode (EN 1991-1-6, 2005), commonly used values include:

- k=1.44 for objects with a square or rectangular horizontal cross-section,
- k=0.70 for objects with a circular horizontal cross-section.

The shape factor influences the calculated hydrodynamic force by modifying the drag coefficient based on the pier's geometry. Structures with sharp corners (e.g., square piers) experience higher drag forces due to flow separation and turbulence, whereas streamlined shapes (e.g., circular piers) reduce resistance, leading to lower drag. This distinction is crucial when evaluating bridge stability under high-flow conditions, as an underestimated shape factor could lead to non-conservative force estimates, while an overestimated value could result in unnecessary reinforcement costs.

In practical monitoring applications, hydrodynamic drag forces can be measured directly using load cells and pressure sensors or inferred indirectly from water flow data from various other sensors (Figure 5).

Direct measurements provide valuable data on flow-induced forces impacting the structure, though these sensors can be sensitive to structural vibrations and environmental conditions like temperature changes.

Several studies have explored methods to measure hydrodynamic pressure. For example, hydrodynamic forces on substructures have been evaluated in small-scale laboratory experiments and with computational fluid dynamics models[45]. This study used the load cells and torque sensors, such as the Interface 3A100-100N-D11 load cell with a 100 N capacity and the Interface MRT2 torque cell with a 10 N-m capacity, to capture force and moment loads in three directions. A customised mounting frame was created to house both the load and torque cells, isolating the instruments from external vibrations and positioning them well above the water surface to prevent submersion-related damage. The load cells were connected to the submerged deck via vertical supports, which transfer the load from the submerged element. Notably, the load cell is also suitable for submerged applications when enclosed in a waterproof housing, as specified by the manufacturer.

For direct measurements of hydrodynamic pressure, pressure sensors or transducers are typically mounted on structural surfaces and are often manufactured specifically for submersion applications. Numerous laboratory studies have examined wave-structure interactions using pressure sensors for measuring wave loads. Examples include studies on wave force impacts on rectangular structures using standard pressure sensors[72], hydrodynamic forces from solitary waves interacting with submerged square barriers using pressure transducers[73], and pressure distributions caused by green water phenomena on structures, measured with Kistler 4043A2 piezo-resistive pressure sensors, which capture static and dynamic pressures within a range of 0 to 2 bars[74].

Pressure transducers, however, provide only single-point measurements, making it difficult to capture a comprehensive pressure field. As a result, multiple sensors are typically deployed to create a pressure map across the structure's surface. These sensors also require careful calibration to ensure accuracy, which can be complex and time-consuming.

Fibre optic sensing is a rapidly growing field, offering advantages over traditional electrical strain gauges, such as high sensitivity, lightweight design, immunity to electromagnetic interference, long-distance detection, and ease of installation[75–77]. A common type, fibre Bragg gratings (FBGs), are widely used in civil engineering for strain and temperature point-based data monitoring (for examples see Table 4). FBGs contain microstructures that reflect specific wavelengths of light, known as Bragg wavelengths, which shift when the fibre experiences strain or temperature changes. This shift allows precise monitoring of structural changes[75,78]. FBG sensors used for strain measurements are sensitive to temperature changes, necessitating reference sensors to isolate strain data from temperature variations[79–81]. FBGs can also measure parameters like tilt, pressure, displacement, and vibration, though their high cost and limited end-user familiarity are drawbacks[76,82]. However, studies suggest FBGs could be a cost-effective solution for monitoring small- to medium-span bridges due to their reliability and low maintenance needs[76,77].

Some studies have demonstrated FBGs for flow monitoring, using deformations caused by hydrodynamic pressures in single- and two-phase flows, as well as to measure substructure cross-sectional load for a semi-submersible floating wind turbine[83,84].

Both load cells and FBG sensors require robust protective housing and secure mounting to withstand harsh environmental conditions and protect against potential debris impact.

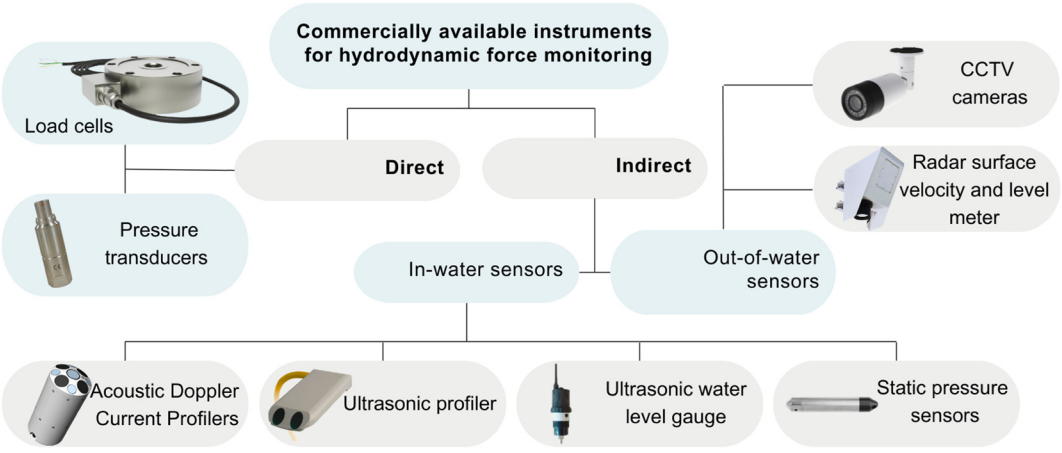

Figure 5. Overview of commercial instruments for hydrodynamic force and flow monitoring.

There remains a gap in the literature concerning real-life applications of direct hydrodynamic force measurements in bridge monitoring systems.

For flow data, including water depth and velocity, acoustic-based instruments, especially Acoustic Doppler Current Profilers (ADCPs), are widely used. ADCPs, which emit sonar pulses, measure the speed and direction of water flow at different depths, offering precise flow velocity and water level data. However, ADCPs are costly, and acoustic instruments used for velocity measurement are vulnerable to debris damage. Their performance may also be limited in high-turbidity or flood conditions, as shown in studies monitoring the Rucúe Bridge in Chile with ADCPs[85] and the Aurence Bridge in France, where ultrasonic water level gauges and profilers were used[69].

Ultrasonic water level gauges measure water level by emitting sound waves and calculating the time taken for these waves to travel to the water surface and back. Since the speed of sound is affected by air temperature, temperature variations can cause measurement errors. So, temperature compensation is necessary for ultrasonic water level sensors[86].

There is another type of pressure sensor, designed for static or slowly varying pressure environments, primarily used for water level and depth measurements. These sensors are employed in hydrodynamic monitoring by submerging them at a specific point in the water column to measure absolute pressure, which is the sum of water pressure and atmospheric pressure. The pressure readings are converted to water depth, as illustrated in the Rucúe Bridge monitoring project[85]. However, the accuracy of pressure sensors can be affected by factors like water temperature, salinity, and sediment content, making them more suitable for controlled environments.

For non-contact water level monitoring, instruments installed above the water surface, such as radar level sensors and closed-circuit television (CCTV) cameras, provide alternatives with fewer environmental vulnerabilities. Radar level sensors emit microwave pulses that reflect off the water surface, with the time delay of the return pulse used to calculate the water level. This method has proven effective in bridge monitoring studies, such as at the A71 motorway viaduct over the Loire River in Orléans, France[87].

Considering the vulnerability of the in-water sensors, and that the mean flow velocity can be estimated from the surface velocity from an out-of-water sensor, which is a more robust solution in a flood context, the non-contact sensors for flow surface velocity can be of interest. For example, a hydrologic station (RSS-2-300 WL) installed on the bridge over Aggitis River, near Simvoli Dam in Greece, has an integrated radar surface velocity and level meter for contactless measurements of surface flow velocity and water level at the current location[88].

Similarly, CCTV cameras are increasingly used in real-time floodwater monitoring, providing visual assessments of water levels and flow patterns. For instance, the Da-Chia Bridge in Taiwan employs real-time CCTV imaging in combination with the Mask R-CNN deep learning model to monitor changes in water levels around bridge structures during floods[89]. In another application, monitoring the hydrodynamic behaviour of the Tara channel near Taranto, Italy, a camera was installed to capture water flow at the bridge base. Using particle image velocimetry (PIV), this setup enabled accurate detection of flow patterns and velocities[90].

From the non-intrusive PIV data, velocity fields can be used to compute the pressure field by solving the Poisson pressure equation derived from the Navier-Stokes equations. This PIV-based pressure measurement method, validated in controlled studies on wave force measurements on rectangular structures[72], offers a promising approach for calculating hydrodynamic forces acting on bridge structures.

When available, flow data from nearby hydrometric stations offer a reliable reference point, correlating well with on-site sensor data. As seen in the A71 motorway viaduct monitoring study, nearby stations provide useful context, especially for long-term monitoring or during periods when on-site sensor readings may be less accurate[87].

Table 2 presents a comprehensive comparison of various indirect water flow monitoring techniques applied in real-world cases, highlighting their underlying principles, key parameters measured, deployment locations, advantages, limitations, and documented applications in case studies.

3.3. Monitoring of scour and erosion

Most formulas for estimating scour depth are empirical, reflecting the complexity of interactions between flowing water, sediment properties, and structural elements. These interactions depend on various factors, including sediment type (cohesive or non-cohesive), flow conditions (e.g., clear water or live bed), and the geometry of the structure (e.g., pier or abutment shape)[69]. Over 25 different methods for predicting equilibrium scour depth are summarised in the Appendix of 91.

The primary limitations of scour depth formulas lie in their reliance on simplifications and limited datasets, reducing their accuracy and applicability to real-world conditions. Consequently, direct measurements of scour depth remain the most reliable approach. Figure 6 schematically illustrates the various instruments used to monitor scour and the associated structural responses, which are discussed in greater detail in the following sections.

In addition to scour depth direct measurements, emerging probabilistic frameworks for scour hazard assessment are gaining attention. These frameworks use data from monitoring systems to update the probability distribution of scour depth at the foundations of bridge networks[57].

To improve monitoring, it is recommended to measure water depth upstream of bridges to identify areas of greatest scour,

Table 2. Comparison of indirect water flow data monitoring techniques on real bridges.

Technology	Principle	Key parameters measured	Location	Pros	Cons	Application in real case studies
ADCP	Doppler effect (acoustic waves)	Flow velocity and direction, water level	In-water	High-precision, multi-depth profiling	High cost Vulnerable to debris Limited in flood conditions	Rucúe Bridge, Chile[85]; A71 Viaduct, France[87]
Ultrasonic profiler (e.g. Ub-flow F156)	Ultrasonic waves	Flow velocity profiles, water depth	In-water	Detailed profiling at multiple depths	Sensitive to air bubbles, debris interference	Aurence Bridge, France[69]
Ultrasonic water level gauge (e.g. LNU06V3-82-3G)	Ultrasonic waves (echo measurement)	Water level	In-water	Non-contact, reliable in various conditions	Requires temperature compensation	Aurence Bridge, France[69]
Pressure sensors (e.g. HOBO U20)	Hydrostatic pressure	Water depth	In-water	Affordable, compact	Affected by temperature, salinity, sediment	Rucúe Bridge, Chile[85]
Radar surface velocity and level meter (e.g. RSS-2-300 WL, Valeport VRS-20)	Microwave reflection	Flow velocity, water level	Out-of-water	Non-contact, reliable in harsh conditions	Limited to surface-level data at the current location	Simvoli Dam, Greece[88]; A71 Viaduct, France[87]
CCTV cameras	Visual imaging	Water level, debris presence, flow velocity	Out-of-water	Real-time flood tracking, cost-effective	Limited in poor visibility	Da-Chia Bridge, Taiwan[89]; Candia Bridge over the Sesia River, Italy,[41]; Aurence Bridge, France[69], Bridge over Tara channel near Taranto, Italy[90],
Hydrometric measuring stations	Hydraulic measurements	Flow velocity, water level	-	Reliable for regional flow data	May be located far from the site	A71 Viaduct, France[87]; Kupa Karlovac Bridge, Croatia[64]

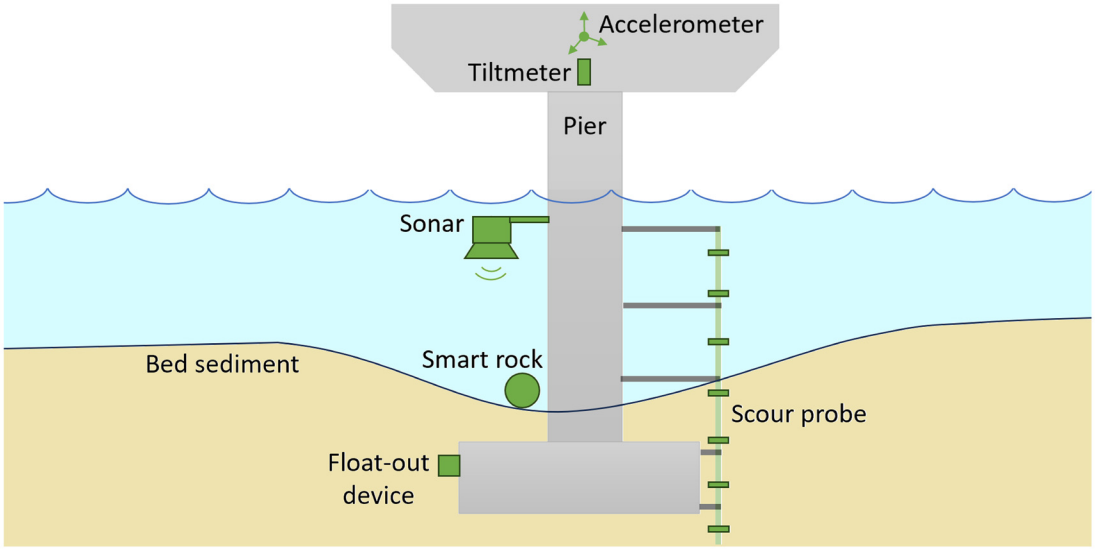

Figure 6. Instrumentation for monitoring scour and structural responses at bridge piers.

typically occurring near the noses of bridge piers[92]. By integrating direct measurements with advanced probabilistic modelling, a more robust strategy can be developed to manage scour risks and improve the resilience of hydraulic structures.

i. Sonar or echo-sounding systems

Sonar or echo-sounding systems use sound waves to monitor water depth and detect changes in the riverbed around bridge foundations. These systems emit sound waves that reflect off the riverbed or sediment, with the return time of these waves used to calculate distance. As erosion, or scour, occurs around bridge piers, the increasing distance to the riverbed indicates sediment loss. By capturing real-time bathymetric data, sonar systems provide critical insights into sediment movement below the waterline. Sonar-based instruments used to monitor underwater characteristics are commonly categorised into four main types:

- ADCP: is typically grouped separately from traditional sonar instruments, as it measures water velocity profiles, depth, and flow dynamics at multiple points in the water column rather than focusing solely on bottom mapping.
- Single-beam sonar: it emits a single sound beam, providing depth information along a line by measuring only at a single point in the water column. Though this limited measurement area can be seen as a drawback, it remains widely used as part of more complex monitoring setups. For example, a single-beam echosounder has monitored scour around a multi-span masonry arch, the Candia Bridge over the Sesia River in Italy[41]. Pier-mounted sonars are also used in the permanent monitoring of over 15 bridges in Alaska, USA, by the United States Geological Survey (USGS), where real-time data is openly accessible[92]. Another example is the Airmar Echorange SS510 ultrasonic scour sensor, which was mounted at a 9° angle on a rectangular pier of the Rucúe Bridge in Chile for scour monitoring[85].
- Multi-beam sonar: it emits multiple sound beams in a fan shape, covering a broader area to create detailed, high-resolution riverbed maps. This approach is valuable for long-term monitoring, enabling comprehensive coverage and high-resolution representation of scour[62]. For instance, the Kongsberg Dual Axis SONAR was used to monitor sediment around the A71 motorway viaduct over the Loire River in Orléans, France[87]. In another case, a Dual-Axis Scanning Sonar System installed upstream and downstream of a bridge pier provided full coverage of the Hangzhou Bay Sea Crossing Cable-Stayed Bridge in China, capturing accurate scour development data[93].
- Side-scan sonar: it uses sensors directed at an angle toward the riverbed to create detailed images of the underwater environment. Typically towed along the river or attached to a boat[94], side-scan sonar is well-suited for rapid underwater inspections[95,96], though it may be less ideal for fixed installations at bridge piers[97].

Sonar-based systems, while powerful for real-time scour detection by plotting cross-sectional data, which can be used for comparison of obtained depth of the scour with allowed levels, share some common limitations. They operate only when submerged, making their effectiveness dependent on the water level of the river, which can lead to gaps in data during low-flow conditions[41]. Additionally, they are sensitive to air bubbles, suspended sediments, turbulence, and debris interference, all of which can create gaps in data or false echoes and require careful filtering and processing[41,92,93,96,98]. Table 3 compares different types of sonar systems, highlighting each one's unique strengths, weaknesses and applications in monitoring scour.

ii. Scour probes

Scour probes are a widely used technology for direct scour monitoring and have become a significant focus in recent

Table 3. Comparison of sonar-based systems for scour monitoring.

Sonar system	Measurement method	Key parameters measured	Pros	Cons	Example use cases
ADCP	Doppler effect, multiple depths	Flow velocity and direction, water depth	Provides flow dynamics, multi-depth data	Costly	Rucúe Bridge, Chile[85]
Single-beam sonar	Single sound beam	Depth at single points	Cost-effective, simple integration	Limited coverage, single-point data only	Candia Bridge, Italy[41]; Alaska bridges[82]
Multi-beam sonar	Multiple beams in fan shape	Detailed bathymetry	High-resolution, broad area coverage	Expensive, requires a complex setup	A71 Viaduct, France[87]; Hangzhou Bay Bridge, China[93]
Side-scan sonar	Angled sonar from moving vessel	Underwater imagery	Detailed mapping, ideal for inspections	Towed setup, limited to fixed locations	Rapid site inspections[95,96]

research and field applications. These measure the position of the bed–flow interface near submerged structures usually by physical insertion into the riverbed. However, the insertion of probes may induce localised scour depths, potentially up to 2.5 times the probe's diameter[99]. Scour probes are effective in environments where direct sediment erosion measurement is critical, offering both resilience and precision in harsh conditions.

Various types of scour probes, each with distinct measurement principles, have been successfully tested in real case studies or laboratory settings. Table 4 summarises notable examples

Table 4. Summary of scour probes used in scour monitoring studies.

Scour probe	Measurement principle	Pros	Cons	Example use cases
EnviroSCAN probe with electromagnetic sensors along plastic rod height, encased in a protective steel sleeve, 10 cm resolution	Electromagnetic sensing based on capacitance measurements. The sensor's LC (L = Inductor, C = Capacitor) circuit resonance frequency changes based on the dielectric permittivity of the surrounding medium, which varies with sediment presence and erosion.	Stable during floods, accurate even in debris-prone conditions	Limited battery lifespan; the main board's 16 channels reduce resolution at higher water levels	3-span stone masonry arch A76 200 Bridge over River Nith, Scotland[99],
Micro-electro-mechanical systems (MEMS) sensors, packaged in a waterproof stainless-steel ball within a rebar cage, spaced at 50 cm intervals	Vibration-based based on MEMS activation at multiple levels	Effectively capture scour and deposition processes during flood event	Continuous exposure to harsh environments demands regular maintenance	Da-Chia Bridge, 1.2 km long, Taiwan[89],
Bed LEvel Seeking System (BLESS), patented by the Politecnico di Milano, with many Fibre Bragg Gratings (FBGs discussed in Section 3.2) placed from the bridge deck to several meters below the riverbed, spaced at 50 cm intervals	FBG thermal sensing based on heat dispersion differences between water (convection) and ground (conduction)	Robust data, especially during extreme events; is useful as a cross-check when echo sounders fail	Placement downstream to avoid debris impacts, but major scouring often occurs upstream; may need heating for sensitivity; better calibration and choice for resolution are still under investigation.	Borgoforte bridge over river Po, Italy, 630 m long with four of the 44 permanently submerged piers[54,98,100]
Distributed fibre optic sensors (DFOS) with ultra-weak fibre Bragg gratings (UWFBG), installed in a spiral form on piers and embedded in soil	The optical fibre detects deformation caused by water flow. Wavelength changes in the grating indicate the transition from soil to water, enabling scour depth estimation. The standard deviation of the wavelength signal is used as the scour indicator.	DFOS offer the same advantages as FBGs, with the added ability to provide thousands of sensing points along a continuous length of the fibre, enabling the measurement of strain distributions in two or three dimensions[74]. Real-time, high spatial resolution (5 cm). Flow velocity and temperature changes have minimal impact on the method's accuracy.	Turbulent water flow can introduce random variations in the wavelength, potentially affecting signal interpretation. Susceptible to failure if the optical fibre is damaged by debris; installation is limited to new bridges or during retrofits.	Laboratory test[101],
Fiber-optic distributed temperature sensing (DTS) device	Utilises temperature variations along a fiber-optic cable to detect changes in sediment levels around structures.	High spatial resolution; real-time monitoring; immune to electromagnetic interference.	Requires active heating.	Laboratory testing[102]

Scour probe	Measurement principle	Pros	Cons	Example use cases
Rod with an accelerometer at the top	Physical detection via cantilever model	Quick scour depth estimation, easier implementation	Rod material flexural rigidity must be much lower than soil stiffness; the water effect grows with scour increase	Laboratory testing[103],
Frequency-based scour sensors with piezoelectric polymer strips	Vibrational frequency analysis	The passive system operates during extreme events even if partially damaged	Requires complex calculations to account for fluid flow effects in the scour depths back-calculate from the obtained fundamental frequencies of the sensor.	Laboratory test[104],

of scour probes, highlighting their measurement principles, benefits, and specific use cases.

iii. Embedded sensors and smart rocks

Using embedded sensors for direct scour monitoring is a practical, adaptable approach that has seen increasing applications. A basic form of these sensors includes passive "float-out" devices, which are simple yet effective fail-safe indicators for critical scour conditions. These devices, either tethered or untethered, are installed in high-risk scour zones at pre-determined depths near bridge foundations and operate by floating to the surface when the sediment erodes to their depth. Tethered float-out sensors remain attached to the bridge structure, making it easy to determine which sensor has surfaced through visual inspection. In contrast, untethered devices rely on motion-activated transmitters to send alerts when activated by scour[105,106]. These devices can be monitored using the same data logger and communication systems as other automated scour monitoring techniques, such as sonic sensors. A key limitation is their dependence on battery life, usually 8–10 years, which restricts long-term monitoring capabilities.

These sensors have been successfully deployed in ephemeral channels and buried in riprap to assess stability. In 1997–1998, more than 40 float-out sensors were installed at 9 bridges in U.S. A notable example is the SR 101 bridge over the Salinas River (California), where a float-out sensor buried at 4 m depth surfaced during a 1998 scour event, confirming sediment loss but staying above the 6 m critical scour threshold, no emergency action was required[107].

Float-out devices are a practical option for low-cost, event-based monitoring but are best combined with other technologies for comprehensive scour assessment. While float-out sensors are effective for threshold detection, they are not suitable for capturing gradual scour progression over time. For continuous monitoring, smart rocks offer real-time insights into sediment behaviour and scour progression. Designed to resemble natural rocks, these engineered sensors are embedded in sediment around bridge piers and move with it as it erodes. Smart magnetic rocks are a commonly used variant, where erosion and deposition patterns are tracked by measuring magnetic fields using magnetometers[105]. By mapping movement and positioning, these rocks provide valuable real-time data on sediment displacement and scour depth.

A notable validation of smart magnetic rocks was conducted on the Masangxi Bridge, a reinforced concrete cable-stayed structure over the Yangtze River in China[108]. Here, smart rocks equipped with a neodymium permanent magnet and a three-gimbal gyroscope provided reliable scour depth data in flood conditions. However, environmental magnetic fields, such as those from the bridge and passing vehicles, introduced potential interference. Additionally, sediment redeposition can bury the smart rocks after a flood, necessitating careful placement and periodic maintenance to ensure reliable data.

To mitigate the impact of environmental magnetic fields, the use of two smart rocks has been suggested. Field tests conducted at the State Highway 1 Bridge (No. 36–0065) over Waddell Creek, Santa Cruz, California, USA, demonstrated that changes in the dispersion of ambient magnetic fields are more pronounced with double smart rocks compared to single ones. However, the effectiveness of the double smart rocks depends significantly on their relative locations, which influence the monitoring range[109].

Another example of the smart rock method was tested at the I-44 W Roubidoux Creek Bridge in Waynesville, USA[110], where an unmanned aerial vehicle (UAV)-deployed smart rock demonstrated precise measurements, with only a 6% error margin compared to sonar scanning. This smart rock consisted of a fibre-reinforced concrete shell with an inner and outer glass ball, filled with low-viscosity propylene glycol, containing two stacked N42 magnets and copper beads for balance. The rock's design, including a vertical polarisation alignment, allows it to track flow velocity and water depth effectively. However, UAV deployment requires additional calculations for location-specific latitude and longitude, as well as assessments of nearby ferromagnetic materials.

iv. Indirect monitoring methods: rotation and vibration-based monitoring, and InSAR

Indirect monitoring methods, such as rotation-based and vibration-based monitoring, and InSAR, focus on the structural response of a bridge rather than directly measuring scour or sediment movement. These methods are particularly effective for assessing stability and load-bearing capacity when sediment erosion, scour, or hydrodynamic forces compromise structural integrity. Indirect monitoring approaches, commonly used for offshore wind turbine monopiles vulnerable to scour, share similarities with bridge pier monitoring. Critical parameters like bottom inclination, vibrational modes and natural frequency have been identified for scour detection[111–113]. These methods could inform bridge monitoring under similar conditions.

Extensive numerical analysis using a finite element model, calibrated by operational modal analysis (OMA) of the remaining part of the arch-type Rubbianello Bridge over the Aso River in Italy[114,115], which was partly collapsed in 2013, recommended monitoring upstream rotations in piers or spandrel walls. For a multi-span brick masonry arch Candia Bridge over the Sesia River in Italy, a tiltmeter-based monitoring system was implemented to detect and localise structural damage from scour[41]. Here, 15 uniaxial MEMS tiltmeters (SISGEO model 0S541MA0202, accuracy ±0.008°) with integrated temperature sensors were installed at the arch skewbacks on the upstream side to measure transverse rotations in the foundation-pier-arch system, thus protecting the sensors from debris. This setup allowed the identification of both local and global rotations, revealing an almost linear correlation between global rotations and temperature changes. Temperature-induced variations were filtered out to isolate abnormal rotational patterns, which could indicate structural issues. Tiltmeters proved effective in capturing abnormal behaviour during a minor earthquake and identifying anomalous patterns in global rotations. However, the study highlighted challenges in interpreting the data and suggested deploying additional tiltmeters on the downstream side to better distinguish between anomalies caused by arches and those from pier-foundation shifts.

Tiltmeters are primarily suited for quasi-static or slow-changing movements, so a new approach in rotation-based monitoring was proposed in 7, where a fusion of accelerometers and gyroscopes was used to achieve a more accurate and reliable estimate of structural rotation and deflection.

Scour affects the modal parameters of a bridge, making vibration-based sensors, typically employing accelerometers, valuable for monitoring scour[55,116]. These methods rely on modal analysis to detect scour-related changes in dynamic behaviour, such as shifts in natural frequencies, mode shapes, and mode-shape curvatures, rather than measuring scour depth directly[117]. Studies show that temperature fluctuations, both daily and seasonal, can correlate with changes in tilt and natural frequencies, and thus filtering and adjusting for these variations are essential for accurate structural assessments[41,87,118–120]. Natural frequencies generally decrease with structural damage[121], and numerical modelling of scour has shown increases in periods of the first two bridge modes and localised variations in mode shapes around scoured piers[55]. However, for shallow foundations, natural frequencies are less sensitive to scour and predicted frequency variations from finite element models are often not observed in field testing[122,123].

An advantage of monitoring mode shapes is their relative immunity to environmental and operational fluctuations, making them more reliable damage indicators than natural frequencies[118]. For instance, the Rubbianello Bridge study demonstrated that transverse mode shapes were highly sensitive to localised scour at a single pier, even in the early stages of erosion, but this sensitivity decreased when multiple piers were affected[61].

In the monitoring of the A71 motorway viaduct over the Loire River in Orléans, France, accelerometers were deployed, including one tri-axial PCB 629A11 sensor under the bridge deck and two mono-axial PCB 393B31 sensors on the piers along the vertical and hydraulic flow axes. However, this study revealed challenges in post-processing vibration data and found no clear correlation between natural frequencies and water levels[87].

In the vibration-based monitoring of Baildon Bridge in Bradford, UK, during its scour repair program, alternative structural response parameters—spectral density and mode shapes—were proposed for capturing behavioural changes resulting from scour[122]. Similarly, in the monitoring of the Hangzhou Bay Bridge in China, the variation of mode shapes was incorporated to qualitatively detect the presence of foundation scour[124]. Comprehensive numerical modelling of a cable-stayed bridge tested four scour indicators: frequency change ratio, modal assurance criterion, mode shape curvature, and flexibility-based deflection. The study concluded that while the frequency change ratio can qualitatively identify scour, monitoring changes in flexibility-based deflection enables both qualitative and quantitative identification of scour in cable-stayed bridges[125].

Another notable example is the Z24 Bridge in Switzerland, which was monitored for nearly a year before scour was simulated by artificially lowering a pier. This study analysed the probability distribution function of natural frequency changes, with effective damage detection achieved through the use of quality control charts, specifically Hotelling's T^2 statistic, implemented with P3P software[119,126].

Introduced in 1947, Hotelling's T^2 statistic is a multivariate control chart that combines information from the mean and dispersion of multiple interrelated variables to detect shifts in their collective behaviour. Although its calculations involve complex matrix algebra, modern software simplifies its

application. This highlights the importance of advanced analytical tools in vibration-based scour monitoring for detecting subtle changes that simpler methods might overlook.

Another example of vibration-based scour monitoring is the application of time-frequency analysis combined with probabilistic trend change detection. This method, demonstrated in studies on the Jintang Bay Bridge and the Anqing Yangtze River Bridge (where scour frequently occurs) in China, leverages natural frequency data extracted from long-term SHM systems using techniques such as the Hilbert-Huang Transform and Short-Time Fourier Transform. Kernel Density Estimation is used to model the probability distribution of frequencies, which are normalised, and then control charts are used for anomaly detection. Continuous frequency deviations beyond preset thresholds effectively signal scour development, showcasing the method's ability to detect scour without underwater operations and its potential for integration with routine SHM systems[127].

Interferometric Synthetic Aperture Radar (InSAR) is a remote sensing technology that detects ground deformation by analysing phase differences between radar images captured from satellites. The temporal resolution of InSAR methods can be increased providing near-real-time monitoring possibilities by combining data from overlapping orbits[128]. Advanced InSAR techniques, such as Persistent Scatterer Interferometry (PSI) and Small Baseline Subset (SBAS), allow accurate deformation monitoring over large spatial areas, making it particularly suitable for bridges under flood conditions or when direct monitoring is infeasible.

A notable application of InSAR was its deployment on the Tadcaster Bridge in the UK, where it detected deformation weeks before the bridge's partial collapse due to scour[129]. This highlighted its potential as an early warning system, complementing traditional visual inspections. However, interpreting InSAR data requires accounting for factors like expected thermal responses, bridge orientation, and water level variations, as seen in studies of the Jacques Cartier and Victoria Bridges in Montreal, Canada, and the A22 Po River Bridge in Italy[130,131].

One key challenge of InSAR is that measured displacements represent one-dimensional projections along the satellite's Line-of-Sight (LOS), which may not fully capture three-dimensional deformation patterns. Converting LOS data into a local reference system (longitudinal, transverse, and vertical components) is essential for understanding bridge behaviour. While longitudinal and vertical deformations are typically influenced by temperature effects and traffic loads, transverse deformations can become significant during events like landslides or localised scour around piers[132].

Table 5 summarises examples of indirect scour monitoring methods, highlighting their measurement principles, benefits, and specific use cases.

4. Summary and prospects

This review analysed flood-related bridge failures, highlighting real-world case studies and key risk factors such as debris accumulation, hydrodynamic forces, and scour. Advancements in SHM technologies were explored, focusing on monitoring

Table 5. Summary of indirect monitoring methods used in scour monitoring studies.

Method	Instruments	Measurement principle	Pros	Cons	Example use cases
Rotation-based	MEMS tiltmeters	Measures slight angular changes in bridge components due to foundation settlement or undercutting.	Effective for identifying foundation-pier-arch rotations. Easy to filter temperature variations. Protects sensors from debris through careful placement.	Data interpretation requires expertise. Distinguishing anomaly sources (e.g., arch movement vs. pier shifts) is challenging without additional sensors.	Candia Bridge over the Sesia River, Italy[41]
Rotation-based	High-performance MEMS gyroscopes, high-sensitivity MEMS triaxial and ultra-sensitive piezoelectric quartz uniaxial accelerometers	Measures quasi-static and dynamic measurements. Sensor fusion using a Kalman filter improves rotational measurement.	Provides a more accurate and reliable estimate of structural rotation and deflection.	Requires significant expertise for setup, calibration, and data analysis. Limited field application, warrants further testing.	Mineral Line Railway Bridge, UK[7]

Method	Instruments	Measurement principle	Pros	Cons	Example use cases
Vibration-based	Tri-axial and mono-axial piezoelectric accelerometers	Operates based on the piezoelectric effect of materials to measure dynamic changes in mechanical variables (e.g., acceleration).	Offers real-time monitoring and global insights into changes in boundary conditions, such as scour.	Highly sensitive to environmental factors; requires signal filtering to reduce noise. Lack of research on a reliable scour assessment.	A71 motorway viaduct over the Loire River, Orléans, France[87]; Kupa Karlovac Bridge, Croatia[64]
Vibration-based	3-axis high-sensitivity QMEMS accelerometers	Detects scour-induced changes in natural frequencies through real-time ambient vibration measurements.	Captures alternative structural response parameters, such as spectral density and mode shapes, which reflect scour-induced behaviour changes.	Scour-induced natural frequency changes predicted by finite element models were not observed using the peak-picking method.	Baildon Bridge during scour repair program, Bradford, UK[122]
Vibration-based	Broad-band high-sensitivity accelerometers with 20 Hz sampling	Monitors scour-induced changes in natural frequencies of the structure using time-frequency analysis combined with probabilistic trend detection to identify anomalies and trends.	Integrates with existing Structural Health Monitoring systems, high sensitivity to scour	Requires long-term monitoring and robust statistical processing. It may need initial calibration to filter environmental noise.	Jintang Bay Bridge, Zhoushan, China (simulation); Anqing Yangtze River Bridge, Anhui, China (field study)[127]
Vibration-based	Piezoelectric acceleration sensors, finite element model	Uses ambient vibration measurements of superstructures to update finite element models for scour identification.	Incorporates mode shape variations to qualitatively detect scour. Accurately verifies findings using underwater terrain mapping.	Quantitative identification requires detailed bridge information for model updates. Effective sensor arrangements are still under investigation.	Hangzhou Bay Bridge, China[124]
Vibration-based	Piezoelectric and MEMS accelerometers	Uses centrifuge modelling to scale soil properties and measure natural frequency variations caused by scour.	Natural frequency can be a potential scour indicator for integral bridges with piled foundations.	Low sensitivity of fundamental natural frequencies to scour in shallow foundations.	Laboratory test[123]
InSAR	Satellite data	Analyses phase differences (interferograms) in multiple SAR images acquired over time at the same imaging geometry.	Provides millimetre-scale deformation data. Wide-area coverage. Effective under diverse conditions (e.g., night, flooding). Demonstrated potential for early warning systems.	Relies on satellite data availability and acquisition planning. Interpretation of displacement data is complex. As measurements are based on phase changes in the radar signal, deformations greater than a quarter of the radar wavelength between consecutive acquisitions is difficult to distinguish.	Tadcaster Bridge, UK[129]; A22 Po River Bridge, Italy[131]; Jacques Cartier and Victoria Bridges in Montreal, Canada[130]

solutions for these risks, including direct methods (sonar, scour probes) and indirect approaches (vibration-based sensors, InSAR).

Effective monitoring requires a hybrid approach integrating these technologies for real-time data analysis and predictive maintenance. However, gaps remain in field validation and the integration of structural and hydraulic monitoring. Additionally, the economic feasibility of SHM implementation is critical for real-world applicability. Table 6 provides a comparative overview of key SHM technologies evaluating their strengths, current limitations, future research needs, and cost considerations.

While high-cost technologies like ADCPs, InSAR, and multi-beam sonar can provide unparalleled accuracy, lower-cost alternatives such as smart rocks, CCTV, and radar-based systems offer cost-effective monitoring solutions for specific applications. The selection of SHM technologies should balance performance, cost, which can vary significanty based on location and project scale, and practicality, ensuring long-term feasibility while addressing infrastructure vulnerabilities.

Despite progress, challenges remain in data interpretation, environmental influences, and field validation. Future research

Table 6. Comparative overview of SHM technologies for bridge monitoring in flood conditions.

Category	Best-suited technologies	Current limitations	Future research needs	Cost considerations[133,134]
Flow & water level monitoring	ADCP, Ultrasonic profilers, Radar meters, CCTV cameras	High cost (ADCP), debris sensitivity, limited visibility in adverse weather	AI-enhanced image processing for CCTV, improved debris protection for Doppler systems	**ADCP & ultrasonic profilers**: High initial cost & maintenance. **Radar meters**: Moderate cost. CCTV: Low-cost but requires manual/automated analysis.
Scour & erosion detection	Sonar-based systems, Smart rocks, Scour probes	Vulnerable to turbidity, debris interference, limited long-term deployment data	Hybrid sonar systems for all water levels, better sediment redeposition tracking	**Sonar**: High setup & maintenance cost. **Smart rocks**: Cost-effective, low maintenance but limited data detail. **Scour probes**: Moderate cost, sensor longevity varies.
Structural response to flooding	Rotation-based (MEMS tiltmeters, gyroscopes), Vibration-based (accelerometers)	Requires expert data interpretation, environmental sensitivity	Deep learning for automated data interpretation, sensor fusion approaches	**MEMS tiltmeters & gyroscopes**: Moderate cost, low maintenance and operation costs, providing long-term monitoring benefits. **Vibration-based methods**: Variable cost (low to high, depending on sensor network complexity).
Surface deformation & large-scale monitoring	InSAR (satellite-based)	One-dimensional displacement data, complex interpretation, dependent on satellite data availability	Line-of-sight displacement conversion into local reference systems to improve applicability	**InSAR**: High satellite data cost but low maintenance, effective for large-area monitoring.

should focus on AI-driven analytics for automated data interpretation, cost-effective sensor deployment, and adaptive SHM solutions to address climate change-driven flood risks on bridges. Advancing SHM technology through multidisciplinary collaboration will improve bridge safety and long-term infrastructure sustainability.

Ethics and consent

Ethical approval and consent were not required.

Data availability

No data are associated with this article.

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Reference Source

Open Peer Review

Current Peer Review Status: ✔ ✔

Version 2

Reviewer Report 16 April 2025

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✔ **Maryam Nasim**
University of Melbourne, Melbourne, Australia

The authors have fully addressed all the reviewer comments with clear, comprehensive revisions. The manuscript has been substantially improved and is now well-structured, technically sound, and ready for acceptance.

Sincerely,

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 14 April 2025

https://doi.org/10.21956/openreseurope.21477.r52146

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✔ **Riyadh Alsultani**
University of Babylon, Babylon, Iraq

I appreciate the authors' efforts in addressing the reviewers' comments and incorporating the suggested revisions. I have now reviewed the revised version of the manuscript along with their responses.

Based on the improvements made — particularly the enhancements in the clarity of the

Introduction and Summary sections, the expanded treatment of debris impact, and the valuable additions to Tables 4 and 6 — I am pleased to confirm that the revised version has satisfactorily addressed my previous concerns.

Accordingly, I update my review status to **Approved**.

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 20 February 2025

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Maryam Nasim
University of Melbourne, Melbourne, Australia

The paper provides a comprehensive review of Structural Health Monitoring (SHM) technologies applied to flood-prone bridges, incorporating case studies and discussing various monitoring techniques. The authors have successfully highlighted the importance of SHM in mitigating bridge failures due to floods, particularly from scour, debris impact, and hydrodynamic forces. The review integrates recent advancements and proposes future research directions.
However, there are areas that require improvements as below.

Detail Comments:
1- The last paragraph in section 1 (Introduction) would be more suitable for inclusion in a summary section rather than the introduction.

2- In "Debris Impact" section, the effect of debris accumulation is described, but the influence of submerged objects (such as log, etc) on flow velocity has not been discussed or differentiated.

3- While the paper provides an extensive review, there are some key SHM technologies that are briefly mentioned but not fully elaborated upon. For example, fiber optic sensors deserve more discussion.

4- Section 3.2 ,Formula 2 introduces several notations that require clearer descriptions. Specifically, the 'shape factor' is inadequately defined. The manuscript should provide a detailed explanation of the shape factor weather its derivation or empirical basis or analytical and how its influence on the calculated outcomes.

5- Section 3.3 mentions float-out devices; however, the discussion lacks details on their operational mechanisms, specific applications, and suitability for different bridge types. For clarity and completeness, it is recommended to include examples of successful implementations, potential challenges, and a comparison with alternative flood resilience solutions.

6- One critical aspect that appears to be underrepresented is the cost analysis of the suggested methodologies. It is recommended to include a comprehensive discussion on the economic feasibility, covering implementation, maintenance, and operational costs, to improve the practical relevance and applicability of the study.

Is the topic of the review discussed comprehensively in the context of the current literature?
Partly

Are all factual statements correct and adequately supported by citations?
Partly

Is the review written in accessible language?
Partly

Are the conclusions drawn appropriate in the context of the current research literature?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: My primary areas of research expertise include Structural Health Monitoring of critical infrastructure and the hydrodynamic impacts of flooding, debris, and log accumulation on bridge structures. My work extensively covers vulnerability assessments of bridges under extreme flood loading, with a particular focus on failure mechanisms, debris-induced hydrodynamic forces, and structural resilience strategies. I have conducted comprehensive studies that explore the interaction between hydraulic forces and structural responses, incorporating both numerical modeling and experimental validation.Given my background, I am confident in assessing all aspects of this manuscript, especially those related to the impact of debris and flood-induced forces on bridge stability, as well as the application of SHM technologies for real-time monitoring and maintenance planning. I believe my expertise aligns well with the core topics discussed in this paper, enabling me to provide a thorough and constructive review.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 03 Mar 2025
Karina Buka-Vaivade

Dear Reviewer, Thank you for your valuable feedback. All recommendations have been taken into account and the article has been modified accordingly. Below there are step-by-step answers for all comments.

Comment #1: The last paragraph in section 1 (Introduction) would be more suitable for inclusion in a summary section rather than the introduction.
Response: We agree with this consideration and we removed the last paragraph of the introduction section.

Comment #2: In "Debris Impact" section, the effect of debris accumulation is described, but the influence of submerged objects (such as log, etc) on flow velocity has not been discussed or differentiated.
Response: We thank you for this valuable suggestion. We have expanded the “Debris Impacts” section to clearly differentiate the effects of floating and submerged debris, and added relevant references. Additionally, we have incorporated findings from experimental studies that demonstrate how submerged debris influences local scour based on its position relative to the flow surface and alters flow dynamics.

Comment #3: While the paper provides an extensive review, there are some key SHM technologies that are briefly mentioned but not fully elaborated upon. For example, fiber optic sensors deserve more discussion.
Response: We have reviewed our discussion on fiber optic sensors and made several enhancements. We added cross-referencing between Section 3.2 and Table 4 where fiber optic sensing is discussed. We added clarification to Distributed Fiber Optic Sensors (DFOS) in comparison to Fiber Bragg Gratings (FBGs). As well, we added additional example of a Fiber-Optic Distributed Temperature Sensing (DTS) device in Table 4.

Comment #4: Section 3.2, Formula 2 introduces several notations that require clearer descriptions. Specifically, the 'shape factor' is inadequately defined. The manuscript should provide a detailed explanation of the shape factor weather its derivation or empirical basis or analytical and how its influence on the calculated outcomes.
Response: We apologize for missing important details in that discussion. We have revised Section 3.2 to provide a clearer definition of the shape factor (k), explaining its empirical basis, how it is derived, and its influence on the calculated hydrodynamic forces. The updated text clarifies that the shape factor accounts for the impact of cross-sectional geometry on drag, with values taken from Eurocode (EN 1991-1-6, 2005). Additionally, we have included a brief discussion on how different shapes influence flow separation and turbulence, which directly affects force estimation.

Comment #5: Section 3.3 mentions float-out devices; however, the discussion lacks details on their operational mechanisms, specific applications, and suitability for different bridge types. For clarity and completeness, it is recommended to include examples of successful implementations, potential challenges, and a comparison with alternative flood resilience solutions.
Response: We have expanded Section “**iii. Embedded sensors and smart rocks**” to provide more details on float-out devices. Specifically, we have clarified their operational mechanism (tethered vs. untethered, transmitter alerts); included an example of field deployment and

scour detection (SR 101 bridge, California); and highlighted their advantages, limitations and the need of combining them with other technologies for comprehensive scour assessment.

Comment #6: One critical aspect that appears to be underrepresented is the cost analysis of the suggested methodologies. It is recommended to include a comprehensive discussion on the economic feasibility, covering implementation, maintenance, and operational costs, to improve the practical relevance and applicability of the study.
Response: Following your suggestion, we have expanded the discussion on economic feasibility. Specifically, Table 6 now provides a comparative overview of SHM technologies, addressing cost considerations. However, we believe that providing a very detailed discussion about economic aspects is outside the scope of the article, as well as difficult to do because instrumentation, installation, and management of the monitoring system have different costs in different parts of the world, also related to the different sensitivities of infrastructure management operators.

Competing Interests: The authors declare that they have no competing interests.

Reviewer Report 18 February 2025

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Riyadh Alsultani
University of Babylon, Babylon, Iraq

- The introduction is well-structured, clearly stating the background and significance of the study. Some sentences are lengthy and could be simplified for better readability.
- The conclusion section is clear and well-organized, summarizing the main findings of the study. However, it can be made more concise by avoiding repetitive phrases and ensuring that conclusions are directly tied to the study's objectives.

Is the topic of the review discussed comprehensively in the context of the current literature?
Yes

Are all factual statements correct and adequately supported by citations?
Yes

Is the review written in accessible language?
Partly

Are the conclusions drawn appropriate in the context of the current research literature?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Hydraulic structures

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 03 Mar 2025

Karina Buka-Vaivade

Dear Reviewer, We appreciate your insightful feedback. All your recommendations have been considered, and the article has been revised accordingly. Below, you will find detailed responses to each of your comments.

Comment #1: Some sentences in introduction are lengthy and could be simplified for better readability.
Response: Lengthy sentences in introduction part have been simplified for better readability.

Comment #2: The conclusion section can be made more concise by avoiding repetitive phrases and ensuring that conclusions are directly tied to the study's objectives.
Response: We thank you of this suggestion and we have revised the summary section to enhance conciseness, removing redundant phrasing and ensuring that findings are clearly tied to the study's objectives. Additionally, Table 6, which contains a comparative overview of SHM technologies for bridge monitoring in flood conditions, has been refined for clarity.

Competing Interests: The authors declare that they have no competing interests.