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Structural health monitoring guidelines for bridges in Germany

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ABSTRACT: With the advancement of digitalization and related technological developments, Structural Health Monitoring (SHM) has become a useful and increasingly widespread tool to assist in the maintenance management of bridges and other engineering structures. The process of implementing monitoring requires expertise in many fields such as civil engineering, bridge operation and maintenance, monitoring technology, and data analysis. In recent years, monitoring has moved from method and technology development to standard practice. However, the implementation of monitoring as a standardized process can be an obstacle, especially for bridge operators, due to a lack of practical experience combined with the various expertise required. This can affect several areas, such as determining the cost-effectiveness of a monitoring measure, proper tendering and contracting, quality control, analysis and evaluation of measurement data, and last but not least, data management. In order to support the introduction of monitoring technologies into the practice of infrastructure operators, several guidelines have been developed in Germany in recent years by different interest groups, each with a different focus and essentially complementing each other. This paper aims to provide an overview of four different recently published guidelines and to highlight their strengths and advantages.

KEY WORDS: Structural Health Monitoring; Guidelines.

1 INTRODUCTION

Germany's road and railway infrastructure faces several challenges, including a significant increase in traffic and a high average age of bridge structures. Bridge maintenance management is currently based on standardized inspections, which largely assess the condition of the structure visually and manually. At the same time, the development of procedures and technical requirements for Structural Health Monitoring (hereinafter referred to as "monitoring" for short) has by now progressed to the point where it is one of the most widely used tools for determining the structural condition of bridges and, if necessary, predicting developments. However, at present the use of monitoring is largely limited to event-related (reactive) actions while a great potential lies in the future support of predictive maintenance.

Surveys conducted among federal and state road authorities found that the use of monitoring is limited to existing damage and deficiencies [1]. According to the survey, barriers include a lack of knowledge about the applications and benefits of monitoring, the procurement process of monitoring services as well as the handling of data storage.

Due to the wide variety of construction methods and building materials, monitoring might vary greatly in its conception and implementation, depending on the specific object. Furthermore, there can be different approaches to the same objectives in terms of the parameters to be monitored, each with its own advantages and disadvantages. Therefore, there is no single approach that can be universally applied to the setup of monitoring systems for civil engineering structures. A recent challenge specific to Germany is that the current version of the German standard for bridge inspections DIN 1076 [2] does not include monitoring as part of the inspection process. This has led to a regulatory gap, as bridge authorities have not yet established a systematic monitoring process. This will change in the near future with the introduction of a current revision of DIN 1076. The next version will include monitoring as a standard inspection routine [3].

The discrepancy between state-of-the-art monitoring methods and technology, on one hand, and the challenges associated with their implementation by bridge owners and operators, on the other, has become more apparent in recent years. One primary method to address this challenge is the implementation of guidelines that can provide direction and regulate the utilization of procedures to some extent. Several institutions have expressed a need for such guidelines, and they have taken steps to promote and facilitate their publication.

The German Concrete and Construction Technology Association (Deutscher Beton- und Bautechnik-Verein e.V. DBV) played a pioneering role in developing and publishing the "DBV-Guideline Bridge Monitoring - Design, Tender, and Implementation" (DBV-Merkblatt Brückenmonitoring - Planung, Ausschreibung und Umsetzung) in 2018 [4]. The document meticulously delineates a range of monitoring applications and, most notably, methodically analyzes and structures the bridge monitoring process into multiple steps. Concurrently, the players involved in the process were assigned to the individual steps. Those involved in the practical application found this structuring to be very helpful. Additionally, the guideline briefly addressed tendering and economic considerations.

As an extension of the support provided by guidelines, the German Society for Non-Destructive Testing (Deutsche Gesellschaft für Zerstörungsfreie Prüfung e.V. DGZfP) has published the "Guideline B09 Structural Monitoring" (Merkblatt B 09 Dauerüberwachung von Ingenieurbauwerken) [5]. The guideline is a comprehensive document that provides

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a detailed overview of the conception of monitoring systems. It also includes a compilation of possible technical systems and sensors, depending on the specific tasks at hand. Additionally, aspects of data processing and data management are addressed. Operators of the structures are further supported by a compendium of best practice examples.

Despite the existence of published guidelines, the practical application of monitoring specifically for road bridges did not gain widespread traction. In response, the German Federal Highway Research Institute (Bundesanstalt für Straßen- und Verkehrswesen BASt) initiated a research project in 2023. The objective of the project was to produce a brochure-type guide that would provide practical application instructions for monitoring road bridge structures. As a brochure cannot be expected to address every potential issue or question that may arise in the context of a monitoring application in great detail, the compendium-type final project report, "Guideline - Strategic application of monitoring for engineering structures" (Leitfaden – Strategischer Einsatz von Monitoring bei Brückenbauwerken), was pre-published in 2024 [6]. This report encompasses both technical aspects and addresses economic feasibility, tendering, and contracting of monitoring services. It includes a collection of typical monitoring applications on road bridges, organized by use cases, describing their common usage and benefits, supplemented by model examples. Currently, the monitoring system operator generally holds the measurement data, with no principal data transfer to the client. As monitoring applications become more widespread, standardizing procedures and establishing data management systems becomes crucial. The road administration is responsible for storing processed measurement data in a machine-readable format to enable future evaluations. The project developed foundations for designing suitable data management systems and explored how user agreements for data description and transfer can be incorporated into contracts.

The final guideline in this series differs slightly from the previous guidelines. The primary focus of this guideline is the monitoring of prestressed wire breaks in prestressed concrete structures using the method of acoustic emission analysis, as opposed to the broader field of engineering structure monitoring. The DGZfP guideline "SE 05 - Detection of tendon wire breaks with acoustic emission" (Richtlinie SE 05 – Detektion von Spannstahlbrüchen mit Schallemissionsanalyse) aims to standardize the application of acoustic emission (AE) analysis for detecting prestressing wire breaks and to outline the method's capabilities and limitations [7]. It provides detailed instructions for planning, tendering, installation, operation, and evaluation of an AE monitoring system. The guideline also offers recommendations on technical and personnel requirements and quality standards to ensure a high-quality information system. Its scope includes bridge and engineering structures with bonded prestressing wires, though the described methods could also apply to unbonded post-tensioning systems.

The contribution presents a compilation of the four different guidelines developed and published in recent years in Germany. These guidelines aim to structure and regulate the conception and implementation of monitoring applications to support the introduction of monitoring into the practice of managing bridge and other engineering structures. In addition to the guidelines presented here, several other documents have been published recently to assist those involved in the management of bridges and other engineering structures. For instance, these documents may include reports on a particular subject, such as corrosion monitoring of reinforced concrete structures [8], or documents that compile reports of applied monitoring activities in civil engineering, such as [9].

2 DBV-GUIDELINE BRIDGE MONITORING

The German Society for Concrete and Construction Technology (DBV) was the first to address the issue of harmonization approaches to planning and implementation of monitoring measures for engineering structures. In 2018, the DBV published the guideline "Bridge Monitoring - Design, Tender and Implementation" [4]. The guideline was developed by a consortium of bridge operators, monitoring providers, and representatives of the scientific community. This consortium was formed to consider the perspectives of all parties involved in the realization of monitoring projects.

2.1 Motivation and objectives

The primary objectives behind developing this guideline were twofold: first, to catalog potential use cases of structural health monitoring throughout the life cycle of engineering structures, and second, to describe the monitoring process in detail, including all its phases, in conjunction with clearly defining responsibilities. The guideline was developed to serve as a practical resource for the planning and execution of monitoring activities. While the guideline is centered on bridge monitoring, its principles can be applied to a variety of engineering structures and buildings.

2.2 Content of the guideline

The guideline underscores the importance of various monitoring applications across a structure's life cycle. However, the text also describes monitoring applications in the pre-construction, construction, and demolition phases. The list of use cases is not exhaustive, but it provides an overview of monitoring's potential.

The implementation of bridge monitoring entails more than just installing sensors on a structure and recording the measured values. To successfully receive the requested structural information based on monitoring, it must be understood as a comprehensive process, from the definition of the task to the extraction of the qualified answer. The success of a monitoring project hinges on a structured process with clearly defined phases and service profiles for all involved parties. The guideline suggests a systematic monitoring process comprising the following six sequential phases:

- Defining the monitoring objective and assessing its feasibility.
- Developing a monitoring concept.
- Detailed design of the monitoring system.
- Implementation, including installation, operation, and data acquisition.
- Data processing and evaluation.
- Assessment, where results are interpreted using supplementary analyses.

Stakeholders involved in monitoring projects have specific roles and responsibilities. While tasks are clearly assigned,

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depending on project size and complexity, a limited number of experts may fulfill multiple roles. In complex projects, there may be a need for different specialists, particularly when advanced measurement techniques are required.

Quality assurance is critical at every stage of the monitoring process to ensure consistent, high-caliber standards. Internal quality control is always required, while external proofs may be necessary for critical projects. The guideline recommends a structured procedure for each of the three main subjects in terms of quality assurance: the monitoring concept, data integrity, and the key feature assessment.

Additionally, the process of tendering monitoring services is complex due to the specialized nature of SHM. A well-structured approach ensures coordinated data flow among stakeholders, leading to consistent quality. As defining monitoring services precisely in tenders can be challenging, functional descriptions focusing on objectives and expected outcomes can serve as an alternative. However, achieving comparable offers and execution quality remains a key challenge. The guideline delineates various approaches, contingent upon the complexity of the monitoring project.

Finally, the cost-effectiveness of monitoring must be assessed before any action is taken. Monitoring provides valuable information that can extend a structure's service life, reduce the need for costly upgrades, and improve risk management. Monitoring is essential for preventing unnecessary restrictions or interventions. It helps optimize infrastructure maintenance and safety. The guideline covers the net present value method and the downtime costs accounting method, and it includes examples that illustrate the economic benefits of monitoring measures. Additionally, the text presents a method for evaluating the risk associated with the uncertainty of the monitoring results.

2.3 Guideline summery

The proposed DBV-guideline "Bridge Monitoring - Design, Tender and Implementation" aims to catalog structural health monitoring use cases and describes the monitoring process with defined responsibilities. The process is structured in six phases, from defining objectives to result assessment. The guideline emphasizes quality assurance, addresses the complexities of tendering monitoring services, and discusses the cost-effectiveness of monitoring. While the primary focus is on bridge monitoring, the principles can be applied to other engineering structures as well. The guideline is intended to serve as a practical resource for the planning and implementation of monitoring actions, taking into account the perspectives of bridge operators and monitoring providers.

3 DGZFP-GUIDELINE B 09 STRUCTURAL MONITORING

3.1 Motivation and objectives

The DGZfP has developed the "Guideline B 09 Structural Monitoring" to assist owners, operators, and those responsible for structural maintenance, as well as qualified planners tasked with designing monitoring systems [5].

Guideline B 09 is a clear complement to the DBV guideline Bridge Monitoring. As the previous section explains, it focuses on the description of monitoring applications, the monitoring process, and economic considerations. The DGZfP B 09 guideline clearly states the objective: to provide readers with easy access to monitoring systems and to illustrate the conditions and limits under which monitoring specific structural parameters can serve as a useful supplement or alternative to manual structural inspections. It provides a solid foundation for a realistic assessment of the financial and time requirements from the initial idea to the evaluation of the results of structural monitoring.

The guideline provides detailed descriptions of the aspects to consider when designing continuous monitoring systems and examines tasks that can realistically be addressed by structural monitoring. It also discusses critical issues for data management and quality assurance. The document emphasizes practical relevance. The explanations of monitoring tasks are formulated from the perspective of typical structural engineering questions rather than from the perspective of sensor technology. The authors of the guideline made a point of including a catalogue of practical examples. This collection includes monitoring applications from various structures (bridges, wind converters, etc.), different building materials (steel, concrete, etc.), and different monitoring objectives (damage monitoring, load monitoring, etc.).

Given the increasing presence of providers of hardware and monitoring services in the marketplace, it is becoming increasingly important to have a common understanding of the factors that need to be considered during the various phases of structural monitoring. It is therefore imperative to ensure that monitoring systems reliably meet customer requirements for specific tasks and to avoid unrealistic expectations of potential results. According to the authors of the new DGZfP Guideline B 09 Structural Monitoring, this document makes a significant contribution to achieving this goal.

3.2 Content of the guideline

The guideline covers all essential technical steps that must be considered during the design and implementation of a monitoring project according to the current state of knowledge. The focus is on large-scale monitoring systems, i.e., sensor networks with multiple sensors at different locations, with special consideration of applications to reinforced and prestressed concrete bridge structures. The substantive chapters of the guideline are presented below.

<u>Conception of Continuous Monitoring Systems:</u> This chapter provides comprehensive guidance on the technical design of continuous monitoring systems. The necessary steps are described in detail along the measurement chain: The structure consists of the following: sensor connection, base station, and peripherals. The text starts by clearly explaining the preliminary investigations of existing structures. These investigations determine potential weak points, existing damage, and probable damage mechanisms. The text also describes the determination of measurement parameters. Next, we will critically assess whether monitoring is appropriate in each case. If the decision is positive, suitable sensors must be selected and suitable measurement locations determined. These locations must take into account the aspects described in the guideline.

The signals collected at measurement points are transmitted to a base station or central computer via cable or wirelessly, depending on the sensor type and system layout. The data converges at the base station, where it is processed, verified,

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and stored. The text explains different data acquisition modes (time-controlled, event-based) and considers event detection, data volume, and energy consumption. Remote transmission components enable continuous monitoring, alarming, and data backup. Actuators trigger events like switching traffic lights. Data evaluation is automated and based on specific standards. Challenges in larger projects include ensuring reliable communication and appropriate measurement intervals.

Monitoring Tasks: This central chapter of the guideline deals with various typical construction issues that are fundamentally accessible to monitoring in civil engineering structures. For each monitoring task, only established methods and sensors are the topics of discussion. The selection and description of monitoring tasks is based on the practical experience and scientific expertise of the committee members. The authors of the guideline were aware that each structure is unique and that each type of sensor and sensor behavior is different. Generalizations are difficult to make, but they are necessary for a foundational document such as this guideline. Monitoring systems must be tailored to the task at hand. Therefore, it is essential to involve a monitoring expert in the design, planning, and implementation of monitoring projects.

The guideline covers the following monitoring tasks:

- Geometric quantities: Strain, displacement, deflection, tilt, cracks.
- Static and dynamic quantities: Force, Stress, Prestressing Force, Vibration, Shock.
- Material Properties: Material moisture, reinforcement corrosion, prestressing wire break detection.
- Environmental influences: Temperature, humidity, other environmental conditions, traffic characterization.

To improve comparability and readability, each monitoring task in this chapter is divided into four identical sections:

- Purpose.
- Sensors and Instrumentation.
- Data Analysis.
- Application and Limitations.

Data Management: The primary task of any monitoring system is straightforward: to collect data from the operation of the monitored structure. This data must be stored and analyzed automatically. It must be visualized, uniquely assigned, and accessible, while ensuring data security. As the scope of the measure increases, data management plays a decisive role. The guideline devotes a separate chapter to this topic, describing in detail the aspects of data management that must be considered for optimal use of monitoring data.

Quality Assurance of Measurement Systems: To ensure the highest quality monitoring results, which is critical for safety-related tasks, it is essential to consider several key aspects, outlined in this chapter. This chapter addresses topics such as personnel qualifications, quality assurance during design and tendering, installation planning, actual installation, and ensuring quality assurance during operation and data preparation and evaluation.

Practical Examples: The guideline concludes with a number of practical examples. We have thoroughly documented both large lighthouse projects and the monitoring of the "broad mass" on bridges, where a significant portion of the currently installed continuous monitoring systems are located. Each project is summarized on about three pages. The summaries include a description of the structure, the task, the monitoring system installed, and the results.

3.3 Guideline summery

The new DGZfP Guideline B 09 Structural Monitoring is one of the most comprehensive publications in the guideline series to date. It comprehensively covers the entire technical process, from the decision for or against monitoring to the practical implementation of extensive instrumentation, focusing on the technical components of monitoring systems. A key feature is a catalog of practical examples that illustrate monitoring applications for different structures, materials, and objectives. The guideline's clear purpose is to provide a common understanding of essential considerations to ensure that systems meet client needs while avoiding unrealistic expectations, given the increasing availability of monitoring services.

4 BAST GUIDELINE FOR THE STRATEGIC APPLICATION OF MONITORING OF ROAD BRIDGES

4.1 Motivation and objectives

A 2020 survey of experts from federal and state road authorities conducted by the German Federal Highway Research Institute (BASt) [1] revealed that the use of monitoring is limited to existing damages and deficiencies, despite the publication of the DBV guideline. The survey identified three key barriers: a lack of knowledge about the applications and benefits of monitoring, the procurement process for monitoring services, and the handling of data storage. The use of monitoring will be actively promoted within the structure's maintenance committee groups. Operators of road bridges must be supported by best practice examples, training, and standardized procedures for the use of monitoring. The German standard governing road bridge inspections is currently being revised, and the next version will include monitoring as a standard inspection routine [3].

In response, BASt initiated a research project to produce a brochure-type guide for the practical application of monitoring road bridge structures. A booklet cannot cover all the issues and questions that may arise in the context of a monitoring application. An additional compendium-type report was published to address these issues and questions. This report must address technical issues and specifically cover the assessment of economic viability of monitoring, the tender and award process for installation and operation of monitoring systems, and the considerations for drafting contracts. The report is available for pre-publication on the BASt website [6].

4.2 Content of the guideline

The content of the guideline is based on the best possible applicability to the use of monitoring within the road bridge maintenance process.

Monitoring use cases: The various possible uses of monitoring are summarized in the following section in the form of monitoring use cases. The project-specific use cases are derived from the project objectives and represent processes that contribute to achieving the defined goals.

Several use cases have already been identified in [1], which are already frequently used in practice or have potential for future application. At present, monitoring is mostly limited to reactive measures, such as monitoring known damage or

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deficits from recalculation or construction. However, the great potential of monitoring also lies in supporting predictive maintenance.

The use cases are structured in the form of fact sheets. This clear and plausible presentation of the comprehensive ways in which monitoring can be used to reduce barriers is essential. Each use case is thoroughly described, including the initial task, the implementation, and the benefits. Concrete examples are used to illustrate the application in practice.

The following list summarizes the various use cases, described in the guideline [10]:

- Known localized damages.
- Known deficits from recalculation or construction.
- Determination of effects.
- Support for regular inspection procedure.
- Accompaniment for major buildings.
- Maintenance and reinforcement measures.
- Load tests.
- Predictive life cycle management.
- Birth certificate.
- Measures during the construction period.
- Protection of buildings during neighboring construction work.

Monitoring Process and its Actors:

As described in the section on the DBV guideline, structural monitoring is a multi-stage process from the description of the objectives to the assessment of the monitoring results. The operating authority of the structure must implement a system that divides the task into phases and assigns actors responsible for processing each phase. The tasks of the phases can be tendered separately or combined. The phases are defined similarly to [4].

Economic feasibility studies: Bridge owners and operators must determine the benefit-cost ratio of any monitoring system before implementation. To evaluate this ratio, it is necessary to estimate the expected costs associated with the future use of a road bridge with and without monitoring. This is a complex task. The expected costs depend on future developments in the condition and performance of the bridge, the quality of the monitoring system and data processing, possible monitoring results, future decisions related to these monitoring results (i.e., decisions on actions such as traffic restrictions, inspection, maintenance, bridge replacement, etc.), the direct and indirect costs associated with these actions, and the costs of installing, operating, and maintaining a monitoring system. The difference between the expected cost of operating a bridge without and with monitoring is the value of monitoring provided by a monitoring system. If this metric is positive, the cost of a surveillance system is justified by its benefits. The guideline draws on literature and the expertise of the German road authorities. It highlights the similarities and differences between existing procedures for assessing the economic feasibility of maintenance measures and analyses for evaluating the benefit-cost ratio of monitoring systems. It also provides clear, practical advice on how to assess this ratio and discusses situations where such analyses are less relevant [11].

Procurement process: As previously outlined, one of the most challenging areas for bridge agencies in implementing monitoring into their daily operations is the management of tendering, awarding, and contracting activities. This is due to the novelty of monitoring as a technique for determining bridge safety measures. The following aspects are the main areas of concern:

- What are the required services to be tendered and provided?
- Who are the players and which specifications and expertise potential bidders must provide?
- What are appropriate award criteria?
- What constraints need to be considered when drafting the contract?
- How should liability claims be regulated and formulated?

The guideline authors' experience with bridge monitoring bridges provides a solid foundation for the proposed procedure. Tendering is a viable option. Parts of the overall service can be tendered separately, depending on the requirements. There are also different types of tenders, depending on whether specific service points or the entire service is functionally tendered. The right choice is influenced by several factors. In addition to price, these include quality assurance criteria such as the qualifications of the bidders. This is especially crucial because vendors sometimes make exaggerated promises. When drafting contracts, it is essential to address specific issues that differ from a standard bridge inspection. It is essential to know how to deal with a temporary outage of parts the measurement equipment, e.g., due to vandalism. Minimum response times must be defined. Rules must be established for very long measurements to account for the additional costs of aging measurement equipment that may need replacing. Liability issues must also be addressed. The guideline provides clear recommendations for choosing the right type and scope of tender. The guideline also provides clear recommendations for negotiating contracts.

Further, the brochure includes checklists for the topics discussed above. These include tendering and awarding, as well as contract design and liability.

Measurement technology: Instrumentation combines all the technical components of a monitoring system. This includes not only the actual sensors, but also components for signal transmission, data processing, and storage. A classical monitoring system is made up of sensors, sensor connection components, data acquisition systems, and a measurement computer to which other external components can be connected. The guideline lists and presents the various aspects that influence the selection of measurement technology to assist in the best practice application of monitoring in bridge condition assessment. The selection of measurement technology is based on the monitoring concept, which considers all aspects of the technical implementation of a monitoring task in the monitoring system. In addition to the monitoring objective, this includes the type and size of the structure to be monitored, requirements for long-term stability or, if necessary, interchangeability, and economic criteria. It is essential that the selection of the sensor technology be based on clearly defined requirements. These requirements include the measuring range, measuring accuracy, sensitivity, measuring resolution, and sampling frequency. Finally, it is essential to consider potential technical and environmental influences.

The guideline clearly describes the different technical components of conventional monitoring systems. Additionally, new types of IoT (Internet of Things) monitoring systems,

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typically organized in sensor network structures, are briefly discussed. The relationship between the measurement task and the measurement technology is presented to assist road bridge authorities. The previous section clearly outlined the most well-known and commonly used sensors. The sensors mentioned have clear applications, measurement, and target variables. The measurement principle is presented, and if necessary, comments on advantages and disadvantages or special notes on application limitations are given.

Data Management: Although managing monitoring data is challenging for road authorities, it is valuable for future inspections and new methods. Data management is covered in national and international literature. The focus is on solving data management challenges as a governmental task to preserve information for the long term. Only one third of the monitoring data is stored at road agencies due to difficulties in structuring and sharing data between private companies and public agencies. This means that data management recommendations are needed. Currently, specialized structural measurement service providers (SSMSPs) handle most of the data. Some advanced road authorities also act as SSMSPs.

Both SSMSPs and road authorities are responsible for storing monitoring data. SSMSPs are responsible for collecting and analyzing data, while road authorities are responsible for receiving, archiving, and sharing it. The requirements for road authorities were collected in user stories to help prioritize data management needs. These user stories are visualized as a user story map, which will help road authorities prioritize their requirements when evaluating data management software. The discussion revealed that road authorities must address SHM data governance and sovereignty but currently lack structured processes for receiving, archiving, and sharing SHM data, including quality control. To address this issue, two business processes were developed to facilitate the receipt of structured data.

The first process begins with an inspection request and involves creating an employer's data requirement (EDR) document that specifies data formats, metadata, and delivery cycles. After the road authority approves the EDR, the SSMSP delivers the data as agreed. Then, the road authority verifies the data delivery and makes it available in asset management systems.

The second process describes how stakeholders who oversee structural assessments use monitoring data. If the SSMSP performs the assessment, they must ensure the data is reusable and well-documented. This process includes negotiating a usage agreement and providing access to the data for automated and manual workflows.

Long-term data preservation should be independent of proprietary software to enable broad accessibility and new business opportunities.

4.3 Guideline summery

The guideline was developed due to a lack of awareness regarding which structural use cases should be monitored to provide information or improve bridge integrity, and which measurement technology is appropriate. Most importantly, there is a lack of a standardized monitoring process, as well as an unknown set of parties involved in the process. Additionally, there is a lack of knowledge on how to determine the economic feasibility of monitoring and how to tender and award monitoring services. Data management is another area of concern. The guide suggests approaches here and describes important boundary conditions that need to be considered.

The final document offers solutions to all these issues. In addition to the detailed guideline report, the most important statements are summarized and published in a short, concise brochure. Throughout the guideline development process, consultations and discussions were held with the target audience of state and federal road agencies. These consultations are seen as a necessary basis for successfully introducing and accepting the guideline. [10, 11].

5 DGZFP GUIDELINE FOR DETECTION OF WIRE BREAKS BY ACOUSTIC EMMISION ANALYSIS

5.1 Motivation and objectives

Prestressed concrete construction began in Germany in the 1950s. It was characterized by experimental approaches and diverse prestressing systems, although the relevant codes were slow to develop. The key was recognizing the need for high tensile strength in prestressing steel to maintain effectiveness despite creep and shrinkage. While tempering and alloying improved the strength of prestressing steels, it also increased their susceptibility to stress corrosion cracking (SCC). This issue affected steels from the 1950s to the 1970s, and in East Germany until the 1990s [12]. SCC can cause brittle fractures in prestressing steel that are observed during construction and are attributed to the storage, installation, and pre-grouting periods. Damage can also occur after prolonged use in well-built structures. Evaluating these structures is challenging due to the difficulty of inspecting internal tendons and detecting wire breaks. Some structures lack sufficient reinforcement to ensure safe load transfer when prestressing steel fails, which can lead to sudden failure. Many structures with vulnerable prestressing steel are still in use today, and significant damage continues to be observed.

The challenge lies in the limited accessibility of tendons embedded within concrete. In recent years, acoustic emission (AE) monitoring has become a key method for detecting prestressing wire breaks in Germany. AE was originally used to test high-safety industrial equipment, and its potential for construction was recognized in the 1990s. AE monitoring was first applied to suspension and cable-stayed bridges, followed by prestressed concrete bridges. AE offers continuous, comprehensive monitoring, enabling immediate detection and localization of damage. Through automated analysis, it provides reliable data on wire breaks, making it indispensable for owners. Affected structures can continue operating safely, which allows for better planning and resource management.

Ensuring safe and reliable bridge operation is critical. Regular inspections according to DIN 1076 are an important tool for this. Shorter inspection cycles are recommended for bridges with SCC-prone prestressing steel. Continuous monitoring methods, such as AE can detect wire breaks permanently and allow for the dynamic evaluation and adjustment of inspection intervals. AE monitoring significantly contributes to safe bridge operation by transitioning from a scientific method to a standardized procedure. In this context, the guideline SE 05 “Detection of prestressing wire breaks with acoustic emission” [7] establishes a framework for procurement and quality-assured operation.

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The SE 05 guideline aims to standardize the application of AE monitoring for detecting prestressing wire breaks as well as outline the method's capabilities and limitations. The guideline provides detailed instructions for planning, tendering, installing, operating, and evaluating an AE monitoring system. The guideline also offers recommendations on technical and personnel requirements as well as quality standards to ensure an effective information system. The guideline's scope includes bridges and other engineering structures with bonded prestressing wires, though the described methods could also apply to unbonded tensioning systems.

5.2 Content of the guideline

The guideline is structured to help interested readers first understand the methodology and a proposed practical approach to applying AE monitoring for lifetime detection of wire breaks. After an introduction to the guideline, important terms, definitions, and abbreviations are presented.

Methodology: AE detects damage by capturing the elastic energy released as shock waves, which can be detected by surface sensors. This guideline explains this principle as it applies to monitoring prestressing wire breaks and provides basic implementation instructions. AE analysis requires high sampling rates and complex data analysis. Recommendations include the type of sensor, the frequency range, and pre-amplification. Piezoelectric sensors with a resonant frequency of 20-80 kHz are typically used to ensure sensitivity and minimize interference from low-frequency noise. Optimal sensor placement is critical for accurate detection and localization. Sensors should be strategically distributed based on the structure's geometry, material properties, and expected signal attenuation. The maximum allowable distance between sensors depends on factors such as signal strength, noise level, and the structure's damping characteristics.

The effectiveness of AE monitoring depends on distinguishing signals from background noise. Additionally, AE only detects active damage and not preexisting wire breaks. Complementary methods, such as non-destructive testing or invasive inspections, are required to establish baseline conditions at the start of monitoring.

Implementation and service description: After identifying the need for continuous monitoring, the system requirements must be defined and the procurement process initiated. Because each bridge has unique characteristics, such as structural geometry (e.g., box girder or T-beam), material properties (e.g., concrete type), and environmental factors (e.g., traffic load), each bridge requires a customized monitoring design. The guideline provides detailed instructions for acoustic analysis, sensor layout, and performance specifications.

Qualification of provider: As no official certifications exist, personnel and operational qualifications for AE monitoring can only currently be demonstrated by reference projects and experience. Design, installation, and operation must be performed by qualified personnel. Detailed recommendations for qualification verification are provided.

Data analysis and reporting process: This section outlines the steps from data collection to action. Automated analysis identifies potential wire breaks that require verification using additional methods or by engineers. Confirmed breaks are then used for structural evaluation. The discussion covers essential information for documenting candidate wire breaks.

Appendices: The appendices offer supplementary technical information, including recommendations for supervising wire removal via acoustic emission, methods for determining background noise levels and signal attenuation, and calculations for maximum allowable sensor distances based on structural geometry and material properties.

5.3 Guideline summery

This guideline introduces acoustic emission (AE) analysis as a tool for continuously monitoring prestressing wire breaks in concrete bridges. AE technology can detect and locate wire breaks in real time, offering critical information about the structural health of bridges. Therefore, it offers a unique opportunity to assess and manage structures at risk of stress corrosion cracking. AE is the only method that can directly detect wire breaks and requires specialized knowledge. This method applies to bonded prestressing systems but not to unbonded tensioning systems. However, it cannot detect wire breaks that occurred prior to the start of monitoring.

The increased interest and use of AE systems has led to better regulation of procedures and requirements, as recognized by the DGZfP committee. This resulted in the SE 05 guideline. This guideline, developed by multiple parties, represents accepted technical standards and provides detailed instructions for the procurement and quality assurance of AE systems during installation and operation.

6 CONCLUSIONS AND OUTLOOK

6.1 Conclusions

The reviewed German guidelines - DBV Bridge Monitoring, DGZfP B09 Structural Monitoring, BASt Strategic Application of Monitoring, and DGZfP SE 05 Detection of Wire Breaks Acoustic Emission Monitoring - collectively provide a structured framework for conceiving, implementing, and managing SHM in bridges and other engineering structures. The guidelines address different aspects, ranging from process structuring and economic assessment to technical system selection and quality assurance, and offer complementary strengths.

Despite these advances, the practical implementation of SHM is limited and is often restricted to event-driven responses rather than proactive and predictive maintenance. Key barriers include a lack of practitioner experience, challenges in procurement and tendering, and unresolved issues in data management and ownership. While the guidelines have helped clarify roles, standardize processes, and provide examples of best practices, they also reveal gaps, particularly the absence of a unified, one-size-fits-all approach and the need for harmonized data management systems.

The transition from technological development to standard practice is underway. However, widespread adoption requires technical solutions, organizational clarity, and contractual clarity. Collaboration among stakeholders, including infrastructure owners, service providers, and researchers, is essential to bridge the gap between advanced SHM technology and practical application. Every phase of SHM projects must include economic evaluation and quality assurance to ensure cost-effectiveness and reliability.

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6.2 Outlook

The upcoming revision of the German bridge inspection standard, DIN 1076, is expected to accelerate the integration of monitoring into standard maintenance practice by incorporating SHM as a routine element. As SHM becomes more prevalent, the need for standardized data management and protocols for data sharing and ownership will grow. Future guidelines should address these topics in greater depth. Furthermore, future guideline editions must include regulations on personnel qualifications and calibration of monitoring hardware. Training programs and knowledge transfer initiatives should be developed to provide practitioners with the expertise necessary for the effective deployment of SHM. Guidelines should address differing expectations between practitioners (e.g., bridge operators) and SHM service providers to promote clear communication and user-friendly solutions.

A unified guideline or standard integrating technical, economic, and contractual aspects is needed to make it easier for practitioners to implement SHM, regardless of project size or complexity.

Future work should also focus on aligning German guidelines with European and international standards to facilitate cross-border projects and knowledge exchange. This includes adopting common terminology, data formats, and quality assurance procedures.

Additionally, future guideline issues should continuously integrate the results of ongoing research focusing on predictive analytics, integration with digital asset management systems, and the development of scalable, adaptable SHM solutions. SHM guidelines should support a shift from reactive to predictive maintenance by leveraging monitoring data to optimize infrastructure management and extend service life.

By fostering collaboration, harmonization, and continuous improvement, SHM guidelines can ensure the safety, reliability, and sustainability of critical infrastructure in Germany and Europe.

REFERENCES

[1] I. Hindersmann, BASt-Heft B 163: Dauerüberwachung von Bestandsbrücken – Quantifizierung von Zuverlässigkeit und Nutzen (Berichte der Bundesanstalt für Straßenwesen, Reihe B: Brücken- und Ingenieurbau - B 163), 2021.

[2] DIN 1076:1999-11 - Ingenieurbauwerke im Zuge von Straßen und Wegen; Überwachung und Prüfung, D. D. I. f. Normung, 1999.

[3] G. Marzahn *et al.*, Bauwerksprüfung nach DIN 1076, Bautechnik, vol. 100, no. 11, pp. 699-706, 2023, doi: 10.1002/bate.202300090.

[4] DBV-Merkblatt Brückenmonitoring – Planung, Ausschreibung und Umsetzung, DBV, 2018.

[5] DGZfP Merkblatt B 09 (2022) Dauerüberwachung von Ingenieurbauwerken, 2022.

[6] BASt, Leitfaden – Strategischer Einsatz von Monitoring für Ingenieurbauwerke - Pre-publication, 2024. [Online]. Available: https://www.bast.de/DE/Publikationen/Fachveroeffentlichungen/Ingenieurbau/Downloads/B-fv-15-0707.html

[7] Detektion von Spanndrahtbrüchen mit Schallemission, DGZfP, 2024.

[8] Merkblatt B 12. Korrosionsmonitoring bei Stahl- und Spannbetonbauwerken, DGZfP, 2018.

[9] B. Novák *et al.*, Monitoring für Brückenbauwerke - Erfahrungssammlung, Dokumentation 2021 - Schlussbericht, in Projekt-Nr. BMVI: StB 247192.7040-3418027, ed: Bundesministerium für Verkehr und digitale Infrastruktur, 2021.

[10] F. Wedel *et al.*, Guideline for the strategic application of monitoring of road bridges in Germany, e-Journal of Nondestructive Testing, vol. 29, no. 7, 2024/07 2024, doi: 10.58286/29582.

[11] F. Hille *et al.*, "Developing a guideline for structural health monitoring of road bridges in Germany," in Bridge Maintenance, Safety, Management, Digitalization and Sustainability, Kopenhagen, Danmark, 24.06.2024 2024: CRC Press, pp. 2009-2017, doi: 10.1201/9781003483755-236.

[12] M. Fiedler *et al.*, Detektion von Spanndrahtbrüchen mit Schallemissionsanalyse, Beton- und Stahlbetonbau, vol. 120, no. 2, pp. 150-164, 2025, doi: https://doi.org/10.1002/best.202400098.