

Corrosion Identification, Location and Assessment of Prestressing Tendon Anchorages in Suspension/Cable-Stayed Bridges: Integrating Image Recognition and Machine Learning with Acoustic Emission Method

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ABSTRACT

The intensive development of transport infrastructure in Poland and worldwide has led to a rapid increase in the number of engineering bridge structures. Prestressed concrete is currently the most commonly used structural material (43.4%). One advantage of prestressed concrete is the ability to achieve considerable span lengths; consequently, the percentage share of the surface area of such bridge structures is even greater, reaching 58.2% by the end of 2017. Although visual checks are feasible for tendon components, assessing prestressing force and diagnosing cable issues (like corrosion, grout condition, and voids) in prestressed structures is a significant technical and research challenge. This paper introduces a monitoring approach, using periodic inspections or continuous electronic monitoring, to evaluate their condition. This approach employs a novel measurement system that identifies anomalies by recognizing patterns in acoustic emission signals. Furthermore, the pattern classes have also been correlated with crack opening widths, allowing for tracking the influence of crack development on the structural stiffness and monitoring other processes such as corrosion and slippage at the anchorage.

INTRODUCTION

Poland's rapid transport infrastructure development over the last 20 years has significantly increased the number of engineering bridges, reaching approximately 8,500 under GDDKiA management by the end of 2024, with over 75% built after 1999. Prestressed concrete is the most common material (43.4%), covering an even larger surface area (58.2% by 2017) due to its suitability for long spans.

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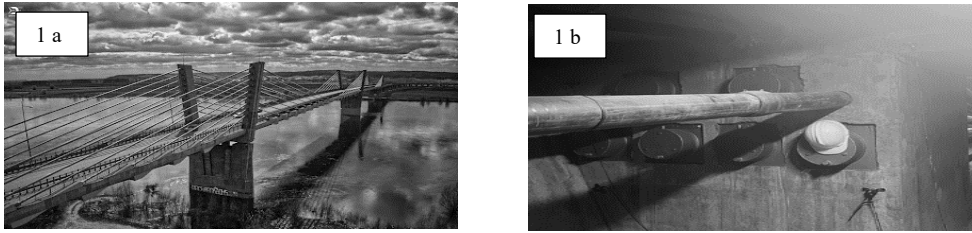


Figure 1. View of the bridge (1a) with an internal anchor block for prestressing cables (1b)

While tendon components are visually accessible, assessing prestressing force and diagnosing cables (e.g., corrosion, grout condition) remains challenging, especially in anchorage zones, despite global research efforts. Life Cycle Cost Analysis (LCCA) emphasizes the importance of monitoring systems to minimize maintenance costs, particularly by tracking the condition of prestressing and stay cables in relevant structures. Recent bridge collapses such as those in Prague (2017), Genoa (2018), and Taiwan (2019) highlights the need for specialized diagnostics and monitoring. Therefore, developing effective diagnostic techniques for post-tensioned concrete and cable-stayed structures is crucial. Implementing monitoring systems, either periodic or continuous, using innovative acoustic emission (AE) signal pattern recognition to identify anomalies and correlate them with crack opening widths, corrosion, or anchorage slippage, may be justified for evaluating their technical condition. This paper details the results of an AE-based monitoring system, that applies the pattern recognition analysis on the reference signal database to automatically identify operational processes in the anchor blocks of prestressing cables in a cable-stayed bridge [Figure 1]. Together with Artificial Intelligence (AI), it forms the Identification of Active Anomalies (IAA) system proposed in this work.

During regular traffic, cable displacement was measured, and AE signals were recorded at selected anchor blocks, where ground-penetrating radar (GPR) tests were also conducted. Widely recognized as a reliable non-destructive testing (NDT) method [1], AE detects and monitors anomalies and their development by sensing signals from micro- and macro-crack formation, growth, and friction, unlike techniques limited to geometric discontinuities [2-3]. AE can identify fiber rupture, delamination, matrix cracking, fiber pull-out, and corrosion. AE signals undergo scattering and attenuation due to wave elasticity. Dang Hoang et al. [4] linked AE energy duration to failures in aluminum plates. Similarly, Mpalaskas A.C [5] correlated AE event rates with fatigue crack growth in steel compact tension (CT) specimens. Biswas [6] found that AE parameters such as rise angle, duration, and rise time are sensitive to the crack propagation rate and helpful in identifying shear fracture in fatigued CT specimens. Their work [6] also demonstrated AE's potential for monitoring fatigue damage in steel and welds, as it is sensitive to changes within cracks, including those from corrosion. Therefore, in the present research, the sensitivity of AE to material degradation, as discussed above was used to identify specific characteristics indicative of layered cable cracking caused by corrosion. To categorize AE signals based on their generating processes, an iterative *k-means* clustering method was applied to AE parameters within the Euclidean space [7-8].

ACTIVE ANOMALY IDENTIFICATION (AAI) SYSTEM BASED ON THE ACOUSTIC EMISSION (AE) METHOD.

An iterative k-means clustering method grouped AE parameters in Euclidean space for signal classification. This method iteratively refines representative patterns for each cluster. Each iteration updates these patterns using predefined calculations. A pattern component can be a member of the data set X or a member of a larger universe $U \supseteq X$, depending on assumptions. The pattern component, calculated as the arithmetic mean, in metric spaces, represents the cluster centroid.

Generally, a ***k*-clustering** algorithm takes a set of objects (X) and the desired number of clusters (k) as input, outputting a partition $\{C_1, C_2, \dots, C_k\}$. Most k-clustering algorithms are optimization algorithms, assuming a loss function of the type $k : \{x | X \subseteq S\} \rightarrow \mathbf{R} +$ defined for each subset S . The goal is to find a grouping that minimizes the sum of these losses, described by the relationship (1):

$$E_q = \sum_{i=1}^k k(C_i) \quad (1)$$

Applying the iterative algorithm requires defining the clustering distance metric. Here, the metric uses a resultant point for each cluster—a representative component calculated, for instance, as the geometric or arithmetic mean, as shown in formula (2)

$$k(C_i) = \sum_{r=1}^{|C_i|} d(\bar{x}^i, x_r^i) \quad (2)$$

where: \bar{x}^i – is the arithmetic (or geometric) mean of the cluster.









This allowed the creation of a reference signal library/database for material-based anomalies in the cable-stayed bridge's structure. Acoustic signals from damage are detected using a zonal location method. In zones including support areas, where friction signals are a concern, surface location with guard sensors should also filter external signals (support contact points). Each zone is assessed, and the entire component is then evaluated based on the degree of damage in each zone compared to reference signals. Damage extent and structural sensitivity should be coded according to Tables I and then compared with traditional assessments of all components. This assessment analyzes changes in acoustic emission intensity within specific structural component zones. Recorded AE signals are grouped into classes corresponding to different destructive mechanisms during the structure's service life. The number of recorded AE signal parameters must match those in the reference database. AE signal grouping and classification should use image recognition. An intensity code indicates the severity of damage processes within a category. These processes are best visualized with scatter plots, where each AE signal is represented as a point, and its color and shape denote its class. Table II compiles these classes, symbols, and codes.

The applied IAA methods also allow for the approximate estimation of crack opening widths and the monitoring of their development over time in prestressed and cable-stayed structures.

TABLE I ESTIMATION OF CRACK WIDTHS CONSIDERING THE HAZARD CODE ASSESSMENT CRITERIA AND THE AE SIGNAL CLASS NUMBER

Codes	Description	Class No.	Crack Opening [mm]
0	Component not fulfilling its function or destroyed	No.8	Cracks > 2
1	Severe defect/damage and/or component is close to failure/breakdown	No.7	(0,8-2>
2	Moderate defect/damage that could lead to a loss of load-bearing capacity	No.6 No.5	(0,3-0,8>
3	Initial signs of deterioration of the structure's technical condition; minor defects/damage appear that do not affect the component's load-bearing capacity	No.4 No.3	(0,1-0,3>
4	New component or component with a defect that does not affect its load-bearing capacity	No.2	(0-0,1>
5	New component with no defects- satisfying the SLS (Serviceability Limit State) requirement	No.1	No scratches

TABLE II AE SIGNAL CLASSES, SYMBOLS, AND CODES

Symbols								
Classes	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8
Degree of danger	5	4	3	3	2	2	1	0

Class 1 Initiation of micro-cracking in the grout

Class 2 Initiation of micro-cracking at the grout-aggregate interface and development of microcracks

Class 3 Initiation of micro-cracks on the component surface

Class 4 Growth of cracks

Class 5 Loss of adhesion in the crack vicinity and prestressing cable corrosion

Class 6 Buckling of compression bars

Class 7 Crushing of compressed concrete

Class 8 Fracture of prestressing strand/cable or rupture of reinforcing bar.

TESTS AND RESULTS

This research project used acoustic emission to investigate selected structural components of a road bridge spanning the Vistula River near Kwidzyn (National Road No. 91, between Korzeniewo and Opalenie). The structure is an 808.5 m long extradosed, concrete box girder bridge (including 1862.5 m access viaducts), with a main span of 204 m. The study focused on eight reinforced concrete blocks anchoring prestressing cables within the bridge's box girder. Bridge Management data indicated three prestressing cable failures due to corrosion between 2021 and 2024 (examples in Figure 2).

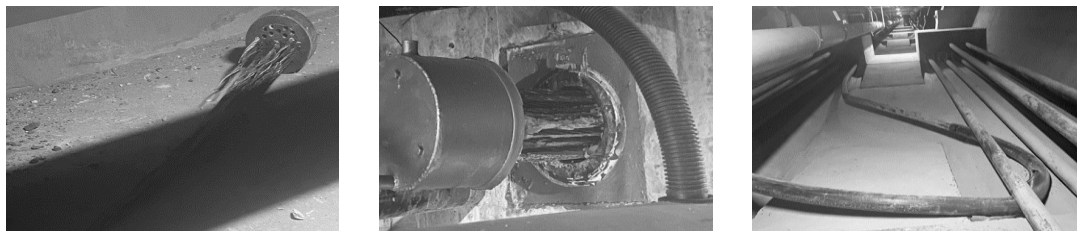


Figure 2. Corrosion of prestressing strands in the anchor block



Figure 3. Representative abutment block subjected to AE testing.

Description of Field Investigations

The field investigations involved acoustic emission (AE) monitoring of crossbeams No. 22, 23, 25, and 26 (Figure 3). Eight sensors (four per side) were installed on each block to detect potential abutment block defects (cracks), cable corrosion, or incomplete grouting. This allowed both surface and spatial localization of AE sources. Investigations used a 24-channel AE processor with AWin and NOESIS 12 software, along with VS-75 flat-response sensors with integrated preamplifiers.

Results

Automated analyses were performed in NOESIS software to demonstrate the IAA system's functionality for two crossbeams: 25P (safe operation) and 25L (corrosion and wire cracking detected).

CROSSBEAMS No. 25L AND 25P

Figures 5 and 6 present graphs of selected AE signal parameters (strength and duration) from monitoring crossbeams 25L and 25P, analyzed using pattern recognition. Scanning the upstream side of block 25P revealed weak signals, possibly indicating minor voids in the concrete and the development of cracks within the anchor block. No signals suggested cable corrosion (Figures. 5a and 5b). Figures 5a, 5b, 6a, and 6b show that signals marked No. 3 indicate the initiation and propagation of new cracks (duration $\leq 100,000 \mu\text{s}$). Signals No. 4 indicate crack propagation. These existing defects are typical during anchor block operation and did not affect its safe service life at the time of investigation. Scanning the downstream side of block 25L (Figures 5b and 6b) revealed strong signals indicating minor voids, inadequate vibration, crack development, prestressing cable corrosion (No. 5), and fracturing of individual cable fibers (No. 7 and No. 8). Signal strength was up to 10 times greater than that in block 25P. Signals also indicated cable corrosion (Figure 2). Signals No. 3 indicate new crack initiation and propagation (duration $\leq 120,000 \mu\text{s}$). Signals No. 4 and No. 5 indicate crack propagation, debonding, and concrete-concrete friction. Signals No. 7 and No. 8 indicate steel corrosion and fiber fracturing. Defects No. 1-5 are standard during operation and did not affect safe service life. However, signals No. 7 and No. 8 indicate unsafe corrosion and fiber fracturing in the prestressing cables.

Close analysis of the red area in Figure 5b identifies the location of corrosion and fiber fracturing within the anchor block.

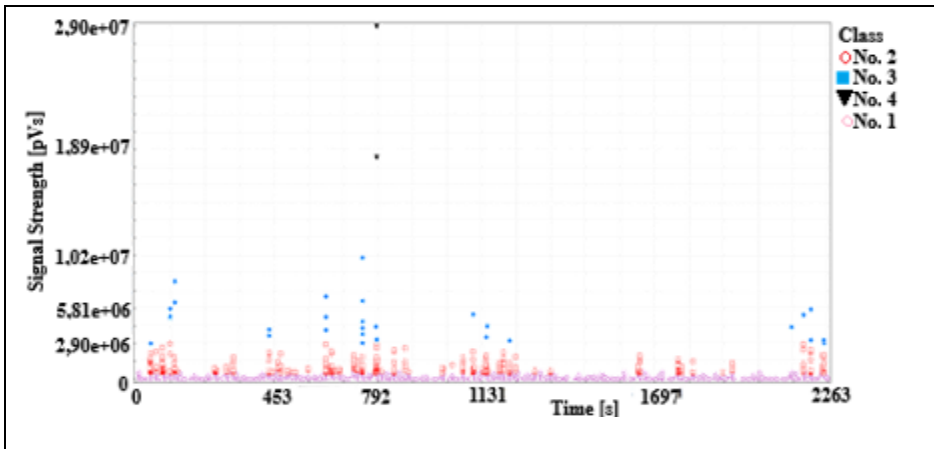


Figure 5a. Scatter plot of signal strength versus time for anchor block No. 25P .

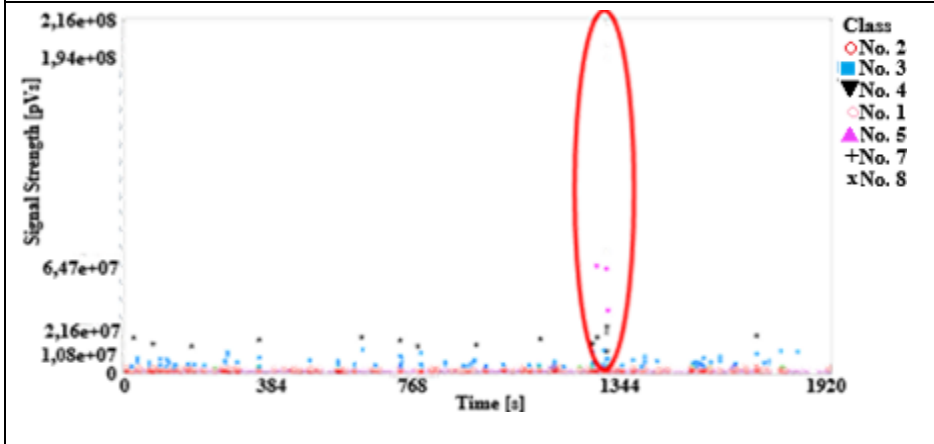


Figure 5b. Scatter plot of signal strength versus time for anchor block No. 25L.

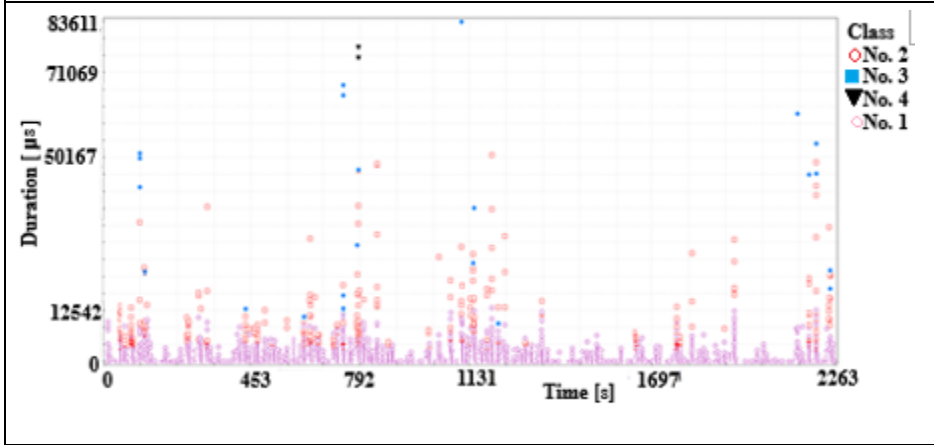


Figure 6a. Scatter plot of AE signal duration versus time for anchor block No. 25P.

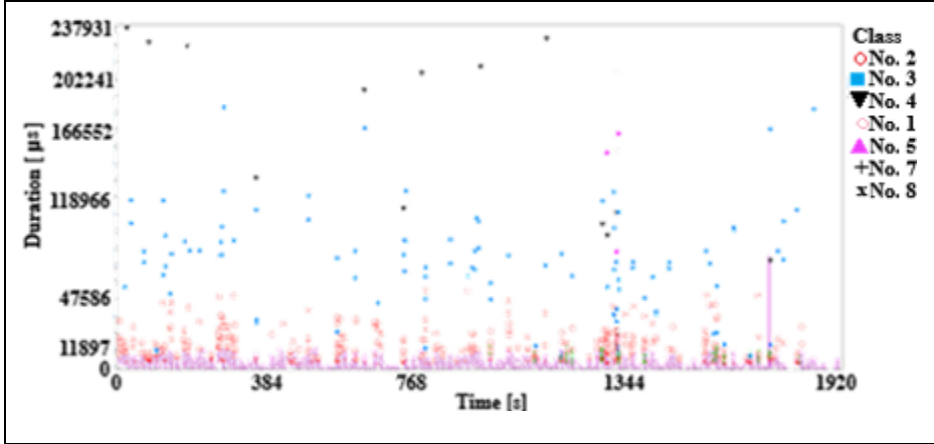


Figure 6b. Scatter plot of AE signal duration versus time for anchor block No. 25L.

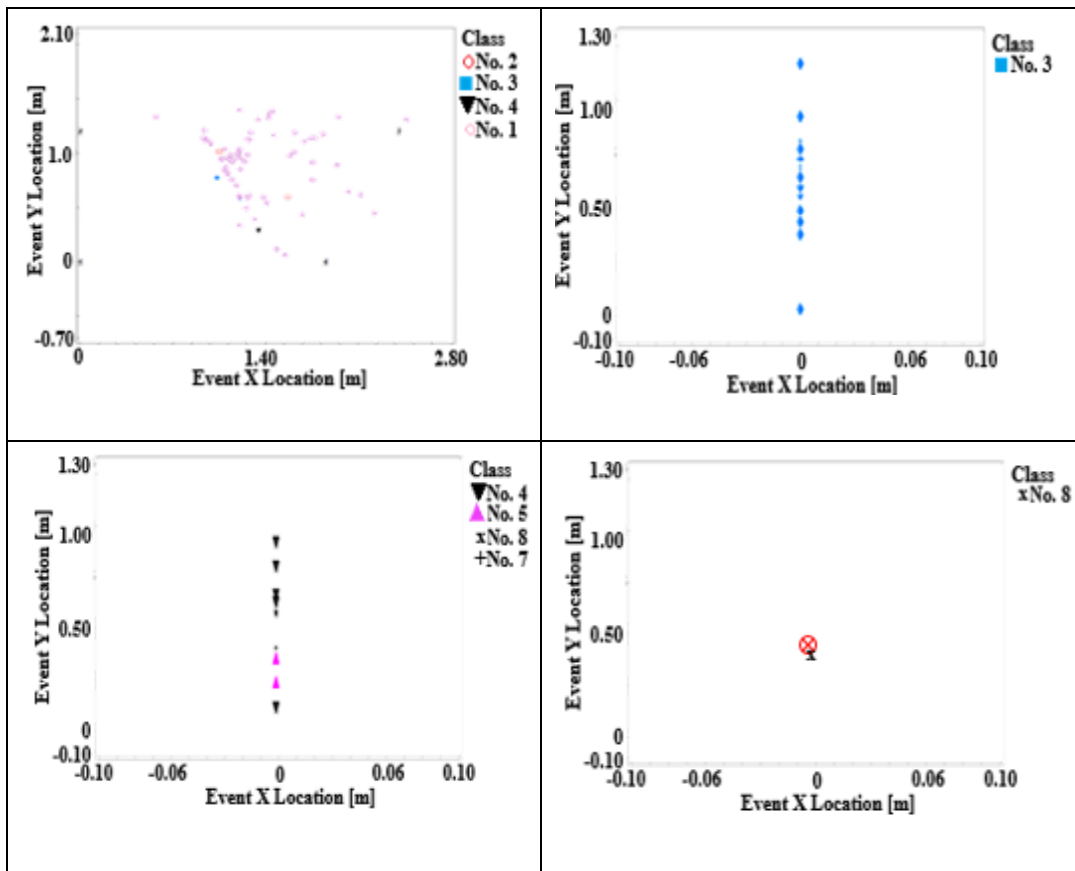


Fig. 7. Location of anomalies affecting the condition of the tested anchor block and the position of the most critical area – cable corrosion and fracturing of individual steel fibers.

Figure 7 shows this localized area with hazardous anomalies.

CONCLUSIONS

1. The signals recorded and analyzed using the reference signal database for anchor blocks 22L, 22P, 23L, 23P, 25L, 25P, 26L, and 26P indicate the regular operation of the reinforced concrete components with existing cracking. New microcracks and cracks were observed at the cement paste-aggregate interface, as well as friction between concrete surfaces within existing cracks, were observed. The identified defects (cracks) do not directly affect the load-bearing capacity of the investigated components.
2. In anchor block 25L, signals indicating destructive processes occurring within the prestressing cable, specifically the fracturing of individual fibers, were recorded. Therefore, the following is recommended:
 - mechanical intervention within the cable anchorage and removal of the cover to confirm the findings, OR
 - periodic monitoring of the indicated area on the abutment block (minimum measurement every 2 months), OR

- replacement of the identified prestressing cable after confirmation of damage.
3. During the investigation of anchor block 25P under traffic load, the locations of crack initiation and propagation locations were identified. Information regarding destructive processes occurring in the prestressing cable due to corrosion, confirmed by GalvaPULS testing, was also obtained. Currently, due to the high dynamic loads induced by transit traffic on the structure, it is recommended to perform acoustic emission testing at least twice a year (April and September) to monitor the intensity of crack propagation and the development of corrosion processes in the prestressing cable.
 4. The complete suitability of the IAA system for monitoring critical infrastructure objects, which are vital for safety, was confirmed.
 5. The system can operate in a continuous or periodic mode, depending on the condition of the monitored structure

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