Detecting Wire Breaks in Prestressed Concrete Pipes: An Easy-to-Install Distributed Fibre Acoustic Sensing Approach

Lisbel Rueda-García,[1] Daniel Tasquer-Val,[1] Pedro Calderón-Bofías[2] and Pedro A. Calderón[3]

[1] Concrete Science and Technology University Institute (ICITECH), Universitat Politècnica de València (UPV), Valencia 46022, Spain.
[2] CalSens S.L., Valencia 46022, Spain.
[3] Department of Construction Engineering and Civil Engineering Projects, Concrete Science and Technology University Institute (ICITECH), Universitat Politècnica de València (UPV), Valencia 46022, Spain.

Correspondence should be addressed to Lisbel Rueda-García; lisruega@upv.es

Abstract

The escalating water stress resulting from drought conditions in certain global regions underscores the imperative to minimize water losses, particularly within drinking water supply networks. One way to achieve this is by improving pipe monitoring systems to allow the early detection of possible structural collapse of the pipes. One type of pipe widely used in water mains is the prestressed concrete pipe, whose main cause of structural failure is the breakage of prestressing wires. This research paper analyses the ability of an easy-to-install DAS (Distributed Acoustic Sensing) monitoring system using fibre optics to identify and locate the acoustic signal produced by the wire breaks in prestressed concrete pipes to make early detection of possible structural failures. For this purpose, a large experimental pipeline stretch was built (approximately 1 m in diameter and 40 m long) where wire breaks were simulated. Several variables were studied: the origin of the signal (to distinguish wire breaks from events of a similar nature), the location of the event in the pipe, the presence of background noise, the internal water pressure, the length of the prestressed wire not subject to bonding with the concrete and the presence of water in the pipe. The results showed that the DAS system could detect almost all events. In addition, two of the multiple parameters measured in the signals, the zero-crossing rate and the short-time energy, made it possible to precisely determine the signal's origin and the event's location. Another parameter measured, the duration of the signal in this case, made it possible to differentiate whether the events had occurred when the pipe was empty or full of water. These and other results in this paper present a highly promising perspective on using this DAS system in water main monitoring.

Keywords: distributed acoustic sensing, fibre optic, prestressed concrete pipe, water main, wire break, structural failure, monitoring

1. Introduction

As indicated in the Technical report of the European Commission, "Drought in Europe March 2023" [1], much of Europe is currently under severe water stress due to an exceptionally dry and warm winter. Water scarcity is forcing a rethink of how the exploitation and supply of drinking water have historically been managed. To efficiently manage natural resources during the supply process, minimising losses in drinking water supply systems is necessary. One of the events that cause significant water losses is the structural failure of pipes in water supply networks. One way to avoid these losses is to detect early and precisely where these structural failures will occur so that it is possible to repair or replace these pipes before the failure occurs.

Since the mid-last century, many water operators have used prestressed concrete pipes in their pipelines because they provide durable, cost-effective solutions for large-diameter mains [2]. For example, in the USA and Canada alone, more than 30,000 km of this type of pipe were reported in major water utilities in 2000 [3], with many of the lines currently in use being more than 50 years old. Although the performance of this type of pipe has traditionally been very reliable, one of the problems that most affect prestressed concrete pipes, and their main cause of failure, is the breakage of the prestressing wires, also known as "wire breaks" [4–6]. Wire breaks can have different causes, such as corrosion, hydrogen embrittlement, high internal pressures, or overloading [7], with corrosion being the main cause [6]. Wire breaks cause the concrete core to deconfine. Thus, when a threshold number of broken wires is exceeded, the pipe fails at a load below its design strength. Corroded precast concrete pipes are prone to explosive failure during rapid changes in pipeline operation, such as periods of high demand, fire suppression, and heat waves [4]. The structural collapse of precast concrete pipes costs significant sums of money due to the repair or replacement of the pipes and the effect on other existing infrastructures where the pipes are buried. It could also present a public health problem due to possible contamination of the drinking water supply.

For all these reasons, it is very important to monitor the water mains to detect broken wires and to be able to act before reaching the structural failure of the pipes. In existing prestressed concrete pipes, the main inspection techniques used to know the current state of the pipe in terms of number of broken wires are (i) internal visual and sound inspections, where qualified personnel walk inside the pipe to perform a visual inspection and impact the interior surface to identify hollow sounds typical of delaminated areas in the pipe, and (ii) electromagnetic inspections, where electromagnetic equipment, which detects the continuity of the prestressing steel and estimates the number of broken strands, is pushed inside the empty pipes [2]. In new or inspected pipelines, acoustic monitoring is sometimes carried out by continuously monitoring the acoustic activity of the pipeline to identify the acoustic event associated with a wire break. This has traditionally been done using hydrophone arrays [8]. This technique, in which hydrophones are attached to hydrants or other network elements, has been widely used due to its effectiveness in water mains. However, they have certain limitations, such as the difficulty of using them in deep buried pipes and the signal attenuation with distance from the hydrophone. In the last 20 years, another acoustic monitoring system has been developed using fibre optic sensors [2,9], known as distributed acoustic sensing (DAS). The system allows the monitoring of several kilometres of pipes with a single data acquisition device. With this system, the attenuation of signals from an acoustic event is minimal. In addition, many of the traditional monitoring techniques require the dewatering of the pipelines and entail the risk of entering confined spaces. This is why the current trend is towards developing monitoring systems that allow their implementation without draining the pipe, that can be placed in both exposed and deep buried pipes, and that do not require the entry of large equipment or people inside them.

DAS is a fibre optic sensing technology that has rapidly developed in recent years, which allows continuous and real-time monitoring of physical phenomena such as acoustic vibrations, temperature changes, and strain. The technology works by sending pulses of light through an optical fibre cable and then measuring the changes in the backscattered light caused by external disturbances or vibrations. Since the entire fibre cable acts as a sensor, the cable is never further than a pipe diameter from a wire break [9]. DAS has multiple advantages, such as anti-electromagnetic interference, corrosion resistance, slenderness, and flexibility [10]. In addition, installing a fibre optic cable with various cores can be used for other purposes, such as telecommunication transmission. The application of this technology to linear infrastructure monitoring has broad potential. However, it faces many challenges, such as the vast amounts of monitoring data, the directional sensitivity of fibre optic cables, the longitudinal positioning of the fibre optic cables along the pipeline and the difficulties in processing data [10], as well as the placement of the cable in the pipeline through a simple and effective installation for locating wire breaks.

Recent research on using DAS technology in pipeline monitoring involves different types of fibre optic cable installation. For example, many researchers directly paste cables onto pipe walls, either along the pipe [11] or even helically around the pipe [12–15]. Although this surface-glued cable method may be more effective, it requires digging up the pipe for sensing or even going inside it, as in [16], which is very expensive and impractical. As explained in [10], other researchers bury cables in the ground soil near pipelines, as in [17–19]. Others place the fibre optic cable outside an uncovered pipe, at some distance from it [20], which would be less practical in a real application because of the danger of fibre interactions with external agents due to being exposed. Another group of authors [2,9,21–23] started in 2005 to introduce the fibre optic cable inside the pipe without gluing it to the inner wall. In particular, Higgins and Paulson in [2] showed an installation of the cable by pushing the fibre optic coil with a trolley along the inside of the waterless pipe and attaching the fibre to strain relief devices in the form of a metal ring attached to the inner wall of the pipeline. This type of installation was used in other real applications by the same group [21–23]. Other professionals in this group indicated in [9] that in the monitoring project of a section of the Great Man-Made River pipeline (Libya), which is one of the most significant water projects in the world, for the first time, it was intended to install the fibre optic cable using a parachute to pull the cable into place while the pipeline was in operation, without the need of dewatering the pipeline as had been done in previous projects. This type of installation would be the simplest and cheapest, although it carries the risk of poorer signal detection due to the attenuation caused by the medium surrounding the cable.

This paper studies the ability of an easy-to-install DAS system, in which the fibre optic cable is laid inside the pipeline without the need for internal fixings and with the possibility of being installed while the pipeline is in operation, to identify and locate the acoustic signal produced by the breakage of wires in prestressed concrete pipes to carry out early detection of possible structural failures. For this purpose, an extensive test programme was carried out in which the DAS system was installed in a large experimental pipeline stretch. In the tests, wire breaks were simulated by opening windows in the mortar of the prestressed pipes to gain access to the wires and cutting them with a shear. Through this experimental programme, multiple variables are studied in this article to analyse the capacity of the DAS to detect wire breaks in different situations accurately. These variables are (i) the origin of the signal, through the study of the ability of the DAS system to differentiate wire breaks from other signals of a similar nature, such as those generated by hitting the pipe with a hammer and noises caused by unidentified events; (ii) the location of the signal origin; (iii) the presence of background noise; (iv) the internal water pressure in the pipeline; (v) the size of the window in which the wire cut is executed; and (vi) the presence or not of water in the pipe.

The present research work provides valuable data obtained under controlled conditions from one of the largest experimental pipelines in the literature purposely created for this research, which increases the state of knowledge on the subject. In addition, multiple variables that can occur in real conditions are studied. Additionally, the research presents an easy-to-install system, as it uses a robust fibre optic cable, which is very easy to handle, and therefore does not require installation by qualified personnel. The contribution of this research in relation to the signal processing carried out is also interesting. Consequently, the present study supports the development of DAS as a continuous, remote, highly sensitive, resistant, simple, and passive monitoring system, making it attractive for real applications in pipeline monitoring.

2. Materials and Methods

2.1. Test variables

To achieve the objectives of this research, a test programme was designed to simulate and detect wire breaks. For this purpose, an experimental pipeline of almost 40 m in length, which included two prestressed concrete pipes, was built, into which the fibre optic cable of the DAS system used was introduced (the details of this test programme are given in the following sections). The experimental programme included the study variables described in the following paragraphs.

Origin of the acoustic signal. The main signal origin studied was the breakage of the prestressed concrete pipe steel wires. In addition, the signals originating from the hitting of the pipes with a hammer were analysed to observe the differences with wire break signals, as hammer blows produce sudden signals and therefore have certain similarities with wire break signals. Unidentified event signals were also analysed to differentiate them from the previous two. The unidentified events were events observed in the signal recorded by the DAS system that had similar characteristics to wire breaks but did not come from any event performed on purpose in the pipeline, so their origin is unknown.

Location of the signal origin. The wire breaks and the hammer blows were performed at various points of the experimental pipeline to analyse the ability of the DAS system to provide the location of the signal origin.

Presence of background noise. To identify wire breaks when there are also continuous acoustic signals from devices or machines, the various acoustic events (wire breaks, hammer blows and unidentified events) were also analysed in the presence of noise from a portable power generator placed on a buried section of the pipeline.

Internal water pressure in the pipeline. Given the limitations of the experimental setup, the tests with the pipe full of water were carried out without water flow. However, the water pressure could be varied, so signals were produced at different water pressures to detect variations in the signal captured by the DAS system according to the internal water pressure in the pipe. These pressures were 0, 0.5, 1.0, 2.0, 3.0, 4.0 and 5.0 bar.

Size of the window in the concrete. Corrosion of prestressing wires often causes spalling of the mortar above the wires, usually before the wire breaks. To detect differences in the signal generated by wire breaks depending on the length of the uncovered wire, windows of different sizes were opened in the mortar coating and different wire breaks were caused in them. Specifically, four window sizes were used: 8, 15, 30 and 60 cm.

Presence of water in the pipeline. To study the ability of the DAS system to recognise signals in different media, signals were generated with the pipeline full of water and empty.

Considering all the variables described above, the present experimental programme seeks to analyse the signal produced by the 138 events shown in Table 1.

Table 1: Summary of events analysed in the experimental programme.

Event type	Height of the window in the mortar [cm]	Without water	With water	TOTAL
Wire breaks	8	2	3	5
	20	7	16	23
	30	1	3	4
	60	3	3	6
Wire breaks + power generator	20	0	8	8
Hammer blows	-	7	47	54
Hammer blows + power generator	-	0	4	4
Unidentified events	-	15	15	30
Unidentified events + power generator	-	0	4	4
TOTAL	-	35	103	138

2.2. Prestressed concrete pipes

There are different types of prestressed concrete pipes depending on their layering. They all have a concrete core and a prestressing wire covered by a mortar coating. In addition, the pipes can have a steel cylinder (prestressed concrete cylinder pipes, PCCP), which can be embedded in the concrete core (embedded-cylinder pipes, ECP) or line the concrete core, so the prestressing wire is wrapped directly on the steel cylinder (lined cylinder pipe, LCP). If no steel cylinder exists, the prestressing wire is wrapped directly on the concrete core (prestressed concrete non-cylinder pipe, PCNP). In these tests, two PCNPs were used. The two pipes were removed from a drinking water pipeline installed in 1969, which was in operation until recently. The design pressure was 7.5 bar, and the operating pressure was 6.5 bar. The pipes were in perfect condition after removal.

The PCNPs tested had a length of 4 m, an outer diameter of 1020 mm and an inner diameter of 850 mm. The tubes had the layers shown in Figure 1. The circumferential prestressing wire had a diameter of 4.75 mm and a spacing of wire of 28.75 mm. The concrete core had longitudinal prestressing wires of 4.00 mm diameter every 83 mm (35 wires).

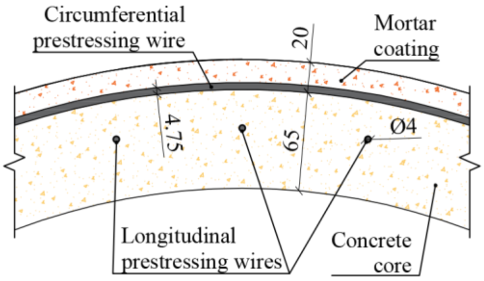
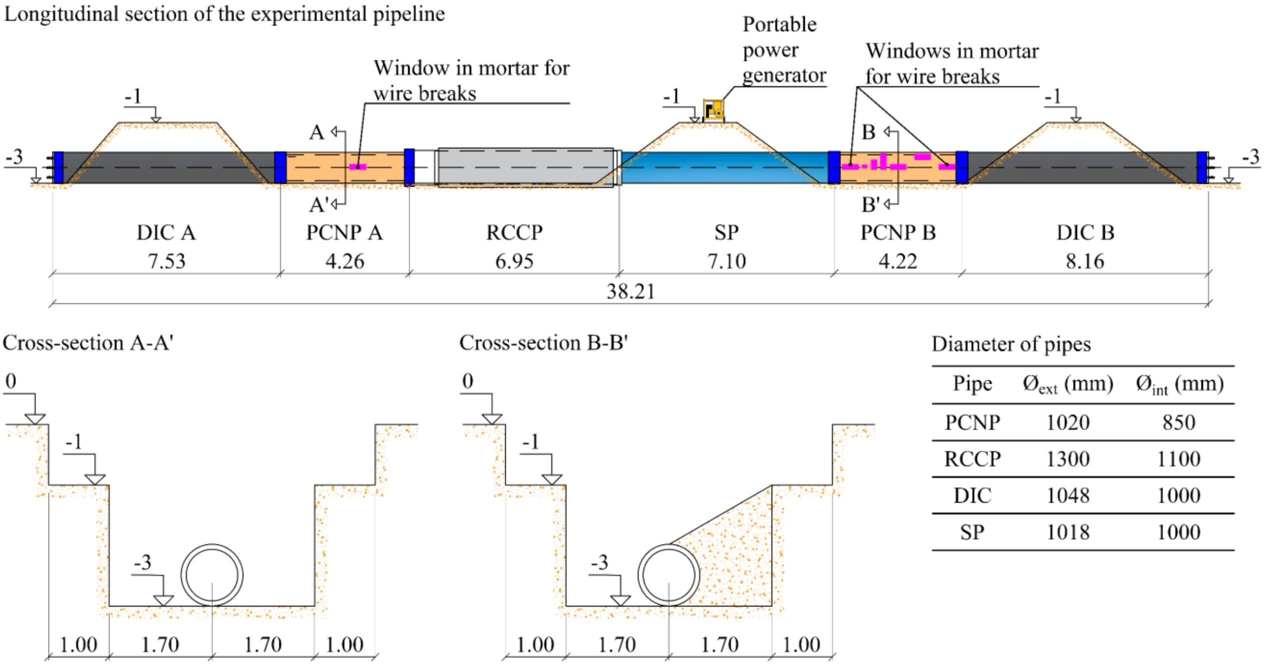


Figure 1: Layering diagram of the PCNPs tested (units: mm).

Due to the age of the pipes, their mechanical properties at manufacture are unknown. However, characterisation tests were carried out to obtain the present mechanical properties relevant to this study. These are the tensile strength and modulus of elasticity of the circumferential prestressing wire and the prestressing stress of the wire. To obtain the former, a tensile test was carried out according to UNE-EN ISO 6892 [24] by averaging the results of three tests. The resulting tensile strength of the prestressing wire was 1,656 MPa, and its modulus of elasticity was 159,250 MPa. To obtain the prestressing stress, a window was made in the mortar coating to access the wire, and a strain gauge was placed on the wire. The wire exposed in the window was cut while the pipe was empty to obtain the strain recovered by the wire after cutting. From the modulus of elasticity and the strain, a prestressing stress of 712 MPa was obtained.

2.3. Experimental setup

A 38 m-long experimental pipeline was built for field tests. The pipeline length was chosen to be long enough to have inside at least three 10-meter segments of fibre optic since, as explained in Section 2.4, the spatial resolution of the DAS system used was 10 m. To accommodate the pipeline, a trench that was 3 m deep and had a 1-meter high berm and 3.4-meter wide base was excavated, as illustrated in Figure 2.



Pipe	Øext (mm)	Øint (mm)
PCNP	1020	850
RCCP	1300	1100
DIC	1048	1000
SP	1018	1000

Figure 2: Experimental pipeline dimensions (units: m).

The experimental pipeline was built using two prestressed concrete non-cylinder pipes (PCNP A and PCNP B), one reinforced concrete cylinder pipe (RCCP), two ductile iron pipes (DIC A and DIC B) and one steel pipe (SP) ranging from 1018 to 1300 mm outer diameter, as shown in Figure 2. The two PCNPs, the subject of this study, were spaced approx. 14 m apart to have sufficiently separated signal locations. Furthermore, the PCNPs were sufficiently separated from the start and end of the pipeline by providing additional pipes (the two DICs) to ensure that the 10-meter segments of fibre optic that capture the signals produced in the PCNPs are entirely within the pipeline. The two ends of the piping were closed by blind flanges with different valves to introduce the fibre optic cable and to fill the piping with water. A manometer was installed in one of these valves to control the internal water pressure. The tests were carried out without water flow.

Although certain pipeline stretches had to be left uncovered to perform the tests and access the pipe couplings for adjustment during the tests, as much of the pipeline as possible was buried to simulate real conditions (see Figure 2 and Figure 3a). A concrete wall approx. 0.5-metre thick was placed at each end of the excavation to secure the shoring of the blind flanges (Figure 3b). Lateral shoring was also provided at the pipe couplings to prevent lateral displacement of the unburied pipes due to the rise in internal water pressure. The portable power generator to introduce background noise during some tests was placed on the buried section of the SP (see Figure 2).

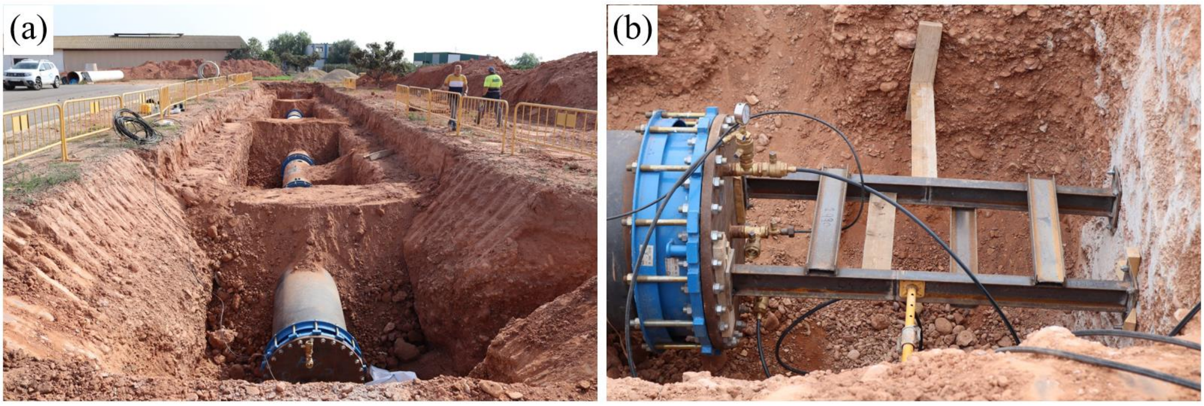


Figure 3: Photographs of the test area. (a) Overview of the experimental pipeline. (b) One of the blind flanges.

2.4. Wire breaks

To make the different cuts in the prestressing wires of the PCNPs, windows of various sizes were opened in the mortar coating with the help of a radial saw and a hammer drill (see Figure 4a), with a procedure similar to that used by other authors [7,21]. In the first PCNP (PCNP A in Figure 2), a 15 cm high window was made. In the second PCNP (PCNP B in Figure 2), one 8 cm high window, four 15 cm high windows, one 30 cm high window and one 60 cm high window were opened.

Figure 4: Preparation of prestressed concrete pipes. (a) Example of opening a 15 cm high window in one of the prestressed concrete pipes. (b) Wire break with a shear.

Wire breaks in PCNPs were simulated by cutting with a shear (see Figure 4b), as other authors did [22]. This method was chosen for its simplicity, speed and for reducing the extra noise during cutting compared to other tools, such as the radial saw. The aim was to simulate as closely as possible the wire break that would occur in an actual situation due to corrosion of the reinforcement. Furthermore, the suitability of this method was confirmed by the publication of Li et al. [15], where the wires were artificially broken with a radial saw and electrochemical corrosion, and it was found that the signal generated by the corrosion was almost identical to that caused by the artificial breakage of the bar.

2.5. Distributed acoustic sensing system

The monitoring system used in this research was a type of distributed acoustic sensing (DAS). The DAS technology employed is based on Chirped-pulse Φ-OTDR (Phase-Sensitive Optical Time-Domain Reflectometry), a variant of the classic Φ-OTDR. Φ-OTDR systems can detect disturbances in the fibre by recovering the induced phase information from the backscattered light travelling through the fibre core. The vibration's location and intensity can be obtained in this way. Chirped-pulse Φ-OTDR uses linearly chirped pulses to measure distributed strain and temperature changes in a single shot without requiring a frequency scan [25]. As explained by Pastor Graells in [25], the system's complexity is not noticeably higher than classic Φ-OTDR while it maintains the best aspects of that method: fast measurements are possible with a bandwidth only constrained by the length of the fibre (potentially across several tens of kilometres with metric spatial resolutions), and temperature/strain fluctuations are measured with resolutions several orders of magnitude lower than Brillouin.

The DAS system used in this research had one nano-strain sensitivity, 10-metre spatial resolution, 90-kilometre maximum range, high low-frequency performance, high signal-to-noise ratio [26] and no fading. The fibre optic cable used was a single-tube cable with a reinforced cover and loose single-mode fibres. This type of cable was selected following satisfactory results in previous studies by the research group. The cable has the advantages of being robust, watertight and inert in interaction with water, making it very suitable for insertion inside drinking water pipes without requiring highly specialised personnel or instrumentation due to its high resistance. Furthermore, only one of the fibres is used in the DAS so that the rest can be used for other purposes, such as telecommunications transmission.

The setup diagram is shown in Figure 5. A 930-metre fibre optic coil that acts as a reference was fused between the measuring cable and the interrogator. This coil was a single-mode optical fibre cable. The coil was introduced in a box to insulate it from outside noise. After the experimental stretch, 90 m of the measuring cable was left over. The fibre optic cable was introduced in the experimental pipeline while it was empty through one of the ends before closing it with the blind flange. The cable was laid down on the inner base of the pipeline with no tension.

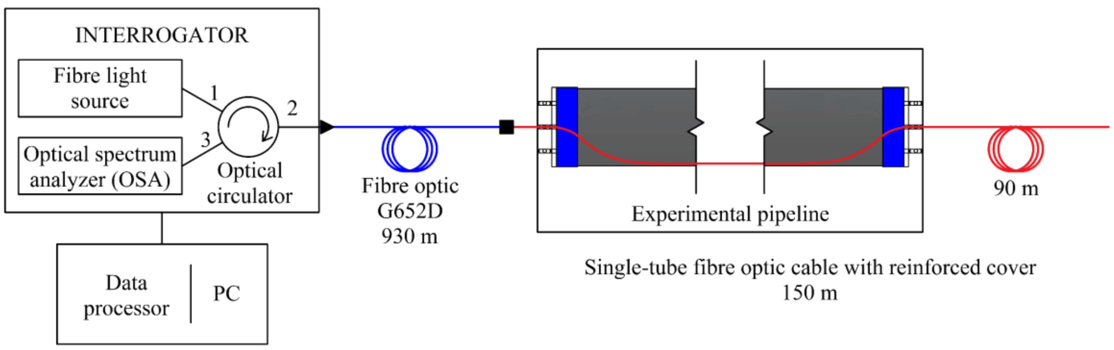


Figure 5: Setup diagram of the DAS system installed for the tests.

2.6. Test procedure

The tests were carried out in four different days. The sampling frequency of the DAS system was set at 1 kHz. In all the tests, hammer blows were dealt at the beginning and end of the pipeline to determine the fibre optic cable segment inside the pipe. For each wire break and hammer blow, the location of the event, the internal water pressure and the time of execution of the event were recorded for searching the events in the files generated by the DAS system. A total of 104 events were performed, 46 of which were wire breaks and 58 were hammer blows (see Table 1). In addition, 34 unidentified events were analysed.

3. Results and Discussion

3.1. Pre-processing of the original signal

When no tests were being run on the pipeline, i.e., during the idle situation, it was observed that the environmental and system noise had low frequencies with very high amplitude, much higher than that corresponding to the higher frequencies of interest in these tests. Consequently, a high-pass filter with a cutoff frequency of 30 Hz was employed to facilitate the visualisation of the data. The result of using this filter can be seen in the example in Figure 6a-b. In addition, other denoising filters were applied to clean the signal from the existing ambient noise to improve the detection of the programmed events. A discrete wavelet analysis (DWT) was carried out. The Haar wavelet transform was used with four levels, as in [15]. The efficiency and simple calculation of this filter allow the results to be processed in real-time, which is very important for the application of the system as continuous monitoring. In addition, the Minimax denoising methodology, also used in [15], is used as a thresholding rule since it is beneficial for signals with complex structures and important features that need to be preserved during denoising. The soft threshold function is also applied for better continuity of the signal. All this results in an amplitude-time plot that makes recognising the signals produced during the test easier. Figure 6b-c shows an example of the signal produced by a wire break in a cable segment inside the pipeline with and without the denoising filter.

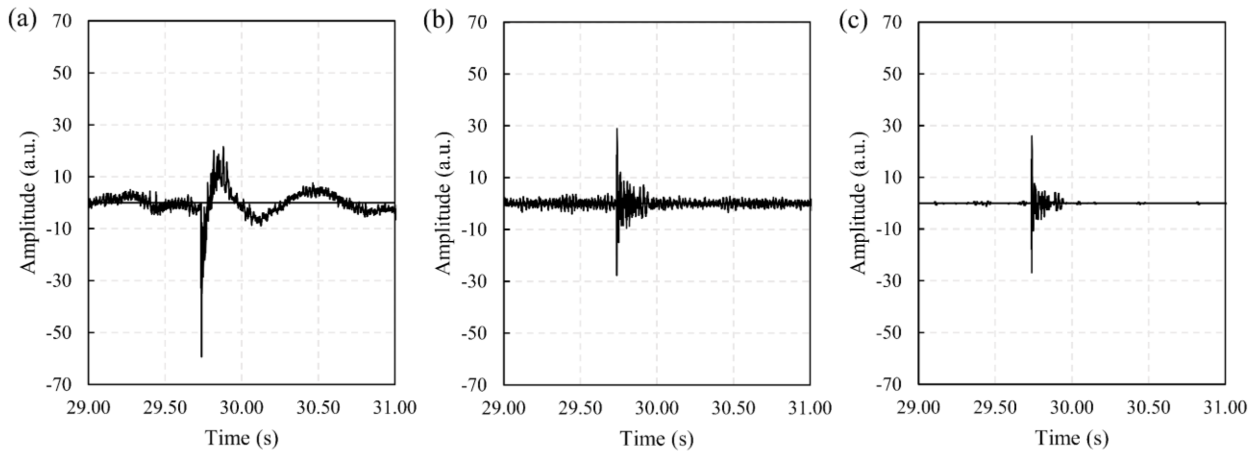


Figure 6: Example of the signal during a wire break. (a) Without filters. (b) With a high-pass filter. (c) With a high-pass filter and denoising filter.

The filters used proved to be appropriate to remove a significant part of the ambient and system noise from the signal without impairing the recognition of the test signals (wire breaks and hammer blows) and to show more clearly where the signals are located.

3.2. Detection of the events and signal parameters used for the analysis

Clean signals were obtained after applying the relevant filters to the signal, as in the examples in Figure 7. This figure shows representative examples of the signal produced by a wire break (Figure 7a) and by hitting a pipe with a hammer (Figure 7b). As can be seen, both signals have similar characteristics: they show a sudden large amplitude that attenuates over time. On the other hand, the signals produced by unidentified events all showed similar characteristics to the example in Figure 7c. Because of their similarity to the signals produced by wire breaks, these were also studied in this article to find the parameters that differentiate them from the other signals.

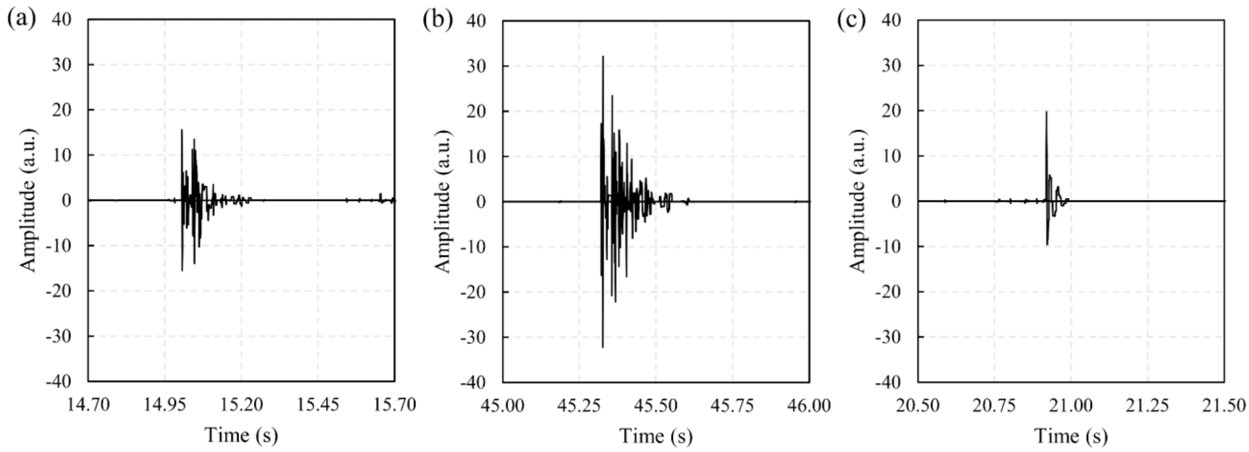


Figure 7: Examples of signals obtained from each type of event analysed in this paper. (a) Wire break. (b) Hammer blow. (c) Unidentified event.

Due to the characteristics of the signals studied in this article, the following five signal parameters were obtained for each event: (i) maximum absolute amplitude (in a.u.); (ii) zero-crossing rate (ZCR). This is the number of times the signal crosses the zero amplitude value in a window of a given duration. Using a threshold of 1 a.u in these tests instead of zero was considered appropriate to avoid possible low amplitude noise. A window of sufficient duration to cover the entire signal was used; (iii) short-time energy (STE) (in a.u.^{2}). This is the accumulated energy under the signal curve for a given time window. A window of sufficient duration to cover the entire signal was used; (iv) duration (in s). It is the duration of the signal between its onset and complete attenuation; (v) dominant frequency (in Hz). It is the frequency, between 30 and 500 Hz, that shows the highest amplitude. The first four parameters were already used by Li et al. in [15] to analyse the signals produced by the wire breaks they studied in their research. They proved to be good indicators of the characteristics of this type of signal.

The analysis procedure consisted of creating a database of all the events analysed (46 wire cuts, 58 hammer blows and 34 unidentified events). The described parameters were obtained from their signals to compare them with each other and analyse the differences that characterise them. Since the system's spatial resolution is 10 m, the data were collected in 10-meter fibre segments. A graphical representation of the location of those 10-meter fibre segments along the experimental pipeline is shown in Figure 8 for better understanding. All the parameters described above were obtained in three fibre segments in the case of wire breaks and hammer blows: the one in which the event originated, the one that showed the earliest onset of the signal produced by the event and the one that showed the highest value of ZCRxSTE. Regarding the unidentified events, as they are events observed in the signal itself during the analysis phase, their actual segment of origin is unknown, so the parameters obtained were always those corresponding to the segment with the highest ZCRxSTE. In all cases, this segment matched the segment with the earliest onset of the signal produced by the event, as unidentified events were generally only detected in one fibre segment, with no alteration of the signal being observed in the remaining segments.

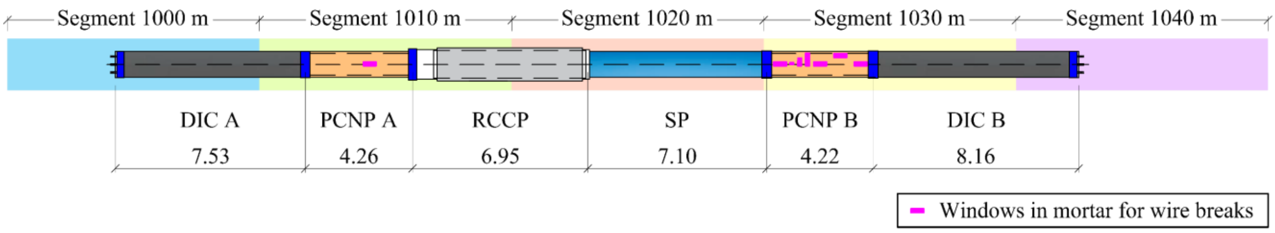


Figure 8: Location and identification of the 10-meter fibre segments located in the experimental pipeline.

Of all the events performed in these tests, only three events, which were three of the five wire breaks performed in 8 cm high windows, were not detected in the signal measured by the DAS system through any of the parameters used in the analysis.

3.3. Effect of the test variables

3.3.1. Origin of the acoustic signal

One of the most relevant objectives of this research is to determine whether the monitoring system used can differentiate what caused the detected signal. For this reason, similar signals were studied to observe the system's capacity to distinguish them through the signal parameters analysed. These signals were those caused by hammer blows on the pipe walls, wire breaks in the PCNPs and noises detected during the tests.

To determine which of the signal parameters analysed show differences depending on the signal's origin, the box-whisker plots in Figure 9 were produced. They represent each event's five signal indicators discussed in the previous section. These plots include all the events that took place in the pipeline with water, i.e., the events in the empty pipeline are excluded, as this is a different problem analysed later. Only the results from the 10-meter fibre segment with the highest ZCRxSTE are included in these graphs for the reasons explained later in Section 3.3.2.

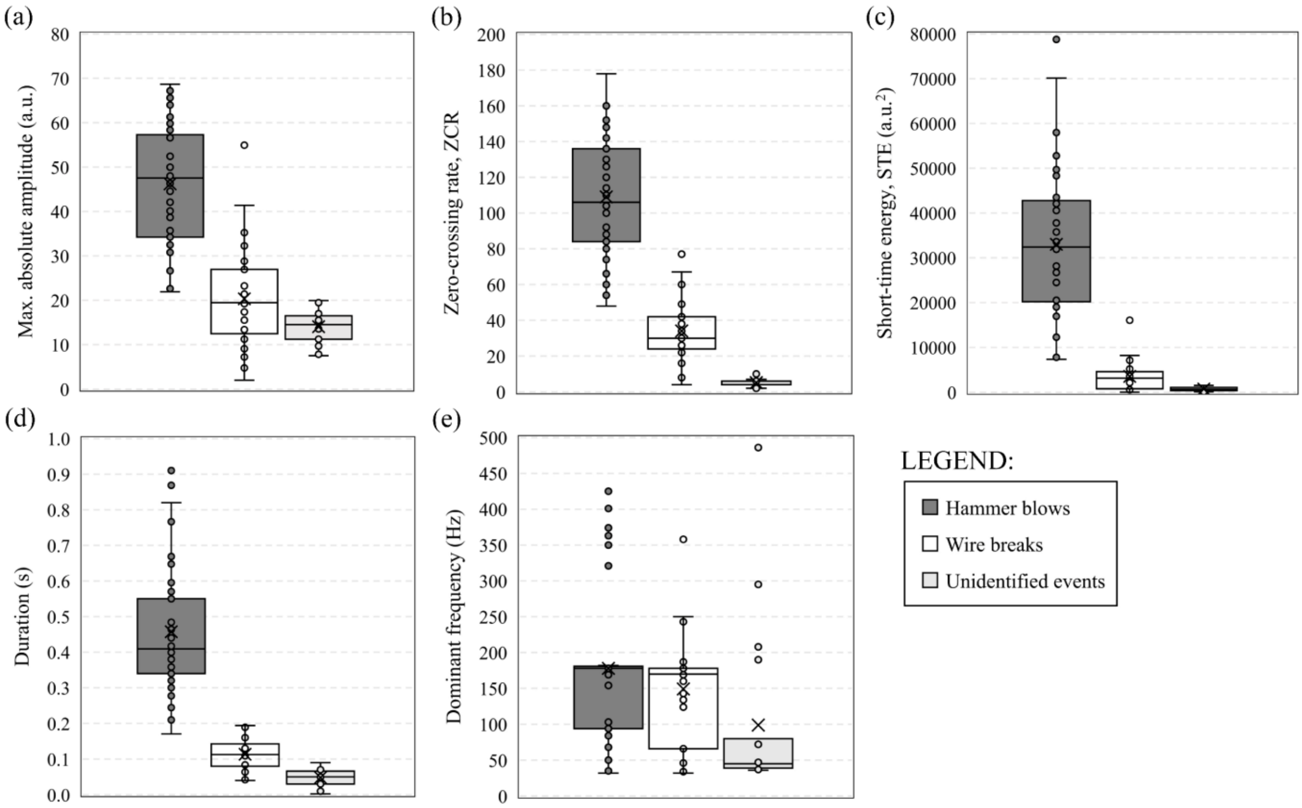


Figure 9: Box-whisker plots of signals produced by hammer blows, wire breaks and unidentified events in the pipeline with water for the five parameters analysed. (a) Maximum absolute amplitude. (b) ZCR. (c) STE. (d) Duration. (e) Dominant frequency.

The box-whisker plots help us to observe the ranges in which the values of each parameter are found. It can be seen that both the ZCR and the STE show very different ranges for the three events analysed, which will allow us to find out the type of event that occurred. The duration of the signal also shows differences between the events, although the difference between the duration of a signal produced by a wire break and that produced by an unidentified event is not clear. As for the maximum absolute amplitude, no significant difference is observed between wire breaks and unidentified events. Concerning the dominant frequency, there are no differentiated ranges, which seems to indicate that the dominant frequency is not a parameter through which we can determine the origin of the signal when it comes to events such as those analysed in this paper since they are impulses that excite multiple frequencies at the same time without one predominating in the short time that the signal lasts.

In addition to analysing each indicator separately, each event was analysed through pairs of values. Thus, the same events were represented in a plot that relates the STE to the ZCR of each event (Figure 10a), and it was observed that the relationship between the ZCR and the STE differentiates quite clearly the type of event that occurred among the three analysed in this paper. In addition, the plotted point cloud shows three distinct areas to distinguish between events, as depicted in Figure 10a. Next to Figure 10a, Figure 10b is shown for ease of comparison. Its content will be explained in Section 3.3.3 below.

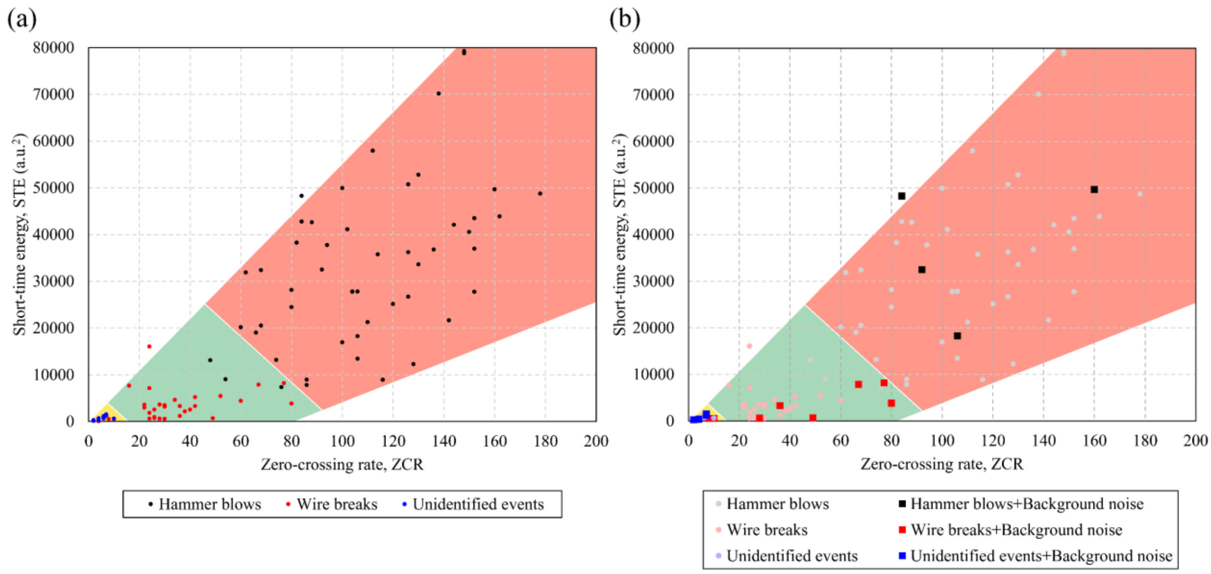


Figure 10: STE-ZCR plot of signals produced by hammer blows, wire breaks and unidentified events in the pipes with water. (a) All the events. (b) All the events, differentiating those with background noise and those without background noise (see Section 3.3.3).

The analysis shows that the DAS system used captured differences that allow the three event types studied to be identified quite accurately by defining ranges (upper and lower limits) for specific parameters. According to this study, the most revealing parameters were the ZCR and the STE. The identification of the event is improved by combining the results of both indicators, as shown in Figure 10a. This allows us to define a map in which the wire break phenomena are located in a clearly defined area that distinguishes them from other events.

3.3.2. Event location

To determine the accuracy of the DAS system in locating events along the fibre, we obtained the percentage of events in which the 10-meter fibre segment showing the earliest signal onset coincided with the 10-meter fibre segment in which the signal originated. We also obtained the percentage of events where the 10-meter fibre segment with the maximum ZCRxSTE coincided with the 10-meter fibre segment where the signal originated. Both percentages were practically identical for both hammer blows and wire breaks. However, the authors have considered using the ZCRxSTE in all the analyses in this paper since both parameters are much easier to identify in an actual application with the DAS system studied than the onset in time of the acoustic signal. It should be noted that it was decided to use these parameters and not those of the stretch in which the signal originated since, in the implementation of an event detection algorithm, the origin of the events is unknown, so other criteria based on the parameters analysed must be used to study the effect on the signal of the different variables.

Figure 11 shows the relationship for both wire breaks and hammer blows between the actual location of the events, discretised into 10-meter fibre segments, and the location detected by the DAS, which is the one corresponding to the 10-meter fibre segment with the maximum ZCRxSTE of the signal. For a better understanding, see Figure 8 for the location and identification of the different segments. The results in Figure 11 are presented as a scatter plot, indicating the event density of each dot on the plot by the diameter of the dot and the number of events. Note that, while hammer blows were performed at multiple distances from the origin of the pipe, wire breaks were only performed at the windows in the mortar coating located in Segments 1010 and 1030 m.

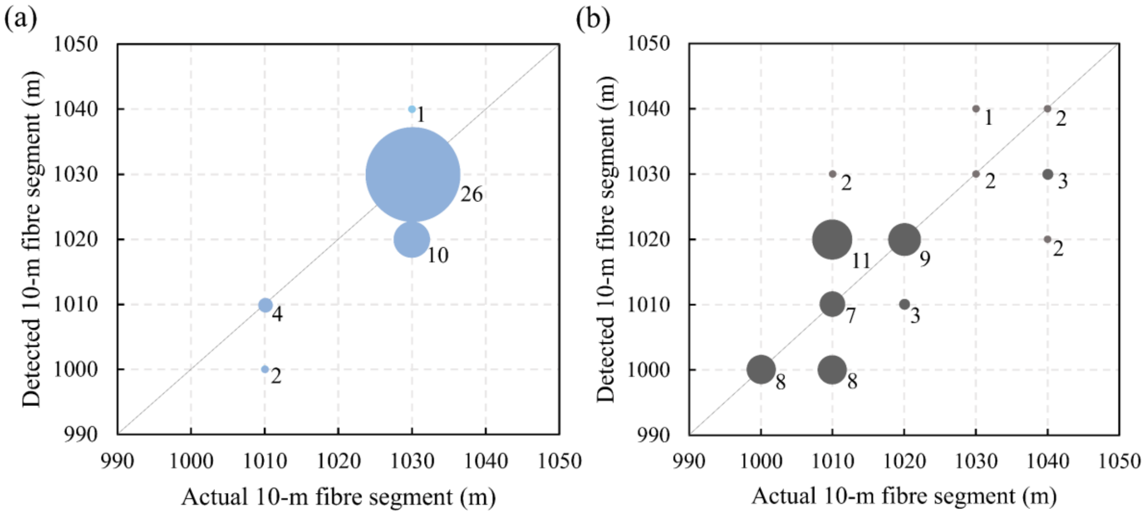


Figure 11: Relationship between the 10-meter fibre segment where the event is actually located and the 10-meter fibre segment where the event was detected by the DAS system. The number of events at each dot is represented by the diameter of the dot and the number of events. (a) Wire breaks. (b) Hammer blows.

Regarding wire breaks, the section with the highest ZCRxSTE coincided with the segment where the signal originated in 70% of the detected events. Hence, the location accuracy was 10 m (the system's spatial resolution). In the remaining 30%, the location was obtained on a 20-meter segment, i.e., in 100% of these events, the wire break was found on the 10-meter segment adjacent to the segment with the highest ZCRxSTE (see Figure 11a).

Hammer blows were events that generated much higher vibrations than wire breaks. In their case, the coincidence between the 10-meter fibre segment with the highest ZCRxSTE and the segment where the signal originated was 48%. In the remaining 52%, in most of the events (87%), the location was obtained with an accuracy of 20 m, while in a low percentage (13%), the accuracy was 30 m, as observed in Figure 11b.

Consequently, it can be concluded that the DAS system used had an accuracy of 20 m in locating 100% of the wire breaks and almost 90% of the hammer blows. Although the system was not very accurate in detecting the fibre segment where the hammer blows originated, it showed high accuracy in detecting lower vibration signals such as wire breaks, which are the most interesting in this project for the early detection of structural failure of prestressed concrete pipes.

3.3.3. Presence of background noise

Continuous acoustic signals from devices or machines, such as the one generated by the power generator placed on the buried section of SP (see Figure 2), show a series of dominant frequencies while the device operates. This means the signal obtained after applying the denoising filters is still very noisy (see Figure 12a). Nevertheless, when an impulse-type event such as the ones analysed in this paper, which excites multiple frequencies, occurred, the DAS system showed a signal disturbance such as the one shown in the example in Figure 12b.

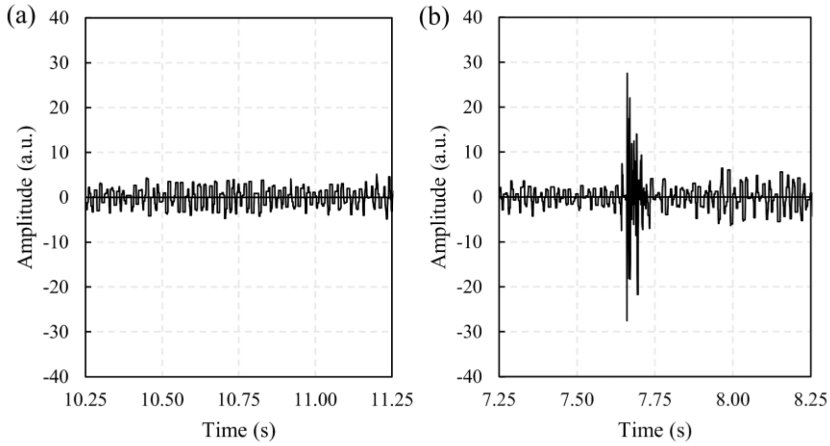


Figure 12: Example of the signal with background noise after applying the high-pass and denoising filters. (a) Only background noise. (b) Wire break with background noise.

The signal obtained from the events analysed when the power generator was running showed very similar values for all the parameters to those of the events without background noise. For this reason, all these events were included in the plots in Figure 9 and Figure 10a. Figure 10b represents again the relationship between ZCR and STE of Figure 10a but highlights the events with background noise. It shows the similarity of the parameters obtained for these signals with those of the signals without background noise, as they generally locate in the same areas represented in Figure 10a. It should be noted that on two occasions, the wire break signal was comparable to the unidentified event signal, either because those two wire breaks in particular produced low vibrations or because the background noise masked the wire break signal.

The analysis in this section demonstrates that the signals studied in this paper, from both wire breaks and hammer blows, could be identified by the DAS system used despite the existence of background noise from continuous acoustic signals from devices or machines. These events produced signals whose main measured parameters showed similar values to those of events without background noise, as shown in Figure 10b. This characteristic will facilitate their implementation in future signal detection algorithms.

3.3.4. Internal water pressure

Figure 13 shows the values of the different parameters analysed as a function of the internal water pressure in the pipeline. The three types of events (wire breaks, hammer blows and unidentified events) have been included in the graphs. Linear trend lines have also been plotted for each data set to observe better possible relationships between the parameters and the internal pressure.

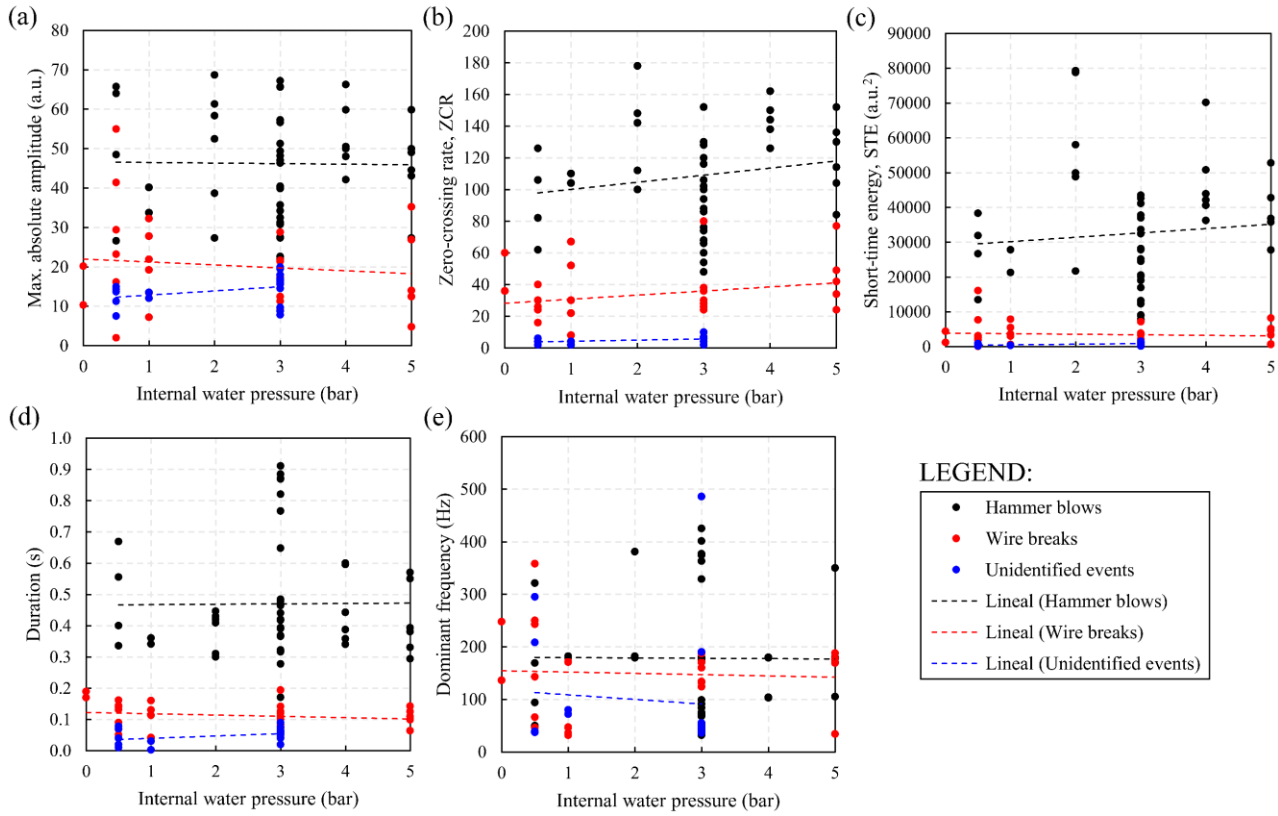


Figure 13: Relationship between the values of the parameters analysed for all events recorded in the pipeline with water and the internal water pressure. (a) Maximum absolute amplitude. (b) ZCR. (c) STE. (d) Duration. (e) Dominant frequency.

Figure 13 shows that, for the same value of internal pressure, events of the same type have a large dispersion for all parameters. Regarding the relationship of the parameters with the internal pressure, only the ZCR shows a certain upward trend so that the ZCR of the signal increases with the internal pressure, but, as already indicated, the dispersion of the results is so high that the linear fit can be considered erroneous (values of the determination coefficients below 0.2).

From the analysis carried out, it is concluded that the results obtained were not sufficient to show a clear relationship between the measured parameter and the internal water pressure in the pipeline. Consequently, the other variables considered in this experimental programme (see Section 2.1) have been analysed without differentiating the events according to the internal water pressure.

3.3.5. Size of the window in the mortar coating

The 46 shear cuts to simulate wire breaks were made in windows of different heights opened in the mortar to reveal the prestressed wire. As indicated above, the heights of these windows were 8, 15, 30 and 60 cm. The DAS system detected wire breaks in all cases except for three of the five wire breaks in the 8 cm high window. Figure 14 shows the relationship between the values of the parameters analysed for all the wire breaks recorded, both in the empty pipeline and the pipeline with water, and the window height.

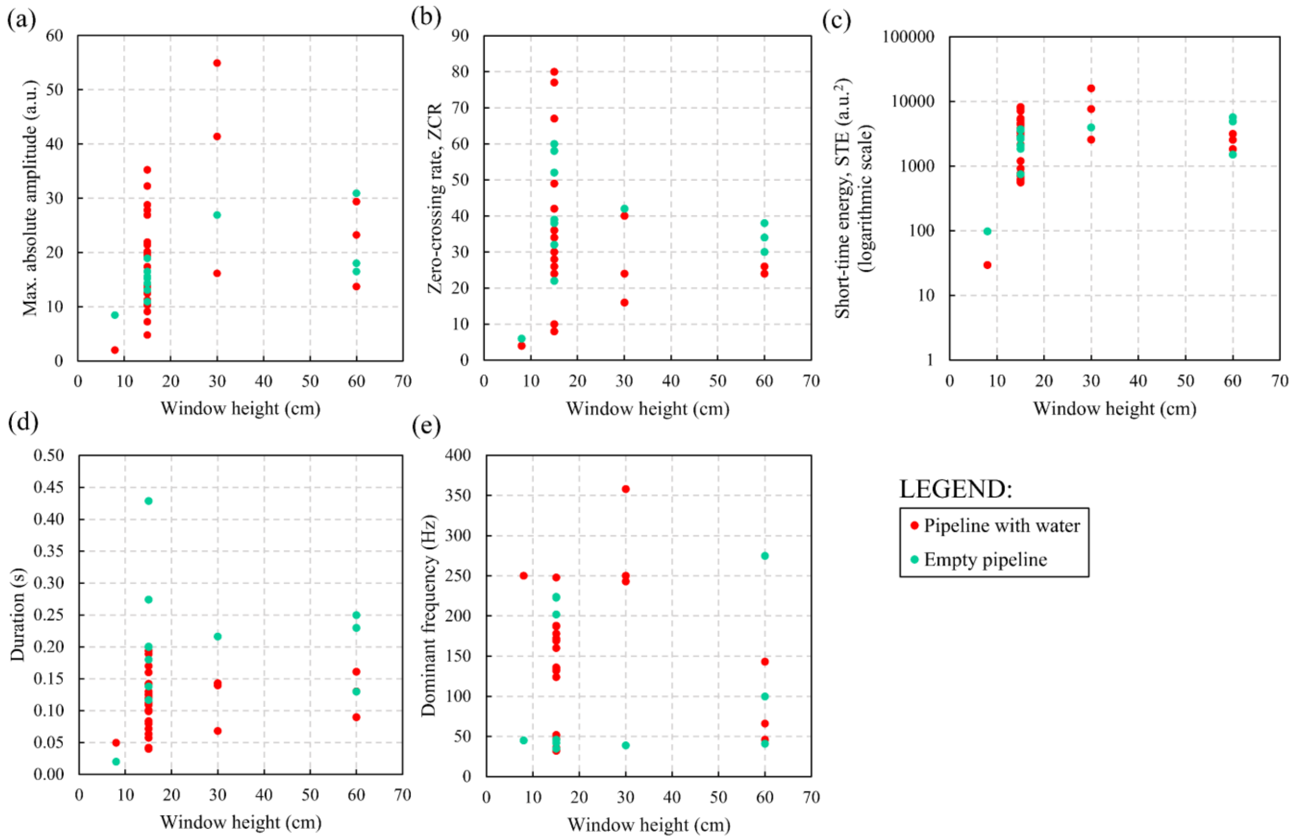


Figure 14: Relationship between the results of the parameters analysed for all wire breaks recorded and the window opening. (a) Maximum absolute amplitude. (b) ZCR. (c) STE. (d) Duration. (e) Dominant frequency.

The analysis of the parameters shows that the two wire breaks recorded in the 8 cm high window had very low values of the maximum absolute amplitude, the ZCR, the STE and the signal duration compared to those of the other windows. Note that in the STE, the large difference makes it necessary to use the logarithmic scale. In fact, in Figure 10a, these two wire breaks in the 8 cm high window are the two red dots that show the ZCR and STE values characteristic of the unidentified events area. However, there is no clear relationship between the parameter and the window height in the rest of the windows. On the other hand, again, the dominant frequency does not show any kind of trend between events with similar characteristics.

This analysis concluded that the DAS system can identify wire breaks when the uncovered wire length is around 15 cm or more. However, if the uncovered wire length is about 8 cm or less, the system may confuse the signal with that of a noise caused by an unidentified event or even fail to detect it. Consequently, if the corrosion of the wire is not limited to a particular area but extends more widely before reaching the wire break, the DAS system used will be able to identify wire breaks with a high probability. This kind of pathology, which causes spalling of the surrounding mortar and leaves a sufficient length of wire not subject to bonding with the concrete to vibrate freely after the wire break, was commonly observed in prestressed concrete pipes that failed under corrosion, such as those reported in [4,27,28]. Only in cases where the corrosion is very localised (local pitting corrosion), with very little or no spalling of the mortar, will the system have difficulties detecting a wire break since the high bond of the concrete to the wire prevents the release of high internal energy.

3.3.6. Presence of water in the pipeline

The tests performed on the empty pipeline were aimed at analysing the capacity to detect wire breaks using the DAS system when there is no water in the pipe, as Li et al. did in [15], since this situation can occur during the operation of water mains. Consequently, the parameters analysed for the three types of events (hammer blows, wire breaks and unidentified events) performed in the empty pipeline and the pipeline full of water were compared. Figure 15 shows this comparison using box-whisker plots. Note that the data from the pipeline with water were already presented in Figure 9, but are presented again together with the new data from the empty pipeline for ease of comparison.

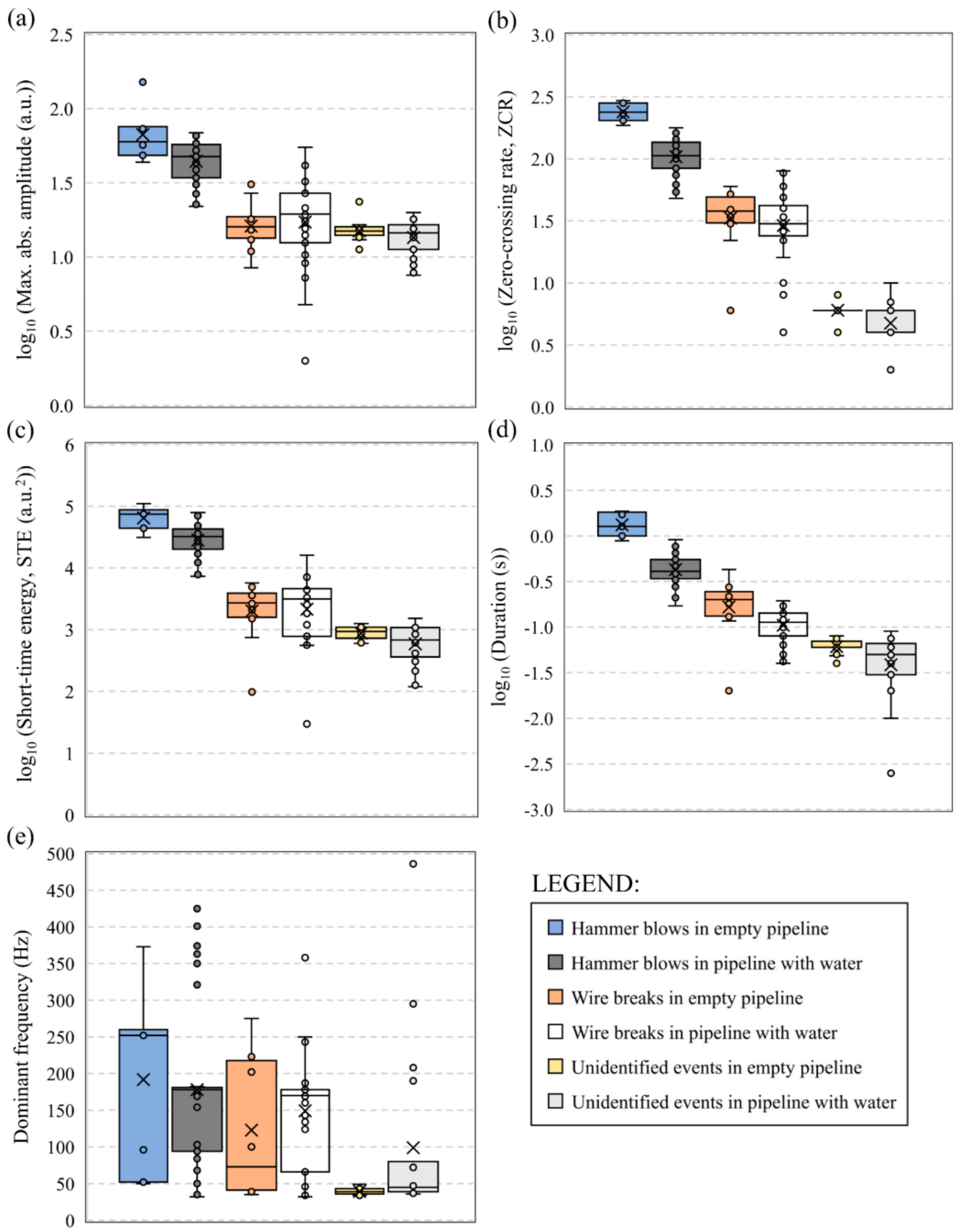


Figure 15: Box-whisker plots of the signals produced by hammer blows, wire breaks and unidentified events in the pipes with and without water for the five parameters analysed. (a) Maximum absolute amplitude. (b) ZCR.

(c) STE. (d) Duration. (e) Dominant frequency. (Note that the data presented in Figure 9 from the pipeline with water are presented again in this figure for comparison with the data from the empty pipeline).

Figure 15a shows that, in terms of the maximum absolute amplitude, if we compare the hammer blows in empty and full pipes, the boxes do not have an offset, but their values overlap, so that, when detecting the events using this parameter, we would not be able to distinguish whether the pipeline is full or empty. The same applies to wire breaks and unidentified events. In Figure 15b, the box boundaries of the hammer blows have a clear offset, so we can distinguish whether the pipe is full or empty depending on the range in which the ZCR is located. However, this is not observed for wire breaks and unidentified events, where again, the boundaries of the boxes overlap. Figure 15c shows that it is not possible to distinguish whether the pipe is full or empty based on the STE because the boxes overlap. However, Figure 15d, on the duration of the signal, shows a clear difference between the full and empty pipeline, so that the events performed in the empty pipeline present a signal of longer duration than those performed in the pipeline full of water, for both hammer blows and wire breaks. This is not the case, however, for the unidentified events, which show little difference in the duration of the signals when the pipeline is full and empty. Finally, Figure 15e shows that, once again, the dominant frequency is unrelated to the type of event or the presence or absence of water inside the pipe.

As a consequence of the above analysis, it is concluded that it is possible to differentiate whether the pipeline is full or empty through the duration of the signals: the signals detected in the empty pipeline showed a longer duration than in the pipeline full of water. This result makes sense since water has a greater capacity than air to absorb the energy of the waves, i.e., to dampen them, so the amplitude of the waves decreases more quickly than when the pipe is full of air and, therefore, the signal dissipates more quickly.

On the other hand, it can be observed in Figure 15 that there are no significant differences in ZCR and STE between the signals of empty and full pipes. Therefore, the possibility of using these parameters to identify the type of event when the pipe is empty was studied, as in Section 3.3.1. Figure 16 represents all the events analysed in this paper, both with full and empty pipelines, and it can be observed that the same differentiated areas in Figure 10 are still observed, which allows for identifying the type of event detected in the water main. Note that the boundaries of the area of hammer blows were prolonged to reach higher values of ZCR and STE.

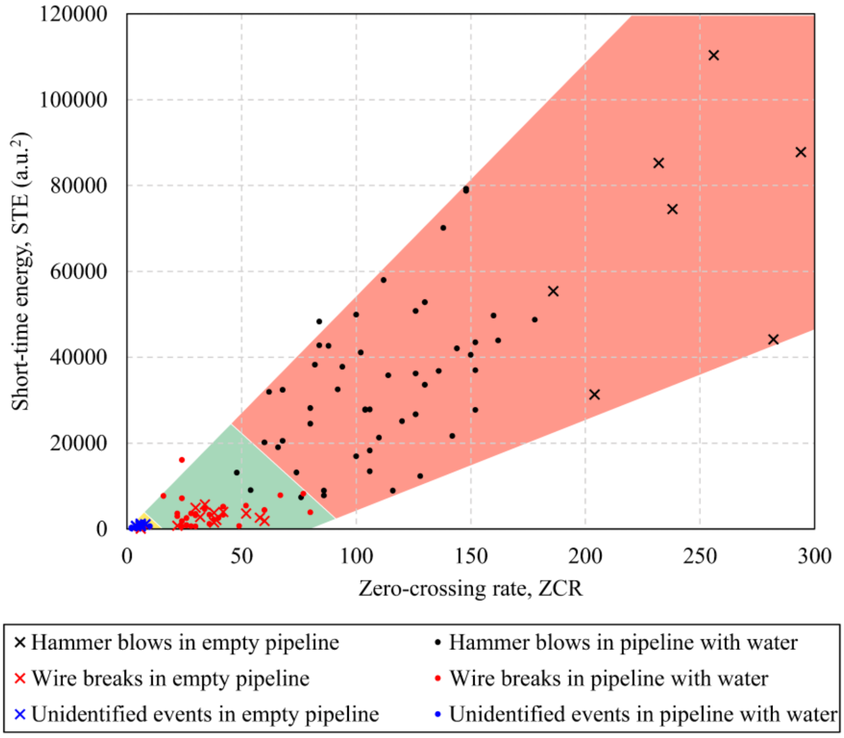


Figure 16: STE-ZCR plot of the signals produced by hammer blows, wire breaks and unidentified events in the pipes with and without water.

4. Conclusions

This paper presents the experimental work carried out to study the capability of an easy-to-install DAS system using fibre optics to identify and locate the acoustic signal produced by wire breaks in pre-stressed concrete drinking water pipes to perform early detection of possible structural failures. The signals from wire breaks made in a large experimental pipeline built on purpose for this research were analysed and differentiated from other sounds of similar characteristics (hammer blows and noises coming from unidentified events). The most relevant aspects to be highlighted from this research are presented in the following paragraphs.

Firstly, although the fibre optic cable was loose inside the pipe (for ease of installation) instead of bonded to the pipe walls, the DAS system used was able to identify wire breaks in 93% of the 46 cases studied. The undetected wire breaks corresponded to cases where the length of prestressed wire not bonded to the concrete had the smallest dimension (8 cm). This case would correspond in a real scenario to very localised wire corrosion with little or no spalling of the mortar coating. Nonetheless, the corrosion failures reported in the literature showed high degrees of spalling.

Secondly, the combination of the zero-crossing rate (ZCR) and short-time energy (STE) values of the signals proved to be a good indicator of the cause of the detected event among the three types of events analysed (wire breaks, hammer blows and unidentified events), whether the events had occurred with the pipe full of water or empty, and whether there was background noise from a power generator. The combination of the ZCR and STE results made it possible to distinguish the signal's origin by means of three differentiated ranges of values.

Thirdly, the DAS system could detect with an accuracy of 20 m the location of 100% of the detected wire breaks and almost 90% of the hammer blows by determining the fibre segment where the highest ZCRxSTE occurs.

In addition, no relationship was observed between the analysed signal parameters (maximum absolute amplitude, ZCR, STE, duration and dominant frequency) and the internal water pressure.

Furthermore, the wire breaks detected when the length of wire not subject to bonding with the concrete was 8 cm showed very low ZCR and STE values, which were comparable to those obtained for noises coming from unidentified events. However, the wire breaks caused when the free length of the wires was 15, 30 and 60 cm showed higher ZCR and STE values that were very similar to each other.

Finally, the duration of the signals proved to be a good indicator of the existence or not of water inside the pipeline so that the events produced when the pipe was empty presented, in general, a longer duration than those produced when the pipe was full of water. However, the signals did not show significant differences by comparing the ZCR and STE, which made it possible to distinguish the signals produced by the three events analysed in the same way when the pipe was full and when it was empty.

It is worth noting that the results obtained in this paper present a highly promising perspective on the use of the easy-to-install DAS system used in this research for the early detection of structural problems in prestressed concrete pipes. In the future, the research team will focus on implementing the results in an algorithm for processing and identifying the signals obtained by the DAS system for the long-term monitoring of a longer section of pipe in operation. Likewise, it would be of great interest to study the capacity of the DAS system to detect other signals that prematurely indicate the possible structural failure of concrete pipes due to other reasons, such as crushing, to improve the algorithm for the premature detection of structural failure. This work could be complemented using machine learning to create a Pattern Recognition System (PRS). Further work may involve the development of a condition assessment programme to determine when pipes should be replaced based on the level of damage they have exhibited during continuous monitoring.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Funding Statement

The Regional Government of Valencia (Spain), through the Valencian Innovation Agency (AVI) and “ERDF A way of making Europe”, supported the present research work through the grant [INNEST/2021/201].

Acknowledgements

The authors thank the support and collaboration in this research of CalSens S.L. and the Concrete Science and Technology University Institute (ICITECH) of the Universitat Politècnica de València (UPV; Spain).

References

1. Toreti A, Bavera D, Acosta Navarro J, et al. *Drought in Europe March 2023*. Luxembourg. Epub ahead of print 2023. DOI: 10.2760/998985.

2. Higgins MS, Paulson PO. Fiber Optic Sensors for Acoustic Monitoring of PCCP. *Pipelines 2006*.

3. Atherton DL, Morton K, Mergelas BJ. Detecting breaks in prestressing pipe wire. *J Am Water Works Assoc* 2000; 92: 50–56.

4. Bell GEC, Paulson P, Galleger JJ, et al. Use of Acoustic Monitoring Data for PCCP Condition Assessment. In: *Pipelines Specialty Conference 2009*. 2009.

5. Hajali M, McNealy A, Dettmer A. Scattered Broken Wire Wrap Effects on Structural Capacity of Prestressed Concrete Cylinder Pipes. In: *Pipelines 2020*. Reston, VA: American Society of Civil Engineers, 2020, pp. 111–122.

6. Loganathan K, Najafi M, Kaushal V, et al. Development of a Decision Support Tool for Inspection and Monitoring of Large-Diameter Steel and Prestressed Concrete Cylinder Water Pipes. *J Pipeline Syst Eng Pract*; 13. Epub ahead of print 2022. DOI: 10.1061/(ASCE)PS.1949-1204.0000603.

7. Huang J, Zhou Z, Zhang D, et al. Online monitoring of wire breaks in prestressed concrete cylinder pipe utilising fibre Bragg grating sensors. *Measurement* 2016; 79: 112–118.

8. Travers FA. Acoustic monitoring of prestressed concrete pipe. *Constr Build Mater* 1997; 11: 175–187.

9. Lenghi A, Amaitik N, Wrigglesworth M. Expansion of Existing Monitoring System on Great Man-Made River Project Using Acoustic Fibre Optic Technology. *Water Pract Technol*; 3. Epub ahead of print 1 September 2008. DOI: 10.2166/wpt.2008.072.

10. Zhu H-H, Liu W, Wang T, et al. Distributed Acoustic Sensing for Monitoring Linear Infrastructures: Current Status and Trends. *Sensors* 2022; 22: 7550.

11. Tanimola F, Hill D. Distributed fibre optic sensors for pipeline protection. *J Nat Gas Sci Eng* 2009; 1: 134–143.

12. Wu H, Sun Z, Qian Y, et al. A hydrostatic leak test for water pipeline by using distributed optical fiber vibration sensing system. In: Lee B, Lee S-B, Rao Y (eds). 2015, p. 965543.

13. Stajanca P, Chruscicki S, Homann T, et al. Detection of Leak-Induced Pipeline Vibrations Using Fiber—Optic Distributed Acoustic Sensing. *Sensors* 2018; 18: 2841.

14. Hussels M-T, Chruscicki S, Arndt D, et al. Localization of transient events threatening pipeline integrity by fiber-optic distributed acoustic sensing. *Sensors (Switzerland)*; 19. Epub ahead of print 2019. DOI: 10.3390/s19153322.

15. Li Y, Sun K, Si Z, et al. Monitoring and identification of wire breaks in prestressed concrete cylinder pipe based on distributed fiber optic acoustic sensing. *J Civ Struct Health Monit*. Epub ahead of print 9 August 2022. DOI: 10.1007/s13349-022-00605-0.

16. Ma B, Gao R, Zhang J, et al. A YOLOX-Based Automatic Monitoring Approach of Broken Wires in Prestressed Concrete Cylinder Pipe Using Fiber-Optic Distributed Acoustic Sensors. *Sensors* 2023; 23: 2090.

17. Tejedor J, Macias-Guarasa J, Martins HF, et al. A multi-position approach in a smart fiber-optic surveillance system for pipeline integrity threat detection. *Electronics (Switzerland)* 2021; 10: 1–19.

18. Wu H, Chen J, Liu X, et al. One-Dimensional CNN-Based Intelligent Recognition of Vibrations in Pipeline Monitoring With DAS. *Journal of Lightwave Technology* 2019; 37: 4359–4366.

19. Bai Y, Xing J, Xie F, et al. Detection and identification of external intrusion signals from 33 km optical fiber sensing system based on deep learning. *Optical Fiber Technology* 2019; 53: 102060.

20. Zuo J, Zhang Y, Xu H, et al. Pipeline Leak Detection Technology Based on Distributed Optical Fiber Acoustic Sensing System. *IEEE Access* 2020; 8: 30789–30796.

21. Bell GEC, Paulson P. Measurement and Analysis of PCCP Wire Breaks, Slips, and Delaminations. In: *Pipelines 2010: Climbing New Peaks to Infrastructure Reliability: Renew, Rehab, and Reinvest*. 2010.

22. Clark BL, Paulson PO, Bell GEC, et al. Advanced acoustic monitoring for PCCP. In: *Pipelines 2014: From Underground to the Forefront of Innovation and Sustainability - Proceedings of the Pipelines 2014 Conference*. 2014, pp. 256–266.

23. Higgins MS, Stroebele A, Zahidi S. Numbers don't lie, PCCP performance and deterioration based on a statistical review of a decade of condition assessment data. In: *Pipelines 2012: Innovations in Design, Construction, Operations, and Maintenance - Doing More with Less - Proceedings of the Pipelines 2012 Conference*. 2012, pp. 298–306.

24. CEN. UNE-EN ISO 6892-1:2017 Metallic materials - Tensile testing - Part 1: Method of test at room temperature. 2017.

25. Pastor Graells J. *Chirped-Pulse Phase-Sensitive Optical Time Domain Reflectometry*. University of Alcalá, 2018.

26. Fernandez-Ruiz MR, Pastor-Graells J, Martins HF, et al. Laser Phase-Noise Cancellation in Chirped-Pulse Distributed Acoustic Sensors. *Journal of Lightwave Technology* 2018; 36: 979–985.

27. Wrigglesworth M, Higgins MS. When to intervene? Using rates of failure to determine the time to shut down your PCCP line. In: *Pipelines 2010: Climbing New Peaks to Infrastructure Reliability - Renew, Rehab, and Reinvest - Proc. of the Pipelines 2010 Conference*. 2010, pp. 803–814.

28. Valiente A. Stress corrosion failure of large diameter pressure pipelines of prestressed concrete. *Eng Fail Anal* 2001; 8: 245–261.