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Recent advances in the TDR-based leak detection system for pipeline inspection

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A B S T R A C T

In this paper, the most recent advances in the time-domain reflectometry (TDR)-based system for leak-localization in underground pipes are described in detail. More specifically, a new design of sensing element and the use of a new connection modality are proposed. Thanks to these new features, the practical implementation of the system becomes much quicker and its use more effective.

Additionally, the present work also describes all the practical aspects and technical details (from installation to functional tests), related to the practical implementation of the system.

Finally, to assess the possibility of further increasing the cost-effectiveness of the TDR-based leak localization system, experimental tests were carried out by comparatively using two TDR instruments, differing in specifications and costs, to identify the position of a leak.

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1. Introduction

The problem of leakages in public water systems seriously undermines water-resource efficiency [1]. Therefore, the localization of leaks in underground pipes is one of the crucial steps for the optimization of the use of water resources [2], as leakage is usually the largest component of distribution loss [3]. Also, considering that water availability is already under pressure across Europe (as one fifth of Europe's population live in Countries where the total water abstraction is threatening the availability of water resources); this aspect should be taken in particular consideration by Member States as an important element of measures to achieve the objectives of the Water Frame Directive [4]. To give a rough idea of the issue, water loss from a single circular hole with 6 mm diameter in a distribution pipe at 60 m pressure amounts to 1.8 m^3 per hour or 1300 m^3 per month [5].

A comprehensive review of inspection technologies for condition assessment of water pipe can be found in [6]. The most widespread leak-detection systems rely on acoustic techniques, and are based on the propagation of mechanical waves. Traditional acoustic leak-detection systems include listening rods, leak correlators, and noise loggers [7]. Despite the extensive use of these systems, their performance depends on the material and diameter of the pipes; also, it can be severely compromised in case of low hydraulic pressure in the pipes, in presence of high environmental acoustic noise, in case of unsuitable sound propagation conditions, etc. [8].

On such bases, recently, an innovative time domain reflectometry (TDR)-based system for the localization of leaks in underground pipes has been developed by the Authors [9,10]. Because this system is based on an the propagation of electromagnetic (EM) waves (rather than acoustic waves), it overcomes most of the limitations that typically affect the performance of traditional leak detection systems. The developed TDR-based system is not influenced by any of the aforementioned limitations that affect traditional, acoustic leak-detection techniques. In particular, the TDR-based system can be used to localize leaks on pipes made of any material and also on non-pressurized pipes: these aspects make it a viable solution also for leak detection in sewer pipes.

Fig. 1 shows a simplified schematization of the TDR-based measurement apparatus. The proposed system requires that, during the installation of new pipes, a wire-like sensing element (SE) be buried along the pipe to be monitored. The SE is laid on the pipe and remains permanently buried with it. The beginning of the SE is connected to a cable, which emerges through an inspection well.

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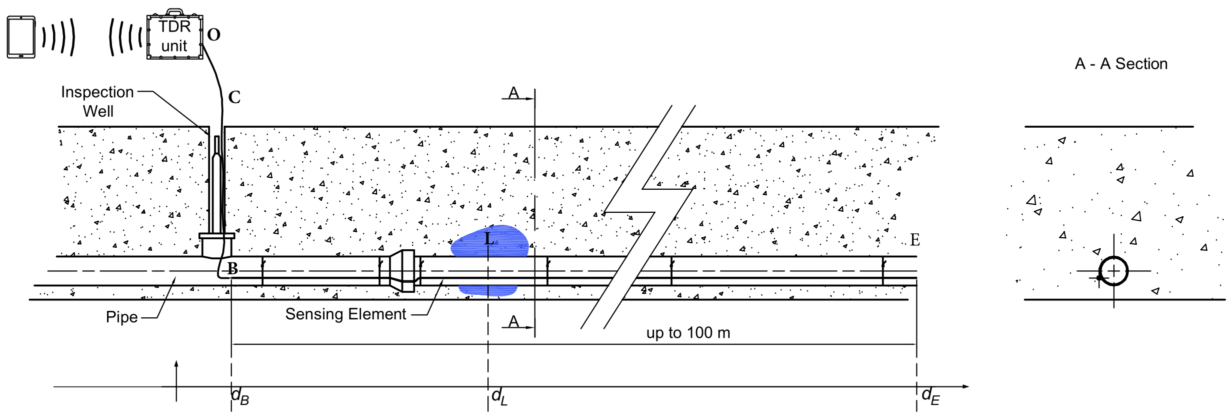

Fig. 1. Schematization of the measurement apparatus for the TDR-based leak localization in underground pipes.

When an operator has to check for the possible presence of leaks, it suffices to connect the TDR measurement instrument to the beginning of the SE, and the system provides in real time the position of the leak. Each single SE can be up to 100 m-long and can follow the topology of the pipe network.

The effectiveness of the this TDR-based system has been demonstrated through an extensive experimental campaign carried out on several pilot plants [10]. As reported in [11], recently, this system has been installed on 10 km of underground water pipes, by the Acquedotto Pugliese S.p.A. (the largest European water operator).

On the basis of the promising results of the large-scale implementation of this system, the present work describes the major recent advances of the TDR-based leak localization system, that have been introduced to expedite the installation phase and to make the leak-detection activity even more effective.

The first enhancement pertains to the adoption of a SE configuration that is different from the one adopted previously [10]. As will be detailed later on in this paper, the choice of a different configuration for the SE allows avoiding the design phase (prior to the installation), in which it was necessary to pre-establish the optimal positioning of the SE's and their length [11].

An additional enhancement consists in the introduction of a new modality for the electrical connection of the TDR instrument to the beginning of the SE (i.e., housed in the inspection well of Fig. 1). In the previous configuration of the TDR-based system, in fact, it was necessary to include a plastic box (inside the inspection well) for protecting the electrical connectors from the environment [11]. In this work, the use of the protecting plastic box has been avoided by resorting to an ingress protected (IP) electrical connector. Additionally, it will be shown that, thanks to the presence of five pins, one single connector can be used for different type of measurements.

Finally, to further increase the cost-effectiveness of the TDR-based leak localization system in view of large-scale implementation, the possibility of employing lower-cost TDR instrument was also addressed. To this purpose, two TDR instruments (with different specifications and costs) were comparatively employed to localize the position of a leak, and their performance was assessed.

This paper is structured as follows. In Section 2, the theoretical background at the basis of the TDR-based leak localization system is provided. In Section 3, the enhancement features brought to the system are described in detail. In Section 4, all the steps for the implementation and use of the leak-localization system are thoroughly described. In Section 5, the experimental results related to the comparative assessment of the performance of two TDR instruments in localizing the leaks are reported. Finally, in Section 6, conclusions are drawn.

2. Background and description of the measurement apparatus

TDR was originally developed mainly for the localization of faults in electric wires [12]; however, thanks to its adaptability, TDR has progressively established itself as an appealing solution in the most diverse application contexts, such as moisture content measurements in soils [13–15] and porous materials in general [16], liquid level monitoring [17,18], electrical conductivity measurements [19], etc.

Generally, in TDR measurements, an EM signal propagates along a SE inserted in the system to be monitored. The response of the system, acquired in terms of reflected signal, is used to retrieve the desired information on the system under test [20].

With regards to the TDR-based leak detection, the basic principles have been described in [10]. However, for the sake of clarity, some important details are also reported herein. It is worth noting that an EM signal travels in a medium different from vacuum, with a specific propagation velocity (v) which depends on the geometric and dielectric characteristic of the line. As a consequence, it is useful to introduce the concept of apparent distance, d^{app}, which is the distance that would be traveled by the EM signal, in the same time interval, if the dielectric medium of the transmission line was air. The direct output of a TDR measurement is a reflectogram, which shows the reflection coefficient (ρ) as a function of d^{app}.

When a leak is present, the reflectogram will show a distinct behavior in correspondence of the leak. This is due to the fact that water has a high relative dielectric permittivity (approximately equal to 78), which is significantly higher than the typical relative dielectric permittivity of the soil (which is in the order of 3–5).

A detailed description on the analysis and estimation of apparent distances from TDR reflectograms can be found in [21].

With reference to the schematization of Fig. 1, B and E indicate the beginning an the end of the SE, respectively, whereas L indicates the leak. When the TDR signal propagates along the SE, the presence of the leak is typically associated to the variation of ρ in correspondence of the position of the leak, as shown in Fig. 2 for step-like signal. In particular, d_B^{app} and d_E^{app} are the abscissae corresponding to the beginning and to the end of the SE; whereas d_L^{app} is the apparent distance of the leak.

As detailed in [10], the position of the leak (L_L) is evaluated from the reflectograms through the following equation:

$$L_L = \frac{L_L^{app}}{\sqrt{\varepsilon_{eff}}} \tag{1}$$

where L_L^{app} is the apparent distance of the leak (derived from the TDR reflectogram as reported in [9,10]) and ε_{eff} is the effective

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