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Time domain reflectometry, ground penetrating radar and electrical resistivity tomography: A comparative analysis of alternative approaches for leak detection in underground pipes

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ABSTRACT

In this work, three different techniques, namely time domain reflectometry (TDR), ground penetrating radar (GPR) and electrical resistivity tomography (ERT) were experimentally tested for water leak detection in underground pipes. Each technique was employed in three experimental conditions (one laboratory or two field experiments), thus covering a limited but significant set of possible practical scenarios. Results show that each of these techniques may represent a useful alternative/addition to the others. Starting from considerations on the obtained experimental results, a thorough analysis on the advantages and drawbacks of the possible adoption of these techniques for leak detection in underground pipes is provided.

1. Introduction

Detection and localization of leaks are extremely important for the efficient exploitation of the water resources; in fact, water losses have a highly negative environmental and economic impact [1]. Consequently, the development of new, effective and reliable leak detection methods is considered crucial for the optimization of water resources [2].

Electroacoustic systems (e.g., noise logger, noise correlator, geophone) are currently the most used leak-detection systems, but their performances can be severely compromised in case of low hydraulic pressure in the pipes and/or high environmental acoustic noise and/or in case of unsuitable sound propagation condition. Non-acoustic methods for leak-detection include tracer gas technique and thermography; nevertheless, their use is not widespread because they are relatively difficult to use and expensive. Generally, in practice, depending on the specific case at hand (in particular, depending on the pipe material and on the environmental background noise), one method can be more suitable than another, and often it is good practice to employ different leak-detection methods and to crosscheck the results. An overview on detection methods can be found in [3].

Based on these considerations, in this work three different techniques, namely time domain reflectometry (TDR), ground penetrating radar (GPR), and electrical resistivity tomography (ERT), were simultaneously employed for the detection of water leaks in underground pipes, and their performances were compared. At the state of the art, TDR has been recently demonstrated to be a promising alternative for the individuation of leaks [4,5], and also GPR and ERT has been successfully employed for this purpose [6–13].

To carry out a synoptic and comparative analysis, these techniques were tested on three *Experimental Cases* (ECs), namely:

EC1—A laboratory experiment on a plastic pipe buried under two different types of soil (one half of the pipe buried in silty soil, and the other half in clayey soil), and in which two leaks were intentionally provoked.
EC2—A field experiment on a *newly-installed* metallic pipe, connected to the water distribution system and in which a tap valve allowed to simulate a leak.
EC3—A field experiment on a *pre-existing* metallic pipe where the local Water Utilities Administration had preliminarily individuated the possible presence of a leak.

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These ECs represent a significant set of possible practical scenarios. In the following, after a brief introduction of the three techniques, the achieved results are reported and thoroughly discussed. The goal of this work is to comparatively assess the viability of the considered techniques as alternative solutions for water-leak detection.

2. Theoretical background on the used measurement methods

2.1. The time domain reflectometry (TDR) method

TDR is an electromagnetic (EM) measurement technique that has been largely adopted for a number of monitoring and diagnostics applications [14] such as liquid level monitoring [15], soil moisture measurements [16], characterization of dielectric materials [17,18] and of electronic devices [19], location of wall thinning in metal pipes [20] etc.

In TDR measurements, a step-like EM signal propagates along a probe or sensing element (SE) inserted in the system to be tested/monitored. The variations of the electric impedance that are encountered by the propagating EM signal provoke partial back-reflections of it. The raw output of a TDR measurement is a reflectogram, which is an *X–Y* graph that displays the reflection coefficient (Γ) as a function of the apparent distance (d^{app})[1] traveled by the EM signal (or, alternatively, as a function of the time) [21]. The quantity Γ is often referred to as time-domain reflection coefficient, and it is a scalar quantity ($-1 \le \Gamma \le +1$).The analysis of the reflectogram, performed through a specific data-processing, allows retrieving the desired information on the system under test.

With regard to the use of TDR for leak detection, this technique can be employed in two main scenarios: (i) for the inspection of newly-installed underground pipes made of any material [4]; (ii) for the inspection of pre-existing underground metal pipes [5]. Each scenario corresponds to a different configuration of the SE.

Fig. 1a shows a schematic diagram of the measurement setup for the scenario *i*. In this layout, the SE is a bifilar transmission line rolled out along the pipe during the installation of the pipe, and it remains permanently buried. Additionally, a portion of coaxial cable emerges through an inspection well. In this way, for the successive monitoring of the pipe (i.e., after burial), it is enough to connect the TDR instrument and carry out the measurement. L_{SE} indicates the length of the SE, and L_{leak} indicates the distance of the leak from the beginning of the SE.

Fig. 1b, instead, shows a schematic diagram of the measurement setup for *pre-existing* metal pipes. In this case, the SE is formed by the metallic pipe itself and by a metallic wire that is rolled out on the road surface, parallel to the underground pipe. Since the pipe itself is part of the SE, this system configuration requires the underground pipe to be electrically conductive.

TDR-based leak detection relies on the variation of the dielectric characteristics of the soil when it becomes moistened because of a water leak. In fact, the relative dielectric constant of water is approximately equal to 78, whereas the relative dielectric constant of dry soil is usually in the order of 3–4. As a result, the leaked water provokes a significant local increase of the permittivity (and, hence, a decrease of the electrical impedance) of the soil in proximity of the leak point. This change of impedance is detected and localized through TDR measurement. As detailed in [4,5], in TDR measurements, the position of the leak (L_{leak}^{eval}) can be evaluated as the distance from the beginning of the SE (the zero point in Fig. 1), through the following equation:

$$L_{leak}^{eval} = \frac{L_{leak}^{app}}{L_{SE}^{app}/L_{SE}} \tag{1}$$

where L_{leak}^{app} is the apparent distance of the leak (directly measured from the TDR reflectogram as reported in [4]); and L_{SE}^{app} and L_{SE} are the apparent and the actual length of the SE, respectively. Eq. (1) has been implemented in an algorithm (specifically developed by the authors) that provides in real time the position of the leak, L_{leak}^{eval}.

All the TDR measurements reported in this work were carried out through the HyperLabs HL1500 TDR unit, a portable measurement instrument that is particularly suitable for on-site applications, which generates a step-like voltage signal with a rise time of 200 ps.

Finally, it is worth mentioning that the TDR method allows the inspection of approximately 200–300 m of pipe in a single measurement, which corresponds to an average productivity of approximately 6 km/day. This is a significant enhancement with respect to the productivity of traditional electroacoustic leak-detection methods (which, typically, is approximately 2–3 km/day [1,3]).

2.2. The ground penetrating radar (GPR) method

GPR is a non-invasive high-resolution geophysical method based on short EM pulses in the microwave range, radiated by a transmitting antenna which is moved along the observation line together with a receiving antenna, usually kept at a fixed distance from the transmitting one (common offset mode [22]). When the EM waves meet buried discontinuities (buried objects, interfaces between two geological strata, etc.), they are scattered in all directions.

Therefore, the EM waves are also partially reflected towards the receiving antenna. The data gathered in this way, while moving the GPR system, provide a vertical image of the underground scenario, corresponding to a sheet under the line crossed by the instrument. The GPR technique is often exploited to detect and focus buried pipes in civil engineering applications. Test site data have demonstrated that this technique is able to discriminate the simultaneous presence of several pipes, even quite close to one another [23], and can also provide information about more refined details, as the presence of flanges between adjacent collinear pipes [24]. However, in general, the data are difficult to interpret without a suitable processing, both because the signal reflected from the air–soil interface often "covers" those scattered by deeper targets and because the echoes coming from any buried target is spread along a distance larger than the size of the target, essentially due to the non-infinite directivity of the GPR antennas. This also leads to nonlinear mutual interactions among the buried targets. With regard to the specific problem at hand, two processing strategies can be followed. The first is to process the data with a focusing algorithm. For this purpose, several focusing algorithms are known, but the most common ones are migrations algorithms [25,26] or, in some cases, linear inversion algorithms [27]. This method is recommended if the humid zone is sharply distinguished from the dry one, so that the area interested to the escaped water can be assimilated to a quite definite underground volume, sharply distinguished from the surrounding soil. Alternatively, the humidity distribution can be associated to a velocity map, retrieved from the change of shape of the diffraction hyperbolas throughout the investigated area. In this case, the variation of propagation velocity in the underground medium can provide a diffuse map of the variation of propagation velocity, that can be qualitatively associated (at least in a homogeneous soil) to the

[1] The quantity d^{app} can be considered as the distance that would be traveled by the EM signal in the same interval of time, if the signal were propagating at *c*, which is the speed of light in vacuum ($c \cong 3 \times 10^8$ m/s).