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AN INVERSE VALIDATION FOR DETECTING PIPE LEAKS WITH A TDR-BASED METHOD

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Abstract: Recently, an innovative system based on time domain reflectometry (TDR) for the individuation of leaks in underground pipes has been proposed and validated. Starting from the results obtained so far, the present works aims at further investigating the practical applicability of the aforementioned system. In particular, the goal of this work is to assess the system in the detection of two close leaks (i.e. leakages that may occur on the same length of pipe). To this purpose, an experimental setup was arranged: two "leakage conditions" were imposed, and the position of the leaks were considered as unknown and calculated through the dedicated developed algorithm. Results show that, differently from traditional leak detection methods (in which the presence of a leak may "mask" the presence of other leaks), the TDR-based system successfully individuates and correctly localizes the presence of two leaks.

Keywords: Leak detection, microwave reflectometry, time domain reflectometry, water leakage.

1. INTRODUCTION

The individuation of leaks is extremely important for the optimization and rationalization of water resources. In fact, water losses have a highly negative impact both environmentally and economically. As a consequence, a constant research effort has been dedicated to enhance the techniques for leak detection and to make them more effective. As a matter of fact, the methods that are currently used for leak detection are very time-consuming (which also translates into high cost of personnel) and become unreliable when the measurements cannot be performed in specific operating conditions of the pipe (e.g., presence of high water pressure). Starting from these considerations, in [1-3], the authors have proposed and validated an innovative system for water leak detection, based on time domain reflectometry (TDR) technique. This leak-detection system is intended for two different application scenarios: *i*) detection of leaks in underground metal pipes [1], and *ii*) detection of leaks in "newly-installed" underground pipes, made of any material [2]. The present paper focuses on the sensitivity/performance analysis of the system in the second application scenario. In particular, the present work intends to validate the suitability of the system for individuating two leaks that may occur close to one another along the same length of pipe.

For the application of the TDR-based leak detection system, a biwire is used as probe (or sensing element) for sensing the presence of leaks. A biwire is constituted of two metallic wires that run parallel to and are isolated by each other through a plastic sheath. For implementing the leak detection system, a biwire is to be laid on the pipe at the time of installation of the pipe. A coaxial cable connected to the buried biwire emerges from the soil through the inspection well. In this way, in successive inspections on the integrity of the pipe (i.e., once the pipe and the biwire are buried), anytime one wants to check on the presence of leaks, it is enough to connect the measurement instrument to the "emerging cable".

As will be detailed later in this paper, to test the performance of the TDR-based leak detection system in presence of two simultaneous leaks, two biwires were buried under some soil, and two "leakage conditions" were imposed at known positions.

It is worth reminding that, in this experiment, there was no pipe; nevertheless, as pointed out in [2], the functionality of this TDR-based leak detection system does not depend on the presence of the pipe. In fact, the system relies on sensing the presence of the water in the soil, due to the pipe leak. For this reason, to create a leakage condition (without a pipe being actually installed and broken), it was sufficient to water (at the point in which a leakage-like condition was desired) the soil that covered the two biwires.

Finally, it is worth mentioning that each biwire acts as an independent sensing element; in fact, the choice of including two biwires (made with different sheath material) was made only for comparative purposes and to see to which extent the performance of the system can be affected by the choice of a different biwire.

2. THEORETICAL BACKROUND

TDR is a well-established monitoring technique that has been used for many different applications, such as dielectric and spectroscopic characterizations of materials [4, 5]; quantitative and qualitative control of liquids [6, 7]; investigation of vegetable oils [8, 9]; fault diagnosis on wires [10]; soil moisture measurements [11]; characterization of electronic devices and components [12]; etc. A review of the major applications of TDR can be found in [13].

As described in [1-3], the TDR-based leak detection system exploits the physical principles of TDR-based investigation of materials. Generally, this kind of measurements relies on the analysis of the signal that is reflected when an appropriate electromagnetic (EM) signal (typically, a voltage step signal with very fast rise-time) is propagated along a probe (sensing element) inserted in the material under test. The reflected signal, in fact, carries useful information on the dielectric characteristics of the material in which the sensing element is inserted. Therefore, through a suitable data-processing, it is possible to retrieve other intrinsic (qualitative and quantitative) characteristics of the considered material.

The method proposed by the authors is based on sensing the change of dielectric characteristics that occurs in the soil when water escapes from the pipe. The presence of water (whose relative dielectric permittivity is approximately equal to 80) provokes a local, detectable change of the dielectric characteristics of the soil (whose relative dielectric permittivity, in `dry conditions', does not usually exceed 2-3).

In the system configuration considered herein (which is detection of leaks in "newly-installed" underground pipes, made of any material [2]), a biwire laid on the pipe, all along the length to be monitored, is used as sensing element for individuating the leak. In fact, the TDR signal travels down the biwire: the plastic sheath around the biwire and the soil represent the propagation medium of the TDR signal.

For the sake of clarity, Fig. 1 shows a schematization of the typical measurement setup. More detailed information can be found in [2].

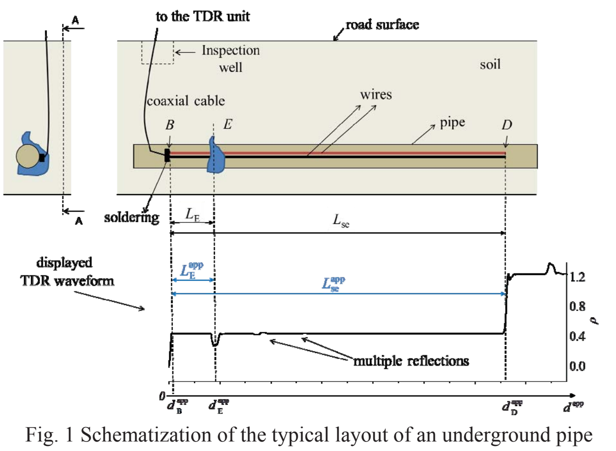

Fig. 1 Schematization of the typical layout of an underground pipe equipped with the distributed biwire. The figure below shows a schematization of a typical reflectogram in presence of a leak.

The measurement output of a TDR measurement is a reflectogram, which displays the time-dependent reflection coefficient (ρ) of the material/device under test as a function of the apparent distance (d^{app}) travelled by the signal that propagates along the sensing element.

The behaviour of ρ is strictly associated with the impedance variations along the electrical path travelled by the EM signal. A constant value of ρ means that the dielectric characteristics in that `portion of path' are practically uniform. Vice versa, variations of ρ indicate that the dielectric characteristics (and, hence, the electrical impedance) change along the travelled electrical path. In the reflectogram in Fig. 1, it is possible to see that there is a variation of ρ (typically a dip of the reflectogram) in correspondence of the presence of the leak.

The quantity d^{app} can be considered as the distance that would be travelled 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 ($c = 3 \times 10^8$ m/s).

The quantity d^{app} can be associated to the `actual' physical length traveled by the signal (d), through the following equation:

$$d^{app} = d\,(\varepsilon_{app})^{1/2} \qquad (1)$$

where ε_{app} is referred to as apparent relative dielectric permittivity of the medium in which the signal propagates.

The evaluation of the position of the leak is done automatically through an algorithm specifically developed by the authors for this application. The algorithm implements specific signal processing technique that allows to enhance the accuracy of the estimation. Additional info can be found in [3].

3. EXPERIMENTAL SETUP

In order to reproduce a typical leak-monitoring condition with the TDR system, two biwires were rolled out and covered with (dry) soil. The length of each biwire was 25.4 m. The biwires were laid down with a U shape, as shown in Fig. 2 (the choice of the U shape was merely due to the dimensions of the room available). Two tubs were positioned at distances of 10.00 m and 19.45 m, respectively, from the beginning of the biwires. Also the tubs were filled with soil. However, the soil in the tubs was moistened, thus mimicking the effect of water leaks. The scope of using the tubs was just to spatially limit the portion of moistened soil (i.e. water was added only to the soil inside the tubs).

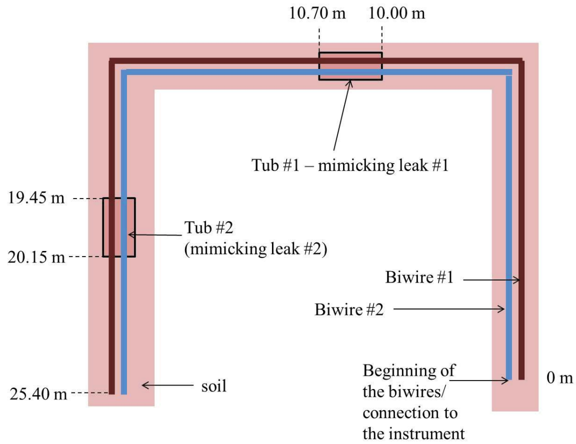

Fig. 2 Schematization of the layout of the experimental apparatus.

Fig. 3 shows a picture of the first tub. It can be seen that a three-rod probe was also placed inside the tub. This probe was only used to verify the homogeneity of the moistening of the soil; but it does not have anything to do with the leak-detection system itself. As can be seen from Fig.s 3 and 4, the biwires were completely covered with soil.

For the TDR measurements, the TDR instrument was connected to the “beginning of the biwire” (see. Fig. 2).

TDR measurements were performed through the HL1500 unit: a portable reflectometer that generates a step-like voltage signal with a rise time of approximately 200 ps.

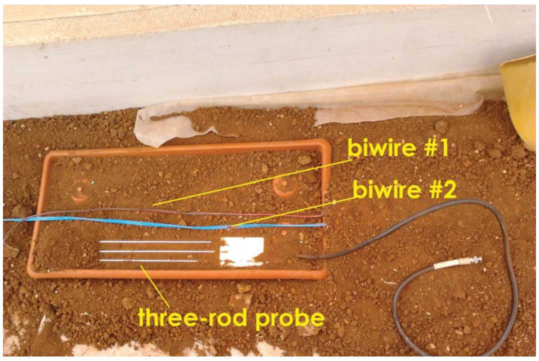

Fig. 3 Tub placed at 10.00 m from the beginning of the biwires. The soil inside the tub was progressively moistened with increasing amount of water. A three-rod probe was used to monitor the moisture content of the soil inside the tub.

Fig. 4 View of one portion of the test site.

4. EXPERIMENTAL RESULTS

The TDR instrument was connected to the first biwire. The first step of the experiment was to acquire the reflectograms (for each biwire) in dry condition of the soil.

Successively, a leakage-like condition was created at a distance of 10.00 m from the beginning of the sensing element: to this purpose, the soil contained in the tub #1 was moistened with approximately three litres of water. In this condition, another reflectogram was acquired.

Then, an additional leakage-like condition was imposed at a distance of approximately 19.45 m from the beginning of the biwires. Also in this case, to “create” a leak, water was added to the soil contained in the tub #2. The soil contained in tub #2 was moistened with an increasing amount of water: adding one litre of water at a time, thus achieving five moistened conditions.

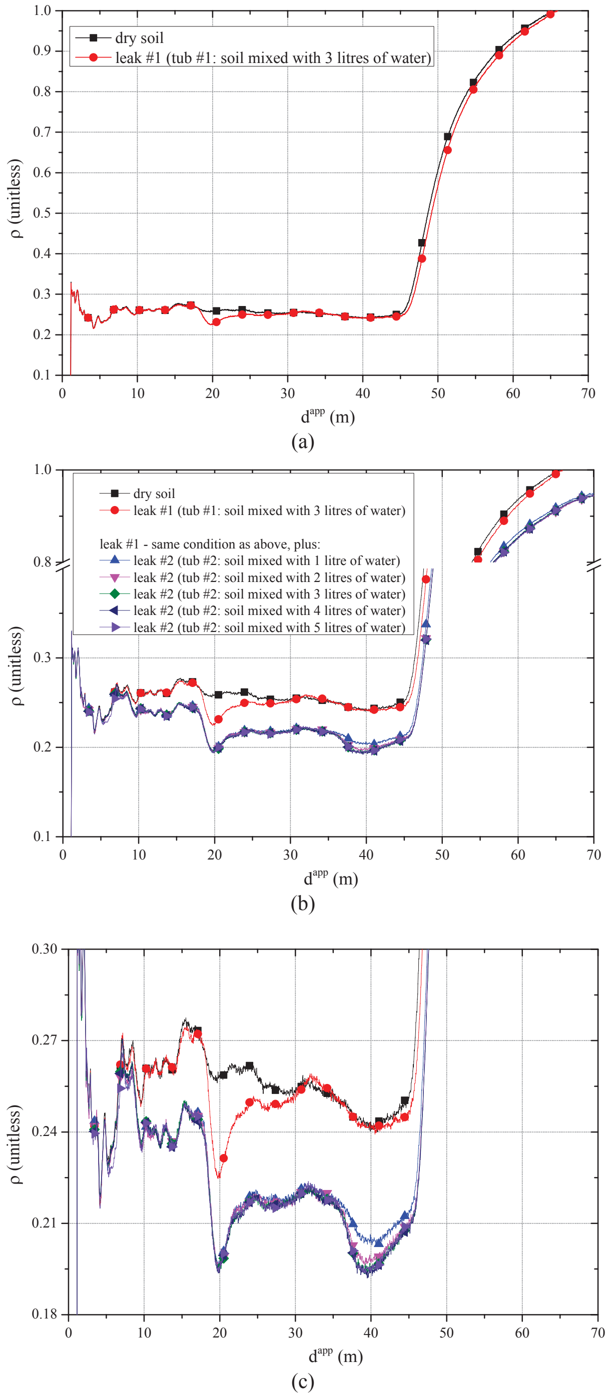

Fig. 5 Reflectograms of the biwire #1: a) reflectograms with dry soil and with moistened soil in tub #1; b) reflectograms for increasing moisture content of the soil in tub #2; c) zoom of the reflectograms of subfigure b).

Fig. 5 shows the reflectograms corresponding to the biwire #1. In particular, Fig. 5a shows the comparison between the reflectogram acquired in dry conditions and the reflectogram acquired in presence of the leak generated at tub #1. As expected, it can be seen that, for dry condition case, the reflectogram in correspondence of the sensing element is practically constant. The reflectogram corresponding to the presence of a leakage condition, instead, exhibits the typical dip associated to the presence of a leak. Fig. 5b shows the comparison of the reflectograms acquired while progressively moistening the soil in tub #2. It can be seen that, as the water content increased, the dip corresponding to the leak #2 becomes slightly deeper and wider. Fig. 5c shows the zoom of the reflectograms.

It can be seen that the effect of the two leakages is clearly present; most importantly, the effect of each "leak" can be separately individuated.

Finally, the position of the leaks was considered as unknown and the acquired reflectograms were processed through the algorithm described in [2]. As aforementioned, the algorithm automatically calculates the position of the leak, starting from the reflectograms. The tubs were considered as leakage points and their positions were considered as unknown. Results of the elaboration are summarized in Table 1. The reference position of leak #1 and leak #2 were 10.35 m and 19.80 m, respectively.

Table 1. Summarized results of the evaluation of the position of the leaks #1 and #2, from measurements on biwire #1.

Reflectogram	**Position of the leak #1 (m)**	**Position of the leak #2 (m)**
Leak #1 (3 litres of water)	10.30	Not present
Leak #1 (3 litres of water) *plus* Leak #2 (1 litre of water)	10.30	20.80
Leak #1 (3 litres of water) *plus* Leak #2 (2 litres of water)	10.25	20.80
Leak #1 (3 litres of water) *plus* Leak #2 (3 litres of water)	10.26	20.52
Leak #1 (3 litres of water) *plus* Leak #2 (4 litres of water)	10.20	20.46
Leak #1 (3 litres of water) *plus* Leak #2 (5 litres of water)	10.25	20.50

As shown in Table 1, the position of the leaks is evaluated with a very low error. In particular, leak #1 is evaluated with extremely high accuracy. Also leak #2 is evaluated with a good accuracy, as the maximum error is 1 m. The same procedure was also followed for biwire #2. As expected, the localization of leak #2 is slightly overestimated, due to the additional contribution in the apparent distance, introduced by the presence of leak #1. This effect might be compensated for by appropriately modifying the implemented algorithm (this work is currently being done).

5. CONCLUSIONS

In the present work, an experimental test for validating the suitability of a TDR-based method in discriminating two simultaneous leaks that occur close to each other. To this purpose, two biwire were rolled out and buried under soil. Then the presence of two leaks was mimicked through the introduction of two tubs. Results show that the TDR-based system is able to accurately discriminate the presence of the two leaks and the accuracy in the evaluation of the position of the leak by the presence of multiple leaks. This is another great advantage of the proposed system, in fact, while applying traditional leak detection methods, the presence of multiple leaks is difficultly spotted, as the effect of one leak often masks the effect of other leaks.

6. REFERENCES

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