Results in Physics 6 (2016) 594–598

Contents lists available at ScienceDirect

Results in Physics

journal homepage: www.journals.elsevier.com/results-in-physics

Accuracy improvement in the TDR-based localization of water leaks

Andrea Cataldo *, Egidio De Benedetto, Giuseppe Cannazza, Giuseppina Monti, Christian Demitri

University of Salento, Department of Engineering for Innovation, Complesso Ecotekne – Edificio Corpo O, 73100 Lecce, Italy

ARTICLE INFO

Article history:
Received 26 July 2016
Accepted 8 August 2016
Available online 13 August 2016

Keywords:
Leak localization
TDR
Time domain reflectometry
Water leaks
Underground water pipes

ABSTRACT

A time domain reflectometry (TDR)-based system for the localization of water leaks has been recently developed by the authors. This system, which employs wire-like sensing elements to be installed along the underground pipes, has proven immune to the limitations that affect the traditional, acoustic leak-detection systems.

Starting from the positive results obtained thus far, in this work, an improvement of this TDR-based system is proposed. More specifically, the possibility of employing a low-cost, water-absorbing sponge to be placed around the sensing element for enhancing the accuracy in the localization of the leak is addressed.

To this purpose, laboratory experiments were carried out mimicking a water leakage condition, and two sensing elements (one embedded in a sponge and one without sponge) were comparatively used to identify the position of the leak through TDR measurements. Results showed that, thanks to the water retention capability of the sponge (which maintains the leaked water more localized), the sensing element embedded in the sponge leads to a higher accuracy in the evaluation of the position of the leak.

Introduction

The improvement of water resource management has become a relevant issue worldwide [1], and water loss reduction remains one of the key strategies for contributing to an efficient use of this important natural resource. As a result, the localization and repair of leaks are the aim of every water utility since it leads to improved economic and ecological efficiency and better service for clients [2]. Also, a recent study [3] has pointed out that there are at least ten reasons that justify an increased focus on water loss management, among these reasons: operating cost efficiency (related to the repair of the leaks); capital cost efficiency (nowadays, water pipes are considered as tangible assets for Water Companies [4]); reduced health risks (pollutants and contaminants can infiltrate the pipes through leaks); and reduced ecological stress.

In such a context, the possibility of carrying out frequent and efficient leak-localization campaigns is crucial for an effective water resource management. However, traditional leak localization systems (which are mostly based on acoustic methods [5]) are time-consuming and their performance in localizing the leaks is influenced by several factors (e.g., environmental noise; water pressure; geometry and material of the pipes). As a result, with traditional leak detection system, the choice of a particular technique depends on the specific conditions at hand [6]. To overcome these limitations, innovative methodologies for achieving the best results to reduce water loss are constantly being investigated.

In this regard, recently, a time domain reflectometry (TDR)-based method for the localization of water leaks has been developed by the authors [7,8]. This system, being based on an electromagnetic measurement technique, has proven immune to the limitations that affect acoustic leak-detection methods.

In this TDR-based system, a wire-like sensing element (SE) is buried along the pipe at the time of installation. The SE remains permanently buried with the pipe and can be interrogated whenever it is necessary to verify the presence of leaks. Once a pipe section has been equipped with the SE, it takes approximately five minutes for the operator to localize the leaks. This TDR-based leak detection system has been recently implemented on a large scale by the largest European Water Operator. Results have already shown that the employment of this TDR-based system expedites considerably the leak-localization procedure and the related costs, thus allowing to carry out more frequent leak-detection campaigns.

Starting from the positive results obtained thus far, in this work, an improvement for further enhancing the accuracy in the TDR-based localization of the leaks is proposed.

In fact, in the TDR-based system, when a leak has been leaking for a long time, the escaped water diffuses through the soil and may end up being sensed by portions of the SE that are 2–3 m far from the leak point. On one hand, this behavior is beneficial

* Corresponding author.

http://dx.doi.org/10.1016/j.rinp.2016.08.012
2211-3797/© 2016 The Authors. Published by Elsevier B.V.

as it gives the operator a tangible idea of the entity of the leak and allows him/her to schedule the repair intervention accordingly. On the other hand, this water diffusion may increase the uncertainty in the localization of the exact leakage point.

To circumvent this issue, in this work, the possibility of employing a low-cost, water-absorbing sponge to be placed around the wire-like SE for enhancing the accuracy in the localization of the leak is addressed. To this purpose, laboratory experiments were carried out mimicking a leakage condition, to comparatively assess the performance of the TDR-based system when used with a 'traditional' SE or with a sponge-equipped SE. Results showed that the presence of the sponge effectively increases the accuracy in the identification of the leakage point. In fact, thanks to the water-retaining capability of the sponge, the water escaped from the pipe remains more localized and, hence, the position of the leak can be identified more accurately.

In the following, after a brief description of the theoretical background, the measurement procedure and the experimental results are presented and discussed.

Background

TDR is an electromagnetic (EM) measurement technique that has been used since the 1960s for a number of applications, such as for the characterization of electronic devices [9,10]; for dielectric spectroscopy measurements [11,12]; for landslide monitoring [13]; for liquid level measurements [14–16], etc. However, over the years, fault detection along cables [17,18] and soil characterization [19–21] have been considered as the pivotal applications of TDR. As detailed in the following, the TDR-based leak localization system, basically, combines these last two applications [7,8].

TDR measures the reflections that result from an EM signal travelling through a transmission line, which is embedded in (or in contact with) the system to be investigated and acts as a sensing element [20]. Typically, a step-like voltage signal is used as test signal.

The TDR output is a waveform which represents the combination of the incident step (V_i) and of the reflections (V_r) generated when the propagating TDR signal encounters impedance variations [22]. The relation between these two quantities is often expressed in terms of reflection coefficient, $\rho(d)$:

$$\rho(d) = \frac{V_r(d)}{V_i}. \tag{1}$$

The quantity $\rho(d)$ can also be expressed in terms of electrical impedance:

$$\rho(d) = \frac{Z_L(d) - Z_0}{Z_L(d) + Z_0}, \tag{2}$$

where Z_0 is the characteristic impedance of the line; whereas $Z_L(d)$ is the load impedance at the line section at distance d and it depends on the effective dielectric permittivity (ε_{eff}) of the transmission line at the considered section.

To summarize, in TDR measurements, variations of the dielectric characteristics of the propagation line will cause variation of the electrical impedance. This, in turn, will provoke the partial reflection of the TDR test signal. Finally, through an appropriate analysis of the reflected signal, it is possible to retrieve the desired information on the system under test.

The output of a TDR measurement is often represented as a reflectogram, which displays the value of ρ as function of the electrical (or apparent) distance, d^{app}, travelled by the TDR signal along the SE. The quantity d^{app} is related to the physical distance travelled by the TDR signal through the following equation:

$$d^{app} = d \times \sqrt{\varepsilon_{eff}}. \tag{3}$$

As a result, TDR allows not only to sense the electrical impedance variations, but also to localize where they occur. This principle is at the basis of the TDR-based leak localization system.

Fig. 1 shows the typical experimental apparatus of the TDR-based leak localization system. Basically, while the water pipe is being installed, a biwire (e.g., two 1-mm^2 copper wires mutually insulated by a dielectric) is buried with the pipe. In the figure, points B and E indicate the beginning and the end of the SE, respectively; and L indicates the position of the leak. For pinpointing the leak, the operator connects the TDR instrument to the connection point (point K in Fig. 1), which remains accessible through a man–hole or through an inspection well. Basically, the SE and the surrounding soil represent a transmission line, along which the TDR signal can be propagated.

When there is no water leak, then the transmission line constituted by SE and the soil exhibits a practically-constant dielectric permittivity; hence, the TDR signal will travel all along the SE and will be reflected back only at the far end of the SE (point E).

In presence of a leak, the escaped water (whose relative dielectric permittivity is in the order of 78) increases the effective dielectric permittivity of the soil (which typically has a dielectric permittivity in the range 3–10). As a result of this local increase of permittivity, the TDR signal will be partially reflected back when it encounters the water leakage and the ρ curve will exhibit a local minimum in correspondence of the position of the leak.

Additional details on the TDR-based leak detection system can be found in [7,23].

Materials and methods

To comparatively assess the performance of the TDR-based system when used with a 'traditional' SE or with a sponge-equipped SE, laboratory experiments were carried out mimicking a leakage condition.

To this purpose, a 300 cm × 20 cm × 28 cm wooden formwork was used as container for the soil. The formwork was filled with soil, thus mimicking the underground soil. A bifilar SE (two copper wires, separated by a dielectric insulator) was cut to the suitable length to fit in the formwork. The SE was inserted inside the sponge (SE1), and then it was placed in the formwork and covered with the soil. The water-absorbent sponge had approximate dimensions 290 cm × 10 cm × 4 cm.

For comparative purposes, another SE (without sponge) was placed inside the formwork (SE2), parallel to SE1.

The length of each SE was equal to $L_{SE} = 2.90$ m.

Figs. 2 and 3 show the schematization of the longitudinal sections of the formwork, in correspondence of SE1 and SE2, respectively. Points B and E indicate the beginning and the open-circuited end of each SE; point K indicates the connection point to the TDR instrument. To clearly identify the position of B in the TDR reflectograms, thus using this point as reference point, an electrical impedance mismatch was intentionally introduced at point B in the SEs.

After the SEs were buried, the presence of a water leak was mimicked as follows. As shown in Figs. 2 and 3, A hollow cylindrical tube was positioned at a distance $L_{L,ref} = 1.40$ m from point B. Water was poured through the tube and diffused through the soil, similarly to a leakage condition when water escapes from an underground pipe.

Water was poured at 0.3 L at a time, every 15 min (so as to give water the time to diffuse). A total of 1.8 L of water was poured in six steps. For each water addition step, a TDR reflectogram was acquired through SE1 and SE2. The acquired reflectograms were

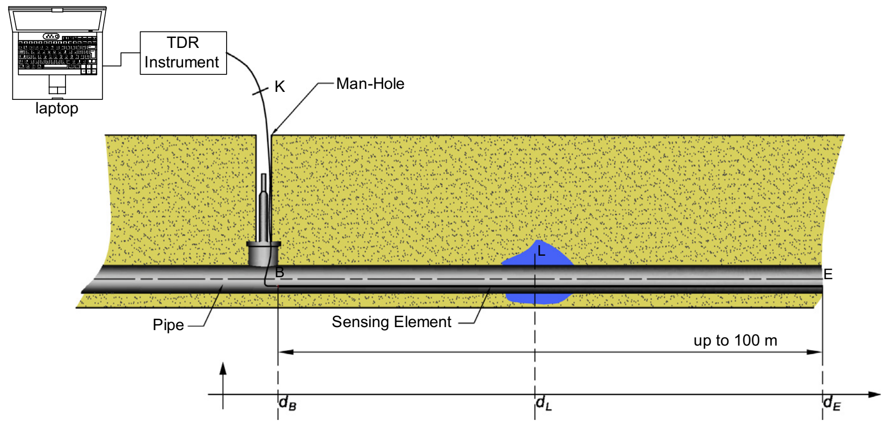

Fig. 1. Schematization of the TDR-based leak detection apparatus (*not to scale*).

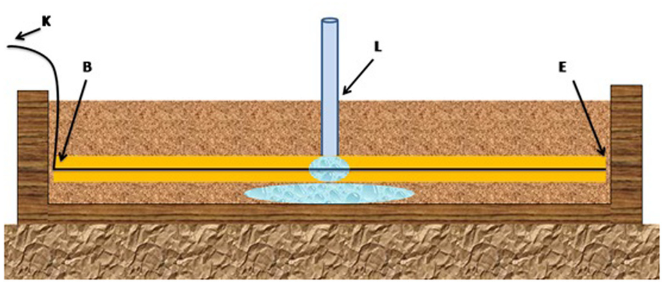

Fig. 2. Longitudinal section of the formwork in correspondence of SE1 (*not to scale*). The yellow-colored area represents the water-absorbent sponge. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

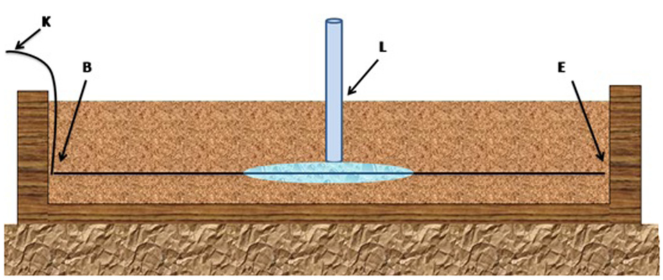

Fig. 3. Longitudinal section of the formwork in correspondence of SE2 (*not to scale*).

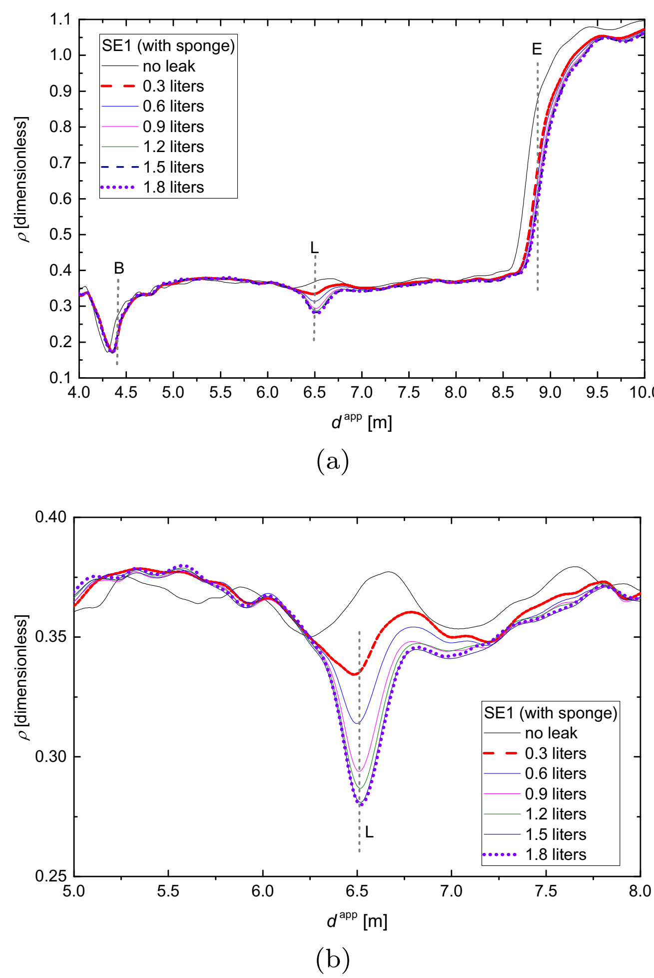

Fig. 4. (a) Reflectograms acquired through SE1, as water content increased. The approximate positions of points B, L, and E are also indicated. (b) Zoom in correspondence of the position of the simulated leak.

then processed to evaluate the position of the leak, as it had been unknown.

The TDR measurements were carried out through the HL1500 [24], a portable reflectometer that generates a step-like voltage signal with a rise time of approximately 200 ps.

Experimental results

Figs. 4 and 5 show the reflectograms acquired from SE1 and SE2 respectively, as the water content increased. With reference to SE1, from Fig. 4, it can be seen the presence of first minimum at approximately $d^{app} \cong 4.4$ m, which corresponds to the impedance variation that was intentionally introduced at point B, so as to identify it more easily in the reflectogram.

The value of ρ remains approximately stable, until $d^{app} \cong 6.5$ m, which corresponds to the apparent distance of the leak (point L). As expected, for increasing values of water content, the value of ρ decreases. Also, from Fig. 4, it can be noticed that the local minimum caused by the presence of the leak is steep and well defined. This is a direct result of the presence of the sponge surrounding the SE; in fact, the sponge retains the water (and then releases it as sketched in Fig. 2), keeping only a limited portion of the SE wet. Once the sponge portion near the leakage point is saturated, the

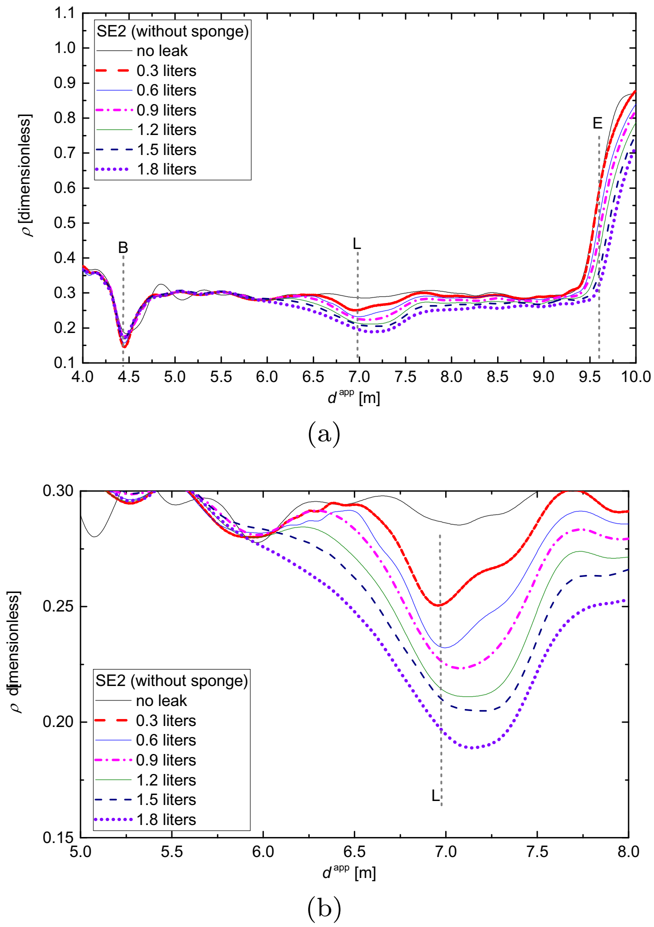

Fig. 5. (a) Reflectograms acquired through SE2, as water content increased. The approximate positions of points B, L, and E are also indicated. (b) Zoom in correspondence of the position of the simulated leak.

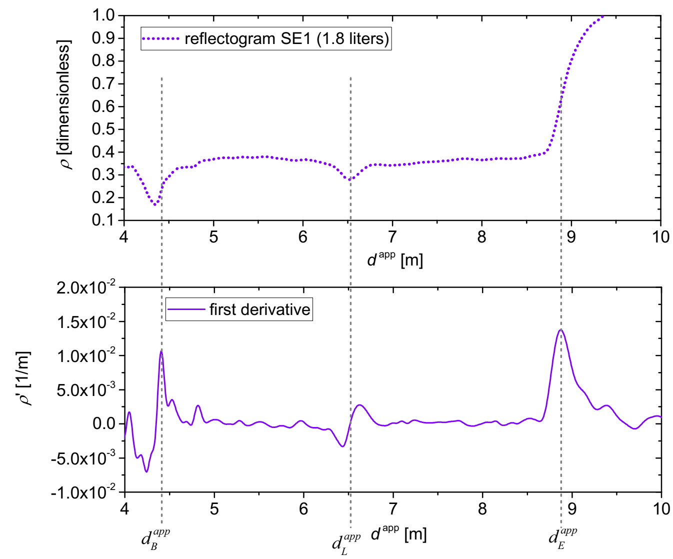

Fig. 6. Reflectogram acquired from SE1, in presence of 1.8 liters of water (*top*). Corresponding first derivative (*bottom*).

Table 1
Summarized results for the evaluation of the position of the leak through SE1.

Water [L]	d_E^{app} [m]	d_B^{app} [m]	d_L^{app} [m]	$L_{L,SE1}$ [m]	$\|Err_{SE1}\|$ [m]
0.0	8.74	4.35	–	-	-
0.3	8.84	4.41	6.49	1.36	0.04
0.6	8.84	4.41	6.50	1.37	0.03
0.9	8.86	4.41	6.51	1.37	0.03
1.2	8.87	4.40	6.51	1.37	0.03
1.5	8.87	4.41	6.51	1.37	0.03
1.8	8.87	4.40	6.52	1.38	0.02

Table 2
Summarized results for the evaluation of the position of the leak through SE2.

Water [L]	d_E^{app} [m]	d_B^{app} [m]	d_L^{app} [m]	$L_{L,SE2}$ [m]	$\|Err_{SE2}\|$ [m]
0.0	9.56	4.36	–	–	–
0.3	9.55	4.37	6.96	1.45	0.05
0.6	9.59	4.36	7.00	1.46	0.06
0.9	9.62	4.36	7.08	1.50	0.10
1.2	9.64	4.36	7.11	1.51	0.11
1.5	9.69	4.36	7.20	1.54	0.14
1.8	9.73	4.37	7.14	1.49	0.09

water falls by gravity towards the underlying area up to the ground and the resulting water diffusion does not wet the SE.

After the leak, in the reflectogram, the ρ value increases again up to approximately 0.36, and it remains approximately constant until the TDR signal reaches the open circuit at the distal end of the SE (point E, at approximately $d^{app} \cong 8.8$ m).

Similar considerations apply for the reflectograms acquired through SE2. From Fig. 5, it can be seen that also in this case, the value of the minimum in correspondence of the leak lowers as the water content is increased. However, differently from the SE1 case, in these reflectograms the valley of the minimum point is wider and extends over a longer portion of distance. This is a direct result of the fact that when there is no sponge (as for SE2), water diffuses through the soil and reaches areas that are far from the actual fault (as also schematized in Fig. 3), thereby increasing the uncertainty in localizing where the fault is.

The acquired reflectograms were processed through the algorithm described in [7] to pinpoint the position of the simulated leak. Basically, the algorithm calculates the position of the leak, L_L from the reflectogram through the following equation:

$$L_L \cong \frac{L_L^{app}}{L_{SE}^{app}/L_{SE}} \cong \frac{d_L^{app} - d_B^{app}}{(d_E^{app} - d_B^{app})/L_{SE}} \quad (4)$$

where L_{SE} indicates the physical length of the SE; L_{SE}^{app} is the electrical length of the SE; and L_L^{app} is the apparent position of the leak. The quantities L_{SE}^{app} and L_L^{app} are inferred from the reflectogram by identifying the abscissae $d_B^{app}; d_E^{app}$; and d_L^{app}, corresponding to points B, E and L, respectively. For the sake of example, Fig. 6 shows one of the reflectograms acquired from SE1 and the corresponding first derivative. Typically, the first derivative of the reflectogram emphasizes the impedance variations in the reflectogram [25], thus allowing a more accurate evaluation of the abscissae $d_B^{app}; d_E^{app}$; and d_L^{app}.

Tables 1 and 2 summarize the obtained results. The quantities $L_{L,SE1}$ and $L_{L,SE2}$ indicate the distance of the leakage point (L) from the beginning of the SEs, as obtained from the SE1 and from the SE2, respectively.

It can be seen that the SE1 reflectograms provide a higher accuracy in the evaluation of the leak position. This is clearly a result of the presence of the sponge which retains the water.

In fact, considering $L_{L,ref} = 1.40$ m as the *true* value of the position of the leak, it is possible to estimate the measurement error (Err) obtained from the two SEs in the evaluation of the position of the leak. Tables 1 and 2 also summarize the results for the error estimate. It can be seen that, as the quantity of added water increased, the absolute error in the evaluation of the leakage point for SE2 is higher than the error that is obtained from SE1. It is worth mentioning that, in practical applications, the presence of the water-absorbent sponge is expected to bring an additional beneficial effect. In fact, the sponge might also act as an equalization layer able to compensate for possible dielectric inhomogeneities in the soil, thus leading to flatter/smoother reflectograms.

Conclusions

In this work, the possibility of employing a SE embedded in water-absorbent sponge for enhancing the accuracy in the TDR-based leak localization system was investigated. To this purpose, experimental tests were carried out by comparatively using a SE embedded within a sponge and a SE without sponge for localizing the position of an imposed leakage-like condition. Results showed that the SE embedded in the sponge effectively leads to a more accurate evaluation of the position of the leak. In practical applications, the employment of a water-absorbent sponge around the SE would represent a cost-effective solution to achieve a higher accuracy in pinpointing the position of the leaks. This, in turn, would be crucial to limit the excavation area (and, hence, the operative costs) when the leak is being repaired.

References

[1] Fantozzi M, Popescu I, Farnham T, Archetti F, Mogre P, Tsouchnika E, et al. ICT for efficient water resources management: the icewater energy management and control approach. Proc Eng 2014;70:633–40. http://dx.doi.org/10.1016/j.proeng.2014.02.069.

[2] Thornton J, Sturm R, Kunkel G. Water loss control. McGraw Hill Professional; 2008.

[3] Guidelines for water loss reduction. <https://www.giz.de/fachexpertise/downloads/giz2011-en-guideline-water-loss-reduction.pdf> (March 2011).

[4] Nafi A, Tlili Y. Functional and residual capital values as criteria for water pipe renewal. Struct Infrastruct Eng 2015;11(2):194–209. http://dx.doi.org/10.1080/15732479.2013.862728.

[5] Hunaidi O, Bracken M, Gambino T, Fricke C, Acoustic methods for locating leaks in municipal water pipe networks. In: International conference on water demand management; 2004. p. 1–14.

[6] Hamilton S, Charalambous B. Leak detection: technology and implementation. IWA Publishing; 2013.

[7] Cataldo A, Cannazza G, De Benedetto E, Giaquinto N. Experimental validation of a TDR-based system for measuring leak distances in buried metal pipes. Progr. Electromagnet. Res. 2012;132:71–90.

[8] Cataldo A, Persico R, Leucci G, De Benedetto E, Cannazza G, Matera L, De Giorgi L. Time domain reflectometry, ground penetrating radar and electrical resistivity tomography: a comparative analysis of alternative approaches for leak detection in underground pipes. NDT & E Int. 2014;62:14–28. http://dx.doi.org/10.1016/j.ndteint.2013.10.007.

[9] Cataldo A, Monti G, De Benedetto E, Cannazza G, Tarricone L, Catarinucci L. A comparative analysis of reflectometry methods for characterization of antennas. In: 2008 IEEE I2MTC international instrumentation and measurement conference proceedings; 2008, p. 240–43. http://dx.doi.org/10.1109/IMTC.2008.4547038.

[10] Chen M-K, Tai C-C, Huang Y-J. Nondestructive analysis of interconnection in two-die BGA using TDR. IEEE Trans Instrument Measur 2006;55(2):400–5. http://dx.doi.org/10.1109/TIM.2006.870318.

[11] Kaatze U. Measuring the dielectric properties of materials. ninety-year development from low-frequency techniques to broadband spectroscopy and high-frequency imaging. Measur Sci Technol 2013;24(1):012005. http://dx.doi.org/10.1088/0957-0233/24/1/012005.

[12] Wilczek A, Szypowska A, Kafarski M, Skierucha W. A time-domain reflectometry method with variable needle pulse width for measuring the dielectric properties of materials. Sensors 2016;16(2). http://dx.doi.org/10.3390/s16020191.

[13] Gueguen E, Bentivenga M, Colaiacovo R, Margiotta S, Summa V, Adurno I. The verdesca landslide in the Agri Valley (Basilicata, southern Italy): a new geological and geomorphological framework. Nat Hazards Earth Syst Sci 2015;15(11):2585–95. http://dx.doi.org/10.5194/nhess-15-2585-2015.

[14] Nemarich C. Time domain reflectometry liquid level sensors. IEEE Instrument Measur Mag 2001;4(4):40–4. http://dx.doi.org/10.1109/5289.975464.

[15] Cataldo A, Cannazza G, De Benedetto E, Giaquinto N, Trotta A. Reproducibility analysis of a TDR-based monitoring system for intravenous drip infusions: Validation of a novel method for flow-rate measurement in IV infusion. In: MeMeA 2012–2012 IEEE symposium on medical measurements and applications, proceedings, 2012, pp. 203–7. http://dx.doi.org/10.1109/MeMeA.2012.6226673.

[16] Cataldo A, Piuzzi E, De Benedetto E, Cannazza G. Experimental characterization and performance evaluation of flexible two-wire probes for TDR monitoring of liquid level. IEEE Trans Instrument Measur 2014;63(12):2779–88. http://dx.doi.org/10.1109/TIM.2014.2318393.

[17] Zhang J, Zhang Y, Guan Y. Analysis of time-domain reflectometry combined with wavelet transform for fault detection in aircraft shielded cables. IEEE Sens J 2016;16(11):4579–86. http://dx.doi.org/10.1109/JSEN.2016.2547323.

[18] Boudjefdjouf H, Bouchekara H, De Paulis F, Smail M, Orlandi A, Mehasni R. Wire fault diagnosis based on time-domain reflectometry and backtracking search optimization algorithm. Appl Computat Electromagnet Soc J 2016;31(4):340–7.

[19] Noborio K. Measurement of soil water content and electrical conductivity by time domain reflectometry: a review. Comput Electron Agricult 2001;31(3):213–37. http://dx.doi.org/10.1016/S0168-1699(00)00184-8.

[20] Robinson D, Jones S, Wraith J, Or D, Friedman S. A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry. Vadose Zone J 2003;2(4):444–75.

[21] Piuzzi E, Cataldo A, Cannazza G, De Benedetto E. An improved reflectometric method for soil moisture measurement exploiting an innovative triple-short calibration. IEEE Trans Instrument Measur 2010;59(10):2747–54. http://dx.doi.org/10.1109/TIM.2010.2045445.

[22] Application note: Tektronix's, TDR impedance measurements: a foundation for signal integrity; 2004.

[23] Cataldo A, De Benedetto E, Cannazza G, Giaquinto N, Savino M, Adamo F. Leak detection through microwave reflectometry: from laboratory to practical implementation. Measurement 2014;47(1):963–70. http://dx.doi.org/10.1016/j.measurement.2013.09.010.

[24] TDR100 instruction manual – revision 2/10, Logan, UT. <http://www.campbellsci.com/documents/manuals/tdr100.pdf>; 2010.

[25] Robinson DA, Schaap MG, Or D, Jones SB. On the effective measurement frequency of time domain reflectometry in dispersive and nonconductive dielectric materials. Water Resources Research 2005;41(2):W02007.1–7.9. http://dx.doi.org/10.1029/2004WR003816.