Journal of Hydrology 505 (2013) 346–351

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

New TDR waveguides and data reduction method for monitoring of stream and drainage stage

Chih-Chung Chung [a], Chih-Ping Lin [b,*], I.-Ling Wu [a], Ping-Hung Chen [c], Ting-Kuei Tsay [c]

[a] Disaster Prevention and Water Environment Research Center, National Chiao Tung University, 1001 Ta-Hsueh Rd., Hsinchu 300, Taiwan
[b] Dept. of Civil Engineering, National Chiao Tung University, 1001 Ta-Hsueh Rd., Hsinchu 300, Taiwan
[c] Dept. of Civil Engineering, National Taiwan University, No. 1, Sec. 4, Roosevelt Rd., Taipei, Taiwan

ARTICLE INFO

Article history:
Received 1 May 2013
Received in revised form 19 August 2013
Accepted 30 September 2013
Available online 8 October 2013
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Ehab A. Meselhe, Associate Editor

Keywords:
Time domain reflectometry (TDR)
Water level
Field measurement

SUMMARY

Less known in the field of hydrological measurements in civil engineering, time domain reflectometry (TDR) has been developed as a new solution to some of the more difficult level measurement problems. This study applied TDR methodology to provide two new designs for a water level sensing waveguide that can be applied in difficult field conditions such as in an underpass, tunnel, culvert, or sewer, etc. Two types of water level sensing waveguides are presented, including a rigid assembled coaxial pipe and a flexible adhered parallel wire. The corresponding data reduction procedure is also proposed to account for uncertainty of travel time analysis and calibrate the velocity of pulse propagation along the waveguides. The satisfactory performance of both the proposed TDR waveguides and data reduction method was experimentally validated. A field case study further demonstrated the feasibility of the TDR technique for water level measurements under typical urban drainage conditions.

1. Introduction

Water level data for stream and drainage systems in urban areas are critical parameters in the planning and management for various uses of hydrological information. Stream stage is also useful in the design of structures that may be affected by stream elevation. In order to obtain the water level data efficiently and accurately, the use of electronic water level sensing equipment has become a common practice.

Sauer and Turnipseed (2010) reviewed the equipment and techniques for observation, sensing, and recording of stage in streams and reservoirs, including float-driven sensors, gas-purge and bubbler systems, submersible and non-submersible pressure transducers, and acoustic, radar, and laser techniques. Basic requirements necessary to all gages, such as gage-datum and stage-accuracy standards, were also described. The Irrigation Training and Research Center (ITRC) (1998) examined most of these methods regarding several aspects such as long term trending, time lag, output stability, linearity and hysteresis, drying effects, and air temperature effects. The techniques suggested by the ITRC in preferential order were float-driven sensors, submersible pressure transducers, and acoustic (or radar) devices. However, several difficulties may arise when monitoring water level in closed space such as a bridge underpass, tunnel, culvert, or sewer. A float-driven sensor requires a monitoring well, which can be difficult and costly to construct and maintain in the aforementioned environments. A submersible pressure transducer, while convenient, is troubled by the drying effect and interference of sediments or sludge to the transducer. Acoustic and radar devices can be troublesome in closed-space monitoring because they may not work properly with wall interference or when submerged.

Less known in the field of hydrological measurements in civil engineering, time domain reflectometry (TDR) has been developed as a new solution to some of the more difficult level measurement problems (Gray and Hollywood, 1997; Nemarich, 2001). It features many of the benefits of radar, but none of its licensing requirements, wall interface or submergence problems. TDR is a measurement principle based on a cable radar (formally called time domain reflectometer) and metallic sensing waveguides. It has its roots in the radar systems developed by the military in the 1930s, and has long been used in the communication industry for cable discontinuity testing. It is based on transmitting an electromagnetic pulse through a coaxial cable connected to a sensing waveguide and watching for reflections of this transmission due to changes in characteristic impedance along the waveguide. Depending on the design of the waveguide and analysis method, the reflected signal can be used to monitor various engineering parameters. In the past

* Corresponding author. Tel.: +886 3 513 1574; fax: +886 3 571 6247.
E-mail addresses: chung.chih.chung@gmail.com (C.-C. Chung), cplin@mail.nctu.edu.tw (C.-P. Lin), f89521314@ntu.edu.tw (I.-Ling Wu), bg@ms61.url.com.tw (P.-H. Chen), tktsay@ntu.edu.tw (T.-K. Tsay).

0022-1694/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2013.09.050

two decades, the TDR technique has been finding its way into various hydrology-related measurements, such as soil water content (Topp et al., 1980), electrical conductivity (Lin et al., 2008), water level (Dowding et al., 1996; Thomsen et al., 2000), suspended sediment concentration (Chung and Lin, 2011), and channel bed scouring and filling (Yu and Yu, 2011; Lin et al., 2012). Moret et al. (2004) implemented TDR to automate water level measurement in Mariotte-type reservoirs for tension disc infiltrometers. Tidwell and Brainard (2005) experimented on simultaneous measurements of stream stage, channel profile, and aqueous conductivity.

Most literature on TDR water level sensing makes use of a multi-rod waveguide for tank measurements (Gray and Hollywood, 1997; Thomsen et al., 2000; Nemarich, 2001) or an air-filled coaxial cable for well measurements (Dowding et al., 1996). Some adaptation is needed for monitoring in a fluvial environment and urban drainage. Furthermore, water level is currently directly determined by travel time analysis of the reflected waveform using an algorithm such as the "intersections of tangent lines" method. The physical position that corresponds to the time of reflection can be ambiguous due to dispersion of radar wave propagation. Positioning of the absolute water level elevation and calibration of pulse propagation velocity along the waveguide require further studies. It is this paper's objective to provide two new designs for a water level sensing waveguide that can be easily mounted in a fluvial environment or urban drainage. The corresponding calibration procedure and automated data reduction method are also proposed to yield stable outputs. Two types of water level sensing waveguides are presented, including the assembled coaxial pipe and the adhered parallel wire. The proposed calibration and data reduction method is verified via laboratory experiments. An actual field implementation is also presented.

2. Background of TDR method

Time domain reflectometry (TDR) was originally developed for the detection of cable faults and later applied to dielectric spectroscopy in physical chemistry (Fellner-Felldeg, 1969). In the past two decades, the TDR technique has been adapted for civil engineering measurements (Lin, 2009). A TDR measurement system is composed of a TDR pulser–receiver device (e.g. cable radar), a transmission line and a sensing waveguide, as illustrated in Fig. 1a. The pulse generator sends an electromagnetic (EM) pulse along the lead cable and the sensing waveguide directs the EM wave into the material under test or environment to be monitored. The sensing waveguide may be a coaxial cable (e.g. for monitoring of localized shear deformation and groundwater level) or a specially-designed multi-conductor waveguide (e.g. for monitoring of soil moisture, electrical conductivity, and deformation). Impedance change occurs when the measurement waveguide is subjected to deformation or an electrical property of the surrounding material changes. Reflections from the impedance change are recorded and used to interpret engineering parameters.

For water level sensing waveguide can be as simple as a twin-wire speaker cable as illustrated in Fig. 1a. The a, b, and c points depicted in the recorded waveform in Fig. 1a represent the reflections from the cable-waveguide connector, air–water interface, and the shorted end, respectively. The reflected waveforms during rising water levels are shown in Fig. 1b. As the water level rises, the reflection off the air–water interface occurs earlier. Multiple TDR sensing waveguides can be connected to a TDR device through a multiplexer. Sensing waveguides are constructed by simple mechanical elements without any electronic components. The TDR device and the data acquisition controller are placed above water at a safe place.

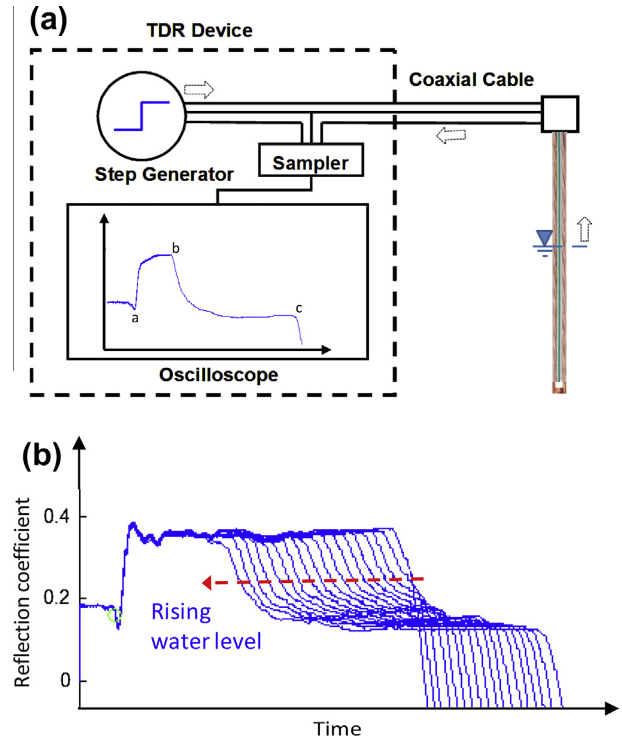

Fig. 1. (a) Major components of a TDR measurement system including a TDR pulser–receiver device (i.e. cable radar), a transmission line, and a sensing waveguide; and (b) an example of recorded waveforms for water level sensing.

3. Materials and methods

3.1. TDR water level waveguides

Two types of TDR water level waveguides are presented and investigated to facilitate simple construction in stream and drainage environments. The first type is the assembled coaxial pipe, which is extended from the coaxial probe for measuring dielectric property of various materials (Siddiqui et al., 2000; Lin et al., 2006). Fig. 2 reveals the design details of the assembled coaxial pipe. It is mainly composed of a stainless steel pipe and a central metal rod. The cross-sectional configuration of an assembled coaxial pipe is the same as the coaxial cable except that the space between inner and outer conductors is air-filled. For practical consideration and

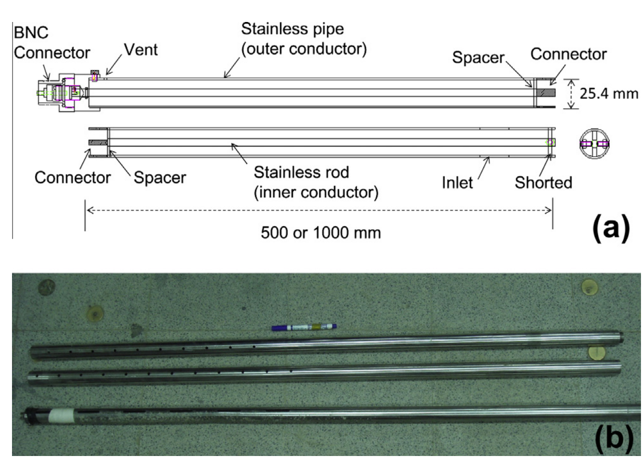

Fig. 2. (a) A schematic of the assembled coaxial TDR water level waveguide and (b) a photo of the prototype.

easy installation, the coaxial sensing waveguide is divided into segments that can be assembled in series depending on the required sensing range. To maintain the central position of the inner rod, spacers are designed at the connectors between segments as shown in Fig. 2. The typical length of segment is designed to be 500 or 1000 mm. The length and number of the waveguide segments can be adjusted depending on the field condition. A vent is installed at the top of the pipe to release air in the coaxial pipe. This type of sensing waveguide is designed to be installed on the wall of a bridge pier or a drainage structure with a planar surface. The steel pipe should be durable enough to withstand transient impact.

The second design type of waveguide proposed is the adhered parallel wire. It is meant to be used in environments where large impacts from debris are not expected, such as in drainage channels, or where the surface for installation is non-planar, such as in sewer pipelines. Taking advantage of existing cable products, the stiff coaxial cable (e.g. cable with solid aluminum outer conductor) with a messenger wire is proposed to form the water level sensing waveguide as shown in Fig. 3a. It is a similar to the type of cable running in sewers for cable TV systems. The outer conductor of the coaxial cable and the messenger wire serve as the two opposing electrodes for water level sensing. The plastic jacket of the cable maintains a constant spacing between opposing electrodes and further provides insulated coating all around the electrodes. As in the case of a coated moisture probe (Scott et al., 2002; Lin et al., 2006), the coating can reduce signal attenuation and allow for a longer distance construction of the waveguide. But due to existence of the plastic jacket, the EM wave velocity along the waveguide is not equal to the velocity of the medium surrounding the waveguide. The equivalent velocity needs to be calibrated in advance. This type of water level sensing waveguide makes use of widely available TV cable. Similar to the installation of TV cable, the adhered parallel wire is quite flexible as shown in Fig. 3b.

3.2. TDR water level data reduction method

The proposed data reduction method involves determination of travel time and calibration of pulse propagation velocity. As in radar and acoustic Doppler measurements, TDR utilizes the round-trip travel time in the air section to determine the water level. The precise time of reflection that corresponds to the position of the interface may not be clear due to the dispersion of wave propagation. The conversion from travel time to distance also requires calibration of the velocity of the EM pulse along the waveguide. A differential approach is proposed below to account for uncertainty of actual travel time and calibrate the velocity of EM pulse along the waveguide.

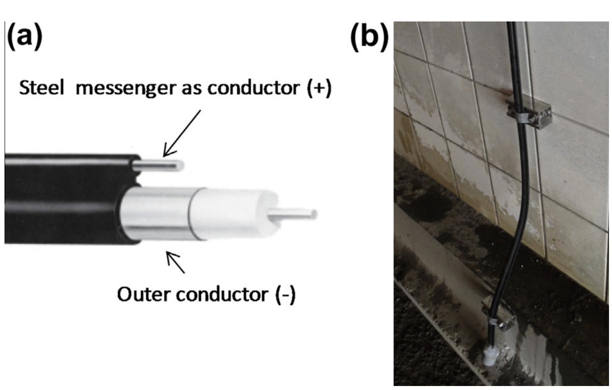

Fig. 3. (a) A schematic of the adhered parallel wire making use of coaxial TV cable with messenger wire to form a level sensing waveguide (modified from CommScope, 2012) and (b) a photo of field installation.

To determine the travel time, a zero time base is first defined. A characteristic point in the reflection spike from the connector, as shown in Fig. 4(b), is selected to be the zero-time base in this study. It is often easier to determine the travel time in the impulse waveform, which is obtained by taking the derivative of the step-pulse waveform. The round-trip travel time τ is measured from the selected point of zero-time base to the apex of the derivative of the reflected waveform as illustrated in Fig. 4(c). Due to dispersion and arbitrary definition of time arrival, there might exist some time difference t_0 between the measured apparent travel time and the actual round trip travel time from the connector to the air–water interface. A reference waveform with known water level is used to calibrate the error term t_0. For the reference waveform and any other measured waveform, the apparent round-trip travel time τ can be expressed as a function of the actual travel time Δt as

$$\begin{cases} \tau_r = t_0 + \Delta t_r = t_0 + \frac{2L_{air,r}}{V_a} \\ \tau_m = t_0 + \Delta t_m = t_0 + \frac{2L_{air,m}}{V_a} \end{cases} \tag{1}$$

where the subscript r indicates the reference case and the subscript m indicates subsequent measurements; $L_{air,r}$ and $L_{air,m}$ represent the length of the air section for the reference case and the subsequent measurement, respectively; V_a is the velocity of the EM wave along the waveguide in air, and t is time. The difference in the length of air section between the reference case and the subsequent measurement is denoted by ΔL_{air}. It can be calculated by the following equation:

$$\Delta L_{air} = \frac{1}{2}(\tau_r - \tau_m)V_a \tag{2}$$

where the ΔL_{air} is the difference between two lengths of the air section, which is equivalent to the change in water level. The algebraic operation in deriving Eq. (2) cancels out the uncertain term t_0. In the cases where the conductor(s) of the sensing waveguide is (are) coated with insulating material, the V_a is not equal to the velocity of light. It should be calibrated before Eq. (2) is used to calculate the change in water level. The V_a of the sensing waveguide may be calibrated beforehand in the laboratory. To calibrate the V_a in the field requires at least two measurements with different known water levels. The reference waveform is first recorded with known water level, which is often the case of zero water depth. Another measurement is later recorded with another known water level. With known change in water level and corresponding arrival times, τ_r and τ_m, V_a can be back calculated by Eq. (2). Once the velocity V_a is obtained, subsequent changes in water level (i.e. ΔL_{air}) can be determined using the same Eq. (2). The absolute water level elevation (EL) can then be determined by the following equation:

$$\text{Measured Water Level EL} = \text{Reference Water Level EL} + \Delta L_{air} \tag{3}$$

where the actual “Reference Water Level EL” of the reference case should be provided initially.

4. Results and discussion

4.1. Laboratory evaluation of TDR water level measurement

A Campbell Scientific TDR100 device with a SDMX50 multiplexer (Campbell Scientific, 2010) was used for the laboratory evaluation of the two types of TDR water level waveguides proposed. Both TDR probes were connected via 25-m CommScope QR320 cables to the SDMX50 multiplexer, simulating the field condition where the TDR device and data acquisition system are placed far away from the sensing point. The number of data points sampled by the TDR device is 2048 and the sampling window was set to

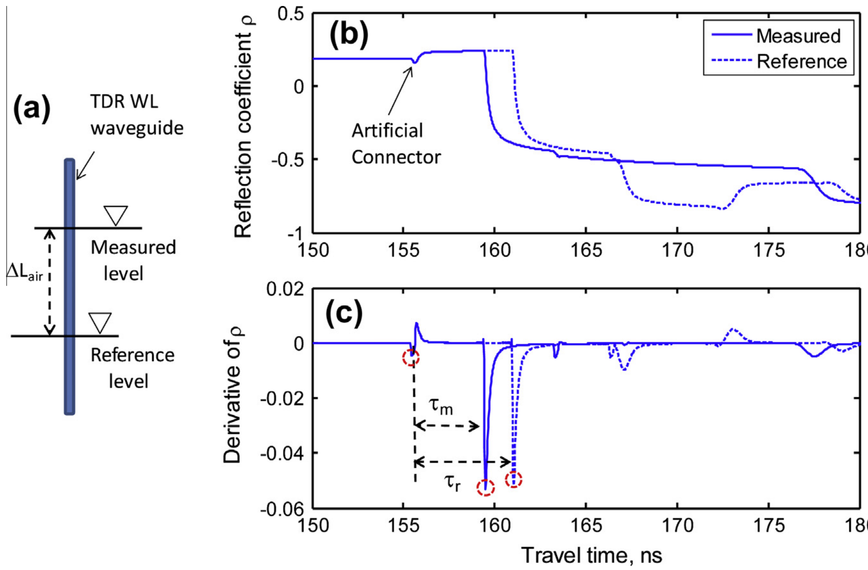

Fig. 4. (a) Water level changes along the TDR waveguide, (b) the corresponding step-pulse TDR waveforms, and (c) the derivatives of TDR waveforms representing the impulse waveforms.

be 5 m. The corresponding spatial resolution is about 2.5 mm. Setting the EM wave velocity equal to the velocity of light, the equivalent sampling interval was 16.3 ps. The probes are placed and centralized in hollow acrylic cylinders with 10 cm inner diameter and 100 cm in height. Water is incrementally pulled into the acrylic cylinders to simulate rising water level. Fig. 5 shows the TDR waveforms for the assembled coaxial pipe waveguide at different water levels ranging from 0 to 90 cm. Similar waveforms were obtained for the adhered parallel wire probe, but not shown.

By setting the 0 cm water level as the reference case, subsequent increasing water levels in the uncoated coaxial waveguide were estimated assuming that V_a is equal to the speed of light (2.998^*10^8 m/s). Fig. 6 compares the estimated values with the actual water levels, which were read off a ruler on the acrylic cylinder with a resolution of 1 mm. The associated measurement errors as compared with the ruler measurements are shown in Fig. 7. For the adhered parallel wire, the velocity of EM wave along the wire needs to be calibrated before water level measurements and the calibration yields $V_a = 2.442^*10^8$ m/s. Using this calibrated velocity, the results of water levels measured with the adhered parallel wire and the associated errors are also presented in Figs. 6 and 7. Fig. 6 demonstrates excellent 1:1 correlations between the water levels measured with the two types of TDR probes and the actual water levels. A closer examination of the measurement errors in Fig. 7 reveals the assembled coaxial waveguide to be more accurate with errors less than 5 mm. The adhered parallel wire produces larger errors, but most errors are within 10 mm. Unlike the uncoated coaxial pipe, the effective EM wave velocity along the adhered parallel wire depends on not only the medium surrounding the waveguide but also the shape and thickness of the coated jacket. Larger errors in the adhered parallel wire can be attributed to the fact that the cable is not rigid and perfectly straight with precise dimension in length and the effect of cable jacket on V_a is not perfectly uniform. The USGS accuracy standard is 0.01 ft (~3 mm) or 0.2% of the effective range in stage (Sauer and Turnipseed, 2010). Accuracy within 10 mm is considered more than satisfactory in many applications. It should also be noted that the measurement accuracy depends on the sampling resolution of the TDR device. The magnitude of error (5 mm) is about twice the sampling resolution (2.5 mm) since each measurement involves two travel time determinations in the proposed differential approach. The accuracy can

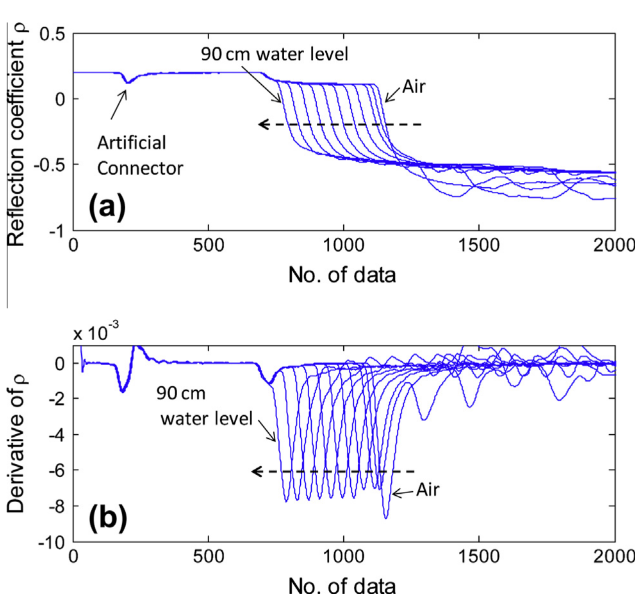

Fig. 5. (a) TDR waveforms for the assembled coaxial pipe waveguide at water levels ranging from 0 to 90 cm; and (b) the corresponding derivatives of the waveforms.

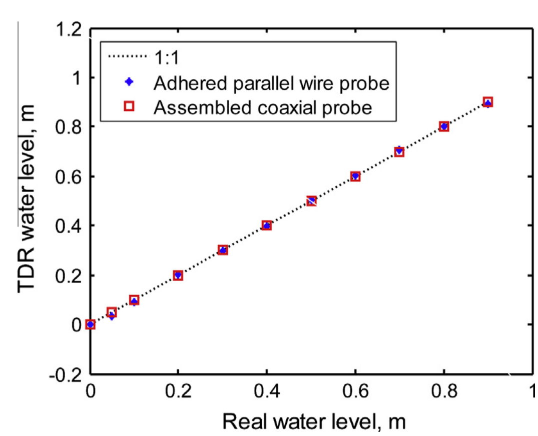

Fig. 6. Measured water levels compared with the actual water levels.

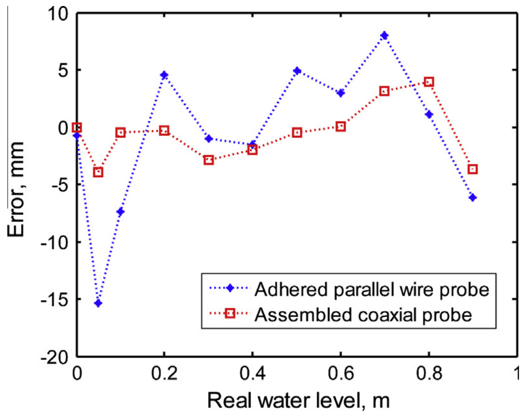

Fig. 7. Measurement errors of the two proposed water level sensing waveguides.

Fig. 8. Aerial photo showing the location of the TDR water level station.

be further improved by increasing the number of sampling points or decreasing the size of the sampling window.

There is no limitation on the range of the TDR probes in water level measurements as long as the total length of the lead cable and probe is within the pulse range (which is about 2 km in the Campbell Scientific TDR100 device). Furthermore, unlike most other sensors having accuracy expressed as percentage of full scale, a nice feature of the travel time-based TDR method is that the measurement resolution or accuracy does not decrease with increasing range (Lin and Tang, 2005).

4.2. Field example of TDR water level monitoring

A field implementation was demonstrated at the Zhonggang East pumping station located in New Taipei City, Taiwan, as shown in Fig. 8. Zhonggang Main Drainage was an irrigation channel built in 1910, and water was introduced to Zhonggang Main Drainage through Dakekeng Stream. Due to the fast growth of local population, there was a demand of space for discharge or temporary storage of domestic wastewater and rainwater. Zhonggang Main Drainage was therefore widened and deepened in 1989 with a total length of 2.6 km and a catchment area of 16.6 km^2. A cutoff wall and two pumping stations were installed at the convergence of Dakekeng Stream and Zhonggang Main Drainage. The slope of the drainage channel bottom is quite flat without much of gravity flow, so it is like a large-scale flood pond. During high stages, the pumping stations pump the water from Zhonggang Main Drainage channel into Dakekeng Stream to help keep the area from flooding. The stage in Dakekeng Stream is often higher than Zhonggang Main Drainage during storm events. The water level of Zhonggang Main Drainage will quickly rise and lead to urban flooding if the pumping stations does not have sufficient capacity or have a breakdown (Lee, 2012).

As a pilot project for future deployment of TDR water level monitoring in the drainage system, a TDR monitoring station was installed next to the trash rack of the Zhonggang East pumping station for continuous water level monitoring. As shown in Fig. 9, the location was selected to mimic the monitoring condition in drainage conduits such as a culvert or a sewer. The assembled coaxial probe was utilized. The total length of the assembled TDR water level waveguide is 6 m (EL −5.8–0.8 m). The waveguide is composed of 6 segments 1 m long as shown in Fig. 9. An existing radar water level station was mounted on the overpass in the pond (forebay) of the pumping station, also shown in Fig. 8. The stage of Dakekeng Stream is recorded at a nearby bridge station.

Field demonstration of TDR monitoring was carried out from July to December 2009. A torrential rainfall event was recorded on August 12th. The results in Fig. 10 show that both TDR and radar instruments recorded a dramatic water level change in the pumping station. The variation of water level in Dakekeng Stream was also recorded but the data collection was disrupted due to malfunction of the measuring radar device. The results of TDR agree fairly well with that of the radar instruments at the beginning and the end of the event. A significant difference between TDR and radar instruments was observed during the period of pumping operation from the 14:00 h until 23:00 h. The water level measured by radar instruments was 0.1–0.3 m higher than the TDR water level. This difference can be explained by the effect of pumping and local flow condition. The radar was installed near the center of the forebay of the pumping station, where the flow surface is stable, while the TDR was installed on the downstream side of the bridge pier at the entrance of the forebay, as shown in Figs. 8 and 9. Due to compression and interference from the bridge pier, the upstream inflow velocity is reduced causing a water level increase on the upstream side and a reduction of TDR water level on the downstream side of the pier. As the pumps were turned on, stronger flow velocity led to lower TDR water level. After the pumps stopped running, the flow velocity reduced to the lowest point and the TDR water level approached the more stable water level measured by radar instruments. The continuous and stable TDR water level measurements observed in the field implementation validated the feasibility of using the TDR technique for water level measurements under typical urban drainage conditions.

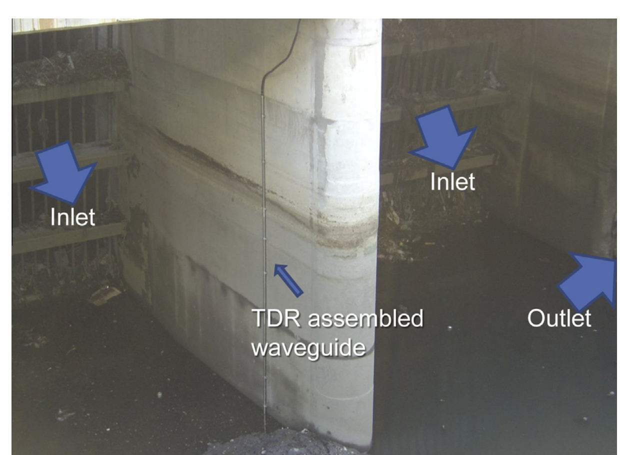

Fig. 9. The 6-m assembled coaxial water level waveguide (EL -5.8–0.8 m) installed at Zhonggang East pumping station.

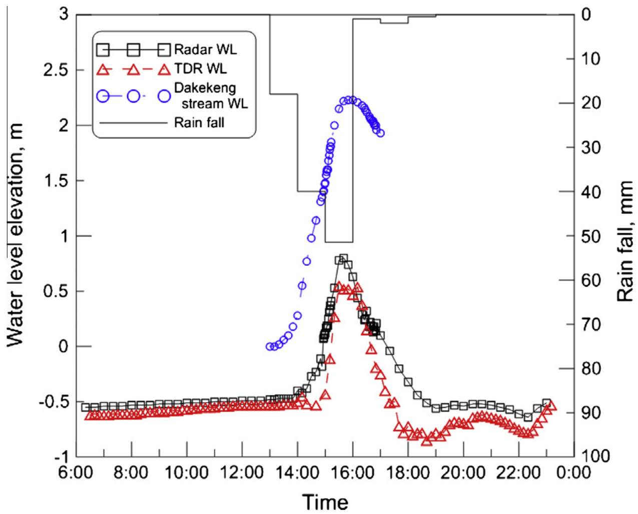

Fig. 10. Field data of TDR water level monitoring in comparison with that of a radar water level station.

The TDR water level measurement is based on the reflection off the interface between air and water. Debris in the water will not affect the TDR level measurements since the water level is determined by the length of the air section. We have not experienced fouling problem in the air section in the field. However, potential fouling on the waveguide after water level retreat should be noted. The adhered parallel wire is less affected by fouling because the most sensitivity area around the conductors is coated by the cable jacket. By the same reasoning, coating can be applied to the central conductor of the coaxial pipe to make it more fouling resistant and less affected by fouling should it occur. But in this case, the velocity of EM wave along the coated waveguide should be calibrated.

5. Conclusions

Various techniques are widely available for water level sensing. But there are still great challenges when conducting long-term monitoring of water level in field environments such as in an underpass, tunnel, culvert, or sewer. This study applied time domain reflectometry (TDR) technique to provide two new designs for a water level sensing waveguide that can be easily mounted in a fluvial environment and/or urban drainage. The rigid assembled coaxial waveguide constructed by stainless steel can be installed on the wall of a bridge pier or a drainage structure with a planar surface, while the flexible parallel-wire waveguide makes use of widely available TV cable and works well in drainage channels and sewer pipelines. Results of a laboratory evaluation show that both water level sensing waveguides are fairly accurate and reliable using the proposed data reduction procedure that accounts for uncertainty of actual travel time and velocity calibration. As a pilot project for future deployment of TDR water level monitoring in a drainage system, a TDR monitoring station was installed next to the trash rack of a pumping station to mimic the condition of monitoring in a culvert or sewer. The field implementation successfully demonstrated the feasibility of the TDR technique for water level measurements under typical urban drainage conditions.

The newly proposed TDR probes provide a new solution for water level measurements in some of the more difficult environments where existing water level sensing methods may not work well. Additional special features include flexible and unlimited measurement range and a measurement accuracy not affected by measurement range. Effect of possible waveguide fouling on TDR water level measurements is considered minor if the waveguide is coated with fouling-resistant coating, but it should be further assessed in an environment where severe fouling is to be expected.

References

Campbell Scientific, 2010. TDR100 Instrument Manual. Campbell Scientific Inc, Utah, USA.

Chung, C.-C., Lin, C.-P., 2011. High concentration suspended sediment measurements using time domain reflectometry. J. Hydrol. 401, 134–144.

CommScope, 2012. P3 500 series cables product descriptions. CommScope Inc. <http://www.tvcinc.com/downloads/CommScope%20P3%20500-2.pdf> (09.07.13).

Dowding, C.H., Huang, F., McComb, P.S., 1996. Water pressure measurement with time domain reflectometry cables. Geotech. Test. J. 19 (1), 58–64.

Fellner-Feldegg, H., 1969. The measurement of dielectrics in time domain. J. Phys. Chem. 73, 616–623.

Gray, J., Hollywood, P., 1997. Time domain reflectometry tackles tough tank level measurements. Instr. Contr. Syst. 70 (11), 33–35.

Irrigation Training and Research Center (ITRC), 1998. Water level sensor and datalogger testing and demonstration. Project on Behalf of the USBR Mid-Pacific Region. ITRC Report No. R-99-002, California Polytechnic State University, San Luis Obispo, CA 93407, USA, 196pp. <http://www.itrc.org/reports/sensors/WaterLevelSensor.pdf> (09.07.13).

Lee, C., 2012. A river and the remaking of Xinzhuang. Taiwan Panorama 37, 70–79.

Lin, C.-P., 2009. TDR as geo-nerve: slope monitoring system example. Geotech. News 27, 38–40.

Lin, C.P., Tang, S.H., 2005. Development and calibration of a TDR extensometer for geotechnical monitoring. Geotech. Test. J. 28 (GTJ12188), 464–471.

Lin, C.P., Tang, S.H., Chung, C.C., 2006. Development of TDR penetrometer through theoretical and laboratory investigations: 1. Measurement of soil dielectric permittivity. Geotech. Test. J. 29 (GTJ14093), 306–313.

Lin, C.-P., Chung, C.-C., Huisman, J.A., Tang, S.-H., 2008. Clarification and calibration of reflection coefficient for electrical conductivity measurement by time domain reflectometry. Soil Sci. Soc. Am. J. 72, 1033–1040.

Lin, C.-P., Wang, K., Chung, C.-C., Weng, Y.-W., 2012. Development of a durable bridge scour monitoring system based on time domain reflectometry. 6th International Conference on Scour and Erosion, August 27–31, 2012, Paris, 76.

Moret, D., López, M.V., Arrúe, J.L., 2004. TDR application for automated water level measurement from Marriotte reservoirs in tension disc infiltrometers. J. Hydrol. 297, 229–235.

Nemarich, C.P., 2001. Time domain reflectometry liquid level sensors. Instrum. Meas. Mag. IEEE 4, 40–44.

Sauer, V.B., Turnipseed, D.P., 2010. Stage measurement at gaging stations. U.S. Geological Survey Techniques and Methods book 3, chap. A7, 45p. <http://pubs.usgs.gov/tm/tm3-a7/>.

Scott, B.J., Wraith, J.M., Or, D., 2002. Time domain reflectometry measurement principles and applications. Hydrol. Process. 16, 141–153.

Siddiqui, S.I., Drnevich, V.P., Deschamps, R.J., 2000. Time domain reflectometry development for use in geotechnical engineering. Geotech. Test. J. 23, 9–20.

Thomsen, A., Hansen, B., Schelde, K., 2000. Application of TDR to water level measurement. J. Hydrol. 236, 252–258.

Tidwell, V.C., Brainard, J.R., 2005. Laboratory evaluation of time domain reflectometry for continuous monitoring of stream stage, channel profile, and aqueous conductivity. Water Resour. Res. 41, W04001. http://dx.doi.org/10.1029/2004WR003416.

Topp, G.C., Davis, J.L., Annan, A.P., 1980. Electromagnetic determination of soil water content and electrical conductivity measurement using time domain reflectometry. Water Resour. Res. 16, 574–582.

Yu, X.B., Yu, X., 2011. Development and evaluation of an automation algorithm for a time-domain reflectometry bridge scour monitoring system. Canad. Geotech. J. 48, 26–35.