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Performance of low-cost fiber optic cables as leak detection sensors for water pipelines in unsaturated soil

S.W. Jacobsz*

University of Pretoria, Pretoria, South Africa

Abstract

Large volumes of potable water are lost from leaks in water distribution systems around the world. Such leaks may go undetected for a long time. A passive means of leak detection can be implemented by burying a suitable fiber optic cable in the pipe trench with water distribution pipes when they are installed. Water leaking from pipes into the ground results in a temperature change at the leak location. Leaks into unsaturated soil also cause changes in the bulk density and strength of the soil, resulting in significant soil deformation. Brillouin Frequency Shift (BFS) in optical fibers is sensitive to changes in both temperature and mechanical strain, allowing fiber optic cables to act as efficient leak detection sensors. Purpose-made fiber optic cables may be expensive, but telecommunication grade cables generally have a low cost and are readily available around the world. This paper investigates the performance of five different fiber optic cables, including communication grade fiber optic cables, to act as leak detection sensors in unsaturated ground. It was found that the most efficient leak detection sensors are flexible tight-buffered fiber optic cables.

Keywords: Leak detection; Brillouin Frequency Shift; fiber optic cable; water leak; pipe

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1. Introduction

Water leaks from potable water networks pose a significant challenge around the world, contributing to water scarcity, economic losses and social impacts. Leaks occur across a variety of infrastructure types, including residential properties, municipal networks and bulk water supply networks. Many countries face water scarcity problems

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* Corresponding author. Tel.: +27-(012) 420-3124.
E-mail address: sw.jacobsz@up.ac.za

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exacerbated by leaks. Around the world 25 to 50% of treated water is lost before reaching consumers due to leaks in aging infrastructure (Pedersen et al., 2013). Water leaks result in substantial economic losses for bulk water suppliers, municipalities and consumers alike. The cost of treating and distributing water that is ultimately lost through leaks amounts to millions of dollars annually. Additionally, leaks can lead to property damage and increased water bills for consumers. The social impact of water scarcity affects communities, particularly vulnerable communities in poorly served areas where access to clean water is already limited. Leaks exacerbate this problem, leading to unequal distribution of water resources and potentially compromising public health and hygiene.

A major challenge with water leaks is that they may go undetected for a long time. When water leaks are suspected to occur from a distribution network, it is usually necessary to appoint a specialist contractor to locate the leak(s), who may then apply a range of technologies for this purpose.

The implementation of automated leak detection systems has the potential to significantly reduce water loss through early detection as it allows for efficient monitoring, potentially enabling cost savings and water conservation. These factors alleviate pressure on water resources and contribute to economic and social development goals.

A passive means of leak detection can be implemented by burying a suitable fiber optic cable with a new water pipe upon installation. A water leak can affect the fiber optic cable in three ways: Firstly, the leaking of usually colder water into the ground reduces the temperature at the leak location. Secondly, water leaks affect the pore pressure in the ground, changing the effective stress, resulting in ground deformation which, in turn, may strain a fiber optic cable passing through the ground. A third effect may occur when the leak causes soil erosion, resulting in significant straining of the cable.

Fiber optic pipeline leak detection may be especially effective in unsaturated soils. These soils typically experience significant pore water suctions in the in-situ state. Leaking water dissipating these suctions may cause significant stress changes and hence detectable deformation in the soil. Brillouin Frequency Shift (BFS) in optical fibers is sensitive to changes in both temperature and mechanical strain and allows optical fibers to act as sensitive leak detection sensors. Purpose-made fiber optic cables may be expensive, but telecommunication grade cables generally have a low cost and are widely available around the world. This paper presents the performance of a range of fiber optic cables, including communication grade fiber optic cables, to act as leak detection sensors in unsaturated ground.

2. Previous fiber optic leak detection study

A study by Jacobsz & Jahnke (2020) reported on the performance of fiber Bragg gratings (FBGs) as leak detection sensors. They investigated the performance of a fiber optic cable with FBGs spaced at 1m as leak detection sensors on a 110mm uPVC pipe buried in unsaturated soil. The FBGs along one half of the fiber optic cable were attached to the pipe using a structural epoxy and the cable was looped back at the end of the trench, with the other half of the cable free-floating in the ground parallel to the pipe, with FBGs not attached to the pipe. The pipe was filled with water and was pressurized from the municipal network. The FBGs attached to the pipe were found to be very sensitive to daily network pressure fluctuations as demand varied. This caused difficulty to distinguish the effects of water leaks, which generally resulted in smaller pipe strains, than those from in-pipe pressure fluctuations. Such sensitivity was not observed for the FBGs on the length of cable free-floating in the ground. These FBGs only reacted to leak effects. A practical leak detection system could therefore simply comprise a fiber optic cable buried in proximity to the pipe in the same trench so that it will be affected by a leak. Not attaching the fiber optic cable to the pipe poses a major advantage in terms of ease of installation. Bragg gratings are not particularly practical leak detection sensors on pipelines as only a limited number can be monitored at the same time, allowing only short pipe lengths to be monitored. Instead, it is more desirable to use distributed strain and temperature sensing for leak detection on pipes. A number of fiber optic interrogation systems are available which are suitable for this purpose. It is envisaged that a practical leak detection system would comprise one or more of these interrogators monitoring many kilometers of fiber optic cables placed in pipe trenches with water pipes when these pipes are installed.

3. Physical effects of water leaks in unsaturated ground

The upper few meters of the soil profile in dry parts of the world typically occur in a partially saturated state, with saturated conditions normally only occurring in the capillary zone and below the water table. The water table may occur at considerable depth, well below the depths where water distribution pipes are typically installed. Capillary forces resulting from surface tension effects result in the pore water in partially saturated soils generally experiencing negative pore pressures, raising the effective stress and hence shear strength of the soil. The relationship between an increment in the soil water content and associated change in pore pressure is defined by the soil water retention curve.

Depending on the characteristics of the soil water retention curve, infiltrating water may have a large influence on the negative pore pressures and hence strength of the soil. As the soil becomes more saturated, its bulk density increases and, in combination with the reduced strength upon saturation, significant soil deformation may occur. These deformations act on pipes buried in the ground and will also act on fiber optic cables when present.

The effect of wetting an unsaturated soil is illustrated conceptually using the Barcelona Basic Model, devised by Gens and Alonso (1992) for unsaturated soils. Figure 1 presents the model schematically, respectively showing plots of suction and specific volume (void ratio plus 1) against net mean stress (total stress minus pore air pressure). Consider four soil samples subjected to a range of net mean stress values, but at the same initial suction s_0. In the left-hand figure the four samples initially find themselves on the same υ_0 line. Upon wetting, soil suction will reduce, potentially to zero, provided the availability of sufficient water. Wetting is accompanied by elastic swelling (samples C1 and C2). Depending on the net stress state, the LC yield curve may be intersected during wetting (C3 and C4) upon which sample volume change will reverse as wetting-induced collapse occurs (right-hand figure). Wetting-induced volume change is associated soil deformation which will transfer to a fiber optic cable present in the ground, allowing the wetting-induced soil strain changes to be detected in addition to a wetting-induced temperature change.

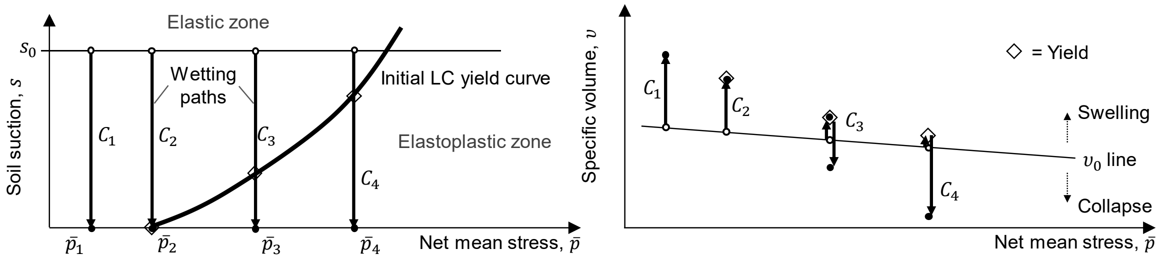

Fig. 1. Swell-collapse wetting paths under constant net mean stress (after Gens and Alonso, 1992).

Further deformation around the pipe is possible due to leak-induced soil fluidization around the pipe (Van Zyl et al., 2013) which will result in a change in support conditions around pipes and also any fiber optic cables which may be present in the ground.

In warmer regions the water in distributions mains typically occur at a lower temperature than the surrounding ground. Water leaks can therefore lower the temperature in the area affected by the leak. Fiber optic leak detection systems based on temperature measurement are widely used in the oil and gas industry (e.g. Mishra and Soni, 2011; Nikles et al., 2004), but application to water distribution systems are rare in the literature. Jacobsz and Jahnke (2020) reported that leak-induced strain changes may significantly exceed the thermally induced strains associated with colder water leaking from a pipe into the usually slightly warmer ground.

4. Field trials on various fiber optic cables

Fiber optic cables are suitable sensors to register the above-mentioned leak-induced strain and temperature changes in the ground because the frequency of Brillouin backscatter in optical fibers is strain and temperature sensitive and these can be detected using a suitable interrogator. The performance of a range of widely available fiber optic cables acting as distributed leak detection sensors on water pipelines was assessed in this study.

4.1. Field installation

Five different fiber optic cables were buried in a 150m long trench excavated for the purposes of this study at the Hillcrest campus of the University of Pretoria to simulate the environmental conditions acting on a fiber optic leak detection system. The fiber optic cables investigated were laid along the base of the trench. The trench was excavated in three 50 m long sections to depths of 0.5 m, 1.0 m and 1.5 m respectively, typical of the depths at which municipal water distribution pipes are buried. Three different depths were chosen to investigate whether depth would significantly affect the leak detection performance of the cables. The shallower a cable, the greater the natural daily and seasonal temperature variation that it will be subjected to. Shallower cables are also more likely to be affected by water infiltration following rainfall. For the leak detection system to be successful it is important that leak-induced impacts must be distinguishable from naturally occurring temperature variation and water infiltration.

No potentially leaky pipe was used in the study. In order to simulate water leaks, nine artificial leak points, three along every 50m section, were installed. These comprised 20mm diameter HDPE downpipes placed at regular intervals along the length of the cable trench before backfilling. The downpipes allowed water to be discharged in the ground near the fiber optic cables to allow their response to the artificially induced "leaks" to be studied. A diagrammatic section of the installation is presented in Figure 2.

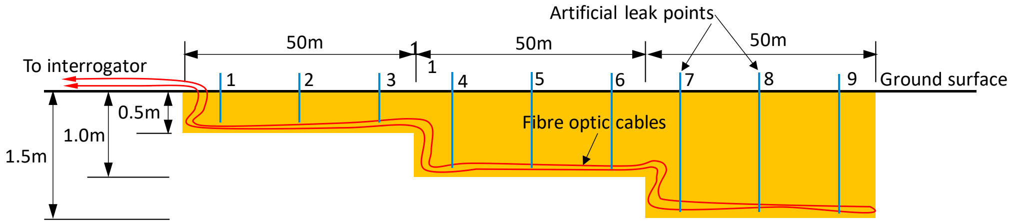

Fig. 2. Diagrammatic section on cable trench used in the study.

4.2. Fiber optic cables studied

Five different single mode fiber optic cables listed below were studied. Some were tight buffered (TB), implying that the optical fiber and cable surround are rigidly joined, while some where loose core (LC) cables, implying that the optical fiber is able to slide within the cable surround by being surrounded in a thixotropic gel. The first four cables listed were general-purpose communication-grade fiber optic cables manufactured in South Africa, while the last cable is a purpose-made cable intended for incasement in concrete for strain measurement. In the remainder of this paper, the cables are referred to using the abbreviations presented in brackets. (OD refers to the cable outer diameter.)

- An Aerial Self Support Cable (industrial strength), 72-fibers in 6 x 12 fiber cores (72F-6C-LC)
- A 6-fiber Tight Buffered Field Deployable Cable (6F-TB); OD = 5.1mm
- A 4-fiber Dual Purpose Drop Cable (4F-DC-LC); OD = 5.8mm
- A 2-fiber Tight Buffered Field Deployable Cable (2F-TB); OD = 5.1mm
- A BRUsens strain V9 cable (BRUsens – TB); OD = 3.2mm

A schematic plan showing the arrangement of the cables in the cable trench is presented in Figure 3.

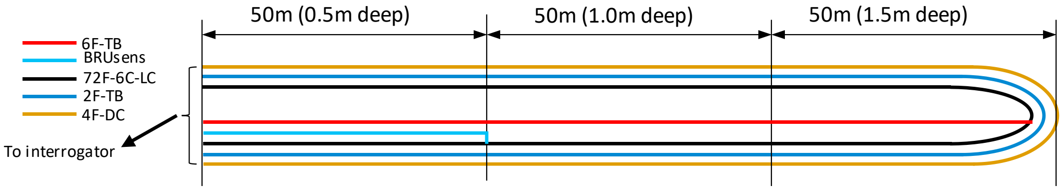

Fig. 3. Diagrammatic plan on cable trench showing cable arrangement.

Ample lengths of the 72F-6C-LC, 2F-TB and 4F-DC cables were available and these cables were looped back at the end of the trench so that 300 m of each cable was buried in the trench. Only 50m and 150m respectively of the BRUsens-TB and 6F-TB cables were available and these cables were subsequently spliced to the 72F-6C-LC cable to create loops for the interrogator to access both ends of the cables. All cables were spliced to a 72F-6C-LC cable at the end of the trench and routed to the interrogator, located in an air-conditioned server room approximately 250m away. The total loop length of each of the five cables was therefore approximately 800m.

4.3. Fiber optic strain interrogator

The strain interrogator used in the experimental setup was a fibrisTerre fTB2505 fiber-optic sensing system. The interrogator was connected to a fibrisTerre fiber optic multi-channel splitter, allowing four of the five different fiber optic cables to be monitored simultaneously. The interrogator uses Stimulated Brillouin Scattering to determine the BFS at a specific point along the length of a fiber optic cable. To perform distributed sensing, the interrogator employs Brillouin optical frequency domain analysis to create a BFS profile of the entire cable length. The interrogator is controlled via the software package, fTView, which was also used to record and export the results.

The interrogator measured the BFS profile as follows: The length of the fiber optic cable being monitored is first determined by injecting an optical signal into one end of the optical fiber and measuring the travel time to the other end. The interrogator then performs a frequency sweep process during which two optical signals of different frequencies are injected into the optical fiber, one from each end. The signal injection timing is adjusted so that the signals meet each other at a specific ordinate along the fiber's length. When the optic signals coincide, Stimulated Brillouin Scattering occurs at that point. The downshifted light travels back to the interrogator and the BFS is logged for the specific ordinate. The interrogator repeats this process for every 5 cm along the cable length and can measure BFS in fiber optic cables up to 25km in length.

4.4. Soil properties

The soil in which the trench for the experimental setup was installed comprised a slightly moist, red-brown sandy clayey soil of intermediate plasticity of transported origin. The clay content was 10%, silt content 40% and sand content 50%. The plasticity index was 15%. The soil's soil water retention curve showed that suctions initially develop gradually as the degree of saturation reduced, but that it increased rapidly once the degree of saturation reduced below 70%. Large suctions can be expected in the soil at the in-situ moisture content. Changes in the degree of saturation associated with a leak can therefore be expect to result in significant soil strains.

4.5. Leak tests

Two leak tests conducted on the setup are presented, the first taking place on 24 March 2021 and the other on 1 April 2021. Both leak tests made use of leak points 1, 4 and 7 (see Figure 2), representing the three depths along the trench to allow the results of leak tests at different depths to be compared. Also, by using the same leak points more than once, the ability of the detection system to identify a leak more than once was tested. If the system could detect two leaks at the same location, the second leak occurring after the soil had already been wetted, it would indicate that first wetting of the soil did not negatively impact the system's ability to detect a subsequent leak.

During the first leak test (24 March) a volume of 36 litres was introduced into the trench at each of the leak points 1, 4 and 7 over the course of an hour, while a volume of 50 litres was introduced into the same leak points during the second test (1 April). Brillouin Frequency Shift (BFS) in the optical fibers were monitored at two-hourly intervals before and after the leak test, commencing at least 24 hours before each leak test to provide baseline measurements.

The leak tests revealed two distinct sets of responses for the tight-buffered (TB) and loose core (LC) fiber optic cables respectively. For the purposes of this discussion, the results of the 72F-6C-LC and 6F-TB cables are compared at the three depths investigated. Figure 4 presents the changes in BFS recorded shortly before and after the leak tests at the three depths investigated. It is evident that the effect of the water leaks on BFS was significantly more pronounced for the TB cable compared to the LC cable. The optical fiber in the LC cable is mechanically isolated from the cable surround by means of a thixotropic gel, which means that the cable only responds to thermal effects, while essentially insensitive to mechanical strain. On the other hand, both mechanical and thermal strains affect the TB cable. Figure 4 shows that the TB cable responded rapidly and then measured a decay in BFS which was probably a results of temperature equilibration following water introduction. After some time only the strain effect remained. There did not appear to be a pattern in responses recorded at the three depths investigated.

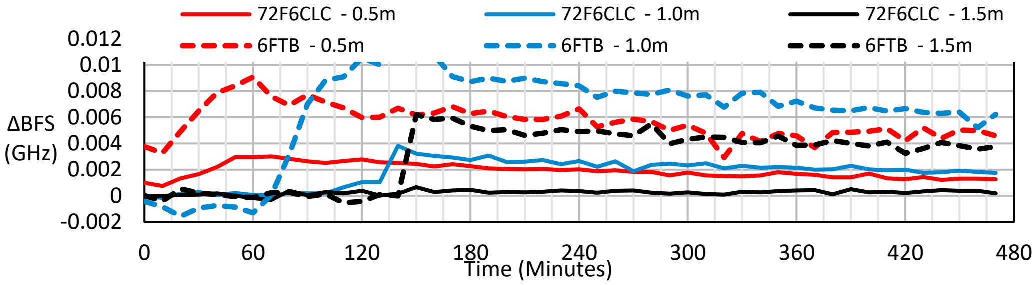

Fig. 4. change in Brillouin Frequency Shift at the three leak locations for the 72F-6C-LC and 6F-TB cables.

4.6. Spatial data processing and presentation

Before the first leak test, BFS baseline readings were acquired at two-hourly intervals over the preceding 24-hours. The baseline was taken as the average of the 12 sets of readings thus recorded. After the leak tests, another 24-hour average was acquired. The change in BFS, when subtracting the baseline from the post-leak average, is shown in Figure 5(a) for the 72F-6C-LC and 6F-TB cables. The left-hand side of the figures represent the 72F-6C-LC cable and the right-hand side the 6F-TB cable. (The 6F-TB cable was spliced to the 72F-6C-LC cable as shown in Figure 3.)

The BFS profile is noisy, especially in the case of the tight buffered 6F-TB cable, potentially obscuring the ability to detect leaks, as sharp peaks may be mistaken for a leak by a leak detection algorithm. A simple algorithm to clean the data and allow leaks to be identified was devised through trial and error. A 25-point centered moving average was fitted to the data and the baseline prior to baseline subtraction. The improvement thus attained is evident from the black curve in Figure 5(b) showing a reduction in random spikes in the raw relative profile. The three spikes in black on the right-hand part of the profile represent the leak tests at leak locations 1, 4 and 7 respectively. The ΔBFS profile was subsequently baselined to zero by subtracting a 601-point moving average. The improvement is shown in black in Figure 5(c). As a last step, the cleaned profile was squared, the result of which is presented in Figure 5(d).

The peaks occurring at 200m, 250m and 300m are very distinct from the rest of the profile and illustrate the success of the 6F-TB cable at detecting leaks. On the other hand, the 72F-6C-LC cable was only able to detect one leak, in this instance at 60m. (Leaks occurred at 10m, 60m and 110m.) Furthermore, a false leak was detected by the 72F-6C-LC cable at 50m. The results indicate how, despite providing an initially more noisy BFS profile, TB cables are more efficient at leak detection than LC cables as they are able to respond to both thermal and mechanical strains. The volumes of water discharged during the leak tests were very small compared to the volumes of water that may be lost from actual pipe leaks. Actual leaks are unlikely to stop and will continue to influence the ground and therefore the leak detection system and are therefore be expected to be more prominent than the small leaks studied here.

The fiber optic cables most sensitive to leaks were found to be the more flexible TB cables. Sensitivity reduced with increasing cable stiffness. The LC cables were significantly less sensitive to leaks compared to TB cables. The cables studied, in sequence of most to least sensitive, were: 2F-TB, 6F-TB, BRUsens-TB, 72F-6C-LC, 4F-DC-LC.

4.7. Repeatability of detection

The first leak tests on 24 March demonstrated the performance of fiber optic cables to detect leaks. During this first leak test, the initially unsaturated soil in the trench was wetted up for the first time, undergoing significant deformation due to processes explained in Section 2. To assess whether the effectiveness of the system may reduce during subsequent leaks, repeat leak tests were carried out at previously tested locations. The results of both leak tests relative to the 23 March baseline are presented in Figure 6. The second test resulted is dated 2 April.

Figure 6 shows that the sensitivity of the system had in fact increased after the first leak test. It is believed that this was due to the first inundation episode causing improved bedding of the soil in the trench around the cables. As moisture would have spread in the soil after the first leak test, negative pore pressure would have reestablished. These negative pore pressures would have been dissipated during the second leak test, again resulting in significant soil deformation, clearly detectable from the BFS records, even using the 72F-6C-LC cable (chainages 10m and 60m).

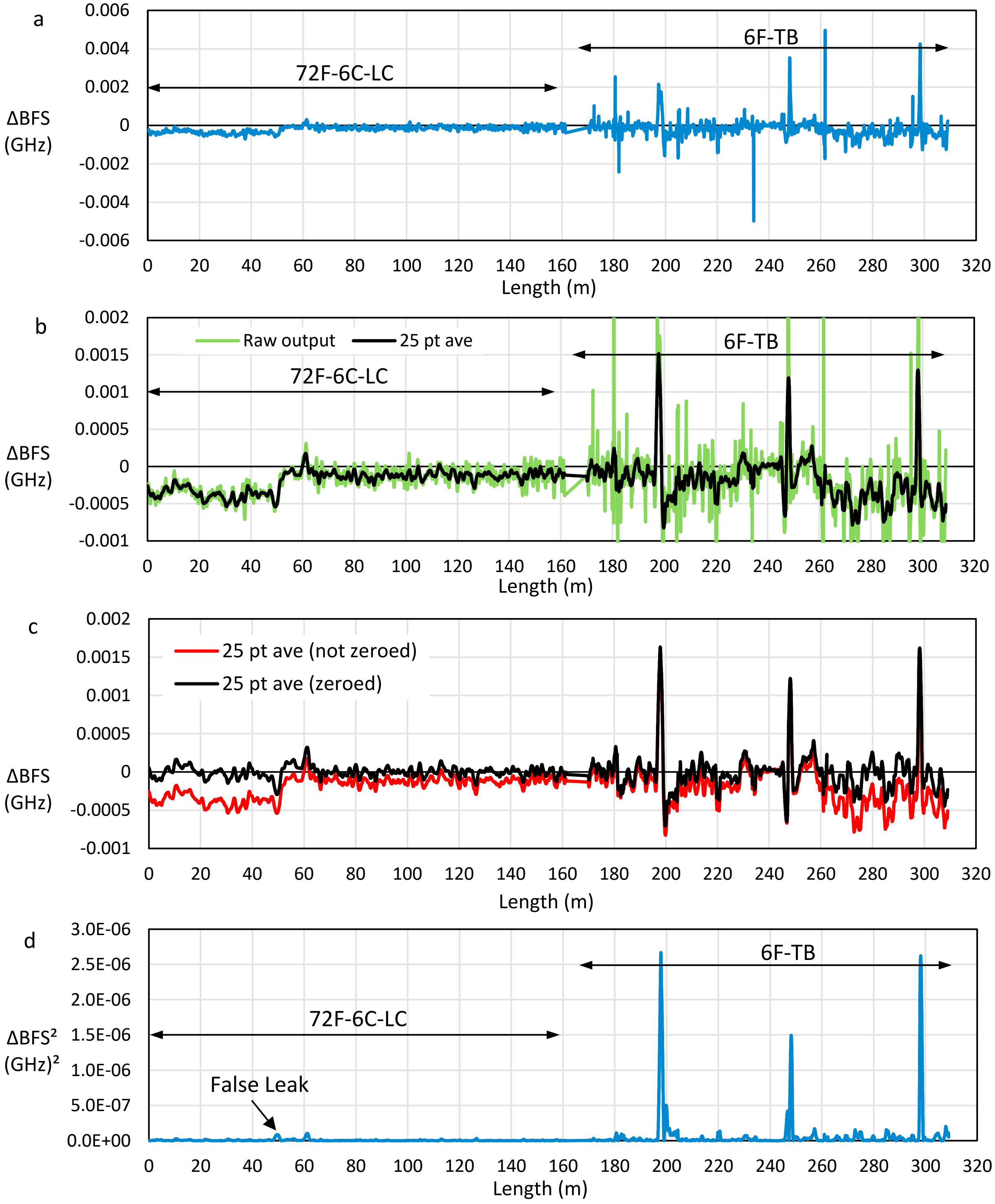

Fig. 5. (a) change in Brillouin Frequency Shift when subtracting the 23 March baseline from the 24 March average; (b) change in Brillouin Frequency Shift when subtracting moving averages of the 23 March baseline from the 24 March average; (c) zeroed change in Brillouin Frequency Shift; (d) squared and zeroed Brillouin Frequency Shift profile.

The repeat test demonstrated the ability of the system to detect more than a single wetting event, which is important because it implies that the sensitivity of the system is likely not to be compromised by natural wetting events such as water infiltration after heavy rainfall.

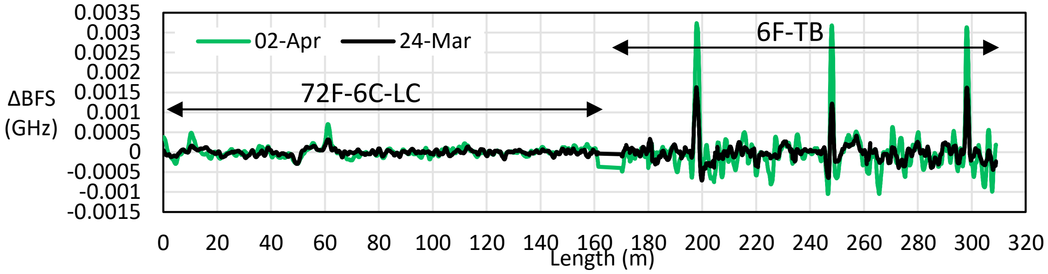

Fig. 6. The zeroed Brillouin Frequency Shift profiles for the first and second leak tests at the same locations.

5. Conclusions

A range of communication-grade fiber optic cables, and a single cable intended for strain measurement in concrete, were investigated to assess their performance as leak detection sensors in unsaturated soil. Water leaks in unsaturated soil cause temperature and significant mechanical strain changes in the ground, affecting Brillouin Frequency Shift in fiber optic cables, allowing leaks to be detected. Wetting-induced strain changes are not applicable to saturated soils, implying that a fiber optic leak detection system in saturated ground will have to rely solely on temperature changes, making it less sensitive than in partially saturated ground, unless the leak also caused significant soil erosion.

Flexible tight-buffered communication grade fiber optic cables were found to be efficient leak detection sensors as they easily deform with the ground and efficiently transfer mechanical strain to the optical fiber. The BRUsens-TB cable, suited to strain measurement in concrete, is quite stiff and less sensitive than the TB communication cables tested. Loose core cables are less sensitive as they do not efficiently transfer mechanical strains to the optical fiber. Telecommunication grade fiber optic cables are cheap and widely available, which benefits the implementation of fiber optic-based leak detection systems, provided that a suitable fiber optic interrogator is available.

The potential success of the fiber optic leak detection was demonstrated by the small volumes of water leaked. Conventional pipe leaks discharge large volumes of water over a long time and should therefore be easily detectable. Heavy rainfall events may trigger widespread false alarms and detection algorithms should therefore consider local rainfall records.

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