# Fibre-Optic Distributed Acoustic Sensing: Aging In-Situ Performance Comparison

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## *ABSTRACT*

*Distributed fibre-optic sensing (DFOS) is a passive continuous monitoring system with known military applications. The simplest form of a DFOS system is a fibre-optic cable connected to an interrogator. DFOS applications include monitoring vibration (distributed acoustic sensing, DAS), monitoring temperature (distributed temperature sensing, DTS), and monitoring strain (distributed strain sensing, DSS). DAS, DTS, and DSS each use an application-specific interrogator coupled with an appropriate fibre-optic cable. The interrogator pulses light into the fibre-optic cable core and then analyses and sorts scattered light returning from the fibre-optic cable length. The DFOS system provides the end-user with a signal (related to backscattered light) that contains information about changes in the medium surrounding the fibre-optic cable along the cable's length. Data feedback resolution varies by DFOS system and array length, but resolution is often less than ten metres for DFOS arrays which are kilometres in length. The coupling of the fibre-optic cable to the surrounding medium, i.e., rigidly fixed or placed in soil, and variations in the medium surrounding the fibre-optic cable affect DFOS performance. Understanding soil-to-cable coupling and anticipating DFOS performance changes due to environmental and/or seasonal effects remains an open area of research.*

*To assess long-term DFOS performance with relation to soil-to-cable coupling, a field-testing program was initiated in 2019. A new portion of fibre-optic cable was spliced into a DAS array installed approximately ten years prior. The fibre-optic cable for the new portion of array is the same as the fibre-optic cable installed ten years prior. Calibrated impacts were performed at set locations along the DAS array to generate a response in DAS array channels. Impact locations could simultaneously stimulate both new and prior DAS array portions installed in native silty sand. Another impact location simultaneously stimulated new portions of DAS array installed in sand, gravel, and a cementitious flowable fill. DAS response to these impact locations was evaluated using signal-to-noise ratio (SNR) as a performance metric. The performance comparison from summers of 2019, 2020, and 2022 data collects indicates that both the prior and new portions of DAS array in native silty sand respond consistently to impacts. Performance of gravel, sand, and flowable fill portions of DAS array are compared between 2019 and 2022. Changes in SNR response to impacts could provide insight into soil-to-cable coupling or interaction over time. These results demonstrate that a DFOS array installed in soil can perform consistently from installation through three years, and over a three-year period after one decade in-situ. DFOS arrays can perform consistently in the long-term, potentially making DFOS a good candidate for continuous monitoring applications to include both civil and military use cases.*

# 1.0 INTRODUCTION

Distributed fibre-optic sensing (DFOS) is a continuous monitoring system with known military applications (Owen et al. 2012). Minimally, a DFOS system is a fibre-optic cable connected to an interrogator. DFOS applications include monitoring vibration (distributed acoustic sensing, DAS), monitoring temperature (distributed temperature sensing, DTS), and monitoring strain (distributed strain sensing, DSS). Different categories of DFOS (i.e., DAS, DTS, and DSS) use category-specific interrogators coupled with an appropriate fibre-optic cable. The interrogator pulses light into the fibre-optic cable core and then analyses and sorts scattered light returning from the fibre-optic cable length (Soga and Lou 2018). The DFOS system provides the end-user with a signal (related to backscattered light) that contains information about changes in the medium surrounding the fibre-optic cable along the cable's length (Soga and Lou 2018). Data feedback resolution varies by DFOS system and array length, e.g., a resolution of five to ten metres for DFOS arrays one or two kilometres in length. DFOS arrays are capable of both much finer resolution (metre scale) as well as longer array lengths (10s of kilometres) dependent on sampling and data management limitations. There are several publications (e.g., Soga and Lou 2018; Gorshkov et al. 2022, Miah and Potter 2017, Schenato 2017) that provide further details on various types of DFOS systems and monitoring applications. For example, fibre-optic distributed acoustic sensing (DAS) is a proven tool for vertical seismic profiling with both passive methods and active methods (e.g., Mateeva et al. 2013). Dou et al. 2017 and Ajo-Franklin et al. 2019 demonstrate that ambient noise that is passively recorded by DAS can be used to estimate shear-wave velocity profiles. DAS can also be used to actively monitor train tracks (e.g., Wiesmeyr et al. 2020). Wiesmeyr et al. 2020 points out the importance of coupling between the fibre-optic cable and the medium, where portions of cable mounted directly to the rail performed best. The method used for coupling of the fibre-optic cable to the surrounding medium, i.e., rigidly fixed or placed in soil, and variations in the medium surrounding the fibre-optic cable both affect DFOS performance (Lindsey et al. 2020). Quinn et al. 2022 demonstrate that seasonal fluctuations may affect DAS performance for an array installed in soil. This multiyear study indicated that portions of the array in gravel and sand outperform portions of the array in cementitious flowable fill for DAS response to offset impacts. The original hypothesis was that the flowable fill would provide more uniform soil-to-cable contact, therefore increased coupling and better DAS response. The lower performance of the portion of array in cementitious flowable fill may have been due to the difference in stiffness between the native soil where the impact occurs and the stiff cementitious soil surrounding the cable, as the in-line response of portions of the array in gravel and flowable fill were similar. Understanding soil-to-cable coupling and anticipating DFOS performance changes due to environmental and/or seasonal effects remains an open area of research.

# 2.0 METHODOLOGY

To assess long-term DFOS performance with relation to soil-to-cable coupling, a field-testing program was initiated in 2019. A new portion of fibre-optic cable was spliced into a DAS array installed approximately ten years prior. The same, single-mode fibre-optic cable that was used in the prior installation was used in the new array. This cable had a water-proof buffer tube, armour, and a polyethylene jacket. Calibrated impacts (2.5 kg weight with a set 305 mm drop-height) were performed at set locations (from August 2019 through August 2022) along the DAS array to generate a response in DAS array channels. Further details on the test bed and the testing program are available in Quinn et al. 2022. Figure 1 provides the DAS array layout and impact locations. Impacts near location No. 1 (Figure 1) simultaneously stimulate both new and prior DAS array portions installed, both in native silty sand. Impact location No. 2 (Figure 1) stimulates new portions of DAS array installed in sand, gravel, and a cementitious flowable fill.

For DAS response prior to 2021, an intensity-only optical time domain reflectometer (OTDR) DAS interrogator was used. This interrogator measured backscatter amplitude (i.e., intensity) at a sampling rate of 2500 Hz with a channel length of 10 metres. DAS response in 2022 was performed using a phase-sensitive DAS interrogator with a sampling rate of 2500Hz and a channel length of 6.381 metres. A different channel length was used in 2022 based on an adjustment recommendation for the phase-sensitive interrogator (an Onyx interrogator was used for the 2022 data collect) on this array. Note that intensity-only OTDR DAS interrogators provide the end user with a signal amplitude proportional to the average strain experienced along the fibre-optic cable channel length, while a phase-sensitive interrogator provides data about both phase and amplitude (Soga and Luo, 2018, Jousset et al. 2018).

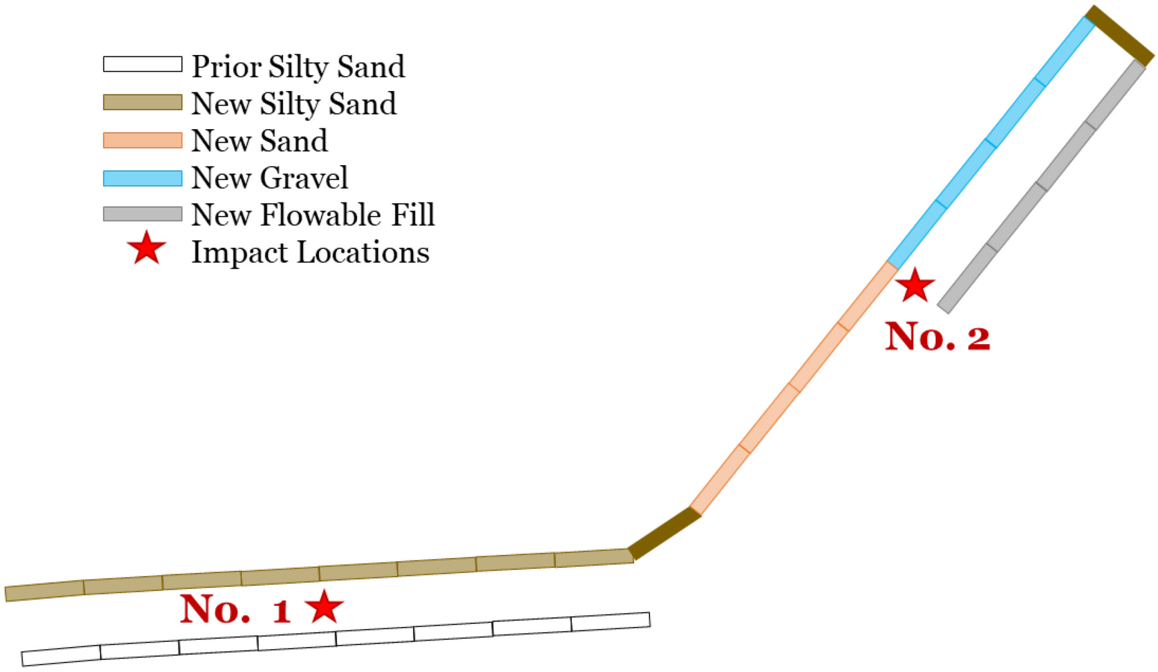


**Figure 1: Site layout and impact locations (channel lengths of 10 metres indicated by segments in silty sand, sand, gravel, and flowable fill).**

The performance comparison between prior and newly installed portions of fibre-optic cable in silty sand consisted of calibrated impacts near impact location No. 1 (Figure 1) along a central axis between parallel sections of fibre-optic cable. Data collects from 15 August 2019, 19 August 2020, and 21 July 2022 are compared in this paper to mitigate the influence of temporal variability. The performance comparison of portions of fibre-optic cable installed in sand, gravel, and a cementitious flowable fill to impacts near location No. 2 (Figure 1) is made using data collects from 15 August 2019 and 21 July 2022.

The DAS time series data was analysed in MATLAB. A sample DAS response to impacts near location No. 1 (Figure 1) as viewed in MATLAB is shown in Figure 2, where DAS response to ten impacts can be seen in portions of DAS array several channels apart (the responses at the bottom of the figure are in the prior installation and the responses near the top of the figure are in the new portion of array, both in silty sand). A MATLAB program was written to identify the locations of each hit in the DAS time series, across a range of specified channels for the prior fibre installation in silty sand and the new fibre installation in silty sand. The program identified the impact signals and logged them as the time series data from 0.1 seconds before the peak crest through 0.25 seconds after the peak crest, for a total signal length of 0.35 seconds. The noise for each signal was observed as the 0.35 seconds of DAS recording in each channel immediately after the impact signal. This relationship between the observed signal and associated channel noise for a 0.35 second capture is illustrated in Figure 3. The Root Mean Square (RMS) is calculated for the signal capture ($RMS_{signal}$) and noise capture ($RMS_{noise}$). The signal to noise ratio (SNR) in decibels (dB) is calculated using the equation below.

$$SNR = 20\ log_{10}\left[\frac{RMS_{signal}}{RMS_{noise}}\right]$$

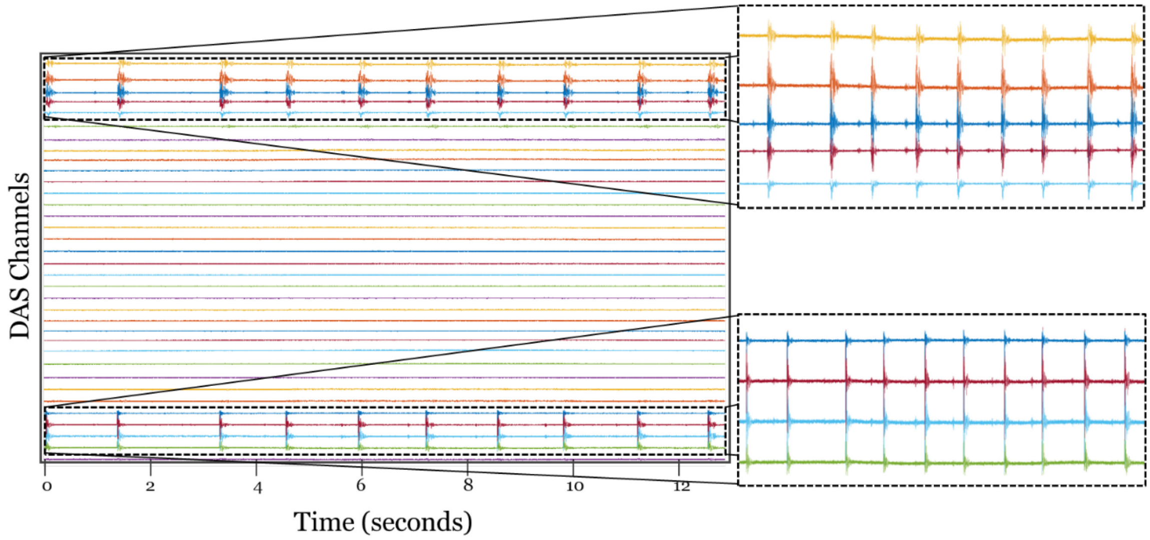


**Figure 2: Sample DAS array response to ten impacts near location No. 1.**

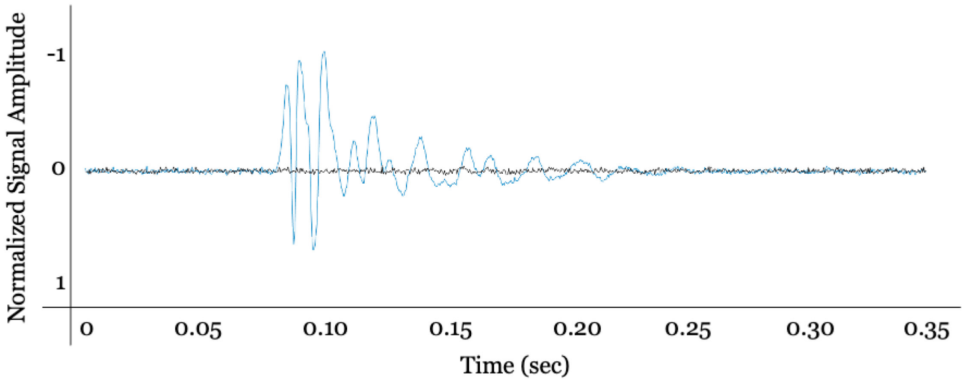


**Figure 3F: Visualization of SNR as a DAS observed performance response in one channel to one impact.**

To lessen the effect of slight variability in impact location across data collection days and years and to compare the SNR response between these portions of array, the "peak" channel response was observed for each impact location. As shown in Figure 1, the impact locations are offset from the fibre-optic cable. For results analysis and display, zero metres is considered a response closest to the impact. The response to impacts near location No. 1 (Figure 1) is displayed in Figure 4 and indicates responsive channels approximately 30 metres to the left and right of the peak responsive channel. As shown in this figure, the response is a relatively symmetrical "bell curve" and for simplification of result interpretation, half of the "bell curve" will be displayed for performance results in the silty sand.

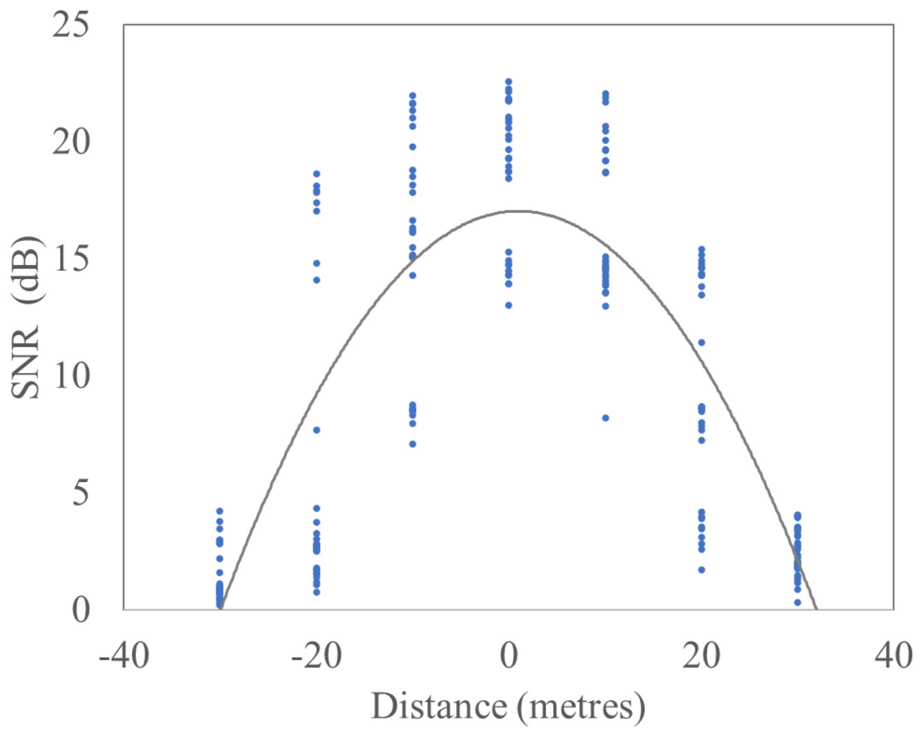


**Figure 4: Example "bell curve" SNR response to offset impacts occurring at locations A, B, and C (prior fibre installation 2019) aligned for peak response.**

## 3.0 RESULTS

The SNR response in portions of array both new installation and prior installation in silty sand is compared for the summers of 2019, 2020, and 2022, as seen in Figure 5. This figure presents half of the SNR "bell curve" (Figure 2-4) response to impacts near location No. 1 (Figure 1) as the impact-generated vibrations propagate and attenuate down the length of the fibre-optic cable. Figure 5 provides peak response as closest to zero metres (offset at about 5 metres for data trend viewability) where 2019 and 2020 responses are at 10 metre intervals from peak response and 2022 responses are at 6.381 metre intervals from peak response. Both prior and new portions of array appear to perform consistently over time within one standard deviation of the average SNR response for each channel length distance away from impact location. Figure 6 compares the new and prior installation performance in silty sand by year (2019, 2020, and 2022). The difference in performance between the prior and newly installed portions of array is approximately 3 dB or less. Differences in response could be due to in part (1) to potentially different installation methods for the prior installation versus new installation, or (2) slight variation in impact location favouring the new installation. Regardless of the difference, the prior installed portion of array performs well after a decade in-situ and the new portion of array performs well through and beyond three years in-situ. It is unlikely that loss in SNR would prevent detection of events or further analysis of this data. These results provide credibility for the long-term performance of DFOS.

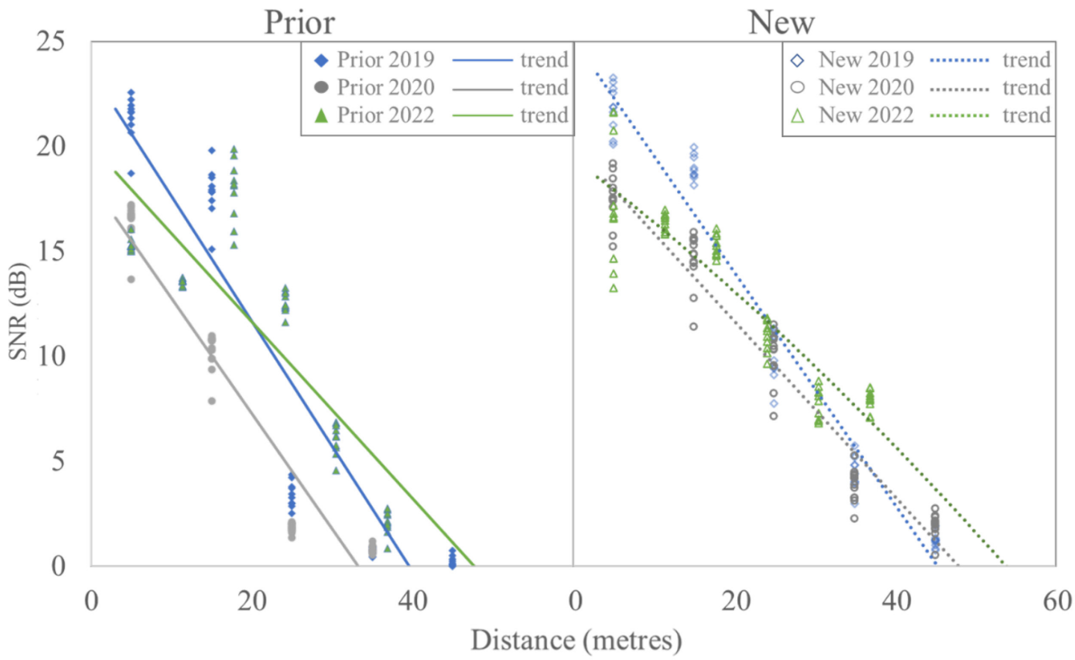


**Figure 5: Prior installation SNR response in silty sand (2019, 2020, 2022) and new installation SNR response in silty sand (2019, 2020, 2022).**

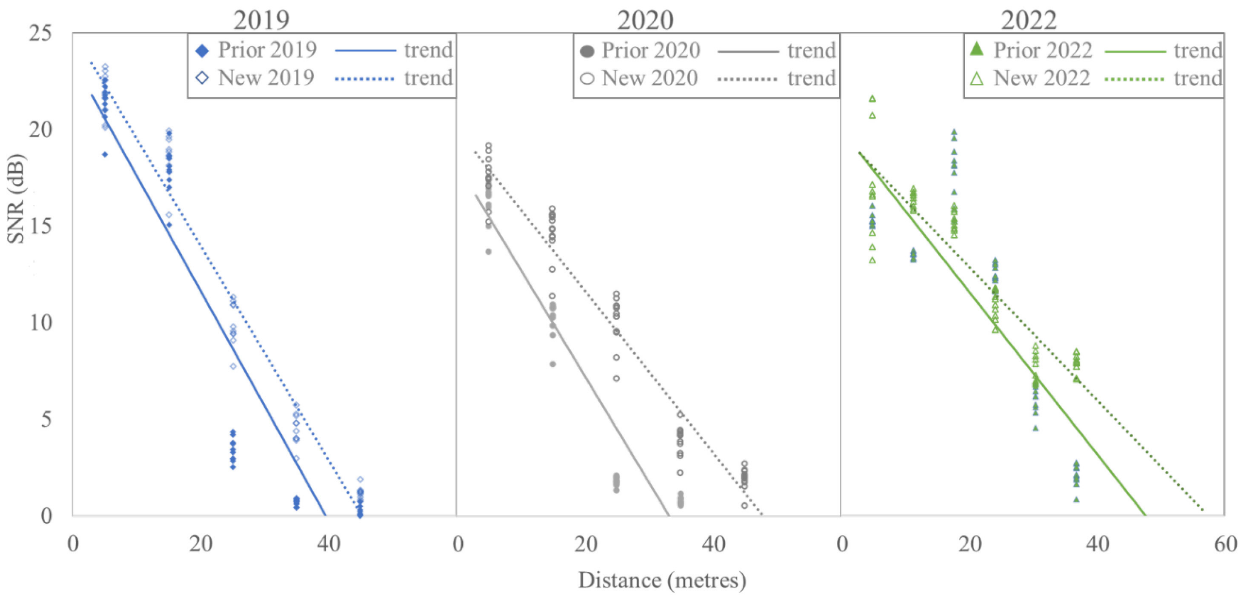


**Figure 6: SNR response in silty sand prior installation versus new installation by year: 2019, 2020, and 2022.**

The performance of portions of DAS array in gravel, sand, and cementitious flowable fill is provided in Figure 7. This figure provides SNR response along the length of fibre-optic cable stimulated by impact location No. 2 (Figure 1). The impact response in all materials appears to have decreased somewhat over time. However, this is only when comparing performance from one data collect in 2022. More research is required to establish performance trends in these materials. The portion of array in cementitious flowable fill, though less sensitive to impacts, performs more consistently than the portions of array installed in sand and gravel. The subtler response in the flowable fill could be due to the stiffness contrast in materials (soft silty sand where the impact occurs to the stiff cementitious material where the fibre-optic cable is emplaced) through which the vibrations from the impact travel. The more consistent performance of portions of array in flowable fill could be due to more consistent coupling to the fibre-optic cable. The variation in response for portions of array in gravel appears to be slightly less by year than the variation in response for portions of array in sand. However, this is response from one data collect on 15 August 2019 (within two weeks of installation) and one data collect three years later; thus the need to compare performance across more data collects.

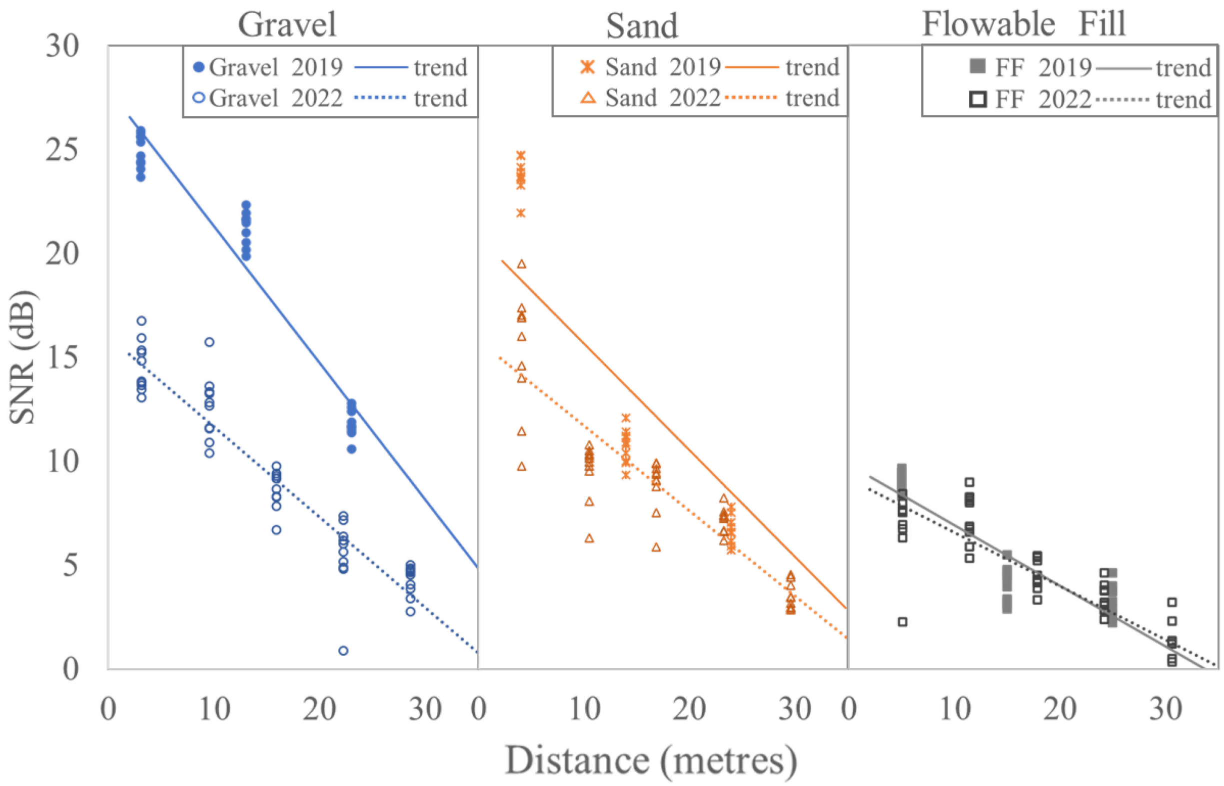


**Figure 7: SNR response 2019 versus 2022 in sand, gravel, and cementitious flowable fill.**

## 4.0 CONCLUSIONS

This research demonstrates that DFOS monitoring systems installed in soil have long-term viability as continuous monitoring systems. DFOS provides the end-user with a continuous in-time and a continuous in-length-of-cable understanding of the environment (vibrations, strain, temperature, etc.) along the fibre-optic cable installation. The high-resolution data feedback of DFOS can complement point sensor instrumentation and other remote sensing capabilities. Understanding the influence seasonal changes have on soil-to-cable coupling remains an open area of research as seasonal fluctuations may have contributed to changes in performance over time. The research presented herein shows that while there is variance in performance, the DFOS remains responsive through time, whether installed over one decade prior or installed new in 2019 and aged in-situ over three years. This research demonstrates that DFOS is a reliable long-term continuous monitoring system solution for both civil and military applications.

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