Accepted manuscript doi: 10.1680/jgele.21.00088

Accepted manuscript doi: 10.1680/jgele.21.00088

Submitted: 28 July 2021

Published online in 'accepted manuscript' format: 11 July 2022

Manuscript title: Distributed Acoustic Sensing in Soil for Infrastructure Monitoring SNR Evaluation

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Abstract

Fibre optic Distributed Acoustic Sensing (DAS) systems provide vibration response information comparable to accelerometers, geophones, and seismometers and may become widely used for infrastructure monitoring. DAS can be used to monitor earthquake activity, carbon sequestration, pipelines, and roadway/railway subgrade integrity, however little is known about the effect of soil type and burial method on DAS response. The objective of this paper is to present the results of a seven-month field study in which a DAS system was installed in different soil types (silty sand, clean sand, gravel, and a flowable fill) adjacent to an existing, decade-old DAS array. Impact tests were performed to evaluate DAS response in the different soil types and a portion of DAS array installed a decade prior. Signal-to-Noise Ratio (SNR) was used to compare performance of DAS response. Results of the monitoring program indicate that portions of the array in sand, gravel, and silty sand had good response with comparable SNR. A newer portion of array performed approximately five decibels better than the decade-old portion of DAS array, both in silty sand, with the old portion still performing well. These results may help build confidence with the geotechnical community regarding the longevity performance of DAS for infrastructure vibration monitoring.

Keywords: Monitoring; Vibration

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1. Introduction

Distributed Acoustic Sensing (DAS) is a relatively new commercially available vibration sensing system. DAS is currently used for monitoring vibrations associated with pipelines, seismic activity, CO_2 sequestration, railway subgrades and more (examples provided in Daley et al., 2016; Dou et al., 2017; Mateeva et al., 2014; Soga and Lou, 2018). It has the potential to become a widely used infrastructure-monitoring tool due to its high data resolution, higher spatial coverage, and ease of installation when compared to point sensors.

DAS typically consists of a fibre optic cable and a fibre optic analyser for transmission, data acquisition, processing, and storage (Soga et al., 2015). The fibre optic cable serves as both the sensor and the means of returning vibrational-strain related information to the fibre optic analyser, which is called an interrogator. An Optical Time-Domain Reflectometer (OTDR) interrogator houses a laser that pulses light into the fibre optic cable core and measures the light scattering back towards the interrogator as the laser pulse proceeds down the fibre. The Rayleigh scattering occurs where there are density changes in the core of the optical fibre, termed a scattering centre. This is an elastic process, meaning that the time difference between the laser pulse and the returned scatter provides information about how far down the cable length the scattering occurred (Sang, 2011; Schenato, 2017; Soga and Luo, 2018; Wang et al., 2019). A DAS interrogator measures variations in Rayleigh backscatter intensity resulting from strain along the fibre optic cable length and the system measures the variations in backscatter intensity changes at the photodetector (Krohn et al., 2014). Rayleigh scattering is collected, monitored, summed, and “binned” by time, which corresponds to distance down the fibre optic cable form the interrogator (Owen et al., 2012). Vibrational strains along the fibre optic cable change the Rayleigh scattering centres in the optical fibre core, allowing for sensing of the vibrational strain field acting on the fibre (Lindsey et al., 2020).

The “distributed” aspect of DAS allows for the capture of a continuous strain/vibration profile at varying spatial resolution (typically 2 to 10 metres) over long distances (i.e. several kilometres) at a high sampling rate (e.g. 2500Hz). The sampling rate achievable in DAS makes its response comparable to accelerometers, geophones, and seismometers. Studies such as Daley et al. (2016) and Egorov et al. (2018) compare DAS to geophones and the studies concluded that DAS response could be processed to yield results comparable to geophones. Martin et al. (2018) provides a comprehensive review of DAS data processing.

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As described in Soga and Luo (2018), the transfer of strain from the surrounding media to the fibre core is caused by shearing along the tightly bonding interfaces between series of materials within the cable from the cable jacket to the cladding to the core. Different coupling between the fibre optic cable jacket and the host medium (e.g. grout versus soil) will change the way strain is transferred to the fibre optic cable core. Mateeva et al. (2014) and Lindsey et al. (2020) observed this effect in vertical seismic profiling surveys where the way the fibre optic cable was fixed to the oil and gas wells significantly affected the DAS response. Studies by Wu et al. (2015) and Friedli et al. (2019) observed response changes over time, suggesting that the coupling between the fibre optic cable and the host medium may change due to aging or other effects.

Achieving strong coupling between the fibre optic cable and the surrounding media remains a challenge for the DAS community. Coupling is a critical component to acquiring efficient and meaningful data (Miah and Potter, 2017), and the method of coupling depends on the application. In addition, the nature of soil makes the cable-soil coupling susceptible to changes in the surrounding environment that affects measured data (Zhang et al., 2016).

The objective of this paper is to present the results of a field study in which a DAS system was installed in different soil types (silty sand, clean sand, gravel, and flowable fill) adjacent to an existing, decade-old DAS array. Impact tests were performed such that the response in the different soil types and prior installation could be evaluated and compared.

2. Methodology

To study the effect of soil type and in-situ aging on DAS response, a fibre optic cable was installed in a trench and was added on to an existing DAS array that was installed a decade earlier (circa 2010). The same fibre optic cable was used for the new portion of test bed as with the prior installation (i.e. the cable came from the same spool). The loose-tube cable is a silica single mode fibre with reflective coating surrounded by a waterproof buffer tube, corrugated steel armour, and a polyethylene jacket. The OTDR interrogator used for this study is a single pulse homodyne system measuring backscatter amplitudes and is not phase sensitive. The sampling rate was 2500 Hz and the channel length was 10 meters. The signal response is proportional to the average strain experienced over the channel length. The lasers in the interrogator used in this study are calibrated, have long coherence length, and low phase noise units. They are not susceptible to phase noise issues or, more importantly given that we are not mixing signals and therefore no interferometer. There is no evidence that phase noise from our lasers affects the measurements. Numerous measurements, including narrowband tones and FM sweeps, have corroborated that the stimulus (signal) put into the cable matches the processed results in frequency. Recall, the backscatter intensity is a result of temporal variations of the local index of refraction at points along the fibre, i.e. scattering centres. These changes are brought about by changes to the strain of the fibre, as no local oscillator is used.

Although an intensity-only OTDR is an older version of the phase-coherent optical time domain reflectometry (ϕ-OTDR) used in studies such as Lindsey et al. (2020), this study focusses on array amplitude performance as a function of soil type. The native material on site is a silty sand with gravel and some cobbles such that about 40% of the silty sand by weight is finer than 0.074mm. Below the fill is one to two meters of glacial till underlain by bedrock.

The new fibre optic cable was spliced into the existing array and installed in a 300-meter-long trench at a depth of 0.5 meters, with the test bed layout and trench profile shown in Figure 1. For the portion of the array in native soil, the trench was excavated to a depth of 0.5 meters and the fibre optic cable was laid at the bottom of the trench. The sand, gravel, and flowable fill trenches were excavated to a depth of one meter so there would be 0.5 meters of non-native material above and below the cable. All trenches were approximately 0.5-meters-wide, the width of the excavator bucket used for the installation. The sand fill has a median grain size of about 0.4mm. The gravel is uniform, angular stone about 20 to 40mm in size. The native fill soil and the sand fill were placed in 30cm lifts and compacted using a plate compactor. In-situ total density of the native fill placed and compacted is approximately 1950 kg/m^3 with an average water content of 15%, which corresponds to 80% percent compaction relative to the Standard Proctor Test. The total in-situ density of the placed and compacted sand fill was approximately 1760 kg/m^3 at a water content less than 3%, which corresponds to 95% compaction. The cementitious controlled density excavatable flowable fill had a seven-day compressive strength of approximately 400kPa, a very weak concrete-like material.

A standard Proctor hammer (24.5 N rammer with a 305mm drop generating 600kN-m/m^3 of compactive effort according to ASTM D 698 (ASTM,2012)) that is used in laboratory compaction testing was the impact source for this study. The hammer was used to strike an aluminium plate at marked locations (Figure 1) for repeatability. At each hammer location, ten hammer strikes were performed. The hammer strike locations were approximately two meters offset from the buried fibre optic cable. Figure 2 shows a typical response in Channel 131 (location shown on Figure 1) to one hammer strike at Location No. 1. The DAS response amplitude has been normalized such that the maximum value is unity. The amplitude of the DAS response was normalized with the maximum response because the instrument response is unquantified (Soga and Luo, 2018 and Lindsey et al., 2020), meaning that the amplitude of the response signal does not precisely correlate to a strain measurement.

Signal to Noise Ratio (SNR), as defined in Equation 1, was used to evaluate the performance of DAS. The OTDR interrogator used for this study is an intensity-only, not phase sensitive instrument, and the response is proportional to the average strain experienced along the cable channel length. The SNR of the response to each strike was calculated for the responsive channels near each strike location. SNR is defined as a logarithmic measure of the ratio of the Root Mean Square (RMS) values of the signal (RMS_{signal}) and noise (RMS_{noise}). A 0.35 seconds capture of the signal is used to calculate RMS_{signal} whereas a 0.35 second capture of the noise immediately following the signal time window is used to calculate RMS_{noise}. The capture length (i.e. time window) was selected as a consistently achievable signal capture time and subsequent noise capture time that could be used across all data sets collected over time when series of ten or more impacts are performed at each location. The optimal time interval for each signal and noise will vary depending on the source of the vibrations to be measured. Figure 2(A) illustrates the time capture selection.

$$SNR\ (dB) = 20\ log_{10}\left(\frac{RMS_{signal}}{RMS_{noise}}\right) \qquad \text{Equation 1}$$

3. Results

The DAS response results presented herein are from impact test data collected over a period of seven months (August 2019 – February 2020). Impact source No. 1 (see Figure 1) was located between parallel portions of the previously installed fibre optic cable and new cable, both in native soil. Figure 3 shows how the SNR of the responsive signals attenuates away from the impact source in both cables. There is considerable scatter in the response to individual hits, but the trend shows that the SNR is higher in the new installation compared to the decade-old installation, which was compacted in a similar method to the new portion of array. The shape of the attenuation curve is comparable in both cables.

Results from a second impact source, located between parallel positions of the sand, gravel, and flowable fill trenches are shown in Figure 4. These results show that the SNR in both the sand and gravel are comparable and are consistently higher than the SNR, and thus the signal response, in the controlled density excavatable flowable fill.

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4. Discussion

The results shown in Figure 3 and 4 strongly suggest that soil type surrounding the fibre optic cable affects the SNR performance of a DAS array. The new portion of the DAS array in native soil generally yields higher SNR values for a longer distance than the prior install (Figure 3). Regardless, at ten-years old, the prior installation still responds well to the impact source, demonstrating the long-term viability of DAS monitoring systems. Differences in DAS response between the new install and the prior install could be due to differences in the methods of installation (specific details of the ten-year old DAS were not available) and/or changes in soil-to-cable coupling over time, i.e. “aging effects”, due to a variety of environmental effects such as water infiltration, desiccation, and freeze-thaw cycles.

DAS response to impact location No. 2 indicates that the portion of fibre optic sensor in the sand and gravel had comparable responses and yields higher SNR values than the portion of fibre optic sensor in the flowable fill (Figure 4). It is possible that the small-strain stiffness contrast between the native soil and the flowable fill (with the flowable fill being stiffer) resulted in lower SNR values in the flowable fill. Due to the shallow cable burial depth, and thus very low effective stresses, small strain shear modulus was not evaluated in this study. The fibre optic sensor portions in sand and gravel also appear to yield high SNR values than the portions of fibre optic sensor in the native soil (Figure 3). Often, larger gravel bits are removed from fibre-optic cable DAS installation trenches so as not to cause bends in the fibre that may reduce the power of the light pulsed into the fibre, and thus lower the performance. However, this was not observed in any of the data over the seven months of testing, suggesting that the impacts of any bending caused by gravel are insignificant, at least in shorter arrays.

Intensity-only OTDR DAS systems are typically used for vibration monitoring. The user is typically interested in events observed along the length of the fibre optic senor that are multiples greater than the baseline noise. This study indicates that the array is capable to responding to the impact source with an SNR of 5 dB at distances greater than 30 meters.

5. Conclusions

The results presented herein indicate that DAS vibration monitoring systems have long-term viability and perform well even after a decade of burial. Geotechnical design considerations, such as installing the DAS fibre optic cable in gravel instead of a controlled density, cementitious excavatable flowable fill, have a positive impact on the overall system performance. Common construction materials such as sand and gravel performed well over a seven-month test period during which impact tests on the ground surface were used to monitor performance of the DAS array. Even though there was a clear improvement of the response in the gravel and sand over the flowable fill and the native silty sand, all the SNR values were acceptable for monitoring purposes. These results suggest that DAS will be highly responsive when buried in readily available construction materials for more than a decade, which supports using DAS as a geotechnical/structural health monitoring tool. Work comparing the DAS array response in the test bed described herein will continue to observe how the response of the new installations change with time and environmental conditions.

6. Acknowledgements

The authors would like to acknowledge the U.S. Army Corps of Engineers Engineering Research and Development Center funding, and Ms. Jennifer Picucci, Dr. Katherine Winters, Mr. Josh McCleave; and our collaborators Mr. Darren Flynn, Mr. Ryan Carlson, and Ms. Jen McGunigal.

List of notations

RMS	Root Mean Square
T	period
f_s	sampling frequency
SNR	Signal to Noise Ratio

Accepted manuscript doi: 10.1680/jgele.21.00088

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Figure captions

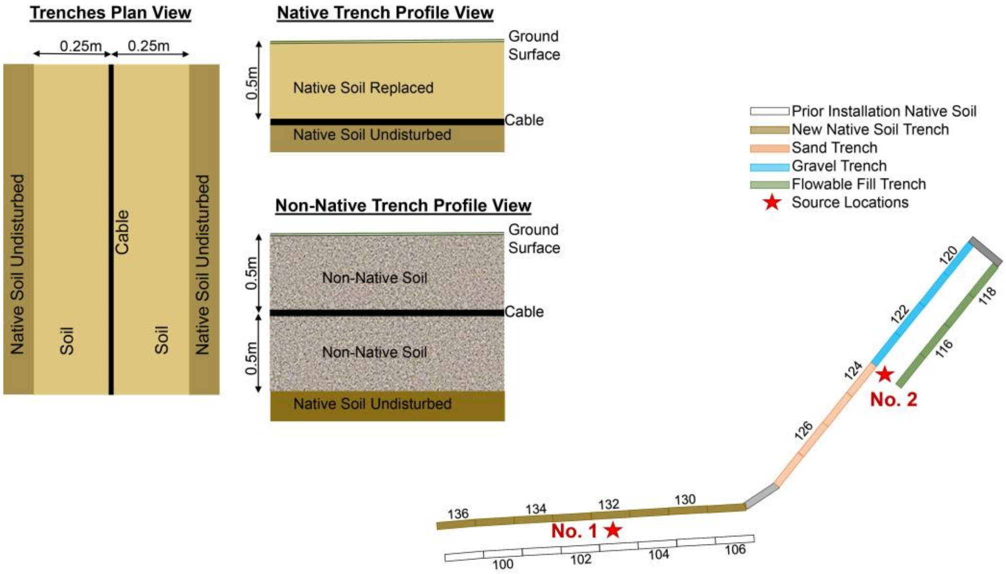
Figure 1. DAS test bed layout showing the prior and new install in the native soil (silty sand), sand fill, gravel fill, and flowable fill. Channel numbers are indicated along the length of the cable in addition to the locations of the impact tests performed for this study.

Figure 2. A typical DAS signal response in Channel 131 due to an impact test at location No. 1, including A) normalized time series, B) the power spectrum of the signal shown in A, and C) the spectrogram of the signal shown in A.

Figure 3. SNR of prior installation vs. new installation in native soil.

Figure 4. Comparison of SNR with distance for the fibre optic cable installed in sand, gravel, and controlled density, cementitious excavatable flowable fill.

Accepted manuscript doi:
10.1680/jgele.21.00088



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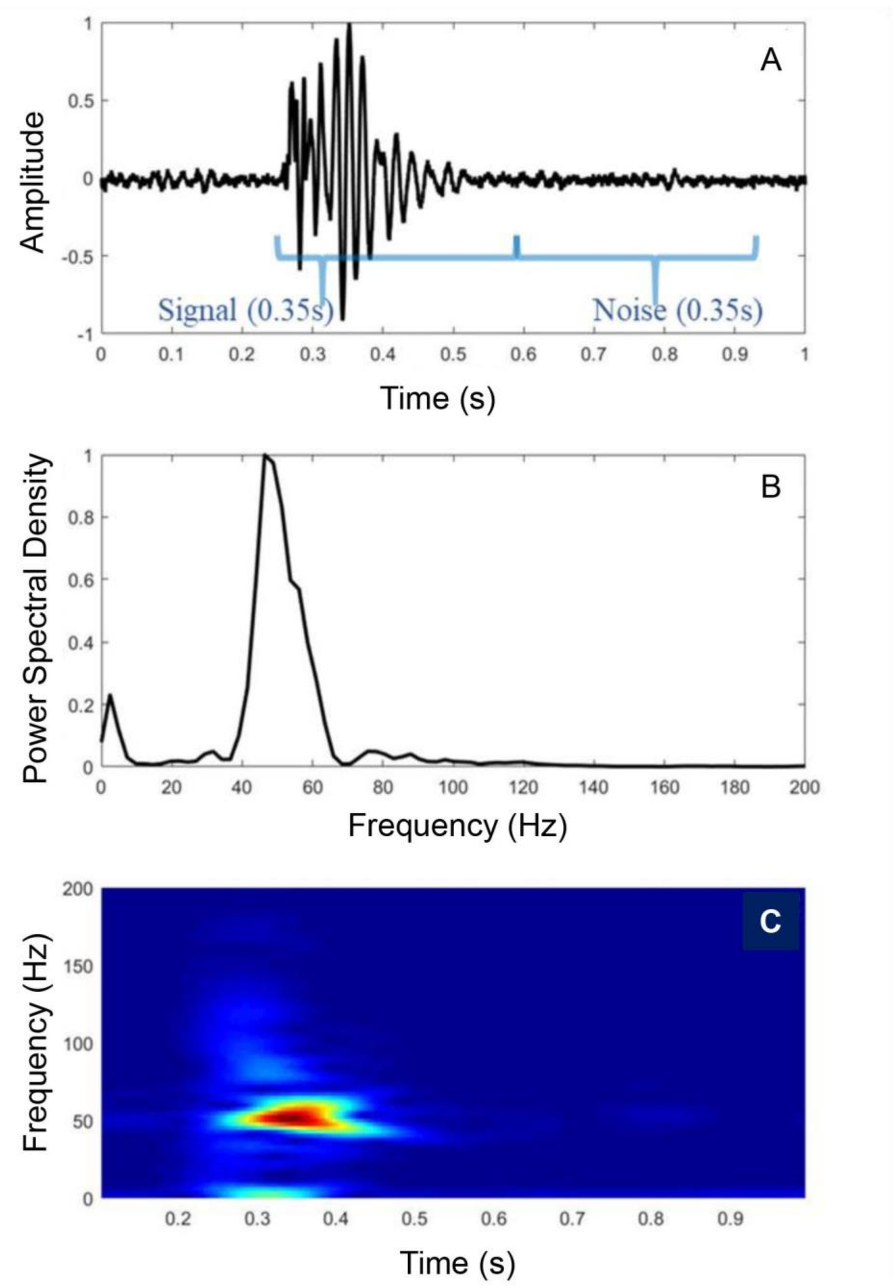
Accepted manuscript doi:
10.1680/jgele.21.00088



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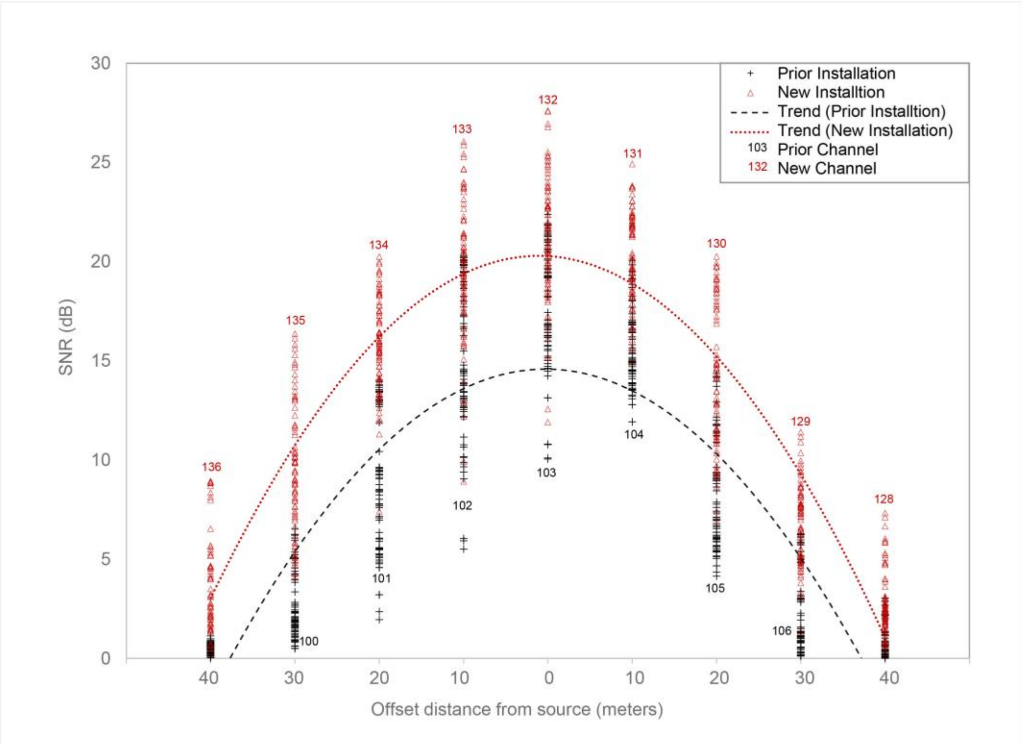
Accepted manuscript doi:
10.1680/jgele.21.00088



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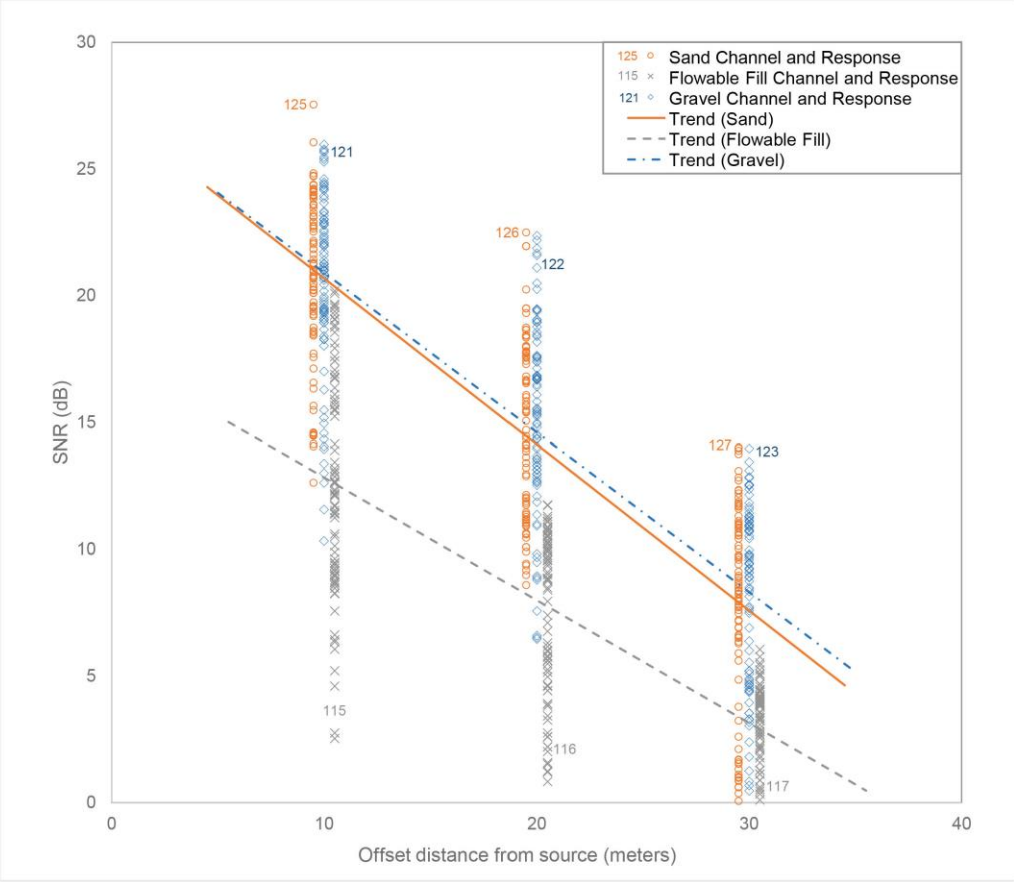
Accepted manuscript doi: 10.1680/jgele.21.00088



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