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Geotechnical Effects on Fiber Optic Distributed Acoustic Sensing Performance

Meghan C. L. Quinn

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Geotechnical Effects on Fiber Optic Distributed Acoustic Sensing Performance

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Abstract

Distributed Acoustic Sensing (DAS) is a fiber optic sensing system that is used for vibration monitoring. At a minimum, DAS is composed of a fiber optic cable and an optic analyzer called an interrogator. The oil and gas industry has used DAS for over a decade to monitor infrastructure such as pipelines for leaks, and in recent years changes in DAS performance over time have been observed for DAS arrays that are buried in the ground. This dissertation investigates the effect that soil type, soil temperature, soil moisture, time in-situ, and vehicle loading have on DAS performance for fiber optic cables buried in soil. This was accomplished through a field testing program involving two newly installed DAS arrays. For the first installation, a new portion of DAS array was added to an existing DAS array installed a decade prior. The new portion of the DAS array was installed in four different soil types: native fill, sand, gravel, and an excavatable flowable fill. Soil moisture and temperature sensors were buried adjacent to the fiber optic cable to monitor seasonal environmental changes over time. Periodic impact testing was performed at set locations along the DAS array for over one year. A second, temporary DAS array was installed to test the effect of vehicle loading on DAS performance. Signal to Noise Ratio (SNR) of the DAS response was used for all the tests to evaluate the system performance. The results of the impact testing program indicated that the portions of the array in gravel performed more consistently over time. Changes in soil moisture or soil temperature did not appear to affect DAS performance. The results also indicated that time DAS performance does change somewhat over time. Performance variance increased in new portions of array in all material types through time. The SNR in portions of the DAS array in native silty sand material dropped slightly, while the SNR in portions of the array in sand fill and flowable fill material decreased significantly over time. This significant change in performance occurred while testing halted from March 2020 to August 2020 due to the Covid-19 pandemic. These significant changes in performance were observed in the new portion of test bed, while the performance of the prior installation remained consistent. It may be that, after some time in-situ, SNR in a DAS array will reach a steady state. Though it is unfortunate that testing was on pause while changes in DAS performance developed, the observed changes emphasize the potential of DAS to be used for infrastructure change-detection monitoring. In the temporary test bed, increasing vehicle loads were observed to increase DAS performance, although there was considerable variability in the measured SNR. The significant variation in DAS response is likely due to various industrial activities on-site and some disturbance to the array while on-boarding and off-boarding vehicles. The results of this experiment indicated that the presence of load on less than 10% of an array channel length may improve DAS performance. Overall, this dissertation provides guidance that can help inform the civil engineering community with respect to installation design recommendations related to DAS used for infrastructure monitoring.

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Preface

This study was conducted for the U.S. Army Corps of Engineers under Army Direct funds, Program Element Number 465416A, Project Number, 08, and Task Number 27. The technical monitor was Mr. Josh McCleve.

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CHAPTER 1

INTRODUCTION

1.1 Statement of the Problem

In the early 2000s, the oil and gas industry began using fiber optic Distributed Acoustic Sensing (DAS) to monitor infrastructure (Miah and Potter 2017). Within the past the past decade interest in other geophysical and engineering applications of DAS has peaked. Researchers are demonstrating that DAS is a vibration monitoring instrument that can be used to evaluating subsurface stratigraphy with methods such as vertical seismic profiling (Mateeva et al. 2014 and Egorov et al. 2018) or multichannel analysis of surface waves (Dou et al. 2017 and Costley et al. 2018). Because of its discrete and distributed nature, DAS has the potential to be a powerful infrastructure-monitoring tool of the future.

A DAS system, or array, is comprised of a fiber optic cable and an interrogator. The fiber optic cable can be as simple as telecommunication fiber optic cable (i.e. discrete and inexpensive) or as complex as a specially fabricated cable with unique materials and orientation. The fiber optic cable connects to the interrogator, which is an optical time-domain reflectometer (OTDR). Figure 1.1 provides examples of two commercially available DAS interrogators (please note there are other commercial vendors). The interrogator houses at least one laser that pulses light into the fiber optic cable core. Light propagates down the fiber optic cable core and the light scatters due to anomalies in the core material (Krohn et al. 2014). Some of the scattered light returns towards the interrogator (termed backscatter) as light continues to propagate down the length of the fiber optic cable. Figure 1.2 shows the general concept of a

DAS interrogator with fiber optic cable. The interrogator measures the power of the backscattered light and sorts the backscatter by return time (Sang 2011, Owen et al. 2012, Schenato 2017, and Wang et al. 2019). This return time is associated with a distance down the fiber optic cable.

DAS measures vibrational strains over channel lengths; 10-meter channel lengths are most commonly in cited publications. Channel length is the segment length over which feedback is distributed along the length of fiber optic cable connected to the DAS interrogator. For example, a 20-kilometer-long fiber optic cable connected to a DAS interrogator set at 10-meter channel lengths would yield 2,000 evenly spaced data feedback channels from one system.



FIGURE 1.1: Commercially available DAS interrogators (Silixa on the left and Optasense on the right). Images courtesy of silixa.com and optasense.com.

DAS is sensitive to the vibrational strain field acting on the fiber optic cable at the resolution of the channel length set in the interrogator (Lindsey et al. 2020). Figure 1.2 shows the general concept of a DAS interrogator with fiber optic cable. The DAS user can select channel length (typically 10 meters), power level, and sampling rate (typically greater than 2,000 Hz) of the system. These criteria are set to balance tradeoffs between spatial resolution and dynamic range (Eyal et al. 2017).

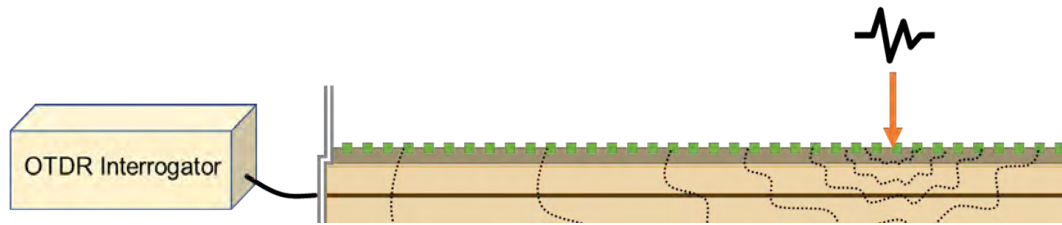


FIGURE 1.2: DAS interrogator connected to a fiber optic cable with vibrations exciting the fiber optic cable.

The fiber optic cable lengths achievable in DAS systems make this instrument ideal to monitor kilometers of infrastructure along roadways and railways. Alsabhan et al. 2019 used the DAS response to train-induced seismic waves seismic and infer changes in ballast and subsurface material below railway rails. With DAS, engineers can localize where changes occur and perform further engineering investigation regarding whether the changes will affect the infrastructure safety and/or performance. Recent research (such as Wang et al. 2018 and Lindsey et al. 2020) indicates that DAS arrays yield results comparable to that of seismometers and geophones, suggesting that DAS arrays might replace several point sensors in the future and/or supplement existing point sensor monitoring systems.

The effect of external influences on DAS performance remain unknown. For the civil engineering community to embrace DAS as the next generation infrastructure vibration monitoring tool, the effects of soil type, in-situ conditions (i.e. seasonal fluctuations), and overburden pressure on DAS performance must be understood. Additionally, civil engineers must have confidence in the long-term viability of the technology to recommend its use.

This dissertation explores the effect of variables external to the fiber optic cable of the DAS system on performance, keeping infrastructure monitoring applications in mind. DAS performance is defined herein as the repeatability and comparability of a fiber optic cable array in different soil types to sense a calibrated impact source on the ground surface through seasonal environmental changes. The hypotheses tested herein were designed to better understand geotechnical installation considerations on long-term DAS monitoring systems.

1.2 Knowledge Gaps

Although DAS is commercially available, fundamental aspects of DAS performance in soil are not yet fully understood. The fiber optic cable portion of a DAS system cannot be coupled to soil the same way it can be rigidly coupled to a pipeline, a metal borehole casing, or the interior of a rock mine. The DAS research community acknowledges that the coupling between the fiber optic cable and the host medium affects the performance of the DAS system (Lindsey et al. 2020). Most of these studies compared grouting a fiber optic cable to a well casing to tying a fiber optic well casing, or hanging a fiber optic cable in a well casing. Lindsey et al. (2020) hypothesized that horizontally installed fiber optic cable for DAS may have more coupling issues than vertical fiber optic installations due to the variability in cable-to-soil contact, including age of installation, installation depth, and changing drainage soil conditions. Zhang et al. (2016) agrees that a major barrier in the accepted use of distributed fiber optic sensing is the lack of understanding about the interaction between fiber optic cable and soil during vibration and strain events. Additionally,

Zhang et al. (2016) recognizes that changes in the medium surrounding the cable would affect the system response, noting that external fluctuations such as rainfall and ground water elevation would likely affect the measured data.

Studying cable-to-soil coupling and the variables that affect this coupling remains a significant knowledge gap in DAS performance. Researchers (e.g. Iten 2011, Zhang et al. 2016, and Winters et al. 2019) have attempted to study cable-to-soil coupling with cable pull-out tests (varying soil moisture and density). Zhang et al. (2014), Zhang et al. (2015), and Zhu et al. (2015) studied soil-cable interaction with overburden pressure in a laboratory setting. The results of these studies indicate that the cable to soil interface is sensitive to overburden pressure, density of soil, and water content of soil. Further, these studies discuss that environmental changes affect the physical and mechanical properties of soils. These studies indicate that an increase in overburden pressure is proportional to the frictional pull-out resistance on the fiber optic cable which could infer better cable-to-soil coupling and thus better performance. Zhang et al. (2014), Zhang et al. (2015), and Zhu et al. (2015) allude that a fiber optic cable imbedded in a soil with high effective stress (and a low water content) will out-perform a DAS array with a fiber optic cable in a soil with a high water content. However, these tests are showing changes in frictional resistance along the fiber optic cable due to overburden pressure, and not directly showing how these changes relate to the DAS response.

While significant gains in DAS performance have been achieved through technological advancements in the DAS interrogation units and fiber optic cable composition, little research has been documented on best soil installation practices, i.e.

improving performance with external influences. Much of the existing body of published research on DAS arrays in soil regard the following:

1. Short-term data collects (e.g. Miller et al. 2018 and Parker et al. 2018)
2. Significant seismic events on previously installed arrays (e.g. Lindsey et al. 2017 and Wang et al. 2018).
3. Advancements in data processing methods (e.g. Martin et al. 2018).

From a civil engineering perspective, knowledge gaps preventing DAS from wide acceptance seem clear. Civil engineers need to be able to provide installation recommendations for DAS that will promote consistent performance over time. Part of providing engineering recommendations for DAS installation include knowing how site conditions, available material, and seasonal changes will affect DAS performance. This dissertation aims to provide information related to these areas of concern.

1.3 Scope of Research

The objective of this research is to investigate the relationship between the material type surrounding the fiber optic cable and DAS performance. It is hypothesized that DAS response is affected by soil type, moisture content, temperature, surface loading, and time in situ.

To test this hypothesis, a permanent, new portion of DAS test bed was constructed alongside of an existing DAS test bed installed ten years prior. The new portion of DAS array includes channels of the fiber optic cable in sand, gravel, excavatable flowable fill, and the native silty sand material. The layout of the array was designed to provide maximum performance comparison between array segments

in differing soil types. This field test bed is exposed to seasonal changes and weather events, allowing for observation of changes in soil moisture and soil temperature that may affect DAS response. Soil volumetric water content and temperature sensors were installed in each soil type as the depth of the fiber optic cable. To evaluate DAS performance consistently throughout this research, impact tests were performed periodically at set locations along the DAS array. The DAS response to impact testing was processed for Signal-to-Noise-Ratio (SNR) as the response performance criteria, where higher SNR equates to better performance. Previous laboratory studies have looked at a single soil type and pull-out resistance of a fiber optic cable, inferring that higher pull-out resistance means better soil-to-cable coupling which infers better performance. Previous field studies looked at DAS in a single soil type under short-term conditions (moisture or loading) and inferred long-term performance. This dissertation presents novel research as it simultaneously investigates DAS performance in four soil types through fluctuating soil moisture and temperature conditions over the course of one year and provides performance of the portion of DAS array installed a decade prior.

To test surface loading effects on DAS performance, a separate temporary test bed was constructed at the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) to test DAS performance with loading and unloading cycles, where the loading is increased to cable failure. The temporary test bed contained ten channels of DAS array surrounded by a dry, silty soil. Load cell pads were placed on the top of the silt blanket containing the DAS array. These load cell pads measured the exact force applied to the top of the silt blanket while impact

testing was performed. Increased load was applied to the test bed through loading and unloading cycles until the fiber optic cable failed.

1.4 Organization of this Dissertation

This chapter, Chapter 1, introduces DAS, existing knowledge gaps, and the objectives and scope of this research.

Chapter 2 provides a literature review on DAS beginning with fundamental concepts, progressing towards how DAS works. This chapter explores published research comparing processed DAS data to that of geophones and seismometers. This chapter concludes with DAS applications in civil engineering and clear knowledge gaps as identified by other researchers.

Chapter 3 presents a detailed description of the construction of the permanent and temporary DAS test beds.

Chapter 4 presents the results of this study and discusses the results.

Chapter 5 provides a discussion of the research presented in this dissertation with conclusions, and a discussion of on-going and future research.

CHAPTER 2

REVIEW OF LITERATURE

The research presented in this dissertation focuses on the response of fiber optic distributed acoustic sensing (DAS) systems embedded in near surface soil. Before discussing civil engineering uses of DAS, this chapter provides a basic explanation of how DAS works and how it responds to vibrations in the material surrounding the fiber optic cable. This review highlights studies comparing DAS to other in-situ vibration monitoring systems. Lastly, this review summarizes civil engineering applications of DAS and knowledge gaps with DAS as defined by the research community that this research aims to address.

2.1 DAS using Fiber Optics

Nearly 60 years ago, research into fiber optics began with a focus on telecommunications (Schenato 2017). In the 1990s, distributed fiber optic sensing (DFOS) was used for distributed temperature sensing (often abbreviated to DTS), see Johansson (1997), and distributed strain sensing (commonly known as DSS), see Peck (1994). For DTS and DSS, the DFOS system exploits changes in light scattering within the fiber optic cable to infer information about the medium surrounding the fiber optic cable, such as temperature and strain. DTS uses Raman scattering to observe temperature and DSS uses Brillouin scattering to monitor both strain and temperature. DAS, however, uses Rayleigh backscattering which is sensitive to longitudinal strain (i.e., down the axis of the fiber). This section discusses fundamentals of DAS, beginning with light transmission, Rayleigh scattering, and

how DAS uses Rayleigh scattering to infer vibrational strains acting along the length of the fiber optic cable.

2.1.1 Basics of Light Transmission

Before discussing Rayleigh scattering of light, here is a review the basics of how photons move inside of a fiber optic cable.

When a laser pulses light (i.e. photons) into one end of the fiber, the composition of the fiber optic cable and Snell's Law (Equation 1 and Figure 2.1) governs how light propagates down the length of the fiber optic core. In Equation 1 and in Figure 2.1, n_0 is the index of refraction of the medium in which the light is initially travelling, n_1 is the index of refraction of the second medium, ϕ_0 is the angle between the incident ray and the normal to the interface, and ϕ_1 is the angle between the refracted ray and the normal to the interface. Some of the ray is refracted and some of the incident ray is reflected. If $\phi_0 = \phi_c$, no refraction occurs, where the critical angle is ϕ_c . For $\phi_0 > \phi_c$, all of the ray is reflected at the interface (i.e. no refraction), which is called total internal reflection (Krohn et al. 2014).

$$n_0 \sin \phi_0 = n_1 \sin \phi_1 \quad \text{EQ. 1}$$

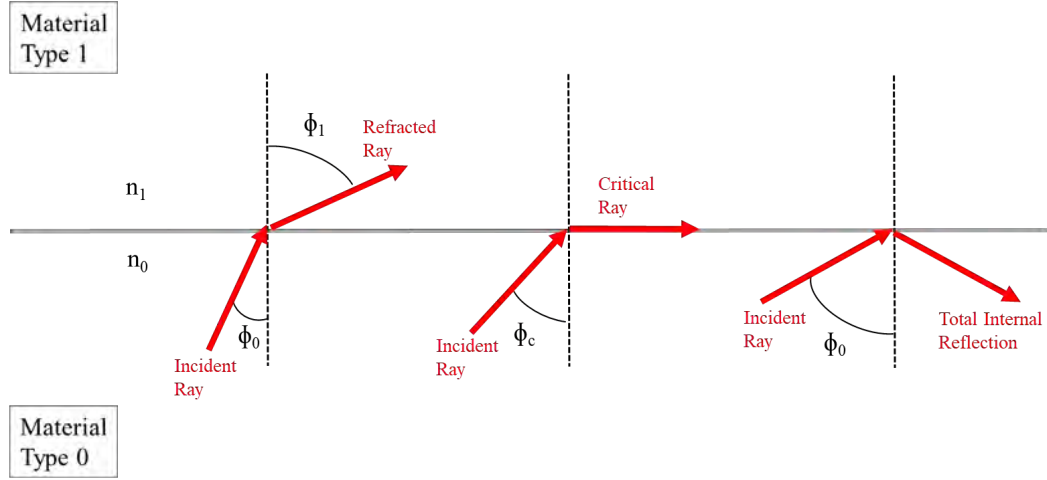


FIGURE 2.1: Illustration of Snell's Law (based off of Krohn et al. 2014)

When considering Snell's Law for a fiber optic cable, Numerical Aperture (NA) is a measure of light acceptance and is affected by the difference between the fiber core and its cladding's refractive index, see Equation 2, (Krohn et al. 2014). In Equation 2, the fiber core has a refractive index n_0 , a cladding refractive index n_1 , and a surrounding refractive index n . For context, a higher NA relates to a higher amount of light remaining in the fiber, allowing for more severe grazing angles and increasing the acceptance angle of light entering the fiber. Maximum light-collection efficiency occurs for large-diameter-core fibers with larger NA fiber optic cables (Krohn et al. 2014).

$$\begin{aligned}
 n \sin\phi_0 &= n_1 \sin\phi_1 \\
 n \sin\phi_0 &= n_1 \sin\left(\frac{\pi}{2} - \phi_c\right) \\
 n \sin\phi_0 &= [1(n_1 n_0)^2]^{1/2} \\
 \text{Numerical Aperture (NA)} &= (n_0^2 n_1^2)^{1/2}
 \end{aligned}
 \tag{EQ 2}$$

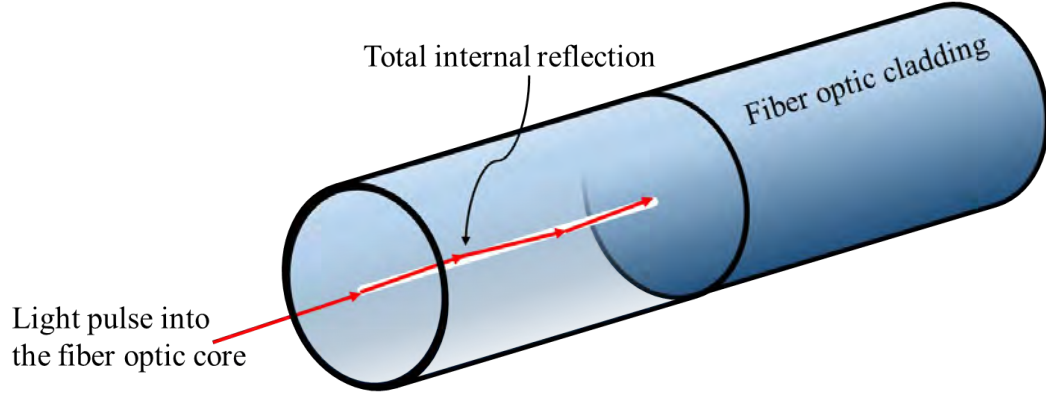


FIGURE 2.2: Reflection of light in the core of a single mode fiber optic cable

The research in this dissertation uses a single mode fiber optic cable. Single-mode transmission requires small fiber core size and low values of NA. Figure 2.2 illustrates how light would propagate down a single mode fiber. A single-mode fiber allows for only one propagation mode and one polarization state due to their small core diameter (Nikles et al. 1997 and Soga and Luo 2018).

The effect of the critical angle and the amount of light that can be injected into the fiber is reduced in a bent fiber. Most bending loss occurs at the transition from the straight to the bent section (Krohn et al. 2014). Fundamentally cable bending increases photo power loss because the photons must slightly alter its direction. Subtle bends do not provide and observable effect on DAS response, but tight bends (i.e. wrapped around a pencil) will cause a noticeable loss. Thus, it is common to mark the end of a test section in the field by wrapping the fiber optic cable around a pencil and thus dropping the power at that location.

Attenuation, measured in decibels per unit length (dB/km), is loss and it is defined by power input (P_i) and power output (P_o), see Equation 3.

$$A = 10 \log \left(\frac{P_i}{P_o} \right) \quad \text{EQ 3}$$

Attenuation in a typical telecommunications fiber optic cable is about 0.15 dB/km (Miah and Potter 2017 and Lindsey et al. 2020). For perspective, attenuation less than 1 dB/km is “ultralow loss” fiber (Krohn et al. 2014).

Aside from bending, other causes of attenuation include absorption, scattering, and microbending. Power losses at the end of the fiber optic cable are due to reflection. Losses also occur in connections between the fiber and optical devices or new fiber spliced onto existing fiber and are part of overall system losses.

2.1.2 Rayleigh Scattering

Changes in Rayleigh scattered light within the fiber optic cable are used in DAS to infer vibrational strains acting along the fiber optic cable length. When a laser pulses light into the core of a fiber optic cable, scattering occurs at sub-microscopic anomalies in the composition and density of the glass (Krohn et al. 2014). Some of the scattered light returns down the fiber towards the laser; the return of the scattered light is called backscatter. Anomalies in the fiber causing these scattering centers could be voids, density variations, impurities, composition fluctuations, and structural variations.

Rayleigh scattering is an elastic process in which no energy is transferred as photons reflect, meaning that returning scattered photons from the laser pulse travel at the same velocity as original outbound photons and have the same wavelength. Other

types of DFOS use nonlinear, inelastic scattering processes such as Raman scattering (used for DTS) and Brillouin scattering (used for DSS).

Combined loss effects cause transmission attenuation in the fiber. The relationship of the exponential decay of optical power (light intensity), termed $P(z)$, down the length of the fiber optic cable (z) is show in Equation 4, where P_o is the input power and α_T is the attenuation coefficient (Krohn et al. 2014). The power of the backscattered light per length is $P_{backscatter}$, Equation 5, is a function Numerical Aperture, NA (related to the angle of the incident photo ray), the fiber core's refractive index n_c , and δl is the backscatter power per unit length. Figure 2.3 illustrates backscattering occurring at scattering centers, while the light from the laser pulse continues to propagate down the length of the fiber. The purpose of displaying Equations 4 and 5 is to show that the power of the photons making their way down the fiber is a function of the input power and the total attenuation. The total attenuation is a function of attenuation due to absorption, scattering, bending, and wave guide losses. For example, a fiber with many significant bends in it will have higher attenuation due to bending. And lastly, as shown in Equation 5, the power of the backscatter (which is the response signal we evaluate with the DAS interrogator) is a function of the input power, attenuation due to scattering, and properties of the fiber optic cable (i.e. numerical aperture and refractive index).

$$P(z) = P_o e^{\alpha_T z} \quad \text{EQ 4}$$

$$\alpha_T = \alpha_{absorption} + \alpha_{scattering} + \alpha_{bending} + \text{waveguide losses}$$

$$P_{backscatter} = \frac{P_{input} \alpha_{scattering} \partial l (NA)^2}{4n_c^2} \quad \text{EQ 5}$$

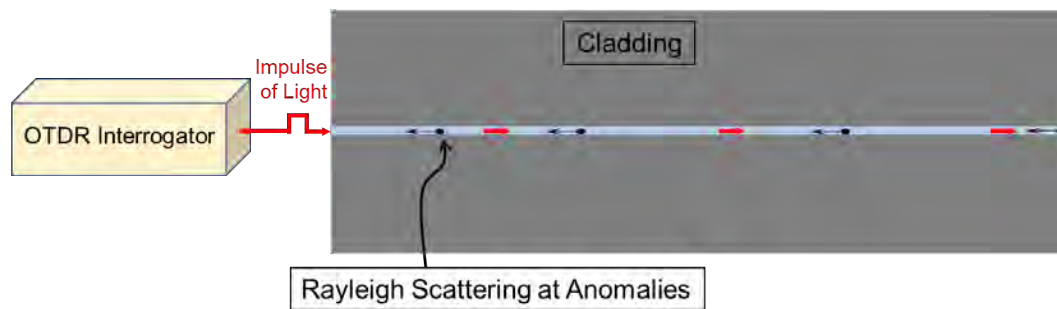


FIGURE 2.3: Rayleigh backscatter due to laser impulse propagating down a single mode fiber optic cable

Sang (2011) and Krohn et al. (2014) provide a detailed discussion on numerical analysis of Rayleigh scattering.

2.1.3 Sensors used to Measure Rayleigh Scattering

In the 1970s, the optical time-domain reflectometer (OTDR) instrument was developed to evaluate attenuation over telecommunication fiber optic cable lengths (Personick 1977). The OTDR was used to troubleshoot bends, breaks and poor connection in telecommunication cables (Sang 2011). The OTDR interrogator houses a laser that pulses light in the fiber core. A photodetector, also in the interrogator, measures the amount of light backscattered from the incident laser pulse. The detected backscatter signal is termed the Rayleigh signature. As light propagates down the fiber, it is sensitive to vibrations acting on the fiber optic cable; and the vibrations are then observed in the Rayleigh signals (Soga and Luo 2018). OTDR profiles help to find fiber breaks/faults, to evaluate splices and connectors, and to assess the overall quality of a fiber optic cable connection. The trace slope represents the attenuation

factor within the fiber such that faults produce a peak intensity of back-reflected signal in the trace profile followed by a drop, as shown in Figure 2.4.

OTDR systems rely on high-sensitivity photodetectors that can capture the low-level reflected Rayleigh signals. Settings in the OTDR interrogator compromise between dynamic range (i.e. the longer the pulse duration, the greater the signal strength) and spatial resolution (i.e. the smaller the pulse width) over the known length of fiber optic cable under test (Eyal et al. 2017, Krohn et al. 2014, Schenato 2017, and Miah and Potter 2017).

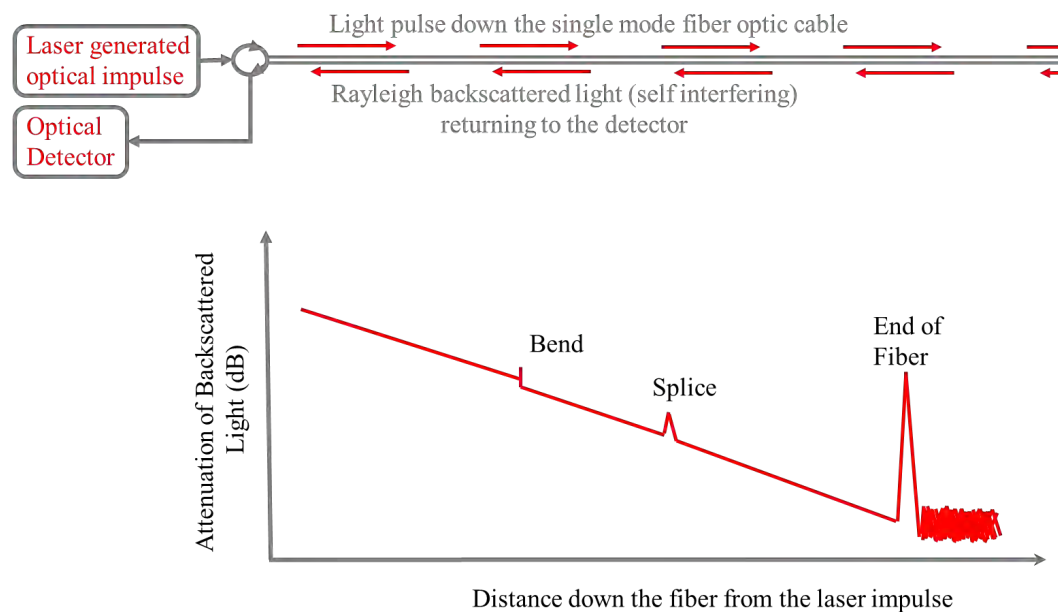


FIGURE 2.4: Basic OTDR set-up and example of OTDR trace.

Rayleigh Backscatter collected by the OTDR interrogator is summed and “binned” by time of return (Owen et al. 2012). The elastic nature of Rayleigh scattering (velocity outbound equals velocity inbound) means that the return time

provides information about how far down the cable the backscatter occurred (Sang 2011, Owen et al. 2012, Schenato 2017, Wang et al. 2019). Soga and Luo 2018 show that to calculate the location of each backscattered light center (z is the distance from the interrogator), one only needs to know the time delay between launch and receive (Δt), the speed of light in a vacuum (c), the refractive index of the core (n), and divide by two because the light is elastically travelling down the fiber from the interrogator and back to the interrogator (Equation 7).

$$z = \frac{c\Delta t}{2n} \quad \text{EQ 7}$$

The OTDR collects the Rayleigh signature signals induced by vibrational strain along the fiber optic cable along with sources of noise. Sources of noise observed by an OTDR include optical fluctuations, amplified spontaneous emission, and thermal noise (Uyar et al. 2019). Another source of noise can occur when a signal is observed in all DAS channels at once, called a common-mode noise, which is usually caused by a seismic event occurring where the OTDR interrogator is located (Ajo-Franklin et al. 2019, Dou et al. 2017, and Lindsey et al. 2020). Poor cable-to-soil coupling, termed “reduced amplitude channel noise,” is another possible source of noise in the signal (Ajo-Franklin et al. 2019, Becker et al. 2017, Reinsch et al. 2017, and Lindsey et al. 2020), which is due to poor energy transferred to the fiber optic cable and within the fiber optic cable. A seismic wave travels through the soil to a poorly coupled fiber optic cable will inefficiently and inconsistently excite the fiber optic cable and thus the backscatter inside of the fiber.

The two most common types of Rayleigh scattering sensors are conventional OTDR and phase-sensitive OTDR (Soga and Luo 2018). The research herein this

dissertation uses a conventional OTDR interrogation system. For more information on phase-sensitive OTDR interrogators (please see Sifta et al. 2015, Muanenda et al. 2016, Miah and Potter 2017, and Wang et al. 2017).

2.1.4 A DAS System

DAS systems must have two major components: 1) an optical fiber cable and 2) an OTDR optical fiber analyzer for data acquisition, processing, transmission, and storage (Soga et al. 2015). This combination allows for sensing of the vibration strain field acting on the fiber optic cable (Lindsey et al. 2020). Figure 2.5 provides a generalized schematic of the interrogator-fiber optic cable system.

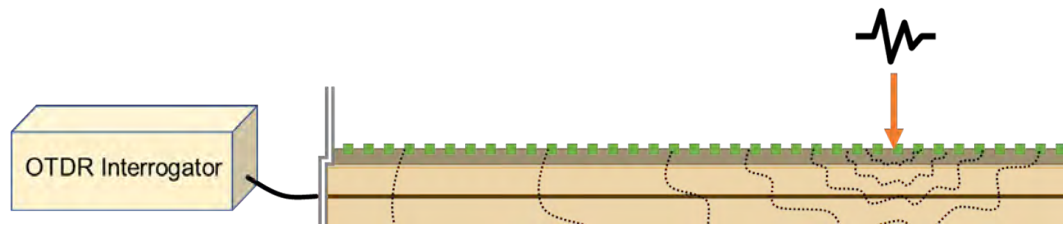


FIGURE 2.5: Typical DAS system.

DAS provides average vibrational strains measured over a channel length, commonly 10-meters-long. The interrogator can adjust laser power levels, dynamic range, and channel length to refine the Signal-to-Noise Ratio, SNR. To improve SNR, typically either power must be increased (pulse width or peak power) or the spatial resolution must be reduced (i.e. longer channel lengths). When adjusting the interrogator settings, the user should be aware that DAS arrays are most sensitive to longitudinal waves propagating along the cable length and at 45° to the cable

centerline and the least sensitive to waves propagating perpendicular to the cable axis (Martin et al. 2018 and Zhan 2019).

Vibrational strains in the soil transfer into strains on the cable jacket, which transfers through the internal fiber optic cable geometry until reaching the fiber core. As described in Soga and Luo (2018), strain transfer to the fiber core is caused by shearing along the tightly bonding interfaces between series of materials from the cable jacket to the cladding to the core, see Figure 2.6. The cable-to-material coupling and the mechanical properties of the fiber optic cable affect the way the vibrational strain is transferred from external material to fiber optic cable core (Ansari 2007, Culshaw et al. 1996, and Soga and Luo 2018). The fiber optic cable cannot be coupled to soil the same way it is coupled rigidly to metal or rock (Mateeva et al. 2014 and Lindsey et al. 2020). Differences in strain transfer due to difference in cable coupling was first observed while performing vertical seismic profiling surveys where the fiber optic cable was fixed to oil and gas wells using different methods (Mateeva et al. 2014 and Lindsey et al. 2020), showing that DAS performance is highly dependent on the coupling. As shown in Figure 2.6 a vibration strain in the soil transfers to the cable jacket and eventually to the fiber core. The vibrational strain compresses the cable in the direction of strain transfer which cause the fiber to slightly elongate accordingly. Currently DAS systems cannot infer which way the strain is occurring, but the vibration will be reflected in the DAS signal response.

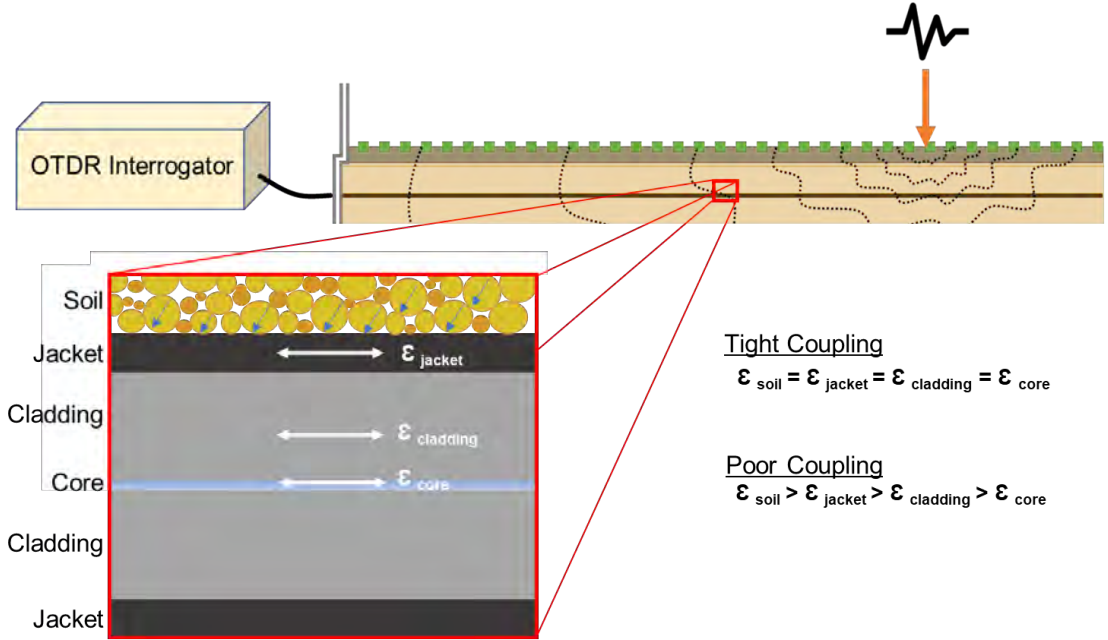


FIGURE 2.6: Strain Transfer from soil to fiber core (based on Soga et al. 2018).

2.2 Seismic Waves and DAS

This section investigates the seismic waves that DAS systems sense. Near surface installed DAS arrays are sensitive to compression waves (p-waves), shear waves (s-waves), Rayleigh waves and, Love waves (Yang 2001, Kouretzis et al. 2007, and Martin et al. 2018). The sensitivity DAS has to seismic waves depends on the DAS gauge length, the wavelength of the source, and the orientation of the wave to the fiber optic cable core (Martin et al. 2018).

The particle movement generated by the seismic waves transfers to the fiber optic cable portion of the DAS system. Figure 2.8 illustrates the different particle motion caused by p-waves (A), s-waves (B), Rayleigh waves (C), and Love waves (D). P-waves, or compression waves, cause particle compression and expansion through the soil medium. S-waves cause a shearing motion (and deformation) between particles.

Near the ground surface, shear s-waves are considered to be in the vertical direction, while Love waves similar to shear waves but in the horizontal direction; both causing deformations (Kramer 1996 and Martin et al. 2018). Rayleigh waves involve an elliptical particle motion, see Figure 2.8 C.

For this dissertation, the impact source used (alluded up in Chapter 1 with a detailed discussion in Chapter 3) is on the ground surface and likely generates p-waves, s-waves, and Rayleigh waves. Therefore, this section will not discuss Love waves. It has been documented that Rayleigh waves and shear waves from a given source typically have similar velocities (Addo and Robertson 1992, Ananasopoulos et al. 2000, and Yang 2001). Therefore, when searching for seismic response in DAS, often the Rayleigh wave and shear wave signals overlap.

The study of Rayleigh wave motion in soil began with Biot (1956), who considered saturated soil a fully saturated porous medium and treated it as a poroelastic continuum. Building upon Biot's work, Tajuddin (1984), Philippacopoulos (1987), and Yang (2001) studied Rayleigh waves in fully saturated poroelastic space. Yang (2002) performed field studies that indicated soil saturation significantly affected p-wave propagation. Yang (2005) followed on this work to study the effect of ground water fluctuation on Rayleigh wave propagation. Yang (2005) found that, with increasing saturation, the Rayleigh wave velocity approaches the S-wave velocity, but that the Rayleigh wave appeared to have greater soil particle elliptical movement with a higher degree of saturation. Zhou and Xia (2006) also studied Rayleigh wave propagation in partially saturated soils, specifically with a

thorough numerical analysis of how soil saturation on Rayleigh waves; and found that saturation has greater affect at low frequencies.

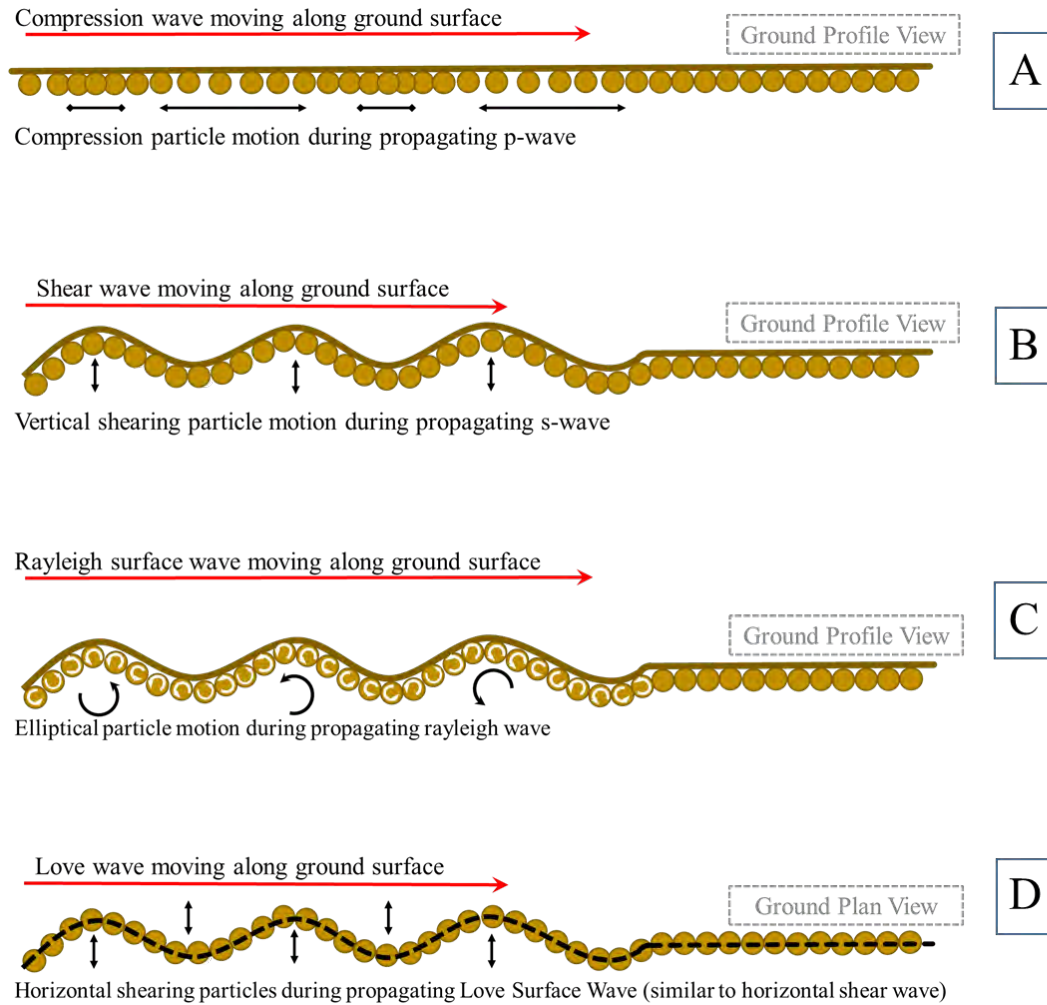


FIGURE 2.8: Seismic waves in near surface soils: compression waves (A), shear waves (B), Rayleigh waves (C), and Love waves (D)

If soil saturation affects Rayleigh wave and p-wave propagation, then soil saturation may also affect the transfer of vibrations to the fiber optic cable core. Some researchers have considered that the fiber optic cable itself affects wave propagation through soil. Kouretzis et al. (2007) assumed that the flexible pipeline (or fiber optic cable) is fully coupled with the ground motion. The authors indicate that this is a conservative assumption because in real life, the pipeline (or a fiber optic cable) is not fully coupled and thus the predicted/modeled strains are greater/stronger than what they would be in reality. Kouretzis et al. (2007) validated this assumption with blast-induced displacement measurements on flexible pipelines in soil (Siskind et al. 1994). Several researchers have studied how seismic events are recorded by DAS (Moran et al. 1999, Dean et al. 2017, and Parker et al. 2014, and Lindsey et al. 2020). Lindsey et al. (2020) acknowledges that there is likely a small effect between the fiber and the soil and the propagating wave, but that this effect can be ignored due its insignificance at most propagating wavelengths.

2.3 DAS versus Geophones and Seismometers

In the past decade, the geophysics community has embraced DAS technology (Daley et al. 2013, Karrenbach et al. 2018, and Zhan 2019). Geophysicists have compared DAS performance to other seismic activity instrumentation, such as the geophones, accelerometers, and seismometers. All these instruments are used to evaluate the motion of the ground in response to mechanical ground vibrations. Researchers such as Martin et al. (2018) detail the intensive data processing required to extract the response of a DAS array to various wave types. Martin et al. (2018)

indicates that the DAS array must be configured to account for directionality of the fiber optic cable components. Her research indicates that the DAS array responds consistently well to propagating Rayleigh waves.

As DAS technology and data processing have improved, DAS response has become more comparable to that of geophones. Several studies have evaluated the use of DAS for vertical seismic profiling, VSP (e.g., Mateeva et al. 2014, Olofsson and Martine, 2017, Egorov et al. 2018, and Miller et al. 2018). Figure 2.10, from Egorov et al. (2018), shows the comparison of processed DAS response to processed geophone response. Also, DAS has been used by several researchers (e.g., Daley et al. 2013, Bakulin et al. 2017, Castongia et al. 2017, Dou et al., 2017, Hornman, 2017, Jreij et al. 2017, Costley et al. 2018, Spikes et al. 2019, and Miller et al. 2018) in ground surface deployments to perform multichannel analysis of surface waves, commonly referred to as MASW. Both VSP and MASW are used to estimate the shear wave velocity of soil profiles.

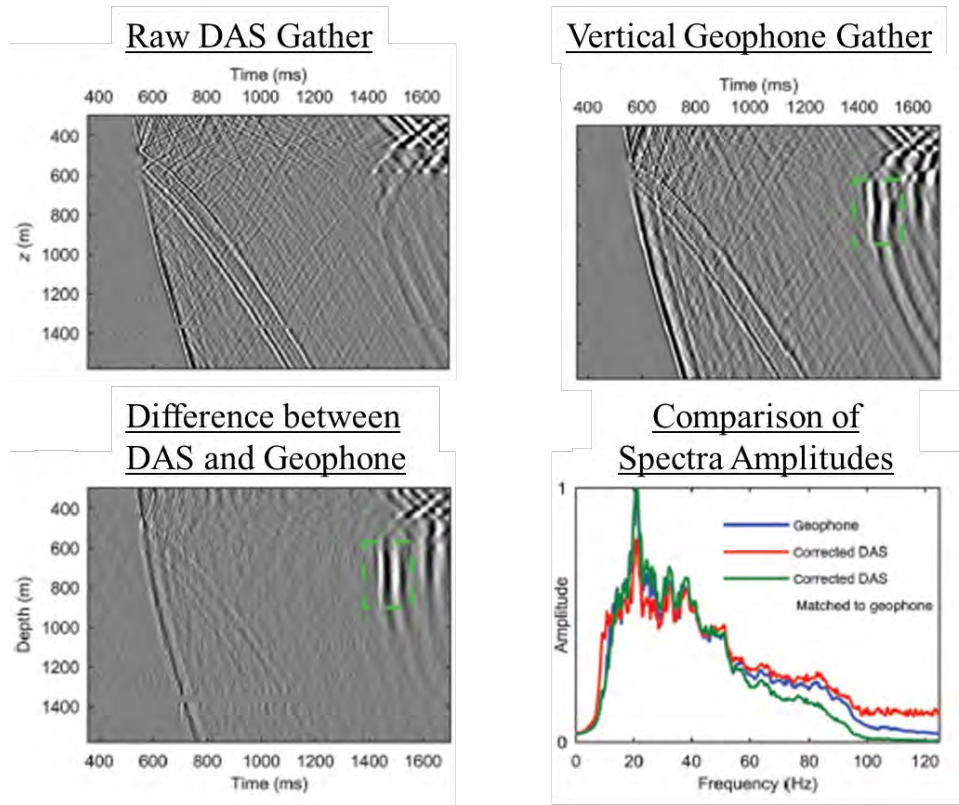


FIGURE 2.10: DAS versus geophones (via Erogov et al. 2018).

Studies such as Daley et al. (2016) and Egorov et al. (2018) compare DAS generated VSP to the VSP generated from the vertical component of the geophone (the direction vertically installed DAS fiber most sensitive) at CO₂ injection sites. These studies found that the DAS and geophones have comparable SNRs, where DAS is slightly less sensitive to some frequencies, as shown in Figure 2.10. Spikes et al. (2019) demonstrates that DAS using different fiber optic cables laid on the ground surface compares well to surface geophones.

Researchers have also compared DAS response to seismometer response. Martins et al. (2019) and Zhu et al. (2019) describe DAS as a dense array of seismometers where a several kilometer-long fiber optic cable, yields seismometer response every

few meters (determined by channel length). Parker et al. (2018) used DAS and nodal seismometers to perform P-wave velocity tomography. Parker et al. (2018) found that seismometers outperformed the DAS system by providing a higher SNR and wider range of frequencies, but that DAS provided more point data. Lindsey et al. (2020) found that DAS response is comparable to a high-quality broadband seismometer, sensing the same broadband frequencies as seismometer. Lindsey et al. (2020) compares DAS response to micro-seismic events to seismometer response, as shown in Figure 2.11.

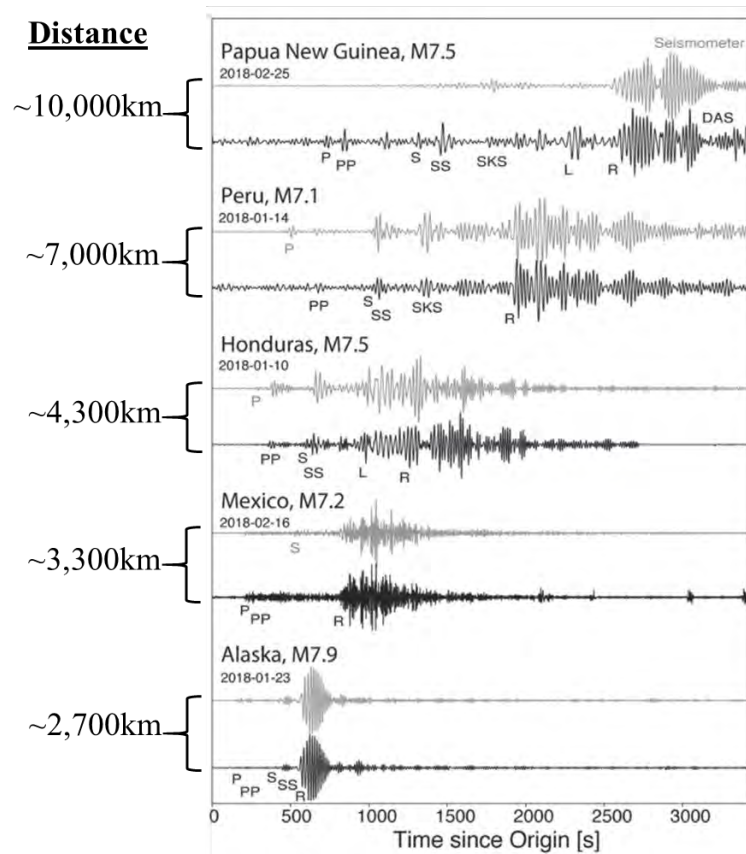


FIGURE 2.11: DAS versus seismometers (via Lindsey et al. 2020).

With confidence in DAS's use to detect seismic events, there is developing research using existing fiber optic cable infrastructure (i.e. dark fiber) to look at ambient noise and potentially pick up earthquake induced seismic activity (Jousset et al. 2018, Martin et al. 2018, Ajo-Franklin et al. 2019 and Yu et al. 2019). Note that the configuration of DAS channel lengths must be selected based on the seismic wavelength of interest (Dean et al., 2017, Lindsey et al. 2017, Martin et al., 2018, Lindsey et al. 2020).

2.4 Civil Engineering Applications of DAS

Due to its discrete, malleable, and distributed nature, DAS has clear applications as a structural health monitoring tool. Common instrumentation, such as strain gauges and piezometers, provides monitoring data for one point in space, whereas DFOS provides monitoring capabilities along the entire length of the fiber optic cable. Researchers (Soga et al. 2008, Bao and Chen 2011, Luo et al. 2016, Luo et al. 2019) are using DFOS to monitor strain in various types of infrastructure. Civil engineering applications of DFOS currently include continuous monitoring of bridges, dams, pipelines, piles, mines, and security (Luo et al. 2016, Soga and Luo 2018, Jousset et al. 2018, Li et al. 2018, Luo et al. 2019). This dissertation focuses on DAS, but if the reader wishes to learn more about other DFOS such as DTS and DSS (Brillouin optical time domain reflectometry or BOTDR), please see Soga and Luo (2018) and Soga et al. (2015) for excellent overviews.

2.4.1 Soil, Slope, and Seismic Monitoring with AE

DAS is one of the technologies under consideration for Acoustic emission (AE) monitoring. The idea behind AE is a form of change detection, such that changes in the AE of a structure relate to changes in its condition. There is ongoing research to link measured AE with strength and deformation behavior of soil (Smith and Dixon 2018). Researchers Heather-Smith et al. (2018), Smith et al. (2017a), and Smith and Dixon (2018) used AE to study wave propagation and attenuation of Rayleigh waves in laboratory samples of soil. Figure 2.12 (from Smith and Dixon 2018) shows that AE is suspected to (a) increase with loading and unloading and (b) increase with increasing displacement. The variables affecting AE and attenuation in soil include the soil density/Young's modulus, Poisson's ratio, subsurface environment, and the above-ground environment.

While there are currently ongoing studies using DFOS to evaluate slope stability (Wang et al. 2019, Zhu et al. 2014, Picarelli et al. 2015), AE monitoring has been shown to be a potential metric used to monitor slope stability (Tanimoto and Tanaka 1986, Smith et al. 2014, Dixon et al. 2015, Smith et al. 2017b, Dixon et al. 2018). DAS could be used to monitor AE within geotechnical infrastructure, as it could be placed within foundation materials or embankments.

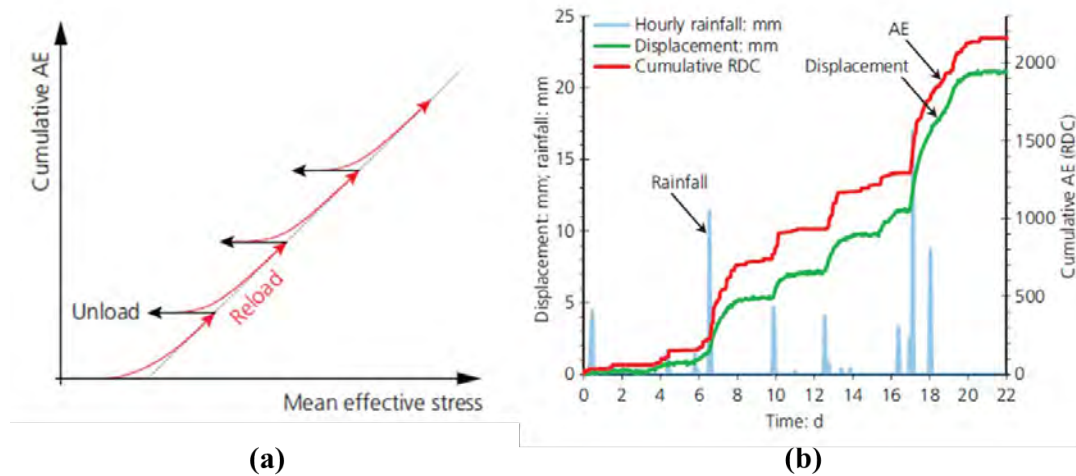


FIGURE 2.12: AE with stress and displacement (Smith and Dixon, 2018)

2.4.2 Fluid Flow Monitoring

The oil and gas industry has been using DAS to continuously monitor for pipeline leaks (Shukla et al. 2020). Researchers have applied DAS monitoring of pipeline leaks to monitor fluid flow through conduits. Johannessen et al. (2012) used DAS in wells to evaluate AE along a well and correlated changes in monitored AE with changes in fluid flow. Paleja et al. (2015) used DAS identified velocity changes that could indicate fluid leaks in pipelines. Shukla et al. (2020) explores the effect soil backfill has on pipeline AE monitoring used for leak detection. Figure 2.13 shows the effect that burying and compacting soil around the pipe has on the measured power spectra density. It appears that soil (whether it is compacted) around suppresses the pipeline AE response.

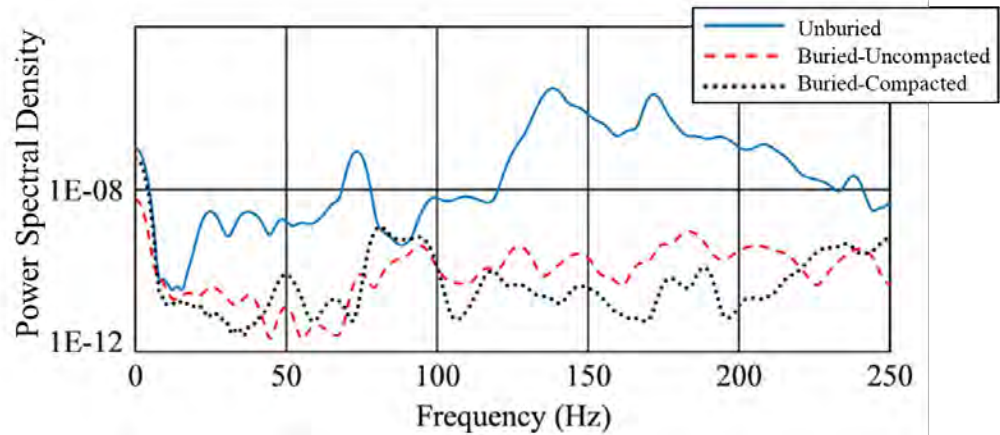


FIGURE 2.13: Effect burial and compaction has on DAS power spectral density (Shukla et al. 2020)

Researchers are beginning to look at using DAS to monitor seepage in dams and levees. Shukla et al. (2020) indicates that DAS through an earth embankment would be sensitive to changes in fluid flow velocities. Miller et al. (2018) discusses co-locating DAS and DTS cables in to evaluate environment processes and fluid flow.

2.4.3 Geotechnical Subsurface Investigations

As discussed in Section 2.3, DAS can be used to estimate soil velocities and thereby supplementing geotechnical subsurface investigations. DAS has been used by researchers to estimate in-situ wave velocities to estimate stiffness. Researcher are using DAS to perform Spectral Analysis of Surface Waves (often referred to as SASW) and MASW (Stokoe et al. 1994, Athanasopoulos et al. 2000, Yang 2005) to interpret subsurface stratigraphy. Duo et al. (2017) uses traffic as the active source for MASW collected by dark fiber buried along roadways to estimate the shear wave velocity in the upper 30 m of soil (termed VS30). Alsabhan et al. (2019) is using a

similar technique with trains as the active source to monitor railway ballast and subgrade.

The discrete nature of a fiber optic cable that makes the sensor simple to deploy on pipelines and in wells also makes DAS relatively easy to install just below the ground surface as a security monitoring system. Vibrations induced by activity near the installed DAS induce submicroscopic changes in the fiber length, core refractive index, and core diameters (Liu et al. 2016). DAS can be trained to identify an activity of interest (Madsen et al. 2008, Wu et al. 2015, and Friedli et al. 2019). Figure 2.14 provides an example of a digging signature recorded by DAS as presented in Parker et al. 2014.

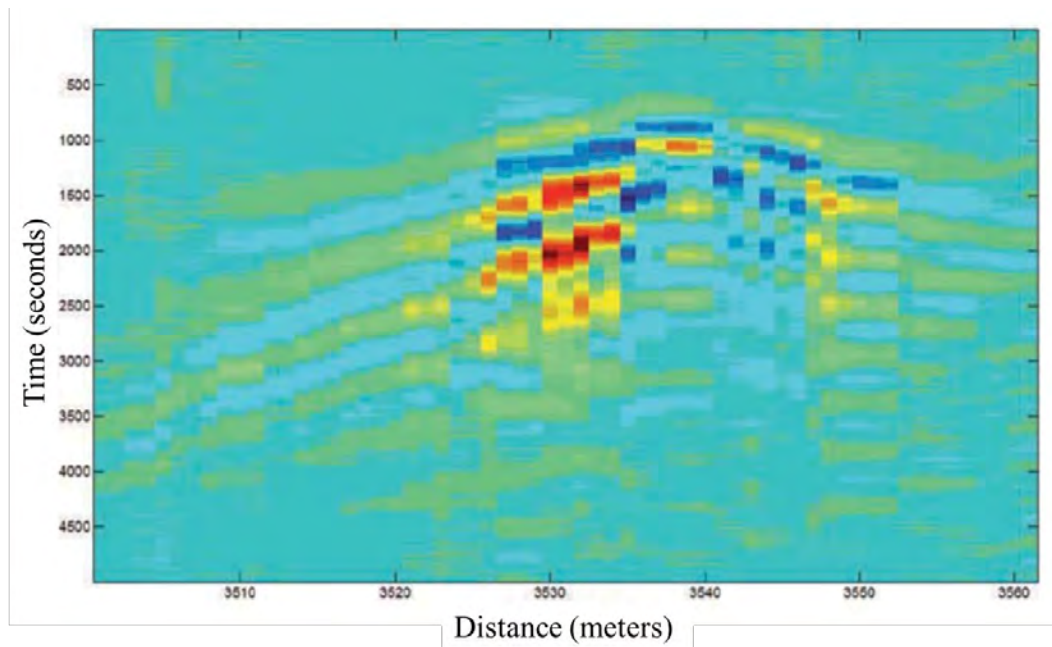


FIGURE 2.14: Example of DAS responding to digging (Parker et al. 2014)

2.5 DAS, Geotechnical Engineering, and the Future

DAS can be efficiently installed for both short term and long-term monitoring programs. The spatial resolution of DAS can help civil engineers understand infrastructure in a way previously not possible. DAS installed during infrastructure construction could help us truly understand infrastructure performance and aging, as well as inform design and maintenance (Soga et al. 2015). Soga and Luo (2018) urge engineering field demonstrations to build confidence in DFOS within the civil engineering community.

While there are many “pros” to using DAS technology for monitoring, one “con” is that DAS response is presently unquantified (Soga and Luo 2018, Lindsey et al. 2020), meaning that the amplitude of the response signal does not precisely correlate to a unit of measurement. However, DAS response is proportional to the actual vibrational strain. While it is possible to evaluate the quantifiable response for one particular DAS channel, the strain measurement will be site specific, channel specific, cable specific, and source specific (Lindsey et al. 2020). Co-locating DAS with another instrument such as a seismometer or geophone could ease engineering concerns about accuracy and precision, allowing the vibration signature to be calibrated by the local point sensor.

While DAS predominantly measures the dynamic strain field acting on a fiber optic cable, changes in temperature could cause the index of refraction in the fiber optic cable core or a slight change fiber optic length, which could noticeably affect the DAS response. Most studies do not consider the effect of temperature changes, as many of the studies herein observe a short-term event on which the timescale cause

seasonal change to be irrelevant (Lindsey et al 2020). The effect of temperature change is one of the variables possibly affecting DAS response considered in this dissertation.

While DAS is sometimes fixed to a well or a pipeline, many of the DAS systems used for research or proposed for future research are shallowly installed parallel to the ground surface. Lindsey et al. (2020) discussed how horizontally buried fiber optic cables will have the same coupling issues (if not more) than vertical installs. The strain transfer from the soil to the cable cladding to the fiber core, the amount of contact between the cable and the surrounding soil, age of installation, trench depth, and drained versus undrained soil conditions will affect DAS performance. Lindsey et al. (2020) states, “more work is required to understand these potential impacts, which... (will likely) vary within each DAS array.”

When DAS is used down-hole, in mines, or on rails, it is fixed to a rigid structure. Fiber optic cables cannot be fixed to soil rigidly making cable to soil coupling an open area of research. Zhang et al. (2016) stated that joining “cables to soil remains one of the major barriers to successful use of distributed fiber optic sensing with regards to strain and vibrations.” Zhang et al. (2016) recognized that everything that affects the medium surrounding the fiber optic cable affects the fiber optic sensor response too. External changes such as seasonal water fluctuations and rainfall infiltration will likely affect the cable to soil interaction, which could affect the overall performance of a DAS array.

Several researchers attempt to study cable to soil interaction with pull-out tests, if changes in pull-out resistance correlate to the bond between soil and cable (Iten 2011,

Zhang et al. 2016, and Winters et al. 2020). Zhang et al. (2014), Zhang et al. (2015), and Zhu et al. (2015) studied the relationship between overburden pressure and cable to soil interaction. These studies indicate that the cable to soil coupling varies with overburden pressure, soil density, and soil water content. They observed that a high effective stress (high overburden and low water content) and high-density soil samples yield an increased pull-out resistance inferring a tighter cable to soil extending sensitivity range. Zhang et al. (2014), Zhang et al. (2015), and Zhu et al. (2015) discuss that changes in water content and density would affect physical and mechanical properties of soils and thus effect DAS response.

This dissertation investigates DAS performance in different soil materials through seasonal water content and temperature, under different overburden pressure, and over time. As discussed in Chapter 3, a new DAS test bed was installed adjacent to an existing DAS array to observe the effects of soil moisture and temperature changes on a new DAS installation and an aged DAS installation. A temporary DAS array installed to observe DAS performance through loading and unloading above the array. These experiments were designed to test the dissertation objectives mentioned in Section 1.3.

CHAPTER 3

METHODOLOGY

DAS is used monitor vibration response along fiber optic cable lengths. For this dissertation, DAS response is observed over time in different soil types with varying soil moisture and temperature and with additional overburden pressure. Two test beds were constructed to study the effects of these variables on DAS performance. The first was a permanent test bed designed to consider the effect of soil type, soil moisture, soil temperature, and time in-situ on DAS response. A second temporary test bed was constructed to test effects of loading on DAS response. The permanent test bed will be discussed first in this chapter.

3.1 Permanent DAS Test Bed

A permanent DAS test bed was constructed by splicing a new portion of fiber optic cable into an existing portion of DAS array installed a decade prior (referred to as the “prior installation” or the “legacy” fiber). The test bed is in a relatively urban area and adjacent to a wetland. The upper meter of soil is a random urban fill consisting of brown silty sand with gravel and some cobbles and some debris. Below the fill is one to two meters of glacial till underlain by bedrock. Groundwater is observed at a depth between two and three feet below the ground surface. The ground surface of the test site is relatively level.

3.1.1 Design Considerations and Layout

The area available for the new portion of DAS test bed limited the fiber optic cable layout options. The 10-meter channel spacing also limited the design options as it was desired to have at least three DAS channels in each soil type for redundancy. The new portion of fiber optic cable used was the same fiber optic cable as that of the existing DAS array (i.e. came from the same spool of original cable). The fiber optic cable in this DAS array is a single mode fiber with a water-proof buffer tube, armor, and a polyethylene jacket. The test bed layout (Figure 3.1) maximizes our ability to compare DAS response in different soil types, while allowing the comparison between new and existing portions of array in native material.

The materials to be tested include the native fill material, a sand fill (well graded sand), an angular gravel fill, and excavatable flowable fill. A long portion of new native fill trench parallel the existing DAS array allowed for the comparison of multiple DAS channel responses. The native fill trench was excavated to a depth of two feet (about 0.5 meters) below the ground surface and the fiber optic cable was laid at the bottom of the trench two-feet-deep (0.5-meters-deep). Portions of the array in non-native material types (excavatable flowable fill, sand, and gravel) were excavated to a depth of three feet (about one meter) such that one foot of non-native fill material would be placed below the fiber optic cable and two feet of non-native fill placed above the fiber optic cable. All trenches are two-feet-wide (about 0.5-meters-wide). The fiber optic cable was placed down the trench centerline and surveyed. Figure 3.2 provides the trench dimensions in plan and profile views.

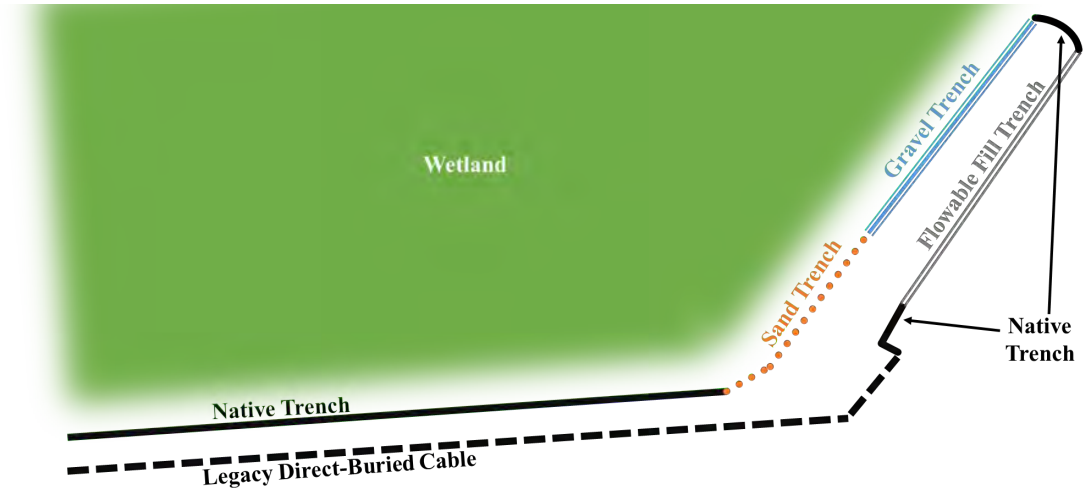


FIGURE 3.1: Rhode Island Test Bed Layout

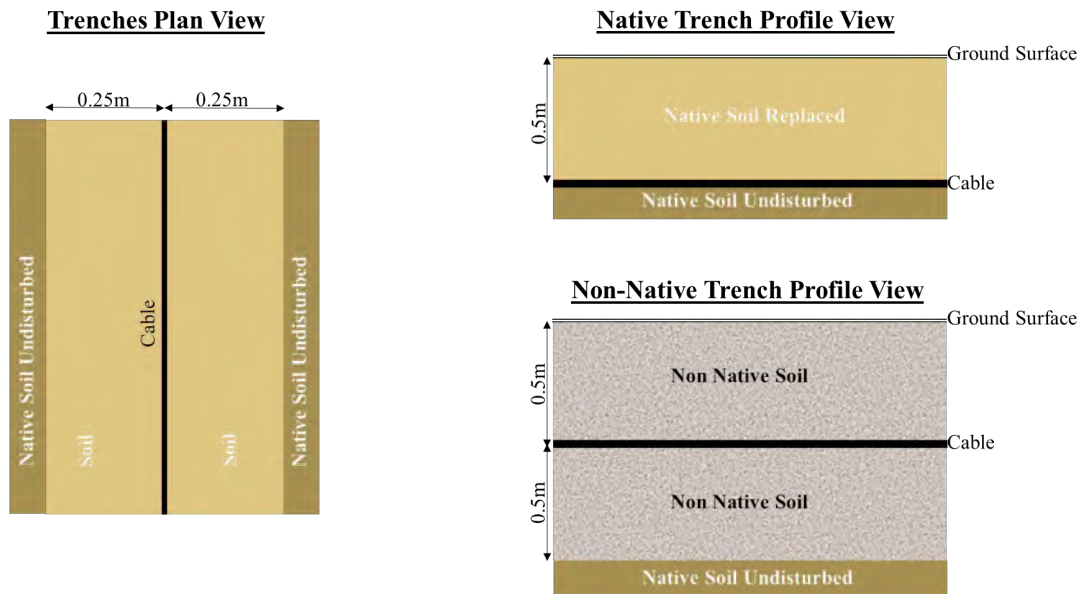


FIGURE 3.2: Trench Dimensions

3.1.2 Test Bed Installation

The new portion of test bed was constructed in August 2019. Native fill was excavated to create one long trench (the length of the entire new portion of DAS array), and the native material was stockpiled onsite to be used as backfill for native fill trenches. Cobbles and debris were removed from the native fill stockpile before being placed and compacted above the placed fiber optic cable in native fill portions of the test bed. Figure 3.3 shows the excavated trench prior to flowable fill placement. Note ground water seepage up from the bottom of the trench. The flowable fill provided for this effort was defined in Rhode Island Department of Transportation (RIDOT) Bluebook Section 603 as a Class I excavatable flowable fill. Excavatable flowable fill is classified as a controlled low strength material that self-consolidates, levels, and stiffens. The sand fill is an ASTM C33 sand, which is a well graded sand. The gravel fill is defined as “keystone” in the RIDOT Bluebook Section M.01.09 Table 1 Column III where most of the stone is between ½ inch and one inch in size.

The sand fill was compacted with a vibratory plate compactor. The gravel was tamped with the excavator bucket, and the flowable fill was poured from one concrete truck. Once the flowable fill cured overnight (and was firm enough to stand on), the new portion of fiber optic cable was placed along the centerline of the flowable fill trench, and a few days later, a concrete truck delivered the second lift of flowable fill. Figure 3.4 shows the transition between sand and gravel soil types in the trench. Figure 3.5 shows the new portion of fiber optic cable placed along the centerline of the sand trench.



FIGURE 3.3: Complete excavated trench for flowable fill



FIGURE 3.4: Transition between gravel and sand in-trench



FIGURE 3.5: Fiber optic cable along the centerline of the sand trench.

A nuclear density gauge (NDG) with a 10-inch probe depth was used to measure the in-situ density and water content at the bottom of each excavated trench, and in each sand and native material layer once compacted per ASTM D6938. The nuclear density gauge values were compared to the optimum density calculated via the Modified Proctor, Method B (ASTM D1557). Table 3.1 provides values of optimum water content and maximum dry density, the in-situ NDG measured water content and dry density, the calculated total unit weight, and the percent compaction. For the flowable fill, four 4-inch by 8-inch cylinders were collected and the seven-day compressive strength of the cylinders ranged from 50 to 60psi.

Table 3.1: Soil water content and dry density

Soil	Avg measured dry unit weight (pcf)	Avg. measured water content (%)	Cal. total unit weight (pcf)	Max dry density (pcf)	Opt. water content (%)	Percent Compac tion (%)
Native material along trench bottom	99.4	25	124	132.5	7.5	75
Native material placed and compacted above the cable	106	15	122	132.5	7.5	80
Sand placed and compacted below the cable	107	2	110	114.5	13.6	94
Sand placed and compacted above the cable	108	3	110	114.5	13.6	95

3.1.3 Moisture and temperature sensors

Moisture and Temperature sensors were installed adjacent to the new portion of fiber optic cable for continuous monitoring of the in-situ soil temperature and moisture throughout this research. Campbell Scientific (CS) 650 volumetric moisture sensors were installed (as shown in Figure 3.6). A CS 650 was installed in each soil type, as shown in Figure 3.7, to continuously monitor soil moisture and temperature over time. Note that no CS 650 sensor was installed in the flowable fill; this choice was based on a previous test install where the CS 650 did not function correctly in flowable fill material. The CS 650 sensors were placed parallel-to, but not touching the fiber optic cable with the power and data transmitting cable placed along the edge of the trench.

The CS 650 sensors were set to take recordings every 15 minutes and save datalogger SD. The recorded data is manually retrieved form the data logger as needed.



FIGURE 3.6: Placement of CS650 sensors relative to the fiber optic cable

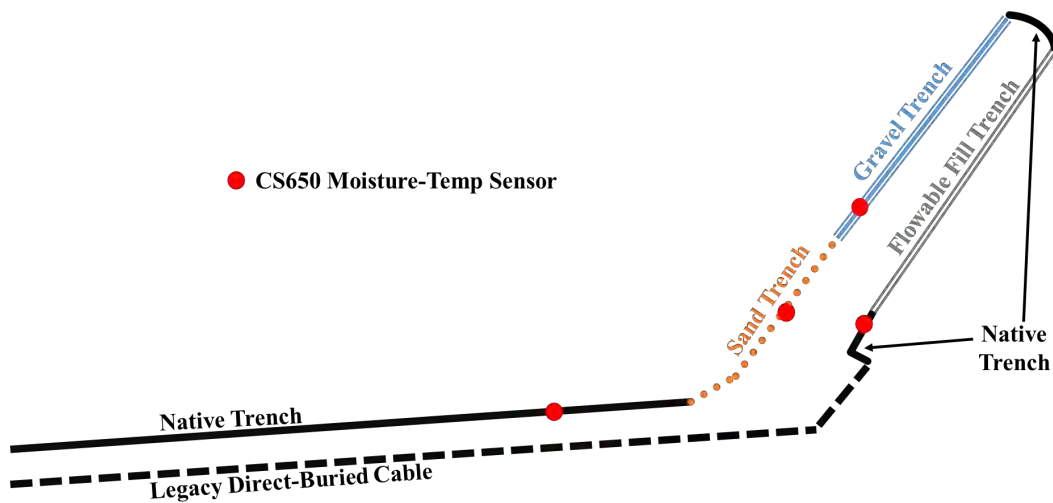


FIGURE 3.7: Location of the CS650 sensors in the test bed

3.1.4 Impact testing and data recording

To evaluate DAS performance, a calibrated, repeatable impact source was used. A standard proctor hammer, used for geotechnical compaction control, was selected as the impact source. A standard proctor hammer is a 2.5kg weight with a set drop-height of 305mm. This source was selected as it is calibrated, does not require power, and is easy to travel, making it a uniform way to compare DAS response at any other DAS array. The impact was delivered to the ground surface by placing the standard proctor hammer on an aluminum plate, lifting the hammer head to the top of the confined hammer and releasing the hammer handle such that the hammer strikes the plate, delivering a repeatable amount of energy to ground surface (see Figure 3.8).



FIGURE 3.8: Impact source: standard proctor hammer and aluminum plate

Impact hammer source locations were established during the construction of the DAS test bed. The source locations (shown in Figure 3.9) were selected to generate DAS responses in comparable section of new and existing portions of the array, portions of the array in different soil types, and in line with portions of the array. The standard operating procedure for the test was to begin at Location A and work towards Location H and to deliver ten impacts at each location. The source locations were marked physically and measured for repeatability with each data collect.

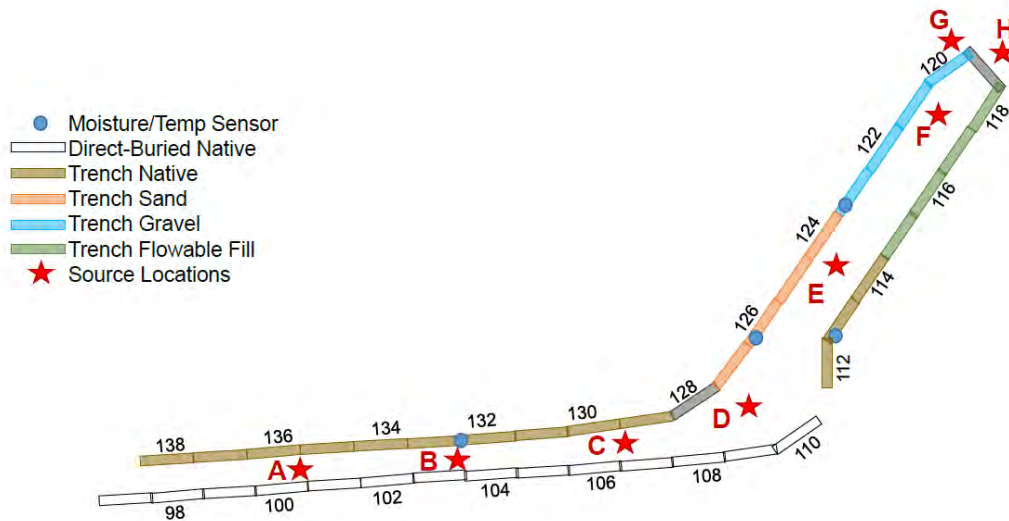


FIGURE 3.9: Location of hammer testing sequence relative to the test bed

The new portion of the DAS array was spliced into the existing array while the fiber optic cable along the trench centerline remained uncovered, and open to the atmosphere. This allowed our first data collect of the entire testing sequence (Locations A through H) to occur on an uncovered array. Impact testing was performed continued throughout construction and then on a bi-weekly to monthly basis. Additionally, impact testing was performed to capture significant changes in temperature, moisture, or weather (e.g. before and after storms). The DAS interrogator

used for this field effort is a conventional OTDR settings of 10-meters-long channels and a sampling rate of 2500Hz.

3.1.5 Channel mapping

A channel map was developed by repeatedly overlaying the known test bed layout, with the known source locations, and the DAS array response. Data sets were processed using MATLAB. Figure 3.10 shows how the DAS array responds to the testing sequence shown in Figure 3.9.

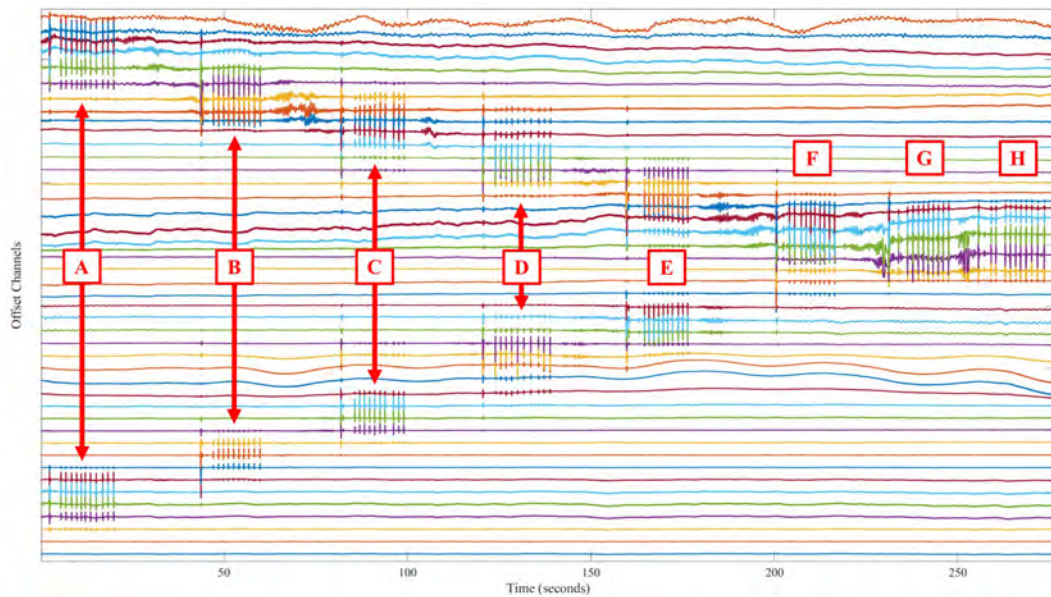


FIGURE 3.10: DAS response to entire testing sequence where channel 95 is on the bottom and channel 138 is at the top

Once several data sets were reviewed, a DAS array channel map was generated and validated. Figure 3.9 presents the validated channel map for this DAS array, i.e. where the channels are located along the array length. Further discussion on the

analysis of the data and results are presented in Chapters 4 and Chapter 5 of this dissertation.

3.2 Temporary DAS test bed

To test the effects of loading on DAS performance, a temporary DAS test bed was constructed at the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH on March 5, 2020. A bed of dry silty material was placed on top of dense, frozen earthen roadway material. The silt bed dimensions were approximately 2.5 meters-wide by 16 meters-long. Fiber optic cable was laid on top of the silt bedding in switch backs such that at least ten DAS channels would be well within the test bed. Impact testing was performed in line with the array channels prior to additional silt material being placed on top of the fiber optic cable. Figure 3.11 illustrates the CRREL test bed layout and location of the impact testing. Figure 3.12 shows a photograph of the impact testing. The impact tests were performed with a modified proctor hammer.

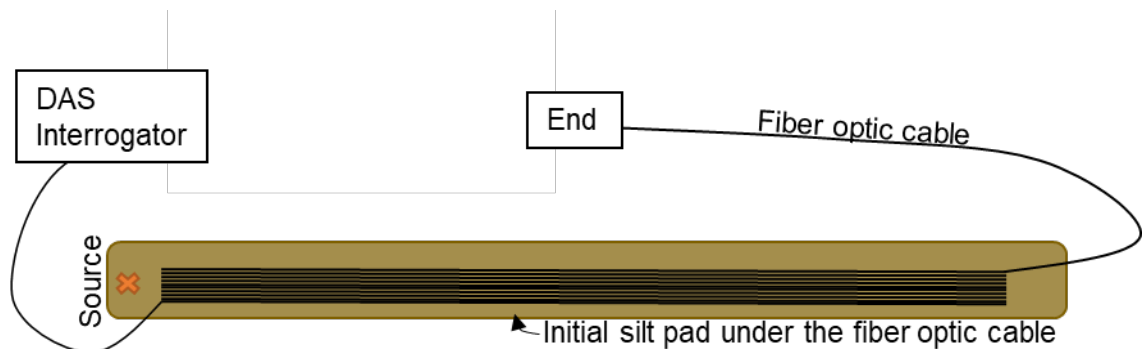


FIGURE 3.11: CRREL DAS array layout



FIGURE 3.12: Impact testing at CRREL test bed

Once the fiber optic cable was embedded within the silt material, another set of impact testing was performed to establish the performance upon initial cable to soil coupling. With data collection for initial coupling complete, load testing was begun. To efficiently test the effect of loading and unloading on the DAS array performance with available time and materials, it was decided to use vehicles of increasing weight as the means of applying load to the array. To measure the load imparted to the array, calibrated vehicle load cell pads (shown in Figure 3.13) were placed on the silt material above where the DAS array was located, and a wooden ramp was placed over the silt material allowing vehicles to carefully drive up on top the load cells without destroying the test bed. Figure 3.14 shows the layout of the array with the location of the load cells and wooden ramp.



FIGURE 3.13: Load cells used for vehicle load testing (Longacre ® Accuset II)

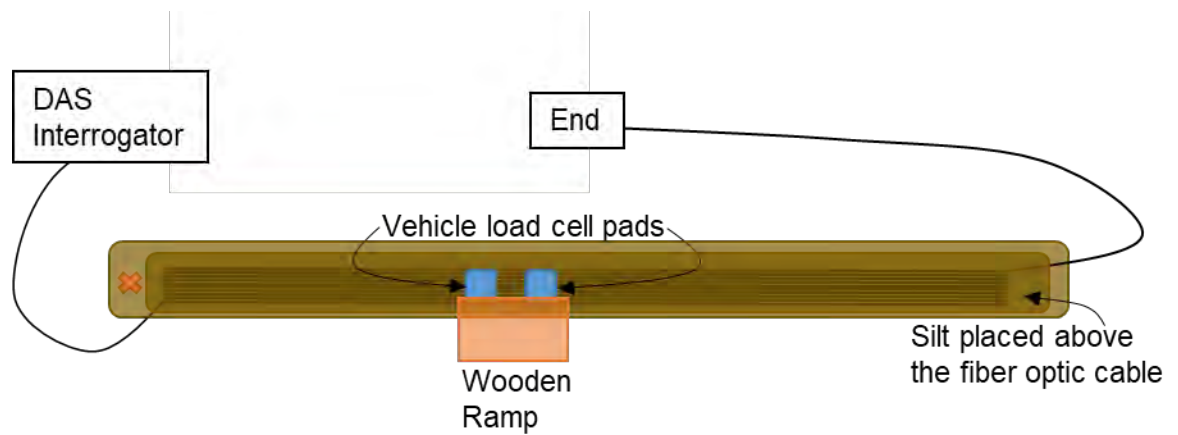


FIGURE 3.14: Experimental layout

Vehicles carefully drove up on to the load cells, beginning with the lightest vehicle. The resulting load, as displayed on the load cells, was recorded and impact

testing was performed. The vehicles were turned off during all impact testing so as not to add to the noise observed in the DAS array. Vehicles carefully backed off the load cells and impact testing was performed on the unloaded array. Table 3.1 presented the loading progression from no-coupling (A) through to maximum loading (K) while the fiber optic cable was still intact. The Surcharge presented in this table was calculated by taken the load read on the load cell (in pounds) and dividing it by one square foot (the surface area of the load cell)., and then converting the pressure from pounds per square foot to kilopascals. All vehicles were relatively balanced, such that both load cells read similar loadings. Figure 3.15 provides a photograph of one of the vehicles associated with loading C stationed on top of the load cells. Results and discussion of the data collected at this temporary test bed are presented in chapter 5 of this dissertation. Figure 3.16 shows which vehicles are associated with each surcharge shown in Table 3.1.

Table 3.1: CRREL test bed experiment loading sequence

Surcharge Order	Surcharge on DAS array
A	No coupling
B	Initial Coupling
C	45kPa
D	Unload after 45kPa
E	57kPa
F	Unload after 57kPa
G	68kPa
H	Unload after 68 kPa
I	115kPa
J	Unload after 115 kPa
K	180kPa



FIGURE 3.15: Vehicle for loading C on load cells



FIGURE 3.16: Vehicles associated with the surcharge (note: the F800 image source is purplewave.com). The F800 used in this study looked like that pictured.

3.3 Data Processing

The performance of the DAS array was evaluated based on the detectability of signals (vibration signature due to hammer impact events) above the ambient noise level. Hence Signal-to-Noise Ratio (SNR) was used as the performance criteria selected to monitor and evaluate DAS performance. Figures 3.17A, 3.17B, and 3.17C show the typical response observed in Channel 123 (location near source E shown on Figure 3.9) due to one hammer impact event. Note that the DAS response amplitude has been normalized such that the maximum value is unity. The signal response from the DAS is presently unquantified (Soga and Luo 2018, Lindsey et al. 2020), meaning the amplitude of the response signal does not precisely correlate to a strain measurement and is unique to each section of DAS array. Subplot 3.17A shows the time series of the channel response whereas 3.17B shows the power spectral density which highlights the frequency content in the signal. Figure 3.17C is a time-frequency diagram showing the evolution of the spectral content over time. The color scale in this figure is proportional to the energy in the measured signal as a function of time and frequency (red indicating high energy and blue indicating low energy).

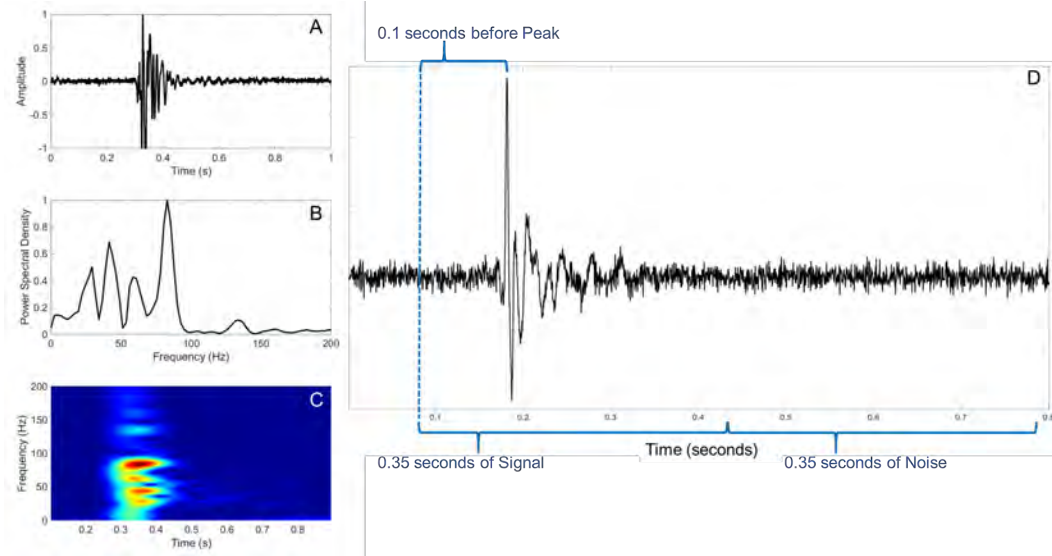


FIGURE 3.17: Typical DAS response to impact testing

SNR response corresponding to each hammer strike event was calculated for each responsive channel. 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}). The RMS value is calculated using equation for RMS is shown in Equation 8. A capture (dt) of the signal is used to calculate RMS_{signal} and the same capture (dt) of the noise immediately following the signal is used to calculate RMS_{noise} . The equation for SNR is presented in Equation 9. Figure 3.17(D) illustrates the time capture selection. Let $x[n]$ be the sampled version of the channel response $x(t)$, sampled for a duration of 0.35 s (T) at a sampling rate (F_s) of 2500 Hz. The window corresponding to the signal was measured starting from 1 second before the signal peak as shown in Figure 3.17D. The number of samples (N) in the 0.35 seconds long time segment is,

$$N = F_s \times T = 2500 \times 0.35 = 875 \text{ samples}$$

The duration of the signal (T) is also equal to,

$$T = N dt$$

The RMS value in the continuous time domain is defined as,

$$RMS = \sqrt{\frac{1}{T} \int_0^T x^2(t) dt}$$

In the discrete time, using the sampled signal $x[n]$ the RMS value can be written as,

$$RMS = \sqrt{\frac{\sum x[n]^2}{N}} \quad \text{EQ 8}$$

The SNR in logarithmic notation is defined as,

$$SNR (dB) = 20 \log_{10} \left(\frac{RMS_{signal}}{RMS_{noise}} \right) \quad \text{EQ 9}$$

Figure 3.18 illustrates what the signal-to-noise looks like on a typical test day presenting response to the ninth impact at source location E on January 2, 2020.

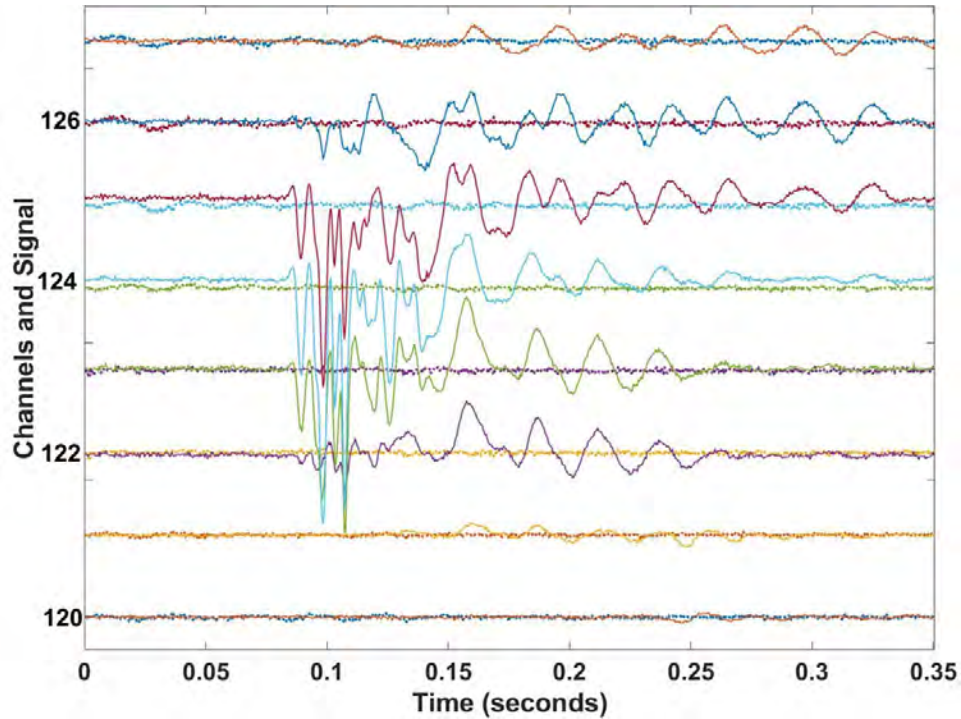


FIGURE 3.18: Signal-to-Noise visual example from January 2, 2020. Response from the ninth impact at source location E.

The ambient noise observed in the permanent test bed is generally far less than that observed at the CRREL test bed. The CRREL test bed's proximity to a variety of industrial systems elevated noise level when compared to the permanent test bed. The capture time selected for the experiments in permanent test bed was 0.35 seconds. Due to the increased ambient noise levels at the CRREL test bed obscuring the signal within the duration of the signal, the capture time was increased to 0.5 seconds to make sure the entire signal was captured.

CHAPTER 4

RESULTS AND DISCUSSION

The results of the year-long 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 are presented in this chapter. The year-long study was performed in a permanent DAS test bed. This chapter will also discuss the results from a DAS vehicle load test performed at a temporary DAS test bed at CRREL.

The results are organized according to the effects of 1) soil type and time in-situ, 2) vehicle loading, and 3) soil moisture and temperature. This chapter includes a discussion of the results.

4.1 Soil Type and Time In-situ

As described in Chapter 3, the seismic source used was a standard proctor hammer striking an aluminum plate. To evaluate the performance of the DAS array in different soil types over time, the SNR response to source locations shown in Figure 4.1 was evaluated.

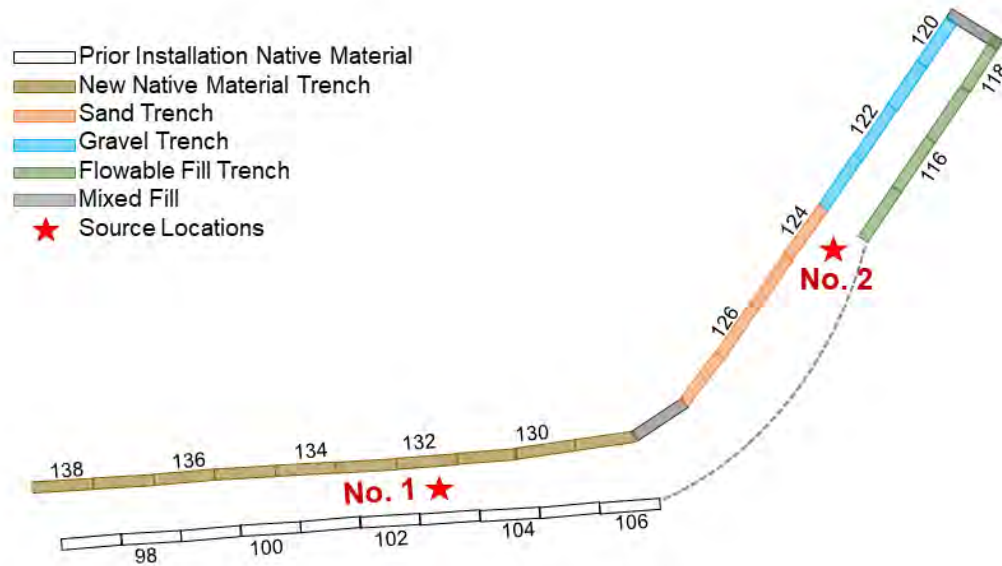


FIGURE 4.1: Source locations used to evaluate DAS performance in different soil types.

DAS performance was evaluated from August 2019 through February 2020.

Impact source location No. 1 (see Figure 4.1) is between parallel portions of the previously installed fiber optic cable and the new fiber optic cable, both in native silty sand material. Figure 4.2 shows values of SNR in the new and prior installation with distance away from impact location 1. The results in Figure 4.2 indicate that the new portion of DAS array in native material generally yields higher peak SNR for a larger range (i.e. distance from source) than that of the prior installation in native material. The response in the new installation is approximately 5 dB greater than the prior installation; however, the attenuation for both portions of the DAS array is similar (i.e. SNR with distance from source).

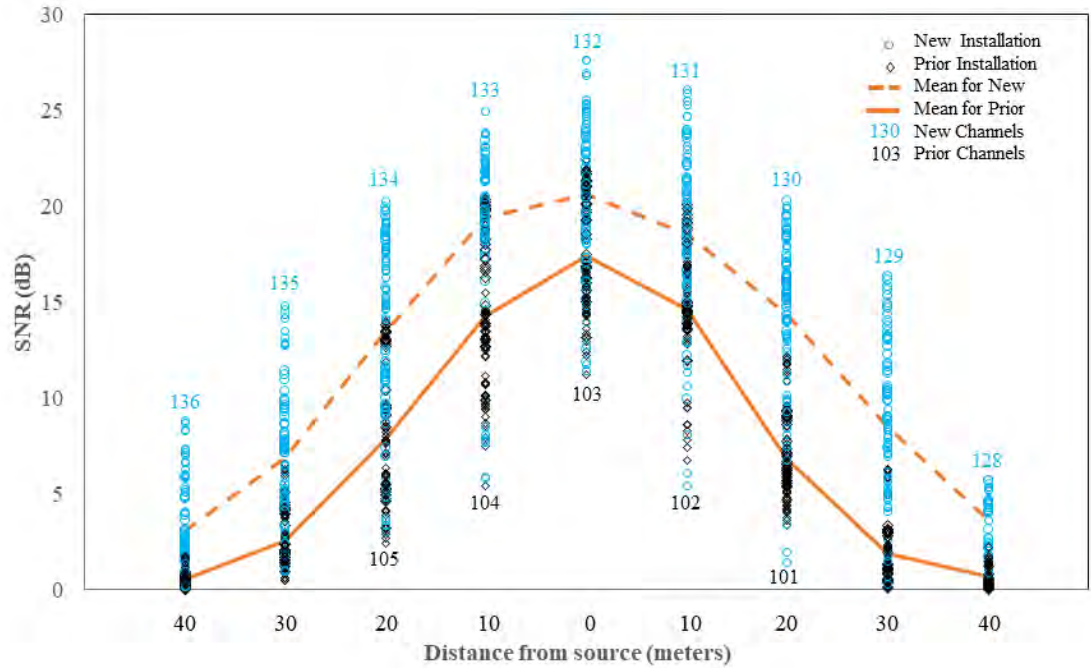


FIGURE 4.2: SNR of prior installation vs. new installation in native material

At ten years old, the prior DAS 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 installation technique.

A second impact source location (location No. 2 as shown in Figure 4.1) is between parallel portions of the DAS array in sand and gravel, and flowable fill to allow for assessment of soil type on DAS response. Figure 4.3 shows the variation of SNR with distance away from source location 2 in each soil type for measurements taken over the course of seven months. The results show that the SNR attenuates in all materials at a similar rate, but that portions of the array in sand and gravel consistently yield higher SNR (about 5dB more) than the flowable fill. The sand and gravel

perform similarly. A discussion of the role that soil stiffness and impedance may contribute to these results is presented in Section 4.4.

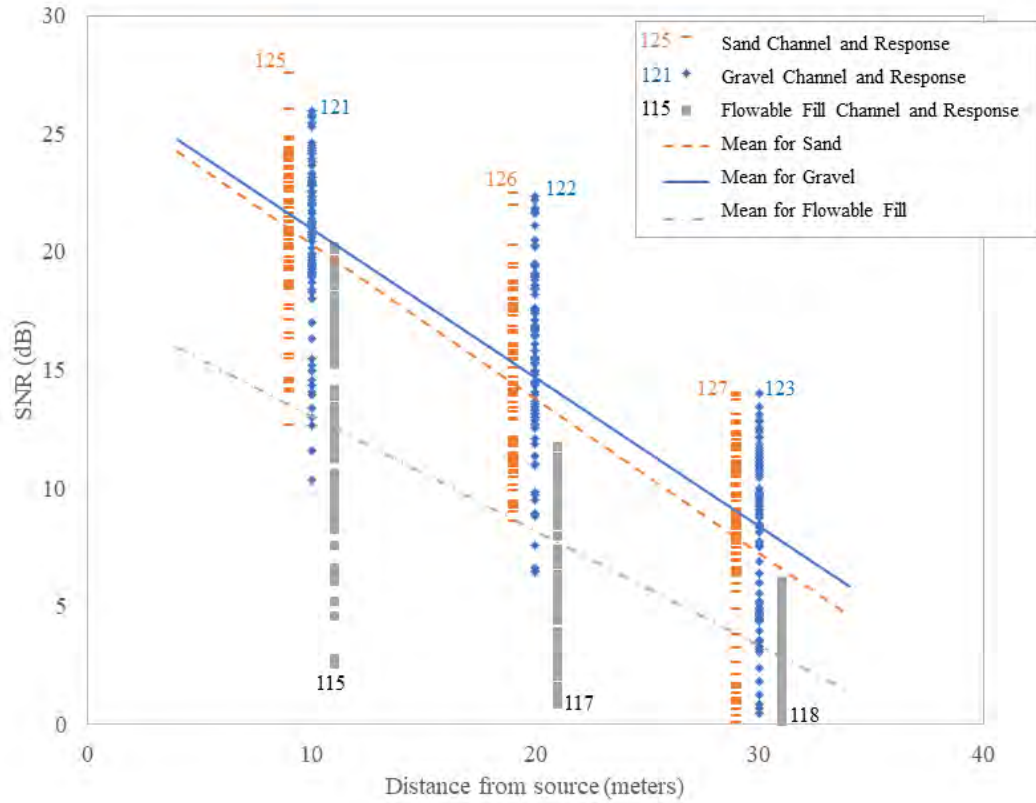


FIGURE 4.3: SNR with distance: sand, gravel, and flowable fill

As shown in Figure 4.3 over the seven months of testing, the portion of DAS array in gravel performed well suggesting that the impacts of any bending caused by coupling with the gravel are insignificant. This is of interest because during routine fiber optic cable installation for DAS use, larger pieces of gravel are removed from the installation trenches to reduce bending losses. Not having to remove gravel from trenches and/or installed fiber optic cable in gravel trenches could save time, reducing cost and opens DAS technology to more civil engineering applications.

4.2 Vehicle Loading

To evaluate the effect of ground surface loading on DAS performance, a temporary DAS test bed was constructed at CRREL. The same OTDR interrogator used at the permanent test bed was used for this temporary study. Vehicle load testing was conducted on 5 March 2020. Ten responsive channels were buried in dry silt at the CRREL test bed. The two most responsive channels in the test bed (Channel A and Channel B) were selected to follow through loading and unloading experiments. Figure 4.4 illustrates the approximate locations of the channels selected for analysis.

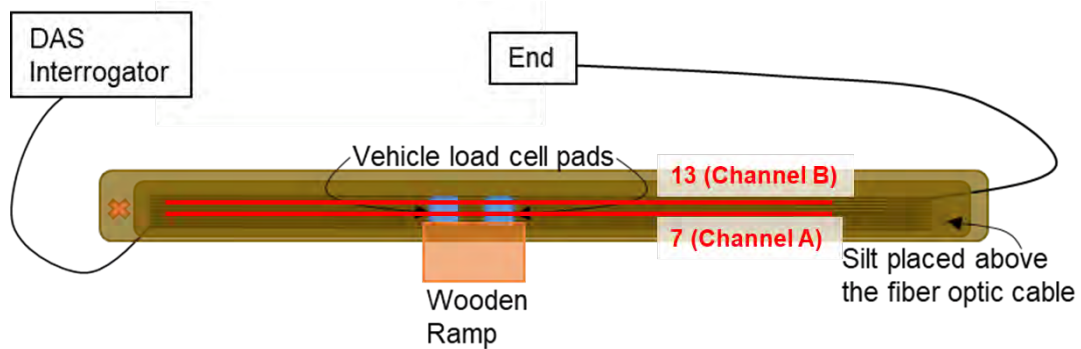


FIGURE 4.4: Approximate location of channels analysed during DAS vehicle load testing.

The CRREL vehicle load testing included data sets collected with fiber optic cable open to the atmosphere (i.e. before more dry silt was placed on top of the laid fiber optic cable, “no coupling”) and after the fiber optic cable was buried with another 15cm of silt (i.e. “coupled”). These initial tests (no coupling and coupling) were performed before the vehicle load cell pads were placed on top of the DAS array. Table 4.1 provides the surcharge loading pressures (beginning at A and progressing

through K) experienced beneath the load cell pads on the silt bedding. Figure 4.5 provides photos of loading C, loading E, and impact location.

Table 4.1: CRREL test bed experiment loading sequence

Surcharge Order	Surcharge on DAS array
A	No coupling
B	Initial Coupling
C	45kPa
D	Unload after 45kPa
E	57kPa
F	Unload after 57kPa
G	68kPa
H	Unload after 68 kPa
I	115kPa
J	Unload after 115 kPa
K	180kPa



FIGURE 4.5: Photos of loading C (A), loading E (B), and impact source location (C) with respect to the temporary DAS array.

For each loading/unloading sequence, ten impacts were performed. Both the average and range of SNR is shown in Figure 4.6.

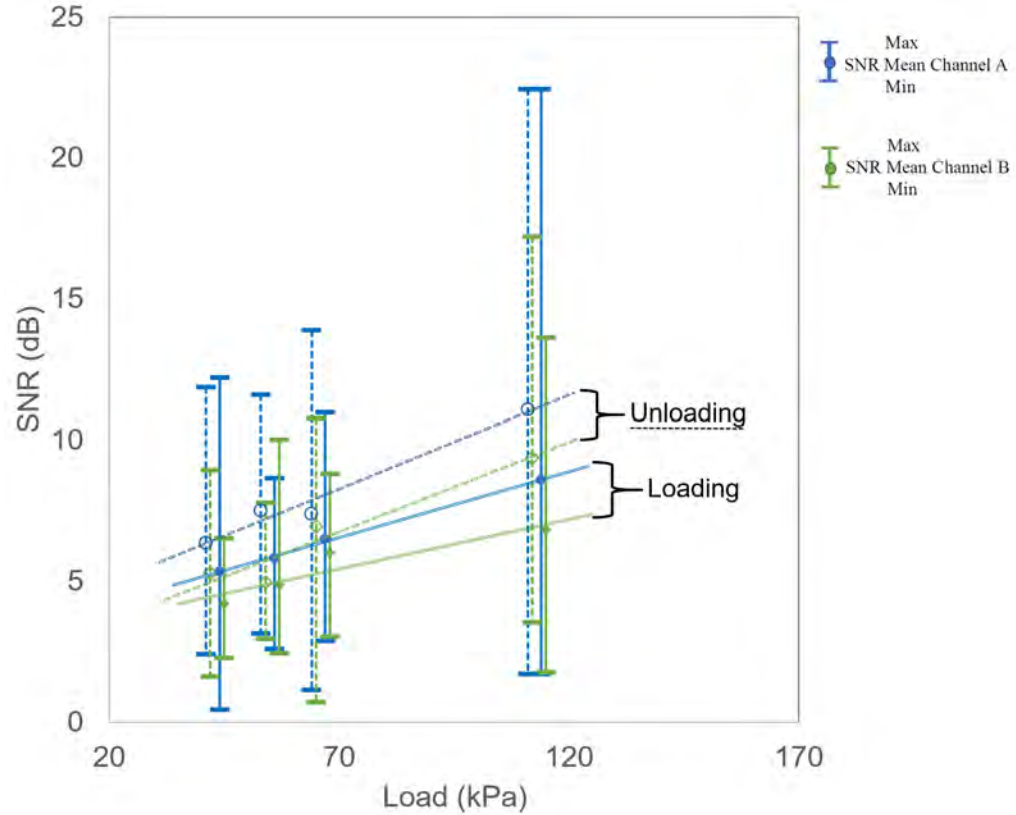


FIGURE 4.6: SNR for loading (closed circles) and unloading (open circles) during vehicle loading experiment. The error bars for loading (continuous line) and unloading (dashed line) are also shown.

The average DAS response under vehicle loading increased as the loading increased. This is consistent with the findings of Zhang et al. 2014, 2015, and Zhu et al. 2015 who that observed overburden pressure increased cable-to-soil coupling (particularly in dry soils) and suggested this would increase sensor performance. As shown in Figure 4.6, this study indicates that an increase in loading generally leads to an increase in SNR (designated by the solid-line data sets). This study also indicates that the performance level was retained during unloading (designated by the dashed-line data sets). While Figure 4.6 indicates that there may have been a slight increase in

SNR upon unloading, the variation in SNR response is too large to suggest SNR increase with unloading is true. The variation in response is likely due to the significant irregular ambient noise at the site. Figure 4.7 illustrates the magnitude of the noise at the CRREL test bed. The red dotted lines are the noise in the active CRREL test bed channel, over laying the noise and signal response at the permanent test bed. The magnitude and the fluctuation of this noise likely contributed to the variance observed in the load test data. Despite this variability, the results of this loading experiment suggest that loading the ground above where a fiber optic DAS array is located can increase array performance.

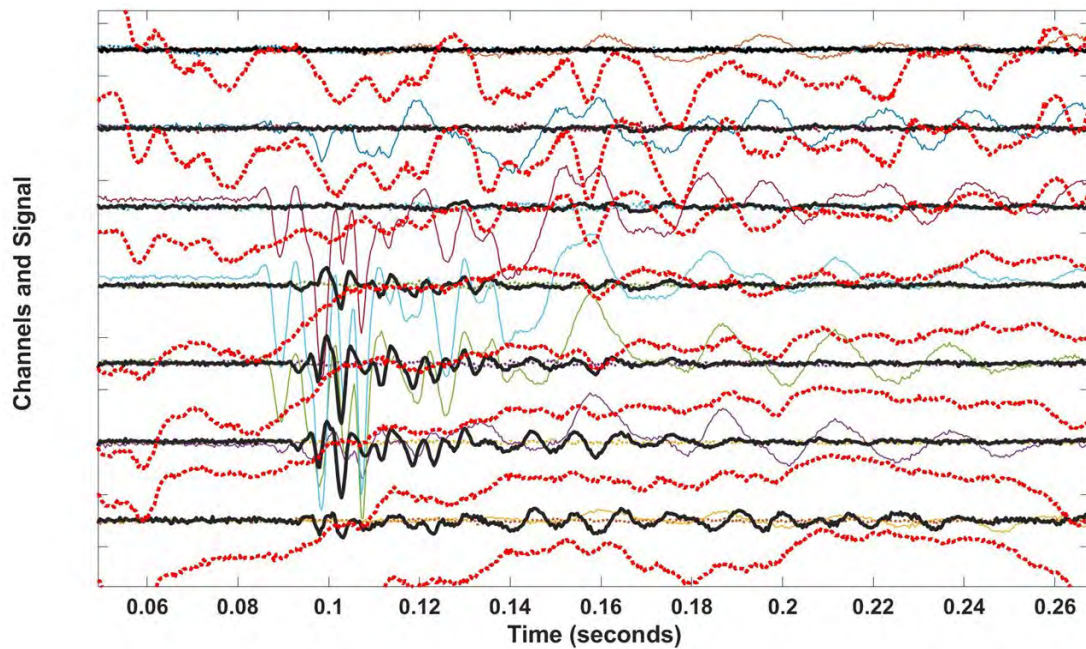


FIGURE 4.7: Noise in the CRREL test bed (red dashed lines) overlaying noise and signal from the permanent test bed to illustrate the magnitude of the ambient noise at CRREL.

4.3 Soil Moisture and Temperature

The permanent test bed was used to study the effect of seasonal environmental changes (i.e. soil temperature and soil moisture) and aging (over one year from installation) on DAS response. Soil temperature and moisture sensors (CS650) were placed in the different soil types (native silty sand, sand, and gravel). Figure 4.8 indicates where the CS650 sensors are located and which channels are evaluated for performance changes with moisture and temperature changes.

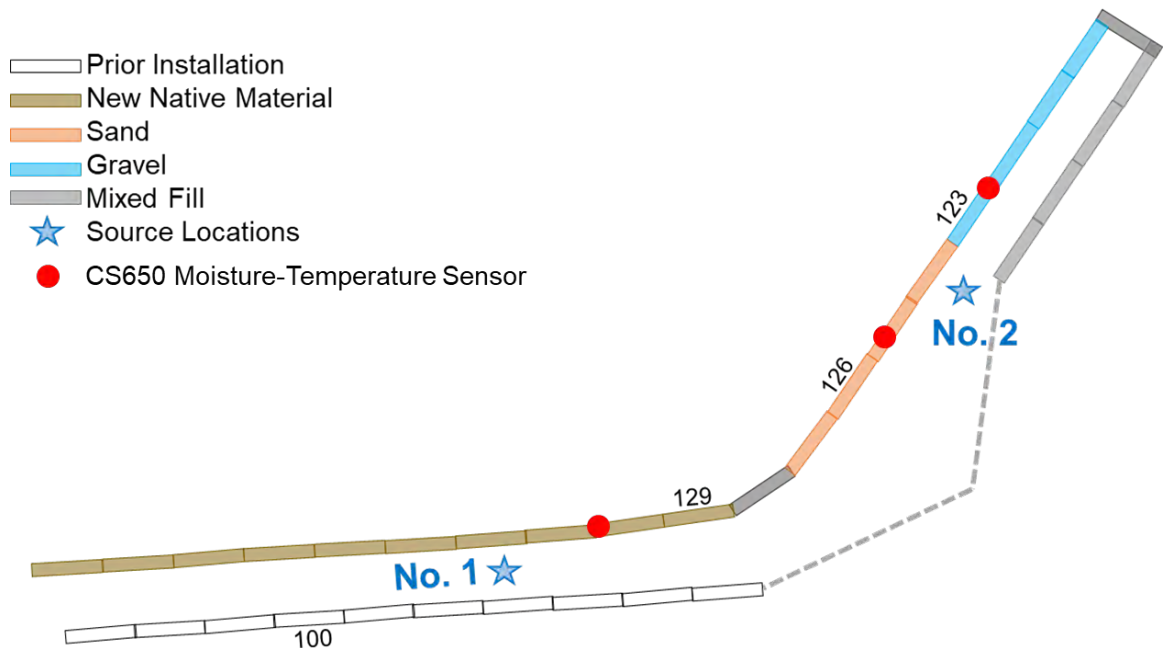


FIGURE 4.8: Permanent test bed layout with Impact and CS650 locations

Impact test responses were collected at the permanent test bed from the time of installation in August 2019 through September 2020. The SNR was calculated in the

prior installation (Channel 100), gravel (Channel 121), sand (Channel 126), and the new native material (Channel 129), as shown in Figure 4.8. The temperature and moisture content data collected from the CS650 sensors is provided in Figure 4.9. Note that volumetric water content for “gravel” is not plotted in Figure 4.9 because the CS650 in the gravel did not detect moisture. However, the CS650 sensor in gravel provides temperature data that agrees with the temperatures recorded in the CS650 sensors, installed in the other materials therefore we assume that the sensor in the gravel is functioning properly and that the gravel remained dry.

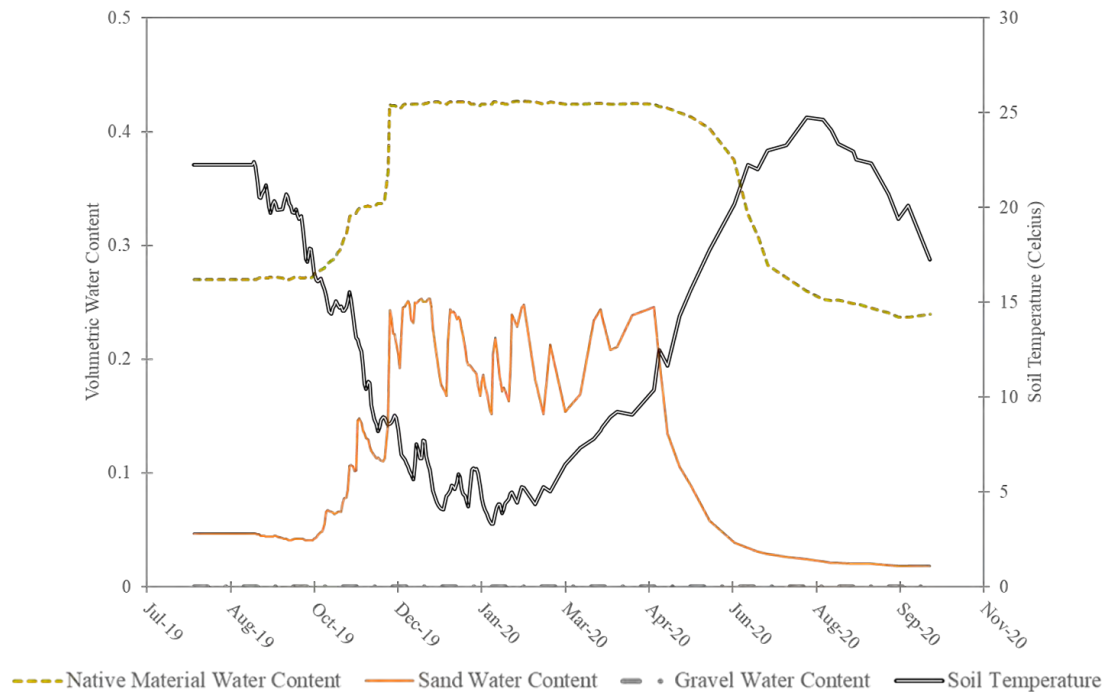


FIGURE 4.9: Permanent test bed layout with Impact and CS650 locations

The SNR results from ten impacts were averaged to calculate the mean signal to noise ratio. The variation of SNR with soil volumetric water content and soil temperature are provided in Figure 4.10 and Figure 4.11, respectively.

Figures 4.10 and 4.11 show that soil moisture and temperature do not significantly affect the SNR performance of the DAS sensor. There is a slight trend of decreasing SNR with increasing water content for all three soil types, but more data is needed to substantiate this finding. In this study soil moisture and temperature are paired data, meaning that the soil moisture and soil temperature were collected occur at the same time and cannot be independently separated or varied. Future testing may include a controlled in-situ study where one variable (e.g. soil moisture) can be held constant, while another variable (e.g. temperature) is fluctuated.

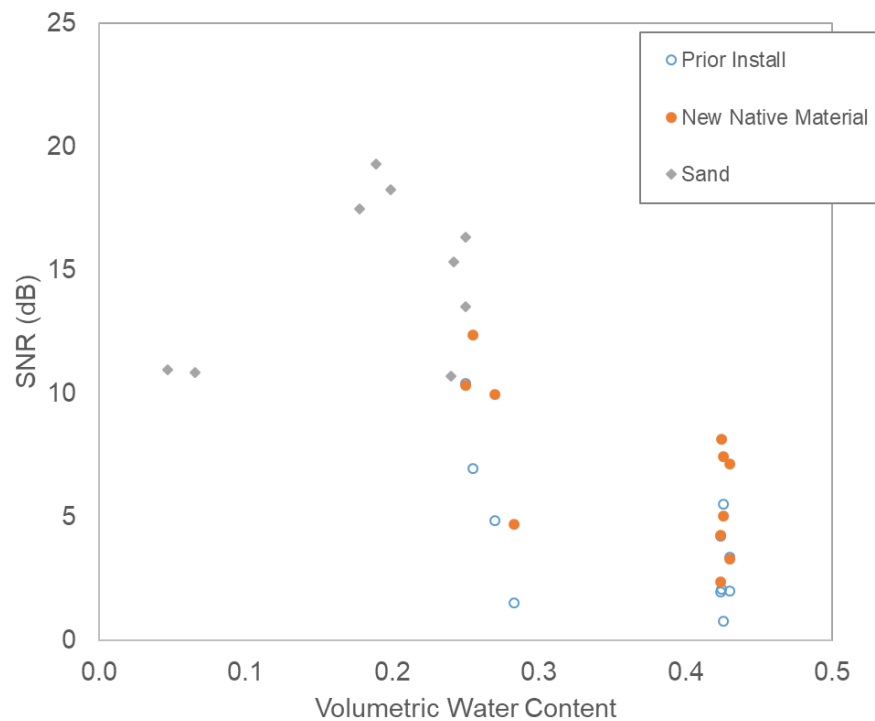


FIGURE 4.10: Variation of SNR with moisture or prior install, new native material and sand.

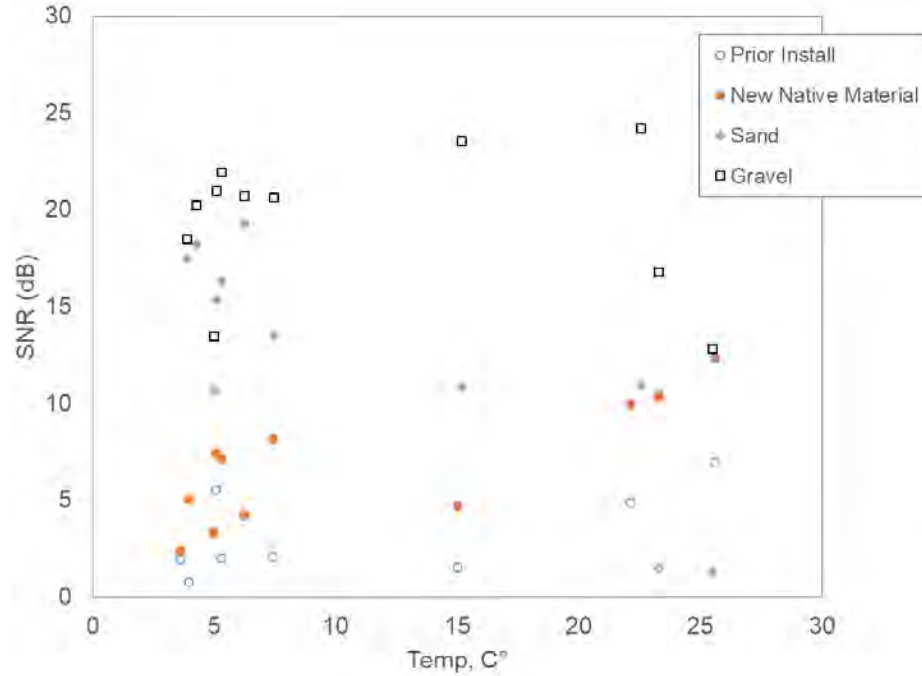


FIGURE 4.11: Variation of SNR with temperature.

While Figure 4.10 does not indicate a trend between DAS performance and soil moisture, work from Zhang et al. 2014, 2015 and Zhu et al. 2015 infers that soil water content and density affect the physical and mechanical properties of soils. Due to the gap in testing from the Covid-19 pandemic, it is possible that with more test data at different water contents, a better trend with soil water content and DAS performance would emerge.

While this research indicates soil moisture and temperature alone do not significantly affect with sensor performance, Figure 4.12 indicates that time in-situ does have an effect on performance over time. Figure 4.12 follows one channel per material (i.e. existing installation, new native material, sand, and gravel). These are the same channels used to plot results in Figures 4.10 and 4.11. It appears that both the prior and new portions of DAS array in native material maintain response levels and

seem to be performing similarly. The response in portion of the array in gravel has dropped a little after 11 months in-situ. The most significant change in observed in the response of the portion of the array in the sand. Unfortunately, no DAS response data could be collected between March 2020 and July 2020 due to the Covid 19 pandemic and we were unable to observe the decline in performance. There does not appear to be a consistent effect of time on the DAS response in this study.

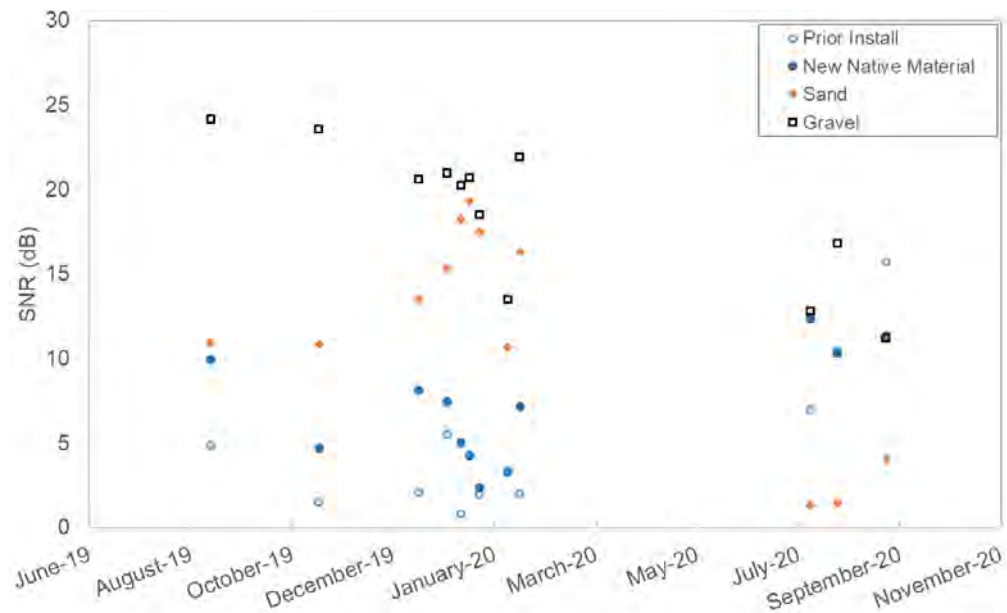


Figure 4.12: SNR in one channel for each material from August 2019 to September 2020.

Initially we suspected that the fiber optic cable may have been fractured near the sand-gravel transition in the trench. However, OTDR power measurements indicate that there is no power loss through this section of fiber optic cable, i.e. the fiber optic cable is intact and not broken or fractured. Portions of the DAS array beyond the sand

are still performing well, which confirms the fiber optic cable is not fractured or broken. Additionally, there is no discernable change on the ground surface above the sand portion of the array. There was no activity onsite between March 2020 and July 2020, so we considered that the drop of SNR in the sand was attributed to overgrown vegetation, damping the impact. However, follow-up impact tests with freshly mowed grass, confirmed that the nearly 10dB drop in response is true and not due to overgrown vegetation.

Spring 2020 was very wet at the test bed, and summer 2020 was very dry. The sand is in proximity to a wetland and it is possible that the sand was near fully saturated at some point in the spring, and the dry summer desiccated the sand, possibly causing the sand to lose coupling with the fiber optic cable. Zhang et al. 2016 proposed that water infiltrations could affect the coupling of a fiber optic cable to the soil, this study indicates that desiccation may have changed the cable to soil coupling affecting the sensor performance.

Our results agree with the hypotheses of Wu et al. 2015 and Friedli et al. 2019 , who observed DAS response changing over time, suggesting that the coupling between the fiber optic cable and the host medium may change due to aging and seasonal environmental changes.

4.4 Discussion of Results: Impedance Ratio, Soil Stiffness, and DAS response

Sections 4.1, 4.2, and 4.3 of this dissertation present the DAS response results for portions on a DAS array in different soil types through seasonal fluctuations. Native silty sand material, sand fill, and gravel fill were placed and compacted in an excavated trench and excavatable cementitious flowable fill was placed in a trench in two lifts such that the flowable fill beneath the fiber optic cable firm before the second lift of flowable fill was placed. Table 4.2 provides the in-situ nuclear gauge (ASTM D6938) dry density and water content, the calculated total unit weight, the optimum dry density and optimum water content (Modified Proctor, Method B (ASTM D1557)), and the calculated dry density percent compaction.

Table 4.2: In-situ average soil density and water content

Soil type	Dry Unit Weight (pcf)	Water Content (%)	Calc. Total Unit Weight (pcf)	Max Dry Unit Weight (pcf)	Opt. Water Content (%)	Percent Comp, %
Native Material (Impact Location)	99	25	124	132.5	7.5	75
Native Material (In Trench)	106	15	122	132.5	7.5	80
Sand Fill	108	2	110	114.5	13.6	94

For impact source locations offset from the fiber optic cable array, the impact-generated seismic wave would travel from the ground surface of the undisturbed native silty sand material towards the trench material containing the fiber optic cable. Figure 4.13 indicates the location of an impact source and the estimated ray path the seismic wave would follow to reach the fiber optic cable in the trenched materials. As shown in Table 4.2 the in-situ density and water content of the undisturbed native material (where the impact source is located) is different than the native silty sand and

sand in the trenches. Differences in these soil properties indicate that perhaps the soil stiffnesses are different enough to affect the propagating waves.

Figure 4.13 shows that the DAS surrounded by flowable fill performed differently than the portions of DAS in sand and gravel for the source location shown in Figure 4.13. To evaluate why this difference is observed, we can estimate the impedance ratio between the undisturbed native material and the trenched materials.

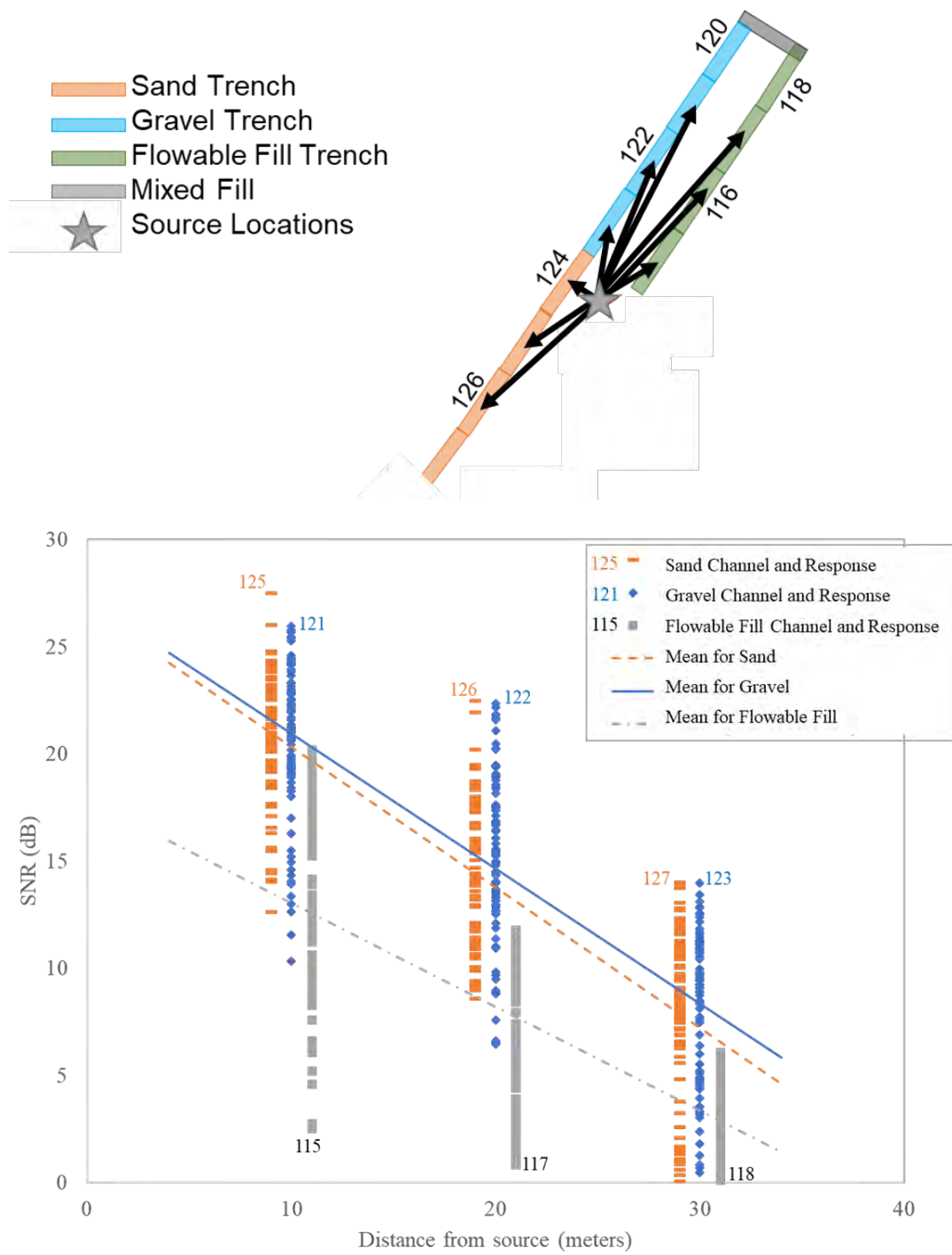


FIGURE 4.13. Impact source wave rays to DAS channels and resulting SNR differences

The impedance ratio of a seismic (incident) wave traveling from one soil to another where the soil stiffnesses are different can provide information on how much of the wave energy (and stress and displacement) will be transmitted into the next material and how much will be reflected back into the origin material. An impedance ratio of less than 1 indicates that the incident wave is approaching a softer, less stiff material (Kramer, 1996). An impedance ratio of zero would mean that the incident wave is approaching a free end (Kramer, 1996). Along the same lines, when an impedance ratio is greater than one, the incident wave is approaching a stiffer material such that an impedance ratio of infinity implies that the incident wave is approaching a fixed end where no displacement can occur (Kramer, 1996). The impedance ratio provides information on the expected displacement (i.e. or strain) amplitude as the incident wave travels from one material to another. DAS response is proportional to strain experienced along the fiber optic cable. In this study seismic strain/displacement in the soil surrounding the fiber optic cable is transferred to the fiber optic cable interior causing a DAS response.

The impedance ratio (α) can be calculated using the in-situ density (ρ) and shear wave velocity (V_s) of the material the wave is in (material 1) and the in-situ density and shear wave velocity of the material the wave is traveling towards (material 2). The equation for impedance ratio is presented in Equation 10. For this study, material 1 is the undisturbed native silty sand on which the impact is occurring.

$$\alpha = \frac{(\rho V_s)_{\text{material 2}}}{(\rho V_s)_{\text{material 1}}} \quad \text{EQ 10}$$

The in-situ densities of the native material and sand fill are known from nuclear density gage testing during test bed installation (Table 4.2). There is no water in the gravel and the gravel unit weight is assumed to be approximately 135pcf (Ryden, 2004) and the excavatable cementitious flowable fill is assumed 140pcf (Ryden, 2004) which is less than typical concrete and similar to the low end of asphalt. Shear wave velocities in near surface material at a depth of 2 feet are difficult to evaluate. Shear wave velocity measurements are often used in geotechnical engineering to assess soil stiffness and associated liquefaction potential (Andrus and Stokoe, 1998). The small strain shear modulus (G_{max}) relates to shear wave velocity with the relationship shown in Equation 11, and an empirical relationship (Equation 12) was used to estimate G_{max} for each soil (Seed and Idriss, 1970). The K_2 coefficient in Equation 12 is estimated using guidance from Seed and Idriss (1970) for imperial units. By setting Equation 11 equal to Equation 12, shear wave velocity can be solved for and placed in Equation 10. The Seed and Idriss, 1970 relationship (Equation 12) relies on mean effective stress (σ'_m) at a depth (d) of about 2 feet. Assuming the horizontal effective stress is axisymmetric ($\sigma'_3 = \sigma'_2$) and the at rest earth pressure coefficient (K_0) is 0.5., then the impedance ratio, Equation 14, can be estimated.

$$G_{max} = \rho V_s^2 \quad \text{EQ 11}$$

$$G_{max} = 1000 K_2 \sqrt{\sigma'_m} \quad \text{EQ 12}$$

$$\sigma'_m = \frac{1}{3}(\sigma'_1 + \sigma'_2 + \sigma'_3) = \frac{1}{3}(\sigma'_1 + 2\sigma'_2) \approx \frac{2}{3}\rho g d \quad \text{EQ 13}$$

$$\rho V_s^2 = 1000 K_2 \sqrt{\sigma'_m} = 1000 K_2 \sqrt{\frac{1}{3}\rho d} \rightarrow V_s = \sqrt{\frac{1000 K_2 \sqrt{\frac{2}{3}\rho g d}}{\rho}}$$

$$\alpha = \frac{\left(\rho \sqrt{\frac{1000 K_2 \sqrt{\frac{1}{3}\rho d}}{\rho}} \right)_{\text{material 2}}}{\left(\rho \sqrt{\frac{1000 K_2 \sqrt{\frac{1}{3}\rho d}}{\rho}} \right)_{\text{material 1}}} \quad \text{EQ 14}$$

Based on Equation 14, Table 4.2 provides the approximate impedance ratio values for an incident wave traveling from the undistributed native silty sand to the sand, gravel, and flowable fill trenches. The impedance ratios of the undisturbed native material to native material in the trench and sand fill are approximately one, meaning there would be relatively little change in the wave energy, stress, and displacement due to the stiffness of different materials. According to Table 5-1 in Kramer (1996) when the impedance ratio is one, the displacement and energy continuing into the new material is relatively unchanged. However, when the impedance ratio is 1.5, the displacement (strain) amplitude of the incident wave will be about 3/4s of the originating displacement.

Table 4.3: Impedance ratio calculations

	In-situ Unit Weight (pcf)	K_2	α
Native Material (Impact Location)	124	60	1
Native Material (In Trench)	122	65	1
Sand Fill	110	70	1
Gravel Fill	135 (130-140)	70-80	1.1-1.25
Flowable Fill	140	90-120	1.35-1.55

The difference in SNR responses shown in Figure 4.13 due to the source location shown in Figure 4.1 of portions of the fiber optic DAS array sand, gravel and flowable fill can be explained, in part, by the impedance ratios shown in Table 4.3. In Figure 4.14, the response of portions of DAS array in the sand and gravel seem to be similar, and likewise their impedance ratios are similar, essentially one. In Figure 4.13, the flowable fill response is approximately 60 to 75% of that observed in the sand and gravel, which agrees with the calculated impedance ratio of approximately 1.5.

Looking at DAS response when the impact source is in-line with the fiber optic cable and the trenched in material, shown in Figure 4.14, it appears that the array in gravel and in flowable fill performs similarly with distance. Once again, the impedance ratio can help explain why this is. The source locations shown in Figure 4.14 deliver the seismic wave energy directly to the trench material (gravel and flowable fill in this case), therefore there is no impedance contrast causing the wave energy, stress, and strain to change. The impact travels from the ground surface through similar amount of native fill (overlaying the trench material, about 2 to 4 inches) before entering the trench material.

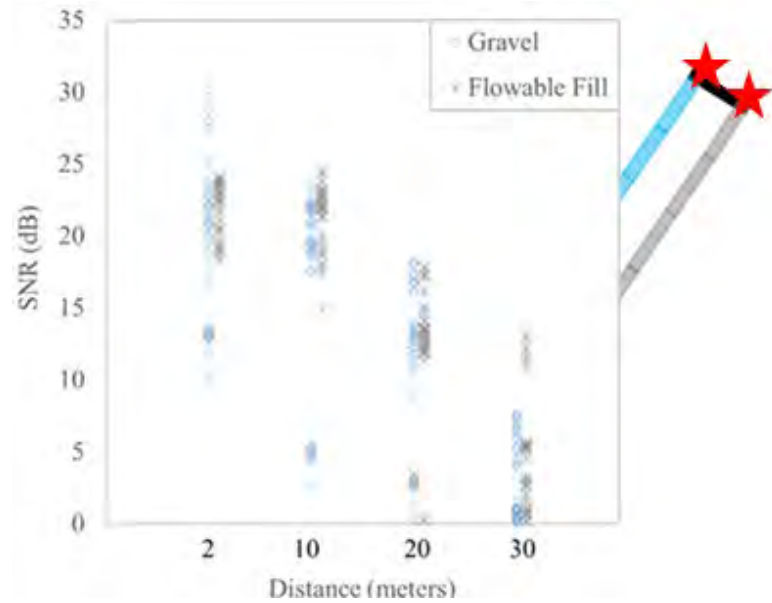


FIGURE 4.14: DAS response in different material types due to in-line above trench material source location.

As shown in Equation 10, the impedance ratio depends on the density and shear wave velocity of material 1 and material 2. Zhou and Xia (2006) show that slight changes on soil saturation can have a significant effect on shear wave velocity and Rayleigh wave velocity, typically increasing velocity with saturation. This means that the soil stiffness ($G_{\max}$) may also change with saturation. Although, Figure 4.10 indicates that SNR did not change significantly with water content that may be because testing was halted during significant water content fluctuations of the 2020 spring and summer (March 2020 through August 2020) due to the Covid-19 pandemic.

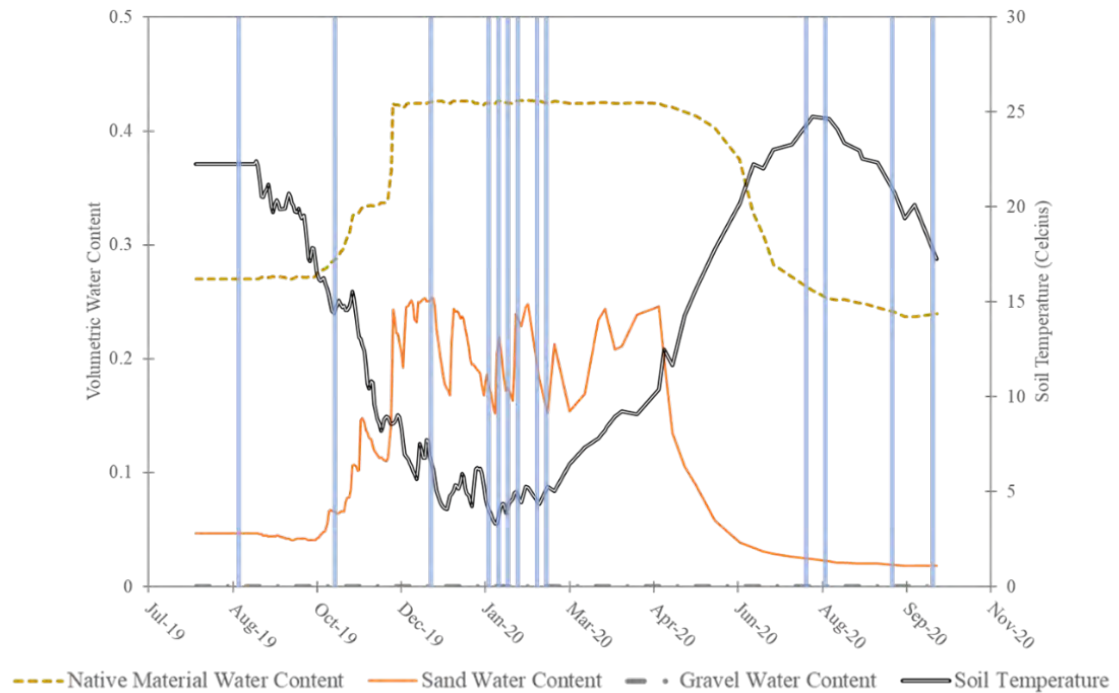


FIGURE 4.15: Observed volumetric water content changes in trench materials over time.

To review the significance that water content fluctuations may have had on the impedance ratio between the native silty sand where the impact occurred and the sand trench, where the most affected portion of DAS array is, consider the following: the undisturbed native silty sand and sand fill dry densities in Table 4.2, we can use the water content fluctuation from the moisture and temperature sensors (as shown in Figure 4.15). The volumetric water content measured in the sand fill was around 0.05 in September 2019, then about 0.25 from December 2019 through April 2020, and then down to nearly zero by August 2020. The native silty sand material in the trench went from a volumetric water content of about 0.28 in September 2019 to about 0.42 from December 2019 through April 2020, and then back down to about 0.25 by

August 2020. Assuming the dry densities stay the same and the undistributed native silty sand material water content fluctuates comparably to the trenched-in material, the approximate impedance ratios of a wave traveling from undisturbed native material to the sand between September 2019 and August 2020 can be calculated. Table 4.3 provides a breakdown of the calculations and water content selected. Note that the relationship between water content (w), saturation (S), and volumetric water content (θ) is provided in Fredlund and Rahrdjo, 1993 as Equation 15. Assume specific gravity (G_s) remains constant.

$$\theta = \frac{Sw G_s}{S + w G_s} \quad \text{Equation 15}$$

The water contents presented in Table 4.4 are approximate and based on Fredlund and Rahrdjo (1993) volumetric water content, saturation, and soil density in conjunction with the volumetric water content information shown in Figure 15. The resulting impedance ratios suggest that the sand becomes slightly softer than the native silty sand overtime due to water content fluctuations. An impedance ratio of 0.95 indicates that the displacement would be very, slightly amplified through the stiffness transition. However, a significant effect of impedance ratio on displacement is not anticipated to be observed until the impedance ratio is less than $\frac{1}{2}$ or greater than $1 \frac{1}{2}$. Therefore, it is unlikely that the impedance ratio between the native material near the impact source and the material in the DAS array trenches would change with seasonal water fluctuations. This agrees with the lack of trend observed between SNR and water content in the native material and the sand material.

Table 4.4: Impedence ratio fluctuations with water content

	Dry Unit Weight (pcf)	Water Content (%)	Calculated Total Unit Weight (pcf)	K_2	α
Native Material (September 2019)	99	25	124	60	1
Sand Fill (September 2019)	108	2	110	70	
Native Material (Winter 2020)	99	30	129	60	0.95
Sand Fill (Winter 2020)	108	14	123	70	
Native Material (August 2020)	99	15	114	60	0.96
Sand Fill (August 2020)	108	0	108	70	

The results in Figure 4.16, which follows the SNR performance of the DAS array in different trench materials over time, cannot be explained with impedance ratio is still below 1, which means that the material from which the seismic wave originates and to which the seismic wave is traveling are of similar stiffnesses. From the water content fluctuation and impedance ratio thought experiment, the impedance ratio between the native material where the impact source is and the sand trench material where the DAS array is not estimated to change significantly, per the source location shown in Figure 4.13. This is in part because both materials experience water fluctuations at the same time. Thus, there must be another mechanism at work causing the performance in the sand portion of the array to change over time. Perhaps there is a slight de-coupling of the fiber optic cable to the sand due to water infiltration fluctuations or drought. This hypothesis would be supported by the relatively insignificant change in performance or the portion of the array in gravel. Perhaps the performance in the gravel remains relatively constant because the material is free

draining and relatively heavy and angular, and there is less chance for changes in stiffness.

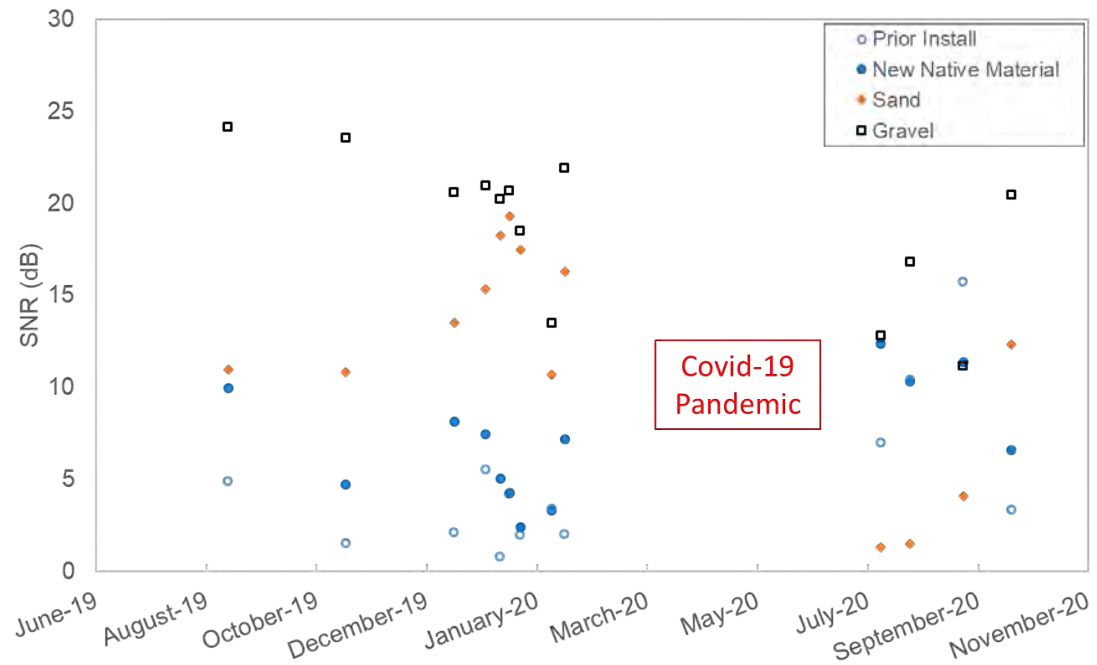


FIGURE 4.16: DAS performance over time.

Impedance ratio (relative stiffness between the material through which a seismic wave travels) explains why the portion of the DAS array in flowable fill under-performs when compared to the other materials for off-set sources. The impedance ratio between native material and sand or gravel seemed was close to one and agrees with the pre-pandemic DAS performance results. Though impedance ratio cannot explain the change in performance of the portion of array in sand over time, impedance contrast and seismic wave travel path should be considered when installing a DAS array.

CHAPTER 5

CONCLUSIONS

Distributed Acoustic Sensing (DAS) is a fiber optic sensing system that is used for vibration monitoring. At a minimum, DAS is composed of a fiber optic cable and an optic analyzer, i.e. an interrogator. The oil and gas industry has used DAS for over a decade to monitor infrastructure such as pipelines for leaks. In recent years, changes in DAS performance have been observed for DAS arrays that have been buried in the ground for long periods of time. This dissertation investigates the effect that soil type, soil temperature, soil moisture, time in-situ, and overburden pressure have on DAS performance for fiber optic cable buried in soil. To explore this problem, a new portion of DAS array was added to an existing DAS array installed a decade prior. The design of the new portion of DAS array includes native silty sand material, sand, gravel, and excavatable flowable fill. Soil moisture and temperature sensors were buried adjacent to the fiber optic cable to monitoring seasonal soil moisture and temperature. Periodic impact testing was performed at set locations along the DAS array for over one year. A separate, temporary DAS array was used to study the effect of vehicle loading. The signal response of the DAS array to the impact testing was processed for Signal to Noise Ratio (SNR), which was the performance criteria used to evaluate the system performance.

The results of the impact testing program indicate that portions of the array in gravel performed the most consistently over the year-long monitoring period. Neither soil moisture nor soil temperature appear to have a significant effect on DAS performance. DAS performance was observed to increase with increased vehicle

loading. Over the course of one year in-situ, DAS performance was observed to slightly lower in the native material and significantly lower in the sand and flowable fill material, while the variance performance was observed to increase all materials.

A significant change in performance occurred while testing halted from March 2020 to August 2020 due to the Covid-19 pandemic. Though it is unfortunate that the data was not collected while these changes in DAS performance developed, the observed changes emphasize the potential of DAS to be used for infrastructure change-detection monitoring. While changes in performance were observed in the new portion of test bed over the course of one year, the performance of the decade-old portion of test bed remained consistent and strong. Though response in the flowable fill portion of the DAS array was observed to be less for offset source locations, this is likely due to the impedance contrast between the native material on which the source is located and the stiffer flowable fill material. Overall, this dissertation provides guidance to the civil engineering community for installation design recommendations related to DAS used for infrastructure monitoring.

5.1 Impact of research on civil engineering

The results of this research will influence civil engineering DAS installation recommendations. DAS arrays installed in silty sand (native material for this study) and gravel have long-term viability and continue to be sensitive to vibrations regardless of soil moisture, soil temperature, and time in-situ. Portions of the DAS array in excavatable flowable fill did not perform as well as portions of the array in other soil types, likely due to the stiffness difference between the native material and

the flowable fill (i.e. impedance contrast). Initially, portions of the array in the sand performed well from August 2019 through February 2020. Due to the Covid-pandemic testing was not performed from March 2020 until the end of July 2020, and when testing resumed the SNR in the portions of the array in dams and flowable fill significantly. Fiber optic cable breakage or bending was ruled out through OTDR testing. Field inspection of the test bed did not provide any clues to the cause of the SNR drop. The spring of 2020 was very wet and the summer of 2020 was very dry, which may have caused the sand to desiccate and de-coupled from the fiber optic cable, or purpose material piped along the fiber optic cable during a significant rain event and de-coupled the cable and sand. The continued performance of the portions of the DAS array installed in native material (both new and existing) and the portion of the array installed in gravel strongly suggest that DAS systems can provide long-term quality performance.

While DAS performance did not correlate to soil temperature or soil moisture, over time the performance was observed to drop in sand and flowable fill portions of the array, indicating that there may be other long-term variables that affect DAS performance. Although soil moisture may not directly correlate with performance, perhaps wetting-drying cycles or freeze-thaw cycles affect performance. After nearly a year in-situ, it appears that the new portion of DAS array in native material may perform comparably to the portion of array installed a decade prior.

The vehicle load testing performed on the temporary DAS test bed at CRREL indicate that DAS performance increases with increased loading. The significant variation in DAS response is likely due to various industrial activities at CRREL and

some disturbance to the array while on-boarding and off-boarding vehicles. The results of this experiment indicate that the presence of load on less than 10% of an array channel length may improve DAS performance.

The results of this dissertation have already had an impact on the installation of DAS arrays. Prior to this study, gravel pieces were removed from installation trenches. Gravel was avoided as a trench material as it was thought to cause micro-bends in the fiber optic cable, which would increase attenuation and lower performance. This research demonstrates that DAS will perform well in gravel, which supports infrastructure monitoring applications such as roadway subgrade, foundations, mechanically stabilized walls, and more.

Similar performance between the new and previously installed portions of the permanent DAS test bed support the long-term viability of the use of DAS as a vibration monitoring system to the civil engineering community. An initial investment in a DAS interrogator and installation of fiber optic cable can provide infrastructure monitoring capabilities for years to come. The ability to monitor 40 or more kilometers of fiber optic cable along infrastructure at 10-meter resolution could transform the way infrastructure aging is understood and the way maintenance is performed. DAS could help the civil engineering community localize repairs before they become more significant, prioritize infrastructure repairs on a national scale, and capture the impact of seismic events on infrastructure.

5.2 Engineering recommendations

This research has filled some existing knowledge gaps regarding DAS arrays in soil and will hopefully increase confidence in using DAS technology in civil engineering projects. The research provides long term feedback on how DAS will perform which may help guide engineering recommendations for fiber optic installation.

Based on the results of this research program the following recommendations are indicated:

- The prior DAS array installation still performed well after ten years in-situ and performs comparably to the new portion of array one year after installation.
- DAS arrays perform well in gravel.
- Until further investigation, it might be prudent to avoid intentionally removing native material to replace with sand material.
- Review the impedance contrast and consider the directionality of the event seismic waves to be monitored.
- Consider using DAS to supplement existing vibration monitoring instruments. What DAS might lack in SNR, it makes up for in response data density.

5.3 Future work

While this research effort has filled in some of the knowledge gaps regarding soil-embedded DAS array, the results have also presented more uncertainties to explore in future research. Testing at the permanent test bed will continue for the foreseeable future. Observing and documenting the performance of a DAS array as it experiences multiple seasonal cycles will help the engineering community set performance expectations. Additionally, conventional and phase-sensitive OTDR DAS interrogators will be used on the same cable to compare SNR response. Future research will include below 0°C temperatures testing and capture potential performance changes during the freezing and thawing process. The performance loss in the portions of the array in sand will continue to be monitored. Perhaps performance will return during seasonal moisture and temperature fluctuations and/or we will observe DAS performance cycles.

Additionally, testing at a similar DAS test bed in a different geographic location connected to an existing array will demonstrate how and if seasonal changes and soil conditions effect DAS performance in a different native materials with different seasonal environmental factors.

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14. ABSTRACT Distributed Acoustic Sensing (DAS) is a fiber optic sensing system that is used for vibration monitoring. At a minimum, DAS is composed of a fiber optic cable and an optic analyzer called an interrogator. The oil and gas industry has used DAS for over a decade to monitor infrastructure such as pipelines for leaks, and in recent years changes in DAS performance over time have been observed for DAS arrays that are buried in the ground. This dissertation investigates the effect that soil type, soil temperature, soil moisture, time in-situ, and vehicle loading have on DAS performance for fiber optic cables buried in soil. This was accomplished through a field testing program. Signal to Noise Ratio (SNR) of the DAS response was used for all the tests to evaluate the system performance. The results of the impact testing program indicated that the portions of the array in gravel performed more consistently over time. The results also indicated that time DAS performance does change somewhat over time. Performance variance increased in new portions of array in all material types through time. Overall, this dissertation provides guidance that can help inform the civil engineering community with respect to installation design recommendations related to DAS used for infrastructure monitoring.					
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