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Fiber optic distributed acoustic sensing monitoring acoustic emissions for geotechnical structure performance in the field

Détection fibre optique DAS pour surveiller les émissions acoustiques pour la performance des structures géotechniques sur le terrain

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ABSTRACT: Geotechnical engineers can use Acoustic Emissions (AE) to monitor the performance of geotechnical components of infrastructure. Changes in measured AE have been hypothesized to reflect changes in the soil properties that can affect infrastructure performance. Fiber optic Distributed Acoustic Sensing (DAS) is a relatively new instrument to the civil engineering community that could be used to monitor AE. DAS uses a fiber optic cable to measure strains along its length at sampling rates close to geophones. This paper presents results of an on-going, 11-month field study on the response of a buried DAS to impact tests on the ground surface. The fiber optic cable was placed in a trench, with different sections backfilled with sand, gravel, and flowable fill. Impact tests were performed by striking a standard Proctor hammer on a steel plate, and the response in the DAS was recorded using a conventional optical time-domain reflectometer interrogator. DAS response in each backfill material was measured as a function of distance from the source and over time. The primary results of this study suggest that a) Signal-to-Noise Ratio might be a better metric by which to observe changes in the soil over time ; b) attenuation of DAS response with distance was comparable among the three backfill materials ; and c) there was a significant reduction in SNR for all materials over the 11-month measurement period. More research is needed to better und erstand these findings for increased acceptance of DAS for civil engineering infrastructure monitoring.

RÉSUMÉ : Les ingénieurs géotechniques peuvent utiliser les émissions acoustiques (AE) pour surveiller les performances des structures géotechniques telles que les culées de ponts. Les changements de l'AE mesuré peuvent être corrélés à des changements dans l'état du contact structure-sol. La détection acoustique distribuée par fibre optique (DAS) est un instrument relativement nouveau pour la communauté du génie civil qui pourrait être utilisé pour surveiller l'EA. Le DAS utilise un câble à fibre optique pour mesurer les déformations sur sa longueur à une fréquence d'échantillonnage proche des géophones. Le DAS donne une réponse tous les 1 à 10 mètres sur sa longueur, chaque réponse distribuée remplace un capteur ponctuel. Ainsi, une matrice DAS pourrait remplacer des centaines ou des milliers de capteurs ponctuels pour la surveillance AE en fonction de la longueur du câble à fibre optique et de la résolution de distribution des données. L'intégration du DAS dans la conception des fondations ou dans la conception des culées de pont pourrait révolutionner la surveillance intelligente des infrastructures. Une étude de suivi sur le terrain DAS à long terme montre comment la performance du DAS dans le remblai structurel sableux et le gravier n'est pas affectée par les changements saisonniers.

KEYWORDS: Distributed Acoustic Sensing, Instrumentation, Monitoring, Structural Health Monitoring, Acoustic Emission

1 INTRODUCTION.

The objective of this paper is to demonstrate that in situ fiber optic distributed acoustic sensing (DAS) can be used to observe Acoustic Emissions (AE) over time. Fiber optic DAS systems are comprised of a fiber optic cable and an interrogator. The fiber optic cable can be as simple as telecommunication fiber optic cable or as complex as a specially fabricated cable with unique materials. The cable can be embedded in soil, placed in a conduit, grouted in a borehole, or otherwise attached to the infrastructure to be monitored.

A DAS interrogator contains one or more lasers which pulses light into the fiber core. Light propagates down the fiber core and scatters due to density anomalies in the fiber core material (Krohn et al. 2014); the location of these anomalies are called scattering centers. Some of the scattered light returns to the interrogator as backscatter, and returning Rayleigh scattering is measured using an optical time-domain reflectometer (OTDR) located within the interrogator. Rayleigh scattering is an elastic process such that the velocity of the light outbound from the laser is the same as the velocity of the light reflected back towards the interrogator. This allows for determination of the distance along the fiber where scattering centers are located (Sang 2011, Owen et al. 2012, Schenato 2017, Soga and Luo 2018).

Vibrational strains acting on the fiber induce changes to the scattering centers. This, in turn, changes the power of backscattered light which is proportional to the magnitude of the vibrations (Lindsey et al. 2020). A typical sampling rate of greater than 2000Hz allows DAS to detect vibrational strains acting along the fiber optic cable to produce observations similar to that of geophones or seismometers. While newer DAS systems claim 1-meter distributed response, there are trade-offs such as shorter DAS array length (Krohn et al. 2014). The DAS community often uses 10-meter channel spacing and the DAS fiber optic cable lengths at this channel spacing can exceed 20-kilometers (i.e. 2,000 responses evenly distributed along the cable length).

1.1 *DAS Applications*

For over a decade, DAS has been used in the oil and gas industry for both security and leak detection along remote pipelines. Examples of current infrastructure monitoring research using distributed fiber optic sensing include monitoring traffic, railways, and landslides (Soga and Luo 2018, Luo et al. 2019). There are several studies showing how DAS can be used for vertical seismic profiling (e.g. Mateeva et al. 2014, Egorov et al. 2018, Miller et al. 2018). Several research efforts (including Daley et al. 2013, Dou et al. 2017, Costley et al. 2018) show that DAS can also be used to estimate the shear wave velocity of soil profiles by multichannel analysis of surface waves (MASW). Parker et al. (2018) indicated that seismometers provide a higher signal to noise ratio and wider range of frequencies than DAS, while DAS provided more response data due to its distributed nature. Lindsey et al. (2020) demonstrated that DAS response is comparable to a high-quality broadband seismometer and DAS was able to measure similar broadband frequencies as the seismometer.

DAS monitoring can be either active or passive in nature. For example, roadway subgrade monitoring and railway ballast and tie monitoring is active, meaning that engineers use the seismic response induced by vehicle traffic and trains to evaluate subsurface conditions. Changes in the way a portion of the DAS array performs along a roadway or railway indicate that further engineering investigation is needed in that zone of the array. DAS in dams or other earthen embankments act as a passive sensor. The DAS system remains in-situ and baseline/ambient DAS performance is reviewed for changes that may suggest localized deformation.

1.2 *Acoustic Emissions*

In this paper, Acoustic Emissions (AE) refer to high frequency elastic waves that are generated when a soil undergoes deformations from applied stresses (Michlmayr et al. 2016). AE have been measured in the laboratory to investigate the mobilization of shear strength in soils (Smith and Dixon 2018) and in situ to monitor slope stability (Tanimoto and Tanaka 1986, Smith et al. 2014, Dixon et al. 2015, Smith et al. 2017b, Dixon et al. 2018). Work from Heather-Smith et al. (2018), Smith et al. (2017a), and Smith and Dixon (2018) indicate that changes in wave propagation and attenuation measured via AE might be caused by mobilized friction and other soil properties.

Recent research by Michlmayr et al. (2016) specifically compared the AE response of DAS and point sensor piezoelectric transducers in model tests of landslide initiation. They found that both sensors produced unique AE responses in response to hammer strikes on the surface of the model and also during triggering of a landslide.

2 EXPERIMENTAL SETUP

To demonstrate that a DAS buried in situ can be used to observe AE over time, an approximately 130 m fiber optic cable was installed in a trench and backfilled with three different materials: a well graded sand, gravel, and an excavatable flowable fill. Figure 1 shows the layout of the cable, including the zones of each backfill material and the number of DAS channels in each material. The fiber optic cable consists of single mode silica fibers with a water-proof buffer tube, and a polyethylene jacket. The interrogator used for this study is a non-phase sensitive OTDR with a sampling frequency of 2500 Hz and 10-meter-long channels. The fiber optic cable was installed a depth of 0.5 meters with 0.5 meters fill material above and below the cable and about 0.25 meters of fill material on either side. The sand fill was compacted with a vibratory plate compactor while the gravel was tamped with the bucket of an excavator. Measurements with a nuclear density gauge indicated that the sand fill had a relative compaction greater than 90% relative to the Standard Proctor test.

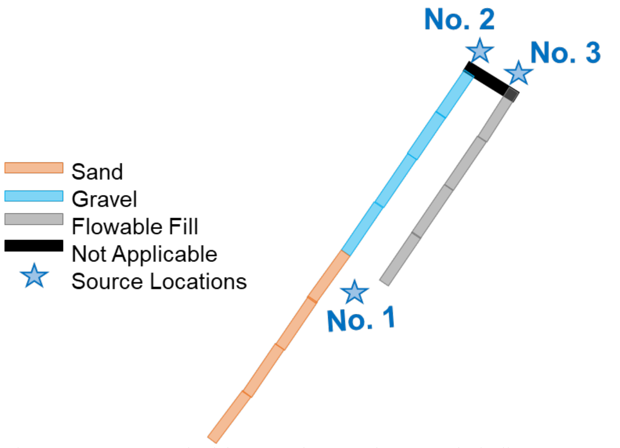

Figure 1. DAS Test bed layout where each rectangle indicates a DAS channel. Each rectangle indicates a DAS channel of approximately 10 m in length.

3 METHODOLOGY

A Standard Proctor hammer impacting a metal plate was used to generate repeatable seismic waves for the DAS test bed to record. At least ten impacts were delivered per source locations shown in Figure 1. Impact testing was conducted onsite from August 2019 through September 2020.

For this study, AE is defined as the Root Mean Square (RMS) value of the signal induced in the DAS channel from the impact source (Smith and Dixon 2018). The RMS value (x_{rms}) of the signal x(t) measured using the DAS channel is defined as shown in Equation 1.

$$AE = x_{rms} = \sqrt{\frac{1}{T}\int_0^T x^2(t)dt} \quad (1)$$

Where T is the signal duration over which the RMS value is evaluated. The DAS signal was sampled at 2500 Hz with a sampling interval (□t) of 0.4 milliseconds. The RMS calculations were made with a time capture of 0.35 seconds, yielding 875 samples (N) in the analyzed time window. Using the discrete values sampled (x[n]), with n=1,2,3,…,N, Equation 1 can be re-written in the discrete form as shown in Equation 2.

$$AE = x_{rms} = \sqrt{\frac{1}{N}\sum_{n=1}^{N} x[n]^2} \quad (2)$$

RMS values were calculated for DAS response in channels located in sand, gravel, and flowable fill materials and used to quantify the AE as described earlier.

It was found in this work that Signal-to-Noise-Ratio (SNR) provided a better measure than AE RMS for observing changes in DAS response to impacts over time. SNR incorporates the RMS value x_{rms}, as shown in equation 3. Note that both xrms_signal and xrms_noise were made with a 0.35 second time capture of signal and the following 0.35 second time capture of noise using the Equation 2.

$$SNR\ (dB) = 20log_{10}\left(\frac{AE}{x_{rms\_noise}}\right)$$

$$SNR\ (dB) = 20log_{10}\left(\frac{x_{rms\_signal}}{x_{rms\_noise}}\right) \quad (3)$$

4 RESULTS AND DISCUSSION

Impact tests were performed on four days between October 2019 and September 2020 and the response of the DAS was recorded. DAS response in the three materials to impulse events occurring at source location No. 1 is provided in Figure 2 and Figure 3, where Figure 2 presents results in terms of AE and Figure 3 presents results in terms of SNR.

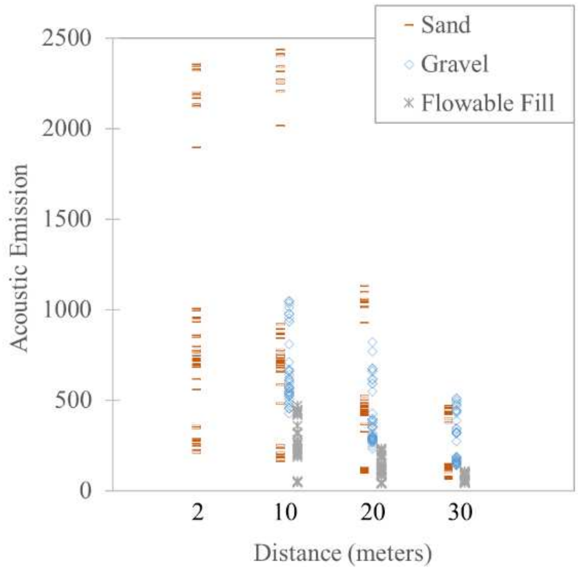

Figure 2. AE response from DAS in sand, gravel, and flowable fill between October 2019 and September 2020 in response to source location No. 1.

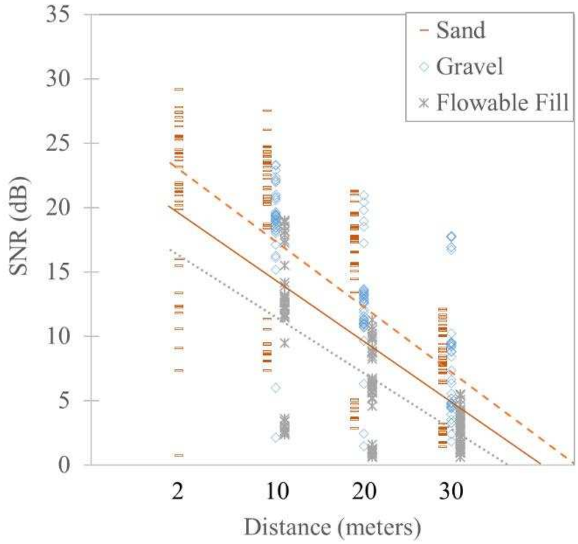

Figure 3. SNR response from DAS in sand, gravel, and flowable fill between October 2019 and September 2020 in response to source location No. 1.

DAS response in the gravel and flowable fill to impulse events occurring at source locations No. 2 and No. 3 is shown in Figure 4 and Figure 5, where Figure 4 presents results in terms of AE and Figure 5 presents results in terms of SNR.

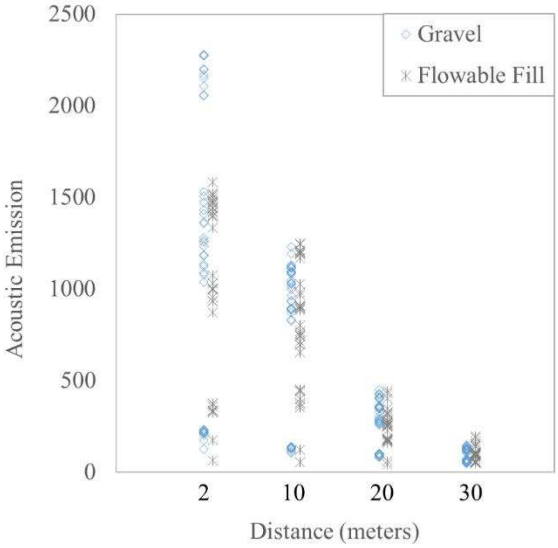

Figure 4. AE DAS response in gravel (source location No. 2) and flowable fill (source location No. 3) between October 2019 and September 2020.

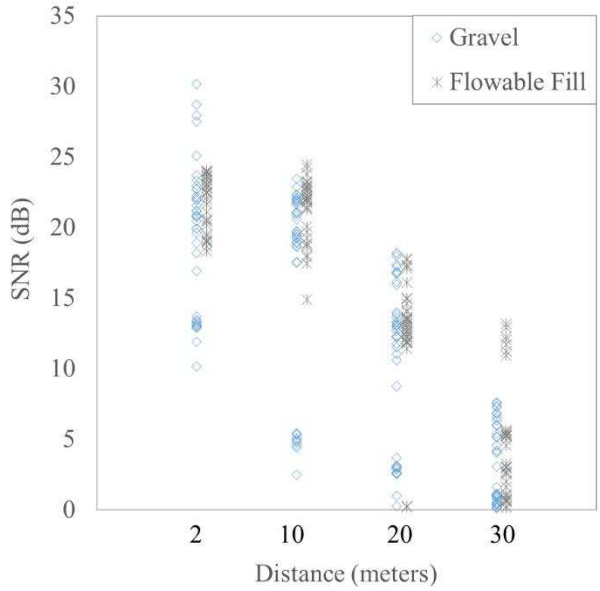

Figure 5. SNR DAS response in gravel (source location No. 2) and flowable fill (source location No. 3) between October 2019 and September 2020.

The differences in Figure 2 versus Figure 3, and in Figure 4 versus Figure 5 show the importance of the metric by which monitoring is being performed. Figures 2 and 4 present results in terms of AE and indicate a large response variation in portions of the array closest to the source. Figures 3 and 5 present the same results in terms of SNR; there is still variability in the results but much less that using AE. Based on this comparison, SNR appears to be a better metric for assessing the long-term performance of DAS as it normalizes the response to the ambient noise conditions that may vary throughout testing (e.g. day-time activity versus night-time activity or a windy day).

While Figure 3 indicates that portions of the array in flowable fill do not perform as well as portions of the array in sand and gravel, Figure 5 suggests that portions of the array in flowable fill perform as well as portions of the array in gravel and with similar attenuation. The improved performance shown in Figure

5 is possibly due to the location of the source being axially aligned with both the fiber topic cable and the trench material. The impact source for the data in Figure 3 is located offset from the trench material and fiber optic cable. Perhaps the diminished response in the flowable fill for testing at location 1 is due to the difference in stiffness between the native silty sand and the stiffer flowable fill. The differing results in Figures 3 and 5 highlight the importance of understanding the intent and goals of monitoring program to optimize the design of a DAS array to yield quality results. The fact that the signal response and attenuation is comparable in gravel and flowable fill can inform those who are burying fiber optic cables for infrastructure monitoring.

To observe changes in DAS response over time, the results from tests performed on 4 dates over an 11-month period are shown in Figure 6. Source location 1 was used for all the results shown in this figure.

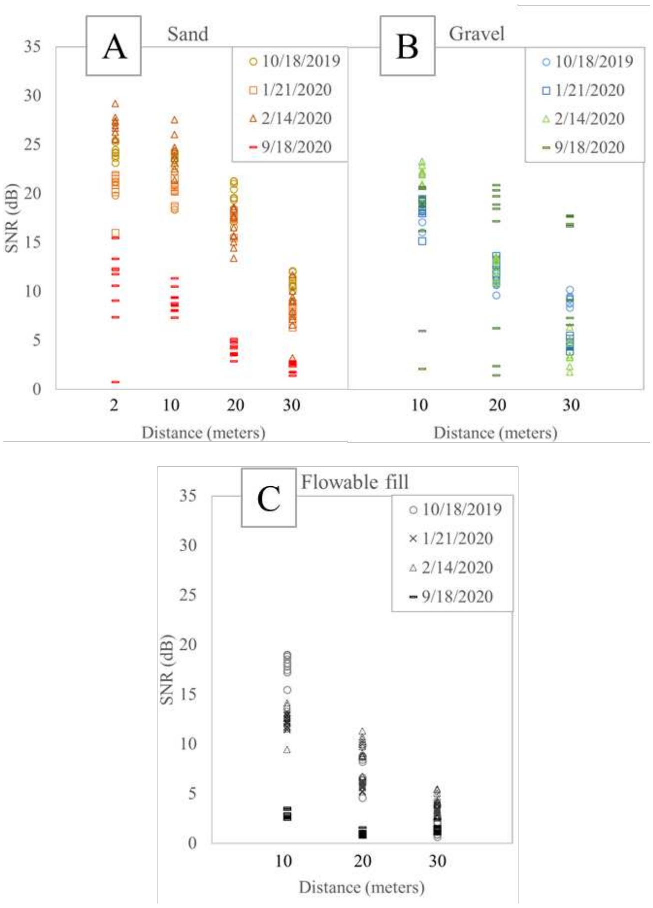

Figure 6. Changes in SNR between October 2019 and September 2020 as observed in sand (A), gravel (B), and flowable fill (C).

The DAS response in Figure 6 highlights the potential benefits and challenges of using DAS for change-detection monitoring. Figure 6 shows that for readings from October 2019 through February 2020 DAS response was relatively consistent in all material, with the response in the sand having the highest SNR. Attenuation with distance from the source was comparable for all three materials.

The DAS response for data collected in September 2020 is very different from the earlier readings. For example, the close-to-source response for portions of the array in sand dropped from roughly 25dB to 10dB with greater variance in the September 2020 data (Figure 6A). Similarly, the portions of the array in flowable fill closest to the source dropped from approximately 15dB to less than 5dB (Figure 6C). While Figure 6B indicates that portions of the array in gravel continue to perform consistently, though there is a significant increase in variability of the response in the September 2020 data.

Due to the Covid-19 pandemic, further investigation on the cause of the AE/SNR changes have not yet occurred, but preliminary observations indicate no change to the ground surface above the DAS array. More investigation is needed to understand the significant reduction in SNR for the 11-month readings.

5 CONCLUSIONS

The objective of this paper was to present the results of an on-going field study on the response of a fiber optic DAS array buried in different materials, to repeated impact tests on the ground surface. The fiber optic cable was placed in a trench and different sections were backfilled with sand, gravel, and flowable fill. Impact tests were performed by striking a Standard Proctor hammer on a metal plate, and the response in the DAS was recorded over an 11-month period.

The results were assessed in terms of both Acoustic Emissions (AE) and Signal-to-Noise Ratio (SNR). SNR exhibited less variability and is recommended for in situ monitoring where on-site noise can be highly variable. Significant finding of the field study included the following:

- The response of the DAS in sand yielded the highest SNR but also the largest amount of scatter in results;
- The initial response in the gravel and flowable fill was comparable in terms of SNR and attenuation away from the source;
- This initial response in the gravel and flowable fill was comparable in terms of SNR and attenuation away from the source;
- There was a significant change in SNR between the 3- and 11-month readings in all three backfill materials. Intermediate readings were not possible due to COVID-19 travel and access restrictions. The reduction in SNR was most pronounced in the flowable fill.

Changes in DAS response might be due to water infiltration, freeze-thaw activity, desiccation, or another seasonal phenomenon. More research is needed to better understand the reasons for the significant reduction in SNR with time. Understanding these effects will lead to more acceptance of DAS for Civil Engineering infrastructure monitoring.

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