Influence of fiber-optic cable structure, sand density, and acoustic frequency on DAS amplitude response: Preliminary results

Tao Xie¹, Cheng-Cheng Zhang¹,², Jia-Song Chen³, Ya-Ping Fu³, Liang Dai¹, Jun Yin¹ and Bin Shi¹,²

¹ School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, China
² West-to-East Gas Pipeline Company, PetroChina Company Limited, Shanghai 200122, China
³ Corresponding authors’ e-mails: shibin@nju.edu.cn (B.S.); zhang@nju.edu.cn (C.-C.Z.)

Abstract. Distributed acoustic sensing (DAS) is an emerging fiber-optic technology that can turn tens of kilometers long fiber-optic cables into dense acoustic sensor arrays. This technology is expected to bring new opportunities for geologic hazard characterization and mitigation. The cable structure and installation method are two critical factors affecting the performance of a DAS system. Here, we report laboratory tests performed in a sandbox to evaluate the acoustic response of different types of cables at variable sand densities and acoustic frequencies. Our initial results indicated that complex cable packaging structures had unfavorable impacts on the DAS amplitude response whereas the influence of sand density was dependent on cable structure and acoustic frequency. Further tests with refined measurement setup will improve the understanding of the combined effects of cable type, medium density, and acoustic frequency on DAS recordings.

1. Introduction

Non-invasive characterization of the deformation and failure behavior of geologic materials is of paramount importance in geologic hazard mitigation. Geologic materials undergoing irreversible changes will generate elastic waves, which can be measured by acoustic emission and/or micro-seismic techniques [1, 2]. Current acoustic/seismic monitoring technologies are often limited to pointwise sensors or sparse sensor arrays. This limitation may be overcome using an emerging fiber-optic technology called distributed acoustic sensing (DAS). The DAS technology enables the acquisition of spatially-dense acoustic data over tens of kilometers of common fiber-optic cables. This technology was first applied in the oil and gas industry for vertical seismic profiling [3] and was later successfully used for earthquake observations [4, 5].

A DAS system functions by detecting the phase change of Rayleigh backscatter in an optical fiber due to minor deformations induced by propagating acoustic wavefields. Bare fibers are often buffered and well packaged to form various dedicated cables to survive in harsh subsurface environments [6]. Hence, the cable structure and installation method affect the DAS signal quality [7, 8]. In the current work, we present preliminary results of an experimental study on the acoustic response of various fiber-optic cables buried in sands. The effect of cable type, sand density, and frequency range on the
measured DAS signal amplitude were investigated. The initial findings presented here are expected to provide a reference for opting fiber-optic acoustic sensing cables.

2. Materials and methods

Five different fiber-optic cables were tested for the present study as presented in Table 1. They ranged from a bare fiber, a loose-tube cable, to tight-buffered cables (TB, SS, and FP) that have been utilized for distributed strain sensing applications as indicated by Zhang et al. [6]. For the purpose of comparing and evaluating the acoustic sensitivity of different cable structures, a test configuration was conceived as shown in Figure 1(a). The test apparatus comprised three components: a sand box with the cables and a tiny loudspeaker buried in, a signal generator, and a DAS interrogator unit (IU); a pictorial view of the test setup is shown in Figure 1(b).

The sand box with dimensions of 460 mm × 460 mm × 230 mm was placed on a sound-deadening pad to minimize undesired noise and vibration. Clean medium river sand with water content of approximately 8% was used to fill the sand box. The sand was compacted layer by layer to obtain two different densities (1.33 and 1.46 g/cm³), corresponding to loose and dense sands, respectively. To enhance signal accuracy, we coiled up a 10-m long cable segment for each cable tested, forming five 350-mm diameter circular cable coils. Each coil of cables (tested separately) was buried at a depth of 100 mm whereas the loudspeaker was shallowly buried at a depth of 30 mm. Moreover, the cable coil was connected to 50-m long single-mode optical fibers at both ends to avoid strong reflections at the ends of the cable.

A PicoScope oscilloscope connected to the loudspeaker buried above the cable coil was used as the signal generator. The simulated signals were sine waves at four different frequencies (50, 100, 150, and 200 Hz) with constant amplitude of 40 mV.

A commercial DAS IU (Fib-Tech’s Ada-5034S) was used to record at sampling rate of 1000 Hz with 6 m gage length and 0.4 m channel spacing. The instrument was attached to one end of the cable inside the sandbox. DAS recordings were made for each stimulated acoustic signal over 10-s time periods.

In summary, we tested five fiber-optic cables at four acoustic frequencies and two sand densities and hence 40 different testing conditions.

| Name | Description |
|------|-------------|
| BF   | Bare fiber  |
| LT   | 5-mm diameter loose-tube cable, without gel |
| TB   | 2-mm diameter tight-buffered, TPU-jacketed cable |
| SS   | 5-mm diameter tight-buffered, steel strand-reinforced, PE-jacketed cable |
| FP   | 7.2-mm diameter steel strand-reinforced, MDPE-jacketed fixed-point cable |
3. Results and discussion

3.1. DAS data processing

A description of the DAS data processing procedure is presented through a typical test result and is shown in Figure 2(a). The figure depicts a 10-s raw DAS time series of the TB cable with 150 Hz sine wave. A fast Fourier transform (FFT) was applied to the signal to obtain the Fourier spectrum as shown in Figure 2(b). The Fourier amplitude at the testing frequency was regarded as the DAS amplitude (e.g., 2986 in this case). This data processing procedure allowed for the comparison of the amplitude response of the five cables at variable acoustic frequencies and sand densities.
3.2. Influence of cable type

In evaluating the influence of cable type on the DAS amplitude response, the Fourier amplitude of each cable was normalized to that of the BF. The relative amplitude ($R_c$) is expressed in logarithmic scale (dB) as

$$ R_c = 20 \log_{10} \left[ \frac{\text{Fourier amplitude (Cable)}}{\text{Fourier amplitude (Bare fiber)}} \right] $$  \hspace{1cm} (1)

As shown in Figure 3, obvious differences in $R_c$ between the tested cables were observed. The maximum difference was 20.4 dB observed at 150 Hz for the loose sand. Although the sand density and signal frequency had a significant impact on the results, the BF had superior DAS amplitude responses compared with all other cables, except for the TB at high frequencies. This result was related to the cable structure; the stimulated acoustic wave could directly affect the BF through the sand, whereas for other cables, complex packaging considerably reduced the acoustic energy. Nevertheless, this effect appeared to be minor at higher frequencies as indicated by a decrease in $R_c$ with increasing signal frequency. The acoustic performance of the TB was better than that of other three cables; it was even better than the BF at 150 Hz (loose sand) and 200 Hz (dense sand). The reason for this was its tight-buffered structure and relatively low elastic modulus that enabled the fiber to be better coupled with the sand. This made it more sensitive to the propagating acoustic waves. Unexpectedly, although also tight-buffered, the SS and FP did not outreach the LT. This was probably due to the steel strand reinforcement, which hindered sand-to-fiber acoustic transfer. Similar results were reported by Freeland et al. [8], who investigated the acoustic sensitivity of various cable structures during a field investigation. Zhang et al. [6] performed analytical modeling of the ground-to-cable strain transfer for cables directly buried in the ground. Although the authors focused on distributed strain sensing (DSS), their calculations indicated that armored cables reduced the strain transfer efficiency due to high cable moduli.

Figure 2. Test results of the TB cable at 150 Hz sine wave. (a) DAS time series; (b) DAS Fourier spectrum.
3.3. Influence of sand density and acoustic frequency

Similar to the cable type, the impact of sand density on the DAS amplitude response was also evaluated by considering the relative amplitude ($R_d$) between dense and loose compaction states:

$$R_d = 20 \log_{10} \left( \frac{\text{Fourier amplitude (Dense sand)}}{\text{Fourier amplitude (Loose sand)}} \right)$$  \hspace{1cm} (2)

Figure 4 shows that the influence of sand density was apparently dependent on the cable structure and acoustic frequency. At first glance, $R_d$ seemed to change sign from positive to negative with increasing signal frequency. This trend was especially evident for the LT with the cutoff frequency being within the range 150–200 Hz. For the SS and FP, the effect of sand density was less evident at 50–150 Hz frequency; however, at 200 Hz frequency the recorded amplitudes in the dense sand were much lower than those in the loose sand. Previously, it was thought that a cable would couple better with surroundings (and hence a better acoustic response for the cable) at higher medium densities. Our initial data here, however, suggested that this effect was strongly frequency dependent, which could be related to the characteristic frequency of different cable structures. It is noteworthy that the site amplification effect might also give rise to such a contrast for field applications. We acknowledge that there were deficiencies in the current test setup: (1) there were reflected waves that interfered with the DAS measurements due to the small sand box size; (2) limited by the sample rate of the DAS IU, the frequency band was narrow. To pursue an in-depth understanding of the DAS amplitude response, the factors mentioned above should be fully considered together with refined experimental designs.
4. Summary
Laboratory tests were conducted to investigate the influence of sand density and acoustic frequency on the acoustic performance of different types of fiber-optic cables. Initial results obtained suggested that complex packaging structures had unfavorable impacts on the DAS amplitude response. The bare fiber and simple tight-buffer structure exhibited higher acoustic sensitivity than the other tested cables; however, the difference became less evident at high frequencies. The influence of sand density on DAS amplitudes was strongly frequency dependent. This could be related to the cable characteristic frequency. Ongoing laboratory tests with a refined setup (larger sandbox and wider frequency band) as well as in-situ tests will strengthen our understanding of the coupled effects of cable type, medium density, and acoustic frequency on DAS signal quality.

Acknowledgments
We thank D. Zhang for providing the PicoScope oscilloscope; P. Yang, J.-Y. Guo, P. Zhong, and J. Liu for laboratory assistance; and Z.-W. Ding for raw data processing. This work was supported by the National Natural Science Foundation of China grant 41427801 (to B.S.). C.-C.Z. acknowledges support by the National Key Research and Development Program of China grant 2019YFC1509601. We also acknowledge support by the project “Research on Key Technologies of Monitoring and Early Warning of Geohazards Along Pipelines with Accompanying Fiber-Optic Cables” granted by the West-to-East Gas Pipeline Company, PetroChina Company Limited.

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