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Fiber optic cable as acoustic sensor in high resolution seismic tests – a feasibility studie

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ABSTRACT: We present results from two consecutive rounds of feasibility studies that aim to test fiber optic cable used as an acoustic sensor in seismic surveys for geotechnical applications. Data from different fiber optic DAS (Distributed Acoustic Sensing) systems, commercial and scientific, is compared with conventional technology, i.e. hydrophones, geophones and accelerometers. Tests are made in different settings and scales, from concrete structures with discontinuities to tests of stabilized ground and site investigation for tunnelling in underwater conditions. The different projects have been carried out as practical field studies where fiber optic cable has been tested under the same conditions that prevail in real life investigations for different types of geotechnical infrastructure projects.
Fiber optic cables placed on the seabed without additional coupling than it's own weight seems to be a good sensor for measuring seismic wave events such as refracted waves. Based on the results, it looks like optical fiber may in the future be a powerful tool for seismic measurements for integrated geophysical surveys in high resolution geotechnical investigations, as it has already proven to be in larger scale surveys in e.g. the oil and gas industry.
The success of fiber optic cable placed in solid medium depends strongly on the coupling that is achieved. Examples from fiber in cemented or grouted installations show encouraging results while installations in soil seem to be more challenging. However, the resolution of the fiber optical system seems to be an important factor, and future developments will most likely provide systems better suited.
As optical fiber systems are new technology under constant development, they are still linked to fairly high costs. However, being a market that is under extremely fast development there will most likely be advanced systems available for geotechnical site investigations within few years.

KEYWORDS: Optical fiber, Digital Acoustic Sensing, Seismic survey, site characterization

1 INTRODUCTION

Distributed Acoustic Sensing (DAS) is a recent development of fiber optic technologies. DAS records acoustic waves, measuring the strain of the optic fibre as it is subjected to elastic vibrations. DAS has gained popularity over the past years and has shown to be a good alternative to standard seismic receivers in seismic and seismological applications (Dou et al., 2017; Ajo-Franklin et al., 2019). The majority of the applications for this innovative methodology have been focused on deep seismic exploration, mainly for the oil and gas sector, due to the relatively low spatial resolution of the technique and the high costs of the instruments. As this methodology is consolidating and the technical developments advances towards higher spatial resolutions and decreased instrument cost, DAS will open extensive possibilities for medium- and small-scale applications in near-surface civil and environmental engineering.

This paper presents the outcome of three projects that were performed in two consecutive stages with the aim of testing the feasibility of DAS applied to high resolution engineering applications. The majority of the work has been focused on underwater refraction and surface wave seismic surveys with the purpose of mapping soil depth and rock quality. There have also been done tests on land, both on virgin soil and cement/lime stabilized soil and on concrete structures. All the tests can be considered small- to mid-scale DAS applications. When talking about high resolution in engineering geophysical applications we normally consider sensor distances of a few meters down to a few tens of centimeters.

1.1 *Stage 1*

The projects in the first stage were "Integrated geophysics for mapping soil depth and rock quality in underwater passages - Test of optic fibre" (Wisén & Rossi, 2021) and "Quality control of soil stabilization through seismic measurements with fiber optics" (Rossi et al., 2020). The two projects where both primarily funded by the VINNOVA strategic innovation program InfraSweden (VINNOVA is the Swedish innovation agency). The "integrated geophysics" project were also co-funded by BeFo (Stiftelsen Bergteknisk Forskning/Rock Engineering Research Foundation).

The projects were planned, managed, performed and reported mainly by the two authors of this paper: Matteo Rossi from the department of engineering geology, LTH; and Roger Wisén from Impakt Geofysik AB. Impakt Geofysik AB supplied the conventional underwater measurement systems and boats while LTH provided the conventional land measurement systems. Both LTH and Impakt Geofysik AB were project partners together with a third company, Hydroresearch AB, who supplied the DAS system.

The system tested was a state of the art, high resolution system, the Carina® Sensing System from Silixa Ltd. And delivered by Hydroresearch AB. It was tested together with a special engineered ("constellation") fiber that was embedded in a ruggedized cable. Different conventional seismic systems were used in parallel to verify the results.

Even though the applications of the seismic method in the two projects where very different they were in practice conducted as one. This worked fine since the tests where a feasibility study of the optic fiber sensor and the seismic signals in both applications were similar. Running the projects in parallel made it possible to make the most out of the funding and maximise the outcome. One specific reason for combining the studies was the high cost for accessing the DAS instruments, and another reason was that it became easier to attract competent advisors and experts to participate in the reference group. This synergy permitted us to develop a deeper understanding of the capabilities and limitations of DAS technology for engineering applications.

Briefly described, the outcome of the stage 1 projects was positive. The optical fiber as seismic sensor showed promising results. However, the choice of the specific fiber that was tested limited the possibility to see some of the interesting wave types. The budget did not allow for further tests and therefore it was decided to apply for a second stage to continue the feasibility study.

1.2 *Stage 2*

The project “Integrated geophysics for mapping of soil depth and rock properties in water passages – Stage 2” was primarily funded by BeFo (Stiftelsen Bergteknisk Forskning) with co-financing from the University of Cagliari (Italy). The project partners in this stage were Engineering Geology at LTH and Impakt Geofysik AB with the same responsibilities as in stage 1. In addition, the Fiber Optic and Photonics unit at RiSe (Research Institute of Sweden) was involved as project partner, with responsibility for the DAS systems, and the department of Chemical and Geological Sciences at the University of Cagliari with special focus on modelling of the seismic data collected.

Instead of only one commercial high-end system this project used a few different and less costly systems: An O-DAS interrogator manufactured by Omnisens with a standard telecommunication cable; a prototype under development by RISE with a standard telecommunication cable;
and an iDAS v2 interrogator manufactured by Silixa ltd with a Helically Wound Cable fibers, containing fibers in jelly filled loose tube, with a wrapping angle of 30 degrees a research prototype system with a telecommunication fiber. One of the purposes was to see if less costly systems could deliver useful data. A collaboration was made with the Fiber Optic and Photonics unit at RiSe (Research Institute of Sweden), who provided the first two systems, and with Deltares (Neatherlands) who delivered the iDAS system. Different conventional seismic systems were used in parallel to verify the results.

This project focused fully on geophysical measurements in an underwater environment and experiments were conducted in lake Västersjön in Sweden, a site that was also used for the underwater experiments in Stage 1.

Figure 1. The test site location (red star) on lake Västersjön in southern Sweden.

Also, the stage 2 project was a partial success and together with the results from the Stage 1 projects we conclude that DAS systems can effectively record low-frequency surface waves. However, more tests and improvements are needed before we can conclude that detection of weaker critically-refracted events can be made sucessfully. The logistical advantages of fiber optics cables are significant, and future steps include deploying cables in a grid configuration for full 3D surveys, improving the characterization of bedrock and identifying faults and weak zones. Applications have been made to secure funding to continue this work.

2 FIELD TESTS AND RESULTS

2.1 *Test site*

As mentioned in the introduction all underwater tests were performed in the lake Västersjön, in the municipality of Ängelholm on the south side of Hallandsåsen (Sweden). This site was selected already in Stage 1 and the same test site was then used also for the following projects, for sake of comparison with previous results and due to the favorable geological conditions. The water depth gradually increases from the shoreline to a max of 10 m at about 300 m out in the lake. The geology consists of quaternary sediments with a thickness of 10-20 m, on top of crystalline bedrock. Seismic refraction data are particularly clear with a high signal-to-noise ratio (SNR), since anthropic noise is extremely limited. Moreover, the logistics are convenient for deploying underwater cables by small boats.

Figure 1 shows the location of the test site on a map. The same test site has been the location of all underwater experiments presented here.

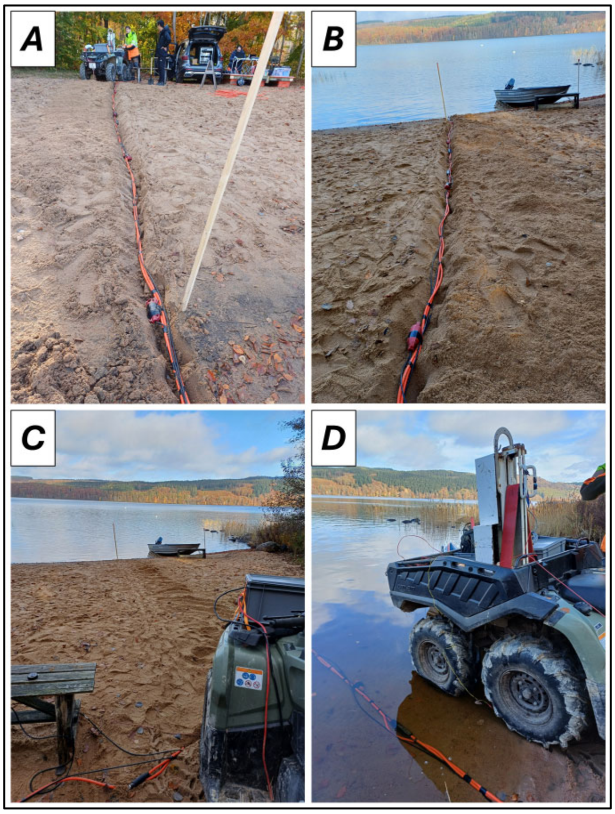

Figure 2. Pictures of the third experiment: A) open trench onshore for the burial of hydrophones and fiber optics cables; B) same open trench as A from the opposite direction; C) closed trench with the buried cables; D) the accelerated weight drop, mounted on a six-wheel vehicle.

2.2 *Experimental setup*

The underwater source differed for the different tests. In stage 1 it consisted of explosives mounted on steel spacers on a hydrophone bay cable. The spacers made sure that the explosive charge had a distance of approximately 60cm from the cable. The explosives consisted of 25g PETN detonated by electronic detonators with high timing precision. In Stage 2 a 20 CuIn airgun was used instead. Calculations and experience show that these two sources are comparable in signal and amplitude. On shore an accelerated 50Kg weight drop mounted on a 6x6 ATV was used as source. Figure 2 shows some pictures from the site.

2.3 *Results*

The results of the underwater test in the Stage 1 project clearly showed that the signal from DAS is analogous to standard seismic receivers.

The site has a geometry of the geological media and a contrast of properties that is particularly favorable for underwater seismic refraction analysis, which was a reason for selecting this experimental site. The results of P-wave seismic refraction tomography presented in Figure 3 clearly show the presence of the fastest bedrock (>3000 m/s) at 15-20 m below the shallower quaternary sediments (<2000 m/s).

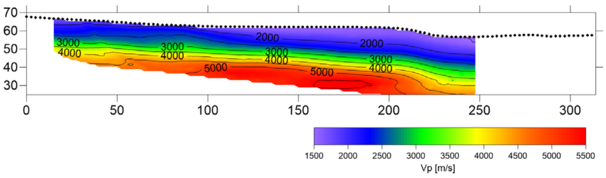

Figure 3. P-wave Refraction tomography section of the hydrophone data for the underwater test in Stage 1.

The DAS recordings contain refracted P-wave energy that can be identified in a shot record, and that compares very well with the hydrophone data that is presented in Figure 4. However, the direct wave and the refracted signal closest to the source is masked by a linear and high-magnitude event that is not present in the hydrophone data. This anomalous event has a constant velocity of about 3050 m/s and it is most likely due to the resonance of the fiber cable itself. The cable used in this study was a very rugged kevlar coated and steel core reinforced cable, loosely settled on top of the lacustrine sediments. The cable could freely vibrate when an external source was applied.

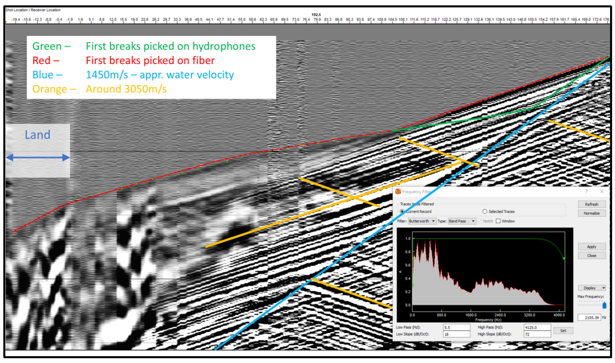

Figure 4. Shot record from the DAS system and the underwater survey in stage 1. The highlighted seismic events: red line, first arrivals picked on the DAS data; green line and dots, position of first arrivals picked on the hydrophone data (from the same shot, note the green dots that follow the red curve along the first 2/3 of the seismogram); blue line, direct wave in water; orange lines, pervasive "vibration" in the fiber optics cable. The plot in the bottom right corner shows the frequency spectra, from 0-4kHz, of the seismic data. The axis of the main plot have the following characteristics: X, tick mark distance 3.6 m and total length of appr. 199 m; Y, toal length of appr. 100 ms.

3 CONCLUSIONS

In these projects, we have tested different fiber optics solutions for high resolution and shallow underwater seismic investigations.

As general remarks, DAS systems can properly record the low-frequency and long-wavelength surface waves, while the direct and refracted events are more difficult. The characterization of surface waves, thus an estimation of the shear wave velocities, is without any doubt a seismic method that can employ fiber optic sensing instead of traditional hydrophones.

Some efforts have been made to develop and improve prototypes of DAS equipment, able to increase the spatial resolution of the method. Even if the amount of resources employed in the development of hardware and software of the DAS systems was limited, the results are satisfying, opening for further improvements of the technologies.

The critically-refracted event was better recorded by the DAS equipment in the Stage 1 experiment, but unfortunately disrupted by a secondary signal deriving from the stiffness of the fiber cable. In that case, the adopted fiber optics was an engineered fiber where additional scattering points are added in the fiber core. This unfortunately means that you need a dedicated instrument that is uniquely developed for this specific type of fiber. The main problem of such custom-made solution is the dependance from a single manufacturer of optical fibers and interrogators, with increased costs. Moreover, this aspect precludes the use of telecommunication "dark fiber" that might be already present in many water passages, especially in archipelagos areas.

Due to the lightness of optical fiber cables, it is necessary to use some kind of heavier material (like weighted rope) for sinking the cable to the bottom of the water body and ensure a good coupling with the sediments that are transmitting the acoustic waves.

The logistical advantage of the fiber optics cables was indisputable during fieldwork operations. The logistics would even have greater benefit if the survey was conducted at a larger scale, where an increasing number of hydrophones is often impracticable and further logistical activities are needed for retrieving and moving the hydrophone cable. In this case, a longer fiber optical cable could be laid out at the beginning of the survey, without impacting the spatial sampling.

Due to the simplicity of handling long fiber optics cables, a future step would be to deploy the fiber cables in a grid configuration, where only the source will be moved around to acquire a full 3D survey, for estimating both compressional and shear wave velocities. A 3D survey of a water passage, as large as the planned infrastructure and acquired at the same time span of a linear survey with traditional geophones, will be a great advantage that can improve the characterization of the bedrock. In a 3D model, faults and weak zones can be better identified in their extension and directions.

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