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STIFTELSEN BERGTEKNISK FORSKNING
ROCK ENGINEERING RESEARCH FOUNDATION

INTEGRATED GEOPHYSICS FOR MAPPING SOIL DEPTH AND ROCK QUALITY IN UNDERWATER PASSAGES – Test of optic fibre

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Cover photo: Figure 14 Workboat and placement of the seismic cables close to shoreline.

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Test of optic fibre

Integrerad geofysik för kartläggning av jorddjup och bergkvalitet i vattenpassager

Test av optisk fiber

Roger Wisén, LTH/Impakt Geofysik AB

Matteo Rossi, LTH

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PREFACE

Unforeseen rock conditions are a risk factor that often leads to delays and extra costs during construction works. There are two geological conditions that are considered important to identify, manage or possibly even avoid, for safe and efficient underground constructions. The first is poor quality rock and the second is a large leakage of groundwater into the tunnel. Water passages are often the parts of a rock tunnel where there is the greatest risk of problems with poor rock quality and water leakage.

The traditional method for finding the fresh rock surface is soil/rock probing, which, however, provides only punctual information. Moreover, extensive and expensive logistics are required to probe on the water.

Integrated geophysical surveys, using both seismic refraction (SR) and geoelectric tomography (ERT), can provide valuable information about the geological structures, which together with traditional geotechnical survey results can create synergy effects and improve the end result.

The project is a feasibility test of DAS (Distributed Acoustic Sensing) for mid-scale underwater seismic surveys. DAS uses fiber optics as seismic sensors and there are several advantages instead of traditional sensors:

- ✓ Lighter and thinner cables enable to use smaller and cheaper boats that are easy to manoeuvre and can be used in shallow water.
- ✓ Co-located ERT and SR cables eliminate uncertainty of sensor positions.
- ✓ Simultaneous acquisitions of ERT and SR via DAS is possible, because the is no signal interference between the methods. This means a considerable reduction of the measurement time in the field.
- ✓ Increased resolution compared to traditional hydrophone cables that usually have a 5 m hydrophone distance.

This project was carried out during the years 2018-2020 at the Department of Technical Geology at Lund University, Lund University. Funding came from BeFo (Stiftelsen Bergteknisk Forskning, id: 214) and Vinnova (id: 2018-00643), and support from Hydroresearch AB, especially Sam Johansson, and Silixa Ltd. Matteo Rossi and Roger Wisén are the main authors of the final report and have performed all seismic measurements and analysis of data.

The project's reference group supported the project and consisted of Björn Lund (Uppsala University), Claes Vahlberg and Fredrik Kullander (Swedish Defense Research Institute), Tara Wood (Ramboll), Lars Nilsson (NCC), Martin Holmén (Swedish Geotechnical Institute) and Per Tengborg (BeFo).

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FÖRORD

Oförutsedda grundförhållanden är en riskfaktor som ofta leder till förseningar och extrakostnader i samband med anläggningsarbeten. Det är framförallt två geologiska faror som bedöms som viktigast att kunna identifiera, hantera eller eventuellt även undvika, för säkert och effektivt bergbyggande. Den första är instabilt berg och den andra är stora inläckage av grundvatten till tunneln. Vattenpassager är många gånger de delar av en bergtunnel där det är störst risk för problem med dålig bergkvalitet och vatteninläckage.

Den traditionella metoden att hitta bergytan är JB-sondering, vilket dock ger information endast i sonderingspunkterna. Det dessutom krävs omfattande logistiska åtgärder för att kunna sondera på vattnet.

Integrerade geofysiska undersökningar, där både seismisk refraktion (SR) och geoelektrisk tomografi (ERT) används, kan ge värdefull information om de geologiska strukturerna, som tillsammans med traditionella geotekniska undersökningsresultat kan skapa synergieffekter och förbättra slutresultatet.

Detta projekt avser en genomförbarhetstest, där DAS (Distributed Acoustic Sensing) används för medelstora seismiska undersökningar under vatten. Det skulle medföra flera fördelar att använda optisk fiber istället för traditionella sensorer för:

- ✓ Lättare och mindre sensorkabel möjliggör undersökning m.h.a. mindre och billigare undersökningsbåtar som är lättmanövrerade och kan användas på grunt vatten.
- ✓ Samlokaliserade sensorkablar eliminerar osäkerhet m.a.p. inbördes sensorpositioner.
- ✓ Samtidig mätning av ERT med elektriska signaler och SR med optiska signaler möjlig eftersom man undviker signalstörning mellan metoderna. Detta innebär en reduktion av mättiden i fält och därmed stora effektivitetsvinster.
- ✓ Ökad upplösning jämfört med att använda traditionella hydrofonkablar som oftast har 5m hydrofonavstånd.

Projektet genomfördes åren 2018-2020 på avdelningen för Teknisk Geologi vid Lunds Tekniska Högskola, Lunds Universitet. Finansieringen kommer från BeFo (Stiftelsen Bergteknisk Forskning, id: 214) och Vinnova (id: 2018-00643), samt stöd från Hydroresearch AB, speciellt Sam Johansson, och Silixa Ltd. Matteo Rossi och Roger Wisén är huvudförfattare till slutrapporten och har utfört alla seismiska mätningar och analys av data.

Projektets referensgrupp har stöttat projektet och bestod av Björn Lund (Uppsala Universitet), Claes Vahlberg och Fredrik Kullander (Totalförsvarets forskningsinstitut), Tara Wood (Ramboll), Lars Nilsson (NCC), Martin Holmén (Statens geotekniska institut) samt Per Tengborg (BeFo).

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Per Tengborg

SUMMARY

Distributed Acoustic Sensing (DAS) is a recent development (last decade) of fiber optic technologies. DAS records acoustic waves, measuring the stretching of the fiber optic subjected to elastic vibrations. The majority of the application for this innovative methodology have been focused on deep seismic explorations, mainly for the oil and gas sector, due to the low spatial resolution of the technique and the high costs of the instruments, still under development. As this methodology is consolidating and the technical developments are rapidly advancing towards higher spatial resolutions, DAS opens extensive possibilities for medium/small scale applications in civil and environmental engineering.

The project is a feasibility test of DAS for mid-scale underwater seismic surveys.

Traditionally, soil/rock probing is used to determine depth to rock, which only provides information at the probing points. Because extensive logistics are required to probe on the water, usually from specialised drilling vessels, jack-up rigs or anchored barges, it is time-consuming and expensive. In some cases, interference with shipping routes might create an even more complicated situation, making probing impossible or at least cause delays in the site investigation program. The integration of Seismic Refraction (SR) acquisitions with Electrical Resistivity Tomography (ERT) surveys can provide valuable information on the geological structures, which can be integrated with traditional geotechnical probing and create synergy, improving the final result.

The project has been focused on the comparison of the Silixa Carina DAS system with standard hydrophones. In addition to seismic measurements, geoelectrical measurements were made to facilitate a complete and integrated engineering geophysical dataset for further analysis, and to get reference data for the seismic results.

The results from analysing the seismic signal in both fiber (DAS) and hydrophone data clearly show that the signal from fiber optics contains refracted P-wave energy that can be used for first arrivals picking, and that compares very well with the hydrophone data. However, the direct wave and the refracted signal closest to the source are 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 frequency 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 then freely vibrate when an external source was applied, much like a pinched “guitar string”.

We conclude that a fiber optic cable placed on the sea bed without further coupling than its own weight is a very good sensor for measuring refracted seismic waves. Due to the type of fiber cable used in this study velocities below 3050 m/s have not been possible to study and therefore it cannot be concluded that it can measure direct waves.

Overall, the result from this study must be considered a success. Beforehand there was no knowledge and no expectations on the fiber cable´s ability to sense refracted energy while placed loosely on the seabed. Now the authors of this study can confirm that fiber can be a powerful tool for near surface engineering geophysical studies. Further tests need

to be done in order to show if fiber can also sense the direct wave in water and then which type of fiber that should be used.

As a final remark, we consider that DAS can constitute a very powerful tool for short and long term seismic measurements as part of underwater integrated geophysical studies in infrastructure projects.

Keywords: Distributed Acoustic Sensing, fiber optic, underwater geophysics, seismic refraction, Electrical Resistivity Tomography.

SAMMANFATTNING

Distributed Acoustic Sensing (DAS) är en ny (senaste decenniet) tillämning av fiberoptiska tekniker. DAS registrerar akustiska vågor genom att mäta den töjning i fibern som uppkommer när den utsätts för elastiska vågrörelser. Huvuddelen av tillämpningarna för denna innovativa metod har hittills varit relaterade till seismiska undersökningar med stort mätdjup, huvudsakligen inom olje- och gassektorn, på grund av metodens begränsade spatiala upplösning och de höga kostnaderna för instrumenteringen, som fortfarande är under utveckling. Efterhand som metoden snabbt utvecklas och mognar, kan vi dock se fram emot högre spatial upplösning, vilket gör att nya möjligheter öppnas för tillämpningen av DAS inom bygg- och anläggningssektorn, liksom miljötekniska sådana.

Detta projekt avser en genomförbarhetstest, där DAS används för medelstora seismiska undersökningar under vatten.

Den traditionella metoden att hitta bergytan är JB-sondering, vilket dock ger information endast i sonderingspunkterna. Eftersom det krävs omfattande logistiska åtgärder för att kunna sondera på vattnet, i form av borrfartyg, jack-up-plattformar eller ankrade pråmar, blir dessa operationer kostsamma och tidskrävande. I vissa fall skapar fartygstrafik i farleder en ännu mer komplicerad situation, vilket kan göra det omöjligt eller i vart fall försena förundersökningarna. Integrerade undersökningar, där både seismisk refraktion (SR) och geoelektrisk tomografi (ERT) används, kan ge värdefull information om de geologiska strukturerna, som tillsammans med traditionella geotekniska undersökningsresultat kan skapa synergieffekter och förbättra slutresultatet.

Projektet har i huvudsak varit inriktat på att jämföra DAS-systemet Silixa Carina med standardhydrofoner. Förutom de seismiska undersökningarna genomfördes geoelektriska mätningar för att skapa ett komplett integrerat ingenjörsgeofysisk dataset för vidare analys och som jämförelsebas för de seismiska undersökningarna.

Resultaten från jämförelsen av fiberdata (DAS) och hydrofondata visar tydligt att den fiberoptiska metoden kan registrera refrakterade P-vågor, och att det även går att se de första ankomsttiderna. Resultatet stämmer väl överens med hydrofonregistreringarna. Dock maskeras i DAS-registreringen direktvågen samt den del av den refrakterade signalen som ligger närmast källan av en linjär störning med hög amplitud som inte kan ses i hydrofondata. Störningen har en konstant hastighet på 3050 m/s, och härrör sannolikt från en resonansfrekvens från själva fiberkabeln. Kabeln som användes i studien är ”ruggad”, förstärkt med kevlar och en inre stålvajer, och läggs ut på de lösa sjösedimenten. Kabeln kan då vibrera fritt när externa krafter påverkar den, ungefär som en ”gitarrsträng” som anslås.

Vår slutsats är att en fiberoptisk kabel som läggs ut på sjöbotten utan annan akustisk koppling än sin egenvikt är en mycket god sensor för refrakterade seismiska vågor. På grund av den aktuella kabeltypens utförande kunde vi dock inte studera hastigheter under 3050 m/s, och vi kan därför inte fastslå att även direktvågen kan registreras.

På det hela taget är projektet framgångsrikt. Innan projektets genomförande fanns ingen kunskap om möjligheterna för fibertekniken att registrera refrakterad energi när kabeln läggs direkt på havsbotten. Vi kan nu bekräfta att fibertekniken kan vara ett kraftfullt verktyg för ytnära geofysiska undersökningar. Det återstår att, med fortsatta försök, visa att även direktvågen kan registreras, och i så fall vilken fibertyp som är lämplig.

Slutligen kan sägas att fibertekniken är ett kraftfullt verktyg för seismiska mätningar över kort eller lång tid, som del av integrerade undervattensmätningar i infrastrukturprojekt.

Nyckelord: Distributed Acoustic Sensins, fiberoptik, geofysik, undervattensgeofysik, seismisk refraktion, geoelektriska mätningar.

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CONTENTS

1. Introduction

1.1 Integrated underwater geophysics

Unforeseen underground condition is a risk factor that often leads to delays and extra costs in connection with construction work. This can also lead to the most suitable technical solutions not being used, which in turn can lead to increased operating costs and reduced technical lifetime for the design. Above all, there are two geological hazards that are considered to be of high importance to identify, manage or possibly also avoid, for safe and efficient rock construction. The first is low quality rock and the second is large groundwater leakage into the tunnel. Leakage of groundwater is a problem that is present in most tunnel projects. Water passages are often associated with those parts of a rock tunnel with the greatest risk of problems with poor rock quality and water leakage. The reason for this is that the water passages are generally located where the largest zones of weakness in the rock are located, and where there is unlimited water supply in the vicinity of the fracture zones. It is therefore extremely important to make good preliminary investigations in water passages.

Generally speaking, it is easiest to influence the design and cost in early stages of a project. As the project progresses, more and more resources are used, while opportunities for influencing the design are reduced, which means that forced changes as a result of unforeseen geology can become very costly because the scope of action is limited (Lundman 2011).

Traditionally in the glacial geology in Scandinavia, soil/rock probing is used to determine the depth to the (typically unweathered) rock surface, which of course only provides information at the probing points. Because extensive logistics are required to perform sub-bottom probing on the water, usually from specialised drilling vessels, jack up rigs or anchored up barges, it is time-consuming and expensive, and in some cases interference with ship traffic might create an even more complicated situation.

Electrical resistivity tomography (ERT) is now an established site investigation method for tunnelling projects on land, and it has been used on a large scale, e.g. for the Hallandsås tunnel project (Dahlin et al. 1999). The method provides continuous models of variations in the rock's electrical properties in two (2D) or three (3D) dimensions that can be linked to variations in the mechanical and hydraulic properties of the rock.

Refraction seismic is also a well-established method that has been used for a very long time in infrastructure related site investigation. It maps changes in elastic properties and density, and is used for mapping of rock depth and zones of mechanical weakness, normally in 2D.

If ERT and refraction seismic are used at an early stage of the feasibility study together with a conceptual geological and hydrogeological model, the result will be a good overview of structural, mechanical and hydrogeological conditions. This combined geological/geophysical model is an excellent basis for placing points for drilling and sampling, so that they are located in representative positions and minimize the risk of missing critical zones. The results of these in situ drilling studies are then used to verify and improve the preliminary interpretation of the geophysical results.

The idea of using an integrated site investigation approach for underwater infrastructure surveys builds on the findings of the project TRUST 4.2 (TRansparent Underground STructure) (http://trust-geoinfra.se/delprojekt/4-2/index.html). Within the framework of TRUST that has been shown that ERT and seismic refraction tomography (SRT) underwater work well in the context of preliminary exploration for tunnels. As has been shown by e.g. Ronczka et al (2018) there are great advantages in combining these geophysical methods. The methods complement each other by mapping two different physical properties that both to some extent can be said to relate to the hydraulic and mechanical properties of the ground. In addition, the use of two methods (sensing different physical properties) will also generally complement each other with regard to geometrical resolution, measurement errors or technical problems (Dahlin and Wisén 2017; Ronczka et al. 2018). In Figure 1 an example of how these results can look is given, in this case results from Ronczka et al. (2018) that originates from a survey in Stockholm. Since this type of investigation is often performed in urban areas measurement errors need to be considered since the presence of external noise is common in such an environment. Normally these methods are well implemented, and the equipment can be considered as technically mature and technical issues are rare. However, working in an underwater environment always induces a greater risk of failure for any type of work, which needs to be considered. Even if a study where both methods are used is done in the same field campaign, it can be difficult to know if the sensors are correctly positioned relative to each other, if done separately. Positioning of the seismic sensors can be done with high precision in a fairly easy way using acoustic signals from a small source in the water surface. The resistivity cable cannot be positioned in this way unless it is attached to the seismic cable and positioned together with this or if it is equipped with separate positioning devices.

Even if the use of the approach described here already is proven cost efficient for underwater investigations (Wisén et al. 2019) there is a large potential in making the seismic sensors lighter and better. Fibre optical and distributed acoustic sensing (DAS) is a good candidate, thanks to the recent technology developments (Parker et al. 2014). When the technology is ready for near surface seismic applications, data with very high resolution could be gathered simultaneously with an ERT survey both for seismic analysis of the ground and for positioning of the cable.

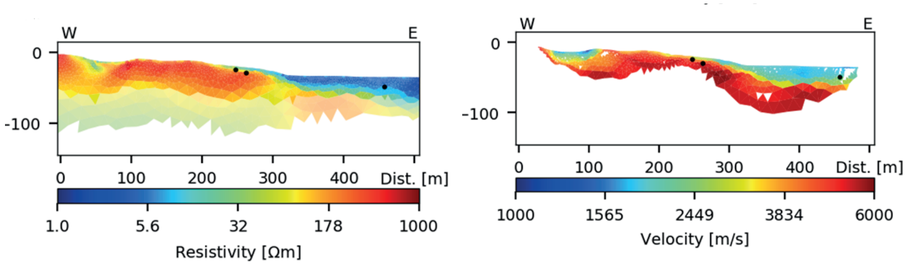


Figure 1 Example of results from joint inversion of ERT (left) and SRT (right) from an underwater survey at Hägersten in Mälaren, Stockholm (Ronczka et al. 2018).

1.2 Background

Distributed Acoustic Sensing (DAS) is a recent development (since approximately 2010) of fibre optic technologies. DAS records acoustic waves, measuring the strain of the optic fibre as it is subjected to elastic vibrations. 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 is advanced 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.

The present document summarizes the outcome of a project that have tested the feasibility of DAS applied to underwater refraction seismic surveys with the purpose of mapping soil depth and rock quality. This can be considered a small- to mid-scale DAS application. This project has run in parallel to another feasibility study of DAS applied in an even smaller scale, *Quality control of soil stabilization through seismic measurements* (Vinnova project number 2018-00643, it has not yet been reported). The two projects where both primarily funded by Vinnova and have, for practical and logistical reasons, been running in parallel with the aim of making an optimal use of the finances and maximising the outcome. Moreover, this synergy permitted us to develop a deeper understanding of the capabilities and limitations of DAS technology for engineering applications. Another reason for combining the studies was the high cost for accessing the DAS instruments, and it has been easier to attract competent advisors and experts to participate in the reference group.

The projects focus on pilot tests for engineering and environmental applications that could largely benefit the DAS technologies. The soil stabilization project tested the DAS performance in a strictly civil engineering application, where we explored the possibility of using fibre optics for assessing the quality of soil stabilization procedures via acoustic measurements. This is generally of very little interest for rock related surveys, but since both projects aimed at testing new technology there are lessons learned from this project that are very relevant. It gives some important insights in understanding the DAS technology for small-scale applications, and in its possibilities and limitations. Also, there were initial questions that needed answers before an expensive marine field survey could be conducted, and these were addressed through an on-land test at the DAS manufacturers facilities. Therefore, some of the tests presented here are not only from underwater surveys, but they are still considered very relevant for this project.

The instrument used in this survey comes from Silixa Ltd, UK, who are among the most experienced and advanced developers and manufacturers of fibre optic sensing technology. Their latest DAS development, the Carina sensing system, was made available to this project very soon after being introduced to the market.

2. Methodology

2.1 Instrumentation

Measurements have been made with four different setups. A first test was performed in December 2018 at Silixa’s facilities in London. These measurements were made with optic fibre using Silixa’s intelligent Distributed Acoustic Sensing (iDAS v3) and a conventional seismic setup using a Geometrics Geode and 3-axial 4.5 Hz geophones.

During the main field campaign in September 2019 measurements were made with three different setups. The Carina Sensing System technology, which encompasses an iDAS v3 interrogator and an engineered (“constellation”) fibre, was used in all of the tests. The DAS data have been compared with different traditional acoustic measurements in accordance with the different applications. In the surveys on land we performed seismic measurements with a DMT Summit X One system with 48 2-axial geophones. The seismic data in water have been acquired through a hydrophone cable with 48 passive hydrophones and an ABEM/Guideline Terraloc Pro. For the underwater test an ERT (Electric Resistivity Tomography) measurement was also performed as reference.

As described in chapters 2.1.2 to 2.1.4 tests presented here are from three different sites, two on land and one in water. The two land sites are the Silixa testing facility outside London, UK, and a test site made available by Skanska and the European Spallation Source (ESS) in Lund, Sweden. On both sites, fundamental insights were acquired about the DAS system’s ability to sense certain wave phenomena that is of interest in this study, even if they are not from underwater tests.

2.1.1 Fibre optic Distributed Acoustic Sensing

Distributed sensing is a technology that enables continuous, real-time measurements along the entire length of a fibre optic cable. Distributed sensing is usually used for acquiring temperature, strain and acoustic data and this project specifically utilizes Distributed Acoustic Sensing (DAS). Unlike traditional sensors that rely on discrete sensors measuring at pre-determined points, distributed sensing does not rely upon manufactured sensors but utilises the optical fibre. The optical fibre is the sensing element without any additional transducers in the optical path.

The interrogator operates according to a time-of-flight process: it sends a series of pulses into the fibre and records the return of the scattered signal against time (cf. radar or lidar) In doing this, the distributed sensor measures continuously along the fibre.

The optical fibre is made of pure glass (quartz) as thin as a human hair. It consists of two parts: the inner core and the outer cladding. Cladding is a glass layer with a lower refractive index to maintain guidance of light within the core. Both parts are encapsulated by one or more layers of primary polymer coatings for protection and easiness of handling.

There are two main types of optical fibre according to communication application standards. These are the *single mode*, intended for long haul communications, and *multimode* for short haul communications. Multimode fibres have a larger core (45 to 50 microns) than single mode fibres (8-10 microns), allowing more light modes to propagate.

The typical diameter of an optical fibre is 125 microns that increases to 250 microns if we include the thickness of standard acrylate coating. For temperature sensing, multimode fibres are usually used, whilst single mode fibres are mostly used in the context of distributed acoustic sensing or strain sensing.

Although Silixa's temperature and acoustic sensors can be used with either single mode or multimode fibre, the performance of the acoustic sensor is better with single mode fibre.

Fibre optic cables can contain many fibres, which can be either a single type or a combination of both. The cable construction depends on the installation, operation and application conditions.

iDAS technology measures the acoustic signal continuously along many kilometres of the optical fibre, with a range resolution that can differ with different applications and types of fibre between 0.25m and 10m.

The iDAS works by injecting a pulse of laser light into the optical fibre. As this pulse of light travels down the optical path, interactions within the fibre occur, which result in light reflections known as backscatter. This backscattered light travels back (inside the fibre) towards the iDAS equipment, where it is sampled. The time synchronisation of the laser pulse allows the backscatter event to be accurately mapped to a fibre distance by using the time-of-flight.

Once the pulse of light has travelled to the end of the fibre and any reflections have travelled back to the interrogator the fibre can be considered to be "dark" and a subsequent laser pulse can be introduced without the risk of interference. For each laser pulse the entire fibre distance is sampled at each point along the length, that could be for example at every 0.25 metre. The result is continuous acoustic sampling along the entire length of the optical fibre without cross talk and with a frequency range from millihertz to over 100 kHz and a dynamic range of over 120 dB.

DAS does not discriminate between the different spatial components of the ground movements (vertical, horizontal in-line with the cable, horizontal perpendicular to the cable), even if the sensitivity is a function of the angle of incidence as reported by Wu et al. (2017). The fibre optic is more sensitive to compressional (P) waves with low-degrees of incident angle (waves propagating in the same direction of the cable), while it is essentially blind to events that propagate perpendicular to the fibre optic. The stronger DAS response to shear (S) waves occurs when the incident angle is around 45 degrees and damps down to no recorded signal for higher and lower incident angles.

Signal to Noise Ratio (SNR) in DAS measurements is largely governed by how much light can be usefully collected from the optical fibre. The ideal fibre should have low signal loss to be able to achieve long ranges, but also high scattering to enhance the amount of reflected light. This apparent contradiction is overcome by the use of a new type of fibre (named "*Constellation*"), where engineered bright scatter centres are implemented along the fibre without introducing significant excess loss in the forward propagating scattered light. Using a dedicated interrogator together with the engineered fibre (Carina system), SNR is increased by 20 dB, equivalent to an improvement of 100 times.

2.1.2 Land seismic setup - Geode system - London test

The measurement system for the London test was comprised of a 3*24 channel Geometrics Geode system with 24 3-axial 4.5 Hz geophones (Figure 1).

The source consisted of a 5 kg sledge hammer applied vertically on a plate and horizontally in the end of a wooden beam (Figure 2).

Figure 2 Line of 3-axial geophones for the London test

Figure 3 Wooden beam as SH source for the London test

2.1.3 Land seismic setup - DMT system - ESS test

The measurement system for the test on stabilized ground at the ESS facility consisted of a 100 channel DMT Summit X One system with 50 2-axial 4.5Hz geophones, vertical and inline horizontal (Figure 3).

The source consisted of an ESS100 Turbo accelerated weight drop applied vertically on a plate. The ESS 100 Turbo use a 50kg (100pound) weight that is accelerated using a powerful rubber band. Shots were also made with a 5 kg sledgehammer horizontally in the end of a wooden beam (Figure 3).

Figure 4 ESS100Turbo accelerated weight drop. The Summit X One Remote Units are also visible together with two geophones next to the wheel of the weight drop.

2.1.4 Underwater seismic setup - ABEM/Guideline system - Västersjön lake test

The measurement system for the underwater test in lake Västersjön consisted of a 48 channel Terraloc Pro from Guideline Geo/ABEM together with a hydrophone bay cable with 48 passive HT96 hydrophones.

The source consisted of explosives mounted on steel spacers on the 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.

2.2 Seismic wave propagation and Processing

Seismic waves are divided into body waves, compressional (P) and shear (S) waves, and surface waves, like the Rayleigh, Lamb or Scholte waves (e.g. Telford et. al 1990). In the land applications we focus on analysis of surface waves, as a base for mapping S-wave velocities, but also look generally at the wavefield and how data from geophones compare with data from fibre optic by looking at e.g. direct or refracted P-waves and S-waves. In the underwater integrated geophysics application, we aim to see if fibre optic can be used for P-wave refraction seismic.

The seismic waves from an active seismic test can be analysed in different ways. Analysis of surface waves is often done as inverse modelling of the fundamental, and sometimes higher, modes to achieve a S-wave velocity profile as those presented in chapter 4.2.

Refraction seismic analysis can be done with a range of different methods. In this project analysis has been made using refraction tomography, with the software Geogiga DW Tomo, where a finite difference model is used for a smoothness constrained iterative inverse modelling (chapter 4.4).

2.2.1 Analysis: Time-Space (TX) and Frequency-Wavenumber (FK) domain

In the present report acoustic data are in many places represented as seismogram images with a coloured pixel for each sample. The seismograms display the amplitude of the recorded signal in time (T) and space (X). They are also named TX plots.

Figure 4 shows the colour bar used for almost all the seismograms plotted in the report. The seismic data is scaled on the absolute maximum amplitude of the recorded waves for each dataset. A direct comparison of the absolute amplitudes recorded by the different seismic techniques is not possible as the acoustic signals, at least from the geophone and hydrophone systems, are not collected with absolutely correct amplitudes. This is normal for many systems used for near surface geophysics as it is enough to know the relative difference in amplitude in many seismic applications.

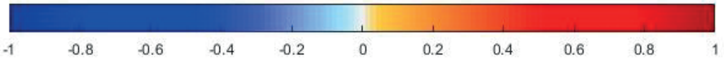


Figure 5 Colour bar used for the seismograms (TX) displayed in the present report. Energy is normalized on the absolute maximum value.

The aim of the project is to investigate capabilities and limitations of the fibre optic fibre as an acoustic sensor for engineering applications. For achieving this goal, it is important to analyse the frequency content of the recorded signal, both in time and space. A tool often used in seismic is what is commonly called the FK transform, where a double Fourier transform is applied: time (T) is transformed to frequency (F) and space (X) is transformed to wavenumber (K). This representation displays the distribution of energy magnitude according to the frequency-wavenumber (or simplified frequency-velocity) content.

Thistransform facilitates the analysis of the frequency content of the acoustic data and permits a better comparison between fibre optic and traditional seismic techniques.

The FK plots highlight the frequency content of surface waves, since they are the most energetic. Less energetic seismic events as refracted and reflected waves are characterized by lower magnitude, so they are not easily detectable in this kind of analysis. There is also high interest in surface waves analysis for investigating stabilized soil, as they might provide information about relevant physical parameters related to the stiffness of the material (i.e. S-wave velocities). However, the kind of seismic that this study is focusing on primarily utilize P-waves and here the FK transform is mainly used to analyse the difference between DAS and geophone/hydrophone data.

Figure 5 shows the colour bar used for all the FK plots in the report. The seismic data is scaled on the absolute maximum amplitude of the recorded waves for each dataset.

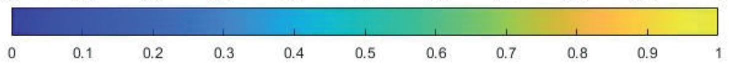


Figure 6 Colour bar used in the FK (double spectral) plots displayed in the present report. Energy is normalized to the maximum magnitude.

3. Fieldwork

For achieving the goals of the project several tests have been performed.

3.1 London test

The first field test was performed on 5th and 6th December 2018 at the Silixa test facility in Elstree, Hertfordshire (UK), where several fibre optic cables are buried in natural soil at a depth of about 30 cm. The experiment was conducted measuring along the fibre optic cables using two different Silixa acoustic instruments: iDAS v3 and iDAS v2 (for the specifications of the acquisition parameters see Table 1).

Several lines with 3-component 4.5 Hz geophones (see chapter 2.1.2) were placed on the topographic surface, exactly on top of the buried fibres.

While this test is on land and therefore does not fulfil the requirements for the specific project there were several arguments for performing it:

- the convenience and cost efficiency of measuring on already installed fibre optic cables
- the site has been extensively used by Silixa, for testing their equipment, hence the quality of the installation is well documented and there is available reference information
- the availability of experts from Silixa
- the possibility of testing two different optical instruments for interrogating the fibre optics (however, this report only present data from the Carina system).

This field test was essential to get familiar with the new type of acoustic acquisition systems and DAS acoustic data and to define their capabilities and limitations compared to the standard geophone seismometers.

We acquired data moving the source in several positions along the profile and also with a lateral offset from the linear location of the sensors. S-waves have additionally been generated shooting laterally on an oak beam (of the type of railway sleeper, see chapter 2.1.2).

Table 1 Acquisition parameters for the different acoustic systems used in the London test.

Parameters	**iDAS v3 (Silixa)**	**iDAS v2 (Silixa)**	**Geode (Geometrix ltd)**
spatial resolution [m]	2	10	Point sensors
spatial sampling distance[m]	0.255	1.021	3, 1 and 0.5
temporal sampling interval [s]	$2 \cdot 10^{-4}$	$2 \cdot 10^{-4}$	$2 \cdot 10^{-5}$
Recording length [s]	1	1	from 0.7 to 1.36

3.2 ESS

The site is located just outside the city of Lund (Sweden), where the new European Spallation Source infrastructure is under construction. Thanks to Skanska Sverige AB and ESS we had the opportunity of performing surveys on top of a slab of stabilized soil, where a comparison between fibre optics and traditional sensors was made. Also this test is on-land and therefore not directly related to the task of evaluating DAS for underwater applications. However, the findings from this study turned out to be very interesting with regard to many aspects of DAS also for the underwater application and has therefore been included here.

The soil has been stabilized mixing layers of natural soil material (clayey till deposit) and layers of binder (quicklime). The area is about 30x20 m and the thickness of the treated soil is around 1.5 m (Figure 6), even if the compaction of the soil during the stabilization process could affect a deeper portion of the ground.

A profile with a fibre installation length of 90 m has been made in the area with the aim of investigating both the stabilized and the natural soil (Figure 8). Along this profile a 30 cm deep trench has been excavated for installing the fibre optic cable (Silixa engineered constellation fibre) within the ground (Figure 7), which is essential to ensure a good coupling between the cable and the surrounding material: i.e. the transmission of acoustic energy from the ground to the cable. The fibre optic cable was placed in the trench on a 2-3 cm thick bed of medium grain sand to reduce the risk of damage due to point pressure from cobbles that are present in the till deposit. The trench has been backfilled with a thin layer of sand and on top of that the soil that was previously excavated. The backfilled trench was then carefully compacted using the weight of the medium sized excavator.

The geophones was placed on the topographic surface precisely above the installed fibre optic cable. Both the geophones and the fibre cable were positioned using a RTK GNSS system, coordinates acquired along the fibre optic cable and at the geophone locations are presented in Figure 9 A. By analysing the elevation of the sensors (Figure 9 B), we can ascertain that the position of the cable in the ground is about 30 cm below the surface along the entire profile.

We acquired data using three different geophone layouts with different receiver spacing (see Table 1), while the acquisition of fibre optic data always involved the entire profile with fixed parameters. Table 2 summarizes the parameters of the acquisitions. For the standard seismic measurements, we used the SUMMIT X ONE system with vertical and in-line horizontal 4.5 Hz receivers. Figure 10 shows an example from Layout 3, where vertical and horizontal geophones are located at the surface with a spacing of 0.5 m.

As source of acoustic waves, we used an accelerated weight drop (see chapter 2.1.3) to be able to transmit enough energy in the ground. This kind of source was necessary to achieve sufficient signal to noise ratio. The noise is mainly due to active construction works in adjacent areas and the heavy traffic along Highway E22 (visible in the north-west corner of Figure 6). For the specifications of the acquisition parameters see Table 2.

Table 2 Acquisition parameters for the different acoustic systems used at the ESS test.

Parameters	**Fibre optic (Carina)**	**Layout 1 (geophones)**	**Layout 2 (geophones)**	**Layout 3 (geophones)**
spatial resolution [m]	2	Point sensors	Point sensors	Point sensors
spatial sampling [m]	0.255	2	2	0.5
temporal sampling interval [s]	$2 \cdot 10^{-5}$	$1.25 \cdot 10^{-4}$	$1.25 \cdot 10^{-4}$	$1.25 \cdot 10^{-4}$
Record length [s]	1.2	1.2	1.2	1.2
local coordinates along the profile [m]	0-90	0-88	1-89	5-24

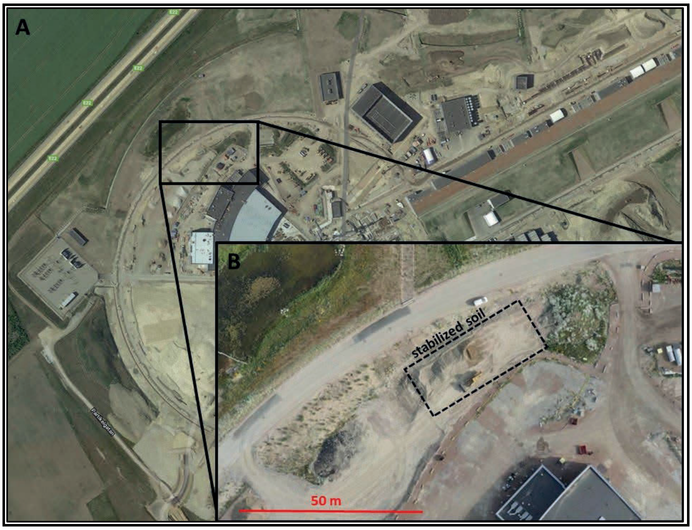


Figure 7 A) Orto photo of the construction area. B) High detailed orthophoto of the area during the construction of the stabilized slab. (courtesy of Skanska ESS Construction).

Figure 8 Pictures of the installation of the fibre optic cable in the ground: left, digging of the trench; middle, cable on top of sand layer; right, backfilling of the ditch with sand and excavated material.

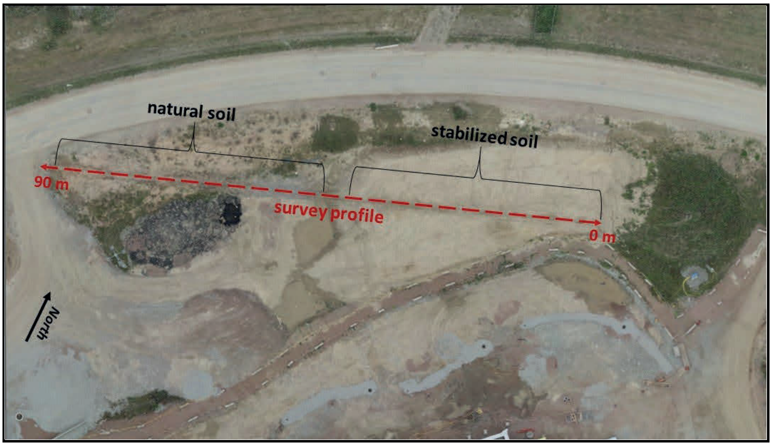


Figure 9 Location of the survey profile with the local coordinates used for the different acquired layouts. The orthophoto (courtesy of Skanska ESS Construction) has been acquired closely after the geophysical survey; the mark of the trench on the soil surface is partially visible below the red dashed line.

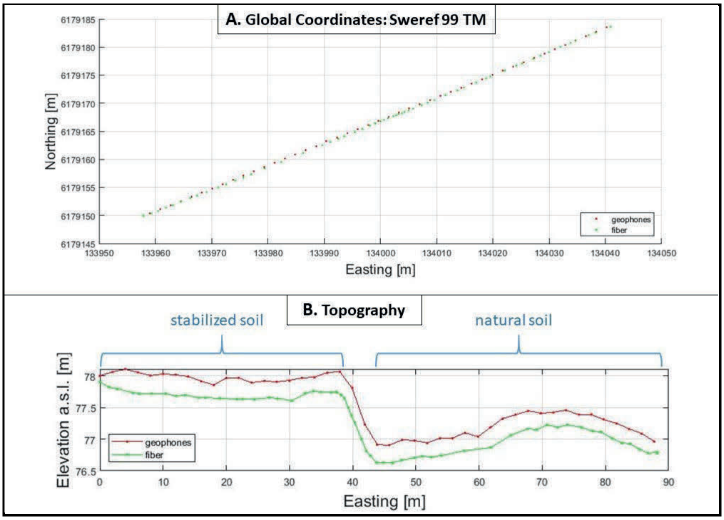


Figure 10 Global coordinates of the location of the fibre optic cable (green dot/line) and the geophones (red dots/line). Plot A shows the planar SWEREF 99 TM coordinates, while plot B shows the elevation of the sensors along the profile.

Figure 11 Example of geophones layout: Layout 3 with 0.5 m spacing, 4.5 Hz geophones. Yellow receivers are the vertical component geophones, while the red ones are the horizontal (in-line) component geophones.

3.3 ESS - pond test

A first underwater test was also made on the ESS site in Lund, placing the fibre cable and hydrophones in a small pond next to the soil stabilization site. The purpose of this test was to assure that the fibre could pick up seismic energy when being placed lying on the bottom of the pond before the more costly field work in lake Västersjön. A hydrophone cable was placed next to the fibre for comparison.

The source for this test was the same accelerated weight drop that was used for the other measurements at ESS. It was not possible to get permission to use explosives in the pond.

The data from this test was not of high enough quality to be useful for a comparative analysis, mainly due to the source being too weak. The hydrophone data also suffered from strong electromagnetic noise most likely originating from a buried powerline at the site. However, it was clear already in the field that the optic fibre could sense the seismic energy and this was enough to decide to go through with the lake test. In addition, it could be concluded that the fibre data did not suffer from the electromagnetic noise.

3.4 Västersjön

The Västersjön site is located in the municipality of Ängelholm on the south side of Hallandsåsen (Sweden). The original plan was to perform this test in connection to an ongoing infrastructure project where there could be reference data from other investigations. However, the timing of the measurements was controlled primarily by instrument availability, due to the fact that the instrument was made available at a much lower cost than for normal commercial projects. In the period when the instrument was available it was not possible to find an ongoing project and the Västersjön site was picked as a replacement based on its proximity to Lund and the conditions at the site that in many ways are what you can expect on an underwater tunnelling site. Thanks to the municipality of Ängelholm we were allowed to perform the seismic test in lake Västersjön. Figure 11 presents the place of the lake in southern Sweden and the position of the investigations in the lake.

The geology at the site was expected to consist of 5-10 m of sand on top of crystalline rock.

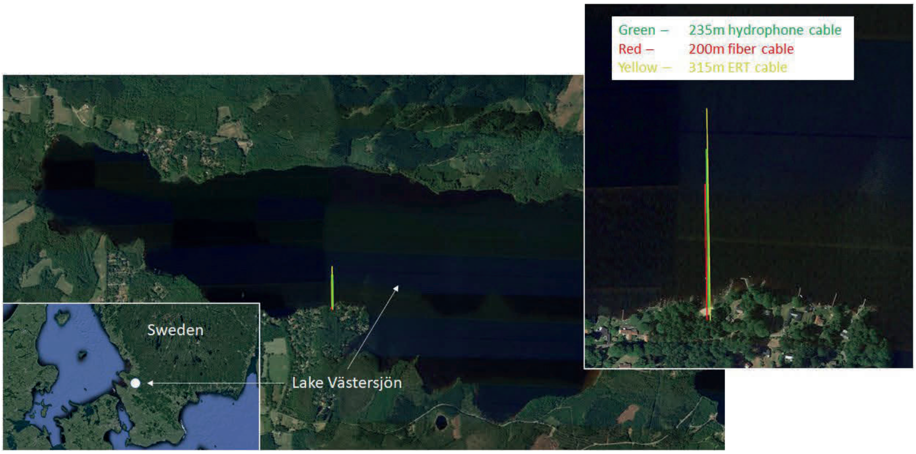


Figure 12 The place of lake Västersjön in southern Sweden and the position of the investigations in the lake.

The cables were placed in the lake by means of an open workboat (see Figure 13). The weather conditions were very good. Except a seismic test using hydrophones and optical fibre (see chapter 2.1.1 and 2.1.4 for description of instrumentation) there was also an ERT (Electrical Resistivity Tomography) measurement made in order to get some more reference data and to get a dataset that corresponds to what could have been collected in a geological/geotechnical investigation in a real project. The ERT was collected using a 64 channel 5m spacing underwater electrode cable (Figure 14).

A single beam echo sounder was used to map the level of the seabed (see Figure 12 for the resulting bathymetric model).

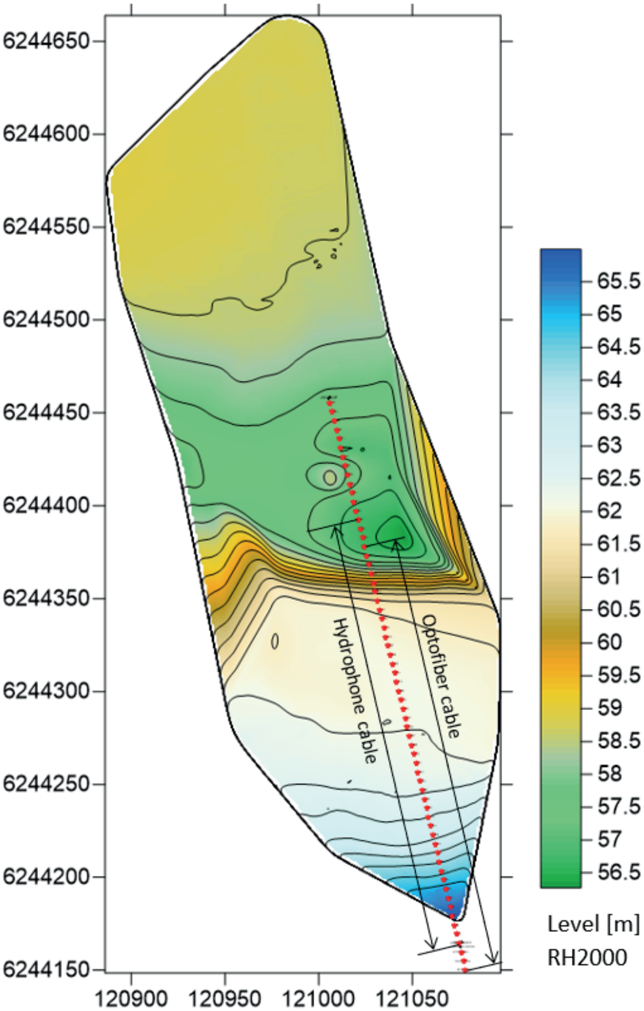


Figure 13 Position of the electrodes for ERT survey on the digital terrain model from single beam echosounder scanning. The coordinate system is SWEREF 99 13 30 and the height system is RH2000. The level of the water at the time of the test was 66.8m.

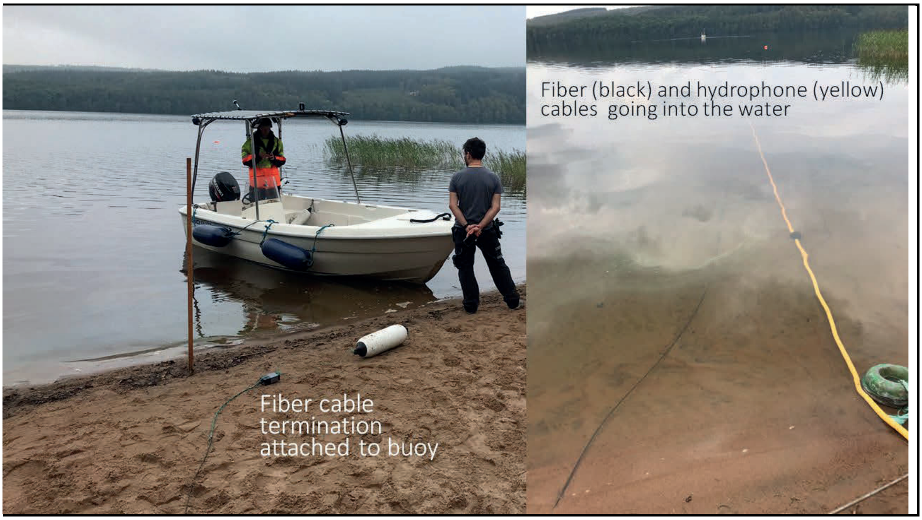


Figure 14 Workboat and placement of the seismic cables close to shoreline.

Figure 15 ERT cable and one installed electrode on the beach. In the water there are no extra connectors or electrodes except the one moulded into the cable.

Table 3 Acquisition parameters for the different acoustic systems used in lake Västersjön.

Parameters	**Fibre optic (Carina)**	**Layout 1 (hydrophones)**	**Layout 2 (electrodes)**
spatial resolution [m]	2	Point sensors	Point sensors
spatial sampling [m]	0.255	5	5
time sampling interval [s]	$2 \cdot 10^{-5}$	$1.25 \cdot 10^{-4}$	$1 \cdot 10^{-3}$
Record length [s]	1.2	1.2	9.5 (1.5s delay and 2 full duty cycles)
local length coordinates along the profile [m]	0-200	15-250	0-315

The tests were performed over two days, one day for the seismic tests and one day for the ERT. All three cables were placed separately in very good weather using an RTK GNSS system and visual aids for determining the vessel position. Anchor positions in the end of the cables in the lake were measured using RTK GNSS. Since the cables were placed separately, they were not in the exact same position but the cables were fixed on shore so the internal misalignment between the three cables in the inline direction was very small. Near the shore they were aligned perfectly and in the end of the fibre optic cable the inline error is estimated to be less than half a meter. Sideways there is risk for a slightly larger misalignment but it should not be more than a few meters.

For the specifications of the acquisition parameters see Table 3.

4. Results and discussion

4.1 London test

The knowledge acquired from this preliminary study has been essential for planning and design of further tests. Looking at the capabilities and limitations of the fibre optic interrogators compared to the traditional geophones array, we decided to limit the following experiments to the Carina system together with the engineered fibre, as the higher resolution of this set-up is an essential requirement for the civil engineering applications that are the aim of the project. This should be set in perspective to the application for this project that included the iDAS system with 5 times lower resolution, something that we now could see would be very difficult to work with in this type of application.

Results from this test are not presented here, since they do not add more information than the experiments that followed and that are presented in chapter 4.2. Moreover, the data quality of the acquisitions in the London test is inferior to successive surveys on other sites, partially due to the source of seismic waves utilized and partially derived by the geology of the area.

4.2 ESS

4.2.1 Analysis of data

The ESS site gives the opportunity to compare traditional and DAS sensors for an engineering application concerning soil stabilization. It was essential to measure on an area where a stabilization procedure was completed, since the acoustic wave velocities are different in different media and predictably higher in stiffer stabilized materials. The correct estimation of acoustic wave velocities in their higher limit is also depending on the resolution of the technique. This is therefore a key point to test the method in such conditions.

The results here presented refer only to acquisition where the source was placed external to the profile (external shots), even if we acquired data shooting also along the line between the geophones. Data recorded with external shots have a higher quality and better show the entire frequency and wavelength content.

Both Layout 1 and 2, with a 2 m inter-geophone spacing (Table 2), cover partially the area of stabilized soil and partially the natural soil (Figure 7). Layout 2 is analogue to Layout 1, the only difference is that the entire array of geophones has been moved 1 m along the profile while the source position was left unchanged. This gives the possibility to combine the acquisitions of both layouts and finally obtain a profile with 1 m resolution. The integration of Layout 1 and 2 has been done by merging seismograms with the same source location, after a careful processing and adjusting of time zero.

Figure 15 shows an example of shot records for Layout 1. The green arrows indicate the limit between the stabilized soil to the left and the natural soil to the right. The transition between the two areas is affected also by a change in topography, coinciding with a slope

(Figure 9 B). A clear change in wave propagation is visible in this portion of the seismograms.

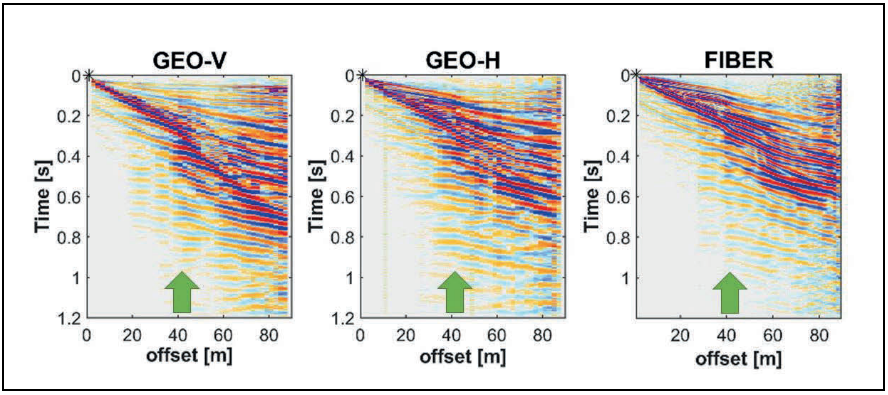


Figure 16 Example of seismograms from Layout 1 survey: left, vertical geophones (GEO-V); middle, horizontal in-line geophones (GEO-H); right, fibre optic sensors (FIBER). The green arrow indicates the transition zone between stabilized soil (left) and natural soil (right). The black asterisk is the location of the source.

The seismograms of Figure 15 show a comparable behaviour; in particular, the DAS and the horizontal geophone (GEO-H) data present a high similarity. This higher similarity between DAS and GEO-H seismograms is a common characteristic of all the datasets acquired at the site. This is mainly due to a similar contrast in relative amplitudes of different seismic events. The seismograms that display the data of the vertical geophones (GEO-V) show high energetic surface waves compared to direct arrivals. A less strong contrast is visible with the other two acquired sensors. This means that fibre optic sensors are less sensitive to vertical displacements of the ground and more sensible to horizontal movements along the cable. It is the proof of a characteristic that was expected. DAS measures the strain of the fibre, so it is more sensible to movements that occur along the fibre optic cable and less sensible to acoustic waves that hit the fibre optic cable perpendicularly.

A relevant aspect that has been highlighted by the present study is the combined effect of the spatial resolution and the spatial sampling distance of the fibre optic data. We acquired a seismic trace every 0.255 m along the fibre. Each trace being a stack of signals recorded from a 2 m interval centred on the trace position. One outcome of this stacking is the stepwise appearance of the fibre optic data, as it is particularly evident in Figure 16, which shows the seismograms of Layout 3. The horizontal geophones (left plot) have a precise location and a spatial sampling of 0.5 m. Even if the spatial sampling distance is lower for the geophones than for the fibre optic data, the seismogram appears to be smoother and the seismic events have a linear appearance. The DAS seismogram (right plot) shows a stepwise behaviour that is more pronounced in some portion of the profile, reaching a maximum of 8 traces (2 m) that display a similar pattern. This is a consequence of the discrepancy between the spatial resolution and the spatial sampling of the DAS system. Along the 2 m resolution segment some positions on the fibre can record a stronger signal that is dominant, and that is commonly present in all traces where data from this point is stacked. The stronger signal in these points can be the consequence of a local greater coupling of the cable with the surrounding soil. This localized and more intense strain in the fibre masks the weaker signals from the other portions of the 2 m segment.

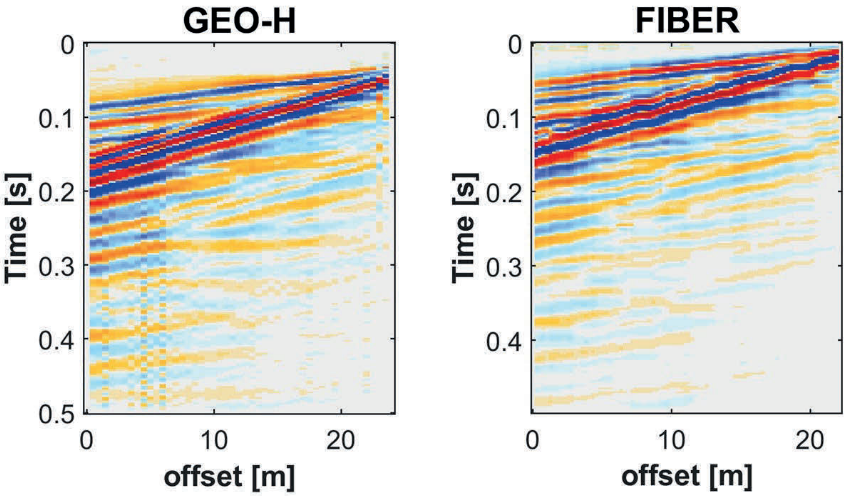


Figure 17 Example of seismograms from Layout 3: left, horizontal in-line geophones (GEO-H); right, fibre optic sensors (FIBER).

To further investigate capabilities and limitations of the techniques the frequency content of the data is analysed. The profile has been divided in two portions: the area of the stabilized soil from 0 to 37 m and the area of the natural soil from 45 to 90 m, avoiding the central part characterized by the transition zone and the topographic slope between 37 and 45 meters. To display the frequency content of the acquired datasets, we transformed and plotted the data in the FK-domain (see chapter 2.1.3).

Figure 17 and Figure 18 show the data from an external shot in Layout 1 (2 m spacing between geophones), for the stabilised soil and for the natural soil respectively. The frequency content is almost analogous between the DAS and the geophone data; in particular, the acquisition with fibre optics presents higher similarities with the horizontal in-line component of the geophones, both in TX and FK plots.

This analysis confirms that fibre optic sensors record an acoustic signal that is fully comparable with traditional surveys using geophones. It is evident both in the seismograms and in the FK plots, where the power distribution shows the same pattern.

Figure 17 (stabilised soil) is in general characterized by higher velocities of acoustic waves compared to Figure 18 (natural soil); this is evident from the different slopes of seismic events, both in TX and FK plots. Both technologies are able to detect variations in the wave propagation, caused by contrasting material properties.

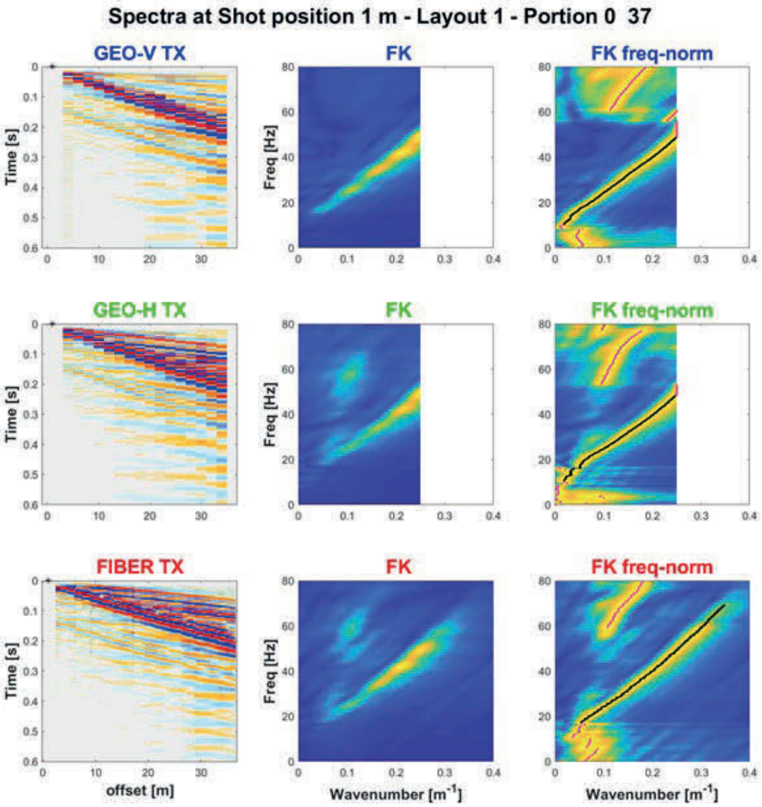


Figure 18 Example from Layout 1 (2 m geophone spacing) in the portion of stabilised soil. In the left column, the seismograms of (from top to bottom): vertical geophones (GEO-V), horizontal in-line geophones (GEO-H) and fibre optic sensors (FIBER). In the right column, the FK power spectrum is plotted normalized for each frequency.

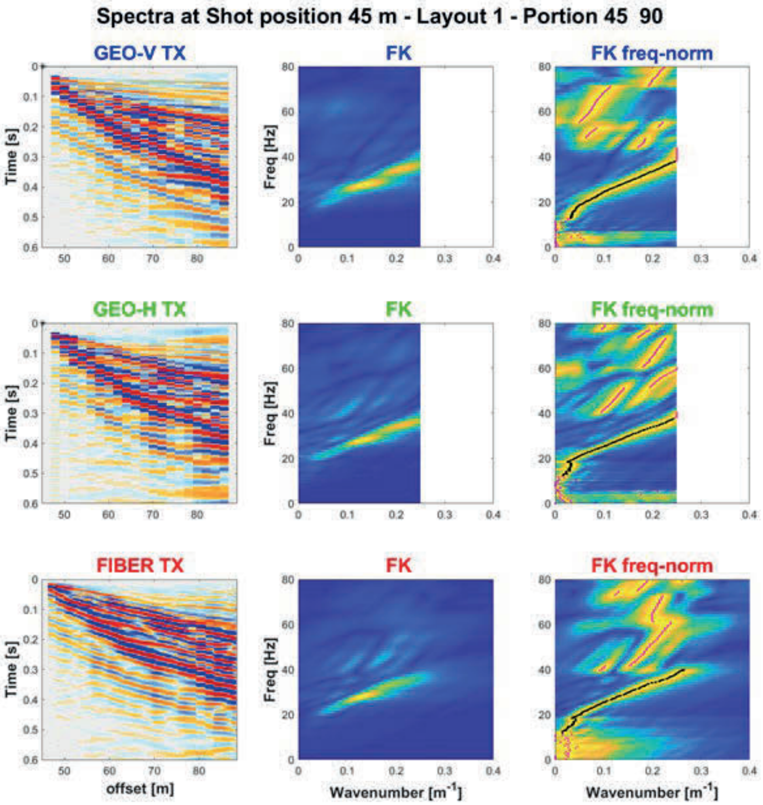


Figure 19 Example of Layout 1 (2 m geophone spacing) in the portion of natural soil. In the left column, the seismograms of (from top to bottom): vertical geophones (GEO-V), horizontal in-line geophones (GEO-H) and fibre optic sensors (FIBER). In the right column, the FK power spectrum is plotted normalized for each frequency.

In both Figure 18 and Figure 19 it can be seen how the geophone data, here with 2m spacing between geophones, does not allow analysis above a wavenumber of 0.25 while the DAS data goes higher. If we instead analyse the plot in Figure 19 (stabilised soil), where the data from the geophone Layout 1 and 2 have been integrated to obtain a final geophone distance of 1 m, some differences are present. DAS data are not able to reveal the signal at higher frequencies and higher wavenumbers, i.e. this is the signal that comes from shorter wavelengths. While the geophone data reveals signal much higher in wavenumber. This outcome may be the consequence of the stacking in the DAS data that gives a 2 m footprint of each trace, even if the spatial sampling comes with a higher frequency (0.25 m; see Table 2).

The difference in the energy distribution inferable from Figure 20 (natural soil) is less pronounced, because in this case the soil is characterized by different material properties, and especially by slower acoustic wave velocities that are characterized by lower frequencies and lower wavenumbers. In particular, the data from the horizontal geophones are more similar to DAS data, where larger wavelengths (smaller wavenumbers) are not present. In Figure 19 and Figure 20 the maximum wavenumber present in the fibre optic signal is around 0.25 m^{-1}, which means that we are able to detect wavelengths toto about 4 m: exactly twice the spatial resolution (2 m). So, the spatial resolution is governing the spectral content of the recorded signal, in spite of the higher spatial sampling.

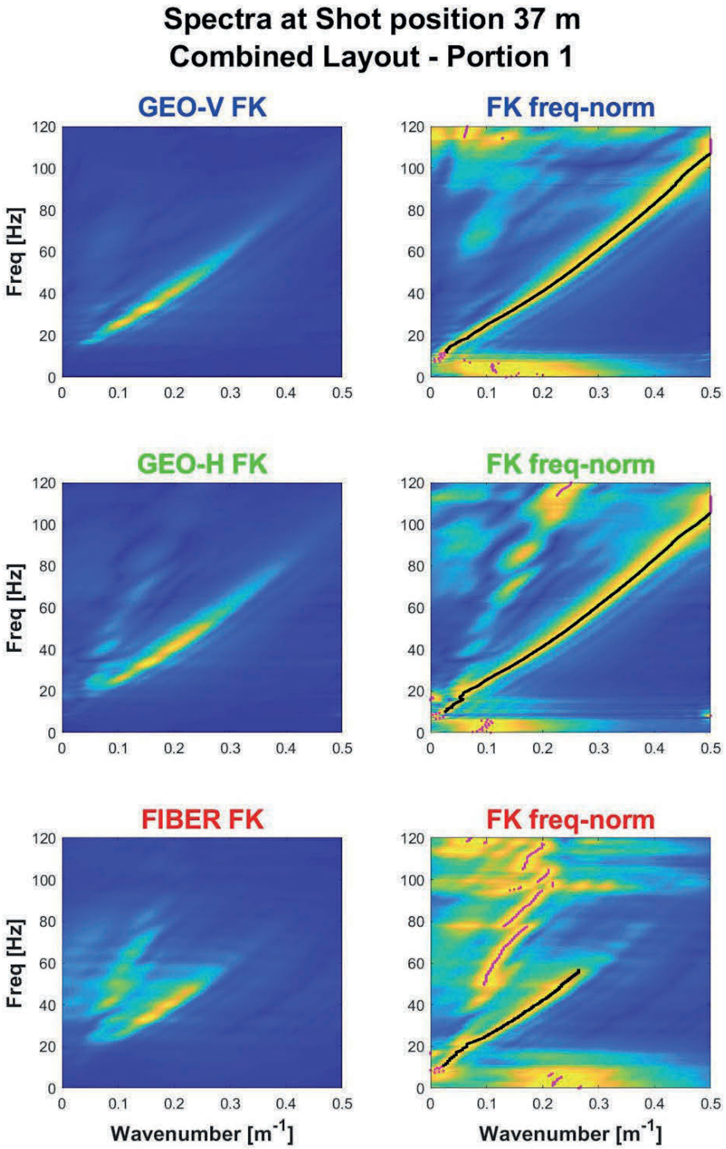


Figure 20 Example of FK plots for the combined Layout 1 and 2 datasets (1 m geophone spacing) in the portion of stabilised soil. In the left column, the FK plots of (from top to bottom): vertical geophones (GEO-V), horizontal in-line geophones (GEO-H) and fibre optic sensors (FIBER). In the right column, the same plots where the amplitude values have been normalized for each frequency. The highest amplitudes for each frequency are plotted as magenta and black dots. Black dots highlight the fundamental mode of Rayleigh waves.

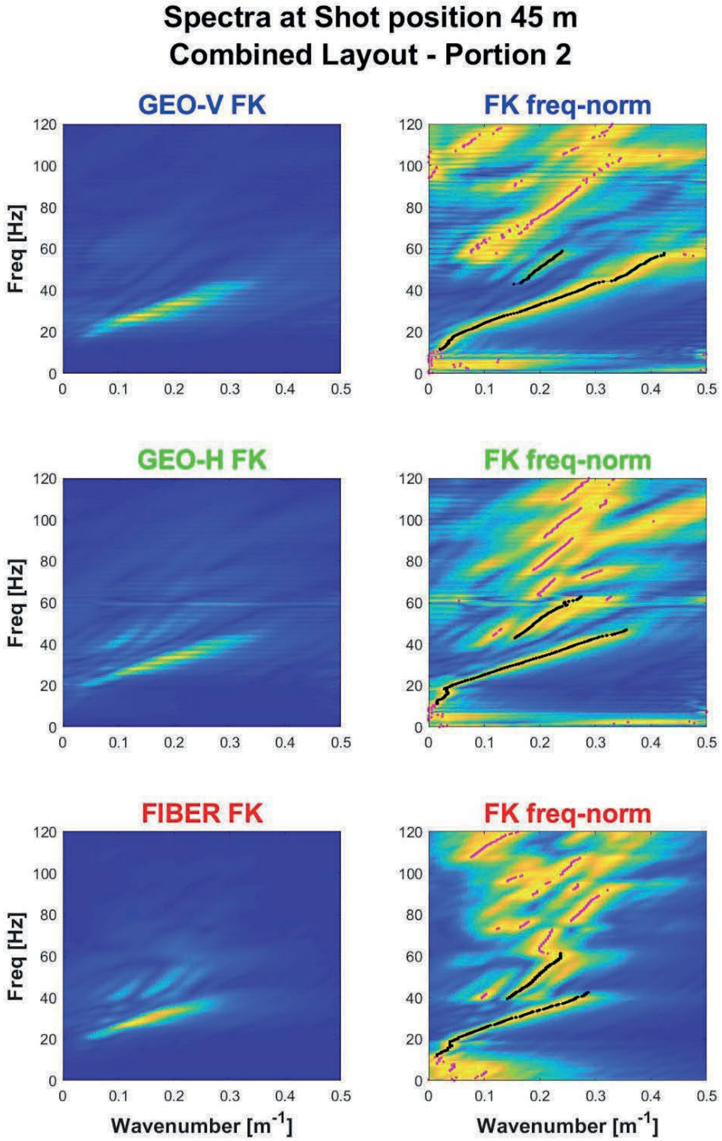


Figure 21 Example of FK plots for the combined Layout 1 and 2 datasets (1 m geophone spacing) in the portion of natural soil. In the left column, the FK plots of (from top to bottom): vertical geophones (GEO-V), horizontal in-line geophones (GEO-H) and fibre optic sensors (FIBER). In the right column, the same plots where the amplitude values have been normalized for each frequency. The highest amplitudes for each frequency are plotted as magenta and black dots. Black dots highlight the fundamental mode of Rayleigh waves.

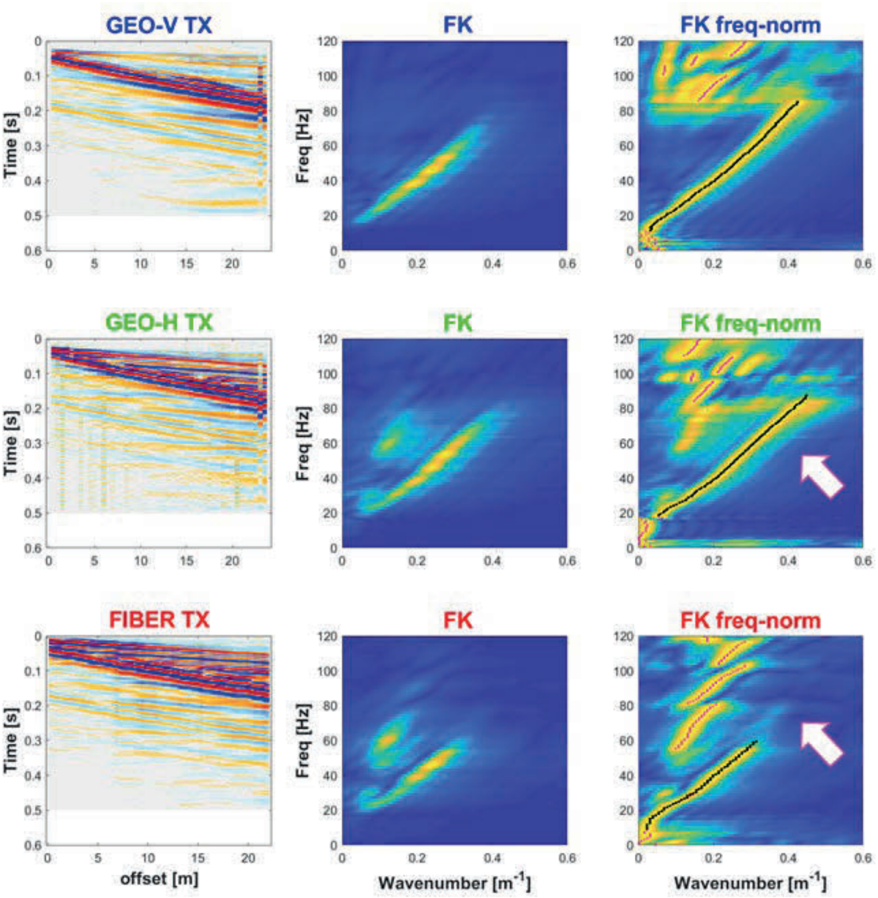


Figure 22 Example of Layout 3 (0.5 m geophone spacing) in the portion of stabilised soil. In the left column, the seismograms of (from top to bottom): vertical geophones (GEO-V), horizontal in-line geophones (GEO-H) and fibre optic sensors (FIBER). In the middle column, the corresponding frequency content plotted as a double Fourier transform (FK). In the right column, the same FK plots with the energy content normalized for each frequency. The maxima amplitudes for each frequency are plotted as magenta and black dots. Black dots highlight the fundamental mode of Rayleigh waves. The white arrow points out an area where the fundamental mode is clear in the geophone data to a much higher wavenumber than what it is in the DAS data.

The effect of the 2 m spatial footprint of DAS data is visible also while comparing the fibre optic spectra with the shorter spatial sampling of Layout 3 (0.5 m between geophones). Figure 21 displays the seismograms and the FK-spectra for a shot external to Layout 3. White-magenta arrows highlight the dissimilarities in the energy distribution of the spectra. We can recognise similar characteristics of the signal as in the previous tests. This verifies the validity of our considerations. It is worth mentioning that even if we have a higher resolution in Layout 3, capable of detecting acoustic waves with 1 m of wavelength, the energy is distributed within a max of 2 m as the longest wavelength (corresponding to 0.5 m^{-1} as wavenumber). This is a consequence of the specific material properties of the stabilized soil that place a limit in seismic wave velocities.

The FK spectra qualitatively look similar, especially between horizontal in-line geophones and fibre optic sensors, as we discussed above. They have an analogue energy distribution among the different modes of propagation. For a clearer and exhaustive comparison, the maxima amplitudes of these spectra of the three different datasets (vertical geophones, horizontal in-line geophones and fibre optic) are plotted in a single figure (Figure 22). It is evident that the different sensors record the same modes of propagation within a small variance due to inevitable environmental noise.

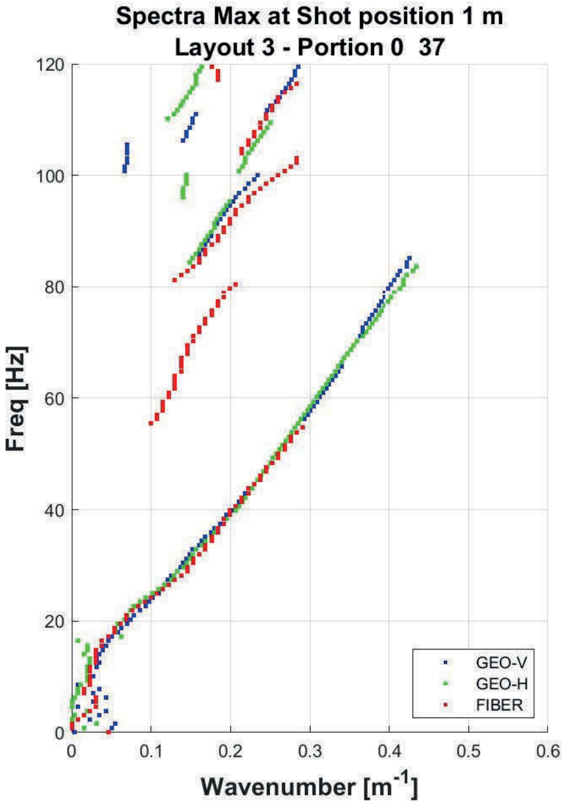


Figure 23 Comparison of the modes of propagation between vertical geophones (blue dots), horizontal in-line geophones (green dots) and fibre optic sensors (red dots). These data are extracted from an external shot of Layout 3 (0.5 m geophone spacing) in the portion of stabilised soil.

4.2.2 Modelling of data – shear wave velocity profile

To give an example of how the dispersion data can be used in a geotechnical investigation a shear wave velocity profile has been calculated. Since the dispersion curves from DAS as well as vertical and horizontal geophones show an almost identical pattern for all the datasets (see Figure 22) only one set of dispersion curves, from vertical geophones, has been analysed. The fundamental mode of Rayleigh waves has been extracted for each FK spectrum, as it is displayed in the right column of Figure 19, Figure 20 and Figure 21 by the black dots. An inversion is conducted to extract a vertical one-dimensional profile of shear wave velocities (V_S), using the algorithm presented in Vignoli et al. (2021). Figure 23 shows the inversion results of the dispersion curves derived from the portions of stabilized and natural soil. Two V_s vertical profiles (Figure 23 A) are obtained from the stabilised soil by inversion of dispersion curves of Layout 3 (0.5 m spacing), light blue dashed line, and the combination of Layout 1 and 2 (1 m spacing), dark blue solid line). The distribution of V_s is almost identical especially in the shallower 8 m, where a low velocity layer (V_s < 250 m/s) is identified between 0 and 3 m below the topographic surface. The inversion of seismic data from the natural soil estimate a V_s vertical profile that is similar in shape to the previous profiles, but it is characterized by lower shear-wave velocities in the shallower 3 m; please note that this profile starts at a depth of 0.75 m to compensate for the average difference in elevation between the two portions of the profile (see Figure 9 B). The stabilization process has been effective, increasing V_s with about 100 m/s.

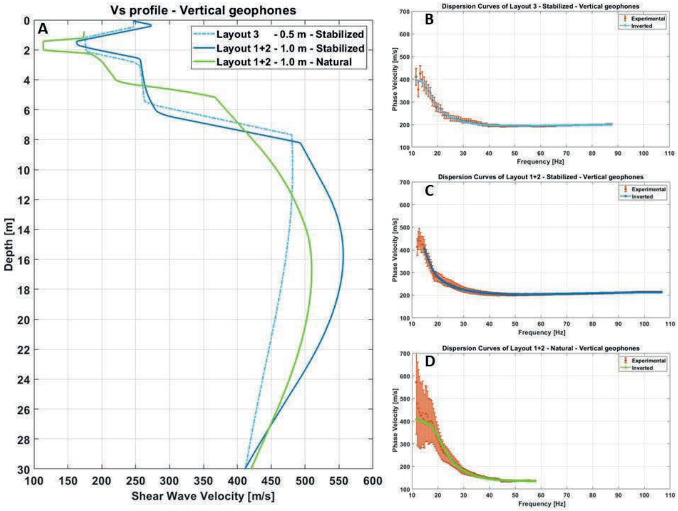


Figure 24 Result of the geophysical inversions as vertical profiles of shear-wave velocities (A) and the corresponding experimental and modelled dispersion curves for: an external shot of Layout 3 in the portion of stabilized soil (B), the combination of Layout 1 and 2 in the portion of stabilized soil (C), the combination of Layout 1 and 2 in the portion of natural soil (D).

4.2.3 Modelling of data – P-wave refraction analysis

The acquired seismic data have been analysed also for processing by means of the seismic refraction method, which is a standard application for estimating the distribution of compressional wave velocities (V_P). A clear refracted event is recognisable in the shot record from the vertical geophones, while it is very weak in the seismogram of horizontal in-line geophones, hardly detectable in 20-30 m from the source (Figure 24). The seismogram from the DAS acquisition does not show any refracted event. In Figure 24 the picked refracted event from the GEO-V seismogram is superimposed on the other two datasets. It is evident that no signal is present at those time-locations in the fibre optic data, merely high frequency noise can be seen.

The refracted waves arrive the surface with a high angle of incidence, due to the slower shallower layer. The consequence is that the wave front hits the fibre optic cable with a direction that is almost perpendicular to the cable itself. As mentioned in chapter 2.1.1, DAS is mainly sensitive to wave motion that propagate along the same direction of the cable (small incident angles), resulting in an unobservable refraction event.

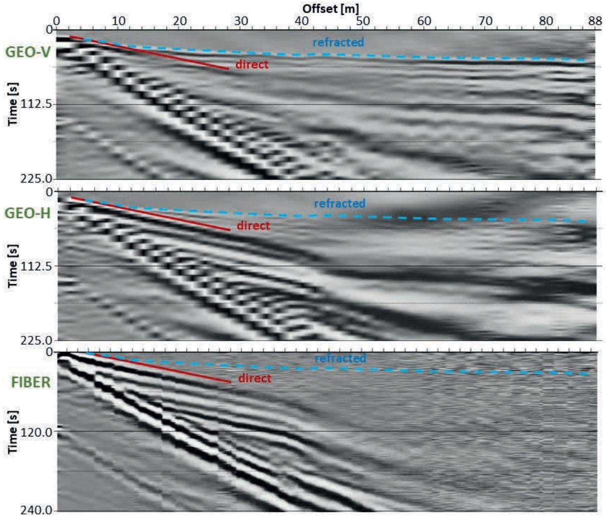


Figure 25 Seismograms from Layout 1 (2 m geophone spacing) of (from top to bottom): vertical geophones (GEO-V), horizontal in-line geophones (GEO-H) and fibre optic sensors (FIBER). Direct and refracted waves are highlighted by solid red lines and blue dashed lines, respectively.

4.3 ESS-pond

As explained in chapter 3.3 the results from the test in the ESS-pond were of very low quality and were only used to verify that the optic fibre could sense acoustic signal when laid out on the bottom of a pond. After verifying that this was the case no further analysis was made on the data.

4.4 Västersjön

The purpose of the test in lake Västersjön is to see if the data from a fibre laid out at the bottom can be used to detect seismic waves for near surface seismic tests. The most important wave types for the engineering relevant to this work (see chapter 1.1) are direct and refracted waves for first break picking to be used in a refraction analysis. Surface waves and reflected waves are also interesting but less often used due to the fact that they are not always present in this type of data.

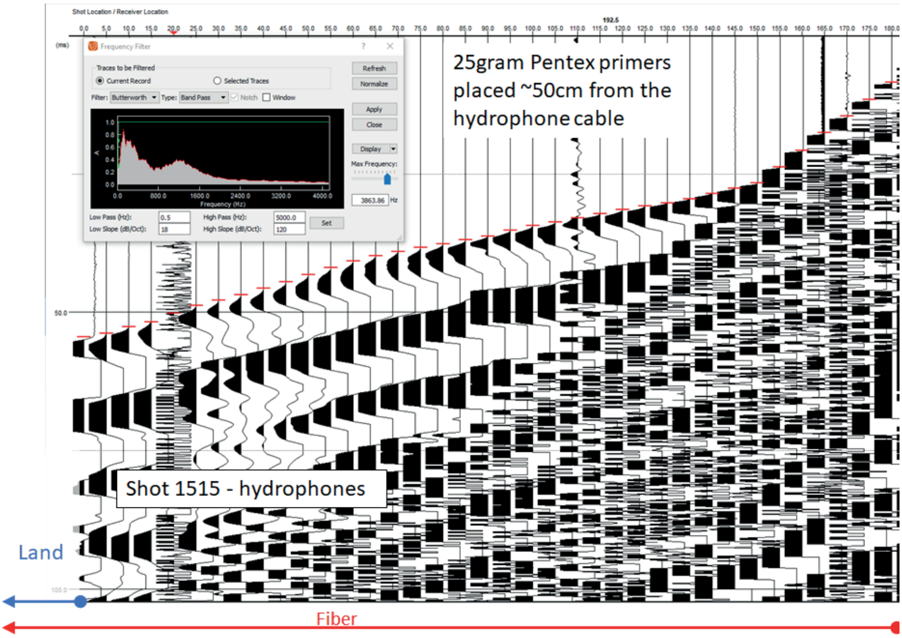
4.4.1 Analysis of data

Data from fibre is here compared directly with data from hydrophones. In addition, an ERT dataset was collected and the results from the seismic and resistivity measurements are presented together.

Figure 25 and Figure 26 presents shot records of hydrophone and DAS data respectively. They both originate from the same shot at distance 207.5 m. Figure 28 presents data from a shot at 285m. The hydrophone data shows a very clear direct and refracted wave. These are marked with red dashes in all shot records. This goes for all the shots along the line and the hydrophone dataset can be considered to be of very high quality.

Looking at the DAS data in Figure 26, the refracted wave can be clearly seen and the picked first breaks agree very well with those from the hydrophones. The part on land has slightly lower quality than the rest and the velocity of the refracted wave looks significantly lower, however, here we have no geophones to compare with so it is not clear if this has something to do with the change of coupling for the fibre or if it is geological. However, the direct wave and the refracted signal closest to the source is hidden behind a strong wave event that is not present in the hydrophone data. This anomalous event at a constant velocity of about 3050 m/s is very likely a wave that propagates in the fibre cable. This is then due to the fibre cable being very stiff due to reinforcement. The cable used in this study was a very rugged Kevlar coated and steel core reinforced cable where a velocity like the one observed here can be expected. The cost of a cable like the one used here is such that there were no resources in this project to test a different cable (with a different internal construction), but it is likely that a softer cable (without or with less reinforcement) would behave differently.

In general, it seems like the fibre is very sensitive to the refracted wave that is characterized by a high signal to noise ratio, allowing for precise first break picking. It differs significantly from what we can see on land (see results and discussion for the ESS test site in chapter 4.2). There might be several reasons for this. It could be due to the fibre simply being pressure sensitive or to some effect from the fibre cable being free to move with the pressure wave in the water emanating from the incoming refracted wave, which might not be possible when the fibre is buried in a solid material where it is constrained to smaller deformations.



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Filter: Butterworth Type: Band Pass ☑ Notch ☐ Window

Max Frequency: 3863.86 Hz

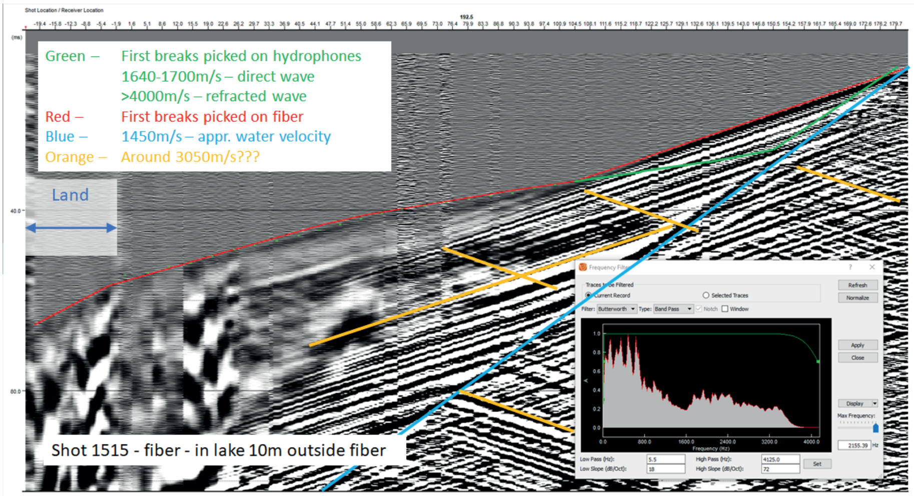
Low Pass (Hz): 0.5

Low Slope (dB/Oct): 18

High Pass (Hz): 5000.0

High Slope (dB/Oct): 120

Figure 26 A seismogram presenting hydrophone data for a shot at 207.5 m. The picked first breaks for the direct and refracted wave are shown by red dashes. The red and blue arrows in the bottom of the figure line out where the fibre is placed and where the land part of the line is. Obviously, there are no hydrophones on land. A frequency spectrum (from 0 Hz to approximately 4100 Hz) is shown in the upper left corner.



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Max Frequency: 2155.39 Hz

Low Pass (Hz): 5.5

Low Slope (dB/Oct): 18

High Pass (Hz): 4125.0

High Slope (dB/Oct): 72

Figure 27 Seismogram presenting fibre data for shot nr 1515 at 207.5 m. The picked first breaks are shown with a red line. The blue arrow in the centre left of the figure line out where the fibre is placed on land. A frequency spectrum (from 0 Hz to approximately 4100 Hz) is shown in the lower right corner. The green line presents first breaks from the hydrophone data. The blue line presents the direct wave in the water. The orange lines present some of the strong wave events that is not present in the hydrophone data.

Figure 27 shows an FK plot of shot 1515, the same shot that is presented in Figure 25 and Figure 26. Velocity lines for 1450 m/s, 3050 m/s and 5000 m/s are plotted in the figure. These velocities would represent the water wave, the internal "cable wave" in the optical DAS fibre data and the refracted wave, respectively. In both the hydrophone and fibre data the water wave can be clearly seen between 50 and 200 Hz. The refracted wave is not seen, this is most likely because it is too low frequency and also very low energy compared to the other waves present. The fibre data presents strong energy events up to high frequencies with a velocity that is not completely clear but that partially fits with the 3050 m/s.

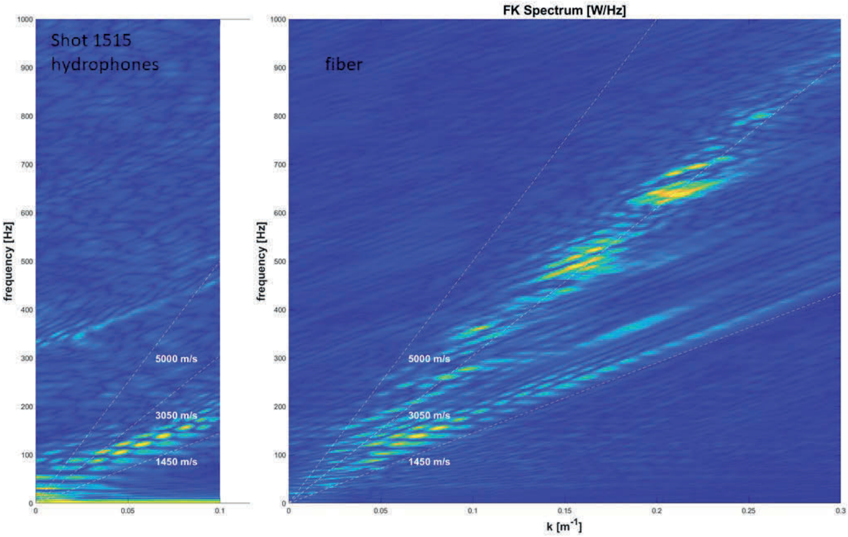

Figure 28 FK plots from shot 1515 (same as in **Figure 26**). Left: hydrophones and; right: fibre. The amplitude of the signal is normalized for each frequency.

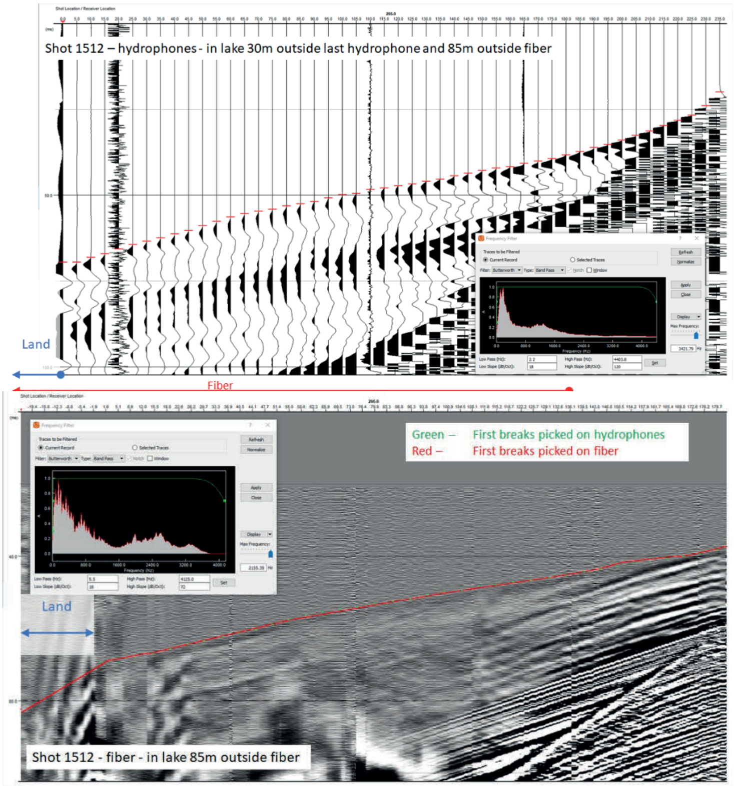

Figure 29 Shot records from hydrophone (top) and fibre (centre) for the same shot, shot nr 1512. In both the shot records the red marks represent first breaks picked on data.

Figure 29 presents a positioning shot. This is a very small detonator fired in the surface of the lake normally used for positioning of the receivers. The hydrophone data show clear first breaks from the direct water wave. The first breaks on the fibre data do not match this along the entire fibre, only in the position closest to the shot point and sometimes at large distances. While there is partial evidence in the data that we see the first arrival of the direct wave on the DAS data we cannot ensure the use of fibre optics for underwater positioning based on this study. Due to the prevailing internal wave, it is not completely clear if DAS is sensitive enough to pick up the wave from a small charge fired in the surface of the water.

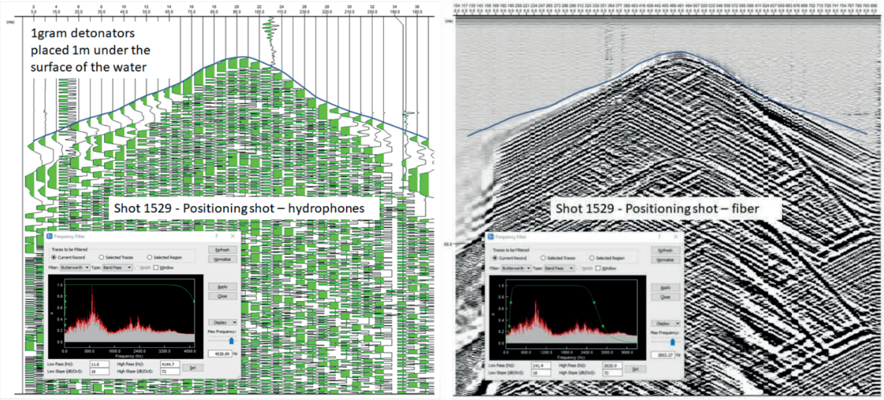

Figure 30 Shot records from positioning shots using a small charge in the surface of the water, hydrophone (left) and fibre (right) for the same shot, shot nr 1529.

4.4.2 Modelling of data – P-wave refraction analysis

Figure 30 to Figure 33. presents the resulting P-wave velocity and resistivity models from processing and inverse modelling of the hydrophone and ERT data. The data quality and inversion fit are both very high and the results are reliable.

Both models indicate a depth to bedrock of around 15 m along the line. The velocity in the soil is around 1700 m/s and the velocity in the rock around 5500 m/s. This fits well with the expected geology (see chapter 3.4) and with the results from the ERT that is presented in Figure 32 and Figure 33. There is a small discrepancy in depth to what would be interpreted as the bedrock from the two different methods at 100-200 m along the profile, but the difference is less than 10% of the interpreted depth which is within the error that is often used as a rule of thumb in the industry for this type of measurements.

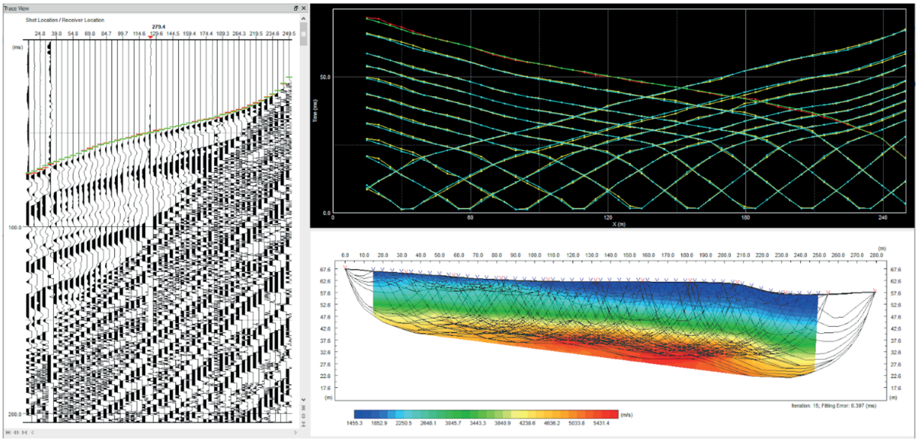

Figure 31 Refraction tomography of the hydrophone data. View from Geogiga DWTomo that was used for modelling.

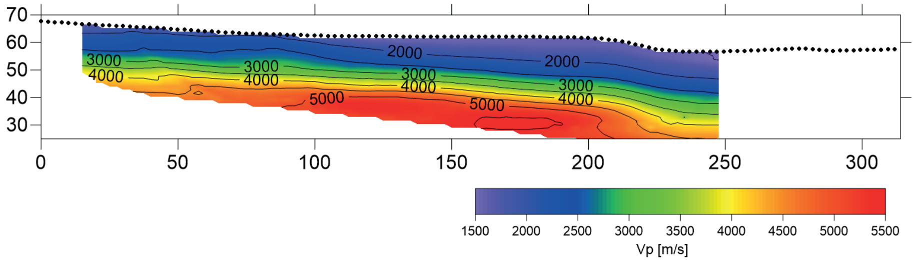

Figure 32 Refraction tomography of the hydrophone data.

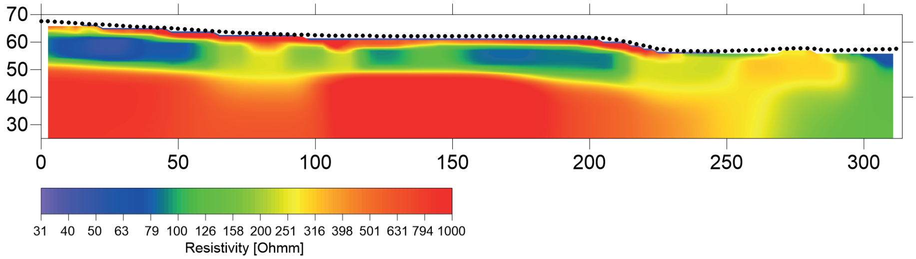

Figure 33 Resistivity profile from inverse modelling of gradient configuration data

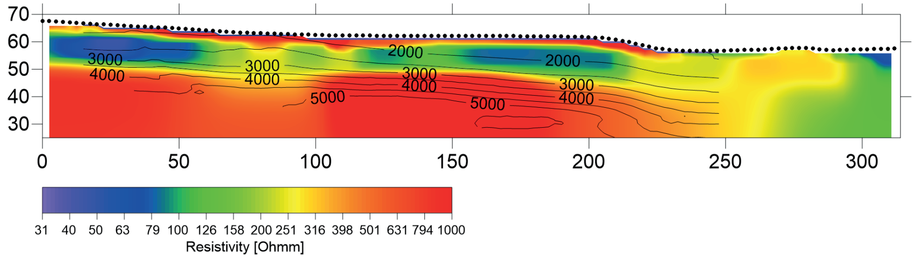

Figure 34 Resistivity profile from inverse modelling of gradient configuration data with P-wave velocities from the refraction tomography.

5. Conclusions

The present project is a feasibility study on the application of fibre optics as acoustic sensors for near surface refraction seismic investigations in connection with engineering geology surveys. The project has been focused on the comparison of the Silixa Carina system with standard hydrophones and geophones. In addition to seismic measurements, geoelectrical measurements were made to facilitate a complete engineering geophysics dataset for further analysis and to get reference data for comparing the seismic results.

The results clearly show that the signal from DAS is analogous to standard seismic receivers and that the signal from DAS contains refracted P-wave energy that can be identified in a shot record, and that compares very well with the hydrophone data. 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, analogously to a pinched "guitar string".

The signal from positioning shots, that are small detonations in the surface of the water used for positioning sensors on the sea bed, shows a similar behaviour to the refraction seismic data. Very near the shot point, where there is no refracted energy yet travelling along the fibre cable, and at far offset, the picked first breaks compare with those in the hydrophone setup. This can however only be seen in a very small portion of the data. For the majority of the data the internal wave in the fibre cable is efficiently masking any signal propagating in the water.

We conclude that fibre optic cable placed on the sea bed without further coupling than its own weight is a very good sensor for measuring refracted seismic waves. Due to the type of fibre cable used in this study velocities below 3050 m/s have not been possible to study and therefore it cannot be concluded that it can measure direct wave. A test using a more flexible fibre cable with an internal velocity well below 1450m/s would show if the direct wave can also be sensed. It would also show if the fibre can sense the direct waves from small positioning shots in the water surface. In this study it cannot be concluded which mechanism the fibre uses to sense the refracted wave. However, it can be concluded that cables buried on land do not seem to be able to sense refracted waves directly, which might be due to that they cannot move freely while being coupled almost completely to the solid medium.

DAS data for a fibre buried on land display a higher similarity with the horizontal in-line component of the geophones, as was expected, since they record the strain (see also Wu e al., 2017) which occurs in the same direction as the movement the in-line geophones sense. This means that they are more sensitive to acoustic waves that propagate along the fibre than perpendicularly to the fibre. Even though the DAS samples at approximately 0.25m distance the fibre optic sensors are less sensitive to shorter wavelengths compared to geophones with a short station distance. This is due to the fact that this DAS system stacks 8 0.25 m segments together to achieve sufficient signal to noise ratio. In practise this gives a 2 m footprint which compares to a 2 m resolution of the applied technique. It has to be mentioned that seismic surveys are rarely conducted with a station spacing less than 1 m.

Overall, the result from this study must be considered a success. Beforehand there was no knowledge and no expectations on the fibre cable's ability to sense refracted energy while placed loosely on the sea bed. Now the authors of this study can confirm that fibre can be a very useful tool for near surface engineering geophysical studies. Further tests need to be done in order to show if fibre can also sense the direct wave in underwater surveys and decide which type of fibre that should be used. For the application of using fibre built into other cables, like ERT cables, for positioning purposes it first has to be verified that fibre can measure direct pressure waves in water. In addition, it has to be considered how the combined cable is designed, so that it has an internal wave velocity that is as low as possible, and definitely lower than the velocity of water. With all the copper wires included in an ERT cable this could be a problem.

As a final remark, it seems that fibre can constitute a very powerful tool in short- and long-term seismic measurements as part of underwater integrated geophysical studies in infrastructure projects.

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BeFo

Box 55545
SE-102 04 Stockholm

info@befoonline.org • www.befoonline.org
Visiting address: Sturegatan 11, Stockholm

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