Charles University

Faculty of Science

Institute of Hydrogeology, Engineering Geology and Applied Geophysics

Fibre Optic Sensing as Borehole Seismic Method

Bachelor thesis

Plzeň 2020

František Sova

Prohlašuji, že jsem nepředložil práci ani její podstatnou část k získání jiného nebo stejného akademického titulu a že jsem práci zpracoval samostatně a uvedl všechny použité informační zdroje a literaturu.

Plzeň, 14th June 2020

František Sova

Abstract

The aim of this text is to show the various seismic methods used for borehole measurements, whether it is a seismic survey or a long-term monitoring. In particular, it deals with systems based on optical fibres, which are commonly used in civil engineering, but are gradually finding their way into other disciplines, including applied geophysics.

The theoretical part briefly introduces the basics of seismology and also discusses the optical technologies, their architecture and sensors used. It also compares them with classical methods of data acquisition and mentions their possible applications.

The case study in chapter 4 deals with a seismic measurements, which took place in LT-1 borehole in Litoměřice, Czechia in February 2020. It was a vertical seismic profiling using two methods - a classic three-component geophone and an optical cable with imprinted Bragg gratings (FBG technology).

Although both methods could not have been directly compared due to technical issues, the final part describes the methodology, encountered problems and obtained data. Finally a conclusion is drawn about the great potential of optically based sensing technologies for geophysical applications.

Abstrakt

Cílem tohoto textu je ukázat různé seismické metody používané při měření ve vrtu, ať už se jedná o seismický průzkum nebo dlouhodobý monitoring. Zejména pojednává o systémech založených na optických vláknech, které se běžně používají ve stavitelství, ale postupně si nacházejí cestu i do jiných inženýrských oborů, včetně aplikované geofyziky.

Teoretická část krátce seznamuje se základy seismologie a dále pojednává o optických technologiích, jejich architektuře a použitých senzorech. Dále je srovnává s klasickými metodami získávání dat a zmiňuje možné konkrétní aplikace.

Praktická část se poté zabývá seismickým měřením, které proběhlo ve vrtu LT-1 v Litoměřicích v únoru 2020. Jednalo se o vertikální seismické profilování za použití dvou metod - klasického trojsložkového geofonu a optického kabelu s imprintovanými Braggovými mřížkami (technologie FBG).

Přestože obě metody nemohly být z technických důvodů přímo srovnány, v závěrečné části je popsán systém měření, problémy a naměřená data. Na závěr je nabídnut pohled na vývoj a použití optických technologií v seismickém vrtním měření, které se zdají velmi perspektivní z hlediska budoucího vývoje v oboru.

I would like to say many thanks to my supervisor Prof. RNDr. Tomáš Fischer, PhD, who showed me the field of seismology and also to doc. RNDr. Jan Vilhelm, CSc. who patiently answered all my questions. Also I would like to thank the crew at the Geophysical section who participated on the field measurements.

Plzeň, 14th June 2020

František Sova

Contents

1 Introduction

When exploring the subsurface, there are several ways how to access the information about the internal structure of the Earth. Traditional geology relies mostly on surface observations like examining rock properties, fractures and faults on the outcrop and then deducing how these elements continue below the surface. This can provide a crude estimate of the geologic situation, but it is not very accurate and omits variations on a smaller scale, which are of a great importance in mineral exploration and civil engineering.

Another, more direct way of subsurface investigation is its intervention by excavating, mining or drilling. Again by taking rock samples or conducting measurements, it is possible to add an accurate vertical component to previous estimations. Nevertheless the area that can be explored in such a way is limited - drilling is relatively time consuming and requires high costs, especially when reaching greater depths.

These difficulties can be tackled by the methods of exploration geophysics, which investigate large areas over a short period of time and enable to map the subsurface without disrupting the ground, so they are referred to as non-destructive. The measurements are taken at the surface and their aim is to spot spatial change in physical properties of different rocks and subsurface bodies. Henceforth it is possible to draw a good picture of what lays underground by interpreting the collected data.

Geophysical techniques in general have lower resolution and are less accurate than direct borehole measurements, but they are more effective within the same time and cost budget. Usually when starting a project, geophysical survey is conducted first, followed by drilling in the particular areas of interest. The exploration methods and their usage can vary, but the most common ones include seismic, gravimetric, electrical, electromagnetic and magnetic surveys. While some of them study Earth's ever-present natural fields (electromagnetic, gravitational), others rely on the occasional events like earthquakes. The geophysical methods are a great tool in natural resources exploration (including water, hydrocarbons, metals, geothermal energy), geoengineering and archaeology (Everett, 2013; Mussett and Khan, 2000).

2 Exploration seismology

The geophysical discipline using seismic waves as a source of information is called seismology and can be divided into two main areas.

The first one is earthquake seismology, which focuses on naturally induced seismic waves (usually due to displacement of rocks across a fault plane) and aims to give a relevant information about the subsurface in a large scale, like the details of the Earth structure and composition.

The latter one is exploration seismology, which uses man-made sources of disturbance (explosives, weight drops) to investigate small scale areas. Usually it is interested in the rock properties like density and elastic moduli.

Seismic waves spread outwards from the source and can be recorded in multiple points at the surface. By timing their arrivals and comparing obtained records it is possible to locate the boundaries of underground objects and map the bedrock topography in detail (Burger, 2006). This technique was also used by the pioneers of earthquake seismology A. Mohorovičić, who has determined the mantle-crust boundary and B. Gutenberg (the coremantle boundary) (Sharma, 1997).

2.1 Seismic waves

The seismic wave is a type of a mechanical wave, which is a local displacement of particles travelling through a medium. In the case of seismology this medium is the Earth itself. By applying stress on rocks a deformation (strain) occurs, particles are put in motion and the displacement spreads spherically outwards from the point of origin in the form of a wave front.

Some basic wave characteristics are the following:

- Wavelength λ (m) is a distance between two corresponding points of consecutive waves.
- Amplitude A is the maximum displacement from a stationary position.
- Frequency f (Hz) is the number of oscillations that pass a certain point in certain time.
- Seismic velocity v (m/s) expresses how fast a certain wave propagates through a medium and can be computed from the following formula $v = \lambda \times f$

The seismic velocity is usually dependent on the rock properties (density, elastic moduli), which can be measured in a laboratory or during a survey. The common velocities of waves (compressional) in materials are (Burger, 2006):

300-1 500 m/s in soil and unconsolidated materials

1 500 m/s in water

2 000-5 000 m/s in sedimentary rocks

3 500-7 000 m/s in metamorphic and igneous rocks

There are several types of seismic waves. The surveying methods are mainly interested in compressional waves (also called primary or P-waves).
They arrive first into the receiver and are able to propagate in liquids.

S-waves or shear waves arrive second, they have less energy and can not propagate in liquids and gases. Another type of waves are surface waves, which are confined to the surface region. They are slower than the forementioned body waves (P and S-waves), but they have particularly high amplitudes (Mussett and Khan, 2000).

If a seismic wave hits an interface between two media, it is partially reflected back and partially refracted to the bottom medium. This and other basic principles are similar to the ones in Optics, where they are dealing with the propagation of light in media - for example the Snell's law ($sin\vartheta_1/sin\vartheta_2 = V_1/V_2$) and Huygens' and Fermat's principle (known as the principle of least time)(Burger, 2006).

As the wave propagates through a medium, its amplitude decreases, because the energy is attenuated in the subsurface due to the spherical spreading, partitioning at interfaces and absorption. This energy loss is greater in higher frequencies, because the Earth acts as a low-pass filter. Seismology works with a broad range of frequencies, from low-frequency earth movements (10 mHz) to high-frequency vibrations (100 kHz)(Sharma, 1997).

2.2 Seismic exploration

There are three main stages of the seismic (or other geophysical) survey. First is the data collection in the field, followed by the data processing and finally the data interpretation.

The conventional data collection consists of initiating a disturbance on the surface with a chosen source (hammer blow, explosive). Then the disturbance travels through the ground in the form of seismic waves. The arrivals of such seismic waves are recorded by receivers (geophones), that are placed in a straight line on the surface. By moving the arrangement and measuring different linear profiles in a predefined network, the 2D image of the area is generated.

Nowadays it is more common to use 3D seismic surveys, which were firstly used in the 1970s. Because the generated wave field and geological bodies are also 3D, it is convenient to utilize this aspect and measure all the additional information that such field carries. This can not be achieved by having the points of detection in a linear array. The 3D seismic method allows to efficiently detect small subsurface bodies or those with a complex structure (Alsadi, 2016).

The signal detected by the geophone is then transmitted via transmission cable to the recorder, where it is digitally processed and stored. The path between receiver and recorder is called a seismic channel. During 3D surveys, up to 2 000 channels are used (up to 240 in 2D), which puts high requirements on the recording unit to process all the signals simultaneously (Gillis, online 2020).

When the field survey is done, data are further reduced and processed in order to enhance the objects of interest (by applying Fourier transformations, filtering and migration methods). The geophysical model of the subsurface is then computed and handed over to a geologist, who forms the final interpretation. Hence the result of a seismic exploration survey is an image or a map of the lithology (Mussett and Khan, 2000).

2.2.1 Reflection and refraction seismic methods

The mostly used method in the seismic exploration nowadays is the reflection surveying (especially 3D). Its widespread use has begun in 1930s in mineral resource exploration (mainly petroleum).

Reflection surveys, which are dealing with great depths (up to several kilometers) and work with P-waves reflected near normal incidence, so the rays intercepted at the surface are almost vertical. The signal processing and interpretation is rather complicated as there are many reflections arriving. Therefore an advanced software is required to determine the arrivals from different layer boundaries (Sharma, 1997). The reflection waves also carry two types of information - the wave transformation information and traveltime information. Both can be used for deriving structural and stratigraphic models (Alsadi, 2016).

The second method is refraction survey. It is based on the phenomena of critical refraction, which occurs when a wave hits an interface under certain critical angle (based on the layer properties). Part of the wave energy is refracted and travels along the interface with the velocity of the bottom layer (which is usually higher then the one of the upper layer). Following the Huygens' principle this wave produces another wave front, that travels back to the surface under the same critical angle. By timing those first arrivals it is possible to determine the velocities and depths of underground layers and boundaries.

The refraction method is especially used for longer distances. By that it is ensured that waves travel predominantly in the horizontal plane. Because of the great distance, recorded frequency is in the lower range.

Most refraction surveys are interested only in the first arrivals of P-waves, because the recording S-waves requires special technologies. This seismic method is usually used in areas of unknown geology in order to determine the depth of the bedrock and fracture zones (Burger, 2006; Sharma, 1997).

2.2.2 Seismic sources

There are several types of sources generating seismic waves - weight-drops, explosives (mostly used) and vibratory.

The hammer blow is one example of an inexpensive weight-drop method. It can be repeated over time reaching depths up to 50 m, depending on the local conditions.

The explosive sources release greater energy, so they can excite particles in greater depths. They need to be placed in drilled holes to ensure a good coupling with the ground and cannot be used in residential areas.

The vibroseis method is used for deep targets (up to several thousand meters) and it requires a truck-mounted vibrator. A large mass is placed in the contact with the ground and vibrates for several seconds. During this time the signal frequency is continuously changed. For this reason, an interpretation of this method requires advanced processing tools (Burger, 2006).

2.2.3 Seismic equipment

The seismic equipment can vary a lot, but it has to comprise of instruments (apart the source) that can detect a disturbance, convert it into a signal, transmit it and record it (Burger, 2006).

The whole path of the signal from the receiver to the recorder is called a seismic channel. First in the channel is a sensor (receiver). In seismology the most commonly used sensors are electromagnetic geophones, which detect a relative motion between a coil and a magnet inside. While the magnet is fixed to the casing (that is provided with a spike and tightly coupled to the ground), the coil is attached by leaf springs. When the ground is disturbed, the magnet moves within the stationary coil and induces an electromotive force which is recorded as an output voltage. Depending on the type of a sensor the voltage can represent particle displacement, velocity or acceleration. This signal is consequently amplified, filtered and stored in a digital form (Everett, 2013).

Seismic cables are usually used for the signal transmission from the receivers to the recorder. Because conventional cables are prone to electromagnetic disturbances (they can interfere with each other), they are recently being replaced with optical cables or telemetry.

Surprisingly greater volume of seismic data is acquired offshore than onshore. On the sea a different instrument, called hydrophone, is needed and the seismic source is usually in the form of an airgun (Hardage, 2013).

In the recent years fibre optic sensors have started to be used apart conventional electric sensors . They are based on fibre optics and hold several advantages over traditional geophones. A description and comparison of those sensing technologies is the main topic of this thesis and is discussed in the following chapters.

2.3 Borehole seismology

When conducting a survey, the high-frequency component of the wave spectrum is essential for a good resolution. Therefore it has to be increased in the source and the receiver (Burger, 2006). This is especially the case of environments with low-velocity zones near the surface (deserts, seabed), where high frequencies are attenuated in the soft unconsolidated material. One of the solutions is placing the sensors in a drilled borehole, so the seismic signal does not have to pass the low-velocity layer again and keeps higher range of frequencies (80-100 Hz) (Knott, 2003).

Borehole seismic methods run on the same principles as surface seismic surveys, only with a different spatial arrangement and results. It is apparent from the name, that the measurements are partially or completely taken within boreholes. This enforces the data resolution in depths and minimizes the surface noise.

Traditionally, a single geophone or an array of geophones is deployed in a wellbore. Modern methods use optical fibres as a sensing instrument, either along the whole length of the cable or at evenly distributed sensing points.

In general the borehole methods comprise of much more types than of those using seismic waves. Nearly all geophysical methods can be applied in boreholes as well as on the surface. The process of logging is extensively used for a detail investigation of the close surroundings of the borehole. The result is a log graphing the change of a certain parameter with depth (Mussett and Khan, 2000).

2.3.1 Applications

The rapid development and increased interest in borehole methods in the past decades has been driven especially by the oil and gas industry.

Seismology is a great tool for a hydrocarbon exploration and because finding new sources is of an economical importance, lots of funding is pumped into the new technologies and research in the field (Hardage, 2013). This can be demonstrated on the dramatic expansion of hydraulic fracturing in the past decade, which requires vast amounts of borehole measurements (Geldmacher et al., 2013).

This also means, that borehole methods have the crucial role in reservoir and wellbore management, because it is possible to scan close surroundings of the well in high resolution. It enables to track the fluid movements, spot structural changes of the casing and map the lithology. Also it is possible to monitor nearby or faraway earthquakes (Knott, 2003).

These demands, alongside with the technology development has opened a new field of borehole monitoring. The downhole conditions require a durable sensor (e.g. optical fibre), which is able to continuously measure seismic signals for a long period of time.Difference can be drawn between passive and active monitoring. The active monitoring involves a seismic source and an intentionally induced seismic signal, while passive monitoring does not (Knott, 2003).

Apart earthquake seismology the applications of borehole monitoring can be found in the forementioned hydraulic fracturing, groundwater and well stability monitoring, CO_2 sequestration, waste disposal or geothermal energy investigation (Knott, 2003; Mussett and Khan, 2000).

2.3.2 Surveying methods

There is no distinct division of borehole seismic methods, but at least some boundary can be applied citing The Schlumberger Oilfield Glossary, which notes that methods using acoustic waves with frequencies higher than 1 kHz are referred to as sonic, while those operating in the range below 1 kHz are called seismic. Furthermore it lists the following methods: single-well imaging (e. g. sonic logging), check-shot survey, cross-well tomography and vertical seismic profiling (Gillis, online 2020).

Sonic logging

Logging is usually carried out in uncased wells using a sonde with sensors. The standard procedure is moving the sonde up the well and recording certain properties as a function of depth. Usually the first logging is already completed during drilling as the respective sensors can be incorporated directly in the drill head.

The sonde for sonic logging consists of two sensors and two sources on both sides to compensate for possible tilting. It can be used in both cased and uncased wells. Pulses are sent alternately from both sources and the wave arrival times at the sensors are averaged. The result is a borehole compensated (BP) sonic log, describing the velocities in different depths (Alsadi, 2016).

Check-shot survey

In a check-shot survey a hydrophone-type receiver is lowered into the well filled with a drilling fluid, while the source is on the surface. In comparison to the sonic logging, this method uses lower frequencies. The first wave arrivals are also detected in order to find seismic velocities in certain intervals, which are plotted against the depth. The check-shot survey can be used for calibration of the sonic log (Alsadi, 2016).

Seismic tomography

This is a relatively modern technique in seismic surveying. Its aim is to produce a 2D or 3D model of the velocity variations in depths. Commonly it is used in earthquake seismology to derive the structure of Earth's interior over great depths and distances. Recently it has been also used for hydrocarbon exploration, to monitor gas and fluid movements or detect bodies of interest.

Seismic tomography has a fine spatial resolution. This requires having either the source or the receiver under the ground - in a borehole (Alsadi, 2016). Such an arrangement can be considered as a variation of VSP survey, which is discussed next (Lines and Newrick, 2004).

In another case both receivers and source(s) are placed in adjacent boreholes. This is called a cross-hole seismic method (Alsadi, 2016). The geological interpretation could be usually derived using some interpolation techniques, but the cross-hole tomography is more adequate. Sonic logs from both boreholes then provide a velocity correction (Lines and Newrick, 2004).

Vertical seismic profiling

VSP is a conventional seismic technique used most up to date (Knott, 2003). It has a similar arrangement to the check-shot survey. The difference is that it involves a geophone array and that both direct and reflected waves are measured (transmission and reflection information respectively). Those are referred to as up-going and down-going waves.

Thanks to the information variety, a vertical seismic profile can serve as both a well log and an imagining tool. The resolution is geometrically determined by a well depth and an array arrangement. Deeply dipping interfaces can be detected within the borehole depth, but further below only near-to-horizontal interfaces can be measured.

VSP usually uses 3-component (3C) geophones clamped to the borehole wall (hence the preference is to use cased boreholes). The alternative is the application of hydrophones as receivers, which provide faster and cheaper acquisition. There are at least 5, but as many as 80 levels (receivers) on the wireline deployed (Stewart, 2001). The common spacing is 25 m (Alsadi, 2016).

There are several types of VSP measurements including zero-offset VSP, walkaway VSP, salt proximity VSP and seismic-while-drilling VSP (Gillis, online). Zero-offset VSPs have the source placed within the first few meters from a wellhead. Different sets of data can be obtained by simply moving the source along the profile from the borehole. Then it is a case of walkaway VSP. Furthermore if the surface grid is dense enough, it is possible to conduct a 3-D VSP survey, usually alongside a surface reflection survey.

The main objective of VSP surveys is the travel-time into depth, which can be obtained from the zero-offset VSP. Later it can serve as a calibration for sonic logging or provide additional information for interpolation with the surface survey. It is also possible to derive the rock properties (for example the angular dependence of velocities is closely related to the rock anisotropy), as well as seismic image and wave propagation characteristics (multiples, conversions). Stewart (2001) states that a VSP survey provides a unique mapping between seismic reflectivity in time and rock properties at depth.

3 Fibre optic sensing

The end of the 20th century saw the first attempts of an implementation of Fibre Optic Sensing (FOS) techniques into the field of exploration seismology. One of the main motives was a surge for a technology that could conduct permanent recordings in the downhole conditions with high network density and fidelity at relatively low costs (Ferraro and Natale, 2002).

Before that, conventional techniques were used. Those usually comprised of a geophone array on a wireline that was temporarily placed into a borehole. Permanent installations were not possible due to the low resilience of such electronic devices and their high costs. Their management required frequent interventions increasing the costs even further (Knott, 2003).

FOS techniques are commonly used in geotechnical and structural monitoring of infrastructures (dams, tunnels, bridges). They bear several advantages over electrical sensing systems. Most importantly, the optically-based FOS is immune to electromagnetic interference. It is light weight, compact and durable, making itself suitable for downhole applications and remote sensing in problematic site assessments. FOS is also capable of real time data acquisition over large network with hundreds of sensing points, resulting in high resolution and large-coverage data (Gong et al., 2019).

Fibre optic sensors can also convey measurements of several physical properties (usually strain, temperature or pressure) within the same network (Gong et al., 2019). In borehole measurements the parameter of interest is usually temperature and strain (Ferraro, 2002).

3.1 Optical fibres

Optical cables (fibres) enable the transmission of large data volumes over long distances and in this respect they are far more effective than usual electrical cables. Moreover they are resilient to electromagnetic interference (Senior and Jamro, 2009) and mechanical disruption (pressure, temperature, chemical reactions) which makes them suitable for downhole applications.

Optical fibres are flexible high-purity silicon glass strands. They consist of an inner core and an outer optical cladding, where the refractive index of the cladding n_2 is smaller than the refractive index n_1 of the core. Following the Snell's law it is ensured, that a light beam interacting with the corecladding interface beyond the critical angle ϑ_c totally reflects and propagates along the fibre (Hartog, 2017).

Common fibre strands are 125 μm in diameter and they are encased in a buffer polymer coating for mechanical protection (Knott, 2003).

Fibres allowing only one propagation path are called single mode fibres (SMF). They are thinner (the core is 5-10 μm), have a higher bandwidths and are used for long distance connections (telecommunication). Multimode fibres (MMF) have a lower bandwidth, core is between 50-100 μm in diameter and they serve as high power transmitters for short distances (Laurin, 1984).

Thanks to the recent development, optical fibres are the most transparent objects manufactured, at the best loosing only 20 % along 5km length. The loss of energy is due to the absorption and scattering. Absorption happens in the UV and mid-IR regions (Fig. 3.1), being the lowest around 1 550 *nm*. An additional absorption is caused by OH ions in the fibre, having its peak around 1 380 *nm*. To eliminate this effect, silicon glass is doped with additives (e.g. Germanium)(Hartog, 2017).

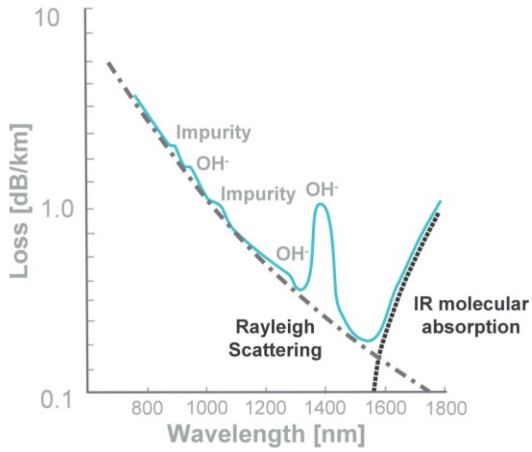

Figure 3.1: *Attenuation curve of an optical fibre (adapted from www.fibercore.com, 2020)*

3.2 FOS System description

Optical fibre sensor system can be crudely described as consisting of a sensor, a transit cable and an interrogator unit (IU). The interrogator is an optoelectronic system which includes a light source (laser) that sends probed pulses through the transit cable to the remote sensor(s). The pulse returns in the form of a backscattered light back to the interrogator, where its properties are measured (e. g. polarization, phase intensity, travel time, wavelength) and converted to the desired physical properties (e.g. strain, temperature).

The relative strain of the fiber is usually expressed in strains (1 ε = double elongation along the axis). The breaking point of common fibres is around 5 *m* (Hartog, 2017).

3.3 Sensor types

FOS sensors (Fig. 3.2) can be generally categorized as point, quasi-distributed or distributed (DFOS), based on the continuity of sensing points (Gong et al., 2019).

Sensing method	Sensors	Parameters[a]	Resolution[b]	Modulation method
Point	Fabry-Perot	Strain/Temperature	0.01% gauge length	Phase
Quasi-distributed	FBG	Strain/Temperature	1–2 με/0.1 °C	Wavelength
Distributed	Rayleigh (OTDR)	Strain/Temperature	1 m/1 °C	Intensity
	Rayleigh (OFDR)	Strain/Temperature	1 cm/0.1 °C	Frequency
	Brillouin (BOTDA)	Strain/Temperature	0.1 m/0.3 °C	Frequency
	Raman	Temperature	1 °C	Intensity

[a] Can be configured to measure displacement, pressure, vibration, acceleration and acoustic.
[b] Represents accuracy for point and quasi-distributed sensors and spatial resolution for distributed sensors

Figure 3.2: *Table of different sensor types (adapted from Hartog, 2017)*

A distributed sensor senses along its whole length, while a point sensor senses only in one specific point. A quasi-distributed sensor senses over the entire length of a cable (fibre), but only in given spaced intervals. In fact it can be viewed as an array of point sensors using the same transit cable. Signals from several points can share one fibre thanks to multiplexing technology, a method widely used in telecommunication (several phone calls on one line). The most common multiplexing techniques are based on wavelength and time division (WDM and TDM technique respectively)(Rao, 2018, Gong et al., 2019).

Point sensors were usually favored for their high precision in seismic measurements, but nowadays the distributed sensors have both large coverage and high precision. By using digital signal processing they exceed the sensitivity of point sensors and also include directional information (Parker et al., 2014).

Another division can be made between intrinsic and extrinsic FOS sensors. In the case of intrinsic sensor, the light pulse is modulated within the fibre. Extrinsic sensors on the other hand are placed aside the fibre as bulk-optic devices (e. g. eletro-optic crystals or crossed polarisers), while the fibre itself is used for transmission (Hartog, 2017).

3.3.1 Point/Quasi-distributed sensors

Quasi-distributed sensors are favored over distributed fibre optic sensing (DFOS) systems in cases, where very detail measurements in specific locations over large distances are required (Hartog, 2017). For such sensing systems there are several technologies including fiber Bragg grating (FBG), long period grating (LPG), Mach-Zehnder interferometers (MZI), Michelson interferometers (MI) or Fabry-Pérot interferometers (FPI)(Madan et al., 2020). Generally, an interferometer is a tool using two sources of light, that interfere with each other forming distinctive patters, that can be used for measuring physical parameters.

Fibre Bragg grating (FBG) sensor is one of the most common quasidistributed FOS techniques and also the first one to be used in geophysical applications. The measured property is the axial strain along the fibre and/or temperature (problems with cross-sensitivity), which modulates the wavelength of incoming light (Gong et al., 2019). An interrogator unit sends laser pulses through a fibre. At every FBG sensor location certain wavelength is reflected back. This shift of wavelength is recorded over time and connected to the respective strain/temperature of the fibre at a certain location (Fig. 3.3)

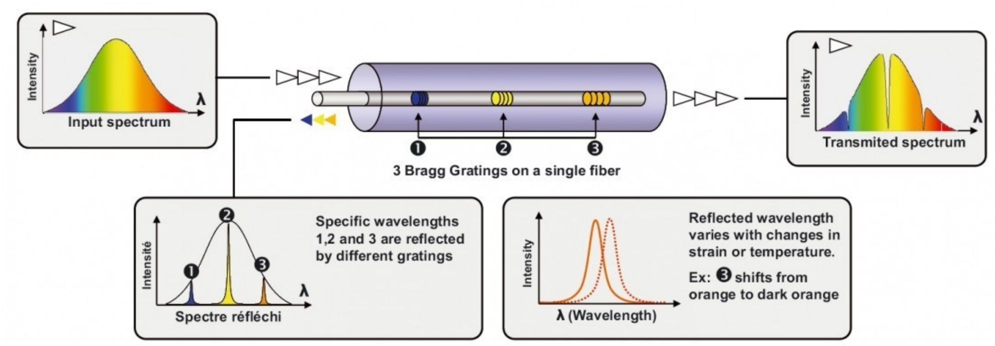

Figure 3.3: *Fibre Bragg Grating technology (adapted from www.scaime.com, 2020)*

The FBG sensor usually measures only at the point of the grating (around 10 mm in length), which is a periodic variation of the fibre's core refractive index n_1 within a short section of a fibre. This variation is photo-imprinted onto the core using ultraviolet light.

The angle of incidental UV light ϑ and its wavelength λ_{uv} are directly determining the pitch length of the grating Λ.

$$\Lambda = \lambda_{uv}/2sin(\vartheta/2)$$

FBG acts as a selective filter for the light sent down the fibre. At each sensing location, certain wavelength of passing light is reflected, while the rest is transmitted. The reflected wavelength is called centre wavelength $\lambda_B = 2n_1\Lambda$ and it is determined by the grating pitch Λ and the refractive index n_1. When strain (or temperature) is applied to the fibre, both of these parameters change (due to elastic elongation and photo-elastic change) causing a change in reflective properties of a fibre section (Ferraro and Natale, 2002). FBG used with a laser source around 1 550 *nm* has a sensitivity of 1.3 *pm/με* and 12 *pm/°C* (Gong et al., 2019).

The number of sensing points per fibre is determined by the interrogator capabilities. In a wavelength division multiplexing (WDM) it is the wavelength range of the laser, which sets the maximum of multiplexed points (they all have to share the same spectrum). A time domain multiplexing (TDM) on the other hand is based on time, hence it requires spacing of at least 1 m between the sensors, so the IU is able to differentiate between incoming signals from adjacent sensors (Gong et al., 2019). FBG system using WDM can serve tens of points per fibre, with TDM it increases to hundreds of sensors per fibre. If both techniques combine the system is capable of sensing several thousands points - approaching the capabilities of a fully distributed sensor systems (Hartog, 2017).

A fibre section with Bragg grating as a sensor itself is not sensitive enough for seismic measurements. For seismic applications it is preferable to use a longer sensing sections. Instead of a single FBG sensor, a pair of FBGs on each side of a longer fibre section (defining the gauge length) can turn it into a sensing element (Paulsson et al., 2014). Therefore the point sensors, instead of a point measurement, measure certain property (strain) cumulatively over a longer section. Then the mean value is prescribed for the whole gauge length (Hartog, 2017).

Paulsson et al. (2014) developed a Fibre Optic Borehole Seismic Vector Sensor that compares the change in phase angle of light between two FBGs caused by strain over a certain distance. In similar cases, the FBG technology is combined with other optic sensors based on interferometric techniques. It was already proved by Legoubin et al. (1995) that two identical, closely separated

Bragg gratings form Fabry-Pérot interferometer, which was proved to have higher strain sensitivity than a single FBG sensor (Madan et al., 2020). For example Abolbashari et al. (2009) proposes a sensor combining two FBGs as point sensors and also as selective mirrors for two overlapping Michelson interferometers sensing the fibre length between the two points.

FOS systems for geophysical applications (e.g. Knott, 2003 or Paulsson et al., 2014) are built in a way that they can sense strain changes in three directions simultaneously. One structure is achieved by coiling the fibre within the sensor so it responds to all axial strain. This allows to determine the phase of a seismic wave.

One of the issues of FOS systems is a temperature-strain cross-sensitivity. There are several approaches for a temperature compensation in strain measurements. A common technique in geoengineering applications is the deployment of a double sensor array, where one of the sensors is loose and insensitive to strain - e.g. not glued to the structure (Gong et al., 2019). Another possibility is the use of interferometric techniques. For example FBG twin-grating based on a combination of Mach-Zehnder and Michelson interferometers which can sense strain and compensate for temperature is mentioned by Abolbashari et al. (2009).

Another limitations of fibre optic sensing is that the bare fibre can withstand maximum strain around 5 $m\varepsilon$ (equivalent to 0.5 % elongation), so a special care should be paid during handling and installation, because the fibre is very sensitive to loading and bending (Gong et al., 2019).

3.3.2 Distributed sensors

Distributed fibre optic sensors (DFOS) sense a certain physical property at every point along an optical fibre. They are of intrinsic type and use similar technique of reflectometry as radar system, to locate the distance along the fibre (Hartog, 2017).

The first and most common type of DFOS is distributed temperature sensing (DTS). The main motivation for its development was a monitoring of cables in electrical networks. Today the driving force comes from oil and gas industry, where DTS is extensively used for well monitoring (Hartog, 2017).

Another type of distributed sensor is DSS (distributed strain sensor) and DAS (distributed acoustic sensor). They have vast range of engineering and energy applications including production optimization and integrity monitoring (Parker et al., 2014). The physical property of the fibre measured by DFOS is the same as in the case of FOS systems - strain and temperature. Depending on the interrogating techniques the desired parameter is sensed and solved for a cross-sensitivity with the other.

The technique of DFOS is based on OTDR (optical time domain reflectometry) which was developed in the late 70s for detection of faults in transmission lines. The IU sends probed pulses down the fibre with high frequency (up to 20 kHz) which are reflected back by rapid changes of refractive index (breaks, poor splices, etc.). This information can be used to localize a problem along the fibre (Fig. 3.4).

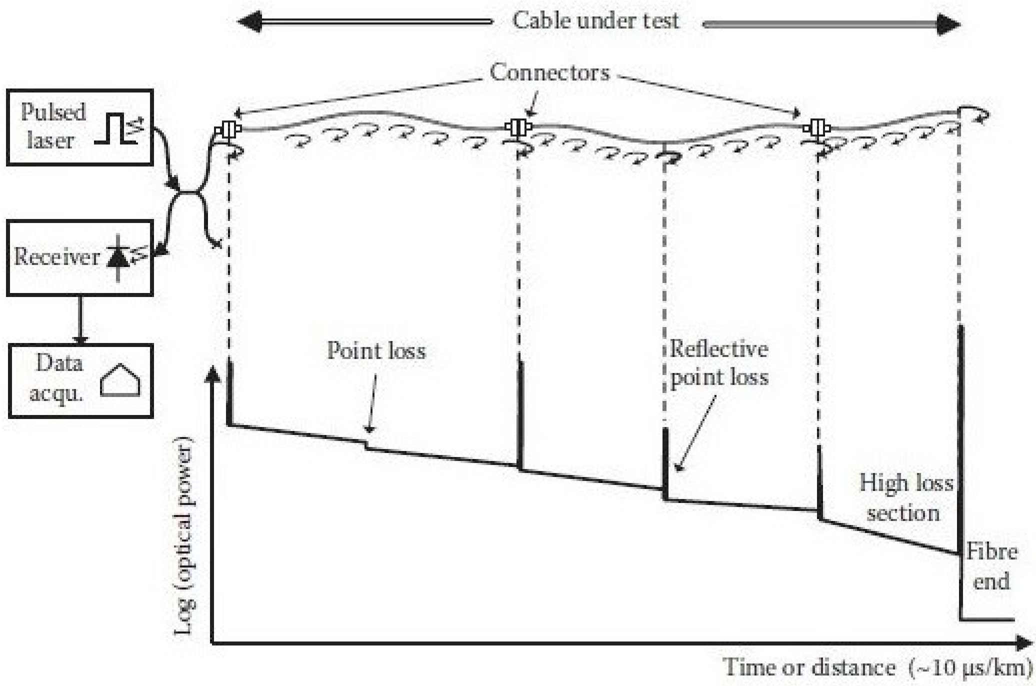

Figure 3.4: *Optical Time Domain Reflectometry system (adapted from Hartog, 2017)*

But for DFOS purposes, there is a different, more important part of a returning signal, which is also detected by the OTDR - the backscattered light caused by the natural impurities of the glass, which cause local variations of the refractive index. The scattering happens in all direction and just a small portion is reflected within the narrow angle back to the detector (usually 0.1 % - 1 % of the scattered light is detected). The biggest contribution to backscatter signal is attributed to Rayleigh backscatter, which is caused by the fixed impurities and does not cause a frequency shift of the returning light. Another type of scatter is Raman and Brillouin scattering, both happening during the interaction of a photon with vibrating molecules in the fibre. Raman is used predominantly in DTS systems, because the intensity (amplitude) of backscatter is proportional to temperature. Brillouin scatter causes a wavelength (frequency) shift, so it is used for determining strain and temperature (Fig. 3.5).

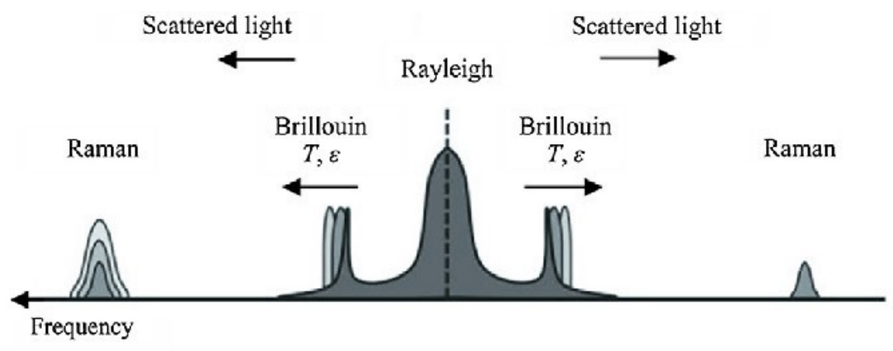

Figure 3.5: *Backscatter spectrum in optical fibre (adapted from Gong et al., 2019)*

The attenuation characteristics of the fibre are ideal for distributed sensing purposes, nevertheless if the attenuation factor is increased, the possible sensed distance is shortened. (Hartog, 2017).

Distributed acoustic sensing (sometimes referred to as distributed vibration sensing - DVS (Hartog, 2017)) is an emerging tool in the geophysical field. It uses the method of phase-sensitive OTDR (Fig. 3.6). Being based on Rayleigh backscatter it measures the strain (or strain rate) along the fibre by sensing the phase shift between many scattering points (Parker et al., 2014).

When seismic waves interact with a fibre, its small compression or extension causes a change of distances between many scattering points (0,1 nm). This alters the time arrivals by a small amount (usually in femtoseconds). The interferometric analysis extracts how the returned signal vary in phase or timing and by further processing it is possible to derive the seismic wave properties, that caused the perturbation and compute a dynamic profile of the strain (Zhan, 2020).

It is good to note that there is no generic architecture for DAS systems and different authors use this term for slightly different technologies.

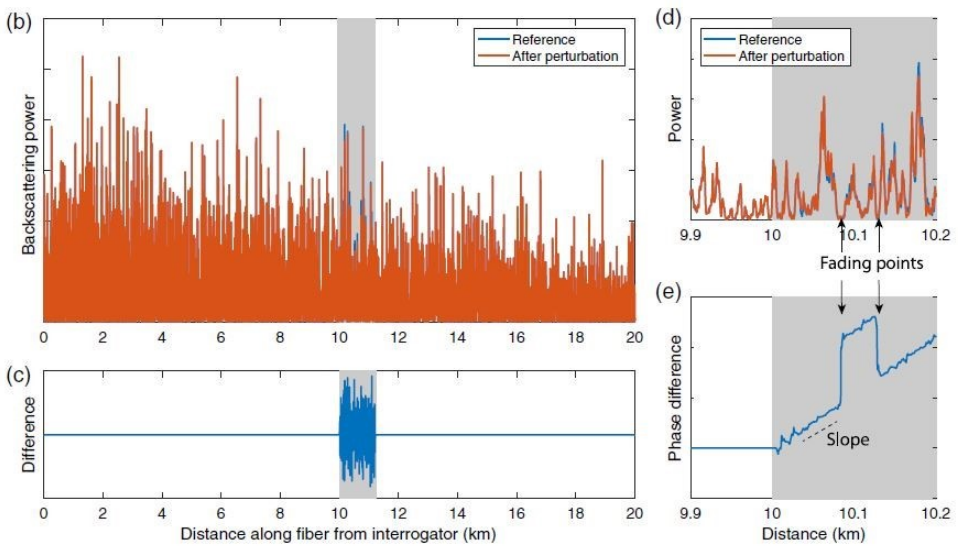

Figure 3.6: *Phase-sensitive OTDR in DAS, where 1km section of a fibre around 10 km distance was a subject of uniform strain, in (e) the slope of phase differences quantitatively measures the applied strain (adapted from Zhan, 2020)*

Parker et al. (2014) from Silixa has developed a DFOS called iDAS (intelligent DAS) sensor, which is based on the DAS technology. They have conducted several lab experiments to test its performance. Their objectives were signal fidelity, acoustic sampling range, acoustic bandwidth, dynamic range, spatial resolution and the possible range of a measurement.

Fidelity is the ability to faithfully record the acoustic signal. To determine the iDAS fidelity, a section of a fibre was excited by a sine wave of known parameters (from a loudspeaker as the source). The harmonic distortion observed was attributed rather to the source response than to the iDAS sensing mechanism, showing its high fidelity.

The DAS sampling rate depends on the time it takes for a pulse to go back to the receiver. To avoid a cross-talk, there should always be only one pulse at a time. If the fibre length is 10 km and the speed of light in the fiber is around 200 000 km/s, it results in the sampling rate of 10 kHz (from *velocity/distance = frequncy*). Alternatively 100 kHz applies for 1km fibre length. The sampling rate can be increased using multi-mode fibres (MMF), but in general the iDAS system is not optimized for that.

The acoustic bandwidth of iDAS was shown to be very broad, ranging from 8 mHz to 50 kHz. Similar applies to the dynamic range, which was determined 120 dB, ranging from strain change of 5 $m\varepsilon$ (close to the breaking strain of the fibre) to 5 $n\varepsilon$.

The sampling resolution is determined by the length of a pulse and it requires high-speed electronics and data processing. For example 10 ns pulse duration equals to 1 m of the fibre. iDAS provides spatial resolution between 1 - 10 m, which allows the sampling resolution (distance between sensing points) to be between 0,25 - 2,5 m.

iDAS uses a laser source with a central wavelength at 1550 nm, which is the optimum for signal losses. Signal-to-noise ratio (SNR) has been proven to be good up to a 40km distance (80km with added amplifiers). Furthermore, iDAS IU is capable of sensing 40 000 points simultaneously, corresponding to 40km long fibre with sampling rate 1 m.

This capability can be used in large arrays interrogated by one sensing unit. For instance a 3D array composed of a 2D surface array and series of boreholes.

Another great advantage of all DAS systems is their possible use within the existing cable networks, because any fibre-optic cable can be used for a DAS measurement if it is connected to an IU (Cox et al., 2012). This could be used in earthquake monitoring (Zhan, 2020).

3.4 Comparison of sensing methods

The FOS and DFOS systems are becoming increasingly used in seismic surveys and monitoring projects. Quite commonly there are both distributed and quasi-distributed systems combined in order to get better sensing performance (Hartog, 2017).

DFOS bears several advantages over the conventional geophone data acquisition. Firstly, one optical cable may comprise of several fibres allowing for multiple distributed measurements (e.g. DAS with DTS). Another advantage is the possible deployment in slim and/or long horizontal wells, where the geophone acquisition would be problematic. Also the DFOS sensor usually covers the whole length of a desired measurement, so there is no need to change the set-up of a survey (e.g. by moving the geophone array). This results in time and cost savings and the entire well can be covered with a single shot (Cox et al., 2012).

One of the main disadvantages of DFOS systems is their sensitivity, which is approximately 2 orders of magnitudes less than in the case of conventional geophones or accelerometers (Hartog, 2017). Repeated measurement are vital allowing for image stacking, that can improve the signal-to-noise ratio (SNR). In general, high fidelity of the sensor and its proper clamping increases the SNR. If a cable is cemented behind the casing, the SNR is better than in the case of cable attached to the production tubing or freely hanging in the well (Parker et al., 2014).

DAS provides seemingly similar results to conventional sensors, but they cannot be simply compared. DAS measures strain rate over certain gauge length (which can be converted to strain by integration). While a standard geophone measures particle velocity at a certain fixed point (Hartog, 2017).

Daley et al. (2016) derives a conversion of the measured strain to particle velocity of the fibre as follows: $v = c \times \varepsilon$

where v is particle velocity, ε is strain and c is apparent velocity along the fibre.

4 Case study using FOS system

The following section describes a seismic survey, that was conducted in the LT-1 borehole in February 2020.

The name LT-1 stands for Litoměřice – provincial town in north Czechia - where the borehole was drilled in 2007. The main goal of the project was an investigation on the possible use of geothermal energy, which would provide electricity and heating for the town. Litoměřice is suitably placed on the Litoměřice fault, which is very near to Eger rift – an area with the highest geothermal potential in Czechia. Hence it was proposed that a borehole could provide more information about the lithology and water permeable boundaries, that could serve as a geothermic pump, when connected with a second borehole, later drilled (Šafanda et al., 2020).

Unfortunately the project has faced major complications, several already during the drilling itself, when uncommon rock facies were encountered. They have diverted the drill rig from its vertical direction and different drilling technology had to be used. Nevertheless, this second technology was not successful either and stopped drilling in the depth of 2 100 m, leaving the aim depth of 2 500 m untouched.

Later on during borehole measurements, the bottom part of the well had caved in, leaving only 1 800 m accessible. At such condition the project was abandoned.

In 2016 a new project has started on the borehole site as a result of cooperation between several research institutes and the Litoměřice town. Named as a Research Infrastructure for Geothermal Energy (RINGEN) it aims to conduct a broad research in the geothermal field.

In 2019 the casing of LT-1 was removed and the borehole was cleared and prepared for another series of measurements which comprised of caliper and sonic logging, followed by hydrodynamic tests and DTS.

The next stage was a seismic survey - VSP survey more specifically, which was conducted over the course of several days in the beginning of February 2020. The VSP was originally suggested to run alongside a geophone deployment, which would serve for a long term earthquake monitoring at depth of 1 500 m. Apart from determining major boundaries and cracks at depth, another goal of the survey was set - a deployment of FOS system for seismic measurements in a borehole and its comparison to the geophon measurements. It was the first survey of such kind in the Czech conditions.

4.1 Methodology

Originally 3-component geophone was supposed to be stepwise lowered into the depth of 1 500 m. From 600 to 1 500 m zero-offset VSP was planned. Furthermore a fibre-optic cable with FBG technology was supposed to sense the region between surface and 1 200 m. Having all sensors in target depths, walk-away VSP was planned on two profiles and multi-azimuth VSP with the source on several locations in the vicinity. Due to technical issues, which later appeared, the complexity of the survey was reduced.

One vibrotruck from the Freiberg University of Mining and Technology was used as the source. The type was VIB 3246 On-Road Vibrator with frequency range 10 – 250 Hz and weight of 32 tonnes. It was positioned few meters from the well head on a paved surface in a facility of an old military complex (RINGEN site).

The geophone from *ASIR seismic* was on the end of 1 510m long cable. It had three gimbal mounted sensors with frequency 4.5 Hz. 6-channel digitizer with sampling frequency of 1 kHz was used for data acquisition.

The optical fibre was specially designed by SAFIBRA company, usually offering FOS systems for civil engineering purposes. There was 600 m of a sensorless fibre and 600 m including sensors (31 altogether). These were placed in 20m intervals, consisting of one Fibre Bragg Grating anchored to 0.4 m length of the fibre. In such sense, this FOS system was quasidistributed with each element sensing strain along 0.4m gauge length. The WDM method was used for separating the traces. The central wavelength was 1 550 nm. The sensitivity of the sensors was 0.8 $pm/\mu\varepsilon$. SAFIBRA company was responsible for data acquisition and used an IU with 11 kHz sampling rate.

Both fibres were deployed into the borehole by a geophysical team from Charles University. It required uncoiling both fibres, and clamping the fibreoptic cable to the thicker geophone cable with the use of zip ties. Also it was ensured that the cables are lowered just by 20 m each time between the measurements.

The source used frequency range 10 – 150 Hz with sweep length 20 s. Each measurement (position of sensors) was repeated three times using three consecutive sweeps. The time synchronization was set using GPS time.

4.2 Results

The survey went according to plan till a problem was detected on the second day, when geophone position was at 900 m depth and the first half of the optic cable was in the borehole. Surprisingly the fibre-optic cable was mistakenly coiled in the opposite direction, so instead of having 600 m of sensors inside, all were still on the coil at the surface . This proved the direct comparison between the geophone and the FOS system impossible, as each of the technologies has measured different depth sections (the FOS system 0 – 500 m and the geophone 600 – 1 500 m).

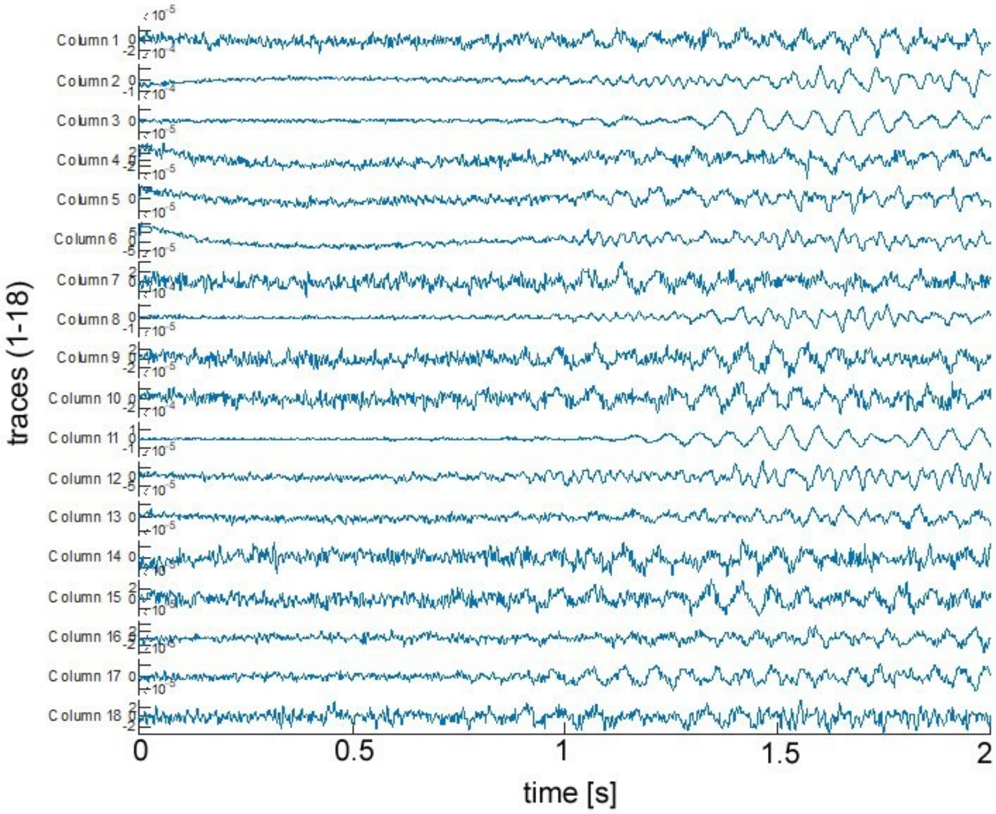

Figure 4.1: *Signal on 18 traces in the first 2 seconds of the sweep after stacking and normalization*

Nevertheless the survey continued to its end, when the geophone reached the target depth of 1 500 m and all fibre-optic sensors were below the surface (0 – 600 m). Unfortunately not all sensors proved to be working (due to possible fibre overloading). Only 26 out of 31 were capable of detection. Those were the ones nearer to the IU and corresponded to the top 500 m of the borehole.

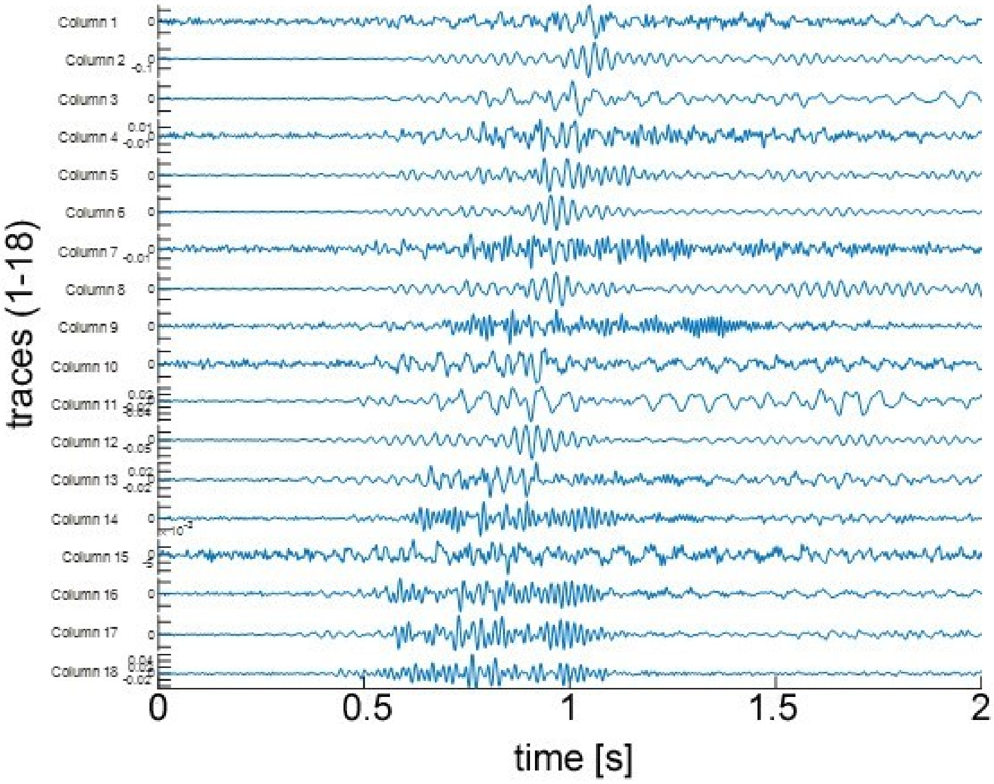

Figure 4.2: *Signal on 18 traces in the first 2 seconds of the sweep after stacking,normalization and correlation*

The measurements were taken simultaneously with the stepwise lowering, so a readable signal was obtained from the first 26 sensors. An example of the data is shown in Fig. 4.1, consisting of 12 stacked sweeps.

The interpretation of such signal is not possible, so a correlation with the sweep signal was applied (Fig. 4.2).

In contrast to the geophone data it was very difficult to detect any first arrivals on the traces from fibre-optic sensors. The only exception would be a strong correlation, later identified as a "tube wave", with the velocity around 1450 m/s, which was induced by the wave traveling through the casing.

Surprisingly the maximum amplitudes on different traces (sensors) showed a great range (between 0.012 - 0.861). It can be noted that the sensors had different sensitivities. Especially sensor 24 (around 60 m in depth) showed approximately 4x greater maximum amplitude than the rest. It is possible that this sensor was not properly attached to the anchor points, which resulted in sensing over longer gauge length. Therefore

The signal spectrum shows three major bands (Fig. 4.3). First one at 13 Hz, another at 30 Hz and the last around 50 Hz. The origin of those bands is unclear. Since seismic interpretation is usually interested in higher frequencies, two types of frequency based filtration were applied to the data. The first used a filter range 20 - 40 Hz (Fig. 4.4) and the second 40 - 300 Hz (Fig. 4.5).

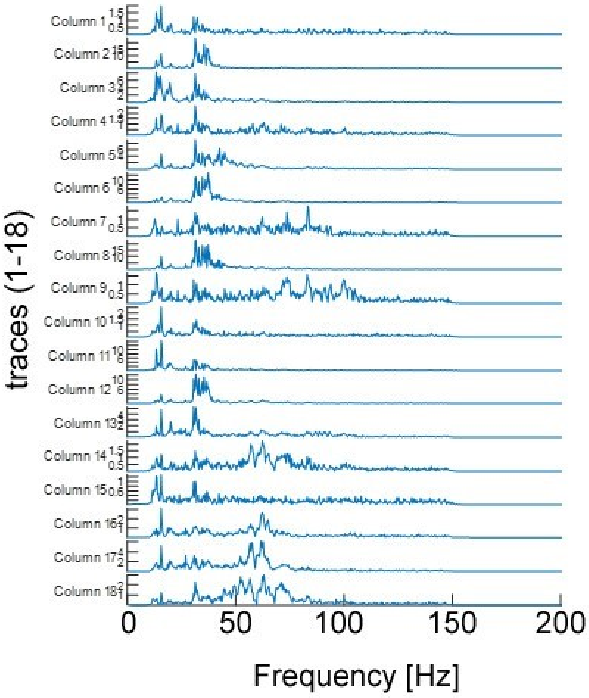

Figure 4.3: *Signal spectrum on 18 traces showing distinctive bands at 13 Hz, 30 Hz and 50 Hz*

Eventually there was no significant decrease of amplitude range between original and filtered signals, apart the sensor 24, which demonstrated maximum amplitudes in lower frequencies (Fig. 4.6).

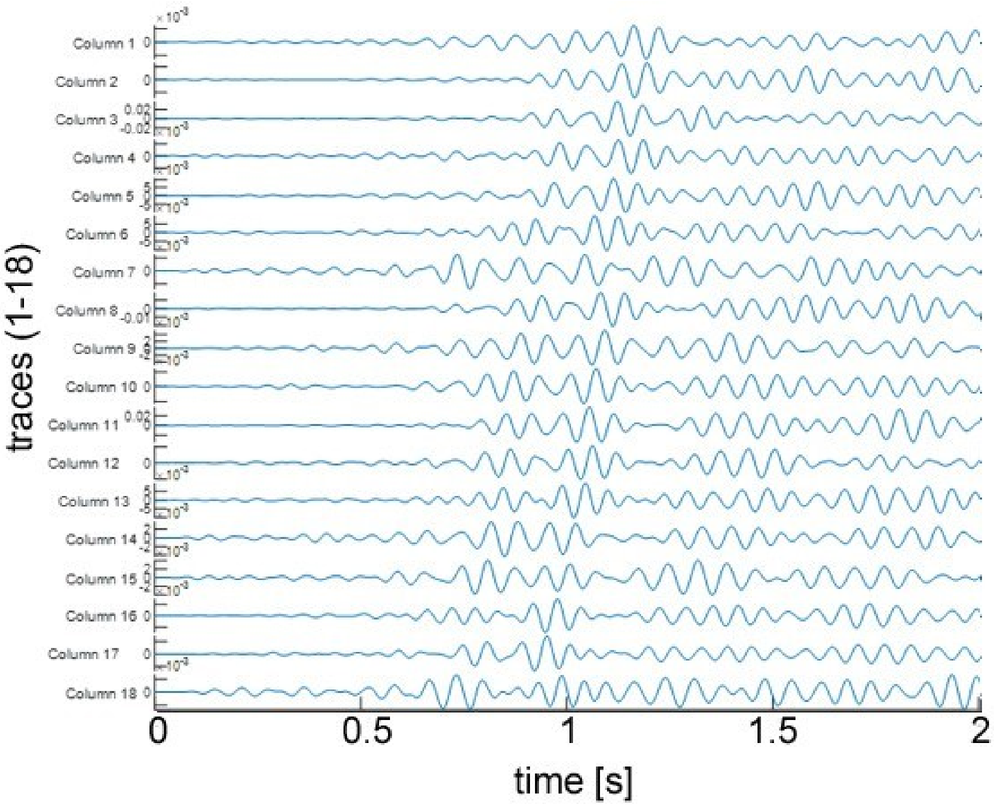

Figure 4.4: *Signal on 18 traces in the first 2 seconds of the sweep, using frequency filtration with a range 20-40 Hz*

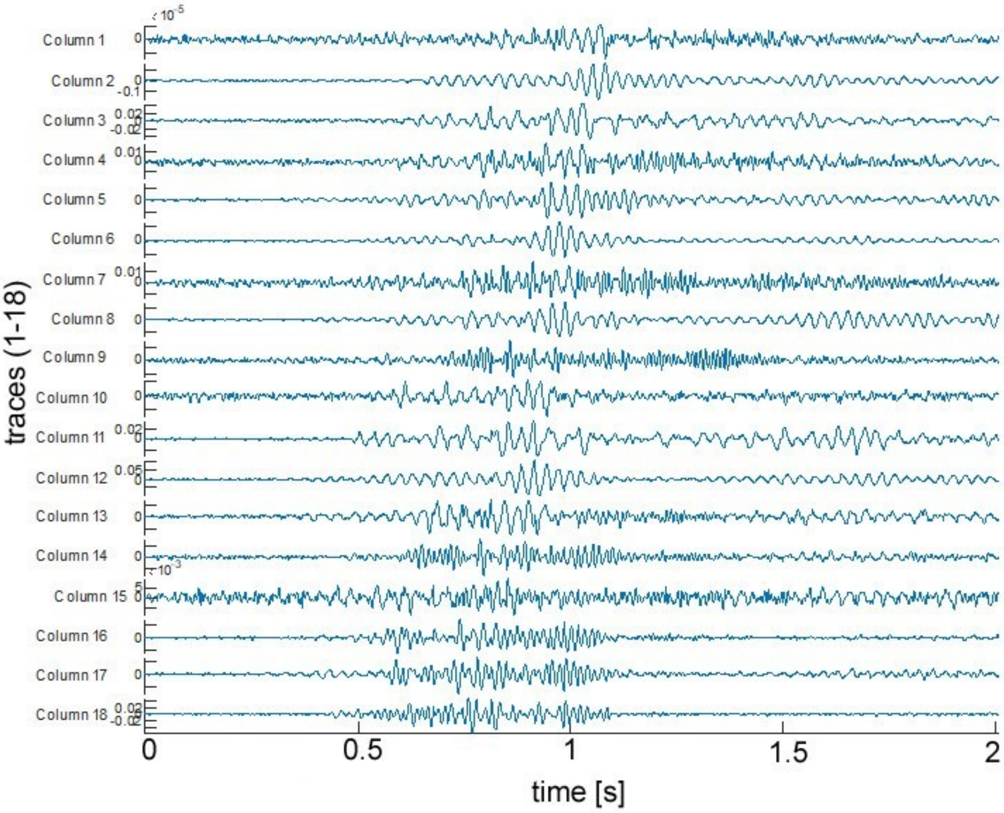

Figure 4.5: *Signal on 18 traces in the first 2 seconds of the sweep, using frequency filtration with a range 40-300 Hz*

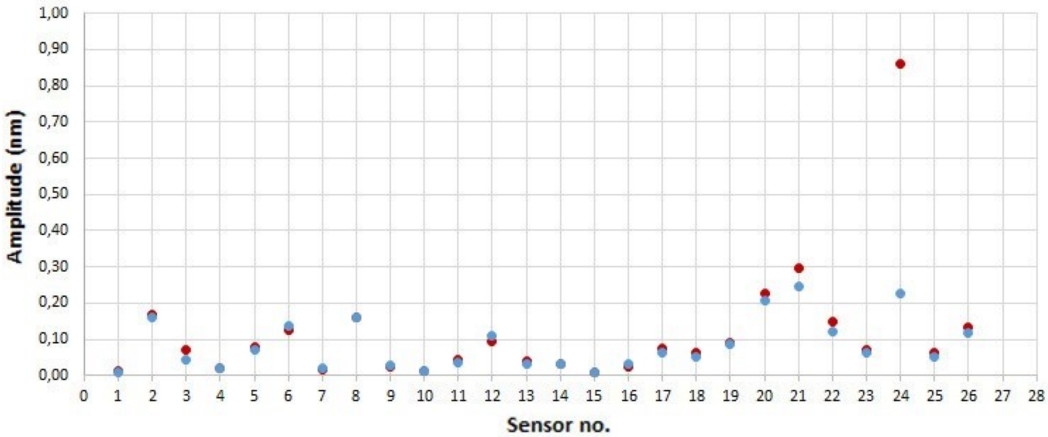

Figure 4.6: *Maximum amplitudes on different sensors, before (red) and after applying filtration 40-300 Hz (blue)*

5 Conclusion and Discussion

Even though the technologies could not be directly compared, there are several interesting results concerning the use of fibre optic technology in borehole conditions.

The manufacture of a FOS system for a downhole application was a new challenge, that has later influenced the results of the measurement. Apart the false coiling direction, it might have also been responsible for the malfunction of one of the sensors and the later drop-out of measurements.

Another source of problems might be the choice of unclamped configuration. Although it has provided consistent data, it also might have contributed to the overload of the optical fibre, which was not able of detection several hours after the installation.

Fibre optic cables for seismic sensing are usually firmly clamped to the production tubing, so the fibres are not exposed to excessive strain and bending. In LT-1 experiment, the fibre optic cable was poorly attached on a wireline (geophone cable) which was not secured from rotation during the deployment. It is probable that the unclamped geophone cable was twisting in one direction, subjecting the thinner fibre to extreme stress and bending by coiling it around.

The detection of first arrivals for the seismic interpretation was difficult, because the signal comprised of a large amount of noise. Also the stacking of 12 sweeps might not have been enough for FOS.

The amplitude variation might be contributed to the sensor sensitivity. Because the filtration has not shown any decrease in the range, none of the spectral bands can be clearly connected to the own oscillations of the unclamped cable.

Overall the deployment of FOS system in LT-1 borehole has not bring the desired seismic data for geological interpretation, neither the option of direct comparison with the geophone measurements.

Nevertheless this experiment alongside with this thesis is presenting the possibility of using FOS systems for downhole seismic applications and not only for civil engineering purposes.

There is still a lot of space for improvement in the future applications on the local ground, but the worldwide trend is showing, that DFOS and FOS instrumentation in seismic borehole measurements may successfully take over conventional sensing techniques.

References

Abolbashari, M., Gerges, A., Farahi, F., 2009. A combined fiber Bragg grating and interferometric based sensor. Proceedings of SPIE - The International Society for Optical Engineering 7503.

Alsadi, H.N., 2016. Seismic Hydrocarbon Exploration: 2D and 3D Techniques. Springer International Publishing. 9783319404363.

Burger, H. R., 2006. Introduction to applied geophysics. Norton, London.

Cox, B., Wills, P., Kiyashchenko D., Mestayer J., Lopez, J., 2012. Distributed Acoustic Sensing for Geophysical Measurement, Monitoring and Verification. CSEG Recorder 37, 7-13.

Daley, T. M., Miller, D. E., Dodds, K., 2016. Field testing of modular borehole monitoring with simultaneous distributed acoustic sensing and geophone vertical seismic profiles at Citronelle, Alabama. Geophysical Prospecting 64(5). 10.1111/1365-2478.12324.

Everett, M. E., 2013. Near-Surface Applied Geophysics. Cambridge University Press, UK.

Ferraro, P., De Natale, G., 2002. On the possible use of optical fiber Bragg gratings as strain sensors for geodynamical monitoring. Optics and Lasers in Engineering 37, 115-130.

Geldmacher, I. M., Marr, A., Rangel, J., Dyer, B., 2013.Equipment Testing and Optimization for Borehole Seismic Monitoring. European Association of Geoscientists and Engineers, Second EAGE Workshop on Borehole Geophysics. https://doi.org/10.3997/2214-4609.20142584.

Gillis, G., 2020 (online). Schlumberger oilfield glossary. https://www.glossary.oilfield.slb.com/.

Gong, H., Kizil, M. S., Chen, Z., Amazadeh, M., Yang, B., 2019.Advances in fibre optic based geotechnical monitoring systems for underground excavations. International Journal of Mining Science and Technology 29, 229-238.

Hardage, B., 2013. Using seismic technologies in oil and gas exploration. EarthSky. https://earthsky.org/earth/ bob-hardage-using-seismic-technologies-in-oil-and-gas-exploration.

Hartog, A. H., 2017. An Introduction to Distributed Optical Fibre Sensors. CRC Press (Taylor and Francis). 1482259575.

Knott, T., 2003. Listening with light. Offshore Engineer, 26-30.

Lines, L. R., Newrick, R. T., 2004. Fundamentals of Geophysical Interpretation. Society of Exploration Geophysicists. 10.1190/1.9781560801726.

Madan, A., Yap, S., Paulose, V., Chang, W., Shum, P., Hao, J., 2020. Investigation of a Bragg Grating-Based Fabry–Perot Structure Inscribed Using Femtosecond Laser Micromachining in an Adiabatic Fiber Taper. Applied Sciences 10, 1069.

Mussett, A. E., Khan, M. A., 2000. Looking into the Earth. Cambridge, NY.

Parker, T., Shatalin, S., Farhadiroushan, M., 2014. Distributed Acoustic Sensing - a new tool for seismic applications. First Break 32, 61-69.

Paulsson, B. N. P., Thornburg, J., He, R., 2014. A Fiber Optic Borehole Seismic Vector Sensor System for High Resolution CCUS Site Characterization and Monitoring. Energy Procedia 63, 4323-4338. https://doi.org/10.1016/j.egypro.2014.11.468.

Rao, S., 2018. Numerical Simulations in Engineering and Science. IntechOpen. 9781789234503.

Senior, J. M., Jamro, M. J., 2009. Optical fiber communications: principles and practice. Pearson Education. 978-0130326812.

Sharma, P. V., 1997. Environmental and engineering geophysics. Cambridge University Press, UK.

Stewart, R. R., 2001. VSP : An In-Depth Seismic Understanding. CSEG Recorder 26, 1-15. https://csegrecorder.com/articles/view/ vsp-an-in-depth-seismic-understanding.

Šafanda, J., Verner, K., Fraňek, J., Peřestý, V., Holeček, J., Fischer, T., 2020. Geology and geothermal potential in the eastern flank of Eger Rift (Litoměřice area, Czech Republic). Geothermics 86, 1-11.

Zhan, Z., 2020. Distributed Acoustic Sensing Turns Fiber-Optic Cables into Sensitive Seismic Antennas. Seismological Research Letters 91, 1-15.