FIBRE-OPTIC DISTRIBUTED ACOUSTIC SENSING FOR DETECTION OF SEEPAGE AND INTERNAL EROSION

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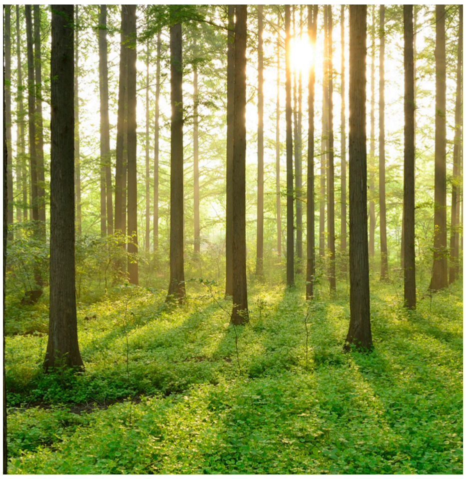

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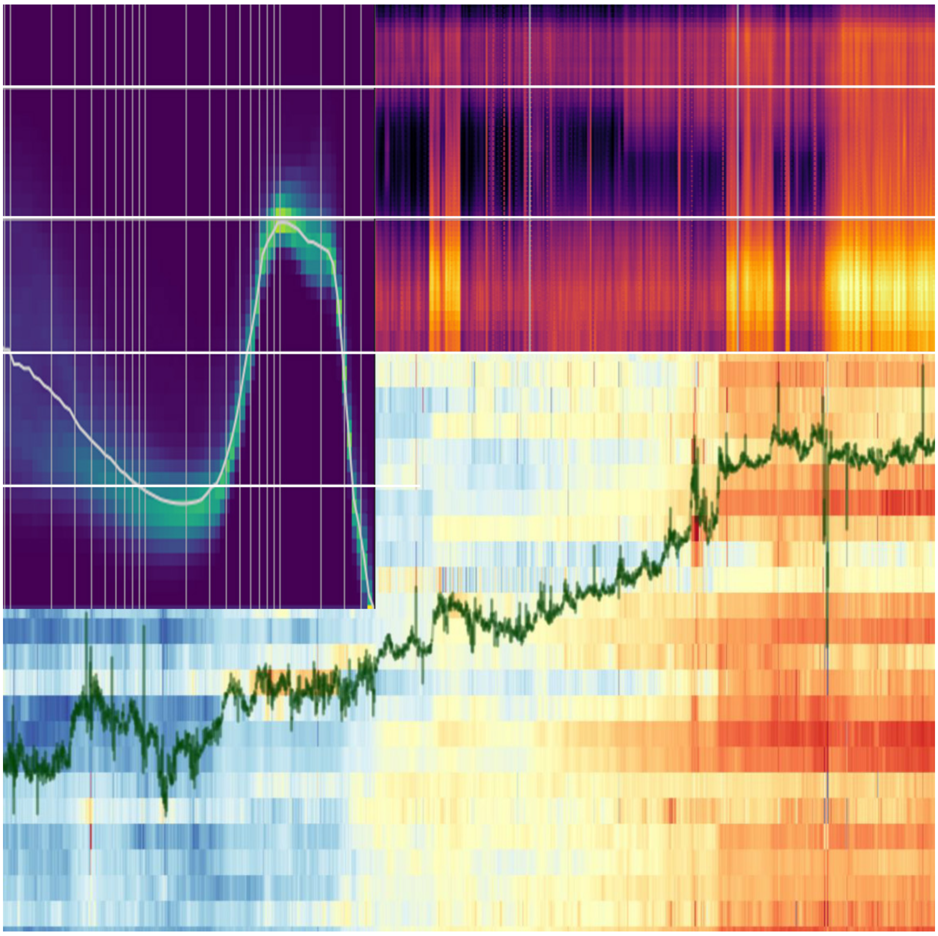

Energiforsk

Fibre-Optic Distributed Acoustic Sensing for Detection of Seepage and Internal Erosion

Measurements in embankment dams

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Foreword

In this study acoustic measurements (Distributed Acoustic Sensing, DAS) have been carried out at a dam equipped with optical fibres. The hypothesis was that it would provide additional information regarding changes of material properties and seepage flow, meaning a chance to obtain more information from already existing installations at dams. The proof-of-concept that has been performed within this study shows that there is great potential in using DAS for dam monitoring purposes.

The work has been performed by HydroResearch (Sam Johansson, project leader and Carl Nygren) and Silixa (Anna Stork, Ari David and Michael Mondanos). Additional seismic evaluation has been performed by Sisprobe (Roméo Courbis, Aurélien Mordret and Richard Lynch). The work has been followed by a reference group consisting of Henrik Arver, Swedish Regulation Enterprises, Christian Bernstone, Vattenfall, Kerim Genel-Waldenström, Vattenfall, Anders Marklund, Vattenfall, Sezar Moustafa, Fortum, and Petter Westerberg, Uniper.

The project has been carried out in the framework of the Energiforsk Dam Safety R&D Program with participation from the Swedish hydropower industry and Svenska kraftnät.

Utökad sammanfattning

Optiska fibrer för distribuerad mätning finns installerade i nästan 100 dammar i Sverige idag. Dessa används för detektion av läckage (baserat på distribuerad temperaturmätning, DTS) eller rörelse (baserat på distribuerad temperatur-, och töjningsmätning DTSS). Flertalet installationer kan även användas för distribuerad akustisk mätning (Distributed Acoustic Sensing, DAS).

Utvecklingen av DAS, beträffande såväl mätteknik som utvärderingsmetodik, har gått snabbt framåt de senaste åren. I denna studie har passiva akustiska mätningar utförts i två av dammarna vid Näs kraftstation. Resultatet visar att seismiska gång-hastigheter kan fastställas och extraheras. Detta innebär att tekniken främst kan användas för undersökning av dammar, genom jämförande mätningar, dvs. eventuella förändringar sedan föregående mätning kan upptäckas.

Projektet har omfattat följande moment:

- Utvärdering av vilken information som ytterligare kan fås från de optiska kablar som ofta finns installerade i fyllningsdammar
- Utvärdering av vad analys av förekommande bakgrundsljud (ambient noise interferometry ANI) kan ge beträffande vattenläckagets läge och storlek.
- Ge kompletterande information som kan jämförs med liknande mätningar internationellt.
- Bedöma metodens potential för dammövervakning samt om metoden kan användas som ”Early Warning System”.

Vid distribuerad mätning i optisk fiber används själva fibern som sensor. Detta har fördelen att mätinstrument kan anslutas externt och bytas ut. När ny mätteknik finns tillgänglig kan således nya instrument anslutas till befintliga fibrer. Flera fibrer i en kabel möjliggör även simultan mätning med olika typer av mätinstru-ment. Eftersom installation av optisk fiber i dammar är vanligt förekommande i Sverige öppnas möjligheten för nya metodiker för dammövervakning i takt med att ny teknik utvecklas baserad på optisk mätning.

DTS mätning ger goda möjligheter att upptäcka skillnader och förändringar av vattenströmningen i närheten av kabeln med hög upplösning längs kabeln. Information om vad som sker på större avstånd från kabeln är dock osäker, varför kompletterande mätningar med DAS är av intresse då de kan vara en metod för att upptäcka förändringar längre bort från kabeln.

Akustiska mätningar utfördes hösten 2019 vid Näs kraftverk under ca 1,5 månads tid med en Silixa iDAS. Mätning har utförts genom single-mode fibern i de befintliga optiska kablarna. Samtidigt utfördes temperaturmätning i multi-mode fibern. Därefter har mätdata bearbetats och utvärderats.

Kombinationen av DAS data och interferometri från existerande bakgrundsbrus (ambient noise interferometry ANI) har testats för att utföra tomografisk analys av dammens egenskaper. Detta inledande försök har visat att kombinationen kan användas för att fastställa seismiska gånghastigheter. Stabila korskorrelerade vågformer har identifierats, vilka kommer från kraftstationens turbiner/ generatorer. Dessa signaler är lämpliga att använda för utvärdering enligt ANI-metoden.

Vid pågående inre erosion i en fyllningsdamm påverkas gånghastigheterna för både kompressionsvågen (P-wave) och skjuvvågen (S-wave). Metoden kan därför potentiellt användas för att upptäcka eventuella förändringar genom jämförelse mot en referensmätning, dock med begränsning av mätnoggrannhet och påverkan från andra faktorer.

Vattenströmningen i den damm där mätningarna gjordes är låg och homogen (förmodligen $<10^{-6}$ m^3/s per meter). Vid höger anslutning förekommer dock ett svagt något högre läckageflöde (totalt ca 10^{-5} m^3/s utmed ca 1-2 m). Denna svaga vattenströmning kunde inte upptäckas vare sig med seismiska gånghastigheter eller akustisk emission. En högre noggrannhet är nödvändig för att tekniken ska kunna användas på så små skillnader. Både mätteknik och utvärderingsmetodik har dock utvecklats snabbt de senaste åren och denna utveckling förväntas fortgå, både beträffande mät- och utvärderingsteknik.

DAS mätningarna har utvärderats längs kabeln med en steglängd av 1 m, vilket möjliggör skapandet av en detaljerad bild av seismiska gånghastigheter i dammen. Ytterligare möjligheter finns om flera kablar kan mätas i samtidigt. De bör då kunna användas för 2D eller 3D tomografi. Högfrekvensvågor i kombination med kortare samplingslängd skulle förbättra upplösningen ytterligare. Detta är möjligt med den senaste DAS tekniken. Detta medför att befintliga installerade kablar kan förväntas få mer användning i framtiden.

Sammanfattningsvis visar studien att det finns potential för användning av DAS och ANI för undersökning av dammar. Seismiska gånghastigheter i dammar kan fastställas och extraheras, och resultatet kan användas för upptäckt av eventuella förändringar sedan föregående mätning. Förbättrad kunskap av hastigheternas koppling till olika parametrar är önskvärd för att kunna göra en bättre tolkning av mätresultatet.

Summary

Optical fibres are installed in almost 100 dams in Sweden today. They are used for detection of seepage (based on Distributed Temperature Sensing, DTS) or movement (based on Distributed Temperature and Strain Sensing, DTSS). Most of those installations can also be used for acoustic measurements (Distributed Acoustic Sensing, DAS). The recent development of the technology, regarding both monitoring and analysis techniques, may give an additional method to study the seepage/internal erosion phenomena in dams and furthermore to provide information on the integrity.

The objective of this study is to make passive seismic (acoustic) measurements at a small dam (Näs Power plant) to evaluate its sensitivity and its potential for subsurface dam monitoring. There are two passive seismic techniques that can be applied using DAS, seismic monitoring/imaging using recordings of the ambient noise field or monitoring of the sound of flowing water, making use of acoustic emissions (AEs). A technique known as ambient noise interferometry (ANI) is used to analyse the noise recordings.

The number of dams where cables have already been installed for DTS or DTSS, is an important asset. In general, we wish to get information further away from the cable. With complementary measurements using DAS it may be possible to detect anomalous seepage flow in dams without a drainage system, and to detect this flow at some distance from the cable.

The current study is a proof-of-concept to investigate the possibility of conducting an ambient noise interferometry (ANI) analysis with DAS data to image and monitor dams. This initial test has proved that the combined technologies can be successfully applied to determine seismic velocities. Stable cross-correlated waveforms are produced and the ambient noise environment at the Näs Dam is suitable for application of ANI. Changes in seismic velocities could be a result of ongoing internal erosion. ANI may therefore be applied to detect such changes compared to a baseline measurement. Results are presented in this study to assess the monitoring parameters and set up conditions required.

The metre-scale channel spacing afforded by DAS enables a detailed image of seismic velocities in the dam to be constructed. The capabilities of the ANI technique could be investigated further if recording was conducted on multiple cables, thereby enabling 2D or 3D imaging. The use of high frequency waves and a smaller gauge length could improve the resolution of the technique. This will be possible with further advancements of DAS technology.

Overall, the study shows there is great promise for imaging dams using DAS and ANI, although some aspects of the results in this study are not fully understood. The application can be improved through optimisation of the monitoring set-up and once the effect of different parameters on seismic velocities in the dams can be determined with better certainty. Following the results of this feasibility study several recommendations are made in order develop the method for further use in embankment dams.

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1 Introduction

Optical fibres are installed in almost 100 dams in Sweden today. They are used to detect seepage (based on temperature measurements) or movement (based on strain measurements). Most of those installations can also be used for acoustic measurements (Distributed Acoustic Sensing, DAS). The recent development of the technology, regarding both monitoring and analysis techniques, may give an additional method to study the seepage/internal erosion phenomena in the dams. The measurements within this project can be seen as an initial test of the technology in order to evaluate need of further improvements and future potential for DAS measurements, especially in dams where fibres are already installed.

An initial study on how to apply acoustic methods using existing cables was made on behalf of Elforsk (contract number 10328), "Acoustic measurements with iDAS™ for detection of seepage and internal erosion", 2013-01-31 by Sam Johansson, Michael Mondanos and Athena Chalari. A report was delivered but at that time the technology was in an early development stage, and it was decided to not publish the report.

The monitoring performance of DAS has significantly improved since 2013, with a much better signal-to-noise performance than the unit available in 2013. During the last year a combination of a DAS unit with a suitable cable (the Carina system) has been introduced with an improvement of 100 times of the standard iDAS unit. The Carina system is the leading product on the market today. Thanks to its excellent performance it has found several new applications, in seismic surveys, microseismic monitoring and slow-strain measurements in the oil and gas, geothermal and carbon capture and storage industries. Silixa's DAS technology has also recently been used to image faults offshore California, in Monterey Bay (Lindsey et al., 2019). The Carina system includes a high-performance DAS and a sensitive fibre with engineering scattered centres. The work carried out under this programme is limited to measurements performed with the standard DAS system.

2 Objective

The objective of this study was to carry out passive seismic (acoustic) measurements at a dam site with existing optical cables that are used for both strain and temperature monitoring. There are two passive seismic techniques that can be applied to dam monitoring, seismic monitoring/imaging using recordings of the ambient noise field or the recording of acoustic emissions (AEs) caused by flowing water. Analysis of the ambient noise field can be performed using a technique known as ambient noise interferometry (ANI, Curtis, et al. 2006).

Based on literature studies, laboratory tests and experience from similar applications, information on the dam's material properties and locations of concentrated or anomalous seepage flow can be detected using these acoustic methods. The actual resolution and sensitivity are however unknown for this application and need to be tested. The aim of this study is to test the feasibility of using ANI to assess dam material properties and detect anomalous seepage events.

The main areas of investigation and objectives for this study are:

- Evaluation of the potential for using existing fibre-optic installations to gain further information regarding changes in material properties and change of the seepage flow (both flow rate and location).
- Evaluation of the ability of the ambient noise interferometry (ANI) technique to detect concentrated or anomalous seepage flow using measurements from dams.
- Achieve complementary information to other test projects being conducted worldwide on a smaller scale.
- Test the capabilities of DAS for general dam monitoring and as an Early Warning System.

Measurements can be related to existing measurements of temperature-based seepage flow measurements using the same sensing element. The results will be compared with earlier control field measurements and will be used to provide real test conditions data for simulation modelling.

3 Acoustic monitoring in embankment dams and their foundations

3.1 MONITORING REQUIREMENTS AND METHODS

Internal erosion is the reason for almost 50% of the failures of embankment dams (Foster et al. 2000; Fell et al. 2005) and a large body of research has been performed to understand, detect and prevent this mechanism (ICOLD 2015).

In the case of internal erosion, there is an expected change in leakage flow, porosity and water saturation (due to higher water level/pressure). To detect damage in dams, any suitable method must be able to measure deviations in those parameters either directly or in a secondary parameter caused by changes in the primary parameters.

Previous studies have shown that methods that record parameters related to leakage flow or changes in leakage flow are more sensitive than those that record material properties/material changes (Johansson, 1997; Sjödahl, et al. 2019). Most methods, however, measure indirect/secondary parameters, which are translated into what is interesting for a dam safety assessment. Methods that focus on flow-dependent parameters such as temperature, self-potential, and resistivity (using the temperature influence) generally have better ability to detect changes than material dependent methods such as ground penetrating radar, electromagnetics, induced polarization and seismic methods.

Seismic methods can be split into two categories, active and passive. Active seismic methods require a source to produce seismic waves. This source can be produced by, for example, dynamite, a vibroseis truck or a weight drop. The more energetic active seismic sources (e.g. dynamite or vibroseis) are not suitable for use on a dam because they may damage the infrastructure. Passive seismic methods make use of the natural or anthropogenic noise. This can include the recording of natural tectonic events or recording of the ambient noise field. These passive methods do not require direct human intervention, resulting in cost savings compared to active methods. Data can be recorded on-demand, independent of weather conditions or time of day, and can be performed continuously if required. All seismic methods make use of seismic wave measurements created by an active or passive source. The recorded signal provides information on the velocity and amplitude of the waves in the dam and these can then be related to material properties. Given the advantages of passive seismic methods, this study tests the feasibility of using ANI in combination with DAS measurements to monitor dams (see Section 5 for a description of the methods used here).

Material properties could vary not only due to leakage or erosion, but also due to other factors such as climate or compaction. The expected small change in material properties may be detected with accurate and precise monitoring. To understand the suitability of a monitoring method it is important to understand the capabilities and limitations of the method. The sensitivity of seismic or electromagnetic methods in space is limited by the frequencies, and hence wavelengths, analysed.

If an anomaly is smaller than ¼ wavelength in extent it will not be resolved because passage of the wave will be undisturbed by the anomaly.

The sensitivity of seismic methods in time is limited by the expected changes in seismic properties due to changes in a dam. The internal erosion of sediment in a dam or seepage through a dam result in changes in the material properties as indicated in the equations below and in Figure 1 . Compressional (P- wave) and shear wave (S-wave) seismic velocities, V_P and V_S respectively, vary with these parameters according to the equations

$$V_P = \sqrt{\frac{K + {}^4/_3\mu}{\rho}} \quad \text{and}$$

$$V_S = \sqrt{{}^{\mu}/_{\rho}}$$

where K is the bulk modulus, μ is the shear modulus and ρ is the density. An increase in water saturation, for example due to water level rise or precipitation/ snow melt, generally results in a decrease in S-wave velocity and an increase in P-wave velocity. This is because an increase in K with water saturation is predicted by the Biot-Gassmann fluid substitution theory (Gassman, 1951; Biot, 1956) and density increases if air is replaced by water.

Where internal erosion occurs in the saturated zone, solid material will be replaced by water, i.e. a decreasing density. The bulk modulus and the shear modulus of the dam will also decrease. From the equations we can see that the effect on V_P and V_S depends on the relative changes between K, μ and ρ.

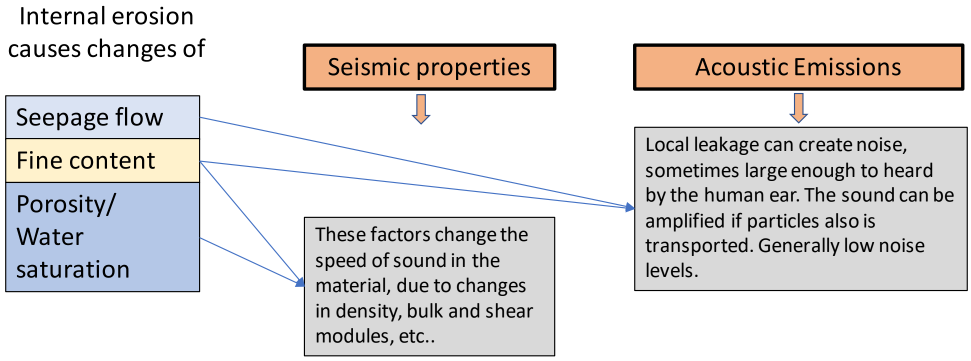

Figure 1 Response for acoustic methods at internal erosion (modified from Sjödahl et al, 2019).

Further seismic investigations can be conducted by recording AEs, produced at high flow rates/flow velocities. These can also be measured using seismic instruments or DAS technology. More noise is generated if fines are transported by the seepage water flow. Research regarding this approach has been performed by Koerner et al. (1976, 1979 and 1981), Buck & Watters (1986), Hung et al. (2009) and Boleve et al. (2012). Seismic events due to movements on cracks in bedrock can also be created and recorded by seismic instruments. This type of events may indicate concern for dam stability but do not present a universally applicable monitoring method.

3.2 DISTRIBUTED ACOUSTIC SENSING (DAS)

DAS technology has undergone significant development and improvements in the last decade. The technique can be used to effectively measure the speed of sound and seismic waves in soils, rocks and fluids in many different scenarios. Like the Distributed Temperature Sensing (DTS), the DAS only requires an interrogator unit, a power source and a fibre optic cable to measure dynamic strain (Parker et al., 2014). DAS technology has been deployed for borehole monitoring, ground movement detection, and pipeline monitoring in many industries, such as oil and gas, geothermal exploration and CO_2 sequestration, and in remote and harsh environments (e.g., Becker et al., 2019; Jousset et al., 2018; Nikles 2009).

DAS measurements are made on fibre-optic cables which may be the same fibre-optic cables installed for temperature sensing. A DAS system provides a sensor array that is unmatched in spatial resolution and sampling with traditional seismic instruments, while allowing the application of the processing methods developed with traditional seismic arrays (Lindsey, et al. 2017). The propagation of the acoustic energy in the ground can be analysed in to determine the speed of sound and assess the ground composition.

The operating principle for DAS is illustrated in Figure 2. A pulse of light is emitted from the DAS interrogator and travels down an optical fibre. Measurements can be made on fibres up 10 km long and a single-mode or multimode cable can be used with the system. A small amount of the light is naturally scattered in the fibre and returns to the interrogator unit. An optoelectronics architecture in the sensing unit measures the amplitude and phase of the backscattered light. When an acoustic or seismic wave exerts tiny pressure/strain changes on the fibre this changes the amplitude and phase of the backscattered light. The relative phase and amplitude can be used to determine the strain rate on the fibre.

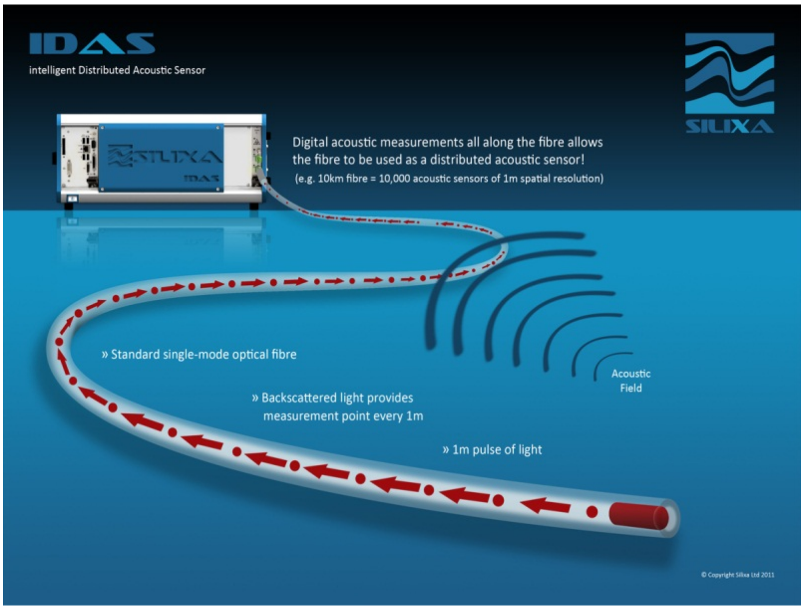

Figure 2 The iDAS™ provides digital acoustic measurements along the entire length of single-mode fibre. The interrogator emits pulses of laser light along the fibre and measures the phase and amplitude of the backscattered light from every measurement point (*channel*) along the fibre.

The sensing system measures changes in strain at a rate of up to several tens of kHz, required to accurately record acoustic fields. The system digitally records the response at evenly spaced measurement points or *channels* along the fibre. The Silixa intelligent DAS (iDAS™) system can offer spatial sampling of 1-m with a dynamic range of more than 120 decibels and with no cross-talk between adjacent measurements. The spatial resolution, or *gauge length*, of the system can be tuned to the particular application. Standard gauge lengths are 3 m and 10 m. Short gauge lengths improve the spatial resolution but results in a lower signal-to-noise ratio (SNR).

The use of fibre optics in acoustic sensing has been validated through the use of traditional seismic processing methods to compare DAS results with those from traditional seismic surveys and laboratory testing (e.g., Jousset et al., 2018; Lindsey et al., 2017; Parker et al., 2014). For example, recording of fluid injection and withdrawal at Mirror Lake Fractured Rock Hydrology site in the United States was conducted to study fracturing in the upper 30 m of bedrock and DAS was shown to be capable of measuring strain orders of magnitude below that of other typical methods in acoustics or seismic systems (Becker et al., 2019).

A study conducted in Iceland compared dense ground motion DAS records with traditional seismometers and concluded that DAS provides potential for resource exploration and seismic hazard assessment (Jousset et al., 2018). This study accessed unused traditional telecommunication fibre, so-called *dark-fibre*, that was not installed with distributed sensing applications in mind. This is another potential benefit of DAS measurements as fibre-optic cables are now widely installed for internet services.

3.3 APPLICATION OF DAS FOR DETECTION OF LEAKAGE AND INTERNAL EROSION

Optical fibres are installed in 79 hydropower dams in Sweden (Figure 3) and in 13 dams mining industry (Figure 4). The first one was installed in 1998. The total cable length is about 72 km in the hydropower dams, and about 63 km in the tailings dams, allowing monitoring of a total dam length of 135 km.

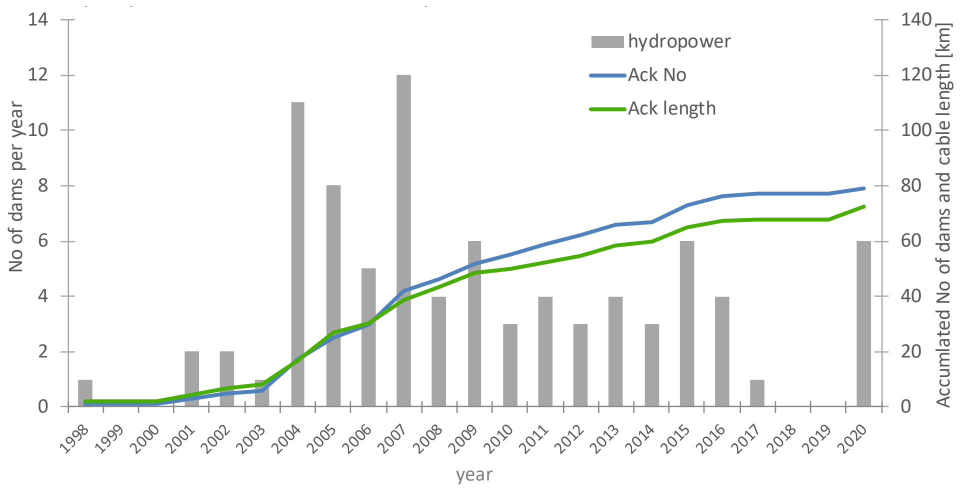

Figure 3 Dams in Sweden with optical fibre cables for seepage detection installed by HydroResearch for hydropower industry.

All those dams have cables in the downstream part of the dam, normally along the dam close to the drainage system. All cables have multimode fibres, but 64% have also single-mode fibres along the toe. Cables with both fibre types are also installed in the crest at eleven dams. Almost all dams for the mining industry have cables with both fibres, just the first installation in 2000 have only multi-mode fibres. All these cables represent an important asset in order to further enhance the dam surveillance both for hydropower and mining industry.

Most existing leakage and erosion detection methods are able to detect seepage changes close to the measuring point. One advantage of the iDAS system is its ability to detect changes far away from the sensor. Both passive and active seismic measurement techniques can be used with DAS to collect baseline measurements and repeat measurements.

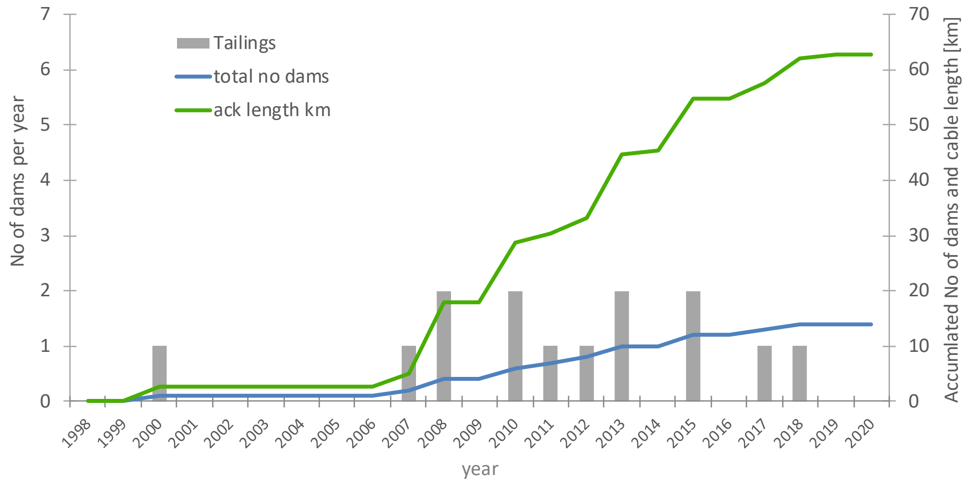

Figure 4 Dams in Sweden with optical fibre cables for seepage detection installed by HydroResearch for mining industry.

Methods that rely on seismic surveys or seismic principles may provide the sensitivity that is desirable for early leak detection in order to prevent serious damage. The resolution of classical seismic methods (metre scale) that use geophones is hard to match with other methods, and new processing techniques continue to improve the ability to extract detailed information from profiles (Campos Halas et al., 2019). Active seismic techniques include reflection, refraction and surface wave techniques, with the latter been most commonly used for levee surveying (Sabatier, 2010). Certain types of seismic monitoring, such as very energetic active surveys, are not available on delicate structures. Active source seismic surveys using vibroseis or dynamite are not suitable to use on embankment dams, due to the risk of damage.

Seismic interferometry is a type of passive seismic survey that eliminates the need for expensive active surveys by using recordings of background noise to image dams (Olivier et al., 2017). This is the method employed in this study and it is outlined in more detail in Section 5.2. The resolution of seismic methods with traditional seismic networks depends on the spacing of geophones. If a large 2D area is to be covered by a survey it is labour intensive and expensive to deploy and run an array with a ≤1 m spacing, the desired spacing to monitor dams (Olivier et al., 2017).

DAS technology offers possibilities to monitor and assess internal erosion. Both passive and active methods should be evaluated to achieve valuable experience for the further development of the method. The results can be compared with earlier laboratory and field studies of dams using seismic techniques with conventional instruments (e.g., Olivier et al, 2017; Planès et al., 2015) . The passive survey conducted as part of this study provides valuable experience and test data for the development of DAS data analysis techniques. The survey aims to identify methodologies using state-of-the-art techniques to achieve a higher performance than today's acoustic emission methods, involving both monitoring and evaluation.

3.4 ADVANTAGES OF FIBRE-OPTIC TECHNOLOGY AND FUTURE PROSPECTS

DTS measurement has been the technique of choice to detect leakage in dams, either used as a complement to, or a replacement of a conventional seepage monitoring system. Simultaneous DTS and iDAS measurements could significantly improve dam integrity monitoring methods offering a better understanding of seepage.

Fibre-optic technologies, DTS and DAS, make it possible to measure the temperature and true acoustic signal along a several km long fibre optic cable. In the past, seismic networks have relied on point sensors (geophones) to predict and anticipate hazards. However, these networks are sparse and difficult to maintain. The main advantages of DAS systems are that they provide permanent, dense, wide area coverage sensing with little or no need for maintenance (Jousset et al., 2018) using the passive fibre as the sensor. As described above, dark-fibre installed for telecommunication purposes can be used if present. Despite being a single component sensor, DAS is able to compete with geophones/seismometers since it can provide data with similar SNRs (e.g., Correa et al., 2017) and the technology has demonstrated its place in the future of acoustic monitoring.

Simultaneous DTS and DAS measurements could significantly improve dam integrity monitoring methods offering a better understanding of seepage. DAS measurements can be related to existing measurements of temperature-based seepage flow measurements using the same sensing element. The results can be compared with earlier control field measurements and used to provide field test conditions data for simulation modelling.

The current survey aims to test state-of-the-art passive seismic techniques to achieve a higher performance than other monitoring techniques. Internal erosion could be monitored using both active and passive acoustic techniques. An evaluation of each of these techniques is required to fully understand their capabilities.

4 Monitoring approach and site description

4.1 GENERAL

The main objective is to apply existing seismic methods with a novel sensing technology to gain experience from existing dams equipped with optical fibres. This will be a good complement to other tests, which will drive the development of fibre-optic monitoring for application in dams.

The number of dams where cables have already been installed is an important asset, since several types of dams can be included in a study. In general, we wish to obtain information at larger distances from the cable than we can achieve using temperature measurements. This can be provided by:

- Detection of anomalous seepage flow at dams without a drainage system (with a cable located downstream the dam); and
- Detection of anomalous seepage flow under a cable (with cable located on the core crest; in the dam toe; or maybe on the crest of the dam).

The placement of a cable on the crest provides a non-continuous monitoring option for investigating seepage/leakage in dams. However, a good contact with dam must be assured in order to achieve good measurement results.

Based on experience from other applications, as well as from initial test measurements at the Näs dam in 2017, measurements were made over 40 days for this investigation.

4.2 NÄS POWER PLANT

The Näs power plant, in the Dalälven river, is owned by Vattenfall Vattenkraft AB. The plant consists mainly of two main embankment dams (Left and Right) on each side of the concrete structures (power station and the spillway), see Figure 5.

An additional new embankment dam was built in 2007. The New Dam was built in order to preserve the old power plant from 1898, which now is used as museum. Thanks to the New Dam, the water level upstream of the old power station was reduced by three meters (from +67 m to +64 m). The old power station could then be preserved in its original shape, and still fulfil the dam safety standards, e.g. for stability.

The dam is founded on natural soil (mainly moraine). The bedrock level is about ten meters below foundation level. The dam has a vertical core of moraine. The core is surrounded by filter of fine sand. Gravel and sand are used for the main support fill.

It was also decided to use the New Dam for different research projects, and the dam was equipped with several monitoring possibilities for different methods, such as pressure, temperature, strain, resistivity, induced polarization and self-potential.

This short dam has no drainage system and thus no seepage flow measurements in the downstream part of the dam. The general flow in the dam is estimated by earlier temperature measurements to be about 0.010 l/s and m, with a minor local increase, about 2-3 times higher in a smaller area close to the right abutment.

Figure 5 Satellite image of the Näs Power Plant area, with water levels (from Eniro.se).

4.3 CABLE INSTALLATIONS AT NÄS

The cable installations in the New Dam are designed for research purposes and are more extensive than normal cable installations in embankment dams. Fibre optic cables are located both in the upstream and downstream filter and also on top of the core crest (Figure 6).

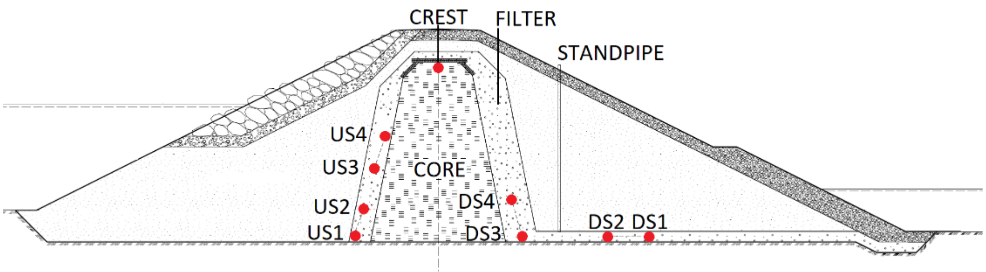

Figure 6 Cross section of the dam showing installed cables.

The four cables in the upstream filter contain only multi-mode fibres, intended for temperature/seepage measurements. One cable in the core crest contains both multimode and single mode cables, intended for temperature and strain measurements. The same cable type was also installed at four locations in the downstream filter, both in the vertical and the horizontal filter. The placement of cables in the dam at different levels is also shown in Figure 7.

Some part of the cables in the downstream side were partly damaged during installation, so measurements can only be performed in the multi-mode fibres. The signal losses reduce the accuracy, but the signal strength is still acceptable for temperature measurements. The signal losses within the single-mode fibre is however so large that no measurements can be done in this fibre. This was discovered when setting up the data collection survey in 2017, when the first measurements were made in the single-mode fibres.

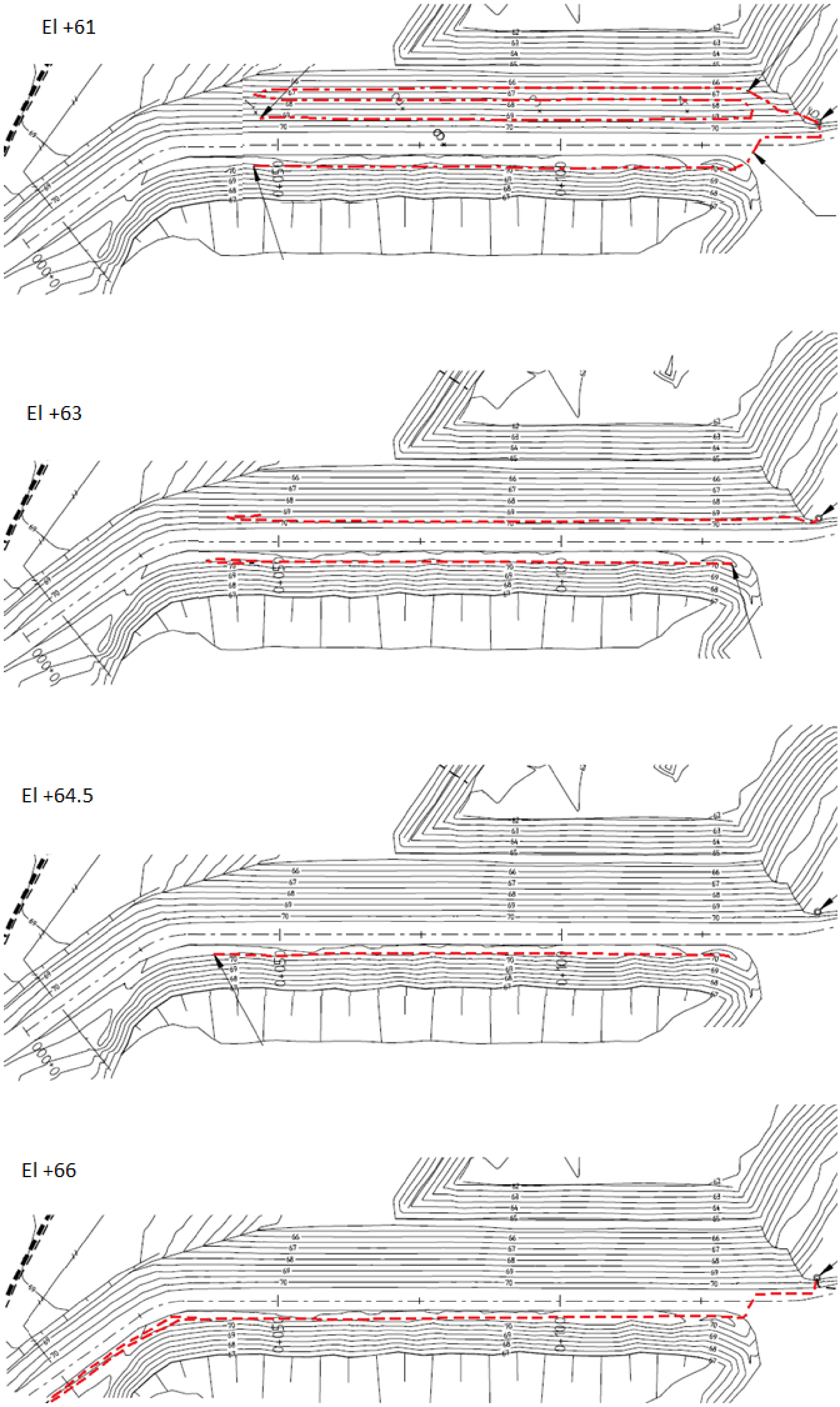

Figure 7 Plan view showing installed cables (red dashed lines) in the New Dam at elevation +61, +63, +64.5 and +66. The cables on the two highest levels are not shown.

Tests were also made before the measurements in 2019, to verify that the splicing was made correctly. The large losses were confirmed, and it was concluded that only the cable in the crest of the New Dam and the cable along the Left Dam could be used for acoustic measurements.

Along the Left Dam towards the spillway, the cable is placed in the toe, close to the downstream water level. The objective is to detect seepage flow changes by evaluation of measured temperature. This cable is the same as was used on the crest and in the downstream part of the New Dam and can likewise be used for strain and acoustic measurements.

4.4 DTS MEASUREMENT SETUP

Temperature measurements have been performed regularly at Näs dam since 2007. Measurements have been made in the Left Dam, and in all cables in the New Dam on behalf of the dam owner.

Continuous temperature measurements started in 2019, at the same time as the iDAS measurement began (2019-09-20). These measurements are made within a research project performed by Lund University and HydroResearch, funded by Energimyndigheten. The project includes also measurements of resistivity, streaming potential and induced polarization. Temperature measurements is in this case essential both for seepage flow comparison and as a factor to be considering at evaluation of the other methods.

The instrument used for temperature measurements in Näs is a Silixa Ultima DTS. Sampling resolution is 0.25 m and acquisition time is 0.5 hours with a repetition time of 3 hours. Some results are shown below in Section 6.6.4

4.5 DAS MEASUREMENT SETUP

All cables installed in the dams are drawn to a junction well close to the crest at the right abutment (Figure 8). From the well to the old workshop, a cable is installed. The cables are spliced to allow simultaneous measurements in all cables. The measurement equipment was installed inside the old workshop (Figure 9).

Figure 8 Junction well on the right abutment where several splices are collected. Standpipes for water level measurements, as well as the stairs to the standpipes can be seen in the background.

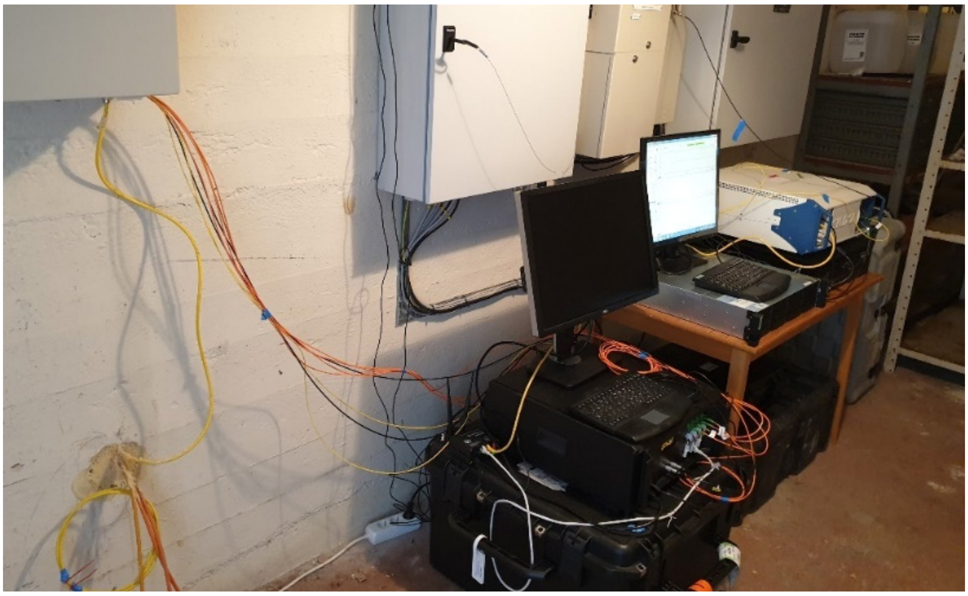

Figure 9 Monitoring room where the DTS and the iDAS were placed during the measurements.

Acoustic sensing can be done both using active and passive methods, based on the single-mode fibres installed at the crest of the New Dam (one cable) and in the downstream part of the Left Dam (Figure 10). Coordinates for the cable location (in RT90, as well as for the dam chainage) is available at each of the points along the cable, based on the length marking on the cable. A labelled version of Figure 10, showing the sec numbers and channel numbers at each end of the New Dam (used in the following descriptions of the results), is shown in Figure 11.

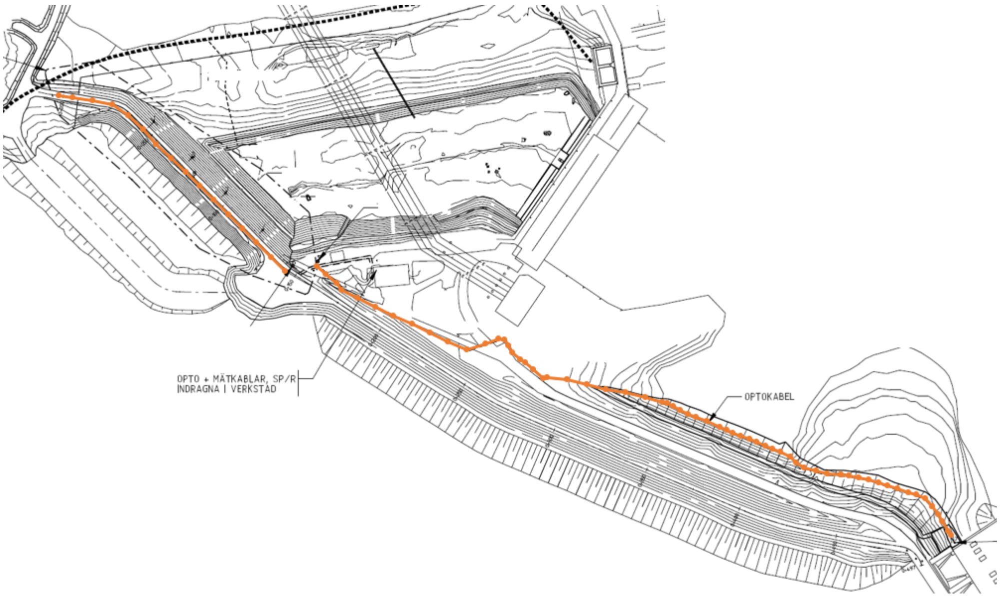

Figure 10 Available cables for measurements in single-mode fibres in both dams.

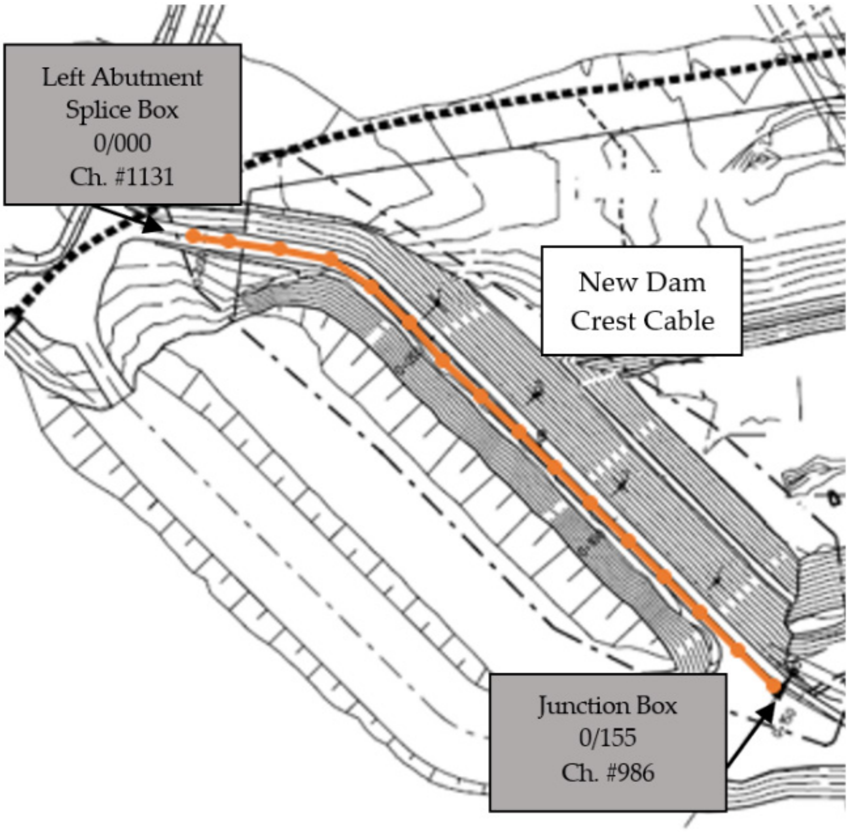

Figure 11 Available cables for measurements in single-mode fibres in the New dam , also showing the sec numbers and channel numbers at each end of the dam (used in the descriptions of results).

Continuous DAS measurements were made at the Näs dam over a period of 40 days, 20 September to 29 October. The field data were recorded on a Silixa iDAS™ system.

Channel locations were estimated from the fibre cable markings and from the turnaround points visible in the acoustic data. The measurement point accuracy is approximately +/-1m. Data was collected at a sampling frequency of 1000Hz with a spatial sampling (channel spacing) of 1m averaged over a 10m gauge length (Table 1). Figure 11 shows the location of the channels used to analyse data collected along the New Dam.

Table 1 Data recording parameters at the Näs Dam 20 September – 29 October 2019.

Sampling Frequency	Spatial Sampling	Gauge Length	Measured Length
1000 Hz	1 m	10 m	1408 m

The noise levels in recorded data depend on the interrogator, the acquisition parameters such as the gauge length and the environmental noise. A check of the iDAS recordings shows that the noise level is close to that predicted for the instrument and this set-up (Figure 12). The recorded data is therefore of good quality for this study.

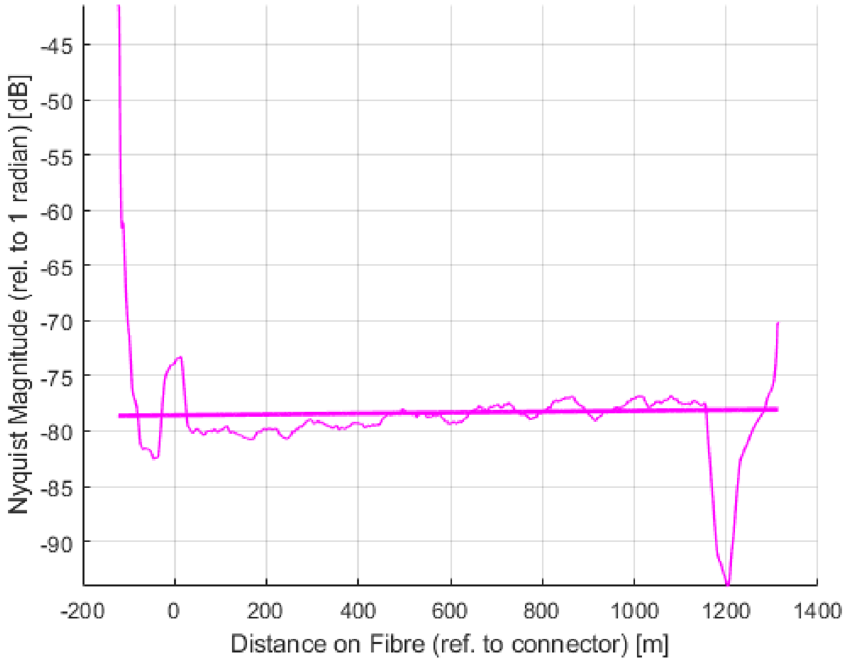

Figure 12 iDAS noise levels along the crest fibre in the New Dam. The straight line is the theoretical noise level of the instrument. The measured noise level is in agreement with the theoretical calculation, indicating the instrument is working as expected.

5 Seismic evaluation principles

5.1 GENERAL

The technique tested in this study is ambient noise interferometry (ANI). ANI makes use of background noise, in this case recorded on a fibre, to image the dam and subsurface to calculate seismic velocities. The output from the analysis is a model of the velocities of seismic waves travelling in the dam/subsurface. The velocity of the waves provides information on the type of material (e.g., unconsolidated ground, rock type) and changes in the velocity may indicate an increase/decrease in water saturation.

The development of capabilities to use ANI with DAS data has significant advantages over traditional methods which use expensive active source seismic surveys and point sensors which require significant manpower to deploy for a large survey. ANI is a passive technique which means the instrumentation is left to record for a given amount of time without needing personnel present. The distributed nature of DAS recordings and the potential DAS provides to use cables up to 40 km-long means that information is available over large distances and down to sub-metre scales, if required.

ANI has been successfully used in the academic community and the oil and gas industry to image the subsurface at different depths and different scales (e.g., Shapiro et al., 2005; Lin et al., 2007). In oil and gas reservoirs the technique can provide information on fluid movement and compaction effects (e.g., de Ridder et al., 2014). In volcanic settings it can aid hazard assessment by tracking velocity changes in the system caused by volcanic gas or magma movement (e.g., Huang et al., 2018). To a limited extent ANI has also been applied to dam structures and landslide sites (e.g., Olivier et al., 2017). These studies have been able to identify changes in the subsurface at the sites. However, the completeness of the imaging has been limited by the use of a small number of point sensors, i.e. geophones. With a dense seismic array, as provided by DAS monitoring, it is possible to conduct a detailed survey of dam and landslide sites. A brief description of the ANI methods used in this survey is given below.

5.2 ANI CONCEPT

The ambient noise recorded in a passive seismic survey is the result of random background vibrations of the Earth due to atmospheric, oceanic, rock fracturing and anthropogenic activity (e.g., Snieder and Wapenaar, 2010). Ambient noise can also be caused by a persistent, stationary noise source originating from a particular direction (e.g., noise from a powerhouse or flow in a spillway). The combination of the random and stationary signals is the measured seismic signal when no source is actively triggered. Ambient seismic noise travels through the same subsurface as wave energy from active sources (e.g., dynamite or vibroseis) and so is similarly affected by earth structure. It is therefore possible to extract some of the same information from ambient noise as from active surveys (Curtis et al., 2006).

ANI estimates the seismic signal between two seismic receivers (e.g., two recording channels on a fibre-optic cable) through cross-correlation of the noise signal recorded at the two receivers. This seismic signal is the equivalent of an active seismic source at one receiver being recorded at the other receiver (e.g., Wapenaar et al., 2010). This response is termed a virtual seismogram. Effectively, this operation allows us to determine the time taken for seismic waves to travel from one receiver to the other, i.e.one point on a fibre to another. The distance between the receivers is known so the velocity can be estimated.

The virtual seismogram contains different types of seismic waves (Figure 13) and these waves sample different parts of the subsurface and travel at different speeds (Figure 14). Analysis of different wave types can therefore provide velocity information for different depths. Body waves (P- and S-waves) may travel directly from one point to another or be refracted or reflected along their travel-path. Surface waves travel along the surface. High frequency surface waves sample the very shallow subsurface. Lower frequency surface waves sample deeper in the subsurface. Surface waves are therefore dispersive, i.e. their phase velocity depends on their frequency. Additionally, as seismic waves travel through the subsurface some of the energy is scattered due to inhomogeneities. These scattered waves arrive later than body waves (because they travel further) and are called coda waves. These coda waves are often more stable than body waves or surface waves in virtual seismograms and therefore can often provide the most precise estimate of seismic velocities. If a permanent array of receivers is used, as is available with a DAS cable, repeatability of measurements can be ensured and therefore small changes in velocity can be detected over time.

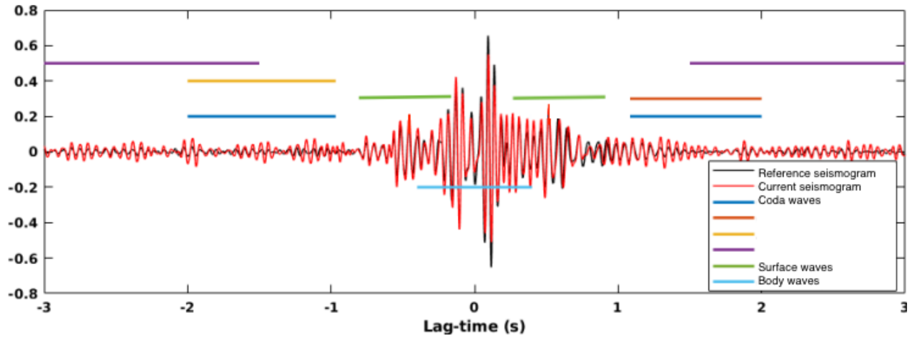

Figure 13 Example of a virtual seismogram. Parts of the waveform containing body waves, surface waves and coda waves are highlighted by the coloured lines.

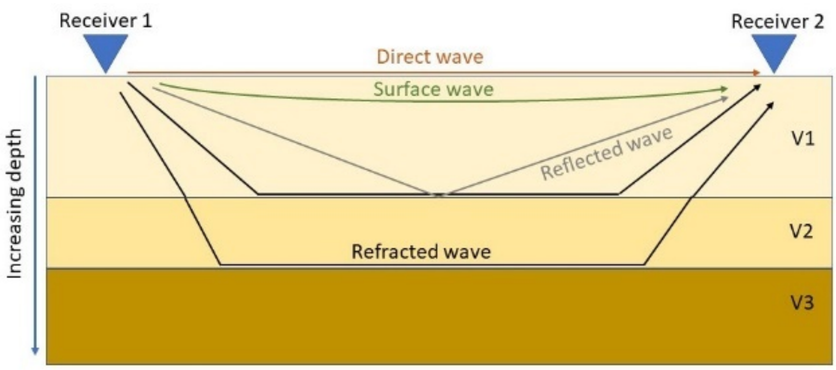

Figure 14 An illustration of the raypaths of body waves and surface waves between receivers (i.e. recording channels on the cable). V1, V2, V3 are seismic velocities of the different layers which usually increase with depth.

5.3 ANI METHODOLGY

The seismic velocities in the dam are estimated using ANI for body waves, surface waves and coda waves. Three different methods are applied to estimate velocities:

1. Time-domain cross-correlation,
2. A cross-wavelet transform method,
3. Spectral phase analysis.

Method 1 is applied to body waves, surface waves and coda waves. Methods 2 and 3 are applied to surface waves only.

For time-domain cross-correlation the data is bandpass filtered and then cross-correlated to determine the travel-time of waves between points on the fibre. This method is fast to implement and robust to random noise in the data.

For the cross-wavelet transform method the cross-correlation of the wavelet transform of two traces is computed to estimate to time-shift between traces using the phase difference between the wavelet transform of the traces. This method is applied in the frequency domain and is sensitive to noise. If more than a single mode of surface wave is present in the data, the modes must be separated beforehand.

To conduct a spectral phase analysis the waveforms are converted to the frequency domain. The phase of the fast-Fourier transform is divided by the frequency to give a travel-time for that frequency. This method is also sensitive to noise and requires good SNR to give a robust result. Similarly, to the cross-wavelet transform method, if different modes are present in the data, they should be separated before the estimating the phase.

In general, for surface waves, Methods 2 and 3 are useful to obtain frequency dependent results and Method 2 is more robust than Method 3.

With sufficient density of velocity measurements, a tomographic inversion can be conducted to produce a 3D image of seismic velocities.

6 Results

6.1 OVERVIEW OF DAS DATA

Data recorded on Channels 986 – 1131 were used in the study of the New Dam (Figure 15). Various seismic analysis techniques were applied to the dataset, including spectral analysis and cross correlation of body waves, surface waves, and coda waves to determine seismic velocities and any variations in these velocities in the dam.

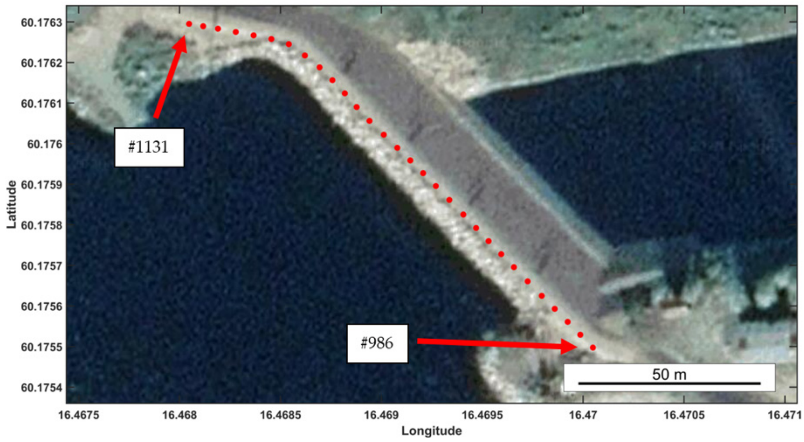

Figure 15 Satellite photo of the New Dam showing the points selected for analysis.

6.2 SPECTRAL ANALYSIS

Spectral analysis of the data from the New Dam gives the power of the noise recorded at different frequencies and Figure 16 shows such a spectrogram for Channel 986 on the fibre. Most of the energy recorded has frequencies above 10 Hz, indicated by the bright colours in Figure 16. There is a constant noise source at 10 Hz because there is little variation in the energy amplitude at this frequency.

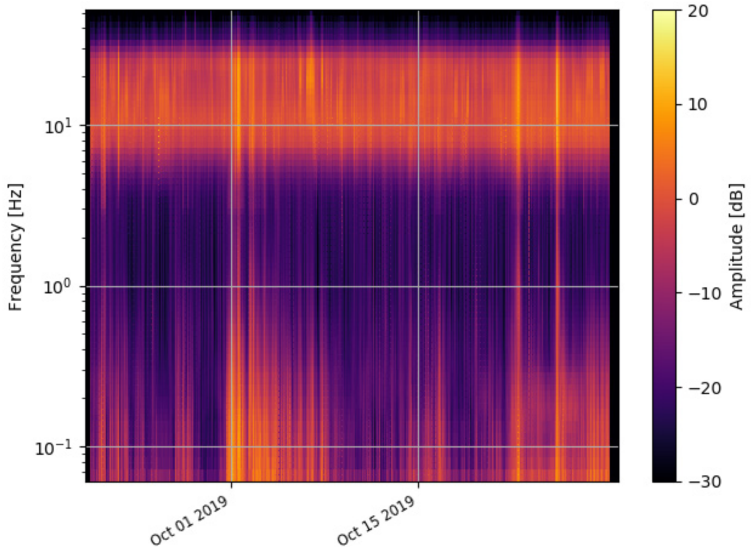

Figure 16 Spectrogram of the data recorded at Channel 986 between 20 September and 29 October 2019. Bright colours indicate higher amplitudes recorded at a given frequency.

Noise source stability is important in ANI analysis because if noise sources appear and disappear during the recording period this affects the waveforms recorded and hence results in variations in the cross-correlated waveforms. The aim of the analysis is to identify changes in seismic waveforms cause by changes in the ground properties and therefore other factors affecting the waveforms should remain constant throughout the measurement period.

The data was downsampled to 100 Hz to speed up processing while ensuring the frequency range of interest (<50 Hz) was correctly recorded. Higher frequencies are not used because they quickly attenuate in the ground and surface waves of frequencies <10Hz are required to determine seismic velocities at depth. A Probabilistic Power Spectral Density, or PPSD, provides a measure of the consistency in the amplitude of a recorded frequency over time. A PPSD of the downsampled data confirms the consistency of energy (shown by the bright colours in Figure 17) recorded around 10 Hz. Frequencies in the region between 5 Hz and 45 Hz were chosen for further analysis since this is the frequency range most stable over time.

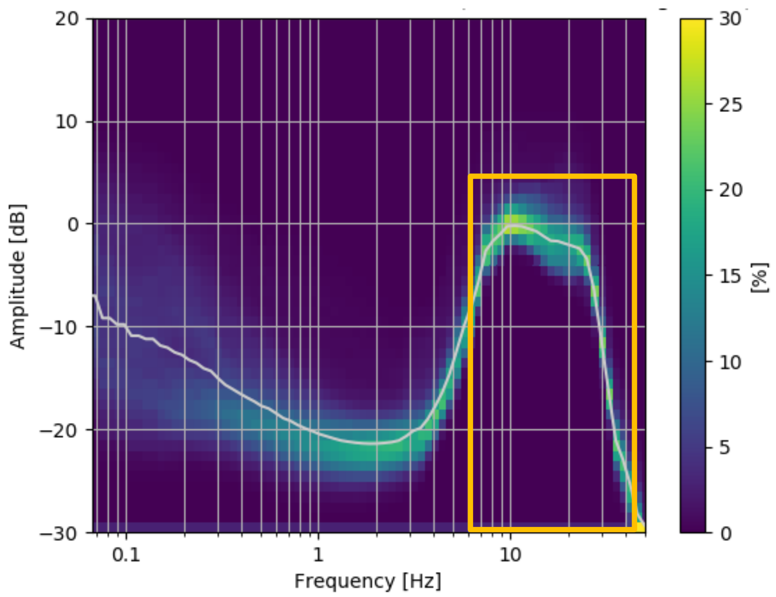

Figure 17 The Probabilistic Power Spectral Density (PPSD) at Channel 986. The frequency range of interest is highlight by the orange box.

6.3 CROSS-CORRELATION

Cross-correlation provides a measure of the similarity between two recordings at a given offset time. Cross-correlation of waveforms in the frequency range of interest at two different points along the fibre enables a measurement of the velocity of these waves along the dam between these two points.

The data is downsampled in space to every 5th channel (one receiver approximately every 5 m). The signal recorded at each of these channels is cross-correlated with the data from the other channels. Example results obtained for channels at either end of the New Dam, see Figure 15, are given in Figure 18. Even without any filtering there is clear propagation of waves between points on the fibre (Figure 18).

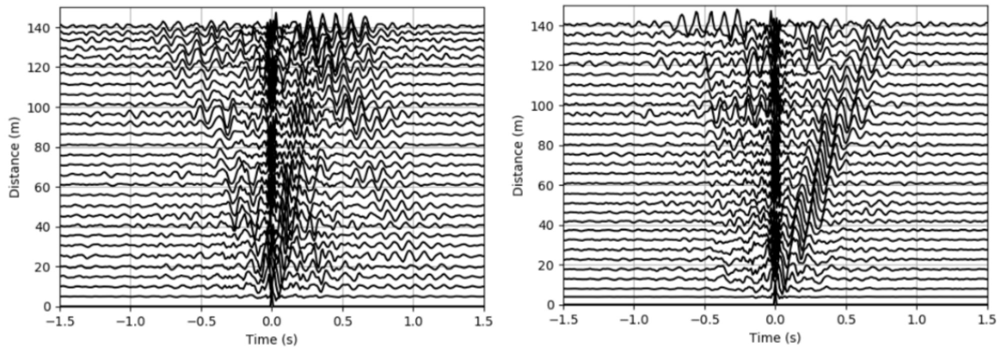

Figure 18 Channel 986 (left) and 1131 (right) waveforms cross-correlated with all other channels along the fibre. No filtering is applied.

The signals recorded 5 – 20 Hz are believed to be surface waves because they display a dispersive nature, i.e. different frequencies travel at different velocities (Figure 19). Most of the energy in the cross-correlated waveforms for Channel 1131 in Figure 19 is positive in time. This indicates that more energy is arriving from the right bank than from the left bank at these frequencies. This is consistent with noise originating from the power plant at the dam.

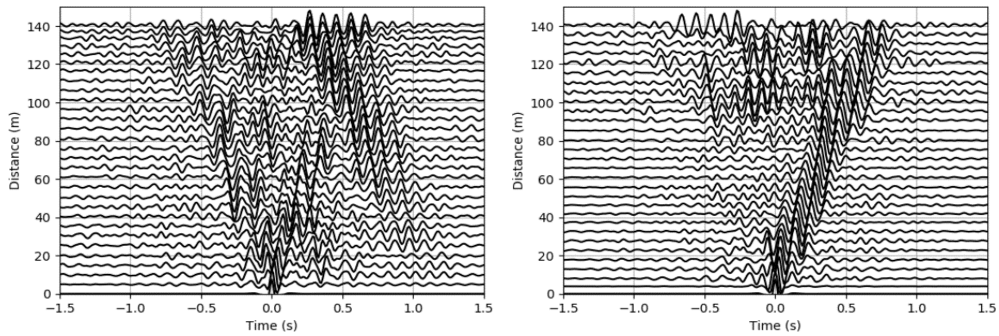

Figure 19 Channels #986 (left) and #1131 (right) cross correlated with all other channels along the fibre with a 5-20 Hz band pass filter applied.

At higher frequencies (20 – 45 Hz) the observations are consistent with recordings of body waves because there is no evidence of dispersion (Figure 20).

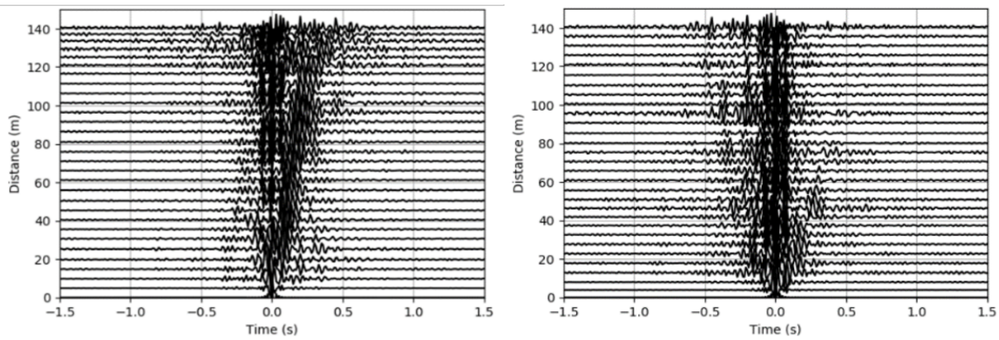

Figure 20 Channels #986 (left) and #1131 (right) cross correlated with all other channels along the fibre with a 20-45Hz band pass filter applied.

As discussed above, it is important to have stable noise sources to provide stable cross-correlations. Cross-correlations between stations were obtained for each 15-minute time interval during the recording and an example is plotted in Figure 21. The waveforms are consistent over the measurement period, shown by the stability of most of the maxima and minima in the waveforms (bright and dark lines) through time in Figure 18. A change in seismic wave velocity would result in a change in the position of the maxima and minima in the waveform. The similarity of the waveforms in the monitoring period indicates any changes observed over time could be attributed to real physical changes rather than artefacts due to changes in the noise characteristics.

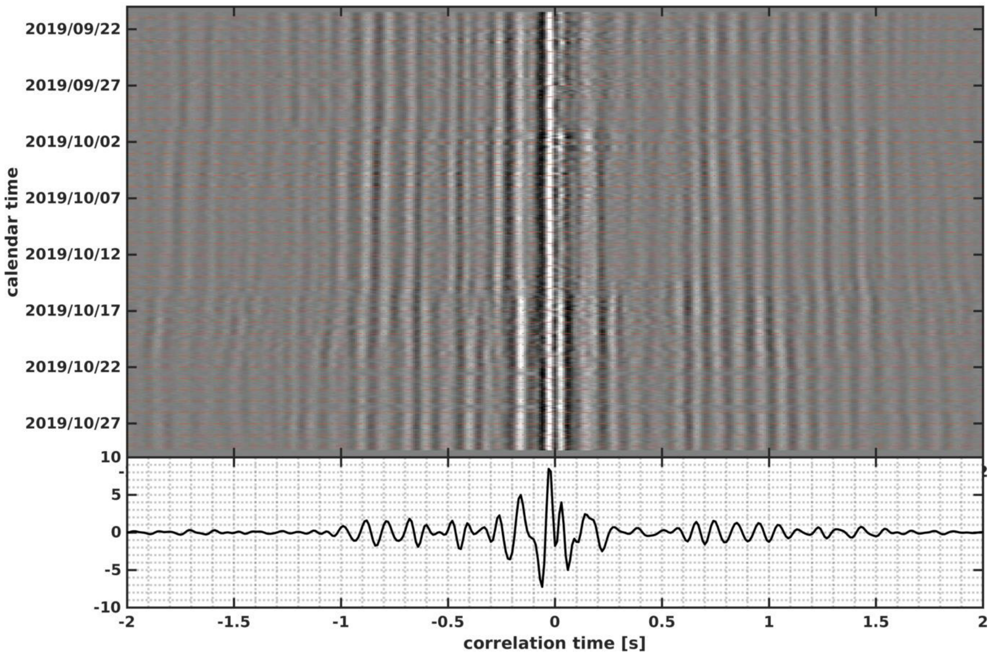

Figure 21 Cross-correlated waveforms for each 15 minutes of data. The mean waveform over 40 days is displayed at the bottom.

6.4 SEISMIC VELOCITIES

In addition to temperature observations, seismic velocity variations in dams could indicate changes in seepage or structural integrity in dams. To calculate the velocity of wave propagation through a medium, we take the distance between stations, δd_i, and divide it by the amount of time it takes for the wave to travel that distance, δt_i:

$$v_i = \frac{\delta d_i}{\delta t_i}.$$

At the frequencies studied here, decreases in seismic velocity over time are likely to indicate an increase in water saturation between the two points. Seismic velocities in the New Dam are estimated for body waves, surface waves and coda waves.

6.4.1 Body waves

An example of body waves identified in the cross-correlated waveforms is shown in Figure 22. The time for these waves to travel between each channel is used to estimate the phase velocity since the distance between channels is known. Figure 23 shows the estimated body wave velocities along the dam. Roughly two velocity zones are observed, one with velocities 500 – 600 m/s in the right part of the dam and one with lower velocities, 450 – 500 m/s in the left part of the dam.

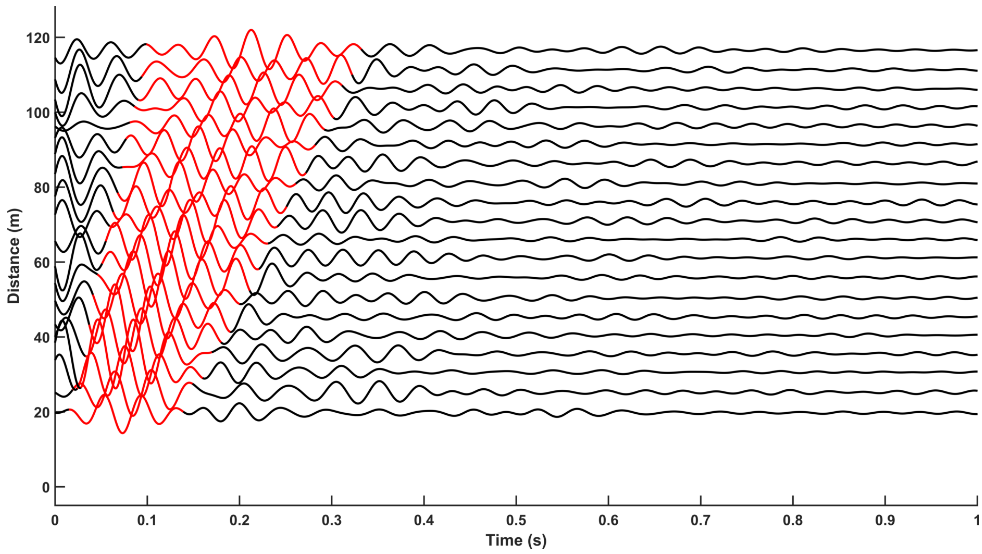

Figure 22 Body waves in cross-correlated waveforms (highlighted in red) with Channel 986 as a virtual source. Waveforms are filtered with a 20 – 30 Hz band pass filter.

The reason for the difference in velocities along the dam is probably due to the compaction of dam material or differences in water saturation along the dam. Further investigation is required most probably in a more controlled environment. The velocities measured here can be used a baseline so future measurements could be made to assess any changes in the dam.

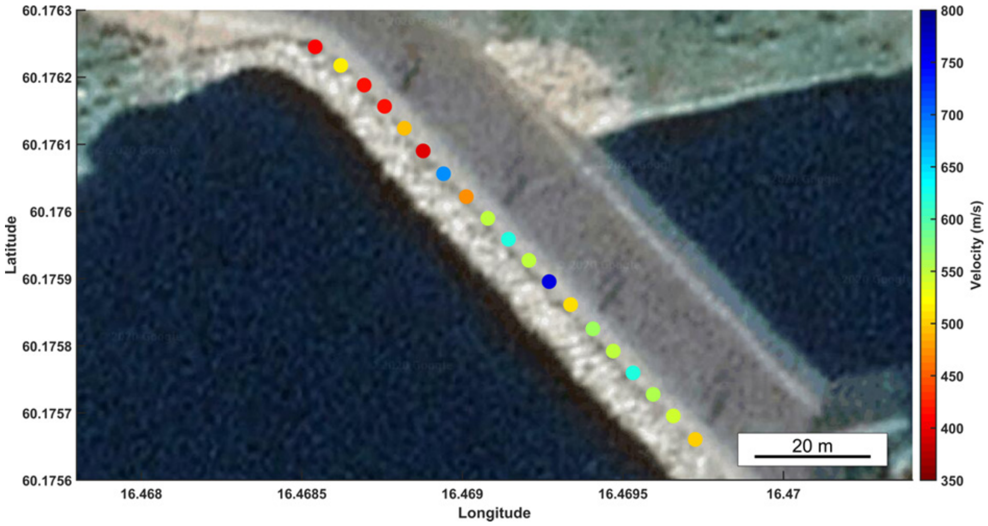

Figure 23 Estimated body wave velocities along the crest of the New Dam.

6.4.2 Surface waves

Surface waves with different frequencies can provide information on the seismic velocities at different depths. An example of 5 – 15 Hz surface waves in the cross-correlated waveforms is shown in Figure 24. Three different methods are used to estimate surface wave velocities: time-domain cross-correlation; the cross-wavelet transform method; and a spectral phase analysis of the waveforms. The three methods were tested to validate the results and check for consistency and all give similar results (Figure 25). Overall, surface wave velocities vary more through the dam than the body wave velocities (Figure 26).

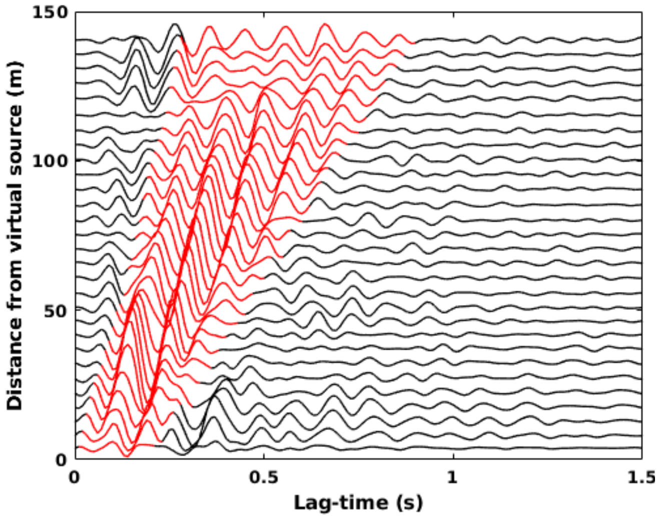

Figure 24 Surface waves in cross-correlated waveforms (highlighted in red) with Channel 1131 as the virtual source. Waveforms are bandpass filtered 5-15 Hz.

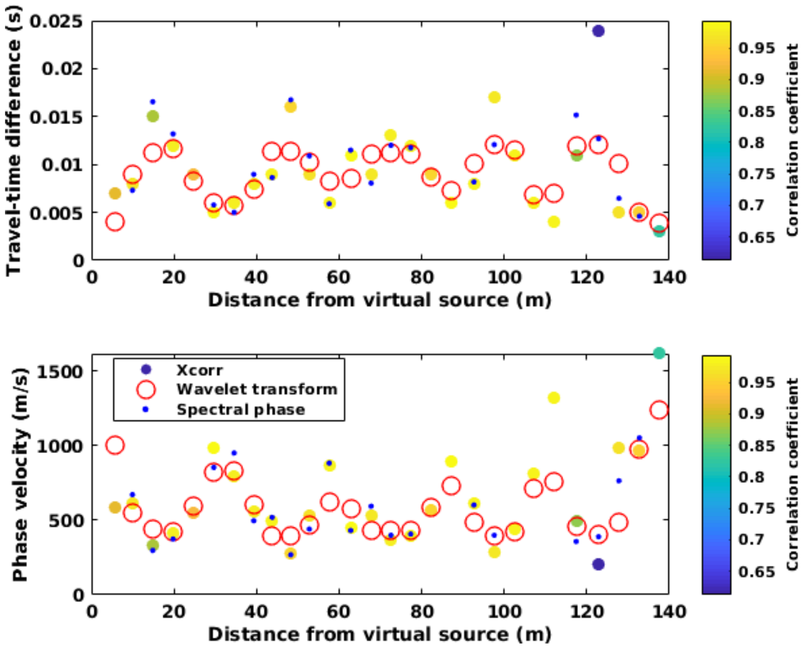

Figure 25 The travel-time difference (top) and estimated surface wave phase-velocities (bottom) along the New Dam. The results are shown from three different methods. For the cross-correlation method the cross-correlation coefficient is indicated by the colour. The higher the cross-correlation coefficient the more reliable the measurement.

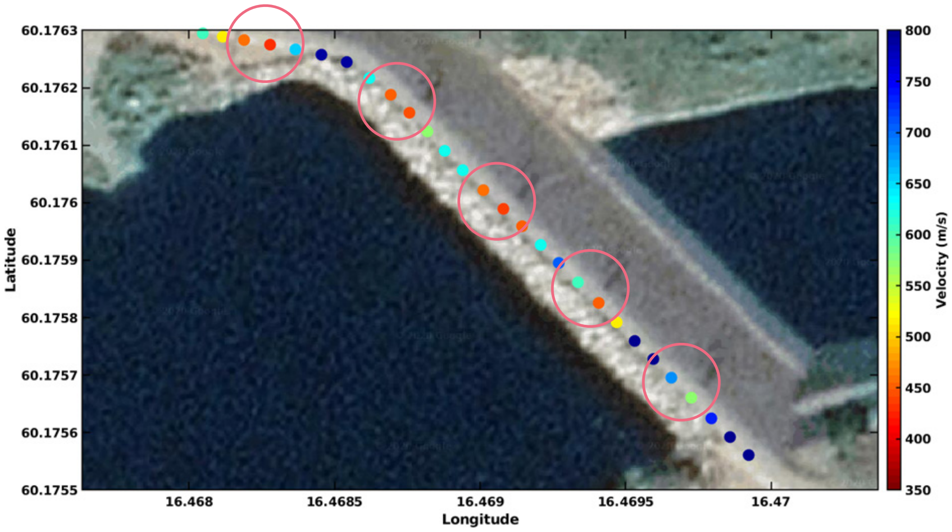

Figure 26 Velocity model of the New Dam calculated with the surface wave, areas of velocity anomaly circled in red. The anomaly closest to the right abutment is around sec 130 where temperature measurements indicate seepage in the dam (see Figure 35d).

Figure 27 shows the variation in surface wave velocity in time relative to the average over the measurement period. The heat of the colour indicates the uncertainty in the velocity at that point, with the warmer colours having higher uncertainty. Throughout the 40-day trial period there is a decrease in velocity of approximately 4% across the dam, with a higher degree of uncertainty in velocities at the beginning of the survey and towards the end of the survey.

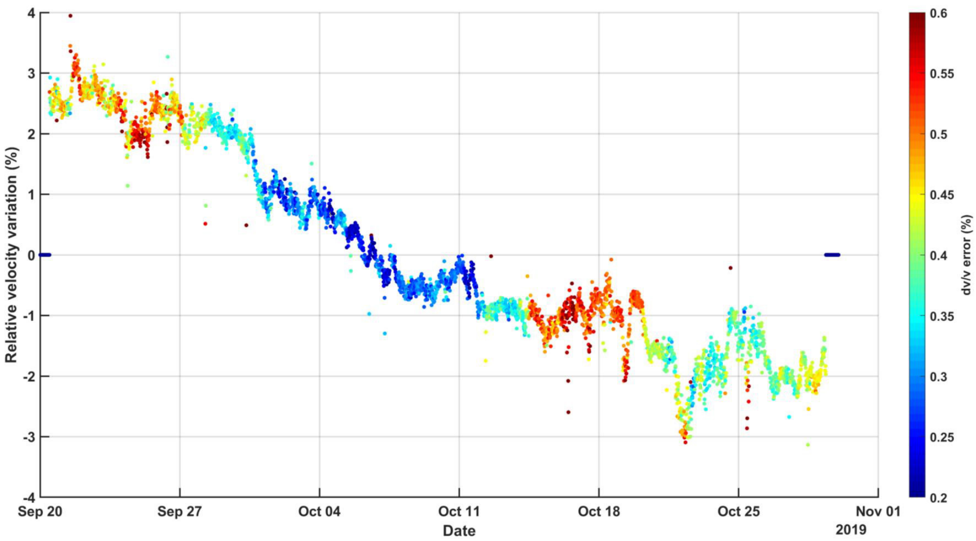

Figure 27 Calculated surface-wave phase velocities across the length of the New Dam measured at 15-minute intervals and shown relative to the reference velocity (the 40-day average velocity).

6.4.3 Coda waves

Coda wave velocities are also estimated and the part of the cross-correlated waveforms used for this analysis is shown in Figure 28. The velocity variations observed between Channels 1021 and 1031 (see Figure 8 for channel positions); and Channels 1121 and 1131 are shown as example results in Figure 29, Figure 30 and Figure 31.

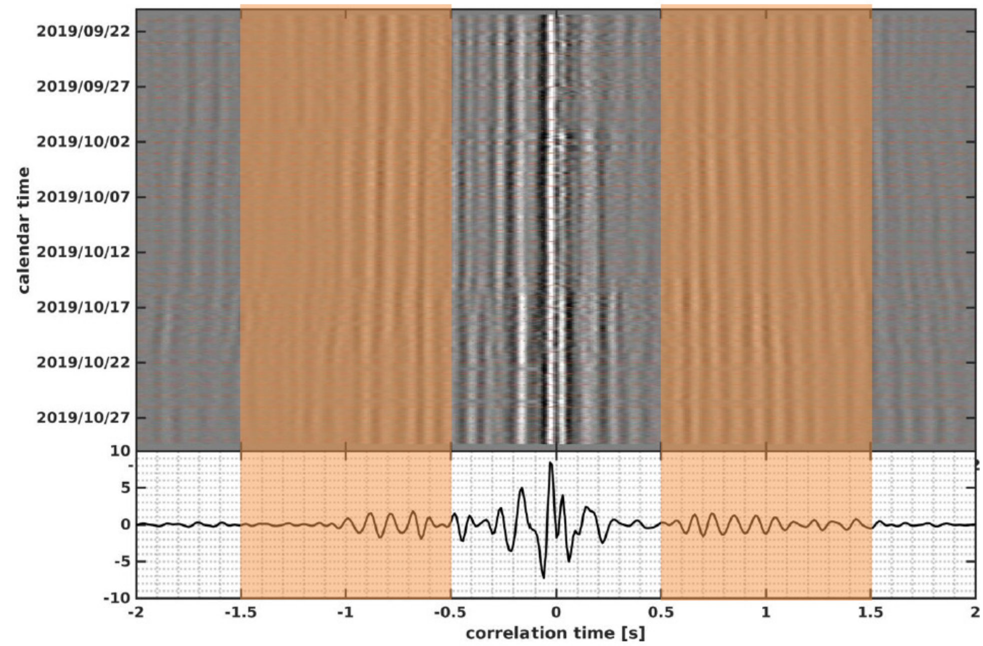

Figure 28 The cross-correlated waveforms for each 15-minute time interval, bandpass filtered 5 – 20 Hz. The time window used to estimate coda wave velocities is highlighted in orange.

The velocity is calculated for every 15 minutes of the entire 40-day survey so any variations in velocity during this baseline survey could be identified. Each 15-minute measurement is plotted as a percent deviation from the average velocity over the measurement period. Between Channels 1021 and 1031 there is an overall decrease in velocity with time of around 4%. Between Channels 1121 and 1131 the velocity remains almost constant although the errors are larger for these velocity estimates. The consistent velocity between Channels 1121 and 1131 could be because these channels are located at the left part of the dam, with water only on the upstream side so this part of the dam is unaffected by changes in the downstream water levels.

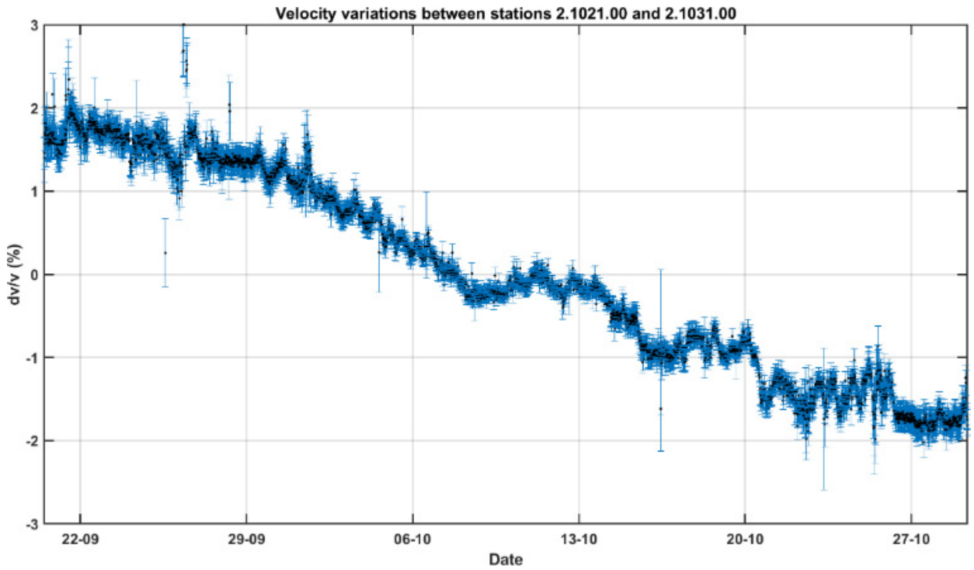

Figure 29 Variations in coda wave velocity from the average velocity between Channels 1021 and 1031.

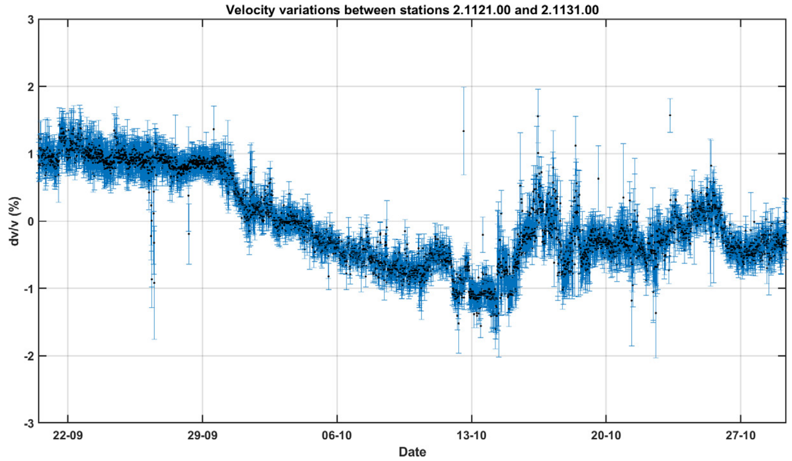

Figure 30 Variations in coda wave velocity from the average velocity between Channels 1121 and 1131.

The results in Figure 30 highlight that there is variation in results across the dam but in general a decrease in velocity is seen over time (Figure 31). There is a clear change in coda wave velocity around the 30 September with an ongoing decrease until around 13 October.

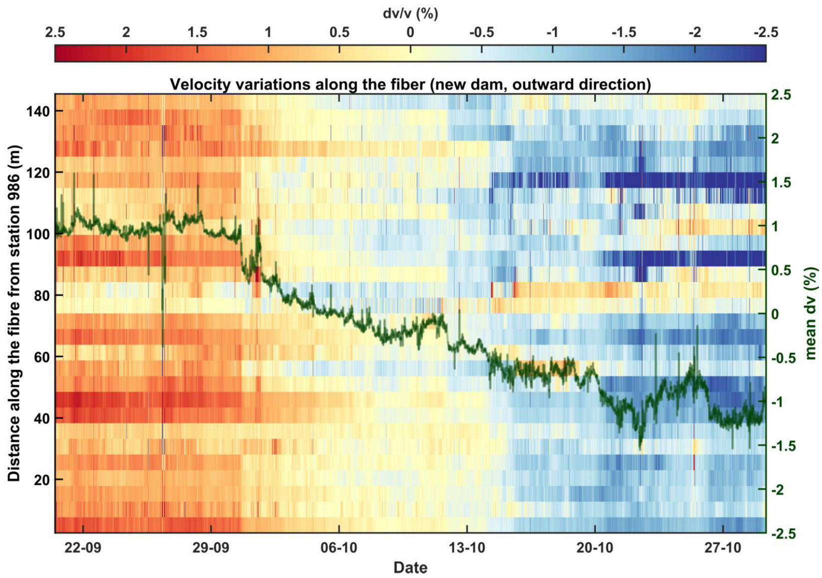

Figure 31 Coda wave velocity variations throughout the 40-day acquisition period. Results are shown for the distance along the dam from Channel 986 (the right abutment). The green line is the average velocity change.

6.5 LEFT DAM

A similar analysis to that described above was attempted on the data collected from the toe of the Left Dam (Figure 5). Spectral analysis shows a similar noise source to the New Dam at around 10 Hz, however the frequency content is more variable than the New Dam data (compare Figure 32 with Figure 16). However, cross-correlation of the waveforms did not show any consistent change in seismic wave arrival times with distance across the array (compare Figure 33 to Figure 18, Figure 19, and Figure 20). The reasons could be due to the interference by noise sources within the array and attenuation of waves in the dam. Further investigation is required to understand the results obtained for the Left Dam.

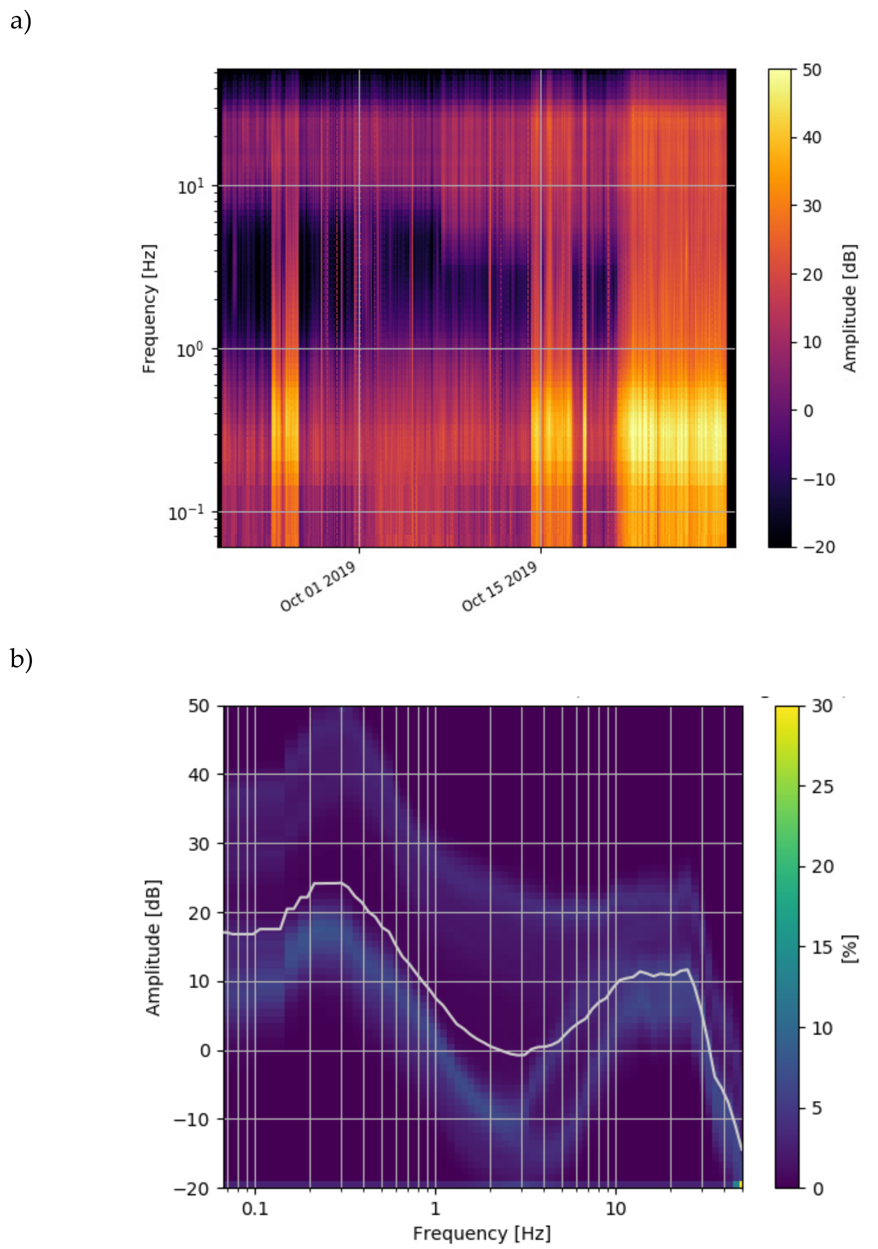

Figure 32 a) Spectrogram of data recorded throughout the 40-day survey for Channel #593 and b) PPSD for Channel #593.

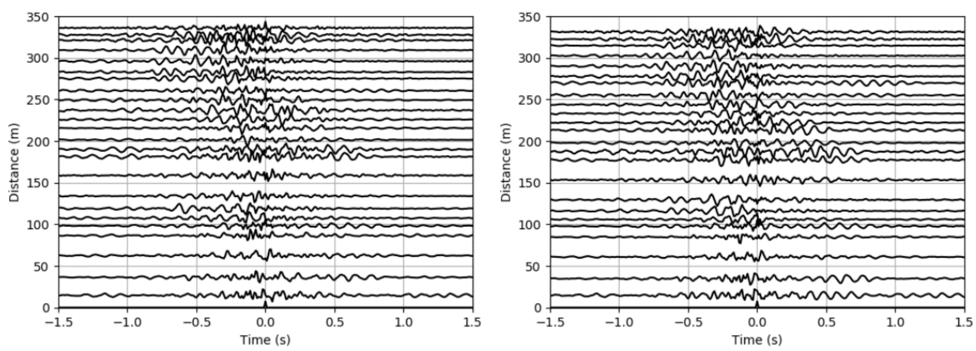

Figure 33 Cross-correlated waveforms with Channels #190 (left) and #976 (tight) as the virtual sources.

6.6 INTERPRETATION

6.6.1 Introduction

To interpret the results presented above several factors are considered, including the effects of measurement precision and accuracy, weather and water level. All these effects could contribute to the variation of velocity in space and time and are discussed below.

6.6.2 Comparison with initial result using iDAS

Initial acoustic measurements using an iDAS were performed in 2017 on behalf of the dam owner. Both active and passive seismic were used, during this short test, about four hours in total. The active seismic survey found a P-wave velocity of approximately 400 m/s along the dam crest. This is in agreement with the body wave velocities reported here for the left part of the New Dam.

6.6.3 Precipitation and ambient temperature

Water saturation affect seismic velocities, but temperature may also have some impact on the velocities. However, in this scenario, it is expected that water saturation has a more significant effect. The precipitation and temperature at a site close to the Näs Dam site are shown in Figure 34.

a)

b)

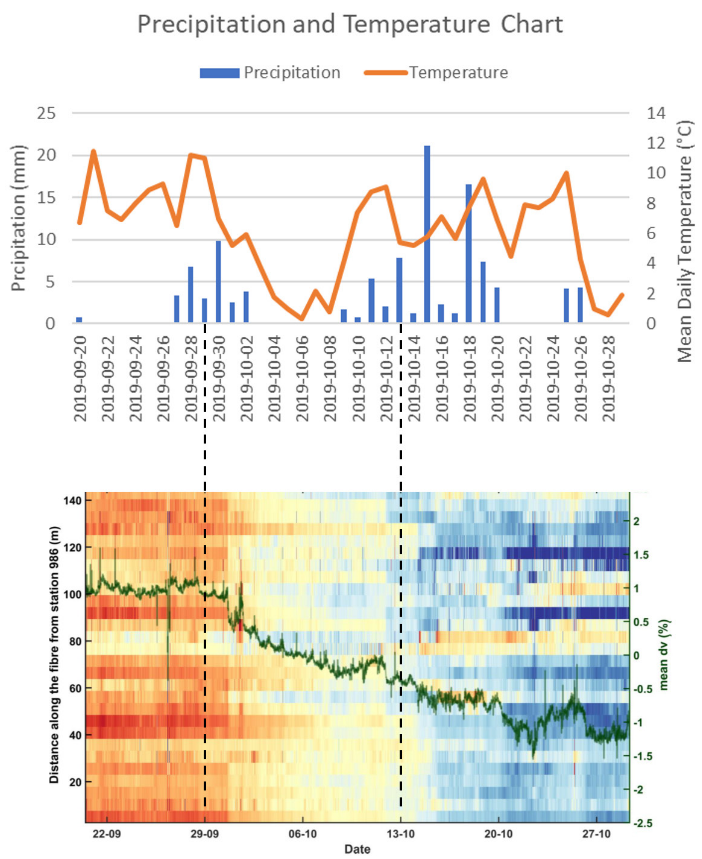

Figure 34 Approximate temperature and precipitation variations throughout the 40-day monitoring period. Data are from Brovallen, 15.5 km from the Näs Dam (a). Figure 31 repeated to allow a comparison (b).

A velocity decrease occurs when it rains and appears to stabilize or increase slightly when it is dry. However, the results are inconclusive because the measurement time period is too short to draw any conclusions on the correlation between weather changes and seismic properties of the dam. It is likely that the precipitation increases the water saturation in the near-surface dam material, resulting in a decrease in velocity. A dry period 3 – 9 October also coincides with an average air temperature drop of approximately 10°C. Further investigation is required to isolate the effect of rain and temperature, for example by recording over a whole year to determine the daily, seasonal and yearly effects. An accurate weather station nearby would be required. Changes in the internal dam temperature (see Section 6.6.4 below) are not instantaneous with changes in air temperature and therefore it is more likely that, when a cable is buried, rapid changes in velocity are associated with precipitation. Observations over a longer time period are required to determine any correlation between the velocity measurements and weather conditions.

6.6.4 Temperature measurements in the dam

Temperature measurements made with DTS as part of the parallel research project do not show the full seasonal temperature response of the dam. However, some initial observations can be made.

Temperature measurements in the upstream filter gives information about seepage inflow areas (see the vertical length sections at different dates in Figure 35a-c, as well as the temperature difference plots in Figure 35d-e for the New Dam). The temperature change during the iDAS-measurements is generally about 2-4°C. A higher temperature change (about 5°C) is measured at the right abutment at sec 130 and at elevation +64m. Deviations in this area have been seen from the first measurements made in 2009. The seepage flow has been evaluated to be about 0.02 l/s, based on earlier long-term temperature measurement. The temperature difference in this area is about 11°C for the entire measuring period (Sep 2019 to Feb 2020).

This small leakage flow can also be seen in the temperature measurements in the dam toe (Figure 36, showing the temperature in a plan view). The largest temperature variations (from Sept 2019 to Feb 2020, Figure 36e) occur at sec 130, i.e. the same area as the inflow. Similar temperature differences are also seen at sec 80. The temperature change in the toe during the iDAS- tests is also about 5°C (Figure 36d), which is similar to the changes in the upstream filter. The smallest temperature change occurs in the inner part of the dam, and the largest in the dam toe. The most significant changes are likely to be due to the decreasing water level downstream, allowing cooling from the air during late autumn.

There is some indication that surface wave velocities are lower in the area of higher temperature changes and small leakage flow (Figure 26). A longer monitoring period and further examples are required to confidently correlate seepage with velocity anomalies.

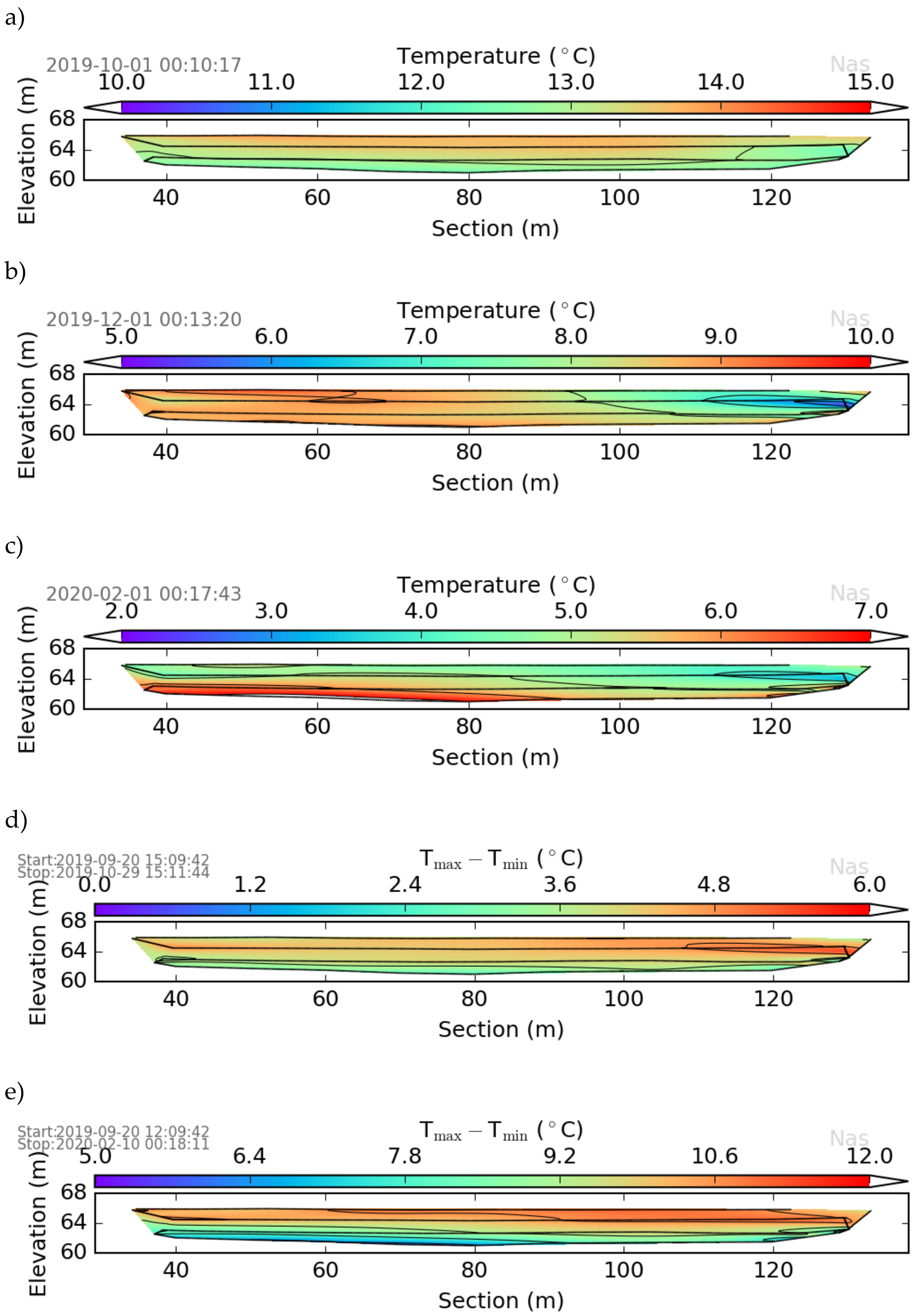

Figure 35 Temperature measurements in the upstream part of the New Dam October 1st 2019 (a), December 1st 2019 (b) February 1st 2020 (c) temperature variation during iDAS measurements (d) and temperature variation from September 20 2019 to February 10 2020 (e), vertical view from upstream side. Sec 0 is the left abutment of the dam and sec 150 is at the right abutment.

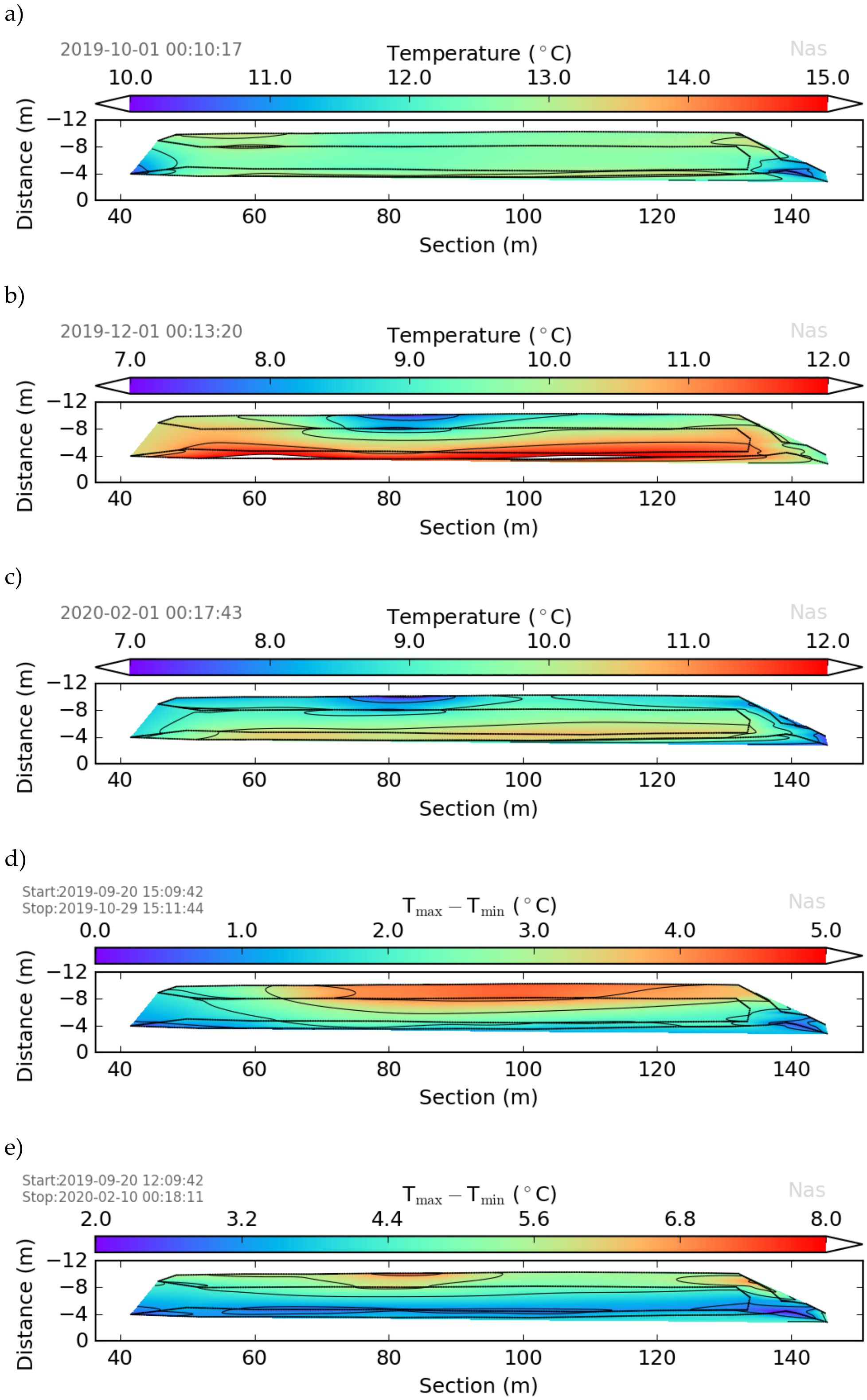

Figure 36 Temperature measurements in the downstream part of the New Dam October 1st 2019 (a), December 1st 2019 (b) February 1st 2020 (c) temperature variation during iDAS measurements (d) and temperature variation from September 20 2019 to February 10 2020 (e), plan view, distance from the center line of the dam. Sec 0 is the left abutment of the dam and sec 150 is at the right abutment.

6.6.5 Spatial variations in velocity

There are lower body wave velocities in on the left side of the New Dam. This may indicate that there is a slightly higher level of water saturation in the left part of the dam.

The location of surface wave low velocity anomalies in Figure 26 seem to coincide with the standpipes V101 – V104 used to measure water levels and wooden steps that are built on the surface of the dam (Figure 37). However, it is not thought such structures would affect the seismic wave velocities because the pipe diameters are much smaller than the seismic wavelength and the wooden steps are light structures which do not cause compaction of the dam. The use of a smaller gauge length for the DAS recordings and accurate channel locations could help determine accurate locations for these anomalies.

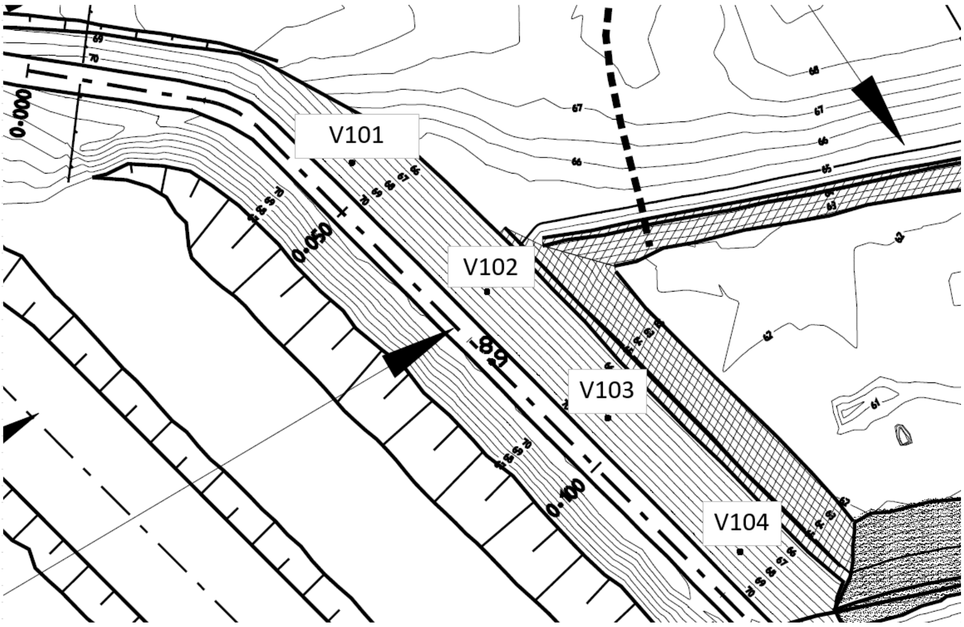

Figure 37 Location of the standpipes in the New Dam.

The reason for the low velocity anomalies, other than that discussed in Section 6.6.4, requires further investigation. A longer monitoring period is needed to determine whether the low velocities are persistent in time. If velocities are consistent over time it is likely that they are caused by permanent features such as differences in compaction along the dam.

6.6.6 Water level downstream

The water level in the pool between the New Dam and the old power station is not measured. However, manual measurements of water levels are made in the four standpipes in the downstream fill (V101-V104, Figure 37). These readings are similar to the water level in the pool.

No readings were taken during our measurement period, but one was taken about one week before and another one week after the measurements finished. The data shows a decreasing water level of about two meters between the two manual readings (Figure 38). The water level is normally decreased on 15 October, by opening the outflow. The water is then released within less than a day. The exact day and time this was done in 2019 is not known but there is no obvious change in velocities around the 15 October so the draining of the downstream pool does not appear to affect the seismic velocities in the dam.

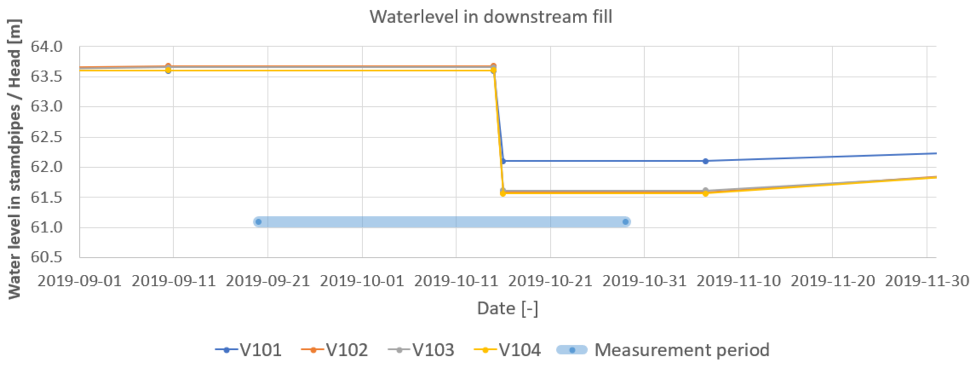

Figure 38 Water levels during September - November measured manually in standpipes V101-V104.

6.6.7 Accuracy and precision of velocity measurements

The seismic velocities in the New Dam determined by this study provide a precise measurement for body, surface and coda waves because the cross-correlated waveforms are stable over time. The estimated error in changes in surface wave velocities are up to 0.6% (Figure 27). The error in estimated coda wave velocities depends on the channels used but a typical error in velocity variation estimates is 0.5% (Figure 30). These errors are smaller than the velocity variations observed during the monitoring period and therefore the variations are considered true velocity variations and are not an artefact of the analysis methods.

The accuracy of the velocity measurements is determined by the accuracy of the channel positions. Through known locations of turnaround points in the cable it is possible to interpolate the position between these points. The error in channel positions over the length of the New Dam is approximately +/- 1 m. This incurs an error in velocity estimates of approximately 0.7% over the length of the dam. Tap tests at several locations along the dam could be made to test the accuracy of the channel locations before further data acquisitions. The tap test serves as a calibration for the fibre channels in space, mapping points in the fibre to precise locations.

The depth sampled by the surface waves in this study could be up to 40 m (depending on the frequency of the wave). The surface wave velocities measured are an average over the depth being sampled. Therefore, any anomalies observed may relate to variations in the bedrock geology rather than to the dam itself. The use of multiple cables to build 2D or 3D velocity models would help remove this ambiguity.

The measurements made with the DAS instrument are very precise since the speed of light and the backscattering qualities of the fibre are well known. Instrumental noise does not significantly affect the analysis in this study.

The study was conducted with a gauge length of 10 m and therefore the recorded DAS signal is an average over this length. To improve spatial resolution data could be recorded with a shorter gauge length (for example 3 m or 2 m) to improve the identification of anomalies smaller than 10 m in spatial extent. In the results presented above the data was decimated spatially to every 5^{th} channel (a measurement approximately every 5 m) to compute cross-correlations. With a smaller gauge length, the analysis should be repeated with a closer spacing of measurement points.

The sensitivity of seismic methods is limited by the frequencies, and hence wavelengths, analysed. Here the maximum frequency considered is 50 Hz and for a wave of this frequency travelling at 400 m/s (the approximate P-wave velocity in the dam) the wavelength is 8 m. We therefore do not expect to resolve features <2 m wide. To improve the spatial sensitivity higher frequencies could be investigated. This is possible with ANI but it may limit the survey to a body wave survey as surface waves at high frequencies are difficult to distinguish from body waves.

7 Conclusions and Recommendations

7.1 CONCLUSIONS

The current study is a proof-of-concept to investigate the possibility of conducting an ambient noise interferometry (ANI) analysis with DAS data to image and monitor dams. This initial test has proved that the combined technologies can be successfully applied to determine seismic velocities. Stable cross-correlated waveforms are produced and the ambient noise environment at the Näs Dam is suitable for application of ANI. The body wave velocities measured are in agreement with those measured during an active survey in 2017, giving confidence in the results. Changes in seismic velocities in dams due to ongoing internal erosion or new seepage locations should be resolvable with this combined technique.

The metre-scale channel spacing afforded by DAS enables a detailed image of seismic velocities in the dam to be constructed. The capabilities of the ANI technique could be investigated further if recording was conducted on multiple cables, thereby enabling 2D or 3D imaging. Additionally, the use of high frequency waves and a smaller gauge length could improve the resolution of the technique. This is possible with the latest DAS technology. The development of the next generation of DAS systems, the new Silixa Carina® sensing system now provides a 2m gauge length and a 100 times SNR improvement over the iDAS. The combination of improvements in the interrogator technology coupled with an engineered fibre enable more detailed surveys. Developments in processing techniques, such as the work carried out in this test, are building on the technology improvements to widen the applicability of DAS. With the advancements made in DAS technology in the past few years, the possibilities afforded by fibre optics are only increasing. DAS technology and ANI techniques continue to develop quickly, and it should be possible to resolve smaller anomalies with smaller gauge lengths and robust analysis techniques.

Some aspects of the results in this study are not fully understood. For example, there is an overall decrease in velocity with time and there are locations of low velocity at several points along the dam. To fully interpret and assess the accuracy and precision of the results further information and investigations are required to:

- Understand the effect of temperature and rainfall on the results.
- Understand the effect of bedrock geology, the geology of the abutments and compaction in the dam.
- A comparison with active seismic measurements in wet and dry conditions.

Ideally, to validate the seismic velocity results, a dam with known compositional or seepage variations should be used as a test site. It would then be possible to verify and benchmark the ability of the techniques applied here to resolve the anomalies. Monitoring for longer time periods (up to a year) would help isolate meteorological and water level effects.

Overall, the study shows there is great promise for imaging dams using DAS and ANI if the range of parameters affecting seismic velocities in the dams can be determined and extracted from the results. A new application of existing cable deployments can be expected in the future.

7.2 EXTENSION OF THE ANALYSIS

Following the results of this feasibility study several recommendations are made.

1. The full extent of the capabilities of ANI to image dam structures could be realised with recordings on multiple cables. This would enable 2D or 3D tomographic studies and a full 3D picture of the state of the dam could be obtained. The ideal layout for the cables would allow the use of seismic ray-paths through each part of the dam, e.g. with cable installations on the crest of the dam and base of the dam. The dense sampling available from multiple fibre-optic cables would provide dense seismic ray-paths, required for accurate tomographic studies.
2. Explore possibilities with the other passive technique (AES) at a dam with known significant flow rates. This is required to understand the sensitivity of passive seismic DAS measurements to identify the sound created by the seepage flow.
3. Measurements should be made at dams with known areas of anomalous seepage flow or under control conditions in a test dam where seepage can be varied. The precision and sensitivity of measurements could then be benchmarked against known anomalies.
4. DAS measurements should be collected over longer time periods, up to 6 months or possibly one year, to enable weather effects on seismic properties to be understood.
5. Further measurements using iDAS with a better spatial resolution. The potential of introducing the Carina system that includes a constellation fibre will be also will be also evaluated.

8 Acknowledgements

The data evaluation shown in Chapter 6 is made by Roméo Courbis, Aurélien Mordret and Richard Lynch at Sisprope. We are grateful to their contribution and experience in applying Ambient Noise Interferometry processing of distributed acoustic data, verifying that the technique can be used in dam integrity monitoring.

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Air temperature data, retrieved February 14, 2020, from: http://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer/#param=airtemperatureMean24h,stations=all,stationid=106040

FIBRE-OPTIC DISTRIBUTED ACOUSTIC SENSING FOR DETECTION OF SEEPAGE AND INTERNAL EROSION

Optiska fibrer för distribuerad mätning finns installerade i nästan 100 dammar i Sverige idag. Fibrerna används för detektion av läckage genom temperaturmätning, eller rörelse genom töjningsmätning.

De flesta installationer kan även användas för akustisk mätning, så kallad Distributed Acoustic Sensing, DAS. Utvecklingen av den här typen av mätning har gått snabbt framåt de senaste åren, det gäller både mättekniken och utvärderingsfjmetodiken. Här redovisas resultaten av passiva akustiska mätningar i två av dammarna vid Näs kraftstation som gjorts för att utvärdera metodens känslighet och potential för att övervaka dammar.

Resultatet visar att seismiska gånghastigheter kan fastställas och extraheras. Det innebär att tekniken kan användas för undersökfjning av dammar, främst genom jämförande mätningar, det vill säga att eventuella förändringar sedan föregående mätning kan upptäckas.