Dark Fibre Optic Cables for Shallow Ground characterization alongside Railroads

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ABSTRACT

We evaluated the feasibility of existing fibre optic telecommunication cable as a Distributed Acoustic Sensors (DAS) for shallow ground characterization alongside railways and using the running trains as seismic source. We utilized 5 km of fibre optic cable alongside a railway segment localized in the Hanzelijn corridor in the Netherlands. For almost a week, we recorded strain generated by passing trains that was utilized to retrieve coherent and multimodal Rayleigh waves at various soil conditions. The data was recorded in a continuous mode, using a channel spacing of 1.0 m and a sampling frequency of 1,250 Hz. The DAS interrogator was set to a gauge length of 2.0 m to reach the highest possible spatial resolution. We captured at least 60 train passages (running alongside the fibre optic cable) per day. We extracted Rayleigh waves by utilizing seismic interferometry method. The seismic interferometry processing provided virtual broad-band shot-gathers with coherent and clear surface waves trends. The computed phase velocity spectrum at frequencies as high as 30 Hz and wavelength as short as 6 m. The retrieved dispersion curves allowed us to determine S-wave velocity profile at a minimum depth of exploration of 2.0 m. The measured Rayleigh waves and calculated S-wave velocities are comparable to reference values measured with standard Geophone and geotechnical data available at the test segment.

Keywords: Surface waves; Dark fiber; fiber optics; MASW.

1. Introduction

In the coming years, ProRail (Dutch Railway Operator, owner, and maintainer of the Dutch railway tracks) forecasts growth in train traffic for both, passengers, and freight trains. Compared to 2018 an increase of 30% is expected for passengers and 50% for freight. To facilitate this growth, more, faster, longer, and heavier trains are needed.

Many of the Dutch railway lines were built more than hundred years ago. At that time, there was less knowledge about building embankments, trains were less heavy, and the speed of the trains was much lower than today. In addition, there were several railway companies at the time, and each had its own way of constructing embankments on the very soft clayey and peaty Dutch soils.

In these soft soils, the bow wave of the trains has a relatively low wave speed. If the train speed is too close to the wave speed of the soil layers, more damage than normal will occur to the track, the embankment, and the catenary supports. Therefore, before increasing the train speed on a trajectory, the critical train speed should first be investigated. If the critical train speed is too low, measures must be taken before any increment in train speed can be applied.

To determine the critical train speed, a geotechnical site investigation is traditionally carried out using CPT (Cone Penetration Tests), and boreholes to understand the underlying soil structure geology that often includes its response to elastic seismic waves. Elastic wave measurements are investigated using e.g. SCPT (Seismic Cone Penetration Tests) at point locations or by means of MASW (Park, Miller, and Xia 1999; Park, Miller, and Miura 2002) (Multichannel Analysis of Surface Waves) that requires the installation of an array of geophones. All these measurements will serve as reference measurements to compare with dark fibre data. The disadvantage of this approach is that apart from being costly is, that the track must be closed for some time (usually during short maintenance windows during night) so there is less time to carry out the work and the measurements only give an insight into the subsoil at the point where they are carried out. It is often possible to carry out a few CPTs, and even fewer VSPTs or MASWs, on a kilometres long track.

Fiber optic cables for communication purposes are laid along all main railway lines in the Netherlands. These fibre optic cables still have some dark (unused) fibres left that can be used for measurement purposes. By measuring the ground borne vibrations caused by the trains in the fibre optic cable, it is possible to derive the local S-wave velocity of the soil structure, in a similar way to an MASW (Ajo-Franklin et al. 2019; Tribaldos et al. 2021). The advantage of the fibre optics sensors is that, by using the moving train as a vibration source, it is possible to evaluate the soil conditions along the track over several kilometres and with fewer personnel along the track. This makes that measuring critical train speed will become faster and safer.

In this research we present the implementation of 5 km of Dark fibre sensors for measuring the seismic waves generated by running trains which are processed using seismic interferometry. The measured records are utilized to characterize the Rayleigh waves and to derive the S-wave velocity structure underneath the track. These results are aimed at demonstrating the feasibility of dark fiber for retrieving relevant engineering properties of soft soil conditions at shallow depths.

2. Test site

The selected test site is localized in the middle of the Netherlands, west of the city of Zwolle and along the so-called Hanzelijn (Fig. 1). The selected test site fulfilled the following criteria:

a) The embankment had to be built at once.
b) The position of the spare fiber available must be known.
c) The thickness of the sand bed had to be known.
d) Geotechnical data such as CPT, and boreholes had to be available.
e) MASW measurements could easily be carried out close to the track and the existing fibre optic cable.

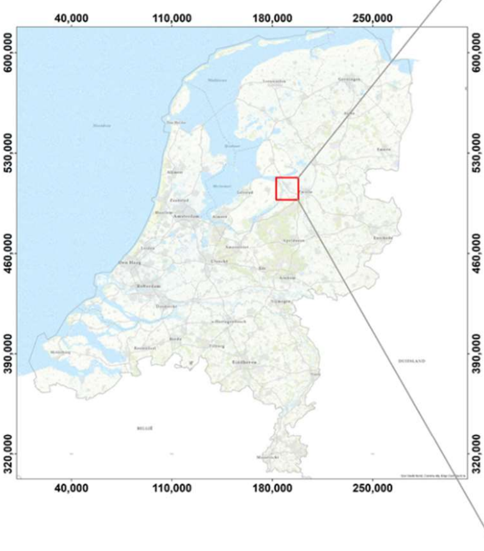
From the geology viewpoint the Netherlands lies mainly in the Holocene and Pleistocene epochs. In the Middle Pleistocene there was the Saline a glacial period (Vos 2003). During this period, the northern part of the Netherlands was covered by glaciers. In the Late Pleistocene, during the next glacial period, the Netherlands was a polar dessert and a lot of aeolian sand was deposited on top of the glacial deposits.

At the test site, these sand deposits are found at a depth of 1 to 6 meters below the surface. In the following period, the Holocene, a peat layer was formed due to the rise in sea level. On top of this peat layer the river IJssel deposited a clay layer.

Fig. 2 shows the lithology, with all the borehole data along the length of the track. These measurements are done about 25 m North of the railway line and shows the original soil layers. This picture also shows that the track lies above the surface. The space in between, the embankment, is filled with anthropogenic sands. The thickness of the embankment varies from 2 m to 7 m.

In Fig. 2, the lithology cross-section along the survey line is plotted together with the selected dark fibre optic channels, indicated by the green colour numbers. The elevation of the fibre optic cable (blue line) respect to the track position (red line) is also indicated. The fibre optics cable is buried about 0.6 m from the free surface.

In the lithology profile between fiber positions 160 – 1020, there is a soft-layer of 4 - 6 m thickness, that is overlaying a sand layer. This part we call it Soft-zone. At the remaining positions (fibre coordinates 1020 - 5000) this soft layer is much thinner (sometimes not present) and in the positions 1800-4000 much deeper in the profile. This part we call it Stiff-zone.



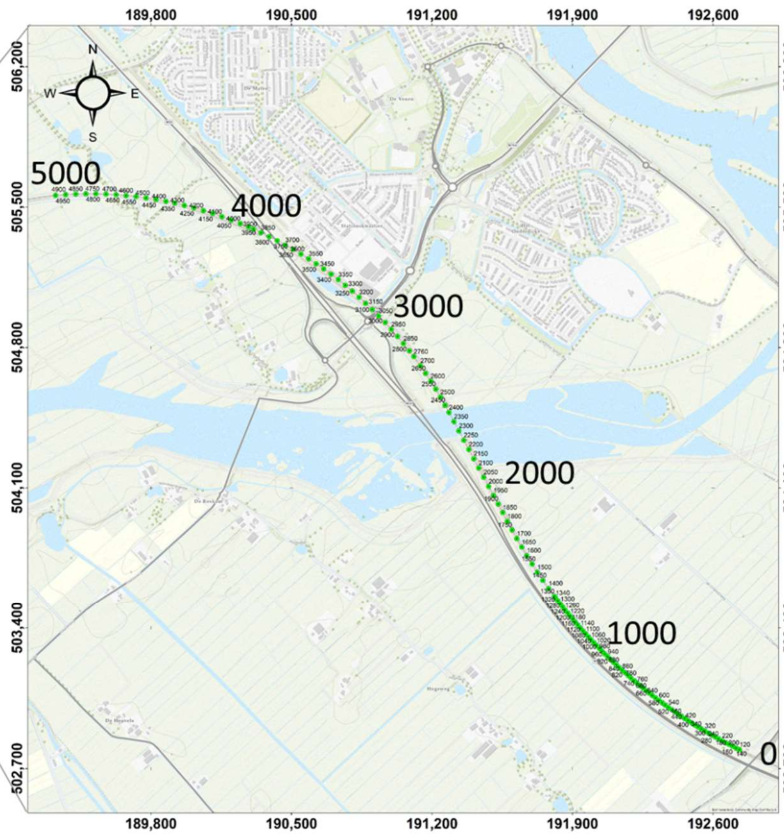


Figure 1. Location of test site near Zwolle (The Netherlands). The fiber optic line is displayed with green colour dots.

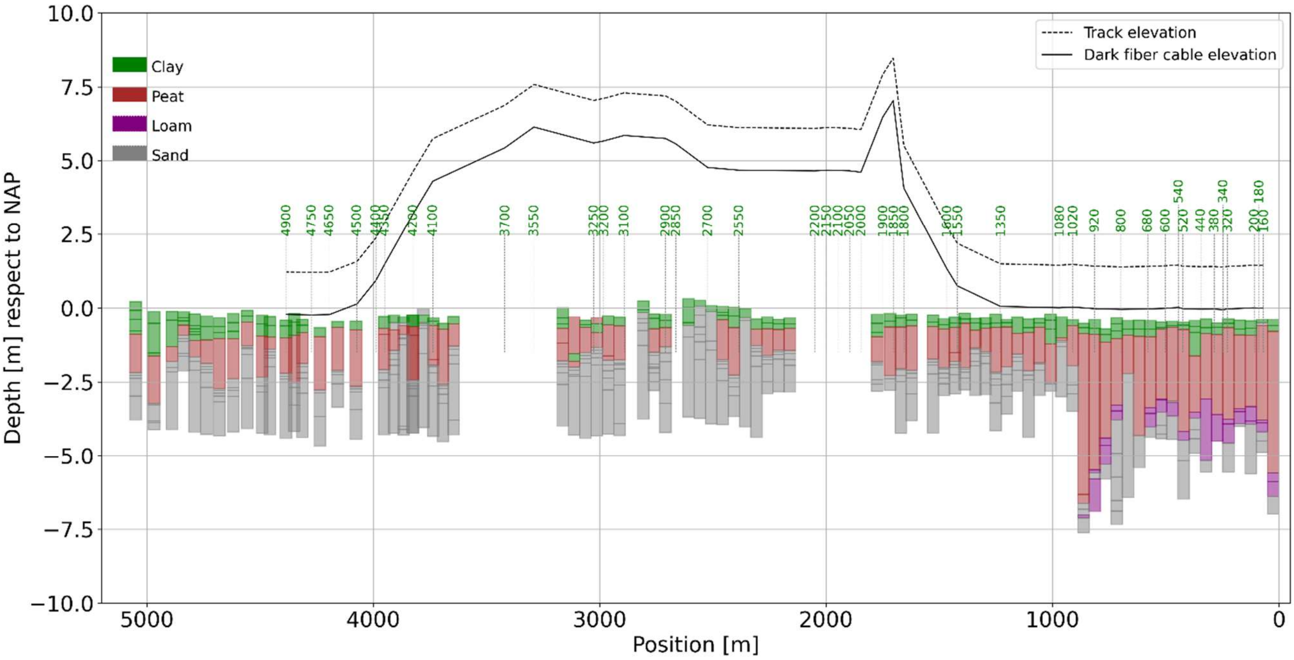


Figure 2. Lithology of Hanzelijn corridor. The elevation (respect to NAP - Normaal Amsterdams Peil) of the track and the dark fiber cable are also indicate.

3. Data recording

The data recording was performed using the DAS interrogator QUANTX manufactured by OptaSense. For this project, the data recording was performed using a sampling frequency of 5 kHz with output signals of 1.25 kHz, allowing a maximum usable frequency of 0.625 kHz. The channel spacing was set to 1.0 m and to achieve the highest possible spatial resolution the gauge length was set to 2.0 m. The data were recorded in HDF5 (Hierarchical Data Format, Version 5) format and stored in time segments of 120 seconds.

As the target records are those where there is a train passage, a selection procedure was implemented to determine either a full or partial train signals. The monitoring campaign was conducted for over 2 weeks. The recorded data is saved in sections of 120 seconds containing 5,000 channels. After 1 week of measurements, segments of 100-channels are selected at various locations to be later processed and extract the local soil properties.

An example of a selected dark fibre record of 100 signals (delimited by dark fibre channels 160 - 260) that contains 1 train passage is displayed in Fig. 3. a).

At two locations of the test site active MASW measurements were carried out as close as possible to the track and on top of the cable at the east side of the test location. Fig. 4 shows an impression of the measurements. The active MASW surveys consisted to 96, 4.5 Hz vertical component geophones deployed in a linear array. The seismic source was a sledge-hammer impact placed inline the geophone array

The adqusition was performed using a sampling frequency of 1.0 kHz. The record duration was set to 2.0 seconds. Notice that the active MASW measurements using geophones were performed when trains were not passing to avoid any undesirable noise perturbation.

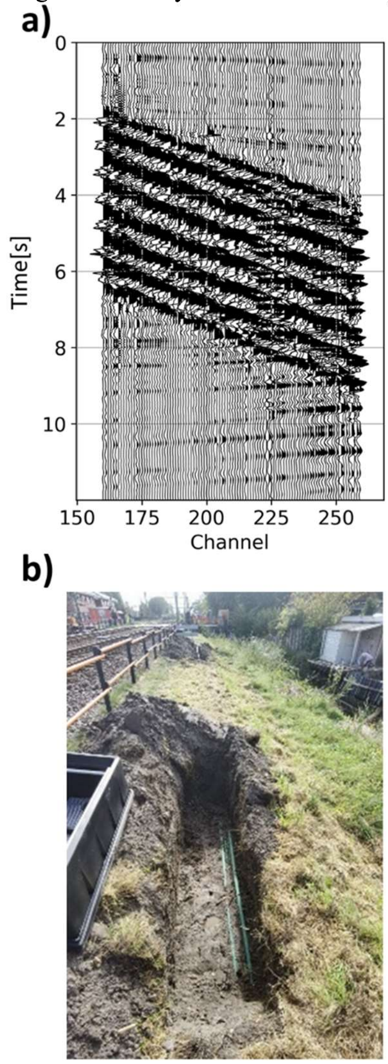


Figure 3. a) Example of a fibre optic recording containing 1 train passage, b) dark fibre cable (green colour cable) buried alongside the Hanzelijn corridor.

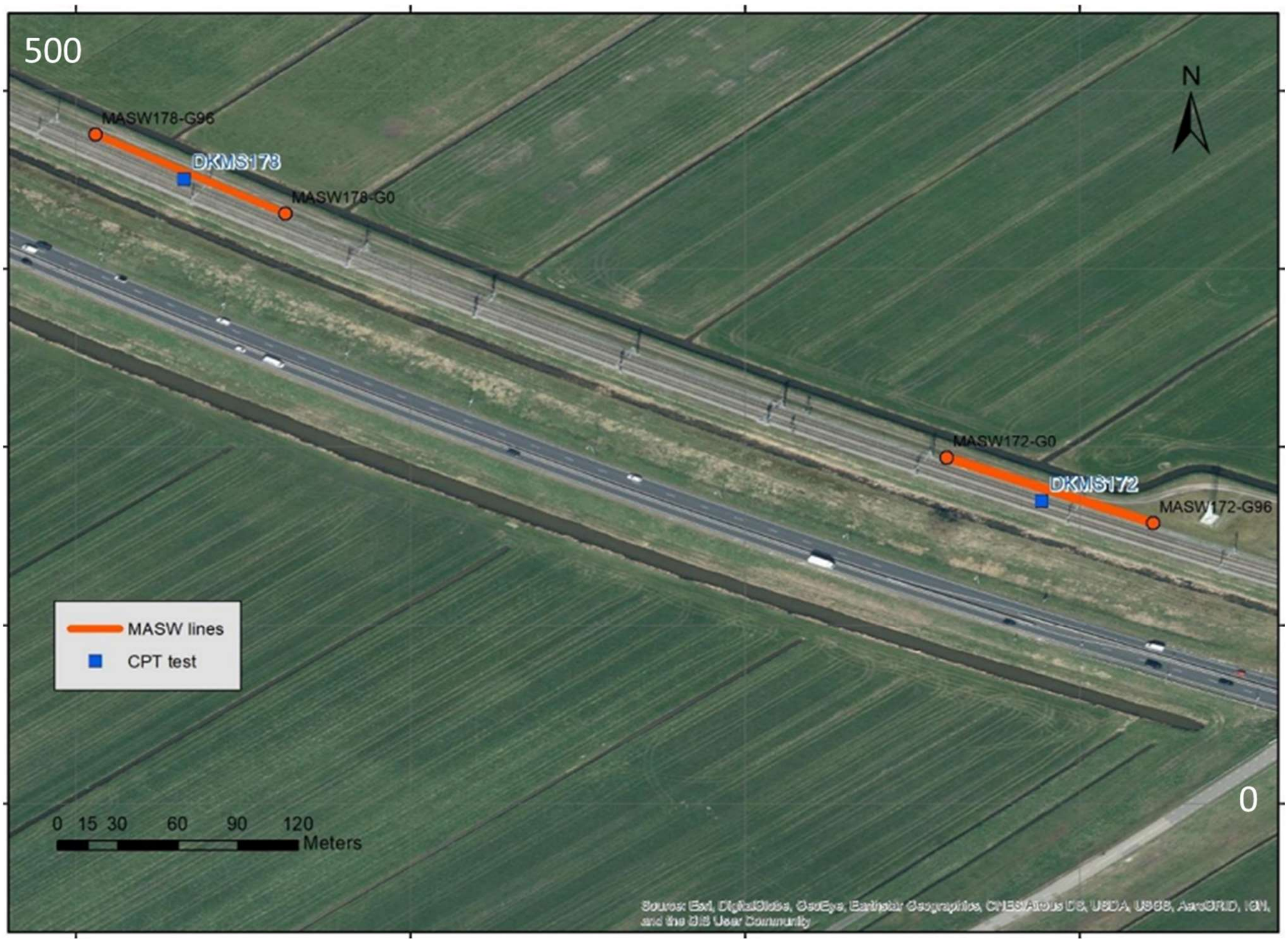


Figure 4.. Location of MASW survey lines at the test site near Zwolle (The Netherlands). (FUGRO 2022)

4. Methods

To get the S-wave velocity profile along the track is obtained the following steps are made: (1) Seismic interferometry analysis on the DAS data leading to virtual shot gathers, (2) derivation of the phase velocity spectrum, (3) inversion of the dispersion curves from the phase spectra to get a vertical S-wave profile (4) linear interpolation between these vertical profiles. The first three steps are discussed here in more detail.

The seismic processing of the DAS data consists of seismic interferometry analysis (Bensen et al. 2007; Quiros, Brown, and Kim 2016) that has been successfully implemented with train signals data (Quiros, Brown, and Kim 2016; Ajo-Franklin et al. 2019). The processing was implemented utilizing well-known open-source codes NoisePy (Jiang and Denolle 2020) based on Obspy (Beyreuther et al. 2010).

The seismic interferometry processing provided the virtual-shotgathers like the ones obtained with active surface waves surveys (Park, Miller, and Xia 1999). The virtual shotgathers are utilized to calculate the phase velocity spectrum using the phase-shift wavefield transformation (Gabriels, Snieder, and Nolet 1987). The interpretation of the extracted measured dispersion curve is focused on determining the minimum and maximum wavelength that can be realistically resolved. The wavelength is defined as the ratio between phase velocity and frequency. The high frequency limits (short wavelength) provide information on the shallowest layer thickness to be resolved, while the low frequency limit (long wavelengths) defines the maximum depth of exploration. As rule of thumb we adopt the criteria proposed in the literature (Foti et al. 2018) that suggest that the minimum and maximum depth of exploration is equivalent to 1/3 of the minimum and maximum measured wavelength respectively.

Finally, the extracted dispersion curves are utilized for inversion using the linear search method (Wathelet, Jongmans, and Ohrnberger 2004) coded in geopsy. The inversion is performed individually for each extracted dispersion curve from all selected locations. Then the S-wave velocity profile along the track is obtained after interpolating all extracted 1D S-wave profiles.

5. Results

5.1. Dispersion analysis

The virtual shotgathers are utilized to calculate the phase velocity spectrum at various positions along the Hanzelijn corridor. The dispersion analysis consists of computing the dispersive energy distribution respect to frequency, that is represented in the phase velocity spectrum. We first display the phase velocity spectra from geophone data that serves as a reference especially in the Soft-zone. Later, we present two characteristic phase velocity spectra obtained from fiber optics at the same geophone position. We also include a spectrum calculated for the stiffer soil position. We briefly discuss the reliability of the measured energy in terms of minimum and maximum wavelengths.

5.1.1. Phase velocity from geophone data

The phase velocity spectrum is computed using 48 channels localized alongside fibre segment 160, localized inside the Soft-zone. Fig. 5 shows the result. At this site, the measured spectrum depicts a prominent dispersion energy trend around 100 m/s that occurs between 5.0 Hz and 30.0 Hz. This prominent trend is associated to the fundamental dispersion mode. Clearly, this phase velocity trend indicates the dominance of a soft layer within wavelengths of about 3.0 m – 45.0 m, that is a depth range between 1.0 m and 15.0 m.

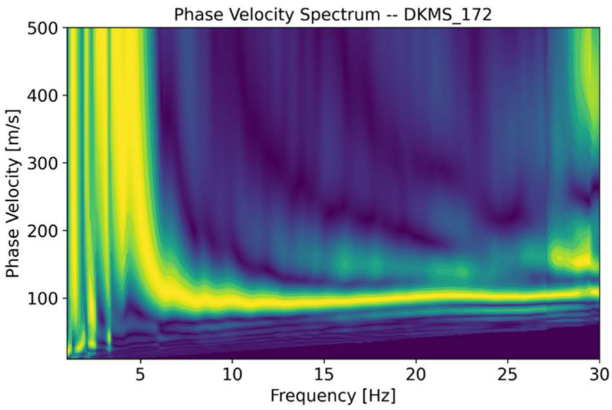


Figure 5. Computed phase velocity spectrum from geophone data alongside DAS segment 160.

5.1.2. Phase velocity spectrum from DAS

Similarly, the phase velocity spectra are also computed using the virtual shotgathers at 44 positions along the Dark fiber cable that were of good quality. We show the phase velocity spectra localized at segments 160 and 3200 (Fig. 6). Fig. 6a, depicts an example of a phase velocity spectrum at the Soft-zone. The spectrum is plotted together with the fundamental mode measured with geophone data at position 160. It appears that, up to about 14 Hz, the measured fundamental mode is observed with both geophones (Fig. 5) and DAS. The DAS spectrum also shows at least 2 higher mode trends, but less energetic, which are not observed in the geophone data.

Fig. 6b, on the other hand, shows a clear dispersion energy trend that extends up to about 29 Hz. The higher energy at high frequencies is very characteristic alongside the Stiff-zone that predominates after position 1020 displayed in Fig. 2.

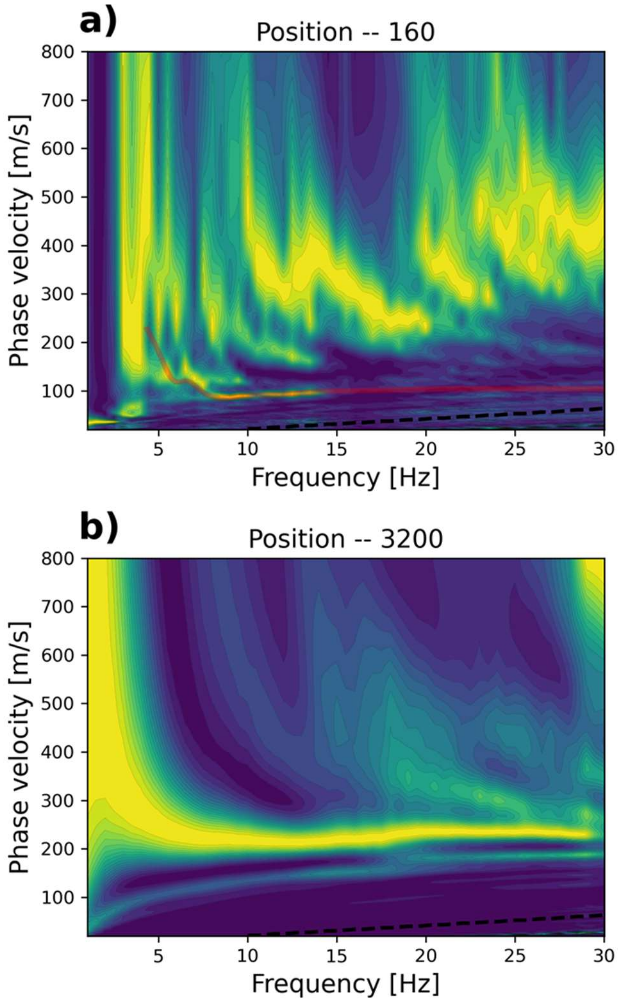


Figure 6. Computed phase velocity spectrum from DAS data a) DAS segment 160 b) DAS segment 3200.

5.2. S-wave velocity profile

From the computed phase velocity spectra, we derived the dispersion curves of the fundamental mode (and higher modes if present). Fig. 7 shows for position 160 (localized at the Soft-zone) the derived shear wave velocity on depth. The background shows the original soil layers (from Fig. 2). The inverted profile seems to match the Pleistocene sand (with the jump at NAP -4 m). The jump at NAP -2 m might be the bottom of the embankment.

The S-wave velocity distribution alongside the dark fiber optic cable, calculated after interpolating the 1D inverted S-wave velocity profiles, is displayed in Fig. 8. The thick-soft sediment layer that is characteristic of Soft-zone displayed in fig. 2, seems to be captured by the S-wave velocity cross-section.

The soft layers with a low_velocity layer between 80 m/s – 160 m/s, is overlaying a stiffer sandy layer with a velocity of around 500 m/s. On the other hand, the thin-soft layer present at the Stiff-zone appears to be undetected by the dark fibre.

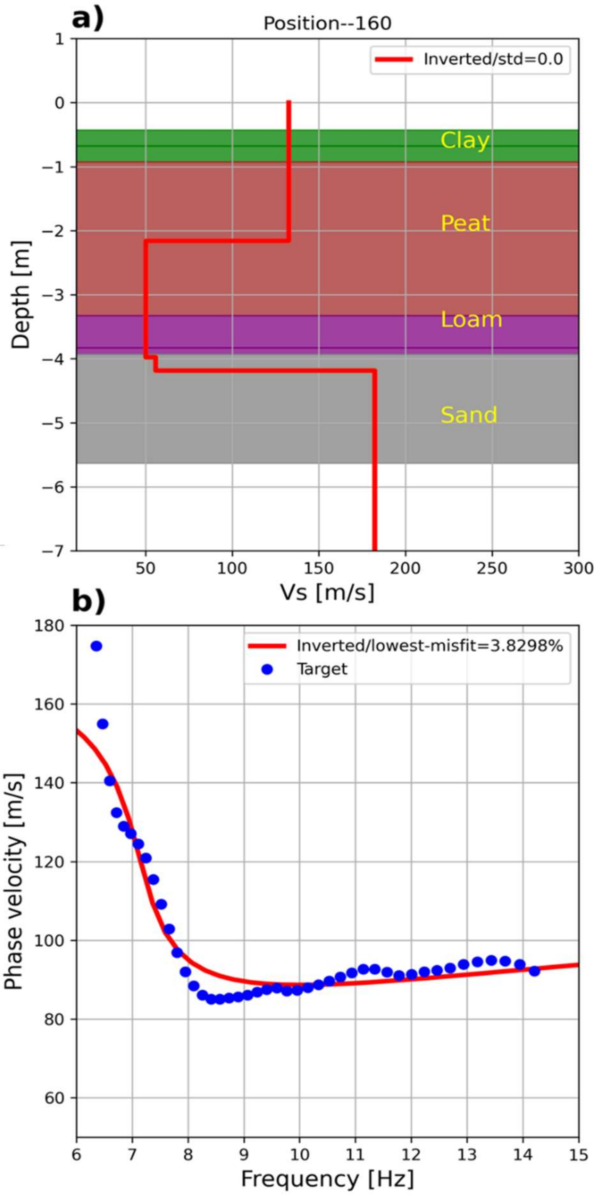


Figure 7. S-wave velocity on depth (a) and inverted dispersion curve (b), DAS segment 160.

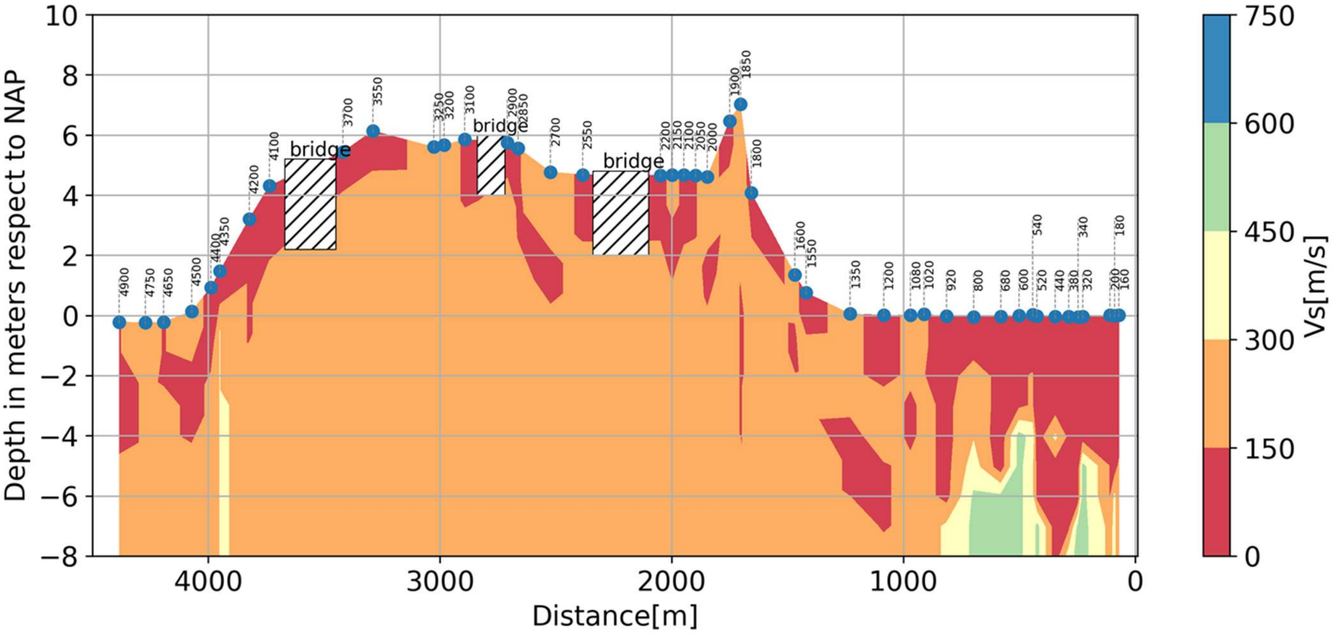


Figure 8. S-wave velocity distribution based on the 1D inverted profiles at selected locations.

6. Discussion

The overall S-wave velocity cross-section derived from measured phase velocity spectrum seems to be in correspondence with the actual site conditions. At the Soft-zone most of the energy occurs below 20 Hz, and with almost no energy at higher frequencies. The low amplitude energy at higher frequencies may be caused by the attenuation induced by the higher damping of the soft sediment.

On the other hand, the dispersion trends at the Stiff-zone seems clearer at both low and high frequency range between 1 – 30 Hz, but the vertical resolution is not high enough to capture the thin soft clayed layer.

7. Conclusions

Dark fibre optics sensors that measure waves generated by train passages appears to provide coherent seismic records at two distinctive soil conditions. The running trains appears as an ideal energy source in a wide frequency-band dominated by strong surface waves energy. The computed phase velocity spectrum at various locations provided information of the S-wave velocity structure, underneath, that seems to be in correspondence with actual soil conditions along the test line. This information is also relevant to identify areas with particularly low critical train speed.

At location 3200 (Stiff-zone) a sandy embankment of 7 m is overlaying a soft layer of about 2 m. This thin-soft layer is obvious not observed by the method. The site conditions at the Soft-zone is for practical engineering more relevant, since the problems with strong settlement and low critical wave speed occur in cases with thin embankments on relatively thick and soft soil layers. It is concluded that the method is applicable to those cases.

Acknowledgements

This research was carried under the joint collaboration of ProRail and Deltares.

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