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Vibration measurements during soil-rock sounding – a comparison between accelerometers and geophones

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There are many different methods to retrieve information about ground properties prior to building and infrastructure projects. In Sweden the most common method is soil-rock sounding (Jb-sounding) which was developed in Norway in the 1990s. Soil-rock sounding is used for identifying the stratification of soil and the depth to bedrock and can be applied in different classes with different accuracy. It is an effective method with low costs but gives restricted information about the penetrated soft soil strata sequences and its properties. Improved knowledge about the presence of different soil and rock layers is necessary for a cost-effective design particularly of deep foundations.

The purpose of this research project is to perform vibration measurements on the ground during soil-rock sounding to gain more knowledge about the penetrated ground. The measurements can be executed without influencing or affecting the sounding measurements and show that the frequency content of the signal is reflecting the properties of the penetrated soil layers. As an important step for developing the new measurement method vibration measurements with an accelerometer are compared to simultaneous measurements with a geophone in order to evaluate which sensor is most suitable for retrieving soil information. The results and recommendations of this analysis are presented in this paper.

1 Introduction

Soil-rock sounding is a geotechnical investigation method that is used to determine general strata sequences of soil and depth to bedrock. The method is frequently used in the Nordic countries and standardized in [1] for Swedish use. It is a drilling method using a hydraulic percussive drilling rig. The system with the rig consists of a vehicle with a hydraulic arrangement that runs the feeding, rotation and the hammer [1]. Furthermore, the system contains a flushing system to remove the media that remains on the drilling rod when drilling into the ground. The process is started by turning on the flushing and the hammer at a constant frequency. Afterwards, the blows are started and the rod is driven into the soil while the sinking speed is measured in seconds per 0,2 m. When the rod is not able to penetrate by only using the hammer, the rotation is switched on. During the drilling process, a computer registers sinking speed, feeding force, rotational speed and depth [2]. This process is usually continued until a penetration of 3-5 m into the bedrock to avoid interpreting boulders as bedrock.

Soil-rock sounding can be divided into four different classes with different levels of accuracy: Jb-1, Jb-2, Jb-3 and Jb-tot and has been standardized by the Swedish Geotechnical Society (SGF) [1]. The differences between the different classes are mainly the amount of parameters that are registered. While it is only the depth and penetration resistance/sinking speed that is registered during the soil-rock sounding for Jb-1, the other three levels are also registering the force input, rate of revolutions, hammer pressure and rotational pressure. In addition to that, Jb-3 is recording the flushing media pressure and flushing media flow [2]. While Jb-1 and Jb-2 allow flushing with air or water, flushing with water is required for Jb-3 and Jb-tot. In comparison to Jb-2, Jb-tot contains a phase where the hammer and flushing are turned off and the sounding is run with a constant rotational velocity and sinking speed. This additional phase can in many cases replace supplementary methods like weight and mechanical pressure sounding.

The advantage of soil-rock sounding is that it is easy to perform and relatively cheap while giving a good overall estimation of general soil layering, depth to bedrock and, to some extent, the quality of the bedrock. It is a suitable method for investigating dense soil layers (such as till), soil layers containing boulders or blocks, or for identifying the transition from hard soil to fractured rock [3]. However, this method provides limited information about soft or loose soil layers and about the geotechnical properties of the penetrated material. In many cases the information gained from soil-rock sounding is nonetheless the only decision basis available for the design of, for example, pile foundations or retaining walls. Therefore improving and developing this method can increase the efficiency and accuracy of geotechnical investigations.

In the 1960s, a method that relied on sound measurements during drilling was developed [4]. The method implied recording and studying the sound as the drilling bit penetrated through soil and rock material to determine the depth to bedrock. A sound transmitter was lowered into an adjacent borehole at a certain distance and the sound was recorded. Lundström and Stenberg observed a difference of the vibration signal when drilling through boulder compared to bedrock. At that time, it was still a challenge to record and analyze large quantities of vibration data. Therefore, it was difficult to perform a large amount of vibration measurements and to promote this method into a commercial process. In the 1980s, an acoustic cone penetration testing (CPT) method was developed to identify soil layers using an acoustic sensor [5]. This sensor was located inside the tip of the cone while the acoustic emissions and their variation were recorded when the cone penetrated different soil layers.

Recently, the concept of analyzing acoustic emissions from soil-rock sounding has been studied by placing vibration sensors on the ground surface in two pilot investigations. This technique is denoted “acoustic soil-rock sounding”. During the first investigation, vibration measurements were conducted during Jb-2 sounding up to a depth of 18 m [6]. The sensors were placed on the ground at distances of 4 m and 12 m from the boreholes. In the second investigation, vibrations were only measured at a distance of 4 m [7]. All measurements showed that the vibration velocity decreased with increasing drilling depth, but increased when stiffer layers were penetrated. Furthermore, the study showed that the frequency content is a promising parameter to evaluate soil characteristics and that especially the frequency range of 0-50 Hz indicated distinct patterns that varied with soil type [3]. The previous studies suggest that acoustic soil-rock sounding is a cost-effective method to retrieve additional geotechnical information but further studies are required in order to correlate soil properties to measured quantities.

In this paper, results of vibration measurements during soil-rock sounding are presented. The main objective is to evaluate the signals obtained by accelerometers and geophones in relation to the composition of the penetrated soil or rock in order to determine the most suitable sensor for acoustic soil-rock sounding. Another objective is to gain more statistical knowledge of the signal characteristics during sounding under various geotechnical conditions to facilitate further development of the technique into practical use.

2 Experimental setup

The measurements were performed in Haninge, south of Stockholm in Sweden. The soil-rock sounding at six boreholes was completed with simultaneous vibration measurements, and the geological conditions differed significantly at the different locations. The depth to bedrock varied from less than 1,5 m at borehole BJ034 to about 8,0 m at borehole BJ032 and BJ035. Since more information regarding soil layering is provided by deeper boreholes, boreholes BJ032 and BJ035 are presented in this paper. The results of the soil-rock sounding showed that the soil at borehole BJ032 consisted of a 0,5 m deep layer of fill followed by 4,7 m non-cohesive soil, underlain by glacial till from a depth of about 5,2 m until the bedrock at about 8,0 m depth. The soil at BJ035 consisted of a 0,5 m deep layer of clay followed by non-cohesive soil down to around 7,2 m, underlain by a thin layer of glacial till. The depth to bedrock was about 8,1 m.

In addition to the soil-rock sounding equipment, a vibration measurement system was installed and the sensors placed at the ground surface. This system is shown in Figure 1 and consisted of three vibration sensors connected to a recording system and a computer, powered by a car battery. The measurement system was connected to the onboard computer of the drilling rig in order to obtain a synchronized depth signal of the soil-rock sounding. The vibration sensors were mounted on a metal stake that was pushed into the soil 4 meters from the borehole. This distance was chosen based on prior measurements that showed that the distance between the borehole and the vibration sensor did not affect the frequency content of the signal significantly [6]. The advantage of placing the sensor at 4 m distance is that it ensures a sufficient signal strength at the same time as it is not affecting the implementation of the soil-rock sounding. The vibration measurements were executed continuously and simultaneously to the soil-rock sounding. This means that the drilling served as the source of vibration. At all boreholes, the soil-rock sounding was conducted with accuracy Jb-2. The individual drilling rods were 2 meters long and were thus spliced every 2 meters. In the signal analysis, the splicing time was eliminated. The typical hammer operating frequency was 1100-1400 blows/minute which corresponds to a frequency of 18-24 Hz. The sampling frequency of the vibration measurements was 1200 Hz.

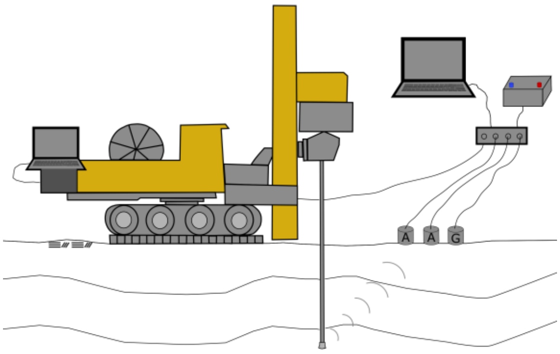

Figure 1: Setup of the measurement system

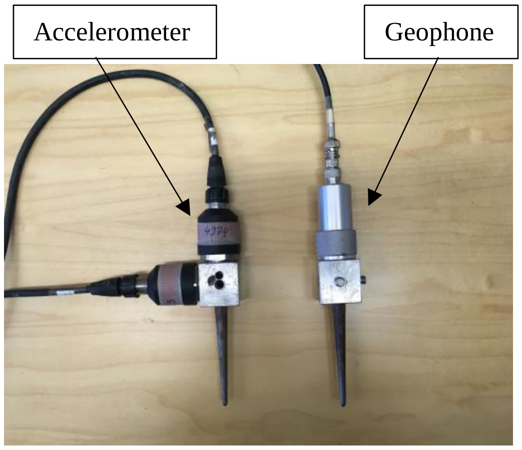

Figure 2: Accelerometers and geophones used for the measurements

2.1 Accelerometers and geophones

The main objective of this study was to determine the most suitable vibration sensor for acoustic soil-rock sounding – accelerometer or geophone. Figure 2 shows the two accelerometers (vertical and horizontal) and the geophone (vertical) that were used during the measurements and their mounting device with a metal stake that was inserted into the soil. In this paper, the vertical vibration signals of the geophone and the accelerometer are compared.

Table 1 presents the properties of the vibration sensors. The main difference between the two vibration sensors is that an accelerometer measures the acceleration in m/s^2 while a geophone measures vibration velocity in m/s, usually presented as mm/s. In this paper, the two different quantities are compared when analyzing the results.

Table 1: Properties of the vibration sensors

Device	Type	Sensitivity	Frequency range
Accelerometer, vertical	PCB 393 B12	10 000 mV/g	0,15 – 1000 Hz
Geophone, vertical	ABEM 20 4010 00	20 mV/mm/s	4,5 – 1000 Hz

In general, a geophone is considered to be more robust and less sensitive to background noise than an accelerometer. Especially, as it usually is high-pass filtered to reduce ambient noise. Accelerometers are considered to be better when recording both low and high frequency data as they have a linear frequency response from a very low to a very high frequency. Besides that, acceleration is more sensitive to high frequency vibrations whilst velocity is more sensitive to low frequency vibrations. In the case of acoustic soil-rock sounding, it has been shown in earlier studies that the frequency range of interest is between 0 and 50 Hz [7] and which suggests that geophones are likely to provide more relevant results in regard to the frequency response.

3 Results and discussion

Figure 3 and Figure 4 show the vibration signals of the vertical acceleration and the vertical vibration velocity of the geophone for borehole BJ032 and BJ035, respectively. It is clearly visible that the vibration levels of the ground acceleration and ground velocity behave similarly. The vibration velocity of the geophone, however, contains more significant peaks than the vibration acceleration of the accelerometer. In general, it can be assumed that the vibration amplitude increases with the stiffness of the penetrated layer but decreases with depth [3]. A stiffer layer can be seen in the accelerometer and geophone signals around the time of 120 seconds for borehole BJ032 and at around 150 seconds for borehole BJ035. In the case of very soft material with low acceleration or velocity levels, background noise from traffic, operation of the drilling rig or other effects may, however, affect the measurements.

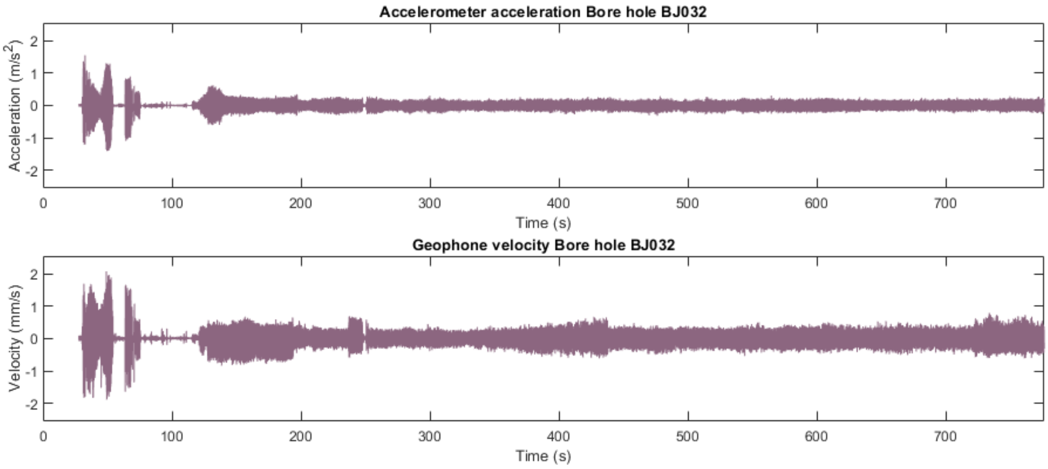

Figure 3: Ground acceleration of the accelerometer and ground velocity of the geophone for borehole BJ032

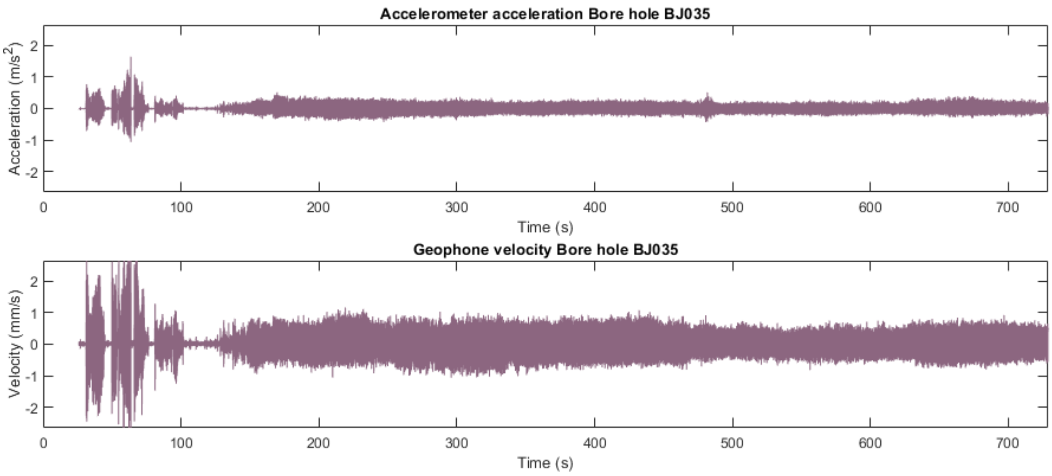

Figure 4: Ground acceleration of the accelerometer and ground velocity of the geophone for borehole BJ035, cf. Fig, 3

To get a better understanding of the penetrated soil, a spectrogram is created and analyzed, based on the signals shown in Figure 3 and 4. These spectrograms are plotted as functions of the sounding depth in order to visualize the variation of the frequency content of the measured signals during drilling. A spectrogram is a two-dimensional diagram where the third dimension – the density of the frequency spectrum (the signal strength) – is represented by colours. The brighter the colour the higher the vibration energy at that frequency during sounding at that particular depth. Figure 5 and 6 show spectrograms of the vibration signal of the geophone velocity to the left and the accelerometer acceleration to the right. For the geophone velocity, the colours for the lower frequency range up to about 50 Hz are more evident and more energy in the low frequencies is therefore registered. In the frequency range above 50 Hz, the accelerometer acceleration is showing more distinct energy levels in the higher frequencies. Earlier studies showed that the most reliable frequency range to identify the properties of the penetrated material is 0-50 Hz [7]. In this paper, a wider frequency range is analyzed in order to fully investigate the difference in potential of the two types of sensors for identifying soil properties. Based on previous published literature where mounting of transducers has been studied [9, 10, 11, 12, 13], the maximum reliable frequency for soil-mounted sensors is assessed to around 200 Hz. The frequency range 0-200 Hz is therefore adopted as a reliable interval for interpretation of these measurements. In order to interpret the acoustic measurements with respect to soil type, it is useful to compare those spectrograms with the results of the soil rock sounding, before drawing any conclusions about the suitability of accelerometers or geophones.

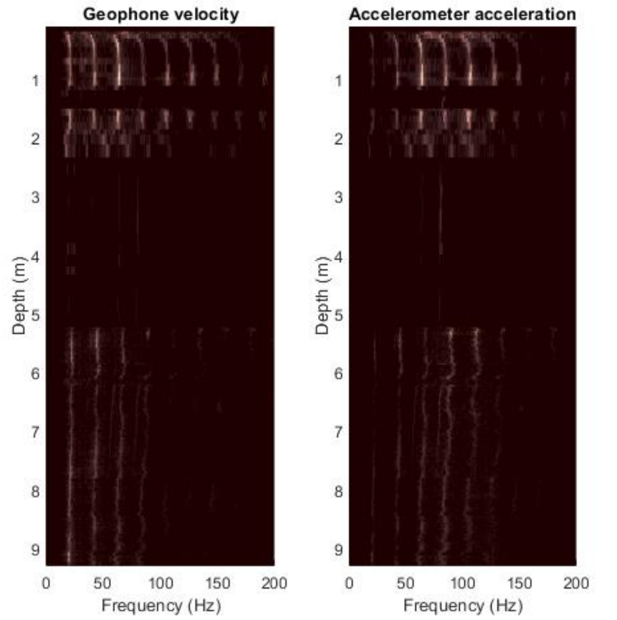

Figure 5: Spectrogram for the geophone (to the left) and the accelerometer (to the right) of borehole BJ032

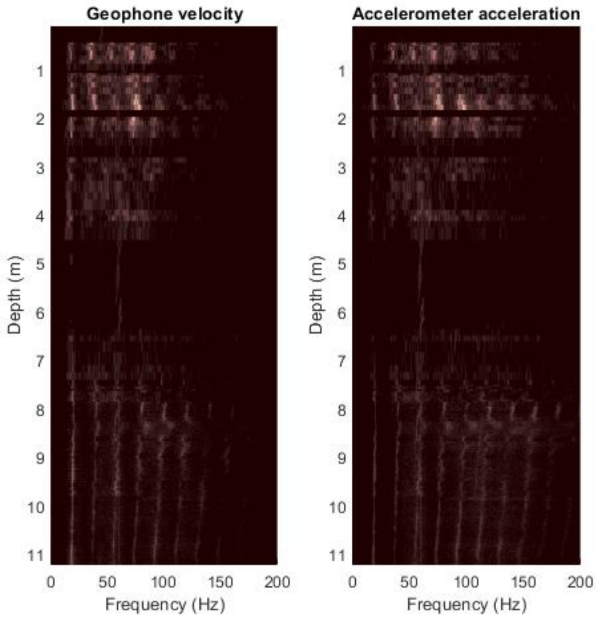

Figure 6: Spectrogram for the geophone (to the left) and the accelerometer (to the right) of borehole BJ035

Figure 7 and 8 compare the results from soil-rock sounding to the spectrograms of the vibration measurements for boreholes BJ032 and BJ035, respectively. The soil layers evaluated from soil-rock sounding are presented to the left, sinking speed and feeding force over depth during soil-rock sounding to the right and the spectrogram of both the geophone and accelerometer in the middle.

For borehole BJ032 (Figure 7), the first layer of fill down to about 0,5 m is characterized by explicit dominating frequencies that are slowly increasing with depth. The stiff layers glacial till and bedrock from about 5,2 m to 9,2 m depth are clearly visible as the hammer frequency, at about 19 Hz, dominates together with its overtones, which is in line with previous studies [3, 6, 7]. This behaviour of the spectrogram is similar for both the geophone recording as well as the accelerometer recording, although the lower frequencies up to around 50 Hz are more distinct in the geophone signal. The transition between glacial till and bedrock at about 8,0 m is not visible in the spectrogram. At a depth of about 6,0 m the frequencies for the till layer are less distinct which suggests a softer material. This behaviour is evident for both the geophone velocity and the accelerometer acceleration but more clear in the frequencies between about 60-100 Hz for the accelerometer. The layer marked as non-cohesive soil (typically materials dominated by sand or gravel) shows a variety of patterns and a frequency content which indicate heterogeneous conditions and a large variation within the layer. These variations cannot be identified by solely the soil-rock sounding and the acoustic method thus seems promising for more detailed soil identification. There are several main patterns in the spectrogram that can be seen for this non-cohesive layer. For example, the sequence in between 2,3 and 5,2 m shows one main frequency, which indicates a stiffer layer. For both the geophone and accelerometer spectrograms, the layers at smaller depths show provide a stronger signal than the stiffer layers of till and bedrock. This fact confirms that the amplitude of ground motion is decreasing with drilling depth. It is also apparent that the vibration energy increases with the stiffness of the penetrated material, thus confirming previous results.

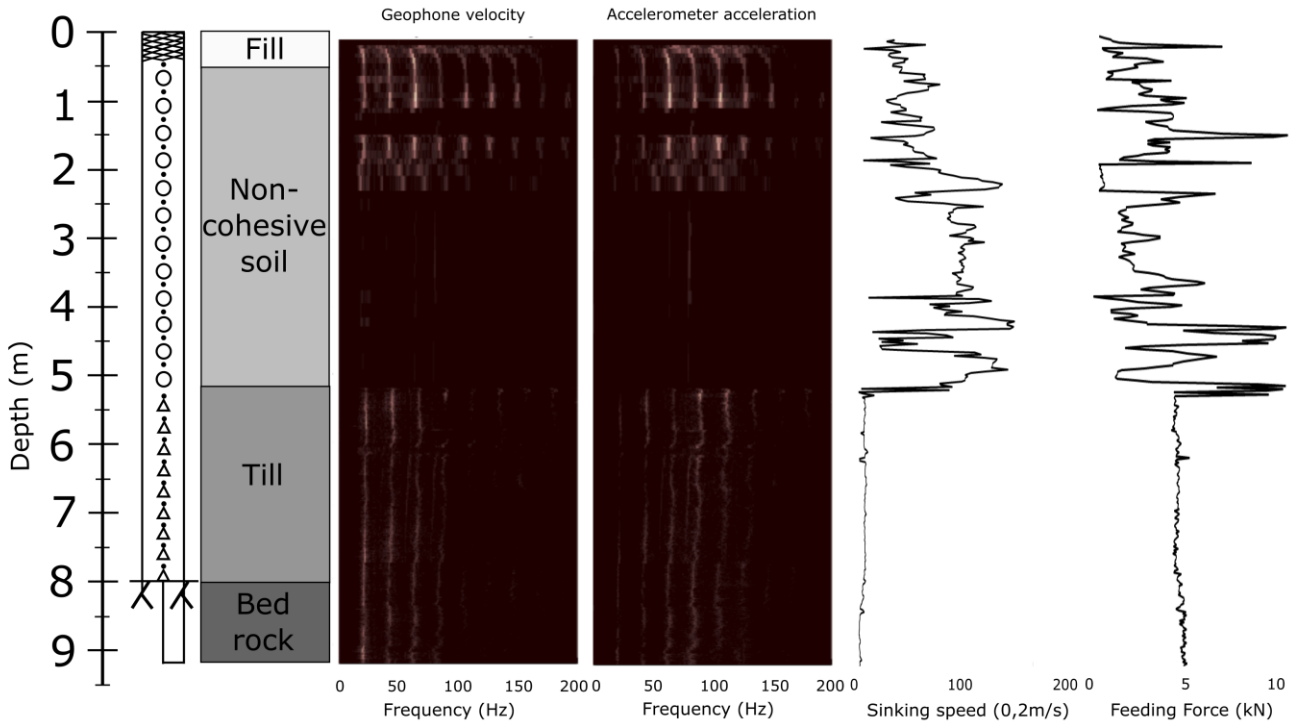

Figure 7: Comparison of results – soil rock sounding and vibration measurements for borehole BJ032

During the penetration of clay down to about 0,5 m at borehole BJ035 (Figure 8) none of the spectrograms show a distinct frequency content, which owes to the fact that the hammer was turned off for the penetration of the very soft material. For the penetration through glacial till and bedrock from about 7,2 m to 11,2 m depth it is once again the hammer frequency, at about 19 Hz, that dominates together with its overtones, which is clearly visible for both the geophone recording as well as the accelerometer recording. However, the transition from non-cohesive soil to glacial till is not as clearly visible as for borehole BJ032 and the spectrogram suggests that the transition occurs more gradually for this borehole, which is also visible in the sinking speed. The pattern of the spectrogram from 7,4 m and downwards indicate a stiff layer for both the accelerometer and geophone and the transition between till and bedrock at about 8,2 m is visible as a slight frequency change. In addition, the frequency shows less distinct peaks in the upper part of the bedrock between about 8,2 to 9,7, which could indicate fractured bedrock. At this borehole the layer marked as non-cohesive soil once again shows a variety of patterns and frequency content. Due to the many different patterns this layer seems to contain significant variation that cannot be captured by the soil-rock sounding alone.

The comparison of the spectrograms and the results of the soil-rock sounding for both boreholes show very similar outcomes for both the geophone and accelerometer which means that the different vibration sensors do not affect the analysis and interpretation significantly. In this case both geophones and accelerometers can thus be used.

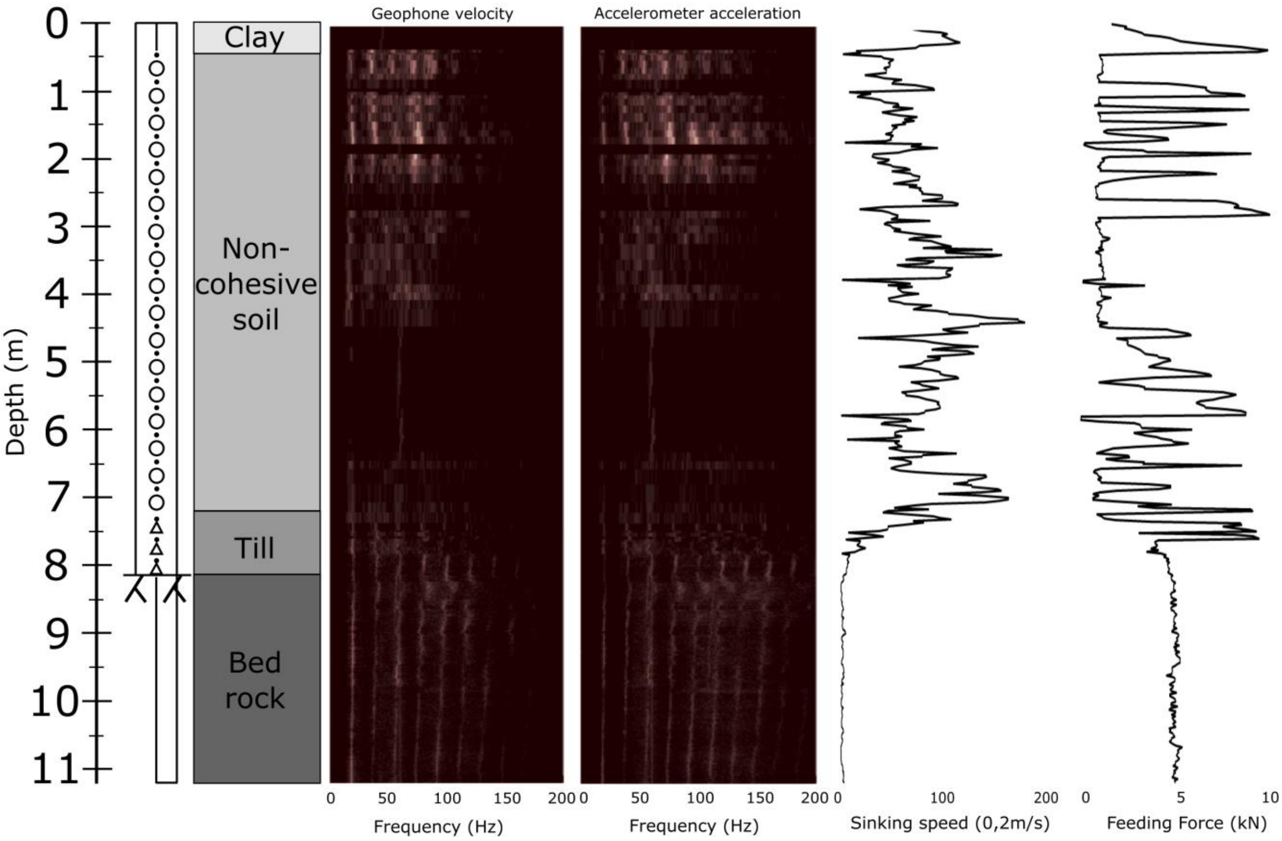

Figure 8: Comparison of results – soil rock sounding and vibration measurements for borehole BJ035

4 Conclusions

The spectrograms of the accelerometers and geophones that were obtained from the measurements in Haninge show a similar frequency content over depth. The geophone spectrograms provide more significant results in the low frequency range between 0-50 Hz while the accelerometer spectrograms show more distinct results above 50 Hz. Both vibration sensors appear to be suitable for performing acoustic soil-rock sounding. As previous studies have shown that the frequency range of interest is between 0-50 Hz, there is a slight advantage of using geophones in further studies.

Besides the comparison between the different types of vibration sensors, the measurements confirm the following conclusions drawn in previous studies:

- The amplitude of ground motion is decreasing with drilling depth but increasing with stiffness of the material penetrated.
- The most distinct results to gain knowledge about the material penetrated are achieved by looking at the frequency content of the signal in the low frequency range.
- Through the acoustic soil-rock sounding technique, additional information of the penetrated material can be gained compared to the sounding alone, thus providing more detailed geotechnical information in a cost-effective manner.

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