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Licentiate Thesis in Civil and Architectural Engineering

Soil identification by vibration measurements during soil-rock sounding

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Stockholm, Sweden 2022

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Abstract

Dynamic penetration tests are frequently used as geotechnical site investigation methods. In Sweden, the main reason to choose a dynamic penetration method is to investigate depth to bedrock, strength and deformation properties of soil, compaction, or piling depth. The advantage of dynamic penetration methods is that they have a better penetration ability than static methods and it is therefore easier to penetrate hard material or rock.

The most common dynamic penetration method in Sweden is soil-rock sounding. During soil-rock sounding, a metal rod is drilled into the ground and measurements are taken of depth, drilling resistance, sinking speed, feeding force, hammer pressure, and rotational speed and pressure. The method is conducted in different classes with varying accuracies. Soil-rock sounding is mainly used to determine depth to bedrock, but as the drilling rod penetrates the whole soil layer profile, there may be opportunities to gain more knowledge about the penetrated material using the same process.

The scope of this licentiate research project was to investigate whether vibration measurements on the ground surface performed simultaneously with soil-rock sounding can yield additional information about the soil layer profile and the thin layers within a material. Measurements were conducted in various building and infrastructure projects in eastern Sweden between Norrköping and Stockholm/Solna and the results were analyzed. It was investigated whether there is a relationship between the vibration results and soil properties as determined by other geotechnical investigation methods in the same area.

The results show that soil-rock sounding with simultaneous vibration measurements constitutes a promising extension of the conventional soil-rock sounding method which can provide additional information about the soil layer profiles at the investigation site. Furthermore, indications can be made about overall soil layer profiles. However, the vibration signals must be adjusted due to distance attenuation before results from different depths, boreholes and sites are comparable.

The different penetrated materials and their properties are correlated to the frequency content of the vibration signal. In this way, more information about the penetrated material can be gained from the vibration measurements. The results show that heterogeneities in the penetrated soil layer can clearly be seen in the vibration results and patterns in these heterogeneities identified. Furthermore, the results indicate that the vibration signals can help to distinguish silt from sand/gravelly soil and boulder from rock, and the ground water table can be seen in the frequency spectrogram for granular soils.

Keywords: ground vibrations, dynamic penetration testing, frequency, seismic test, vibration velocity, in-situ tests

Sammanfattning

Dynamiska sonderingsmetoder är vanliga geotekniska undersökningsmetoder. Den främsta anledningen till att välja dynamiska sonderingsmetoder i Sverige är när djup till berggrund, hållfasthets- och deformationsegenskaper av olika jordar, packning eller påldjup ska undersökas. Fördelen med dynamiska sonderingsmetoder är den bättre genomträngningsförmågan jämfört med statiska metoder. På så sätt är det enklare att sondera genom hårt jordmaterial eller berg.

Den mest vanliga dynamiska sonderingsmetoden i Sverige är jord-berg-sondering. Vid jord-berg-sondering används en borrstång för att sondera marken och parametrar som djup, borrmotstånd, sjunkningshastighet, matningskraft, hammartryck liksom rotationshastighet och -tryck registreras. Metoden genomförs i olika klasser med olika noggrannheter. Jord-berg-sondering används huvudsakligen för att bestämma djup till berggrund men med tanke på att metoden genomtränger hela jordlagerprofilen vid undersökningsplatsen finns det en stor möjlighet att erhålla mer information om det genomträngda materialet i samband med jord-berg-sondering.

Målet med detta forskningsprojekt var att undersöka om man kan erhålla ytterligare information om jordlagerföljden och förekomsten av tunna lager inom ett material när vibrationsmätningar på marken genomförs samtidigt som jord-berg-sondering. Mätningar genomfördes i ett flertal byggnads- och infrastrukturprojekt mellan Norrköping och Stockholm/Solna i östra Sverige och resultaten analyserades. Korrelationen mellan resultaten av vibrationsmätningarna och jordegenskaperna som utvärderades genom andra geotekniska undersökningsmetoder vid samma försöksplats.

Resultaten visar att jord-berg-sondering med parallella vibrationsmätningar utgör ett lovande tillägg till den konventionella metoden där man kan erhålla ytterligare information om jordlagerprofilen vid undersökningsplatsen. Vibrationssignalerna måste dock justeras på grund av avståndsdämpning innan resultaten från olika djup, olika borrhål och olika undersökningsplatser kan jämföras mot varandra.

De olika genomträngda materialen och deras egenskaper korreleras mot frekvensinnehållet av vibrationssignalen. På det sättet kan ytterligare information om det genomträngda materialet erhållas från vibrationsmätningarna. Resultaten visar att heterogeniteter av det genomträngda jordlagret ses tydligt i vibrationsresultaten och att olika mönster kan identifieras. Utöver det indikerar resultaten att vibrationssignalerna kan hjälpa till att skilja mellan silt och sandiga/grusiga jordar och mellan block och berg. Grundvattennivån kan identifieras i frekvensspektrogrammen för friktionsjordar.

Nyckelord: markvibrationer, dynamiska sonderingsmetoder, frekvens, seismiska försök, vibrationshastighet, in-situ-försök

Preface

The research presented in this licentiate thesis was conducted between 2019 and 2022 at the department of Civil and Architectural Engineering and the Division for Soil and Rock Mechanics at KTH Royal Institute of Technology in Stockholm, Sweden.

The experimental work was performed in projects in eastern Sweden between Norrköping and Stockholm/Solna in cooperation with the companies Tyréns Sverige AB, Gaia Survey AB, Skanska Sverige AB, Structor Geoteknik Stockholm AB and Sweco. A part of the field work was conducted by master's students Sofie Pöder and Sofie Tranblom. The work of this thesis was supervised by Professor Stefan Larsson and co-supervised by Carl Wersäll at KTH Royal Institute of Technology. I am very grateful for their support during both the good and the tough times of the thesis work. Thank you to Carl Wersäll for your quick responses and long and short Zoom meetings. K. Rainer Massarsch made significant contributions to the project with his experience and input. He sketched and developed the new method presented in this thesis and performed two pilot projects together with Carl Wersäll for the Swedish Geotechnical Society. His enthusiasm and interest in the field of soil dynamics is singular and encouraged me during my research. Mats Tingström from Geotech AB and Kent Lindgren from KeLi Mätteknik provided fantastic support in the practical development of measurement equipment and the measurement setup. A big thanks to PhD student Ida Samuelsson, who helped me to understand how soil-rock sounding is performed and analyzed. My reference group consisted of Fanny Deckner (Geomind KB), Jan Laue (Luleå Technical Univeristy), Staffan Hintze (Trafikverket), Nils Rydén (PEAB), Mats Tingström (Geotech AB), Mats Tidlund (Skanska) and Göran Pyyny (Trafikverket), who spent valuable time giving their suggestions and comments.

I am also grateful for the support I have received from my father, my favorite measurement assistant, who supported me through thick, thin, and the Swedish winter. And last but not least, Holmgren, who had to listen to a lot of random information about geotechnical engineering and endure many monologues about my research.

Stockholm, February 2022
Editha Ehrmanntraut

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List of appended papers

Paper I

Ehrmanntraut, E., Wersäll, C. 2021. Vibration measurements during soil-rock sounding – a comparison between accelerometers and geophones. Baltic-Nordic Acoustics Meeting, Oslo, Norway, 3rd-4th of May 2021.

I performed the field measurements together with Carl Wersäll. I analyzed the data and wrote the paper. Carl Wersäll supervised the work and assisted with comments on the writing. K. Rainer Massarsch and Ida Samuelsson reviewed the work and supported it with helpful comments.

Paper II

Ehrmanntraut, E., Wersäll, C., Massarsch, K.R. 2021. Soil identification by vibration measurements during dynamic penetration testing – a field study. International Conference of Geotechnical and Geophysical Site Characterization, Budapest, Hungary, 26th-29th of September 2021.

I performed most of the field measurements, except for two boreholes that were measured by master's students Sofie Pöder and Sofie Tranblom, whom I supervised. I analyzed the data and wrote the paper. K. Rainer Massarsch and Carl Wersäll helped with the report structure, supervised the work and assisted with comments on the writing.

Paper III

Ehrmanntraut, E., Wersäll, C., Massarsch, K.R. 2022. Identification of soil layers and properties by vibration measurements during dynamic penetration testing. Submitted to *Geotechnical Testing Journal*.

I performed most of the field measurements, except for one borehole that was measured by master's students Sofie Pöder and Sofie Tranblom, whom I supervised. I analyzed the data and wrote the paper. Carl Wersäll helped to analyze and choose the relevant outcomes to be presented. K. Rainer Massarsch and Carl Wersäll supervised the work and assisted with comments on the writing.

Other publications

Within the framework of this research project, I have also contributed to the following publications. However, these are not appended as part of this thesis.

Massarsch, K.R., Wersäll, C., Fellenius, B.H., Ehrmanntraut, E. 2021. Bedeutung der Frequenz für das Vibrationsrammen von Spundbohlen [Significance of the frequency during vibratory driving of sheet piles] (in German). *Bautechnik*, 98:410-422.

Ehrmanntraut, E., Massarsch, K.R., Wersäll, C. and Larsson, S. 2021. Vad berättar vibrationerna som uppstår vid Jb-sondering om undergrunden?. *Bygg & Teknik*, 1/21: 56-59.

Contents

1 Introduction

1.1 Background

Urbanization has been increasing for the past few centuries, with more and more people moving to urban areas. The bigger and denser modern cities become, the more buildings and infrastructure are required, often built on sites with complicated and complex soil-layer profiles. At these sites, it is crucial to perform a thorough geotechnical site investigation prior to the planning and building process in order to achieve sustainable constructions, and ultimately build a sustainable society. There are many different geotechnical site investigation methods, which can be divided into sampling, probing and geophysical methods. During sampling, specimens of the soil at the investigation site are taken to determine its material properties. The main disadvantages of sampling are high costs and the difficulty of collecting undisturbed samples that do not change their original properties when analyzed in the laboratory. To avoid these disadvantages, it can be beneficial to perform probing. There are many different probing methods that can be used for different material. These methods can be divided into static and dynamic methods. Static methods have a lower penetration ability than dynamic methods but yield a higher resolution in soil layers with a higher fines content. Due to Sweden's varying geology, it is often important to determine the depth to bedrock in construction projects. To be able to penetrate down to the bedrock, a dynamic probing method is usually required.

A commonly-used dynamic penetration method in Sweden is soil-rock sounding (Swedish Geotechnical Society, 2009). According the field manual of the Swedish Geotechnical Society (2013), it is mainly used to determine the depth to bedrock and the thickness of different soil layers at the investigation site. Soil-rock sounding can also be used to get an estimate of the soil layer profile, the piling capacity at the site, and the quality of the bedrock. During soil-rock sounding, a metal rod penetrates the ground using a hydraulic hammer, and parameters such as penetration resistance and sinking speed are measured and recorded. These recorded parameters are correlated empirically to the properties of the soil at the investigation site. In general, it is assumed that the higher the penetration resistance, the denser the penetrated material.

The method of soil-rock sounding is described in a method description by the Swedish Geotechnical Society (2012), including its execution, the equipment involved, and quality control of the method. This information was initially published in 1999 as a report by the Swedish Geotechnical Society and then upgraded in 2006 to a method description, which was further updated in 2012. Soil-rock sounding is a crude method that is useful for getting an understanding of the depth to bedrock and an estimate of the thickness of different soil layers, but it cannot be used to determine soil properties other than those related to stiffness. The method comes in four different classes with varying accuracies. The most common classes are Jb-2 and Jb-tot (soil-rock total sounding). During soil-rock total sounding, a static phase without flushing or hammer rotation is added with a constant rotary and sinking speed. This method is favorable when coarse soil superposes soft soil.

Since the method description on soil-rock sounding was initially published by the Swedish Geotechnical Society in 1999, the research that has been published about soil-rock sounding in Sweden was almost solely about soil-rock total sounding in particular. Wister (2010) wrote a master's thesis comparing soil-rock total sounding to other probing methods to determine geotechnical properties like friction angles and stiffness moduli. The tip resistance was evaluated from the feeding force recorded at soil-rock sounding and a comparison made between the calculated tip resistance and the one gained from CPT. When comparing these two tip resistances, a factor was retrieved to describe the correlation between them. With the help of this factor, friction angles and stiffness moduli were derived from the parameters recorded at soil-rock total sounding. Fransson (2011) studied the correlation between soil-rock sounding and column penetration test data of lime-cement columns and found that it was possible to evaluate the undrained shear strength of the lime-cement columns by analyzing the soil-rock sounding data. Larsson et al. (2018) investigated whether soil-rock-total sounding could be used for production control of lime-cement columns and compared their results to the results of the conventional column penetration test method. It was shown that the determination of the sounding rods friction level was the biggest source of error in the soil-rock-total sounding method used for lime-cement columns. Therefore, the friction of the sounding rod is to be determined when using it. Nilsson and Löfroth (2012) carried out a study investigating the correlation between the calculated tip resistance derived from the parameters recorded during soil-rock total sounding and the tip resistance at CPTu. The results indicated that an empirical relationship between the two can be found for a specific investigation site but not when comparing different sites. In an attempt to gain more information from the soil-rock total sounding results, Haugen et al. (2016) defined and evaluated three new parameters from the recorded penetration resistance force: the smoothed normalized penetration pressure, the standard deviation of the penetration force, and the gradient of the smoothed normalized penetration pressure. The correlations between these parameters and the grain size distribution were investigated and a draft was made for a possible soil classification chart containing four general soil types.

The existing research mainly investigates how to correlate the data collected during soil-rock sounding to the geotechnical properties of soil, and how to derive new parameters in order to find correlations. There is however little research into how the method of soil-rock sounding can be improved and developed further. As soil-rock sounding is such a frequently-used method that penetrates the whole soil layer profile at an investigation site, acquiring more knowledge about particular soil layers could be very cost- and time-efficient. Depending on the nature of this new knowledge, soil-rock sounding could become more cost- and time-efficient, contributing to a more sustainable society. In some cases, this new knowledge might even allow other geotechnical site investigations at the site to be skipped.

1.2 Project and thesis aim

The overall aim of the licentiate research project is to develop a new method that combines vibration measurements on the ground surface with conventional soil-rock sounding to find out whether more information about the soil layer profiles can be gained using the drilling tip as a vibration source.

Specifically, the following aims were outlined:

- Development of a new investigation method, including its measurement setup
- Investigate whether new information about the soil layer profile can be gained
- Investigate whether boulder and rock can be distinguished using the new method
- Investigate whether different types of granular soils can be distinguished using the new method

1.3 Outline of the thesis

This thesis begins with a literature review in the field of vibrations generated in connection with geotechnical field investigation methods. The literature review summarizes the literature presented in the three appended papers. The literature review also includes previous work that has been carried out in connection with this research project.

The next section presents the different evaluation parameters and evaluation methods used to compare the outcomes of the vibration measurements to soil parameters. The thesis then concludes with a summary of the results and the appended papers.

1.4 Limitations

The new method suggested here adds supplemental vibration measurements on the ground surface to the existing method of soil-rock sounding. Therefore, the new method heavily depends on the existing method of soil-rock sounding, and its limitations are mainly related to those of soil-rock sounding. To better understand the limitations of the new method, these are divided into three subcategories: method, fieldwork and evaluation process.

Soil-rock sounding is a frequently-used method regulated in a method description by the Swedish Geotechnical Society (2012). According to the Society’s field manual (2013), soil-rock sounding is used to determine the depth to bedrock and the depth of the individual soil layers at the investigation site. However, there is no national or international standard for the method, and the existing method description has not been updated since 2012. Alongside the process of updating the method description, a European standard was developed called ‘CEN/TC341/WG1 Drilling and sampling methods and groundwater measurements’. These two processes were coordinated (Swedish Geotechnical Society, 2012). Since soil-rock sounding is mainly used in the Scandinavian countries, there is little internationally-published research about this method. This is a limitation of this research project. During discussions with machine operators and suppliers, it became clear that the method is not always performed according to the method description. The execution depends on the machine operator and the interpretation of the results on the responsible consultant, even if the goal is to conduct the method as independently of the performer as possible. Some of the machine suppliers have developed software that is not capable of recording and measuring time while soil-rock sounding; the results are interpreted solely via depth. The method description does not require the time to be recorded during the process, and it is not necessary when performing soil-rock sounding alone. However, for the purposes of this research project, it was necessary to record the time in order to synchronize the penetration depth of the drilling rod with the vibration measurements.

When performing soil-rock sounding, the driving frequency of the drill is normally not recorded, which results in a limitation when analyzing the outcomes and a degree of uncertainty in the evaluation process. Some modern machines have the ability to record and control the driving frequency, which is an advantage in the evaluation process and a limitation if it is not recorded. Since the drilling rods penetrate the whole soil layer profile down to the bedrock, problems sometimes arise connected to drilling rods breaking and being lost in the ground. When these or other problems arise during the sounding process, the vibration measurements also have to be stopped, which is a limitation of the method. A further limitation is that the method cannot be used for soft soil as there are no or almost no vibrations generated when soft soil is penetrated.

There are many limitations connected to the evaluation process of soil-rock sounding. The results are often interpreted along with results from other geotechnical investigation methods. These other methods are either performed at the same borehole or in the vicinity of the borehole. In addition, individual knowledge and experiences from previous projects connected to the soil layer profiles in a certain area may be taken into account. Therefore, different companies, operators and consultants can influence the evaluation process and the outcomes of soil-rock sounding. The fewer material properties retrieved from other geotechnical site investigations at the measurement site were known with certainty, the harder it was to analyze the outcomes of the vibration measurements with a high reliability.

2 Literature review

2.1 Acoustic emissions during geotechnical investigations

The first evidence of acoustic measurements combined with geotechnical investigation methods in Sweden can be seen in photographs from 1925 in Gothenburg which are published in a report of the Swedish Geotechnical Society (2000). In the pictures (see Figure 1 as an example), weight sounding was carried out in soft clay, sand and gravel. Due to the penetration of the granular layers with the penetration tip, vibrations in the sounding rod arose. These vibrations could be recognized by touching the top of the sounding rod.

Instead of merely listening to the vibrations of the sounding rod, Lundström and Stenberg (1965) also recorded them. In 1965, they investigated a new method of determining the level to bedrock using the acoustic emissions during soil-rock drilling. The measurement device, a microphone, was lowered into a borehole onto solid rock. The sound generated from the drilling arriving at this microphone was listened to and recorded. According to the authors, this method can be used to distinguish boulder from bedrock. However, insufficient forms of data storage at the time restricted further development of this method.

Figure 1. Swedish weight sounding, around 1925 in Gothenburg, Sweden.

Villet et al. (1981) published the results of a research project recording the acoustic emissions generated by soil grains sliding over one another during penetration. The investigations were conducted with a cone penetrometer and a microphone mounted in the tip of the cone. Laboratory tests were performed on one sand type, and the field tests were performed at one investigation site. The study found that the amplitude of the signal increases with penetration rate and that the amplitude is larger in a dry than in a saturated sample. A similar new method was described and investigated by Massarsch (1986) combining cone penetration tests with acoustic measurements. For this method, an acoustic sensor was attached with a thin needle to the tip of the cone and the acoustic emissions when penetrating the soil were recorded. It was concluded that the results of the acoustic cone penetrometer gave consistent information about the soil stratification, and that thin layers of silt and sand can be detected using this method. A similar concept using an acoustic cone penetrometer was developed by Houlsby and Ruck (1998). A standard audio microphone was built into the tip of a conventional cone penetrometer and the signal characterized by an autoregressive model. In this case, the autoregressive model embodied that the magnitude of the measured signal at any sampling point was estimated as a weighted average of the previous samples. The authors investigated whether the density and stress level of different sand types could be characterized by the acoustic signal in laboratory tests. The evaluation was done using a neural network which is described in the paper. The results show that neural networks are tools can be used to find correlations between measurement data and soil characteristics such as the density of sand types. However, the acoustic signals of this method are not heavily dependent on stresses, and the method should therefore not be used to define stress levels (Houlsby and Ruck, 1998). Besides cone penetration testing, the method of Swedish ram sounding has been used to investigate the relationship between testing outcomes and material properties. Yamada and Oshima (2016) evaluated the correlation of the sound recorded during direct shear testing and Swedish ram sounding to the grain size properties of the tested Silica sands with various fines contents. In both cases, the sounds were recorded with a microphone. For the shear tests, the condenser microphone was directly built into the shear apparatus. For Swedish ram sounding, the microphone was embedded into the tip of the penetrometer. The observation was made that the presence of fines could be estimated by the shape of the frictional sound spectrum. Furthermore, it was observed that the frictional sound of soils without fines might be affected by the particle size of the tested medium.

2.2 Seismic while drilling

The use of the drill-bit signal of a geotechnical site investigation as a seismic source was developed into a method called ‘seismic while drilling’. For this method, the generated vibrations are measured and recorded at the ground surface. A broad study of seismic while drilling was performed by Rector (1990). Anchliya (2006) published a review of the development of seismic while drilling for the years between 1986 and 2005. Meehan et al. (1993) summarized the principles of seismic while drilling, its development and usage, and how recent research projects were rekindling interest in the method. Wang et al. (2015) proposed a new method to retrieve the drill-bit signal by an array of receivers on the ground surface in order to be able to improve the signal-to-noise ratio during seismic while drilling. Petronio and Poletto (2002), for example, were using the vibration generated by a tunnel-boring machine to estimate the geology of the surroundings where the tunnel was to be excavated. Some research has looked further into how different drill bits affect seismic while drilling. Sun et al. (2013) studied the feasibility of diamond-impregnated drill bits used for seismic while drilling. The results show that the frequency band for diamond-impregnated drill bits is usually broad with distinct peaks, but is influenced by the rig power setting and the state of the drill bit. Gradl et al. (2008) found that different drill bits can be distinguished when analyzing the frequency spectra of recordings with a microphone pointed at the bit when drilling in rock. For drag bits, drill bits that are usually designed to be used in soft material, the frequency characteristics may be related to the bit’s design.

Many research studies have been published in recent years investigating the relationship between rock properties and the sound generated when drilling in rock. In 2010, Kumar et al. attempted to use the sound as a by-product when drilling in rock to estimate rock properties for the mining industry. During field investigations, measurements were taken of the equivalent sound pressure level – the steady sound pressure level over a given time interval – generated by the drill bit when drilling in different rock types with an 8 kg weight on the drill bit. The results revealed a possibility of estimating the strength of the rock by the sound level generated during the drilling process. Govindarah and Vardhan (2011) investigated the relationship between rock properties and the sound level generated during drilling in the rock material. The focus of the research was to develop empirical models to determine the relationship. Samples of three different metamorphic rocks with a variety of different strengths were collected and the uniaxial compressive strength, P-wave velocity and dry density of the samples determined. Rock-drilling operations were performed in the laboratory at 15 mm distance from the periphery of the drill bit. The results showed that the measured rock properties were fairly close to the properties calculated from the regression model. Kumar et al. (2013) used computing techniques such as multiple regression and artificial neural networks to predict rock properties from sound levels produced when drilling. Seven different rock types were tested in the laboratory and the sound pressure level when drilling into it recorded at 1.5 m distance for different rotation speeds and penetration rates. The results from these laboratory tests were used to predict rock properties through multiple regression and artificial neural network models. The results show that the two different approaches yield similar results and are efficient to determine rock properties from measured sound levels.

Shreedharan et al. (2014) performed field experiments to test whether the sound measured when drilling in rock can provide additional information about the rock properties. The experiments were run with a rotary drill with a hydraulic feed mechanism and a microphone at 10 mm distance from the drill bit-rock interface. During drilling, parameters such as the drill-bit diameter, number of flutes on the drill bit, downward thrust on the drill, and the rotational speed of 325 rpm were constant. It was found that identification via rock class can be made by running a frequency analysis of the sounds recorded during rotary drilling. However, it was not found possible to estimate rock properties by analyzing the dominant frequency of the generated signal. In the most recent study in this field, Kumar et al. (2021) developed artificial neural networks to predict rock properties from an acoustic signal recorded while drilling in rock. Their results showed that the artificial neural networks efficiently predicted the geomechanical properties of the rock.

2.3 Ground vibrations during pile driving

Ground vibrations generated during pile driving is a related topic to ground vibrations produced during dynamic penetration testing. The pile that penetrates the soil during pile driving can be of similar shape and material as the drilling rods that are used during dynamic penetration testing; however, the most substantial similarity between soil-rock sounding and pile driving is the stress waves produced during these two processes. There have been many studies investigating vibrations generated during pile driving. Attewell and Farmer (1973) studied the attenuation behavior of vibrations generated while pile driving and suggested that for practical estimates of the attenuation, the influence of the geotechnical character of the ground can largely be ignored. A new equation to calculate the vibration level at different distances from the source was proposed by Attewell et al. (1973) and Attewell et al. (1992). Nilsson (1989) investigated the maximum vibration velocity arising during pile driving by comparing values from a literature review to the outcomes of field measurements. The author found that the highest vibration velocities arose when the piles were driven through the fill made of compacted sand. The measured values never exceeded the maximum vibration velocity calculated from empirical relationships found in the literature review. Thandavamoorthy (2004) investigated vibration levels caused by piling in fine and medium sand and concluded from the measurement results that the ground vibrations were severe compared to permissible vibration limits. A numerical model for calculating the free field vibrations due to vibratory and impact pile driving was presented by Masoumi et al. (2007). It was observed that with increasing distance from the pile, the frequency content of the ground vibrations will decrease. Khoubani and Ahmadi (2014) ran numerical studies to simulate the penetration process during pile driving by applying hammer impacts. Their results showed that the peak particle velocity can increase with the increase in pile diameter, hammer impact force, and soil-pile friction, but with a reduction of the soil elastic modulus. Cleary and Steward (2016) collected ground vibration data from three piles while pile driving and analyzed the outcomes via different approaches using the horizontal distance, the scaled distance whereby the horizontal distance is divided by the square root of the input energy, and the seismic distance between the source and the receiver. They found that the soil attenuation coefficients for the horizontal and scaled distance were the same, while the soil attenuation coefficient for the seismic distance was larger. It was concluded that the scaled distance and seismic distance methods required more effort for the analysis, but were more beneficial than the horizontal distance approach. Farmani et al. (2016) ran a case study using impact piling as a seismic source to produce seismic images of the soil layer profile. They proved a high signal repeatability of measured hammer impacts for the same depth of the pile tip and a sufficient signal-to-noise ratio after signal processing at far offsets. Deckner et al. (2017) studied the wave patterns in the ground in order to gain a better understanding of the particle motion during vibratory sheet pile driving. They concluded that the wave patterns of measurements performed at the ground surface had an elliptical shape resembling the wave patterns of Rayleigh waves, while the wave patterns of the measurements at depth were strongly polarized in diverse directions. This indicates the presence of P- or S-waves.

2.4 Vibration measurements during soil-rock sounding

A new method was proposed in 2016 combining conventional geotechnical site investigation methods with vibration measurements on the ground surface. The outcomes of the pilot projects on the method called acoustic soil-rock sounding were published in two reports by the Swedish Geotechnical Society in 2016 and 2017 and summarized in a conference paper by Massarsch and Wersäll (2017). These studies are the groundwork for the research presented in this thesis. For the developed method, the drilling tip in soil-rock sounding is used as a vibration source and the generated vibrations are recorded using geophones on the ground surface. The vibration measurements were synchronized with the drilling depth measurements. Different lateral distances between receiver and borehole were investigated, and it was found that a distance of 4 m from the borehole yielded consistent results. The evaluated vibration parameters were the peak vibration velocity, the vibration time signal, the frequency spectra of the signals, and the spectrogram showing frequency, depth, and frequency content. The vibration velocity increases when hard materials are penetrated, while in very soft material, very low vibrations are produced. In granular soils, a broad frequency spectrum is generated. In particular, the frequency content of the vibration data seems to be a useful indicator for the material properties.

The method was further developed in a master's thesis by Kalm (2019) that contained a field study at one site where acoustic soil-rock sounding was performed at 13 boreholes. The results of the vibration signals analyzed in the domains of both time and frequency showed that there was great potential to discover additional soil layers in clay layers from the vibration results. Furthermore, it was concluded that geophones ought to be fastened in the ground to produce satisfactory results. The following year, a master's thesis by Pöder and Tranblom (2020) investigated whether vibration measurements in connection with acoustic soil-rock sounding could be performed with the receiver mounted on asphalt. In an urban environment, layers of asphalt are common at potential geotechnical investigation sites, and it is therefore crucial for the development of the new method that it is able to be performed on asphalt. A field study was carried out on eight boreholes. At each borehole, at least one receiver was mounted on asphalt and one on soil. Equivalent results were achieved from the measurements on asphalt and on soil. Therefore, it was concluded that measurements on asphalt are suitable, as they do not substantially affect the vibration signal.

2.5 Summary

Already in the early 20th century, researchers utilized and investigated the relationship between geotechnical investigations and sound and vibrations arising during these investigations. In the beginning, the main restriction to such work was insufficient methods of storing and evaluating the data. The more advanced data storage techniques became, the more research on this topic was published. Studies have looked at seismic measurements while drilling to use the drilling equipment as a vibration source. However, most studies published are either related to the method of CPT, were used to determine rock properties for the mining industry, or investigated the vibrations generated during pile driving. Most developed seismic methods are complex and time-consuming. There is a lack of a practical and economical vibration measurement method that can be used in construction projects to correlate geotechnical properties to recorded vibration parameters.

3 Experimental methods and procedures

The overall aim of this licentiate research project is to develop and improve a new method combining vibration measurements on the ground surface with conventional soil-rock sounding with the aim of collecting more information about soil layer profiles and soil properties at the measurement site. This chapter presents and describes the experimental methods and procedures that were used within the scope of this study.

3.1 Soil-rock sounding

Soil-rock sounding is a common geotechnical site investigation method in Sweden and is described in a method description by the Swedish Geotechnical Society from 2012. During soil-rock sounding, a hydraulic drilling rig is used to penetrate the ground with a drilling rod. Every two meters, the drilling rod is spliced. According to the method description, the drilling rig should have a weight of at least 2000 kg, a compressive force of 50 kN, a traction force of 80 kN, a torque of 2200 Nm and a rotational speed of at least 80 rpm. Furthermore, the impact energy of the hammer should be at least 2200 J. As a flushing medium, water or air is used depending on the desired accuracy of the method. Water flushing reduces friction along the rod and drill bit. The drilling rig's driving frequency is dependent on the hammer model, the oil flow of the hammer, and the gas pressure in the accumulator. Typically, it is around 1400-1500 rpm (between 23-25 Hz) but can be up to 1900 rpm (32 Hz). Depending on the chosen sounding class, a number of drilling parameters are recorded, such as depth, drilling resistance, rate of penetration, feeding force, rate of revolutions, hammer pressure and rotational pressure.

3.2 Soil-rock sounding with vibration measurements

During soil-rock sounding with simultaneous vibration measurements, a vibration sensor, a data acquisition system, a car battery and a computer are added to the conventional soil-rock sounding equipment, which includes the drilling rig, drilling rods and sounding computer. The setup can be seen in Figure 2-Figure 4. The data acquisition system is connected to the computer on the drilling rig used for soil-rock sounding in order to synchronize the measurement time with the depth of the drilling tip. Other than this, the measurement setup for taking the vibration measurements does not disturb or affect the performance of soil-rock sounding. For most of the measurements performed, the vibration sensor was mounted on a steel plate with a weight of 2 kg which was positioned on the ground surface at a lateral distance of 4 m from the borehole.

Figure 2. Measurement setup of soil-rock sounding (background) in combination with vibration measurements (foreground).

Figure 3. Vertical and horizontal vibration sensors mounted on a steel plate.

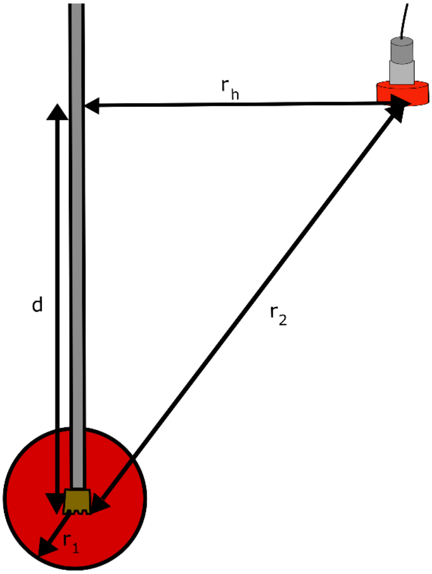

Figure 4. Geometric setup of soil-rock sounding in combination with vibration measurements.

Table 1. Parameters acquired from the sounding and measurement process.

Parameter	**Acquired from**	**Obtained from**
Penetration depth (m)	Soil-rock sounding synchronized with vibration measurements	Recorded
Feeding force (kN)	Soil-rock sounding	Recorded
Penetration resistance (s/0.2m)	Soil-rock sounding	Time (s), penetration depth (m)
Vibration velocity (mm/s)	Soil-rock sounding with vibration measurements	Recorded
Frequency (Hz)	Soil-rock sounding with vibration measurements	Fast Fourier Transform of the vibration velocity (mm/s)

During soil-rock sounding with vibration measurements, several parameters are recorded electronically such as time (s), penetration depth (m), feeding force (kN), hydraulic pressure (MPa) and rotation speed of the drill (rpm) as well as vibration velocity (mm/s). Relevant parameters for the analysis are evaluated based on empirical relations of the recorded data and the required parameters. Field observations during soil-rock sounding as well as the recorded data are usually used to estimate soil stratification and depth to bedrock. Table 1 presents a list of the parameters acquired from the sounding and measurement process.

3.3 Wave propagation and distance attenuation

When dynamic forces are induced into the ground, stresses arise which cause ground vibrations. Ground vibrations are stress waves spread from the source into its surroundings. The kind of stress wave that is produced depends on the direction, size and frequency of the vibration source. How the stress waves spread depends on the properties of the surrounding material as well as the source geometry. Different soil layers with different stiffnesses and geometries cause reflection and refraction of the stress waves. Furthermore, the amplitude of the stress waves decreases with the distance travelled.

The further the distance between a vibration source and the receiver, the smaller the recorded signal will be. This attenuation is caused by geometric and material damping. To get an estimate of the vibration velocities arising at the vibration source, wave attenuation adjustment compensating for the damping can be used. For a point source in an elastic, homogeneous full space, the attenuation adjustment can be described by the following equation:

$$\frac{v_2}{v_1} = \left(\frac{r_2}{r_1}\right)^{-\mathrm{n}} e^{-\alpha(r_2-r_1)} \tag{1}$$

with v_1 and v_2 as the vibration amplitudes at distances r_1 and r_2 and n as the exponent that defines the wave type. For body waves in full space, this exponent n is 1.0. Material damping is taken into consideration by the absorption coefficient α,

$$\alpha = \frac{2\pi\, D\, f}{\mathrm{c}} \tag{2}$$

with D as the material damping ratio, f as the vibration frequency, and c as the wave propagation speed of the wave. According to Massarsch et al. (2000), for elastic wave propagation, the material damping ratio D is usually in the interval of 3 % to 6 %.

This research project investigated several different ways of adjusting the measured data to wave attenuation. The vibration source is the tip of the drilling rod during soil-rock sounding. Throughout the penetration process of the soil layers, the vibration source will move further and further away from the receiver on the ground surface. To achieve vibration data as independently as possible of the increasing distance between the source and the receiver, the measured vibration signals should therefore be adjusted.

3.4 Frequency analysis

In order to retrieve different parameters for the evaluation of the characteristics of the penetrated material, different concepts are used and new parameters defined. At the measurement site, the vibration velocities are measured and recorded over penetration time. Within the same process, the penetration depth and penetration time are synchronized. To transfer the recorded signal from the domain of time to that of frequency, a Fast Fourier Transform (FFT) algorithm is used. The Fast Fourier Transform algorithm generates a frequency spectrum for a selected time/depth interval; in this case the chosen time interval was 2 seconds. The Fourier transform of the function $f(t)$ is the function $F(\omega)$ according to the following equation:

$$F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-i\omega t}\, dt$$

with $\omega = 2\pi f$ as the angular frequency of the frequency f.

The running root means square value (RMS value) of the vibration velocity and frequency spectrum is derived as a function of depth. The RMS value of the vibration velocity is directly related to the vibration profile's energy content:

$$v_{rms} = \sqrt{\frac{1}{T} \int_{t_1}^{t_2} v(t)^2\, dt}$$

with v as the vibration velocity and T as the time interval of the vibration signal.

A spectrogram is a powerful tool that is frequently used for the frequency analysis of vibration data. It takes several FFTs and adds them up to show how the frequency changes with time or depth. The spectrogram usually shows the variation of the vibration frequency and velocity over time. However, in this project, the spectrogram is presented over penetration depth instead of time. It is presented with frequency on the horizontal axis, penetration depth on the vertical axis, and the vibration velocity as a third dimension in colors. The brighter the color of the spectrogram, the higher the vibration velocity at the particular depth and frequency.

When analyzing the frequency spectra of different investigation sites or material properties at different depths from the ground surface, it seems to be fundamental to consider how the signals differ in frequency peaks and the distribution of the frequency content. In this research project, it was found that one property seems to differ fundamentally between different soil types, which is the shape of the frequency spectrum around the driving frequency. Massarsch and Wersäll (2017) showed that the frequency content is concentrated as a distinct peak around the driving frequency (the drilling frequency of the hammer) in rock. Therefore, the parameter of spectral concentration was introduced in an attempt to describe this behavior. The spectral concentration was defined as the spectral amplitude at the driving frequency divided by the overall vibration velocity as an RMS value over time at a certain depth interval (see Figure 5).

Another parameter that was defined to attempt to capture the behavior of the frequency content is the overtone ratio, the ratio between the spectral density at the first overtone (the driving frequency multiplied by two) and the spectral density at the driving frequency. This is an approach commonly applied in soil compaction, through the so-called compaction meter value (CMV), where the ratio has been correlated to stiffness properties of the soil (Forssblad, 1980; Thurner and Sandström, 1980).

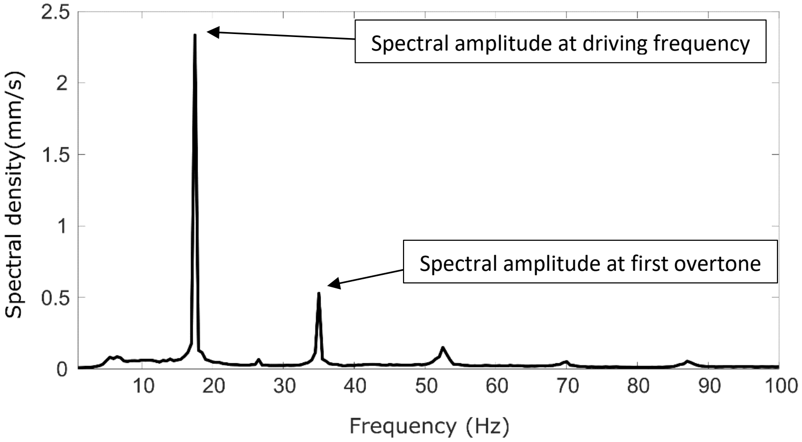

Figure 5. Typical frequency spectrum showing the spectral amplitude at the driving frequency and its first overtone.

4 Results

During this licentiate project, soil-rock sounding with simultaneous vibration measurements was conducted at 37 boreholes in six different building and infrastructure projects in eastern Sweden. In the first part of this chapter, the results of the three appended papers are summarized. In the second part, results influencing the development of the measurement setup are presented which were not published in any of the three appended papers. In addition, some supplemental investigation outcomes are presented.

4.1 Summary of appended papers

4.1.1 Analysis of frequency content

All three appended papers present results that show that the frequency content of the vibration signal measured during soil-rock sounding in the low frequency range between 0-50 Hz gives information about the penetrated material. Spectrograms are a useful tool for investigating this frequency content in order to identify soil layers, boulders or rock. By analyzing the frequency content of the vibration signal, additional information about the penetrated material can be collected compared to the soil-rock sounding alone.

To provide an overall understanding of the results of the appended papers, the outcomes from soil-rock sounding with additional vibration measurements for borehole 1 are presented in Figure 6. Furthest on the left, the estimated soil layer profile gained from soil-rock sounding can be seen, consisting of 2.7 m of fill, underlain by 8.6 m of clay, followed by 2.2 m of non-cohesive soil until bedrock is reached at a depth of 13.5 m. Looking at the penetration resistance in the middle of Figure 6, the transition between non-cohesive soil and bedrock is clearly visible as the penetration resistance rises. In clay, the penetration resistance is very low, and in both fill and non-cohesive soil it is slightly higher and less consistent. The feeding force is rather constant around 5 kN in bedrock and less constant in all other layers. From the soil-rock sounding parameters, the difference between the fill and non-cohesive soil layer is however not clearly visible.

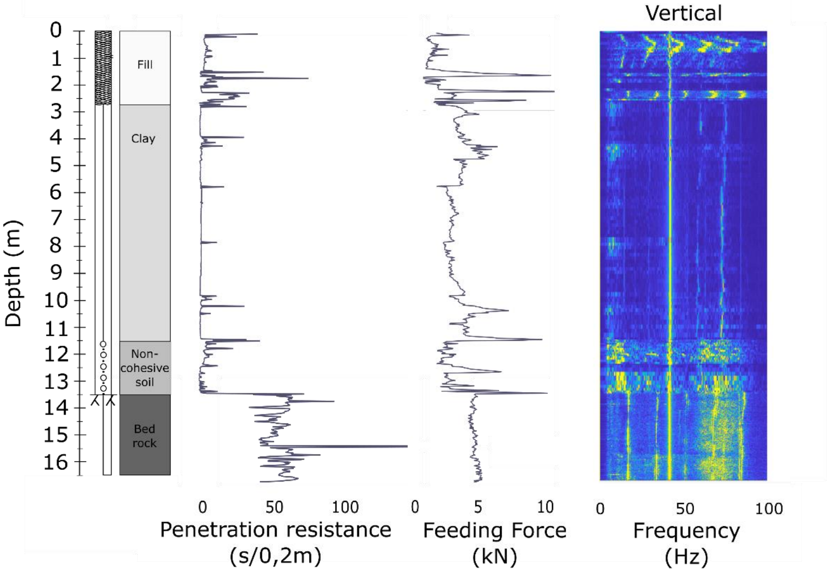

Figure 6. Borehole 1: Results from soil-rock sounding (left) and simultaneous vibration measurements (right).

Looking at the spectrogram to the right in Figure 6, clear patterns can be seen in the frequency content via depth that cannot be seen in the soil-rock sounding results only. A background disturbance at 42 Hz that likely originates from the water pump used for the flushing medium is seen throughout the whole profile. The heterogeneity of the fill is visible. At the depths where distinct frequency peaks can be seen in the spectrogram at the driving frequency and its overtones, also the penetration resistance and feeding force have peaks. In the clay layer, brighter areas are seen at certain depths in the frequency range of about 8-14 Hz. The difference in pattern between the fill layer and the non-cohesive soil (till) can be clearly seen in the spectrogram. While the fill layer mostly has frequency peaks at the driving frequency and its overtones, the till layer has broad frequency peaks from 4-15 Hz and 59-84 Hz. The bedrock layer has very distinct frequency peaks around the driving frequency of 17 Hz and its first overtone at around 34 Hz.

Borehole 1 (see Figure 6) has a soil layer profile typical for eastern Sweden and the profile can easily be interpreted from the soil-rock sounding results. However, it was shown that additional information about heterogeneities within the individual soil layers can be gained from analysis of the results of the vibration measurements. Furthermore, a clear difference between the characteristics of the fill and till layers can be seen in the spectrogram. Due to the third dimension of the spectrogram, these differences are not only shown by high or low values, but also by a distribution of vibration levels within the presented frequency range.

4.1.2 Adjustment for distance attenuation

In the three appended papers, different methods are suggested for adjusting the vibration signals for attenuation adjustment.

In Paper I, published at the Baltic Nordic Acoustics Meeting in Oslo, Norway in 2020, the vibration signals were not adjusted for distance attenuation. The results clearly show that the vibrations of the layers closest to the ground surface are the highest, while the vibration levels when penetrating the bedrock furthest down are lower. This method entails that absolute values of the vibrations of material in different boreholes are not comparable.

In Paper II, published at the International Conference of Geotechnical and Geophysical Site Characterization in Budapest, Hungary in 2021, the vibration signals were adjusted for geometric and material attenuation. As the material properties of the soil layers at the measurement site were unknown, the values for the damping ratio, the hammer frequency and the wave propagation speed were estimated. These estimations influence the calculations of the vibration signal, and the results of Paper II are therefore influenced by these assumptions.

In Paper III, only geometric damping was taken into account for the adjustment due to distance attenuation while material damping was neglected to avoid influencing the calculated vibration signal with assumptions about material properties, as suggested by Attewell and Farmer (1973). Therefore, the vibration velocity was calculated according to the following equation:

$$\frac{v_2}{v_1} = \left(\frac{r_2}{r_1}\right)^{-n} \tag{3}$$

with v_1 as the vibration amplitude at reference distance r_1 (close to the vibration source) and v_2 as the vibration amplitude at distances r_2 (at the ground surface). The exponent n is dependent on the wave type. In the case of body waves emitted from the drill bit in a full space, $n = 1.0$. With $n = 1.0$, the equation becomes:

$$v_1 = v_2 \frac{r_2}{r_1} \tag{4}$$

where $r_1 = 1\ m$. With this equation, the vibration amplitude at the reference distance is solely dependent on the measured vibration amplitude and the seismic distance between the vibration sensor and the drilling tip.

4.1.3 Geophones vs accelerometers

Paper I presents the results of field measurements in Haninge, south of Stockholm in Sweden, where vibration measurements were performed on the ground surface simultaneously with soil-rock sounding at six different boreholes. The objective was to improve the measurement setup by comparing the outcomes of the vibration measurements when accelerometers or geophones are used as a vibration sensor.

The results from two boreholes are presented in detail in the domains of both time and frequency as spectrograms. The vibration results from the accelerometer and geophone are compared to each other as well as to the conventional soil-rock sounding results.

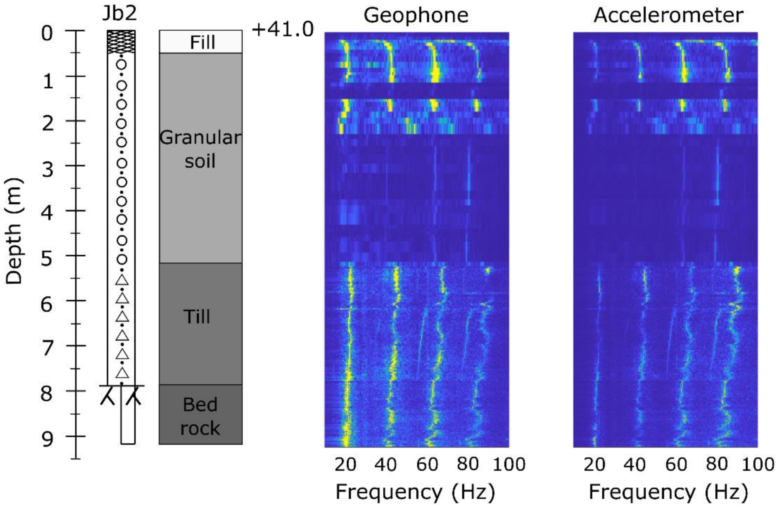

Figure 7. Comparison of the frequency spectrogram measured with a geophone and an accelerometer.

It is concluded that all measurements performed with accelerometers and geophones show similar frequency content over depth. Figure 7 presents an example of the results of the study and shows the frequency spectra derived from measurements with a geophone and with an accelerometer, respectively. Due to the fact that previous studies determined 0-50 Hz as the frequency range of interest for this method, the conference paper suggests that the measurements are performed with geophones. Based on this paper, the measurement setup for future measurements was adjusted and all measurements conducted with geophones as a receiver.

4.1.4 Boulder vs bedrock

Paper II and Paper III investigated the characteristics of boulders and bedrock in the vibration results to see whether the two materials can be distinguished from one another. Paper II presents the outcomes from two boreholes where both boulders and bedrock were penetrated. The results indicate that the dominant frequency generated during the penetration of boulders is slightly lower than that of bedrock. In addition, the peaks in the frequency spectra when penetrating boulders seem to be less distinct than for bedrock. Paper III presents the results from two boreholes containing both boulder and bedrock. In order to be able to describe the frequency characteristics and differences in the frequency content between the vibration results in boulders and in bedrock, new parameters were defined and relevant parameters identified. The parameters derived for the analysis were median depth-adjusted spectral amplitude at the driving frequency, depth-adjusted particle velocity (RMS), median overtone ratio and median spectral concentration. The results indicate that boulders and bedrock can be distinguished by looking at the adjusted spectral amplitude of the vibration signal. Furthermore, a trend in the overtone ratio is found whereby the overtone ratio of boulders was higher than for bedrock.

As an example, Figure 8 shows the frequency spectra that were determined as boulder (in red) and bedrock (in grey) via soil-rock sounding for boreholes 2 and 3. A background disturbance is seen around 52 Hz for all layers. Both boulders and bedrock have a distinct peak around the driving frequency at 31 Hz. This peak is however lower for boulders than for bedrock at both boreholes. Around the first and second overtone at around 62 and 93 Hz, the distinct peak is higher for boulders than for rock. Furthermore, the frequency peak is at a 0.5 Hz higher frequency for boulders than for rock.

From the results of Papers II and III, it is suggested that boulders and rock can be distinguished by comparing the frequency spectra. In general, it can be concluded that there is an indication that boulders and rock can be distinguished from each other by the level of the spectral density at the driving frequency. However, so far, the results are not more revealing than what can already be seen from the results of soil-rock sounding.

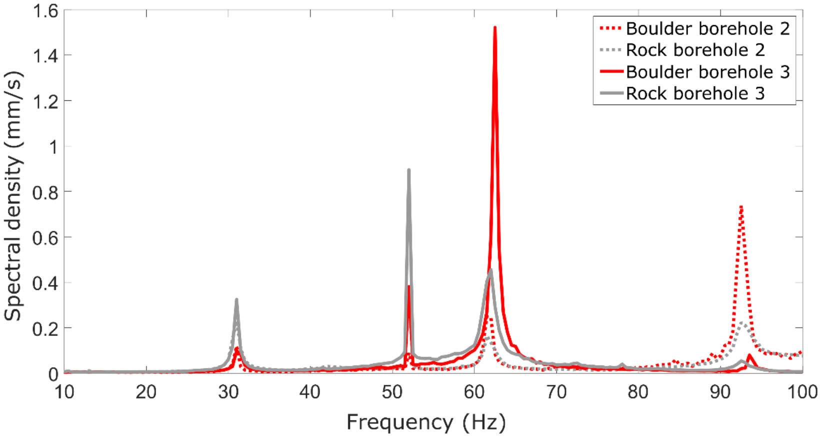

Figure 8. Borehole 2 + 3: Spectral density of rock and boulder.

4.1.5 Comparison between different granular soil types

Usually, different granular soil types are denoted as 'non-cohesive soil' in the evaluation of soil-rock sounding results. Sometimes, however, the engineer evaluating the results specifies the type of granular soil. There is no clear guidance regarding under which circumstances this further specification is used, and it is unclear which parameters are evaluated to be able to specify a particular granular soil type. It might be the case that the evaluator uses prior experience of the soil properties at different investigation sites but the amount of parameters needed to distinguish granular soil types is not defined in the Swedish method description. It would therefore be a great advantage if the vibration measurements taken during soil-rock sounding could give further information about the type of penetrated granular soil.

In Paper III, several granular soil types at five different boreholes were investigated. The results show that the frequency content of unsaturated and saturated silt as well as sand and gravelly soil has clear characteristics concerning the frequency distribution of the

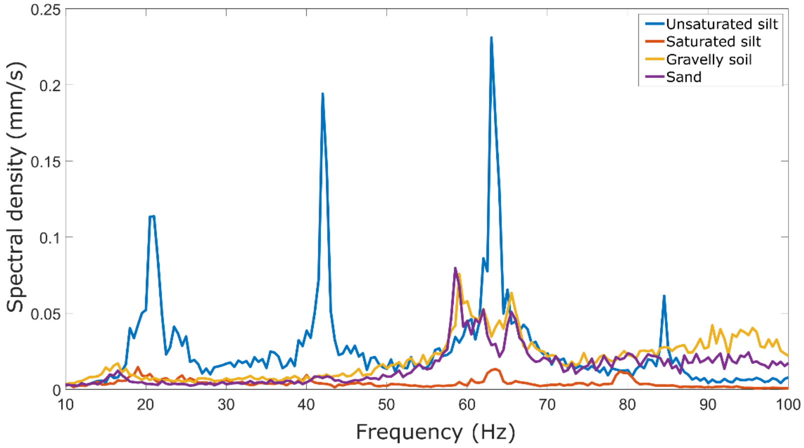

Figure 9. Typical frequency spectra of different granular soil types.

penetrated material. While the signals for unsaturated silt contain vibration energy in a broad frequency range between about 10 to 100 Hz, saturated silt has significantly lower vibration levels.

The frequency spectra of sand and of gravelly soil show the same behavior with distinct peaks at a certain frequency, lower values at the frequencies above and insignificant vibration levels below the peaks. The conclusions of Paper III state that unsaturated and saturated silt can be distinguished from each other by the analysis of the frequency content. Silt can also be distinguished from sand and gravelly soil, while sand and gravelly soil are difficult to distinguish from each other. Figure 9 shows typical frequency spectra of the aforementioned granular soil types at two different boreholes.

4.1.6 Ground water table

In a previous study, Kalm (2019) investigated whether the location of the ground water table of the clay layer could be estimated using the spectrogram of the vibration results. The final conclusion was that, from the results of the study, it was not possible to estimate the ground water table as there was no distinction seen between the saturated and non-saturated clay. From the frequency analysis of the vibration measurements presented in Paper III, it was found that the ground water table of the site can be seen in the spectrogram of the vibration measurements in granular soils, specifically in the results of vibration measurements in silt and till. This could not be seen from the soil-rock sounding results only. However, also in this study, no clear difference between the frequency content of saturated and non-saturated clay could be seen in the spectrograms. Figure 10 shows the soil-rock sounding results as well as the spectrogram of the vibration measurements for two boreholes where the transition between saturated and unsaturated soil is marked. For the left borehole, the transition between unsaturated and saturated silt is clearly seen in the spectrogram. For the right borehole, the transition between dry crust clay and clay cannot be seen in the vibration results.

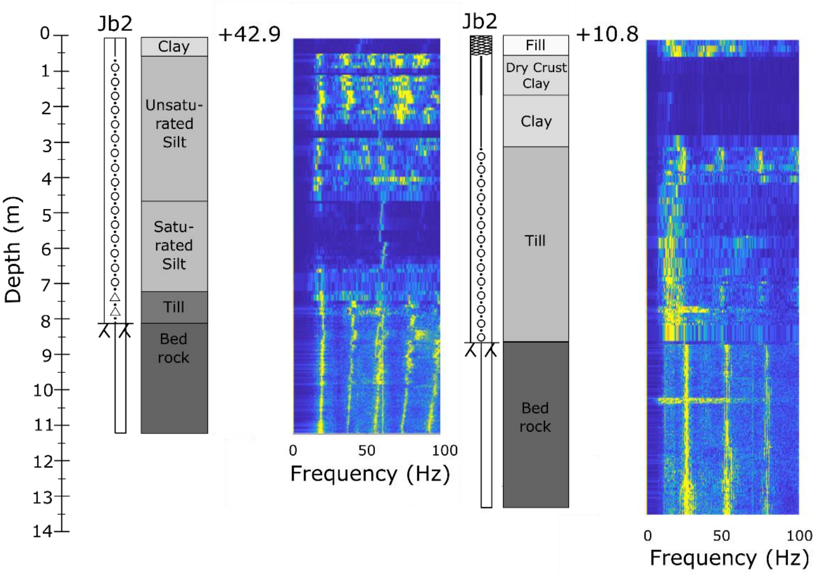

Figure 10. Soil-rock sounding and vibration results for two boreholes. The transition between unsaturated and saturated silt can clearly be seen in the left spectrogram. The transition between dry crust clay and clay cannot be seen in the spectrogram to the right.

4.2 Supplemental results

4.2.1 Mounting techniques

During the measurements at the project in Mälarbanan, north of Stockholm, three different mounting techniques for the vibration sensors were used and compared: a soil pin (length: 9 cm), a metal stake (length: 20 cm) and a steel plate (weight: 2 kg). Vibration sensors mounted with the different mounting techniques are shown in Figure 11. The practical applicability of the mounting methods and the results of the vibration measurements were compared. As the method of vibration measurements during soil-rock sounding should be time-efficient and practical, the metal plate is the preferred mounting technique, providing that its outcomes are accurate. The better the vibration sensor is attached to the ground, the more accurate results are expected. The objective was to find the most practical and convenient mounting technique with the lowest mounting time that would produce good results. The results show that all mounting techniques produce about equally good results when mounted correctly. The metal stake and the soil pin were however not always easy to install in the ground and therefore in some cases low vibration levels were recorded due to improper installation. Figure 12 shows the vibration results over time from borehole 4, where the vertical vibrations were measured with accelerometers mounted on a plate and on a metal stake.

Figure 11. The three different mounting techniques. Soil pin (left), metal stake (middle) and steel plate (right).

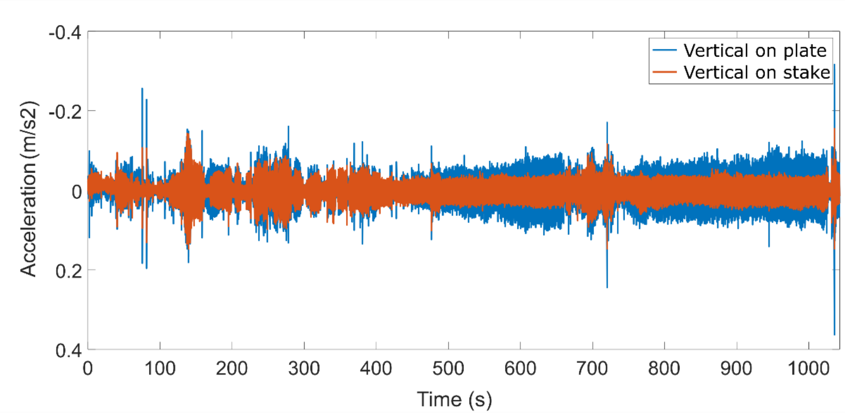

Figure 12. Borehole 4: Vertical acceleration levels for two different mounting techniques: A steel plate (blue) and a metal stake (orange).

The results show that the acceleration levels are very similar until a penetration time of around 480 seconds. From this point onwards, the acceleration levels measured by the accelerometer mounted on a metal stake are lower than for the accelerometer mounted on a plate. However, both mounting techniques still show the same trend over time.

Since the mounting technique with a metal plate was to be preferred due to its practical applicability, and since it showed similar results compared to the metal stake, it was decided to continue the measurements for this research project by mounting the vibration sensors on a metal plate. Since the ground acceleration was significantly lower than 1 g, the risk of plate-soil detachment was considered minor.

4.2.2 Background vibrations

For some of the boreholes and measurement sites, background vibrations during the measurement period were recorded by a vibration sensor. Usually, this vibration sensor was positioned at a distance of 10-15 m from the drilling rig, close to a potential background vibration source (e.g. a railway track). At some measurement sites, it was found that the pump of a water tank providing water as a flushing medium for soil-rock sounding caused background vibrations around 40-50 Hz. These vibrations were recorded at the measurement site in Loddby in the vicinity of Norrköping and can be seen in Figure 13. As the frequency of these background vibrations is steady, it can easily be accounted for during the evaluation process.

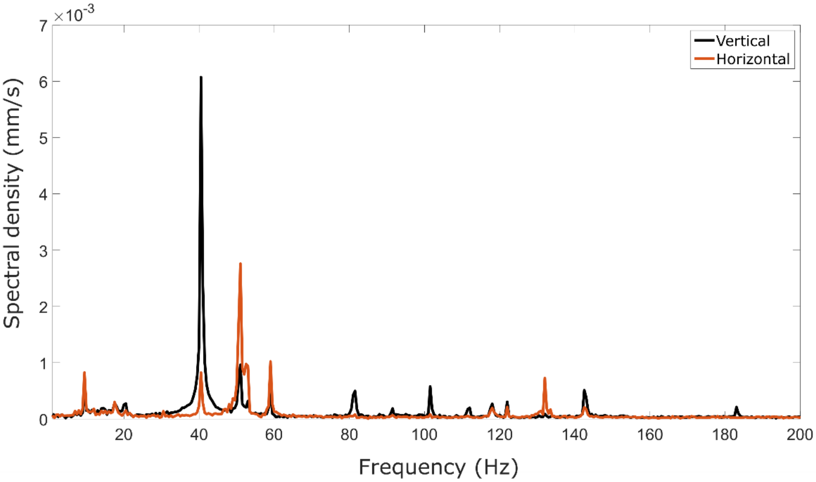

Figure 13. Background disturbances measured in Loddby.

Furthermore, the time of the background disturbances that were experienced at the measurement sites such as trains and cars passing by was noted in the measurement protocols. However, short disturbances seem not to have any major influence on the measurement results. It was concluded that the method of vibration measurement simultaneously with soil-rock sounding is not sensitive to background vibrations.

However, if there is a technical source causing steady vibrations between 0-200 Hz in the vicinity of the drilling rig, these background vibrations should be identified.

4.2.3 Comparison of Geobor-S triple tube sampling and soil-rock sounding with vibration measurements

In Loddby, in the vicinity of Norrköping, soil-rock sounding with vibration measurements and Geobor-S triple tube sampling were performed at the same borehole. The results were not published in any of the appended papers. The outcomes from soil-rock sounding with vibration measurements for borehole 2 can be seen in Figure 14. The soil-rock sounding results are shown to the left, while the spectrogram of the vibration measurements is shown to the right. According to the soil-rock sounding results, the soil layer profile at this borehole consists of about 14.4 m of upper till with a boulder between 7.5 and 7.9 m, underlain by a 10.4 m layer of lower till, until bedrock is reached at 24.8 m. Analysis of the recorded penetration resistance shows that the levels in the upper till are low and a increased levels at the depth of the boulder is clearly seen for both the penetration resistance and feeding force. For the lower till layer, the average of the penetration resistance is higher. No clear transition between the lower till layer and bedrock is visible for either the penetration resistance or the feeding force. However, the feeding force decreases to 4.5-5.0 kN at a depth of about 29.5 m.

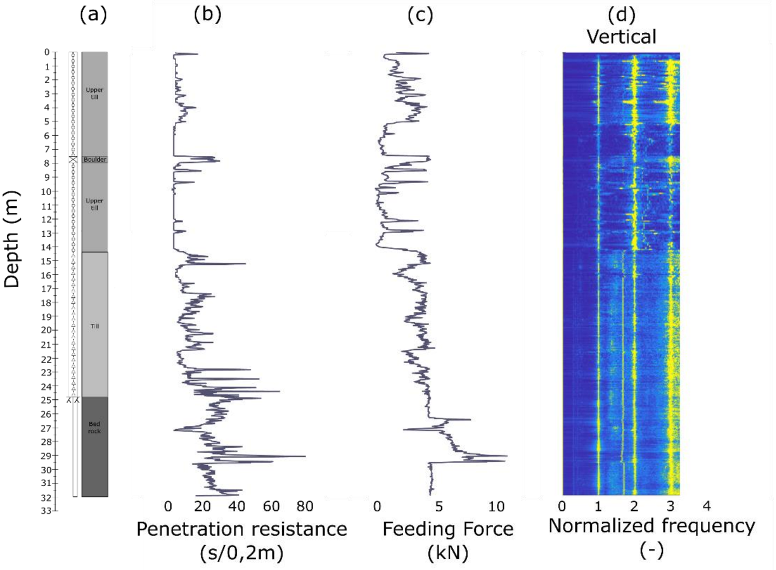

Figure 14. Borehole 2: Results from soil-rock sounding (left) and simultaneous vibration measurements (right).

As the dominating frequency varied with the feeding force, the spectrograms were normalized by dividing the frequency by the driving frequency, which varied with depth. The results of the soil-rock sounding (a, b, c) and the vibration measurements (d) are shown in Figure 14. In the spectrogram, the boulder and the transition from the upper till to the lower till are clearly visible. In the upper till, however, different patterns in frequency content are seen. There is a distinct peak at the normalized frequency of 1 and at the overtones at 2 and 3 throughout the whole soil layer profile. Starting at a depth of about 5.2 m, however, less vibration energy is seen. This observation is confirmed by the feeding force and penetration resistance which are both seen decreasing substantially at this depth. This is an indication for the groundwater table at the measurement site. According to the results of the soil-rock sounding interpreted along with the results of Geobor-S triple tube sampling, the transition between till and bedrock is at a depth of about 24.8 m. This transition is not clearly visible in the vibration spectrogram. To aid a better understanding of the transition between till and bedrock and the potential properties of the rock layer, frequency spectra, normalized by the driving frequency, as a

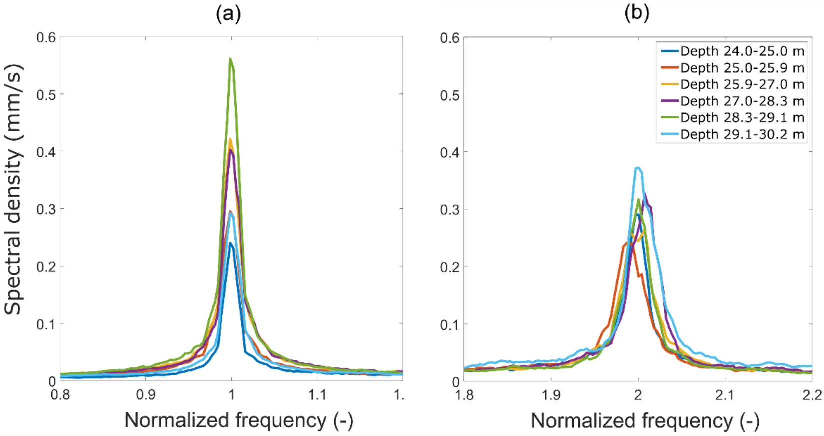

Figure 15 Frequency spectra of rock at different depths at the normalized frequencies 1 and 2.

median of about 1 m rock intervals are presented in Figure 15. When analyzing the frequency spectra in Figure 15, it is visible that all frequency spectra have similar shapes at the first normalized frequency (a). The spectral density varies and is the highest at the depth of 28.3-29.1 m and the lowest at 24.0-25.0 m.

The soil-rock sounding results indicate state that bedrock starts at a depth of 24.8 m. The frequency spectra of rock at the second normalized frequency can be seen in Figure 15 (b). The shape of the frequency spectra varies slightly and the frequency spectra at a depth of 25.0-25.9 m stands out with a lower spectral density and a broader frequency peak.

The median depth-adjusted particle velocity, RMS and spectral amplitude at the driving frequency as well as the spectral concentration and median overtone ratio are presented in Table 2. The median depth-adjusted spectral amplitude at the driving frequency increases with depth until the last meter, where it decreases substantially. The median depth-adjusted particle velocity, RMS, is rather constant for the first three meters and

Table 2. Borehole 2: Adjusted spectral amplitude and adjusted particle velocity [RMS].

	Borehole 2					
Depth	24.0-25.0 m	25.0-25.9 m	25.9-27.0 m	27.0-28.3 m	28.3-29.1 m	29.1-30.2 m
Median depth-adjusted spectral amplitude at the driving frequency (mm/s)	0.25	0.28	0.34	0.39	0.57	0.17
Median depth-adjusted particle velocity, RMS (mm/s)	3.37	3.50	3.60	4.61	4.17	4.13
Median overtone ratio (-)	1.11	1.09	0.60	1.01	0.38	0.73
Median spectral concentration (-)	0.08	0.08	0.10	0.08	0.14	0.04

increasing for the last three meters. The median overtone ratio is similar for the first 2 meters and the 4th meter, but much lower for meters 3, 5 and 6. The median spectral concentration is more or less constant until the 5th meter, where it first increases and then decreases for meter 6. An analysis of the results in Figure 15 and Table 2 reveals that the penetrated material has rather homogeneous properties at the first 2 meters and the 4th meter. No clear transition is seen between till (down to about 24.8 m) and bedrock (starting at a depth of around 24.8 m). At the 3rd, 5th and 6th meters, the results in Table 2 indicate that the bedrock is less stiff and therefore most likely has more fractures and contains more crushed rock material.

Geobor-S triple tube sampling at borehole 2 was performed throughout the whole soil layer profile as well as in almost 6 m of rock. Samples were taken from the bedrock at a depth of 25.0 – 30.7 m. According to the core mapping report published as an appendix to the Swedish Transport Administration's report (Trafikverket, 2018), about 1.3 of these 6 m were core recovery, a large part of which consisted of crushed material and sand. The remaining part of the core consisted of core loss. The beginning of the rock core contained the largest part of sand which is interpreted as weathered and crushed rock as it mainly consisted of potash feldspar. Towards the end of the core sample, clay was found to a greater degree, and the very end was completely rinsed. According to the results from Geobor-S triple tube sampling, the beginning of the rock is found at 24.95 m. For the first 1.3 m, weathered bedrock is found that is strongly affected when retrieving the triple tube samples, which is also reflected in the results of the normalized frequency spectra at the second frequency in Figure 15. From a depth of around 27 m, the triple tube sampling caused problems due to sand that got stuck between the tubes. From the results in Figure 15, at the second frequency it can be seen that the spectral density is highest from a depth of 27.0 m. The triple tube sampling had to be stopped at around 30.7 m because of troublesome drilling at that depth. The core samples achieved are shown in Figure 16 – Figure 20.

When comparing the Geobor-S triple tube sampling results to the results of soil-rock sounding with additional vibration measurements, the best correlation between the results is found using the normalized frequency spectra of the vibration signal.

Figure 16. Borehole 2: Samples from Geobor-S triple tube sampling at a depth of 24.35 – 24.95 m (modified after Trafikverket, 2018).

Figure 17. Borehole 2: Samples from Geobor-S triple tube sampling at a depth of 24.95 – 25.65 m (modified after Trafikverket, 2018).

Figure 18. Borehole 2: Samples from Geobor-S triple tube sampling at a depth of 25.65 – 26.95 m (modified after Trafikverket, 2018).

Figure 19. Borehole 2: Samples from Geobor-S triple tube sampling at a depth of 26.95 – 28.45 m (modified after Trafikverket, 2018).

Figure 20. Borehole 2: Samples from Geobor-S triple tube sampling at a depth of 28.45-30.70 m (modified after Trafikverket, 2018).

5 Discussion

The geotechnical site investigation method of soil-rock sounding is frequently performed in Sweden. Improvement of the method could reduce the time and financial costs of all kinds of construction projects where soil-rock sounding is to be performed. The discussion is divided into several sections: the method, fieldwork, evaluation process, and overall outcomes.

5.1 Method

Since the complementary vibration measurements during soil-rock sounding are easy to perform, and do not affect the conventional soil-rock sounding method, not many improvements are necessary in order for this to be a practical and valuable new method. However, the evaluation results of the vibration measurements heavily depend on the performance of soil-rock sounding. Currently, not all sounding computers are equipped to register the time during the whole sounding process, which means that a cable between the sounding and the vibration computer is needed in order to synchronize time and depth. If the function to register time during soil-rock sounding could be added to all sounding softwares, this cable could be removed, which would improve the simplicity of the method. In this case, the time recorded on the sounding and the vibration computers would need to be synchronized accurately. If the method were to be used more frequently in the future, it would be advisable to standardize it or add it to the method description of the Swedish Geotechnical Society.

5.2 Fieldwork

Since the new method of vibration measurements simultaneously with soil-rock sounding is an extension of conventional soil-rock sounding, it is largely dependent on how the conventional method is performed. Within the scope of this study, the influence of different drill bits on the vibration measurements has not been investigated. Prior research, however, shows that different drill bits can affect the outcomes of seismic while drilling (Sun et al., 2013; Gradl et al., 2008). Typical problems arising during the performance of soil-rock sounding are that spillage gets stuck within the drilling rod so that the penetration must be stopped until the spillage is removed, or that the water flushing does not work. Once penetration with the hydraulic hammer stops, no vibrations are generated and therefore no vibrations can be measured. Even if the measurements are independent of the sounding procedure, additional steps are added to the method and therefore the operator’s field of responsibility is expanded. Commonly, working environment guidelines prescribe that two operators shall be in the field during construction projects. If there are two operators in the field, additional responsibilities might not add to the total time needed for performance of soil-rock sounding, but there is a risk that problems related to the vibration measurements will make it more time-consuming. Furthermore, there is a great advantage if the operator has general expertise in the field of ground vibrations. In that case, however, higher demands are placed on the operator.

5.3 Evaluation process

The first challenge of the evaluation process of the vibration measurements was the adjustment of the data to distance attenuation. As mentioned earlier, different methods of attenuation adjustment were investigated in Papers I, II and III. The results of Paper I were not adjusted to either geometrical or material damping, which made it challenging to compare vibration levels of different boreholes to each other, especially the vibration values of boreholes with different depths. Furthermore, for very deep boreholes the relative values of different penetrated materials within the same borehole were hardly comparable. In Paper II, the vibration results were adjusted to both geometrical and estimated material damping using a reference distance of 0.1 m from the source. An important factor is that the distance between source and receiver was not the vertical distance between ground surface and the tip of the drilling rod, as is used in some research, but the actual distance between source and receiver. To estimate the material damping, several assumptions were made about the penetrated ground type and its properties; for example, the wave type and speed in the material and the damping loss factor. This adds uncertainty to the measurement results, and the outcomes are directed towards the material type that one expects for the borehole and the surroundings. Thus, the results depend on the performer’s assumptions. The influence of the assumptions made about the material type and its properties has not been investigated. In Paper III, the attenuation adjustment due to material damping was neglected and the results only adjusted for geometrical damping at a reference distance of 1 m from the source. This method adjusts the results in such a way that the vibration levels of different boreholes at different sites and with different depths are more easily compared, while not affecting the results due to anticipating the material properties of the investigated soil layer. This approach is therefore the recommended method for future investigations.

Even with the chosen attenuation adjustment method, it is difficult to compare the results from different boreholes. As the vibration levels at the investigation sites are heavily dependent on the stiffness of the penetrated material, one expects that higher vibration levels would relate to a stiffer penetrated material. However, the vibration levels can be influenced by factors like mounting technique and the material of the ground surface. A study similar in scope to this research project (Pöder and Tranblom 2020) has shown that it is possible to perform the vibration measurements on asphalt and still get similar frequency content and vibration patterns compared to measurements on soil. However, the measured vibration level is affected by the ground surface. Therefore, an attempt was made to define new parameters for the vibration measurements that are independent of the signal strength. While the driving frequency (mm/s) and the median depth-adjusted particle velocity, RMS (mm/s), depend on signal strength, the spectral concentration (-) and overtone ratio of the signal (-) do not. The latter two parameters are therefore the ones to be preferred and the parameters depending on signal strength only to be used with caution.

5.4 Soil identification

The outcomes of the vibration measurements in this study were used to provide knowledge about soil layer profiles and geotechnical properties of the penetrated material. A limitation of the method under study is that it cannot be used for soft material like clay and saturated silt, as very low vibrations are generated in these materials. During the development phase of the method, it was critical to be able to compare the outcomes of the vibration measurements to the outcomes of other geotechnical site investigation methods. The more information about the ground properties was found from other investigation methods, the more certain the ground properties were. However, it was a challenge to compare the outcomes of other site investigation methods to the results of this study. Different methods have their advantages and drawbacks, and every method has its own field of application. This makes it even harder to compare the outcomes of the different methods and gain knowledge about the penetrated materials with certainty. Even very distinct and sophisticated methods like Geobor-S triple tube sampling were difficult to evaluate for comparison to the vibration measurements.

Figure 21 shows typical frequency spectra for different material types. The rock layer has a clear frequency peak at the driving frequency at about 26 Hz, whereas both till and fill have a broad frequency spectrum. The spectral density of the clay layer is very low, as no vibrations are generated when penetrating the clay layer. The following section outlines the challenges related to the method of soil-rock sounding with vibration measurements for these different material types.

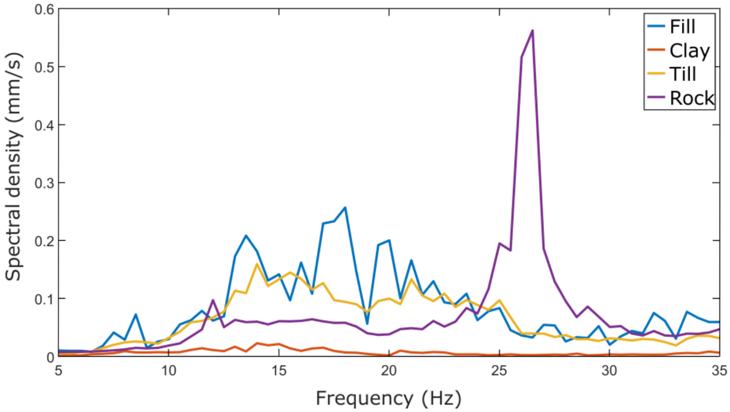

Figure 21. Typical frequency spectra of different material types.

5.4.1 Fill

A typical layer of fill can consist of various material types. It can be composed of gravel, clay and other materials and can contain remainders of plants and rubble. Fill layers are usually inhomogeneous, which is also shown clearly in the vibration analysis. The degree of inhomogeneity is reflected in the results. It is difficult to evaluate fill properties from sounding results. The outcomes and frequency content of the vibration measurements in the fill layer were not investigated thoroughly within the scope of this study.

5.4.2 Granular soil

From soil-rock sounding only, it is usually difficult to distinguish different granular materials. In the interpretation of soil-rock sounding results, these materials are often denoted as ‘non-cohesive soil’. The results of the vibration measurements during soil-rock sounding showed that it is possible to distinguish silt from other granular soil types like sand and gravelly soil. However, sand and gravelly soil showed similar vibration results and were therefore not distinguishable. It would be beneficial to look more closely into the characteristics of different granular soil materials in order to be able to correlate the vibration results to the typical properties of each material. In addition to distinguishing different granular materials, the research in this study has shown that the frequency content differs in granular material in dry or saturated state. In dry granular material, the vibration amplitude is higher than in a saturated material. This result is in line with results published by Villet et al. (1981). So far, it has not been possible to correlate any additional properties of the same granular material type by the vibration results measured during soil-rock sounding, such as stiffness or stress level.

5.4.3 Boulders

Boulders are easily recognized during soil-rock sounding once the whole boulder is penetrated. However, it is critical not to mistake a large boulder for bedrock. If the evaluation of the vibration measurements during soil-rock sounding showed that boulder and bedrock can be distinguished with certainty directly, i.e., before the bedrock is penetrated, it would not be necessary to drill between 3-5 m into the bedrock in order to tell boulder and bedrock apart. With a sinking speed of about 3-7 mm/s in rock, this could mean a reduction in drilling time per borehole of between 7-28 minutes.

During the evaluation of soil-rock sounding, boulders and bedrock can be distinguished, but only once the whole boulder is penetrated. The analysis of the vibration results indicates that it is possible to distinguish boulder from bedrock, which has also been shown in a previous study by Lundström and Stenberg (1965). However, thus far, no way has been found to clearly tell boulder from bedrock in situ where the boulder is penetrated. This means that as it stands, no verified additional information can be retrieved from the vibration measurements taken during soil-rock sounding, although there are indications that the two materials can be distinguished by the vibration measurements.

5.4.4 Till

In many construction projects, it is difficult to identify the transition between till and bedrock from soil-rock sounding. During this study, it was analyzed whether this transition could be made clear from the vibration results. As no direct clear indications were found that this could be done, there was no emphasis put on evaluating the difference between till and bedrock in this project.

5.4.5 Bedrock

Soil-rock sounding is mainly used to evaluate the depth to bedrock and is a reliable method for this purpose. Wherever the depth to bedrock is clearly detectable from soil-rock sounding, it is also clearly seen in the vibration results. Therefore, the depth to bedrock does not constitute additional knowledge to be gained from this new method. However, there were preliminary indications that the vibration results can provide additional information about the properties of the bedrock, such as the state of weathering and fractures and the stiffness of the bedrock. If reliable correlations can be made between these properties and the vibration measurements, this would be of great benefit to the proposed method. Similar outcomes have been demonstrated in studies by Kumar et al. (2010, 2013) and Govindarah and Vardhan (2011) which related the equivalent sound pressure level measured when drilling in rock to the properties of the rock.

6 Conclusions

Soil-rock sounding with simultaneous vibration measurements is a promising extension of the conventional soil-rock sounding method for increasing knowledge about the soil layer profiles at the investigation site. As soil-rock sounding is a geotechnical site investigation method that can penetrate the whole soil layer profile as well as bedrock in a relatively short amount of time, the cost of projects could be reduced if the additional vibration measurements yield additional knowledge. The number of boreholes within the scope of a project remains the same with or without vibration measurements, but the more new knowledge is produced by the vibration measurements, the fewer other geotechnical site investigations have to be performed at the same borehole. In the scope of this thesis, vibration measurements were performed at 37 boreholes in different construction projects in eastern Sweden. Using the method, overall soil layer profiles interpreted from soil-rock sounding results can be validated and confirmed.

Paper I concluded that both of the studied vibration sensors – geophones and accelerometers – show similar results. Geophones produce more accurate results in the low frequency range between 0-50 Hz, whereas accelerometers show better results over 50 Hz. As the main frequency range of interest was around the driving frequency, which is around 15-31 Hz, it is an advantage to use geophones for the vibration measurements.

The results of Paper II indicate that different granular soils, till or boulders can be distinguished by the frequency content of the vibration signal. While sand has a wide distribution, more distinct peaks appear in glacial till. Furthermore, the results indicate that boulders and rock can be distinguished from each other and that vibration signal attenuation adjustment can be a useful tool to obtain signals that reflect the characteristics of the penetrated material.

Paper III introduces two new evaluation parameters for the vibration analysis, spectral concentration and overtone ratio, and shows that these parameters are a valuable aid for distinguishing different materials and material properties from each other (see Table 2). Furthermore, the paper shows that vibration measurements during soil-rock sounding can identify the depth to the ground water table in granular soils, and indications can be made that silt and sand/gravelly soil as well as boulders and bedrock can be distinguished from each other.

In conclusion, the study and the results of the three appended papers demonstrate the following:

- The amplitude of the measured vibration signal increases with the stiffness of the penetrated material.
- The amplitude of the measured vibration signal decreases with source-receiver distance and therefore with drilling depth. Therefore, attenuation adjustment should be applied to the vibration signal to be able to compare the vibration measurements of different materials and different boreholes.
- The results of the analysis of the vibration signal’s frequency content in the low frequency range can be correlated to different penetrated materials, and additional information about the soil layer stratification can be gained that cannot be gained from soil-rock sounding only.
- A spectrogram is a useful tool for presenting an overview of the soil layer profile at the borehole.
- The frequency spectra of granular soil have a wide distribution, while the spectral density is concentrated around the driving frequency and its overtones in till and rock.

6.1 Suggestions for improving soil-rock sounding

The main aim of this research project was the development of a new measurement method where the vibrations generated from soil-rock sounding were recorded in order to gain more information about the penetrated ground. During this study, several observations were made about the geotechnical investigation method of soil-rock sounding.

The Swedish Geotechnical Society offers two-day courses in soil-rock sounding and its practical use. At the present time, the method description of the Swedish Geotechnical Society (2012) is not followed strictly by machine operators performing the method. This is not because operators in general are not aware of the description of the method set out in the guidance document, but rather that not all of the relevant guidelines are practically applicable. It would be a great advantage if the Swedish Geotechnical Society and the operators in the industry would contribute to keeping the method description updated regularly.

One way of improving the method of vibration measurement in combination with soil-rock sounding would be if the driving frequency of the hammer could be continuously measured and recorded by the sounding computer. Furthermore, some machine suppliers use a computer software for soil-rock sounding that registers the parameters of depth and time during the penetration process, whereas others only register the depth of the drilling tip. To further develop the method of soil-rock sounding in parallel with vibration measurements, it would be beneficial for all machines and their associated softwares to be able to register time as a parameter at all times. In that case, the cable between the vibration and the soil-rock sounding computer could be discarded.

An area of the guidance document that would be advantageous to update is the coordination of the evaluation of the soil-rock sounding results with results from other geotechnical site investigation methods. During the evaluation process that follows the fieldwork, the evaluator is usually analyzing the soil-rock sounding results along with the results from other investigation methods. If only soil-rock sounding is performed at the borehole, the evaluation results will commonly show a general estimated soil layer profile, with granular soil and till denoted by the broad term ‘non-cohesive soil’. When other geotechnical investigations are conducted at the same borehole or in the vicinity of the borehole, this term is often specified. As an example, an addition to the method description could be made about when ‘granular soil’ should be denoted as ‘granular soil’ in the results and when further distinctions like ‘sand’, ‘gravel’, ‘silt’ or ‘gravelly soil’ are allowed. For instance, the guidance document could set levels of various parameters for denoting the soil as a certain material.

Furthermore, it would be beneficial to state in the analysis of the sounding results whether solely the soil-rock sounding parameters were used for the evaluation and determination of soil layer profiles and soil properties or whether other geotechnical site investigation methods were taken into account for the evaluation. It would then be easier to follow prior geotechnical investigations and use the outcomes in other projects.

6.2 Suggestions for future work

Even if the developed method was not as easy to analyze and evaluate as expected, it still shows promise as a method of gaining more knowledge about soil properties and soil layers while soil-rock sounding. Based on the work of this research project, the following topics are suggested for further and future research:

- The method should be further investigated for simultaneous use with other dynamic geotechnical site investigation methods such as Swedish ram sounding.
- The method of soil-rock sounding should be adjusted to reflect its practical implementation, first and foremost by regularly updating the method description of the Swedish Geotechnical Society and including the industry in the process to achieve a practically applicable method description.
- The influence of different drill bits on the recorded vibration signal should be investigated.
- More data on vibration measurements taken simultaneously with soil-rock sounding would be beneficial. In particular, there is a need for more data on boulders, rock and different types of granular soil in order to be able relate vibration results to material properties with certainty.
- More vibration data showing the difference between boulder and rock should be evaluated.
- More vibration data showing the transition between till and bedrock should be evaluated.
- It should be investigated whether more correlations can be found between the vibration signals and the geotechnical properties of the penetrated material by

comparing to other geotechnical investigation methods. In particular, to identify properties and further characteristics of boulders, granular materials, till and bedrock should be aimed for.

- An investigation of whether new parameters can be defined to correlate the vibration results and the geotechnical properties should be conducted.
- A soil characterization chart for evaluation of soil-rock sounding with simultaneous vibration measurements should be developed.

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