Soil identification by vibration measurements during dynamic penetration testing – a field study

Editha Ehrmanntraut
Division of Soil and Rock Mechanics, KTH Royal Institute of Technology, Stockholm, Sweden, edithae@kth.se

Carl Wersäll
Division of Soil and Rock Mechanics, KTH Royal Institute of Technology, Stockholm, Sweden, cwersall@kth.se

K. Rainer Massarsch
Geo Risk and Vibration Scandinavia AB, Bromma, Sweden, rainer.massarsch@georisk.se

ABSTRACT: The identification of soil and rock in connection with dynamic penetration tests of hard soils, boulders and rock often requires the retrieval of samples. The process is, however, time-consuming and expensive. A more efficient and cheaper dynamic penetration test for the investigation of dense and hard soils or rock is soil-rock sounding. Only limited information of the soil and its properties is retrieved by this method. For soil-rock sounding a percussion drill is operated in a frequency range between 15 and 30 Hz. During penetration, the impacting drill generates continuous vibrations, which propagate as waves to the ground surface.

This paper describes a new concept, called Jb-Vib, where the vibrations generated by this impacting drill are measured at the ground surface. The objective is to evaluate whether additional quantitative information can be gained which describes the properties of the penetrated material. The vertical and horizontal components of the vibration velocity are recorded with vibration sensors from which the variation of vibration amplitude and the frequency content with depth can be determined. The RMS-value of the vibration velocity and the frequency spectrum can be derived as a function of depth. Furthermore the effect of geometric damping - the decrease of vibration amplitude with distance – can be accounted for. Prior studies suggest that an important parameter, which can help to identify the type of penetrated material, is the frequency content of the signal. Spectrograms can be used to present the variation of frequency and signal intensity as a function of depth. It is shown that the frequency content reflects the material which is penetrated by the impacting drill.

Keywords: ground vibrations; in-situ tests; dynamic penetration test; vibration velocity; frequency

1. Introduction

One of the most common geotechnical site investigation methods in Sweden for the investigation of hard soils as well as rock is soil-rock sounding. Its purpose is to identify soil stratification, existence of boulders and depth to bedrock. A hydraulic percussion drill is used for this method. The drilling rod penetrates the soil layers and different drilling parameters, such as depth, penetration speed, torque and applied force, are recorded by an electronic measurement unit. From an interpretation of the measured parameters, different soil layers, boulders and rock can be identified [1]. An important advantage of soil-rock sounding is that hard or stiff layers and boulders can be penetrated and the depth to bedrock and stratification in rock can be determined. It is an effective method in soil and rock formations which cannot be investigated by other in-situ tests. Limitations of the method are that only approximate knowledge about soil properties can be gained.

In the present study, a new concept of soil-rock sounding is being developed: dynamic soil-rock testing with supplementary vibration measurements (Jb-Vib). Jb-Vib measures the ground vibrations generated by the impacting drill to gain additional information about the penetrated material. It can be conducted independent of the drilling process. The main purpose is to obtain additional quantitative parameters which can provide knowledge about the properties of the penetrated material.

Probably the earliest acoustic measurements in connection with penetration tests were carried out around 1925 in Gothenburg, Sweden. The vibrations generated during weight sounding when penetrating granular layers were determined by touching the top of the sounding rod [2]. Several efforts have since been made to use vibration measurements for soil and rock characterization and the determination of depth to bedrock. In 1965, Lundström and Stenberg measured the sound generated from soil-rock drilling by a microphone installed at the bottom of a borehole that was drilled into bedrock [3]. The results showed that boulders, layers of till and bedrock could be identified by the sound level generated during drilling. The method was considered more reliable than conventional soil-rock drilling. The restrictions of the method, however, were the limitations of digital data recording, storing and processing at that time. Different types of acoustic vibration measurements have since been developed in connection with static penetration tests [2]. Studies have found that acoustic properties are related to the grain size distribution [4] and that acoustic emission during CPT sounding is related to soil type [5]. Many authors have studied vibrations generated during similar loading conditions, such as pile driving, e.g. [6-10]. However, no studies on vibrations from soil-rock sounding have been published to the best of the authors' knowledge.

Two pre-studies of the Jb-Vib method from four different sites with varying soil conditions were conducted [11, 12]. The vibrations generated by the drill bit were recorded at the ground surface by tri-axial geophones and accelerometers and the signal amplitude and frequency content were analyzed. In the first stage, the sensors were placed at 1, 2, 4, 8 and 12 m distance from the bore hole. The results showed that the frequency content of the measurements reflected the soil stratification and depth to bedrock. At this stage the vibration measurements had to be manually correlated with the depth of the drilling tip. During the second stage, vibration measurements at two different sites close to Stockholm were performed at a distance of four meters from the bore hole [12]. During these tests, the vibration measurements were directly synchronized with the drilling depth. Results of these measurements showed that the frequency content of the vibration signal could be correlated to the penetrated material. The outcome of the two investigations were further analysed and summarized in [13]. It was concluded that very low vibration levels are generated when penetrating very soft soils (clay and silt) while the levels increased significantly in granular soil layers (sand and gravel) where a broad frequency spectrum was obtained. When penetrating into rock, the vibration velocity increased markedly and the dominant frequency of the spectrum corresponded to the vibration frequency of the percussion drill. In a subsequent study, it was found that either geophones or accelerometers are suitable for measuring vibrations from soil-rock sounding but that geophones are more practical [14].

In this paper, results from a field study are presented. Jb-Vib was conducted in connection to conventional soil-rock sounding and other geotechnical investigations. The signal amplitude and frequency content of the vibration measurements are analysed in order to identify soil and rock layers.

2. Method

Soil-rock sounding is standardized and described in a guidance document by the Swedish Geotechnical Society [15]. Different execution alternatives ("classes") are available. The most common class is Jb-2 where the drilling parameters depth, penetration resistance, rate of penetration, force input, rate of revolutions, hammer pressure and rotational pressure, are recorded. Either air or water can be used as a flushing medium. Fig. 1 shows the equipment used for soil-rock sounding. The drilling rig can apply a static force of 50 kN, a pushing force of 80 kN and a torque of 2200 Nm. The impact frequency of the hydraulic hammer is typically 1400-1500 rpm (23-25 Hz) but can reach up to 1900 rpm (32 Hz). Every two meters the drilling rods are spliced.

Figure 1. Drilling rig with hydraulic hammer

2.1. Wave attenuation

The vibration amplitude of the measured signal decreases with increasing depth due to geometric and material damping. This wave attenuation effect can be compensated approximately as described below [16]. It can be assumed that the drilling tip is a point source in an elastic, homogeneous half-space. Fig. 2 shows the geometry of the vibration measurements. The vibration sensor is placed at a lateral distance (r_h) from the bore hole, which is 4 m in the present study. The reference distance from the source (r_1) was arbitrarily chosen as 0.1 m. During penetration the distance from the source to the sensor (r_2) increases, resulting in an attenuation of the vibration amplitude. In addition to the effect of geometric damping, energy is absorbed due to material damping.

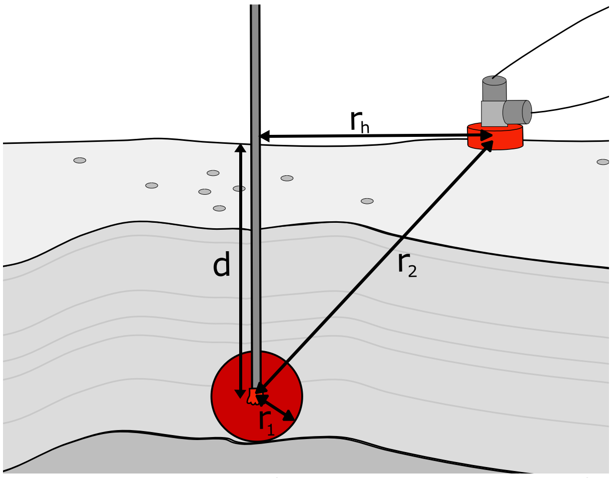

Figure 2. Geometrical setup of the vibration measurements and definition of parameters used in Eq. (1)

The attenuation of elastic waves inside a full space can be described by the following relationship

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

where v_1 and v_2 are the vibration amplitudes at distances r_1 and r_2, respectively, the exponent *n* defines the wave type. For body waves in a full space the exponent *n* is 1.0. Material damping is taken into account by the absorption coefficient α,

$$\alpha = \frac{2\pi\, D\, f}{c_{p/s}} \quad (2)$$

where *D* is the material damping ratio, *f* is the vibration frequency and $c_{P/S}$ is the wave propagation speed of the body wave (P- or S-wave) [16]. In the case of elastic wave propagation, the material damping ratio *D* normally ranges between 3 % and 6 %. In this study, the ratio $D = 4\%$ has been assumed. The hammer frequency is typically in the range of 15-30 Hz. For the calculation of geometric damping an average frequency of $f = 20\ Hz$ is applied. Since drilling is mainly conducted below the ground water level, an average wave propagation speed of $c_P \approx 1450\ m/s$ is assumed, corresponding to the P-wave speed in saturated soils. Eq. (1) has been shown to accurately estimate the geometric attenuation from various vibration sources in the field, such as pile driving [17].

2.1.1. Estimation of vibration velocity at source in full space

During soil-rock sounding, the vibration velocity, v_2, is measured at the ground surface. The distance from the geophone to the vibration source, r_2, is known and the magnitude of the vibration velocity in the vicinity of the source can be estimated using Eq. (1). For engineering purposes, it is sufficient to assume a reference distance from the source, r_1 (e.g. 0.1 m). The concept is illustrated in Fig. 2. With this knowledge the vibration velocity v_1 near the source (at an assumed reference distance, r_1) can be estimated. As Eq. (1) is valid for vibration attenuation in a full space, and since the amplitude is doubled due to reflection at a free surface, the vibration velocity v_2 must be multiplied by 0.5 to account for vibration amplification at the ground surface. Hence, the vibration velocity v_1 at a reference distance from the source can be determined from

$$v_1 = \frac{0.5\, v_2}{e^{-\alpha(r_2 - r_1)}} \left(\frac{r_2}{r_1}\right) \quad (3)$$

By applying Eq. (3) it is possible to present the variation of vibration amplitude independent of penetration depth.

2.2. Field tests

2.2.1. Test site

Field trials were carried out at a test site in Solna, Sweden, in connection with the construction of a new track for the Mälarbanan railway. In this study, several soil-rock soundings with vibration measurements (Jb-Vib) were performed. Additional geotechnical investigations in some locations included soil sampling, cone penetration tests (CPT) and super heavy dynamic probing (DPSH-A). The results of Jb-Vib of seven different bore holes are presented in this paper. Two bore holes were chosen for detailed analyses and one of these compared to other geotechnical site investigations.

The penetration test results at location BH20T728 are shown in Fig. 3. The soil deposit consists of approximately 1.5 m of man-made fill, overlying soft normally consolidated clay down to 8-9 m depth, followed by about 2 m of sand. The CPT was stopped in the sand layer at 9 m depth where the cone resistance exceeded 5 MPa. Around 10.5 m depth, the dynamic penetration resistance (DPSH-A) increased markedly, indicating stiff glacial till, and was stopped in the dense till at about 12 m depth when the blow count reached 165 bl/0.2m. Below this depth, the only method that could penetrate through the very hard till, boulders and into bedrock was soil-rock sounding, which was stopped at 19 m depth.

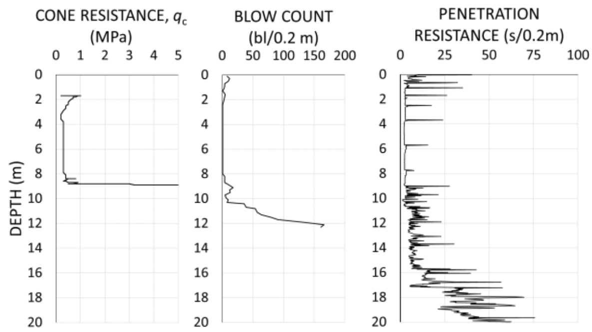

Figure 3. Results of CPTU (left), DPSH-A (middle) and Jb-2 (right) in test location BH20T728

Fig. 3 illustrates the advantages and limitations of different types of penetration tests. The CPT works well to determine properties in the clay layer where the cone resistance was about 0.2 to 0.3 MPa, indicating an undrained shear strength of 10 to 15 kPa. The method was stopped in the sand layer at about 9 m depth. DPSH-A, on the other hand, is not suitable for investigating the soft clay, where the number of blows/0.2 m was close to zero. However, this method is useful in the medium dense sandy deposit showing a penetration resistance of about 5 to 15 blows/0.2 m. The DPSH-A had to be stopped when penetrating dense till (> 150 blows/0.2 m) at about 12 m. Soil-rock sounding is the only method that was able to penetrate into very dense soil layers like till, boulders, fractured and intact rock. In this case, soil-rock sounding was stopped after approximately 3 m penetration into the bedrock, which is according to Swedish practice. Although conventional soil-rock sounding can be used to identify different soil layers and rock, it does not provide detailed geotechnical information like other penetration tests. Fig. 4a presents the interpreted soil profile from soil-rock sounding in bore hole BH20T728. By also taking the results of the DPSH-A and CPTU tests into account, a more detailed soil profile can be estimated, shown in Fig. 4b.

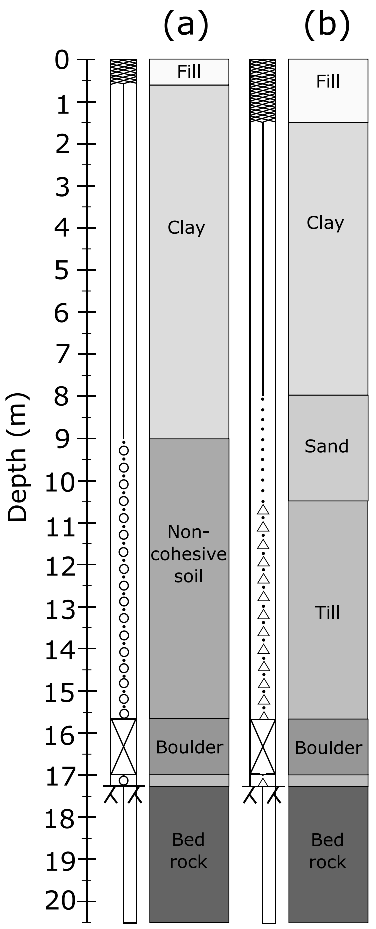

Figure 4. Interpreted soil profiles for bore hole BH20T728 based on (a) only Jb-2 and (b) on all available geotechnical investigations

2.2.2. Test setup

The experimental setup is shown schematically in Fig. 5 and consisted of a drilling rig and vibration measurement equipment. Three different drilling rigs were used for the presented bore holes and their properties are shown in Table 1.

Table 1. Properties of the drilling rigs

Drilling rig	Hydraulic hammer	Maximum operating frequency	Bore holes
Geotech 807DD	Atlas CP-150	24 Hz	BH20T501 BH20T723 BH20T728
Geotech 505FM	Sandviken BR-315	32 Hz	BH20T793 BH20T794
Geotech 505FM	Atlas Copco TT110	28 Hz	20SG111 20SG113

The vibration sensors consisted of vertical and horizontal geophones of type ABEM 20 4010 00 (sensitivity: 20 mV / mm/s; frequency range: 5-1000 Hz) and were mounted on a metal plate (2 kg) that was placed on the ground surface, Fig. 6. Only the horizontal component in the direction towards the bore hole was measured. The distance between the bore hole and the vibration sensors was 4 m at all measurements. Previous studies have shown that the vibration measurements are not significantly affected by the horizontal distance [12]. At a distance of 4 m from the drilling rod the vibration measurements do not interfere with the soil-rock sounding process and this distance has thus been used. The sampling frequency of the vibration measurements was 1200 Hz. Every two meters, the drilling rods were spliced. The vibrations recorded during the splicing process were eliminated manually from the analysis.

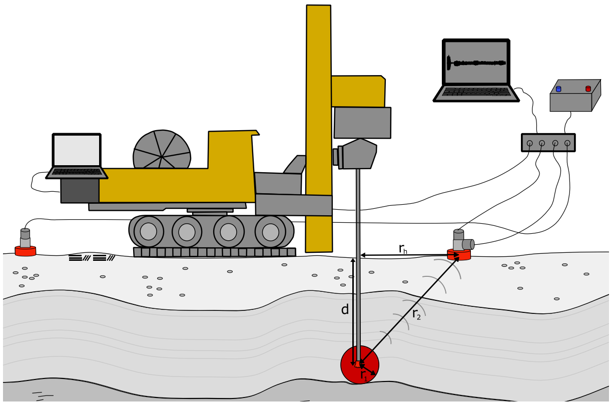

Figure 5. Experimental setup

Figure 6. Vertical and horizontal geophones mounted on metal plate

3. Results and discussion

For each test, the measured vibration velocity was determined as a function of the drilling depth. The variation of the velocity amplitude with depth is presented by the one second root mean square (RMS) value. The frequency content of the vibration measurements is presented in the form of frequency spectra and spectrograms that show the variation of frequency content with depth.

3.1. RMS-values of the vibration velocity

Fig. 7 presents the RMS-values of the vibration velocity over depth for bore hole BH20T501. The figure shows the vertical and horizontal vibration components separately as well as the calculated resultant. The vibration velocity depends on the stiffness of the penetrated material, a stiffer material generates stronger vibrations. However, the vibration energy is decreasing with increasing distance between drilling tip and vibration sensor, i.e. the vibration amplitude is decreasing with depth. The results indicate a dense, heterogeneous soil layer from the ground surface to a depth of approximately 2.7 m. Between 2.7 m and 11.4 m the vibration velocity is very low which indicates a soft clay layer. Below the clay layer the results indicate a stiffer layer with a distinct decrease in vibration velocity between 12.4 m and 12.6 m. The vibration measurements were stopped at 16.7 m.

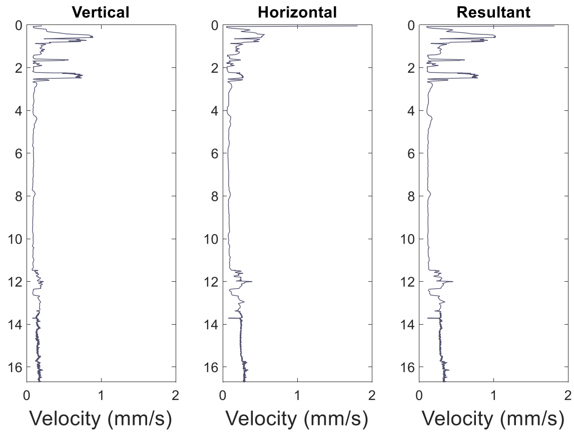

Figure 7. BH20T501: RMS-values of measured vibration velocity over depth

Fig. 8 presents the RMS-values of the measured vibration velocity over depth for bore hole BH20T728. The vibration measurements started below the fill. For this bore hole the different soil layers are not as clearly visible as for the previous bore hole. Down to about 3.6 m the vibration velocity is low and almost constant which indicates a clay layer. Between a depth of 3.6 m and 5.0 m the vibration velocity increases, indicating a stiffer layer in the clay that cannot be seen in the results based on soil-rock sounding. This can especially be seen in the vertical vibration component. Below 5 m, the vibration velocity is constant and low down to approximately 8.2 m, indicating the start of a stiffer/denser and less homogenous layer. The vibration measurements are stopped in the stiff layer at 19.6 m depth.

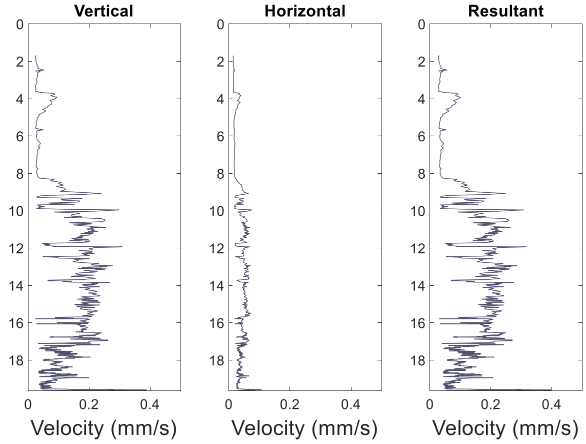

Figure 8. BH20T728: RMS-values of measured vibration velocity over depth

3.2. Spectrogram

Fig. 9 presents the spectrograms of the vertical component of seven bore holes. At this location, a layer of man-made fill is underlain by a layer of clay. Below the clay a layer of till on rock can be found. In addition, some investigations show a layer of sand embedded between the clay and till or some granular soil in the clay layer.

In the spectrograms, a brighter colour implies a higher energy content, i.e. a higher vibration velocity, at the respective frequency. The fill closest to the ground surface is represented by a broad spectrum of varying frequencies (the vibration measurements at bore hole BH20T728 were started after the fill already had been penetrated, i.e. the fill is not visible in its spectrogram). The clay layer is represented by dark colours as there is a low vibration energy content in the whole frequency range. In the soft material, hammer impact is not required. For some bore holes, higher vibration levels with a broad frequency range can be seen embedded in the clay. This indicates a thin layer of a denser material that cannot be seen by conventional soil-rock sounding. Below the clay layer follows glacial till that is characterized by a broad frequency

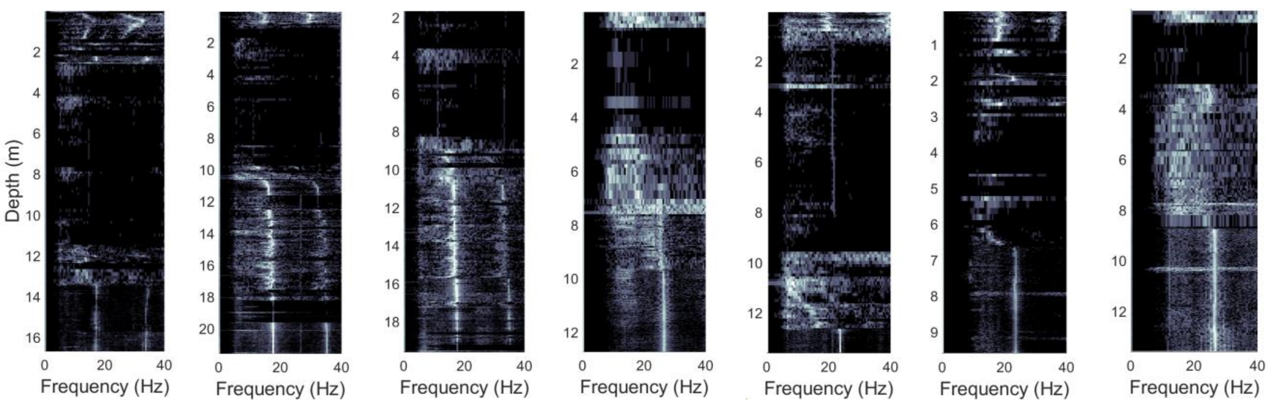

Figure 9. Spectrogram of the vertical vibration component for bore holes (from left to right) BH20T501, BH20T723, BH20T728, BH20T793, BH20T794, BH20T111, BH20T113

content. Drilling through rock is clearly visible as a distinct frequency peak (a vertical line in the spectrogram), corresponding to the impact frequency of the hydraulic hammer. The overtone at twice the impact frequency is usually present. These findings confirm results from previous studies that a higher soil strength produces stronger vibrations and a more distinct frequency peak corresponding to the hammer impact frequency. It is also apparent that the vibration measurements add detail to the information obtained by soil-rock sounding, which motivates further studies about correlating measured vibration data to soil properties.

3.3. Bore hole BH20T501 and BH20T728

In order to efficiently evaluate the results of Jb-Vib, the drilling and vibration measurements are displayed together. Two bore holes have been selected for a more detailed evaluation. Fig. 10 shows (from left to right) the interpreted soil profile from the conventional analysis of the drilling parameters, the penetration resistance and the feeding force during drilling, the spectrograms from the vertical and horizontal vibration measurements and the RMS-value of the resultant vibration velocity for the vertical and horizontal component as well as the calculated resultant.

As has been showed previously, harder soil layers generate a stronger vibration velocity, also leading to a more distinct frequency content. It can also be observed that the pattern of the spectrogram depends on the soil and rock type where transitions between different layers are clearly visible. The vibration velocity correlates to the feeding force and thus to the hardness of the soil and a higher velocity implies more energy in the frequency spectrum. The transitions between different layers at 2.6 m, 11.5 m and 13.5 m are visible in Fig. 10. The distribution of vibration energy in the spectrogram, however, reveals additional information about the different layers compared to soil-rock sounding results and vibration velocity measurements. In the fill down to 2.6 m, varying patterns can be seen in the spectrogram. At a depth of between 0 and around 0.9 m, two dominant frequencies are visible at 12-17 Hz and an overtone at 26-34 Hz. According to prior studies, this could imply that the fill material is quite firm at this depth, e.g. gravel or rock-fill. Between 0.9 and around 2.2 m, the frequency content is more varied with no dominant frequency. This could indicate a softer material in the fill layer. Between 2.2 and 2.6 m, high vibration levels at 17 Hz and an overtone at 34 Hz are clearly visible, which resembles the frequency content of a very hard material such as boulder or rock. Varying properties in the fill can be expected since it normally consists of very heterogeneous material. Even in the granular soil layer between 11.5 and 13.5 m depth three different patterns can be seen in the spectrogram. Down to 12.3 the frequency spectrum shows a broad frequency content, between 12.3 and 12.7 m almost no vibration energy is visible. Below 12.7 m the spectrum is broad once again, indicating a 0.4 m thick soft layer or void is embedded in the layer denoted as ‘granular soil’ from soil-rock sounding. At depths below 13.5 m, two dominant frequencies around 17 Hz and around 34 Hz are clearly visible, which is a typical pattern for drilling in rock.

Fig. 11 presents the analysis of the second bore hole, BH20T728, where both the interpretation of only the soil-rock-sounding and the interpreted soil profile from all geotechnical investigations (Jb-2, DPSH-A, CPTU) are included.

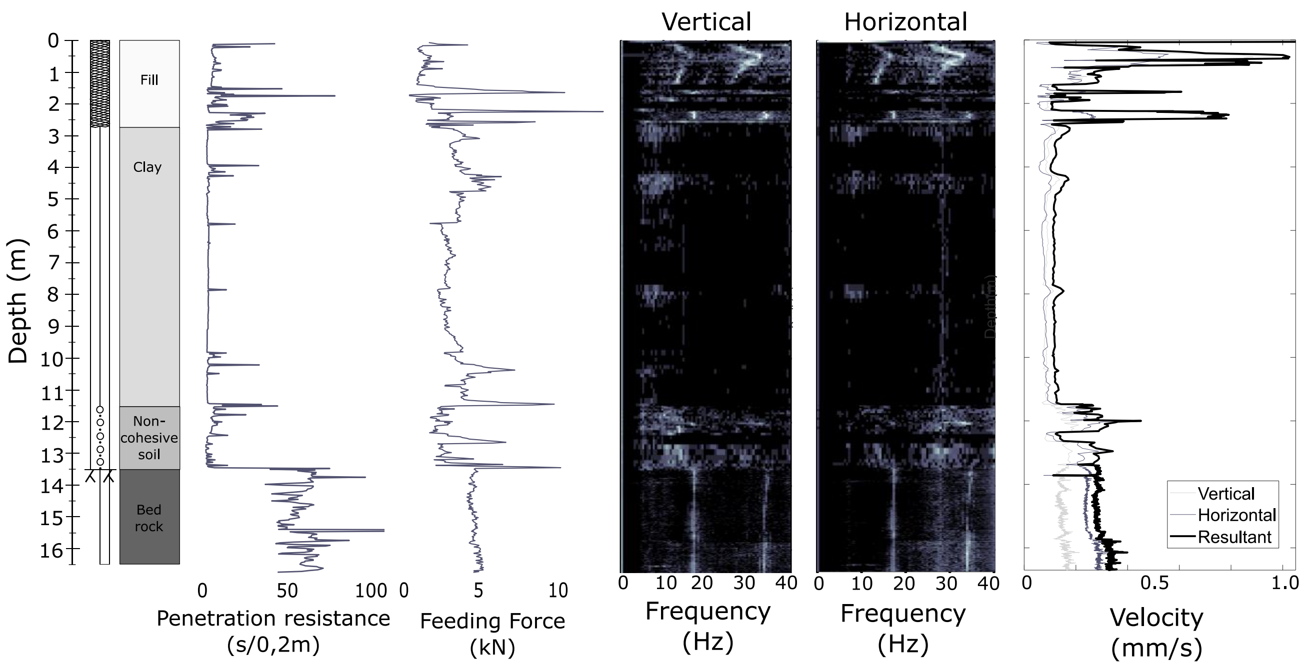

Figure 10. Soil-rock sounding results (left); spectrograms and vibration velocity of Jb-Vib (right).

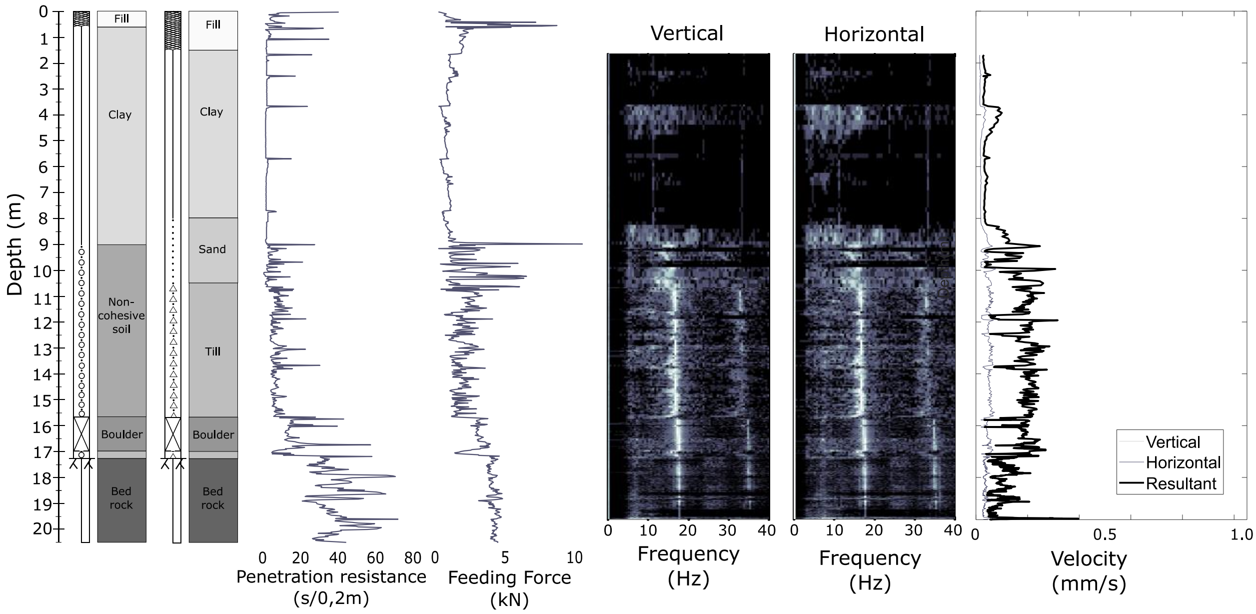

Figure 11. BH20T728: Soil-rock sounding and geotechnical investigations (left). Spectrogram and vibration velocity of Jb-Vib (right)

The vibration measurements are started after the penetration of the surface fill layer and therefore no conclusion about fill can be drawn. In the clay, both the feeding force and the penetration resistance are low which is typical for soft clay. Between 3.6 and 5.0 m, however, a broad frequency content and a higher vibration velocity can be seen in the Jb-Vib results. This could be due to a denser soil layer embedded in the clay, such as sand or silt. This information is not visible in the results of soil-rock sounding. The results of the soil-rock sounding indicate that granular soil starts at around 9.0 m. In the spectrogram and vibration velocity, however, the transition seems to be at a depth of around 8.3 m. This transition depth can also be seen in the CPT and DPSH-A results and therefore the soil-rock sounding results seem to be less accurate. At a depth of 8.3 to about 10.8 m a broad frequency spectrum is obtained that is identified as “sand” in the DPSH-A results. Below 10.8 m, distinct frequencies around 16.5 Hz and 33.0 Hz are visible, which is where the till layer starts. The next layer transition can according to the soil-rock sounding results be seen at a depth of about 15.6 m where a boulder is located. The transition to the boulder is visible in the spectrogram where the two distinct frequencies of about 17.0 and 33.5 Hz for the till layer are rising to 17.5 and 34.5 Hz. Below, the transition into the rock is visible at a depth of about 17.0 m. In the rock two distinct frequencies are visible once again. In general, the results show that Jb-Vib helps to identify different soil layers that cannot be identified by soil-rock sounding.

3.4. Frequency spectra

For each soil layer and each bore hole, one representative frequency spectrum was determined from a time signal with a duration of four seconds. The most relevant information regarding soil properties is found in the frequency range of up to 40 Hz. Furthermore, at higher frequencies, background noise and other disturbances may affect the measurements. Fig. 12 presents the frequency spectra for the different soil layers: clay, granular soil, till, boulder and rock. The thickness of these layers varies. In the clay layer, very low ground vibration levels are recorded as the hammer is not operating. Therefore, mainly background noise is measured by the vibration sensors. Most bore holes show spectra resembling previous measurements in clay, except for bore holes BH20T728 and BH20T793. These bore holes show higher vibration levels between 13-17 Hz and 10-27 Hz respectively. The increase in vibration velocity may originate from thin layers of stiffer/denser material in the clay layer that are not visible in the results from soil-rock sounding. Most likely, these thin layers consist of embedded sand or silt. For granular soils, broad spectra between about 5-40 Hz can be seen, with peaks at the hammer frequency (17 Hz). When comparing the frequency content of granular soil to that of rock, the peaks are less pronounced and at a lower frequency than for rock.

According to prior studies, the stiffer the material the more pronounced the frequency spectrum will be at one dominant frequency. In this case, it could indicate that the frequency spectra of granular soil with a larger number of peaks, e.g. bore holes BH20T723 and BH20T728, represent a denser material. It is noticeable that some spectra in granular soil include vibrations in a wide frequency range between 10-40 Hz (see bore hole BH20T501 and BH20T794) while other spectra show a narrower frequency range with more pronounced frequencies between 12-17 Hz (see bore holes BH20T723 and BH20T728). The lower frequency range between 12-17 Hz is closer to the hammer frequency and could therefore indicate that these spectra reflect a harder material.

When comparing the frequency spectra of granular soil to the deviating frequency spectra of bore holes BH20T728 and BH20T793 in clay, a resemblance is visible as the higher vibration levels are in about the same frequency range. This may indicate that some of the bore holes include a thin layer of granular soil embedded in the clay layer.

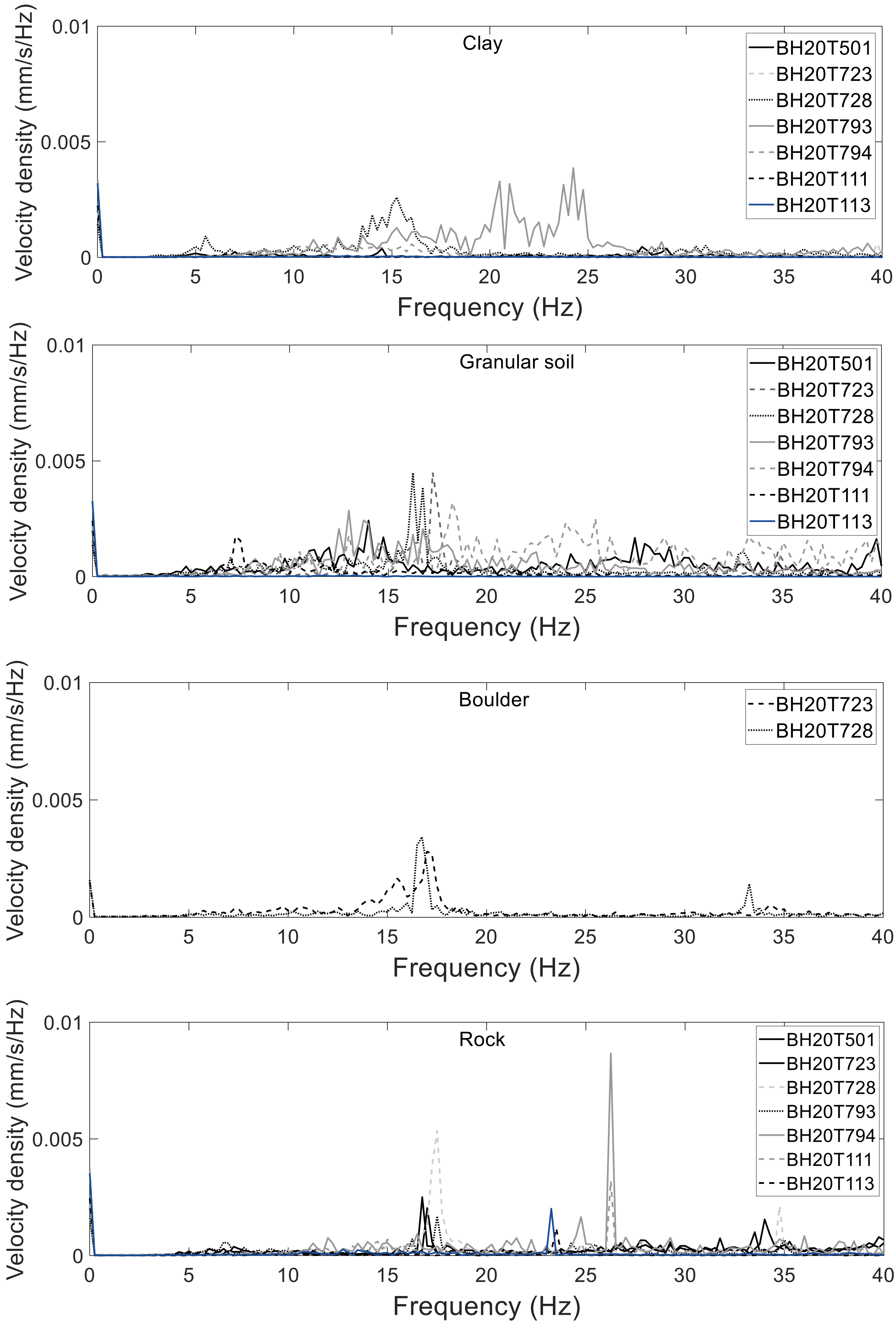

Figure 12. Spectra of clay, granular soil, boulder and rock

As the Swedish guideline for soil-rock sounding [15] requires that the drilling process must be continued for 3-5 m into the bedrock to avoid mistaking boulders for bedrock, it is interesting to see whether boulders and bedrock can be distinguished using Jb-Vib. Only two of the bore holes evaluated in this study, however, contain vibration measurements when penetrating through boulders. For bore hole BH20T723, there is a peak in the frequency spectrum at 17.0 Hz when penetrating the boulder, as well as a small peak around 34.3 Hz. For bore hole BH20T728, the peaks are at 16.8 Hz and 33.3 Hz. This can be compared to the spectra for rock, where the dominant frequency for both bore holes is at 17.5 Hz. It indicates that the dominant frequencies when penetrating boulders are slightly lower than the dominant frequencies when penetrating bedrock. Furthermore, the peaks when penetrating boulder are less distinct than for bedrock. For these two bore holes, a clear difference can be seen between the frequency spectra when penetrating boulder compared to the penetration into bedrock.

In all spectra for rock, the hammer frequency of the different hydraulic hammers can be seen by distinct peaks. For the drilling rig Geotech 807DD, the peaks are around 17 Hz, for Geotech 505FM with a hydraulic hammer of Atlas Copco TT110, around 24 Hz and for Geotech 505FM with a hydraulic hammer of Sandviken BR-315, around 26 Hz. The impact rate depends on the type of hammer but also on the flow of oil through the hammer and gas pressure in the accumulator. That explains why the frequency of the distinct peak varies somewhat for the same hydraulic hammer. The recorded dominant frequencies of all vibration measurements are 4-7 Hz lower than the maximum impact frequency of the respective hydraulic hammers that are presented in Table 1. Overall, the frequency spectra at different bore holes show similar trends. For all bore holes, the vibrations generated when penetrating rock are concentrated around a very distinct frequency and their overtone of around twice the dominant frequency. Very low vibration energy is seen at other frequencies than at the dominant frequency and its overtone.

3.5. Velocity attenuation adjustment

Fig. 13 presents the RMS-values of the vibration velocity for bore hole BH20T501. The left figure shows the measured velocity without attenuation adjustment with depth and the right figure shows the velocity adjusted according to Eq. (3). For bore hole BH20T501, the fill between 0-2.7 m has a higher vibration velocity without attenuation adjustment than the bedrock, which is due to the shorter distance between the drilling tip and the vibration sensor. With attenuation adjustment, however, the bedrock at a depth of 15.7-16.7 m shows a significantly higher vibration velocity, which better reflects the geotechnical conditions.

One limitation of attenuation adjustment is that it also amplifies background noise. This can be seen in Fig. 13, where the vibration velocity during penetration through clay is increasing with depth although the hydraulic hammer is not operating.

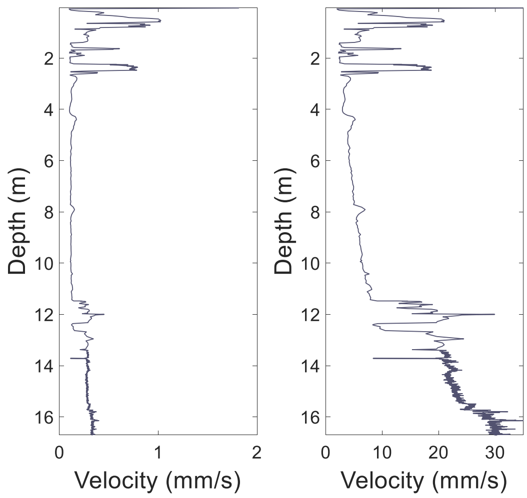

Figure 13. BH20T501: RMS-vibration velocity without (left) and with (right) attenuation adjustment

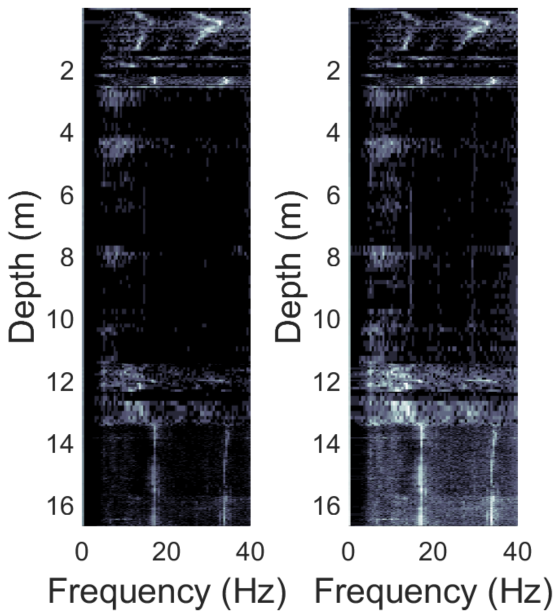

Figure 14. BH20T501: Spectrogram of the vertical vibrations without (left) and with (right) attenuation adjustment

Fig. 14 presents the spectrograms of the vertical vibration component for bore hole BH20T501. The left figure shows the vibration intensity without attenuation adjustment and the right figure shows the adjusted intensity. Adjustment implies that the energy is amplified at larger depths compared to the non-adjusted signal. In general, the spectrograms for the two different bore holes without and with attenuation adjustment are quite similar and do not provide much additional information for identification of soil layers. However, a greater difference can be seen for the results without and with attenuation adjustment as the bore holes get deeper. This means that for sites with large penetration depths, comparing the results could be more informative with attenuation adjustment. Furthermore, since the vibration velocity is more representative of the hardness or stiffness of the material, it is envisaged that the adjusted signal may be more useful for identifying soil properties as the Jb-Vib method is developed further.

4. Conclusions

Field tests with soil-rock sounding and simultaneous vibration measurements (Jb-Vib) were conducted in seven bore holes and compared to conventional geotechnical investigations. The results confirm and further strengthen the conclusions of prior studies:

- Jb-Vib measurements reflect the penetrated soil layers and additional information of the stratification can be gained.
- Thin layers of different materials can be identified in the Jb-Vib results that cannot be seen by inspecting the results of soil-rock sounding.
- Analyzing spectrograms is a useful concept for identifying soil layers, boulders or rock.

In addition, the following conclusions can be drawn:

- The frequencies generated when penetrating through sand have a wide distribution while in glacial till more distinct peaks appear. This indicates that the Jb-Vib method efficiently can distinguish between different granular soils, till or boulders.
- The results indicate that boulders can be distinguished from rock by analyzing the frequency spectrum. Boulders generate less distinct frequency peaks than rock. However, this aspect will be investigated further.
- Attenuation adjustment can be used to obtain signals that are more related to geotechnical properties.

In conclusion, Jb-Vib is a promising method that can be used in addition to soil-rock sounding to gain further knowledge about properties of the penetrated soil layers, boulders and rock. The method does not interfere with the drilling operation and is therefore efficient and cost-effective. Further measurements are required to develop a knowledge base for interpretation of different soils and rock.

Acknowledgements

The research presented in this paper is supported by the Swedish Transport Administration, Better Interaction in Geotechnics (BIG), the Development Fund of the Swedish Construction Industry (SBUF) and Peab AB. We thank Geotech AB for the development of the software and the supply of adequate equipment as well as Dr. K. Lindgren, Keli Mätteknik, for assisting in development of the measuring equipment. We also acknowledge the support by Skanska AB, Tyréns AB and Structor AB for measurements in connection to their projects. The measurements at bore hole 20SG111 and 20SG113 were conducted by KTH MSc students Sofie Pöder and Sofie Tranblom.

References

[1] Nilsson, G., Löfroth, H. (2012). ”Comparative study of soil-rock total sounding and CPTu in glacial deposits”, In: 4th International Conference on Geotechnical and Geophysical Site Characterization, Porto de Galinhas, Brazil, Vol. 1, 2012, pp. 313-317.

[2] Massarsch, K. R. "Cone penetration testing - a historic perspective", In: Proceedings of 3rd International Symposium of Cone Penetration Testing, CPT14. Las Vegas, Nevada, USA, 2014, pp. 97-134.

[3] Lundström, R., Stenberg, R. "Soil-rock drilling and rock locating by Rock indicator", In: International Conference in Soil Mechanics & Foundation Engineering Proceeding, Vol. 2, 1965, pp. 69-72.

[4] Yamada, S., Oshima A., "An attempting research on evaluating grain-size characteristics based on acoustic properties of soil for liquefaction assessment by Swedish Ram Sounding", Japanese Geotechnical Society Special Publication, 2(7), pp. 321-326, 2016.

[5] Houlsby, G. T., Ruck, B. M. ”Interpretation of signals from an acoustic cone penetrometer”, Geotechnical Site Characterization, 2, pp. 1075-1080, 1998.

[6] Attewell, P. B., Farmer I. W., “Attenuation of ground vibrations from pile driving”, Ground Engineering, 6(4), pp. 26–29, 1973.

[7] Jongmans, D., ”Prediction of ground vibrations caused by pile driving: a new methodology”, Engineering Geology, 42(1), pp. 25-36, 1996.

[8] Thandavamoorthy, T. S., ”Piling in fine and medium sand—a case study of ground and pile vibration”, Soil Dynamics and Earthquake Engineering, 24(4), pp. 295-304, 2004.

[9] Masoumi, H. R., Degrande, G., Lombaert, G., ”Prediction of free field vibrations due to pile driving using a dynamic soil–structure interaction formulation”, Soil Dynamics and Earthquake Engineering, 27(2), pp. 126-143, 2007.

[10] Khoubani, A., Ahmadi, M. M., ”Numerical study of ground vibration due to impact pile driving”, Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, 167(1), pp. 28-39, 2004.

[11] Swedish Geotechnical Society, "Akustisk JB-sondering – Resultat från Etapp 1 [Acoustic soil-rock sounding – Results from Phase 1]", SGF Notat 1:2016, Linköping, Sweden, 2016 (In Swedish).

[12] Swedish Geotechnical Society, "Akustisk JB-sondering – Resultat från Etapp 2 [Acoustic soil-rock sounding – Results from Phase 2]", SGF Report 2:2016, Linköping, Sweden, 2017 (In Swedish).

[13] Massarsch, K. R., Wersäll, C., "Acoustic soil and rock sounding", In: Proceedings of the 6th International Workshop: In situ and laboratory characterization of OC subsoil, Poznan, Poland, 2017, pp. 193-203.

[14] Ehrmanntraut, E,. Wersäll, C., "Vibrations measurements during soil rock sounding - a comparison between accelerometers and geophones." Accepted for publication in: Proceedings of Baltic-Nordic Acoustics Meeting, Oslo, Norway, 2020.

[15] Swedish Geotechnical Society, "Metodbeskrivning för jord-bergsondering, utförande, utrustning och kontroll [Method statement for soil-rock sounding, execution, equipment and control]", SGF Report 4:2012, Linköping, Sweden, 2012 (In Swedish).

[16] Massarsch, K. R., "Man-made vibrations and solutions, state-of-the-art lecture", In: Third International Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri, USA, Vol. 2, 1993, pp. 1393 - 1405.

[17] Kim, D. S., Lee, J. S., "Propagation and attenuation characteristics of various ground vibrations", Soil Dynamics and Earthquake Engineering, 19, pp. 115–26, 2000.