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ABSTRACT

In areas with an unknown geology, boreholes are usually placed either at the planned location of buildings and infrastructure or following a semiregular pattern. The number of boreholes is typically limited by installation cost, especially the number of boreholes to be used for geophysical testing, such as those used for downhole, crosshole, or tomographic analyses. An alternative approach to conventional drilling is the use of mobile pushing devices, *i.e.,* direct-push procedures. By placing geophysical tools into the pushing rods, geophysical methods become more flexible and adaptive during drilling, and investigation techniques can be implemented more expeditiously. From a geoengineering perspective, the in-situ tests are relatively efficient because they generate near continuous data and are considerably more accurate in comparison to laboratory consolidation tests. In this paper we present a combination of a direct-push system with seismic crosshole measurements as a cost effective alternative to standard investigation techniques. The new methodology was successfully tested at the site for Technical Safety (TTS) in Horstwalde, Germany. A complete crosshole dataset of P-, SV- and SH-waves was acquired between previously installed PVC cased boreholes and the direct-push borehole. Furthermore, the in-situ profiles of paired shear wave velocity profiles (SH and SV) were used to evaluate the stress history of the soils.

Introduction

The crosshole survey, *e.g.*, seismic crosshole testing and seismic tomography (Becht *et al*., 2007), is a common geophysical method to determine soil dynamic properties with high resolution between boreholes. Engineers use these key parameters to predict the response of soils to dynamic loading. Direct-push technologies (also known as cone penetration testing (CPT) or direct drive technology, Fig. 1) refer to a growing family of tools to obtain subsurface investigations by pushing or hammering small diameter hollow steel rods into the ground (Dietrich and Leven, 2006; Ohio EPA, 2016). The higher speed and lower costs allow for a greater density of measurements than can affordably be obtained by monitoring wells using standard drilling techniques (Maliva, 2016). Experience shows that the installation of direct-push boreholes are approximately three to five less costly compared to PVC cased boreholes. The direct-push technology, therefore, offers a broad applicability for investigation of unconsolidated sediments by being mobile, flexible and cost efficient (Leven *et al*., 2011).

To avoid high drilling costs and to drive seismic crosshole testing as a commonly used method, the combination of direct-push technologies and seismic crosshole measurements is proposed as an innovative methodology for geotechnical ground investigations. Paasche *et al*. (2009) evaluated the suitability of the direct-push technology for near-surface seismic travel-time tomography, where a reversed VSP geometry enabled fast acquisition of high-quality seismic data, allowing for reliable reconstruction of velocity variations in near-surface unconsolidated sediments. However, they placed only the seismic source in direct-push installed steel rods. Our study is more expansive and focuses on the application of direct-push techniques for seismic crosshole measurements.

By generating S-waves of SH and SV type, paired shear wave profiles could be obtained to potentially describe the soil stress history. Many geotechnical parameters are influenced by the soil stress history, for example deformation properties and soil stiffness.

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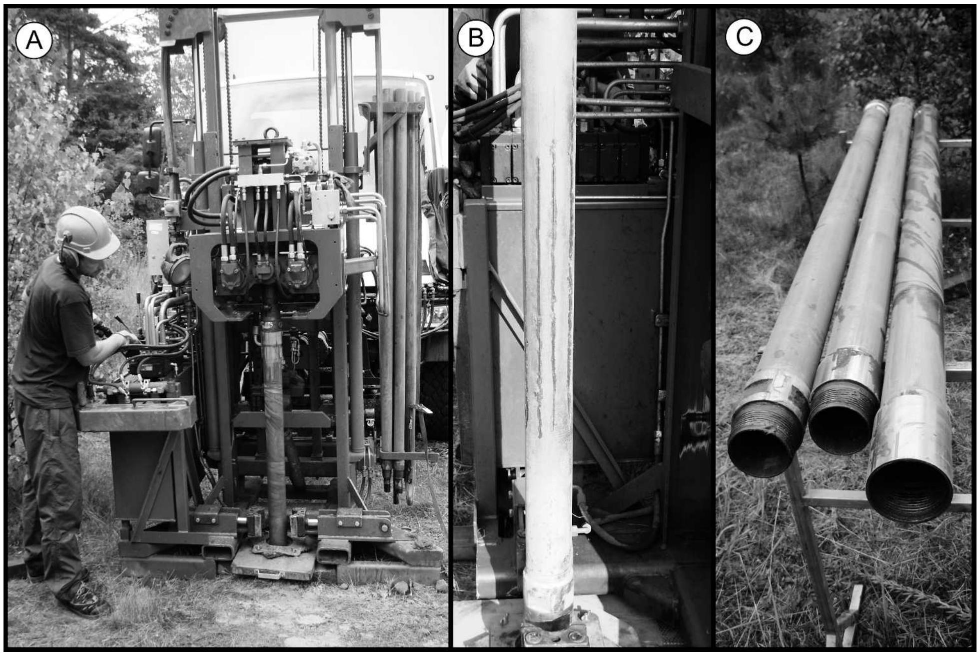

Figure 1. (a) Direct-push procedure, where high frequency vibrations (sonic) and the weight of the mobile platform push the probe devices into the ground. (b) Direct-push steel rod with slots, sealed with resin. (c) Steel rods without slots.

Furthermore, it plays an important role in other parameters such as lateral stress state (K_0), coefficient of consolidation, and liquefaction response (Ku and Mayne, 2013, 2014). In geotechnical engineering, the stress history of soils is usually represented through the overconsolidation ratio (OCR $= \sigma'_p/\sigma'_{vo}$), derived from the overconsolidation difference (OCD $= \sigma'_p - \sigma'_{vo}$) with σ'_p representing the magnitude of the effective preconsolidation stress and σ'_{vo} the current effective overburden stress. A soil can experience consolidation through several mechanisms including mechanical loading, glaciation, or others. After Roesler (1979) the stress induced anisotropic S-wave velocity V_s can be expressed as follows:

$$V_S = C(\sigma'_x)^{nx}(\sigma'_y)^{ny} \tag{1}$$

where σ'_x is the principal effective stress in wave propagation direction and σ'_y is the principal effective stress in the wave polarization direction. C, nx and ny are material constants. Therefore, depending on the different static stress state of a soil, SH- and SV-waves generated by a crosshole test have individual site specific velocities.

Field Test

A field experiment was conducted in July 2016 at the test site for Technical Safety (TTS) of the Federal Institute for Materials Research and Testing (BAM) in Horstwalde, Germany, to demonstrate the direct-push based crosshole technique and its general applicability. The TTS is a general validation facility for various investigation purposes and techniques, located approximately 50 km south of Berlin. The geological and geotechnical soil conditions are well known. For example, in 2013 dynamic pile load tests of bored piles in a sandy environment were evaluated (Niederleithinger *et al*., 2013). The extensive tests were performed around 15 m from our test location and a detailed site investigation program was completed. CPT measurements indicated the presence of medium sands with some fine sand at the top and coarser material at the bottom. Soil samples obtained from drillings showed a varying mixture of sand, silt, coal and gravel. It should be noted that despite similar soil profiles, the CPT results showed some significant differences that hinted at a highly variable subsurface structure. Additionally, crosshole tests that were carried out to support the CPT trend, showed faster P- and S-wave velocities in the upper 6 to 8 m and lower velocities in the sands below 8 m.

Geologically, the site belongs to the northern German Basin and consists of various sediments with a thickness of several thousand meters affected by salt tectonics. The surface of the test site is dominated by post glacial sediments and the groundwater table is about 3 ± 1 m below surface, varying seasonally (Niederlei-

Table 1. Test setup for crosshole testing.

Test	Source in	Receiver in	Characteristics of Direct-Push steel rod	Source interval	Receiver depth	Wave-type
1	PVC cased borehole	Direct-Push steel rod	4–12 m: Unslotted 12–13 m: Slotted	1 m	4–13 m	P, SH, SV
2	Direct-Push steel rod	PVC cased borehole	4–12 m: Unslotted 12–13 m: Slotted	1 m	4–13 m	P, SH, SV

thinger *et al*., 2013). The direct-push based seismic crosshole test was carried out between a previously installed standard PVC cased borehole and a direct-push borehole. The direct-push borehole is effectively a steel rod with an inner diameter of 77 mm which is pushed into the underground with high-frequency (sonic) vibrations and the weight of the mobile platform (Fig. 1). The distance between the two boreholes was set to 5 m.

To generate seismic signals two different borehole sources were used. The borehole source type BIS-SH (Co. Geotomographie GmbH) generates mainly SH-waves but also a good amount of P-waves. To generate SV-waves, the borehole source type BIS-SV (Co. Geotomographie GmbH) was used. Both source modes of operation were similar, in that a solenoid was activated by high voltage and pushed either a copper plate against the borehole wall to generate a SH-wave impact or pushed the plate up and down to generate SV-waves. During operation the source was pneumatically clamped to the borehole wall or to the wall of the steel rod. Seismic signals were received by the Multi-Station Borehole Acquisition System (MBAS), which was a 10-station 3C digital acquisition system having a station spacing of 1 m. The MBAS was developed in 2011 within the framework of the research project “MuSaWa” – Multi-Scale S-wave Tomography for Exploration and Risk Assessment of Development Sites (Paasche *et al*., 2011), where P- and S-wave tomographic acquisition technologies were developed. That research project focused exclusively on the P- and S-wave tomography, whereas the present study focused on crosshole applications with either source or receiver in the direct-push borehole.

The crosshole measurements were carried out below the water table between 4 to 13 m below ground with a source interval of 1 m. Two source and receiver configurations were tested in order to compare the influence of different casings, *i.e*., a PVC casing and a direct-push steel rod (see Table 1). Additionally, the steel rod was slotted between 12 and 13 m to change wave transmission conditions. The slots were filled with resin. For test 1, the borehole sources were placed in the PVC cased borehole and the MBAS was placed inside the direct-push steel rod. During test 2, the sources were placed inside the direct-push steel rod and the MBAS was lowered into the PVC cased borehole.

Results

Raw seismic data for different source and receiver configurations are displayed in Fig. 2. Data are record normalized for each wave type, *i.e*., for the SH-waves in Fig. 2(a) and 2(b) as well as for the SV-waves in Fig. 2(c) and 2(d). The flat signal traces at 7 m depth in Fig. 2(c) and 2(d) are caused by incorrect digital amplification. Nevertheless, data quality is excellent and data analysis is possible for the complete dataset.

It was expected that the signal quality depended on the test setup and configuration, as the source and receiver coupling and transmission conditions may differ from PVC casing to steel rod. Generally, if the borehole source was placed in the PVC cased borehole (Fig. 2(a) and Fig. 2(c)) higher amplitudes (better signal-to-noise ratio) for S-waves can be observed compared to reverse positioning of the borehole source inside the steel rod (Fig. 2(b) and Fig. 2(d)). Polarization of the S-waves seems to not be affected or only slightly affected by the type of casing. Therefore, determining the S-wave by changes in polarization was excellent in both cases. It was also observed that the signal quality of P-waves improved significantly in positions where the BIS-SH source was placed in the slotted part of the steel rod (Fig. 2(b), depth position 13 m). In contrast, the signal quality of neither SH- nor SV-waves changed noticeably (Fig. 2(b) and 2(d), depth position 13 m). While pulling the steel rod back, additional positions were measured by placing the source in the slotted part of the rod, confirming the improvement of P-wave signal quality while SV- and SH-wave signals were not affected by the steel rod.

We can see that the signal quality remained more or less constant over the measured depth using the source and receiver configuration from test 1. The results of test

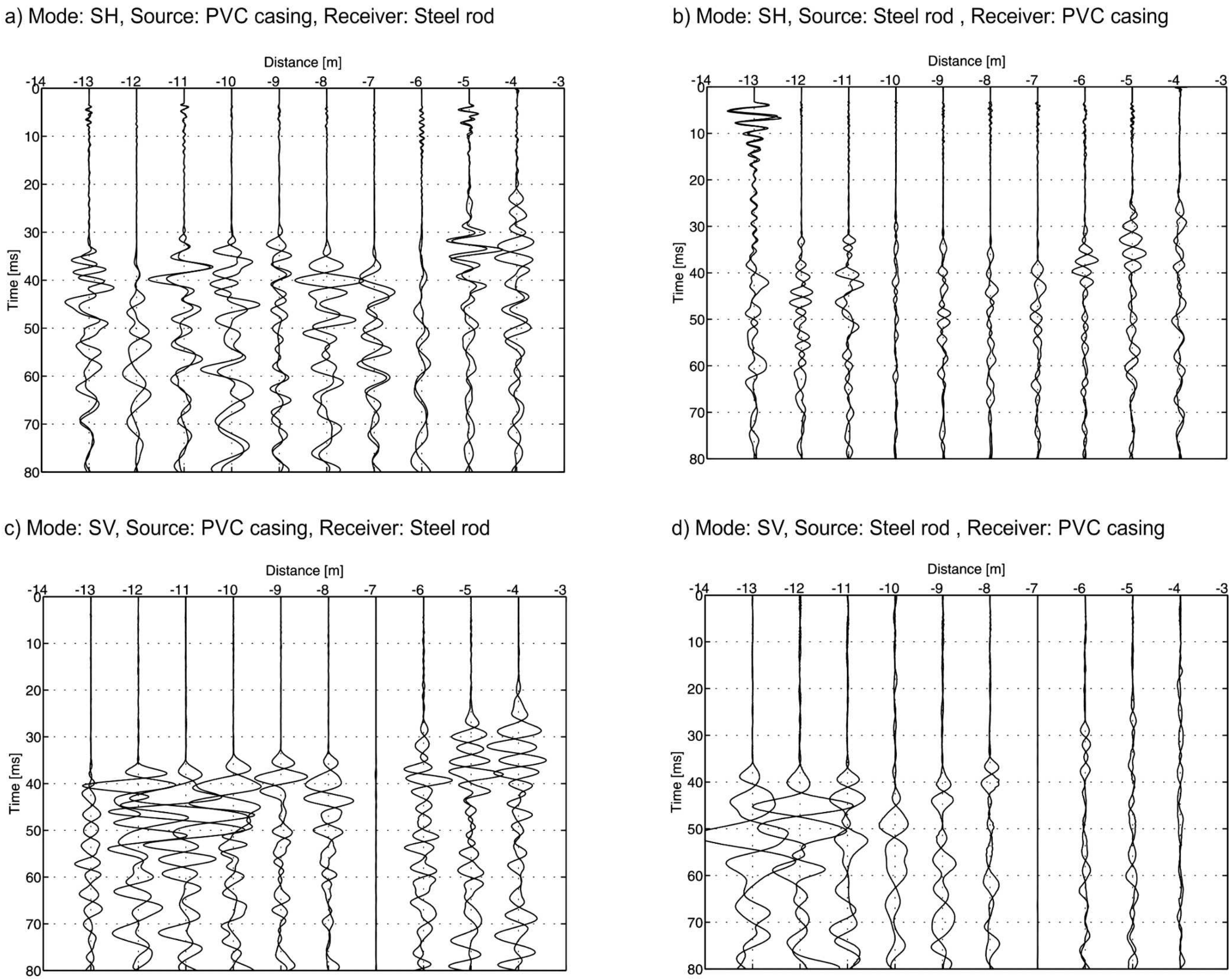

Figure 2. Data examples for source-receiver configuration listed in Table 1.

2, where the SV source was placed in the steel rod, showed marginal reduction of signal quality indicated by an amplitude decrease towards the surface. However, the results show that both of the tested source and receiver configurations could be used to obtain a dataset of P-, SH- and SV-waves with good quality.

For further analysis, the first arrival traveltimes for all wave types (P, SH and SV) were picked for each crosshole source and receiver configuration and velocities were calculated based on source and receiver distances. Borehole deviation measurements could only be made in the PVC cased borehole. The steel rod borehole was assumed to be vertical. The results are displayed in Fig. 3. The velocities obtained from the source placed in PVC casing differ only marginally from the data acquired with the source placed in the steel rod. However, it was observed that the P-wave velocities were generally faster if the source was placed in the steel rod. For this configuration, we noted a slightly better signal quality for the P-waves. The average traveltime difference between both configurations was about 0.05 ms with a deviation of approximately 1.6% from the total average traveltime. The sampling interval for data acquisition was set to 0.0625 ms. Thus, the difference for the P-wave seems to be negligible.

In contrast, the difference of measured S-wave velocities between both test configurations did not show a general trend. The average traveltime difference for the S-waves was about 0.5 ms, which corresponds to a deviation of approximately 2% from the total traveltime. These small traveltime differences for both P-waves and S-waves led to the conclusion that the determination of

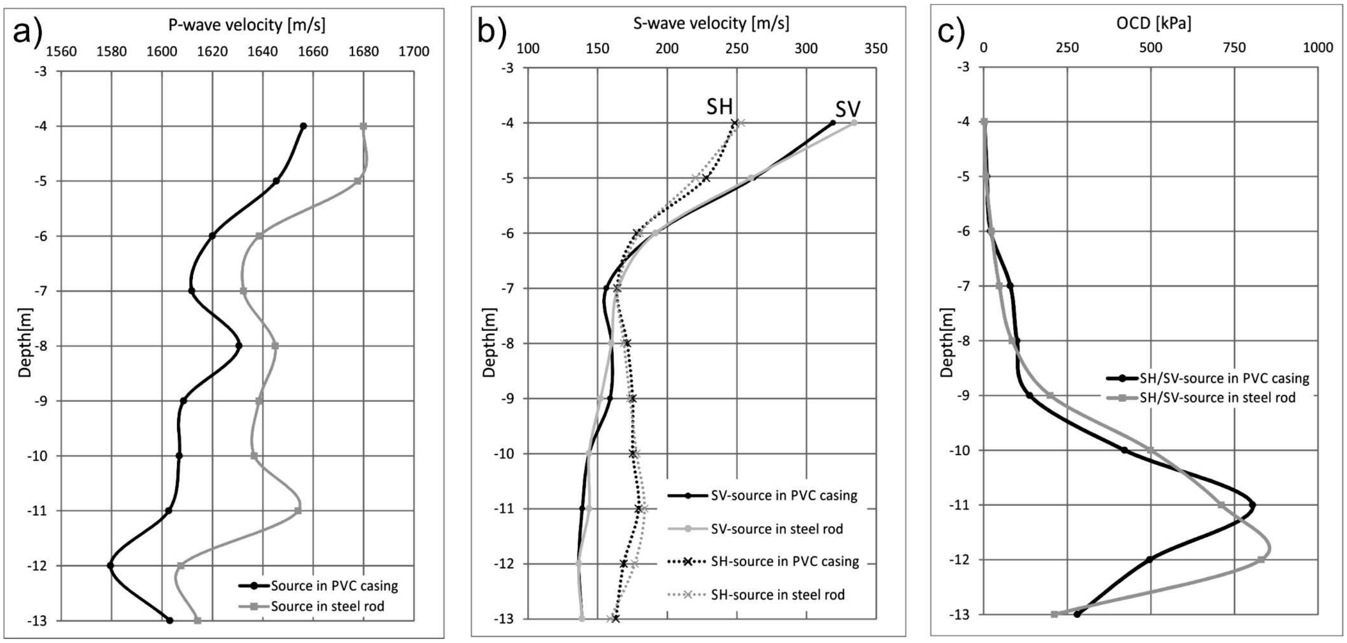

Figure 3. 1D depth velocity profiles measured with different source and receiver configurations for (a) P-wave, (b) SV- and SH-waves, and (c) overconsolidation difference, OCD.

P-, SH- and SV-wave arrivals can be determined precisely in both configurations.

In general, the velocities varied slightly for the P-waves between 1,580 and 1,680 m/s, whereas the variation for the S-waves was much higher and between 140 and 300 m/s (Fig. 3). Above 7 m, a velocity increase for all wave types was noticed. This was in agreement to the observations published by Niederleithinger *et al*. (2013). P-wave and S-wave velocities did not vary much in the depths between 7 and 13 m, and the velocities were lower compared to the seismic velocities in the upper layer. According to the previous geological (sieve analysis) and geotechnical (CPT) studies at this test site (Niederleithinger *et al*., 2013), the sediments below 7 m were dominated by a poorly graded medium sand with only a small amount of coarser grain sizes showing low resistance values, which indicated a low compactness of the soil. In contrast, the seismic velocities in the upper layer above 7 m increased significantly. According to Niederleithinger *et al*. (2013) this layer consisted of well graded sand which contains particles of a wider range of grain sizes. This led to higher cone resistance values and indicated a higher degree of compactness. We also noticed a velocity separation of SV- and SH- waves. While the SV-wave velocities were marginally higher compared to the SH-waves in the upper layer, the opposite was observed in the deeper part below 7 m: SH-waves traveled faster than the SV-waves (Fig. 3(b)).

The directional characteristics of the shear waves are useful for evaluating the soil stress history in terms of the OCR (Ku and Mayne, 2014). OCR is the ratio between the effective preconsolidation stress and the current effective overburden stress and it is related to historical changes in the state of stress in the subsoil. It is well recognized that natural soils can experience over-consolidation by way of several mechanisms, including mechanical unloading due to erosion, glaciation, and changes to groundwater elevation. In fact, many soils will have undertaken two or more of these processes over their geologic history. According to Ku and Mayne (2014) one approach to represent the stress history is through the OCD, which is related to OCR as follows:

$$\mathrm{OCR} = (\mathrm{OCD} + \sigma'_{vo})/\sigma'_{vo} \qquad (2)$$

where σ'_{vo} is the effective overburden stress. OCD is strongly correlated to the paired stiffness ratio ($G_{0,HH}$/$G_{0,VH}$). The small strain shear modulus, G_0, is determined by the shear wave velocity (V_s) measurements (*e.g.,* Ku and Mayne, 2014):

$$G_{0,ij} = \rho_t V_{s,ij}{}^2 \qquad (3)$$

where $G_{0,ij}$ is the small strain shear modulus in the '*i*-*j*' soil plane, $V_{s,ij}$ the shear wave velocity in the *i* propagation direction and in *j* polarization direction, and ρ_t the total mass density of the soil medium. The directional V_s characteristics in soils can be obtained by geophysical field measurements, such as the presented crosshole testing.

Ku and Mayne (2014) measured the $V_{s,HH}$ mode, represented by rotary source crosshole testing, and the $V_{s,VH}$ mode was produced by common downhole testing (subscript 'V' denotes vertical, and 'H' denotes horizontal). OCD was calculated by:

$$\mathrm{OCD} = 0.466(\sigma_{atm})(G_{0,HH}/G_{0,VH})^{5.57} \tag{4}$$

where σ_{atm} is the reference atmospheric pressure. In contrast, our study applied the standard crosshole testing method (ASTM D4428, 2007) using the horizontally polarized shear wave borehole source BIS-SH to measure the velocity of horizontally propagating and SH-polarized shear waves ($V_{s,HH}$). We also applied the vertically polarized shear wave borehole source BIS-SV to measure the velocity of horizontally propagating and vertically polarized shear waves ($V_{s,HV}$). Supposing a transverse isotropy along the vertical axis, we assumed that $V_{s,VH}$ and $V_{s,HV}$ were identical and used Eq. (4) to calculate values of OCD after assuming a density of sand equal to 2,000 kg/m^3. The results are displayed in Fig. 3(c).

The calculated values of OCD showed a maximum of around 40 kPa for the upper layer (Fig. 3). This corresponded to a G_0 stiffness ratio ($G_{0,HH}/G_{0,HV}$) < 1. In contrast, below a depth of 7 m, the OCD values increased significantly to around 100 to 800 kPa. These high values were correlated to the shear wave velocity difference of $V_{s,HH} > V_{s,HV}$, indicating a G_0 stiffness ratio ($G_{0,HH}/G_{0,HV}$) > 1. According to Ku and Mayne (2014), the lower OCD values calculated for the upper layer were characteristic for normal consolidated sand. The unusual high values in the lower sandy layer were typical for overconsolidated clay and indicated that the soil had experienced a higher preconsolidation stress compared to the current effective overburden stress. This soil behavior is controversial, in that non-cohesive sandy soils may store a permanent deformation induced by primary loading (Kindler, 2016).

Summary and Conclusions

In this work, we proposed an alternative to conventional drilling by using the direct-push technique combined with seismic crosshole measurements in order to reduce characterization costs. The new methodology was demonstrated successfully at the TTS test site in Horstwalde, Germany. Various source and receiver configurations, as well as different casings, were tested to evaluate the data quality. Reversed traveltime determination showed excellent agreement for measured P-, SH- and SV-waves. We also showed that the method is sufficient to measure geotechnically relevant parameters such as the G_0 stiffness ratios and values of OCD in order to evaluate the soil stress history based on the directional characteristics of the shear wave. The SV/SH velocity ratio observed at the TTS test site gave an indication of an anisotropic material behavior due to preconsolidation in the course of the geological history.

We can conclude that the proposed direct-push based crosshole testing method promises several benefits. With the help of direct-push techniques, geophysical methods become more flexible, because test positions can be adapted easily and changed according to the findings, the local conditions, or the customer's requirements. Especially, if the crosshole method is going to be validated between two steel rods made by the direct-push technique in the near future, it would become an extraordinary economical procedure. Furthermore, the paired S-wave crosshole measurement is a promising direct in-situ measurement to allow access to the stress history of soils in terms of the OCD value. Currently, alternative in-situ methods to determine OCD are not available. Furthermore, most of the in-situ soil sampling methods are intrusive and therefore have inevitable soil displacement issues during penetration that might cause significant changes from the actual state of stress. Laboratory experiments do not retain the ambient environment and intact status of the prevailing stress regime. Consequently, the proposed crosshole testing method using direct-push technique measuring paired shear wave velocity profiles (SH and SV) promises to be a non-destructive, in-situ procedure to evaluate the prestress history and provide geotechnical engineers more reliable parameters to predict expected settlement.

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