A novel CPT-based seismic tomographic system for geotechnical applications

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ABSTRACT: A thorough understanding of the spatial distribution of geotechnical parameters in the subsoil is essential, especially for site-specific risk assessment studies or construction projects. The uncertainty of interpolating the spatial distribution of geotechnical parameters can be reduced by applying seismic tomography between the CPT positions. In the frame of the R&D project CPTTOMO, a novel CPT-based tomography system has been developed. This system integrates multi-station three-component geophones as well as P- and S-wave sources in small-bore Direct-Push CPT rods. Results from test sites indicate that a joint recording and evaluation of geotechnical and seismic parameters improves the spatial representation and informative value of geotechnical data. The presentation introduces this novel system, shows one data example and highlights the potential for geotechnical subsurface investigation and site assessment.

Keywords: Direct Push technique, Cone Penetration Test, Cross-hole seismic Tomography, Deterministic Transfer Functions, Soil Stress History

1. Introduction

The thorough understanding of the spatial distribution of geotechnical parameters in the near-surface is essential, especially for site-specific risk assessment studies or construction projects. Geotechnical laboratory and in-situ tests serve as standard methods to determine point information of geotechnical and soil parameters. For nearly 20 years the Direct Push technology offers the possibility of vertically resolved, multi-level recordings of various geotechnical, geophysical and geochemical parameters with simultaneous sampling, regardless of the availability of drill holes.

One of the most versatile direct push methods for subsurface investigation in unconsolidated rocks which determines the geotechnical engineering properties of soils and delineating soil stratigraphy is the Cone penetration test (CPT). A CPT sensor probe with a cone-shaped tip is pressed perpendicularly into the ground at a constant feed rate of few centimeters per second and generates 1D high-resolution in-situ records of resistance at the cone tip, the sleeve friction, penetration speed of the probe and the deviation of the tip from the perpendicular. The Cone Penetration Test (CPT) is especially employed for accurate determination of soil stratigraphy, soil type, lithologic anomalies, and some other soil geotechnical parameters.

The spatial distribution of the geotechnical parameters between the CPT locations is often estimated by using various interpolation methods. However, the reliability of the predicted layering depends significantly on the homogeneity of the local geology as well as the distance between the test locations and can, therefore, be questionable in many cases. Nowadays, seismic is an accepted geophysical method to determine soil dynamic properties of soils with a high resolution between boreholes.

Especially, cross-hole seismic tomography for structural subsurface investigation has been widely used for high-resolution determination of spatially differentiated parameters between existing wells or boreholes. Cross-hole seismic tomography determines the distribution of P- or S-wave velocities along with vertical slices or even spatially. The application of S-waves and P-waves increases the geotechnical benefits due to their higher resolution and the immediate link to soil dynamic properties.

Seismic tomography between boreholes has been widely recognized as a high-resolution imaging tool for structures as well as processes within the subsurface. Therefore, seismic cross-hole tomography might also be able to fill the information gap between the CPT positions.

The velocity distributions obtained may be used as a backbone for correlations used to obtain 2D images of related geotechnical parameters. By directly linking the seismic velocity to soil dynamic parameters (e.g. Poisson

Ratio, Young's modulus, Shear modulus) the high-resolution tomographic method is ideally suited to transfer the 1D information from CPT into the 2D measuring plane or even into 3D space.

Additionally, new theoretical approaches allow the assessment of the seismic wave attenuation by analyzing the dispersion of body waves. The attenuation is a major factor in controlling the impact of vibrations to e.g. soil liquefaction processes. Therefore, seismic tomographic measurements can be regarded as an important contribution to stability assessment.

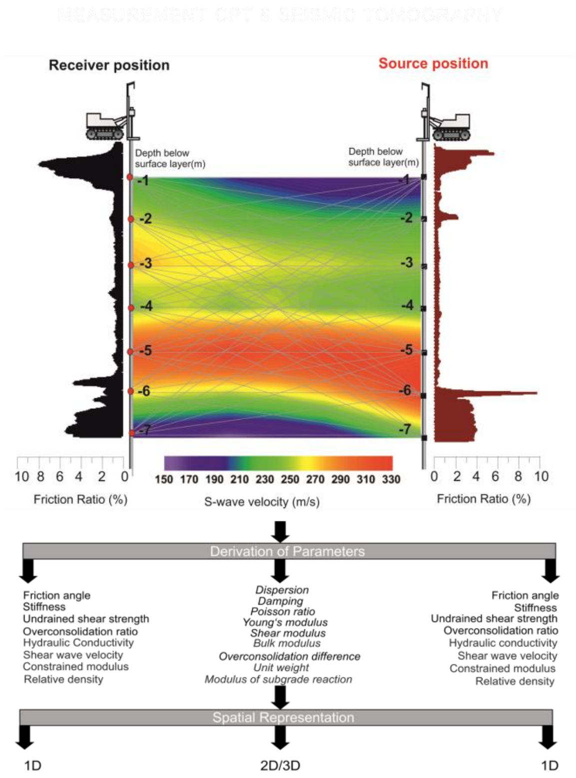

Figure 1. Overview of the derived geotechnical parameters and the spatial representation of a joint interpretation of CPT and seismic measurement parameters; Combination allows the transfer of 1D point information (CPT) into 2D measuring plane or even 3D space by linking seismic velocity to soil dynamic parameters

2. CPT-based Tomography System

The method of seismic tomography between boreholes has been widely used in the structural subsurface investigation because the tomography does not only depict the material properties but also its location in the plane or in space. It provides great opportunities to detect inhomogeneity's such as disturbance zones or cavities as well as to control cement injections. In most cases, P-wave tomography is used to predict the spatial continuity of lithological structures. However, P-wave is strongly influenced by the water table. Hence its application to derive geotechnical parameters is limited.

However, P- and S-wave tomographic results of previous studies show a significantly higher velocity contrast for the S-wave tomograms and these tomograms cover both the saturated and the unsaturated soil zone. So far, little effort has been made to develop devices that enable efficient acquisition of tomographic S-wave data. Shear waves are sensitive to changes in dynamic soil parameters, e.g. shear strength or elastic modulus, these parameters also have a 3-dimensional structure due to the heterogeneous soil structure.

Within a German R&D project (CPTTOMO - ZF4318901LT6 & ZF4315801LT6), a prototype of a CPT-based tomography system was developed. It consists of a receiver system, i.e. a number of tri-axial geophones mounted inside the 44mm CPT rods and seismic sources that emits P- and S-waves in small bore Direct-Push rods.

2.1 Seismic CPT Receiver

Tri-axial small-sized geophones having a natural frequency of 28 Hz were placed inside a rod using 3D printed mounting frames. There is one tri-axial sensor per 1m rod. Data are digitized right at the sensors and transmitted via a COM interface with a 4-wire transmission. Robust 4-pin jack plugs and sockets, similar to those used in the aircraft industry, have been selected to electrically couple the digital modular stations from rod to rod. Tests showed a problem-free screwing of the individual rods. This modular system enables a site-specific configuration according to the measuring depth.

2.2 Seismic CPT Source

Within the project, a seismic CPT source was developed to be placed inside the CPT rod working on the well-known sparker principle. The sparker source generates mainly P-waves. A 5KV high voltage generator placed at the surface supplies the electrical energy for the sparker discharge through a coaxial cable. Anyhow, if the sparker pulse is directed to one side of the borehole wall waves of SH type are also generated.

The generated SH waves propagate perpendicular to the direction of generation. Accordingly, for measurements between two CPT boreholes, the SH source must be aligned.

2.3 Measurement Workflow

The application of this prototype allows less effort and it is cost- and time-efficient compared to conventional drilling methods.

To carry out CPT-based seismic tomographic measurements, one or ideally two DP machines are required which is often impractical from a cost- and logistic aspect. If only one DP machine can be used, both the rods with the geophones and seismic sources needs to be pushed one after the other into the ground. It makes sense to position the geophones at first and then move the machine to the new position for positioning the rod with the seismic source because the multi-station geophones do not need to be moved until the end of the measurement. For interpretation of the seismic data the knowledge of the borehole orientation, i.e. the XYZ location of the sensors and source in space is essential. Therefore, a deviation probe measuring the drill deviation has been also developed and tested.

3. Field test

Experiments were carried out with the CPT based Tomographic System at the test site about 1 km north of the village Selbitz and about 8 km southwest of Wittenberg in Saxony-Anhalt. The main soil types are Gleysols and Gleyic Cambisols, with substrates of alluvial loam (loam and clay) above fluvial limnogenous sand. The substrate has accumulated mainly during the Holocene due to the flooding of the area by the Elbe and its tributaries. On this test site, the groundwater level is about 2 meters below the ground surface.

Two Direct-Push devices (GeoProbe) were used to push the source and receiver CPT rods at a distance of 3 meters into the ground. Four 3C receiver modules at 1m spacing were pushed into the ground to a depth of 7 meters (first layout from -7 to -4 meters). The seismic source was also pushed to a depth of 7 meters, taking care that the sparker electrode was aligned "cross-line" for generating mainly SH-waves. After data registration for this source position, the receiver modules were repositioned at the depths of -4 to -1 meters (second layout) and then the source was excited from the same depth position. After that, the source was lifted by 1m and shooting was repeated. A continuous seismic profile of -7 to -1 meters was obtained with shots every 1 m.

Figure 2. Application of two DP machines for CPT-based seismic tomographic measurements.

4. Data Example and Interpretation

A complete tomographic data set was available for a depth range of -7 to -1 meters. P and S wave travel times were determined for all source and receiver positions for tomographic data evaluation. The data quality can be seen as good. A total of 57 S-wave travel times and 56 P-wave travel times were determined. The numerical inversion of the data was performed after incorporation of the borehole deviation information.

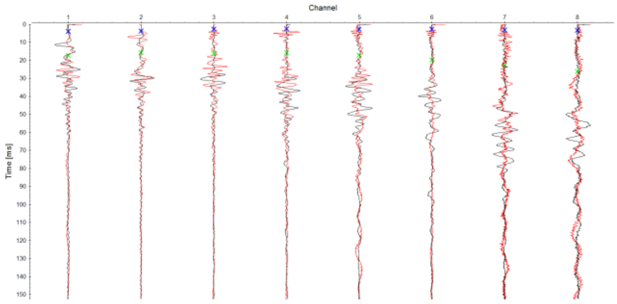

Figure 3. Example data showing arrival times of P-wave (blue) and S-waves (green)

The coverage and inversion result (after 10 iterations steps) can be seen in Figures 4 and 5.

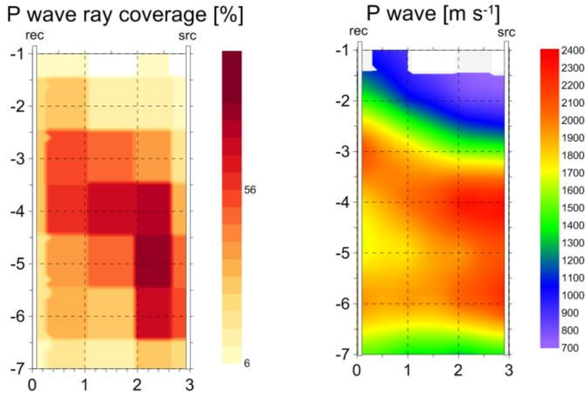

Figure 4. P-wave ray coverage and inversion result for P-wave

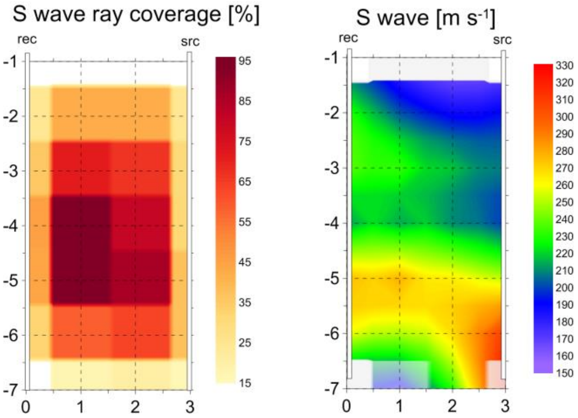

Figure 5. S-wave ray coverage and inversion result for S-wave

In both tomograms, horizontal layers can be seen. Low seismic velocities within the P-wave tomogram are due to the presence of the water table and data above and below it. High seismic P-wave velocities of up to 2300 m s^{-1} are calculated below this boundary. This area is obviously highly compressed even to a depth of -6 meter. Below this depth, the P-wave velocity decreases slightly to 1500 m s^{-1}. The S-wave tomogram shown in figure 5 shows similar structural features, i.e. a horizontal layering.

5. *Potential for geotechnical subsurface investigations and site assessment*

The thorough understanding of the spatial distribution of geotechnical parameters and the response of soils to small-strain dynamic loading is essential for risk assessment studies. Such risk assessment studies comprise e.g. the evaluation of the vibrational impact induced by railway, subway and roadway traffic. The combination of the seismic high-resolution tomographic method and CPT measurement is ideally suited to transfer the 1D information from CPT into the 2D measuring plane or even into 3D space. There are several deterministic transfer functions reported in the literature (Table 1).

Table 1. Examples of deterministic transfer functions for the derivation of S-wave velocity from CPT data

Transfer Function	**Reference**
$v_s = 118.8 * \log(f_s) + 18.5$	Mayne (2006)
$v_s = 32.3 * q_c^{0.089} * f_s^{0.121} * y^{0.215}$	Piratheepan (2002)
$v_s = 134.1 + 0.0052 * q_c$	Sykora and Stokoe (1983)
$v_s = (10.1\ \log(q_c) - 11.4)^{1.67} * \left(\frac{100 * f_s}{q_c}\right)^{0.3}$	Hegazy and Mayne (1995)

These deterministic transfer functions can be used to determine the S-wave velocity with the help of CPT data and vice versa to get geotechnical parameter distribution from S-wave tomographic data. According to studies by Ahmad et al. 2015 transfer functions developed by Mayne (2006) showed the greatest predictive capability.

The theoretical derived v_s data show a good correlation with real v_s data. Especially, the transfer function of Mayne (2006), Hegazy & Mayne (1995) and Sykora & Stokoe (1983) show a good fit for the CPT dataset. These transfer functions were derived from studies with different materials. Hegazy and Mayne (1995) developed the reported deterministic transfer function for all soils based on data from 61 sites worldwide, Mayne (2006) studied also all soils and Sykora & Stokoe (1983) refer the conditions of quaternary sands.

The derivation of the sleeve friction from seismic tomographic data using the transfer function of Mayne (2006) are in good compliance with measured sleeve friction data (see Figure 7).

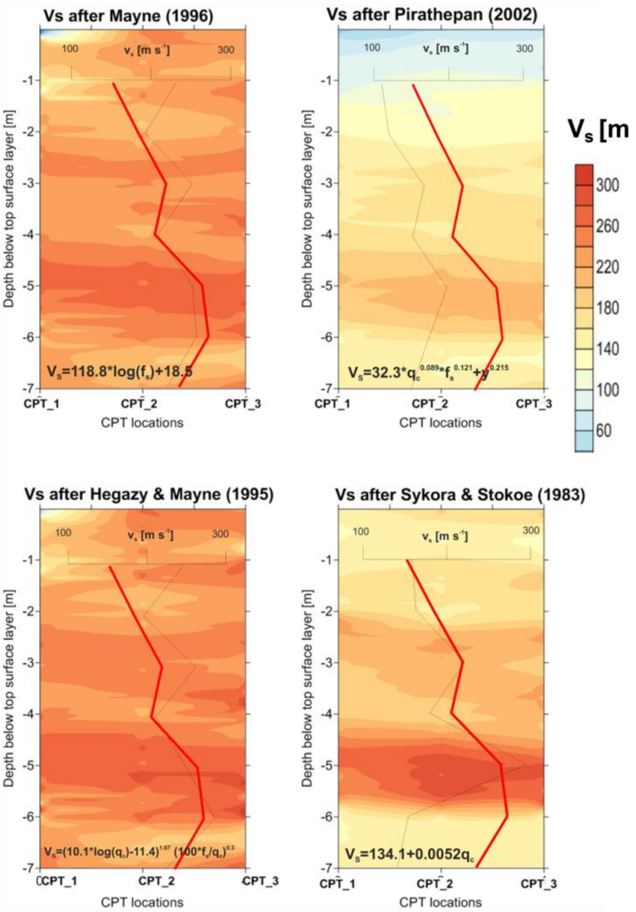

Figure 6. Examples of shear wave velocity derived from some reported deterministic transfer functions for trend analysis and comparison with measured v_s data (red line)

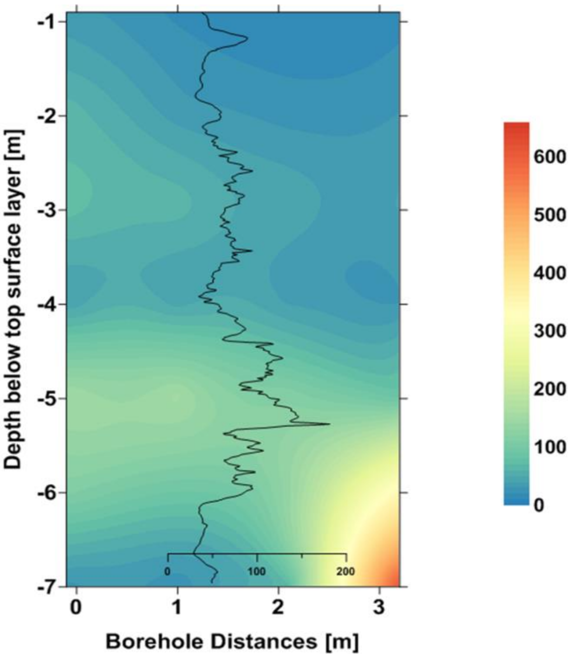

Figure 7. The plot of derived sleeve friction after Mayne (1996) and comparison with measured CPT sleeve friction data

6. Conclusion

The reliability of the predicted layering by interpolated CPT measurements depends significantly on the heterogeneity of the local geology as well as the distance between the test locations and is maybe questionable in many cases. The uncertainty of the interpolation can be reduced by applying seismic tomography between the CPT positions. In the frame of the R&D project CPTTOMO, a CPT-based tomography system has been developed by integrating multi-station three-component geophones as well as P- and S-wave sources in small-bore Direct-Push CPT rods. The developed prototype of a CPT-based seismic tomographic system is able to record simultaneously P- and S-wave velocity. Therefore geotechnical parameters could be derived with improved spatial representation. This system is cost- and time-efficient compared to conventional drilling methods and during measurements, an optimization to site-specific requirements is always possible.

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