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A CPT-based seismic tomographic system for geotechnical subsurface investigations and site assessment

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ABSTRACT: The spatial distribution of geotechnical parameters between CPT locations is often estimated by using various interpolation methods. However, the reliability of the predicted layering depends significantly on the heterogeneity of the local geology as well as the distance between the test locations and may be 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. This paper introduces this novel combined system, explains new data interpretation approaches and highlights the potential for geotechnical subsurface investigation and site assessment. Two examples for the determination of geotechnical parameters such as damping ratio and over consolidation ratio as a indicator for soil stress history will be presented.

RÉSUMÉ: La distribution spatiale des paramètres géotechniques entre les sites CPT est souvent estimée à l'aide de diverses méthodes d'interpolation. Cependant, la fiabilité de la stratification prévue dépend de manière significative de l'hétérogénéité de la géologie locale ainsi que de la distance entre les sites de test et peut être discutable dans de nombreux cas. L'incertitude de l'interpolation peut être réduite en appliquant une tomographie sismique entre les positions du CPT. Dans le cadre du projet de recherche et développement CPTTOMO, un système de tomographie basé sur CPT a été développé en intégrant des géophones à trois composants multipostes ainsi que des sources d'ondes P et S dans des cannes CPT Direct-Push de petit diamètre. Ce document présente ce nouveau système combiné, explique les nouvelles approches d'interprétation des données et met en évidence le potentiel d'investigation géotechnique en sous-sol et d'évaluation de site. Deux exemples de détermination de paramètres géotechniques, tels que le coefficient d'amortissement et le taux de surconsolidation, en tant qu'indicateur de l'historique des contraintes du sol, seront présentés.

Keywords: Direct Push technique, Cone Penetration Test, cross-hole seismic tomography, damping ratio, soil stress history

1 INTRODUCTION

The stability of stockpiles, dumps, opencast mining holes as well as renatured mining areas is influenced by anthropogenic induced and natural events leading to some fundamental changes in the soil structure. In extreme cases, these changes cause subsidence-related failures of the load-bearing soil capacity. The catastrophic consequences of resulting landslides, pitfalls, rock falls and rockslides form a high risk potential for people and property. Since 1999, approx. 3.8 billion euros have been invested in the remediation of abandoned lignite opencast mines in Eastern Germany. The success of the remediation measures is associated with mainly the increase in stability which depends on the terrain shape, the embankment geometry, the geochemical properties of the solid and loose material, the soil and rock mechanical properties and the hydrological conditions.

Therefore, 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 horizontally resolved, multi-level recordings of various geotechnical, geophysical and geochemical parameters with simultaneous sampling, regardless of the availability of drill holes.

A standard application of DP technology is the Cone penetration test (CPT) where a sensor probe with a cone-shaped tip is pressed perpendicularly into the ground at a constant feed rate of few centimeters per second. The CPT represents 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.

The CPT device 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 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 derive this required spatial information. Especially, crosshole seismic tomography for structural subsurface investigation has been widely used for high-resolution determination of spatially differentiated parameters between existing wells or boreholes. Therefore, seismic crosshole tomography may fill the information gap between the CPT positions.

Crosshole seismic tomography determines the distribution of P- or S-wave velocities along 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.

Thus, the velocity distributions 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 gives an overview about possible derived parameters of the CPT based tomographic system.

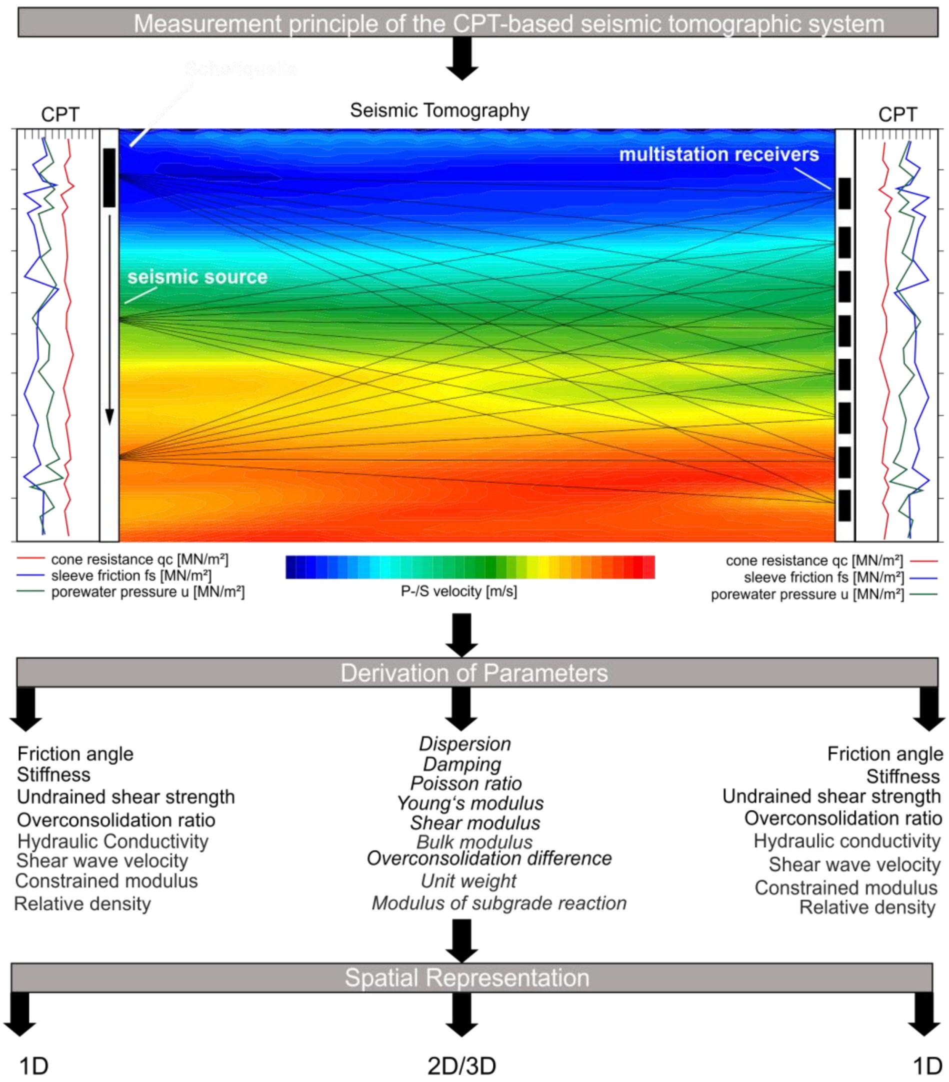

Figure 1. Overview of the derived geotechnical parameters and the spatial representation of a joint interpretation of CPT and seismic measurement parameters

2 CPT-BASED TOMOGRAPHY SYSTEM

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

Tri-axial small sized geophones having a natural frequency of 28 Hz were placed inside a rod using 3D printed mounting frames, i.e. one tri-axial sensor per 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 couple the modular stations. Tests showed a problem-free screwing of the individual rods.

Seismic sources were developed and placed inside the CPT rod. A sparker source having its sparking electrodes mounted on the outside wall of the rod has been developed. This source generates mainly P-waves and operates on the electric spark principle where high-voltage energy is released between two electrodes and the flashover produces a high-frequency sonic wave. A second seismic source generating SH-waves is under development.

Though, 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 does 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 developped and tested.

Figure 2. DP machine pushes the CPT based seismic tomographic system into the ground

Tests were carry out to validate the performance of the newly developed probes and will be presented at the conference.

3 DETERMINATION OF GEOTECHNICAL PARAMETERS

3.1 Damping ratio

The thorough understanding of the spatial distribution of geotechnical parameters in the near surface and their response of soils to small-strain dynamic loading is essential, especially for site specific risk assessment studies evaluating the vibrational impact induced by railway, subway and roadway traffic, ground response analysis at stable sites. Especially, shear modulus and damping ratio as key dynamic soil parameters are the topic of interest to geotechnical engineers.

The factors affecting the damping ratio in the soil are mean effective stress, void ratio, geological age, cementation, overconsolidation ratio (OCR), plasticity index, cyclic strain, strain rate and the number of cycles loading (Karl, 2005). The damping ratio D can vary for the different types of body waves. Small-strain stiffness and damping ratio are often problematic and onerous to obtain under field conditions (Badsar et al., 2010). Alternative techniques to determine the damping ratio include both laboratory methods and in-situ methods.
Nowadays, in-situ geophysical seismic methods (e.g. among others the borehole cross-hole and down-hole tests, SCPT, VSP, SDMT, SASW, MASW and seismic tomography) are accepted suitable method to derive this required information about the dynamic behaviour of soils at small-strain (Lai & Özcebe, 2015; Basdar et al., 2010).

Studies of Meza-Fajardo, 2005; Meza-Fajardo & Lai, 2007 and Lai & Özcebe, 2015 assume that for a viscoelastic solid means that the material stiffness and damping ratio can be also considered as frequency dependent and that both the velocity functions and the damping functions are not seen as independent parameters.

The functional dependency is expressed by the Kramers-Kronig (KK) equations also known as dispersion equations. Meza-Fajardo & Lai, 2007 indicate an excellent agreement of the exact solution of KK equations with a simplified dispersion relation derived by Aki & Richards 2002 predicting the same values of phase velocity.

With help of the in situ phase velocity measurements of shear waves the material damping ratio D is determined using this dispersion relation (Aki & Richards 2002).

$$V(\omega) = \frac{c(\omega_{ref})}{1+\frac{2D}{\pi}\ln(\frac{\omega_{ref}}{\omega})} \qquad (1)$$

Where D is the damping ratio [%], ω_{ref} reference frequency [Hz], c phase velocity [ms^{-1}] and ω frequency [Hz].

The vertical seismic profiling (VSP) experiment was done using a 3 component geophone. For an improved signal to noise ratio, a shear-wave vibrator system MHV-4S (developed by LIAG) was used. Two linear, 10-s sweeps were recorded ranging from 25 to 150 Hz. Due to the inhomogenity of the subsurface the damping ratio should be determined for pre-defined depth intervals. The assignment can be done with a fast interactive velocity adaptation. Then, the phase velocity spectrum of the test data was calculated using the Fourier transform (FFT) algorithm. The phase velocity maxima in the spectrum were picked manually and the mean was calculated for further reference. Then, an optimization algorithm for Eq. 1 was applied to find the parameters D, c (ω_{ref}), ω_{ref} that minimize the sum of squared errors.

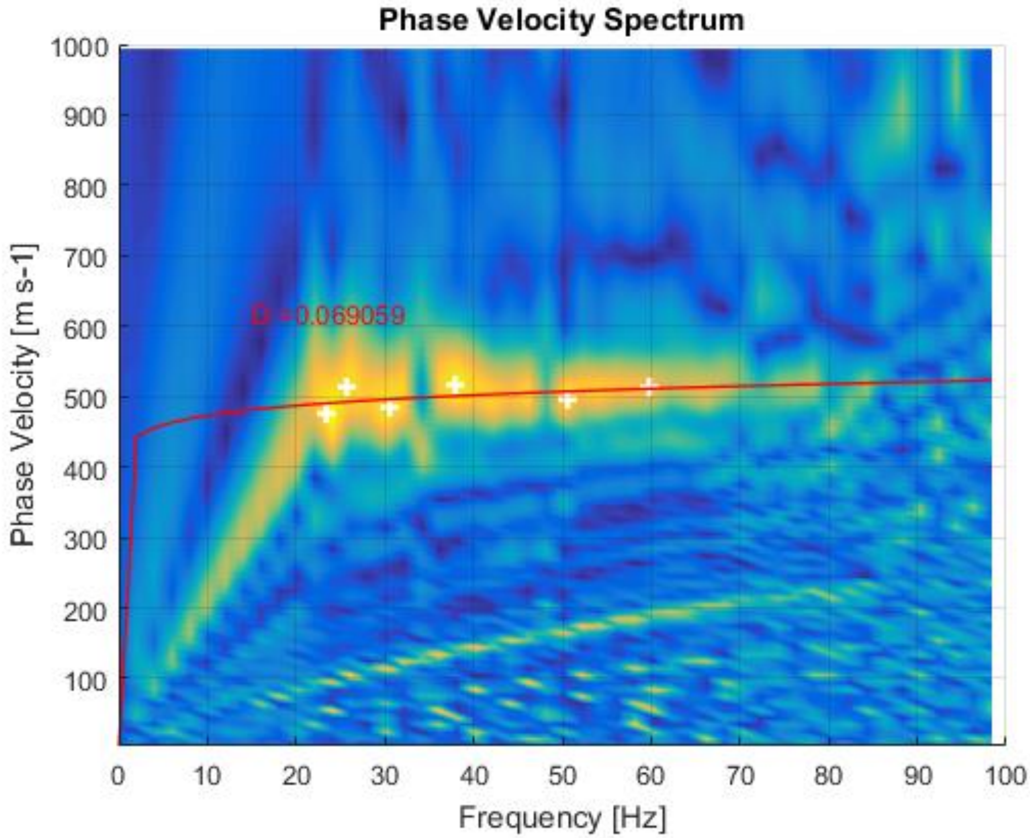

Figure 3. Example for determination of damping ratio with phase velocity spectrum; the damping ratio is 7.0% which represents claystone. Both the velocities $v_p \cong 1900\ ms^{-1}$ and $v_s \cong 450\text{-}500 ms^{-1}$ for this interpretation interval and a lithological log confirm this value.

3.2 Stress history (Overconsolidation Ratio)

Geotechnical engineers determine relevant physical and mechanical soil properties to evaluate stability of natural slopes, assess risks posed by site condition and design structure foundations. However, over a time period the soil can experience consolidation through several mechanisms like mechanical loading, glaciation or others.

The combination of a Direct-Push technology and paired S-wave cross-hole measurements are a cost-effective tool to evaluate the soil stress history usually represented through the so-called over-consolidation ratio derived from the over-consolidation difference. The paired S-wave cross-hole measurement is a direct in-situ measurement to potentially describe the soil stress history in terms of the OCD value.

The study used the standard crosshole testing procedure (ASTM, 2007) using the horizontally polarized shear wave borehole source BIS-SH to measure the velocity of horizontally propagating and SH-polarized shear waves ($V_{s,HH}$) and the vertically polarized shear wave borehole source BIS-SV to measure the velocity of horizontally propagating and vertically polarized shear waves ($V_{s,HV}$). The distance between the boreholes were 5 m.

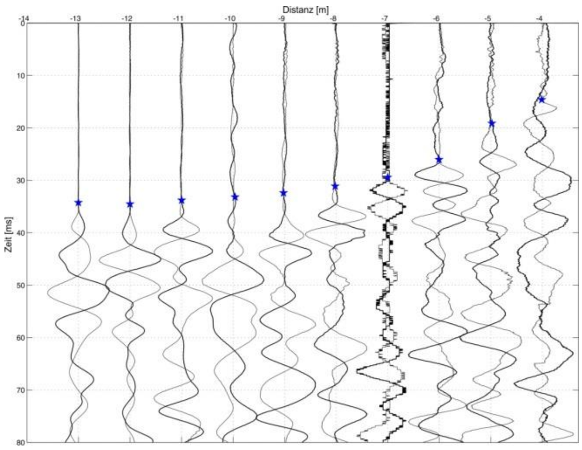

Figure 4. Seismogram of SV-wave generated by BIS-SV seismic source with picked arrival times (Mackens et al., 2017)

The first arrival times for SH and SV wave were picked for each cross-hole source and receiver configuration and velocities ($V_{s,HH}$, $V_{s,HV}$) were calculated based on the source and receiver distances.

Supposing a transverse isotropy along the vertical axis where material properties the same in all horizontal directions, it can be assumed that $V_{s,VH}$ and $V_{s,HV}$ are identical. Hence, the directional characteristics of the shear waves are used to calculate the OCR based on the empirical relationship by Ku und Mayne (2014).

$$\text{OCD} = 0.466 * \sigma_{atm} * \left(\frac{\rho(v_{s,HH})^2}{\rho(v_{s,HV})^2}\right)^{5.57} \quad (2)$$

Where OCD is the overconsolidation difference [kPa], σ_{atm} reference atmospheric pressure [Pa], ρ total mass density of the soil medium [kg m^{-3}], horizontally propagating and horizontally polarized shear waves $V_{s,HH}$ [ms^{-1}] and $V_{s,VH}$ horizontally propagating and vertically polarized shear waves [ms^{-1}].

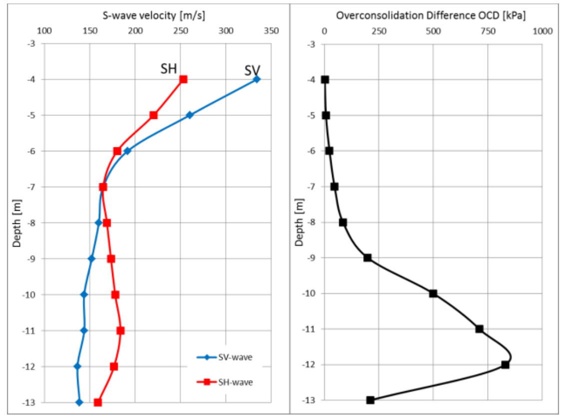

Figure 5. 1D velocity profile of SV-and SH-waves and the derived OCD values assuming a density of sand of 2000 kg/m³; Upper layer (<7m) has a maximum OCD of around 40 kPa which is characteristic for normal consolidated sand; Lower layer (>7m) has unusual high OCD values stiffness ratio ($G_{0,HH}/G_{0,HV}$) > 1

4 CONCLUSIONS

The developed CPT-based seismic tomographic system is able to record simultaneously P- and S-wave velocity and therefore derives geotechnical parameter 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.

5 ACKNOWLEDGEMENTS

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