# Comextech - actual state of ongoing work on the improvement of the geotechnical characterisation of the subsurface

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## 1. Introduction and aims

The improvement and enhancement of traffic infrastructure on and below the earth's surface requires a comprehensive investigation and description of the ground. This includes the analysis of the structure and mechanical properties of soils and sediments. Beside information on stratification or consolidation, the prediction of ground deformation is one of the most important topics in geotechnical engineering. The forecast of ground deformations requires knowledge on soil stiffness that can be assessed on-site by Cone Penetration Tests (CPT) and load bearing tests as well as off-site by laboratory tests. These tests, however, provide selective information only. For continuous ground information as well as for the selection of individual test locations, geophysical methods are applied in the frame of Comextech.

High-resolution geophysical methods are applied in combination with geotechnical exploration techniques for an efficient and complete description of ground conditions. Seismic methods provide an image of the subsurface with a resolution in the range of decimetres and meters in a capable and reliable manner. If a sufficient accuracy of seismic measurements is achieved, required ground parameters such as stiffness can be deduced. To manage this task, the understanding of the relationship between seismic and geotechnical parameters (relation shear strain – stiffness) has to be improved, also for a more effective use of the combination of seismic and geotechnical methods. Aspects, which have to be considered in this context, comprise the development and assessment of measuring and interpretation methods including the evaluation of their resolution as well as the optimisation of geotechnical investigations.

The main goal of the project is to offer a targeted investigation technique for a suitable acquisition of field data with different measurement techniques (Fig. 1). The different seismic methods, CPT and vertical seismic profiling (VSP) are to be combined with each other for an appropriate preparatory investigation of construction sites. By means of such techniques or methods developed in the project, an optimisation of the construction work and the reduction of the economical risks arising from an incomplete knowledge on the ground condition should be achieved. By repeated application, the investigation technique could be used for the monitoring of time dependent changes of the subsurface during construction work.

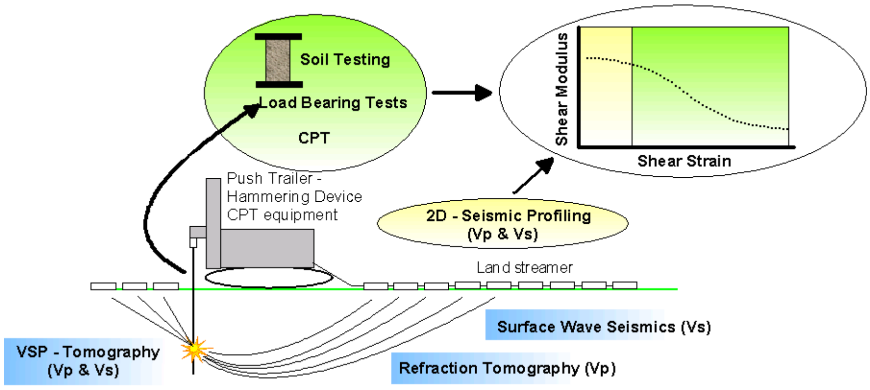


**Fig. 1: Combined exploration techniques – The derivation of geotechnical parameters (e.g. shear strain, shear modulus) by combination of seismic and geotechnical surveys.**

## 2. Actual state of the project

In the following, an overview of the present state of two main topics of the project will be presented. At first the development of technologies for site characterization in the field scale is outlined, followed by the description of the approach for the analysis and the derivation of relationships of geotechnical and geophysical parameters.

### 2.1 Technologies for efficient site characterization in the field scale

#### 2.1.1 Development of a seismic landstreamer

The development of the landstreamer aims to provide a receiver array to perform seismic surface wave (MASW) and seismic refraction tests more economically than with conventional sensors stuck into the ground.

Until now four prototypes of potential streamer design have been built and compared with the performance of conventional spike mounted geophones by in situ tests. This was a water hose streamer, a water pocket streamer, a rubber mat streamer and a sledge streamer. Comparison showed great advantages of the sledge streamer compared to commercially available streamers, which have been used as a reference.

The sledge streamer uses accelerometers installed separately on small steel sledges (refer to Fig. 2). The sledges are screwed onto a textile belt connecting them to the towing vehicle. Within the textile belt air wave absorbing material can be placed to reduce noise. The main advantage of using accelerometers is their broad frequency band, which covers a range of 0.1 Hz to several KHz.

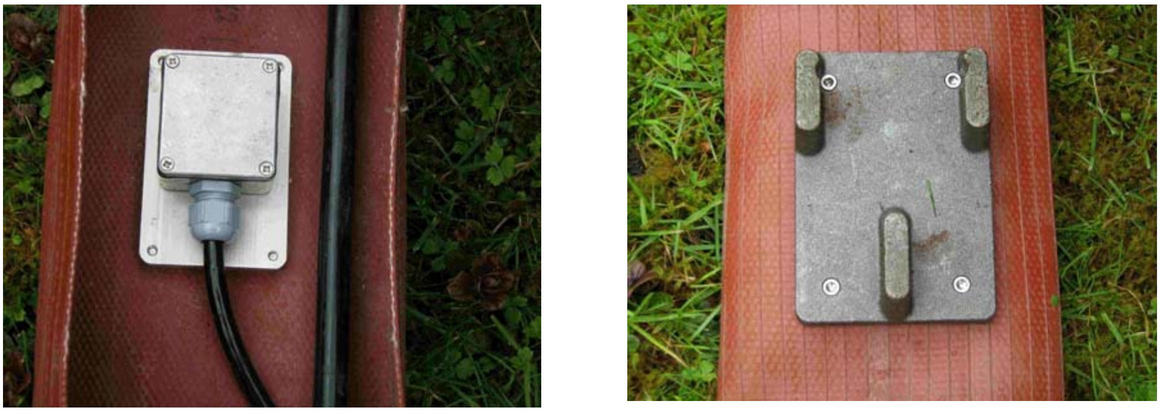


**Fig. 2: Sledge streamer design with accelerometers (left picture shows the inside textile belt, right picture shows steel sledge mounting).**

Considering the advantage of the new streamer design tests have been made on surface conditions where streamers are usually used, i.e. on paved areas. The new 12-channel sledge streamer (1 m spacing) was compared to a 24-channel streamer with 4,5Hz geophones (0,5m spaced) on four different surface conditions, i.e. gravel, asphalt and paved ground as well as on grass. A sledge hammer was used to generate seismic signals. Fig. 3 shows both streamers on gravel surface.

A shot offset of 5 m was used for the test. The software Surfseis was used to analyze the data. Fig. 4 shows the overtone analysis of the data obtained on gravel surface. It can be recognized that the dispersion curve retrieved from the sledge streamer data are of better quality (higher S/N ratio, extension to higher frequencies). Further improvement shall be made by extension of the sledge streamer to 24 channels.

Fig. 3: Test location for land streamer.

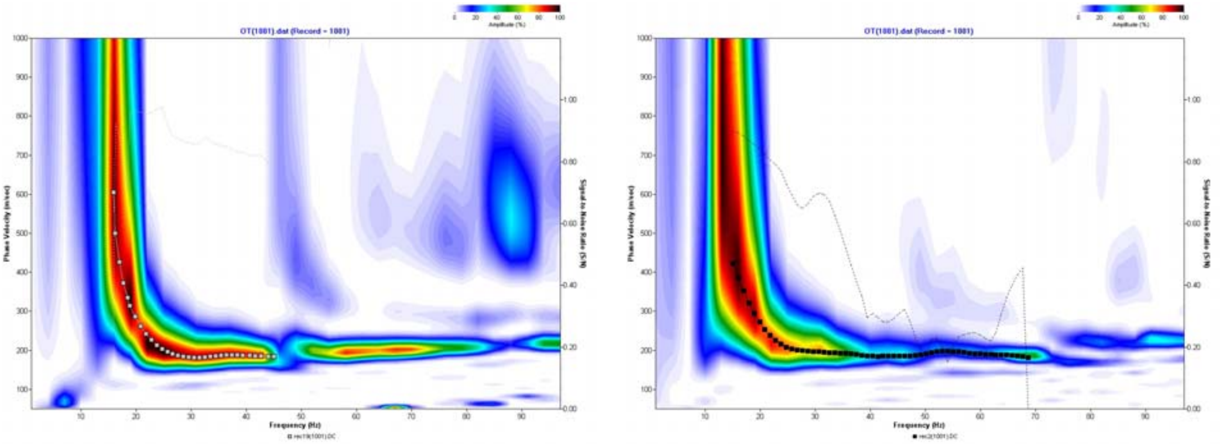


Fig. 4: Dispersion curves for sledge streamer (left) and commercial 4,5Hz streamer (right)

### 2.1.2 Development of seismic sources

Source design for CPT surveys faces challenges as seismic signals have to be generated below and above the water table. Further, the small-diameter boreholes drilled by CPT machines restrict the source design. Nevertheless, a SCPT-source (Seismic Cone Penetration Test) should generate also different wave types like P- and S-waves, if possible. In any case a seismic source for CPT equipment has to meet special requirements.

Within the research project, well-established seismic sources (like borehole sparkers) were tested to qualify the special demands. Whereas sparker sources need water coupling or a certain moisture content to work, a new source based on electrodynamic principle (ED) was designed to avoid this restriction. This new source type, i.e. electrodynamic source qualified to be superior to the well-known sparker source because of their potential use within the unsaturated and saturated zone. A prototype of the ED source fitting to a 2 1/8” rod was developed (see Fig. 5) and laboratory tested.

**Fig. 5: SCPT source mounted in a 2 1/8” rod.**

The source is powered by a newly developed 800V impulse generator. The new HV unit runs from a 24V source and is therefore independent of external AC power supply. Field test shall be conducted end of 2008.

## 2.2 Further development and evaluation of methodologies for site characterization

During the current period of the project, field investigations have been carried out at the sites Dreiskau-Muckern, Löbnitz, and Nauen. At these sites seismic applications have been tested with different measuring approaches. CPT-soundings and additional ground-penetrating radar (GPR) surveys have been performed at the newly introduced site Nauen. This site near the town Brandenburg west of Berlin is superficially characterised by glacial and periglacial deposits (loess-like sediments and sand above till), and suitable for CPT-soundings. Nauen is used as hydrogeophysical field-test site of the TU Berlin and Federal Institute for Geosciences and Natural Resources (BGR) since several years, and thus a number of data are published and available. Ahead of the field work, for example, seismic test P- and S-wave tests were performed by the GGA in consultation with the UFZ.

### 2.2.1 Geophysics

Seismic measurements have been carried out with a landstreamer, tipped with different geophone arrays. The focus of field investigations lay on the site Nauen, where two field campaigns had been performed in summer 2008. The landstreamer used for the profile measurements was tipped with 72 geophones. The first 24 positions were filled with 4.5 Hz geophones, the remaining positions were filled with 14 Hz geophones with a distance of 1 m, respectively (Fig. 6). A similar arrangement of geophones was already tested at the site Dreiskau-Muckern, where 4.5 Hz geophones had been combined with 60 Hz geophones. The idea behind is that the positions close to the shot point, which are not utilisable for reflection seismics, can be used for the interpretation of surface waves. The signal was given with an accelerated weight drop mounted on vehicle. Shots were arranged every meter, and four shots per shot point were executed for an increased signal/noise ratio. Three registration units (Geode$^{TM}$ by Geometrics), which were connected in series, were applied for signal recording.

At the Nauen site, two profiles with lengths of 164 and 198 m were investigated, whereas one profile was recorded in bidirectional manner, which results in three recorded lines. The purpose of bidirectional recording is to check the reliability and sensitivity of the seismic array and to increase the resolution of the image of the subsurface (Fig. 7).

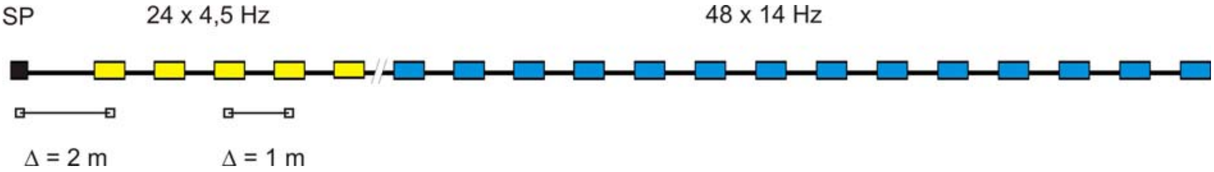


**Fig. 6: Geophone array with 72 channels of the landstreamer for the profile measurements at the Nauen site. The offset was 2 m and the respective geophone distance was 1 m. SP = shot point.**

By using the same shot points forth and back, a multiple overlap rate for certain common depth points (CDP) can be achieved, which is thought to result in an increased data quality. First results of data processing are presented in Fig. 8, showing the interpolated shear wave velocities (Vs) of the analysis of the Rayleigh-type surface waves on a multichannel record (MASW) by using the program SURFSEIS. The velocities are more or less laterally layered with zones of lower velocities in the upper subsurface and in about 5 m depth at the southern part of the profile (right edge in the figure, approx. between 100 and 150 meter). The strong increase of shear-wave velocities in 10 m depth and below is supposed to correspondent to a glacial moraine underlying the sandy sediments. By comparing both images it turns out that the methodical approach of bidirectional seismic measurements still needs some tests since the forward/backward data show slight but distinct differences in detail. Furthermore, the data of the recorded lines are to be generated for analyses of reflection- and refraction seismics.

Also in progress is the processing and analysis of vertical seismic profiling (VSP) data, collected at the Nauen site. In contrast to the latter profiles, VSP measurements were carried out with stacked 14 Hz geophones. Altogether 24 geophones were arranged along a profile with 1 m spacing. The signal was given with a sparker, a source that was placed into the subsurface by direct-push soundings. While the geophones in spot remained, the sparker was displaced in various depths, which results in a large vertical overlap in seismic information.

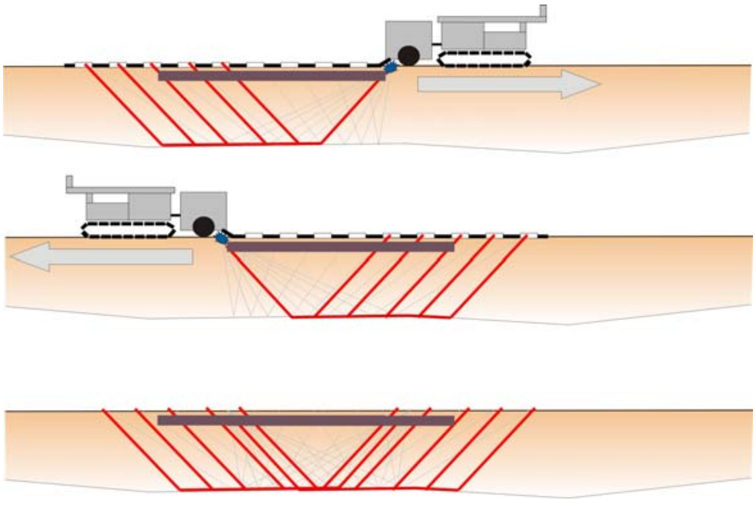


**Fig. 7: Scheme of bidirectional seismic measurements performed at the site Nauen. By bidirectional recording, the overlap in seismic information increases for a more detailed image of the subsurface. Grey line: reflected waves; red lines: refracted waves; violet line: surface waves.**

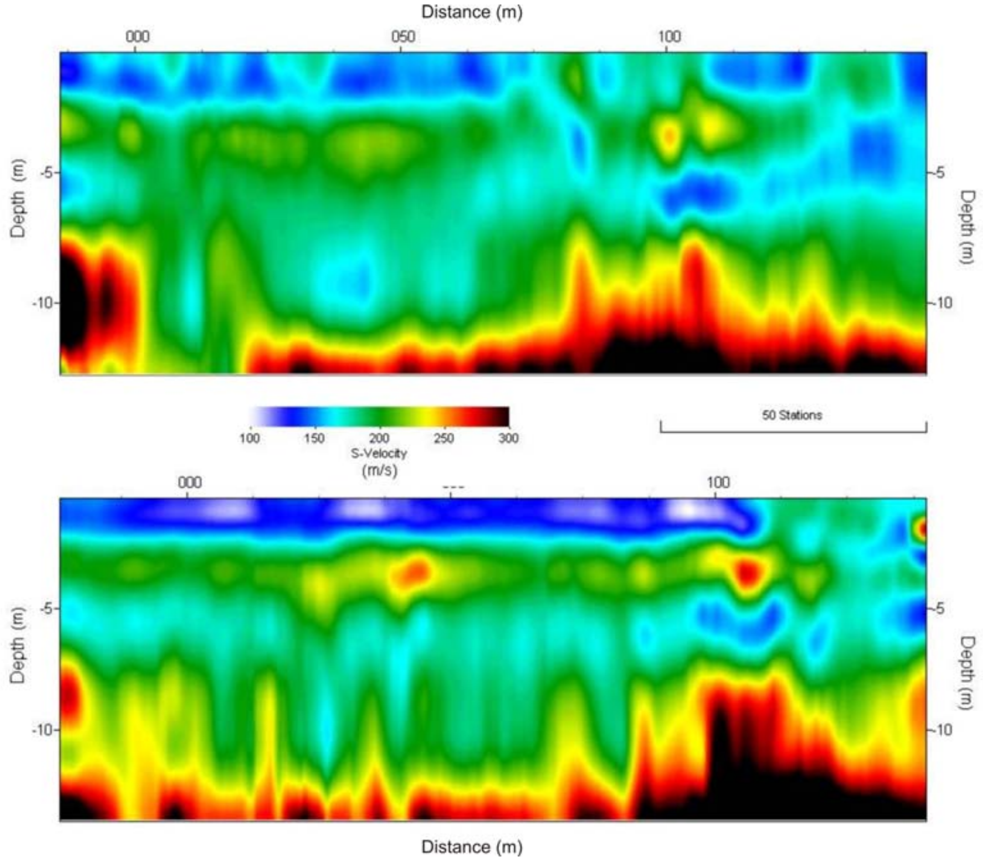


**Fig. 8: Shear-wave velocities analysed by MASW along a 164-m profile, measured forward (above) and backward (below).**

### 2.2.2 Cone Penetration Test (CPT)

Contemporaneously to the seismic investigations at the Nauen test site, 14 CPT soundings have been performed along or near the seismic profiles. The final depths of the CPT surveys range between 14 and 36 meter below the surface with the absolute maximum depth of 36.6 m. All CPT soundings include Cone Resistance (qc), Sleeve Friction (fs), and the inclination. An example of a CPT profile is given in Fig. 9. Zones of increase cone resistance are found in 10 m depth and below 12 m depth, which is basically consistent with the results of MASW. A detailed analysis of CPT soundings with reference to the seismic field tests will be performed in a next step. The technology of CPT is well tested in the meantime and can be applied in a suitable manner.

### 2.2.3 Summary of site-characterisation methodologies

At the present state of the project, the methodology for near-surface field investigation is in applicable and efficient conditions. We are able to explore the subsurface with various seismic methods (multi-channel analysis of surface waves (MASW), reflection and refraction seismics) at once with the described geophone array. By using the landstreamer a profile may easily investigated in forward and backward direction. VSP and CPT soundings are in applicable conditions as well. The improvement of the quality in data processing, analysis interpretation regarding the reliability of ground information is in progress. Furthermore, the soil penetration technique of SonicSampDrill for high-quality soil/sediment sampling is ready for operation in the frame of the project. The intention is the recovery of sediment cores useable for geotechnical laboratory tests. Drilling tests are planned at selected sites.

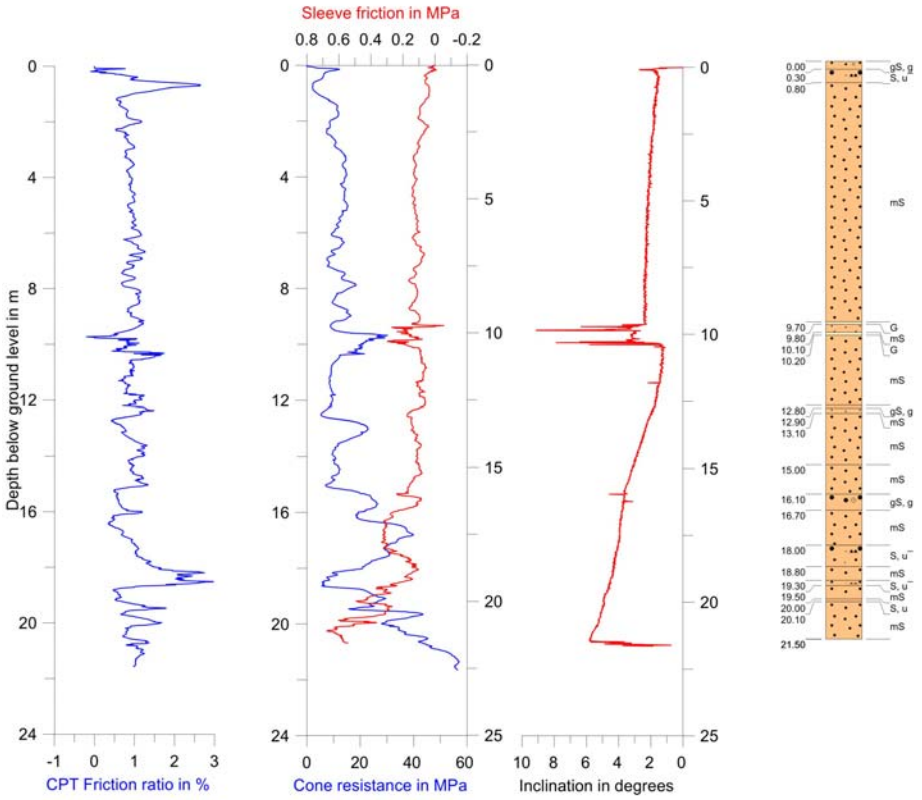


**Fig. 9: Example of one CPT sounding near the seismic profile shown in Fig. 8. The derived lithology from the Friction ratio value is shown right of the CPT curves.**

## 2.3 Approach for the analysis and the derivation of the relationship of geotechnical and geophysical parameters

### 2.3.1 Interface between Geotechnics and Geophysics

From the foregoing investigation, some points in the search of the interface between Geotechnics and Geophysics were found. More detailed knowledge has to be presented in the interpretation and the transfer of the ex and in situ seismic analysis, in the interpretation and transfer of the geotechnical ex situ field test and the extended application of the obtained physical parameter in geotechnical analysis. The essence of the link between Geophysics and Geotechnics are not contentious and proved by the foregoing research results. The named open points in research are mostly the interpretation of the results, interpretation in physical meaning, the geotechnical use as well as the parameter influence for certain geological conditions. Following subsequent tasks occur by the interface definition: a) developments in field measurements, b) developments in laboratory testing, c) development in signal processing and d) developments in constitutive modeling in small strain stiffness of soils.

### 2.3.2 Field investigations

By the different test, it is obvious the application of Cone Penetration Test, Dynamic Falling Weight and further geotechnical tests have a regular place in the whole range of field testing. But the interpretation of the results is by far more complex as the application in field tests. The widely used Cone Penetration Test in geotechnical, geotechnical earthquake engineering and geoenvironmental engineering fields is more or less empirical interpreted in engineering practice. The objective in geotechnical field test research was the embedding of more complex models for further interpretation knowledge. Actually the research in Cone

Penetration testing based on more or less five different theories: a) the Bearing Capacity Method, b) the Cavity Expansion Method, c) the Steady State Deformation Method, d) the Incremenental Finite Element Analysis and e) the Calibration Chamber Testing.

The Bearing Capacity Method determines the cone resistance and cone factors by different approaches according to whether the soil is more sand or clay type. For the cone resistance the theory based on the collapse load theory for deep footings, whereas the cone factors are determined by limit equilibrium or slip line analysis. The advantage of this theory is the determination of the friction angle φ by back calculation of the CPT field tests (figure 10).

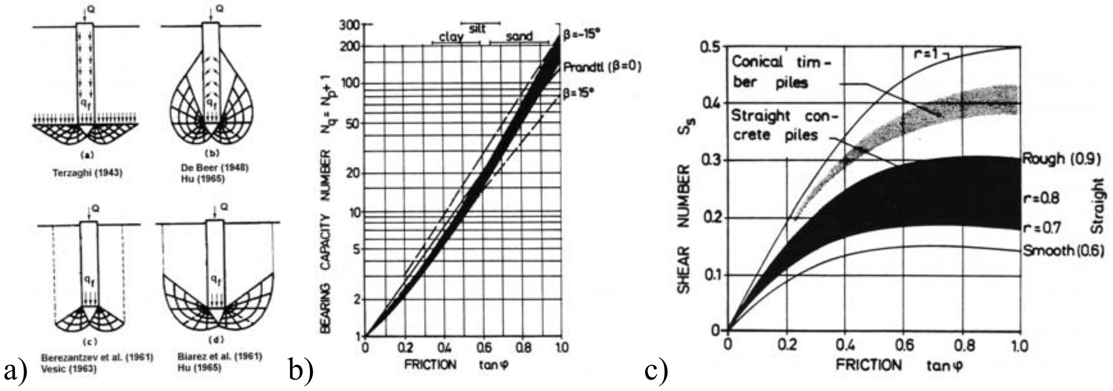


**Figure 10: a) Failure mechanism, b) & c) back-calculated typical values $N_q$, $S_s$ , $f_s$ and φ**

In opposite of the Bearing Capacity Method (BCM) the Cavity Expansion Method (CEM) is more appropriate for non-failure processes. The Cavity Expansion Method is based on the cavity expansions solution in elastic-plastic materials. The non-reversible deformation behaviour is determined by the determination of the cylindrical cavity pressure due to elastic and plastic deformations during penetration. By this approach the CEM is more realistic than the BCM and actual under development.

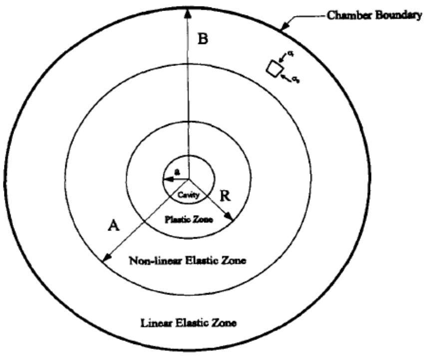


**Figure 11: The generation of plastic, nonlinear elastic and linear elastic zones due to cavity expansion**

### 2.3.3 Laboratory investigations

The focus in the current laboratory testing research is the deposition of the above described objectives in the laboratory investigations, that means, a development in interpretation of the measurement results and its interpretation are necessary. The advantage of lab testing – the study of soil behaviour under lab conditions and lab control with advanced interpretation knowledge is to be transferred into field testing. Actually the main focus put on granular soils – sands and sandy soils. Different types of sands were studied regarding the deformation characteristic, the porosity behaviour under different confining pressures and wave velocity characteristics with the corresponding stiffness behaviour. To avoid the difficulties in the wave velocity determination an advanced method based on the Wavelet transform were developed and compared with more conventional methods.

In the foregoing research new testing equipment were developed to analyse dependency of the wave velocity to different soil conditions. The equipment was developed to analyse soil samples under laboratory conditions. The developed piezoelectric transducers are controlled and the seismograms recorded by a developed LabView program. In the past different conventional signal shapes for wave field excitation were tested. Several problems exist in determining the right wave velocity. Additionally the element transfer functions are specified: the element transfer function, the resonance function and the time delay between transmitter / receiver. Following conventional method were analysed to determine the wave velocity in soil samples under different conditions: time domain methods – first arrival determination by using start-to-start method, peak-to-peak method, cross correlation of the first half / one period. Additionally to the time domain methods different frequency domain methods were analysed - cross power spectrum method, phase difference method by using an impulse and sweep excitation. The objective of the different wave field analysis in laboratory testing was to determine the shear wave velocity with the time domain method and the phase velocity by using the frequency domain method. By assuming that the wave propagation is a non-dissipative material, the wave velocity is equal to the phase or group velocity.

To overcome the difficulties during the conventional tests, several advanced time-frequency methods were used to determine the group velocity. Following time – frequency methods were analysed and new developed: windowed Fourier transform, Wavelet transform in time domain (WTtime), Wavelet transform in frequency domain(WTfrequency), Wigner-Ville distribution (WVD), Choi-Williams disdribution (CWD). The basis signal form during the time-frequency analyses was a sweep signal with a linear increase of frequency within the 1kHz and 20kHz.

To analyse the non-stationary sweep signal the continuous Wavelet transform was chosen (figure 10). In opposite to the orthogonal Wavelet transforms the continuous wavelet transform has a better redundancy of the signal's information content. For the mother wavelet a complex-valued wavelet- the Morlet wavelet is chosen. The complex-valued wavelets are able to reduce the oscillation of the real and imaginary wavelet transformed part and the $L^2$ norm module gives the energy density of the transformed signal.

$$W_{s,\tau} = \frac{1}{\sqrt{|s|}} \int_{-\infty}^{\infty} f(t)\,\psi\left(\frac{t-\tau}{s}\right) dt \quad \text{mit} \quad \psi(t) = \pi^{-0,25} e^{j\omega_0 t} e^{-\frac{1}{2}t^2}$$

By choosing the Morlet wavelet the wavelet window is described by an modulated Gauss function $\psi(t)$. The large disadvantage of the continuous Wavelet transform is the high numerical effort and calculation times.

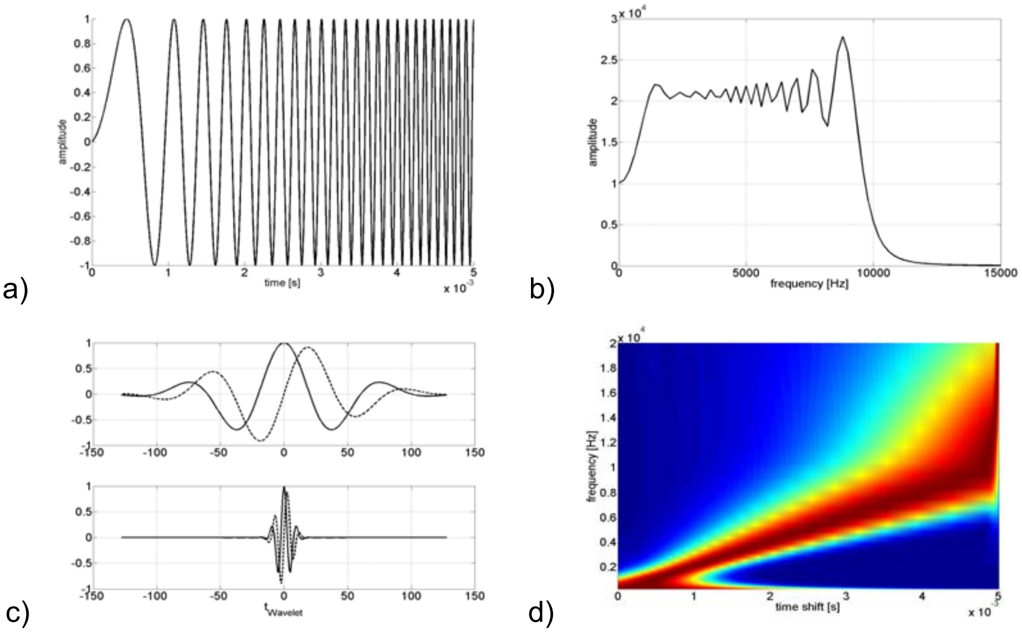
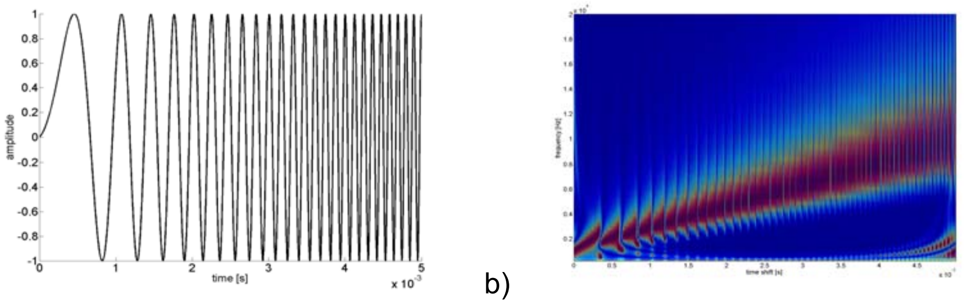


**Figure 10: Wavelet transform of Sweep signals; a) Theoretical sweep signal, b) Frequency content of the Sweep signal, c) Morlet Wavelet, d) Wavelet transform of the Sweep (Time-Frequency Spectrum)**

To compensating this disadvantage for large sample numbers different capabilities were analysed. The application of orthogonal Wavelet transforms, like fast Wavelet transform, fails due to the weak resolution of the Wavelet transformed signal. A better option to analyse large signals is the transfer of the continuous Wavelet transform into the frequency domain and the realization of the convolution between the signal and the wavelet transform in this domain.

$$W_{s,\tau} \xleftarrow[\text{back transform}]{\text{IFT}} \mathsf{F}\left\{W_{s,\tau}\right\} = \mathsf{F}\left\{f\left(t\right)\right\} \cdot \mathsf{F}\left\{\psi_{\text{Morlet}}\left(\frac{t-\tau}{s}\right)\right\}$$

By different comparative studies the developed method was several hundred times faster than the conventional continuous Wavelet transform. The improved method could be used without problems during running laboratory tests (figure 11).

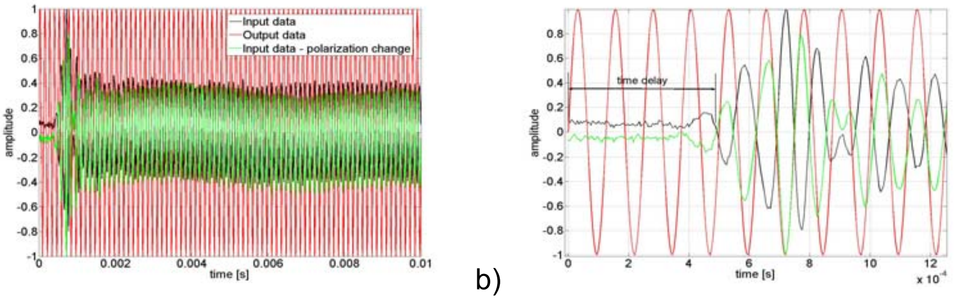


a) b)

**Figure 11: a) Applied theoretical sweep signal, b) Surface plot – magnitude of the wavelet transformed signal**

Within the laboratory studies the different methods were compared and analysed to determine the development of wave velocity behaviour under change of confining properties.

In figure 12, 13 and 14, the principal comparison of time domain methods, frequency domain methods and time-frequency methods are shown. Due to the different inscribed energy content between the resonance and the non-resonance range of the piezo ceramic elements, inside the wavelet transformed signal normalized spectra are used (figure 5). The determined group velocity varied over the frequencies as shown in figure 6. To study the occurring wave field effects a theoretical model with the laboratory boundary conditions were created. The used finite element model will serve afterwards to the comparative study of the constitutive models at the interface to the initial modulus connected with the determined wave velocity.



a) b)

**Figure 12: a) Analysing study by using harmonic excitation, b) screen shot of about 1 ms**

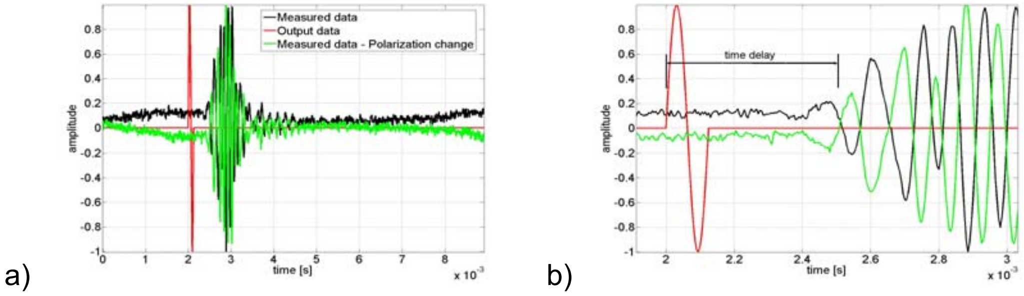


**Figure 13: a ) Analysing study by using impulse excitation, b) screen shot of about 1 ms**

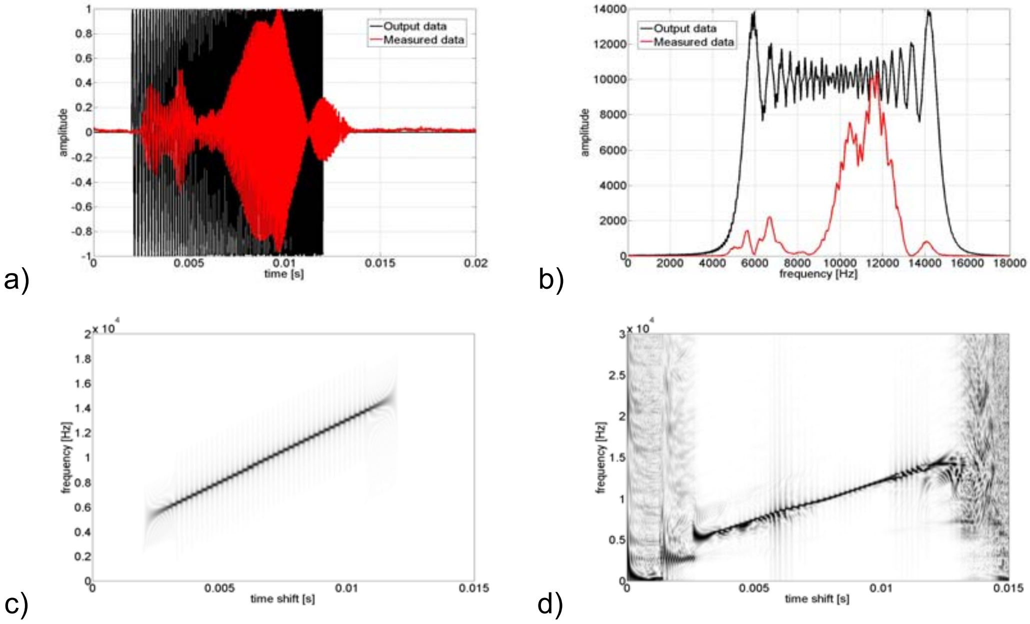


**Figure 14: a) Analysing study by using sweep excitation, b) Frequency content of the time histories, c) normalized time-frequency spectra of excitation by WVD, d) normalized time-frequency spectra of measured sweep signal by WVD.**

The objective of the different laboratory tests is to find the relations between wave velocities and soil parameter in order to interpret and transfer the in-situ results into relevant geotechnical parameter. From the whole investigated type of sands only the results of two different sands are shown. These two sands show different grain size distributions, wave velocity and void ratio (see figure 15). It is obvious that the results are depending on the confining pressure, void ratio and the grain size distribution.

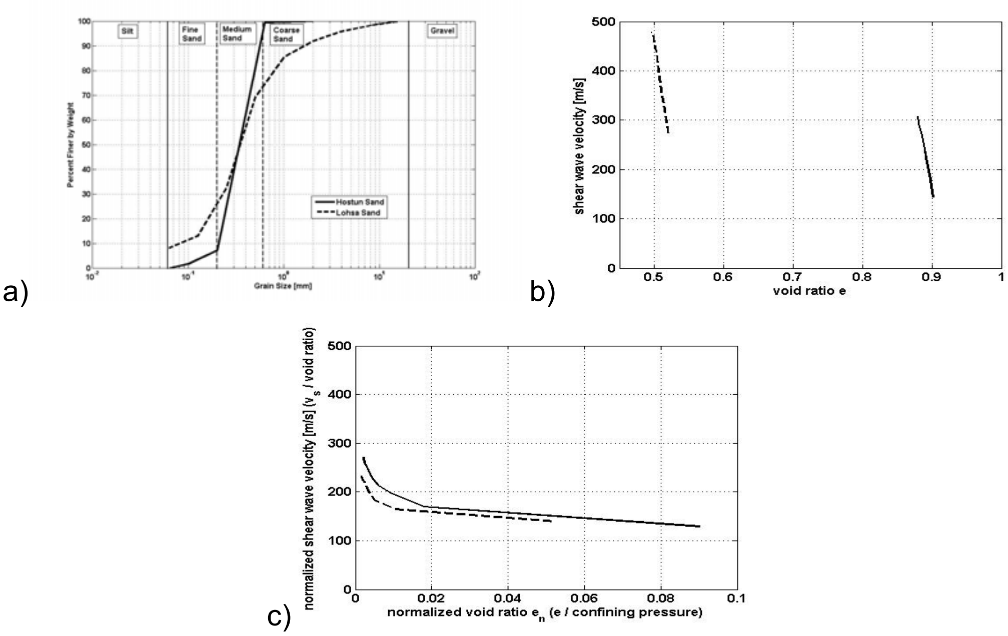


**Figure 15: a) Grain size distribution of two different sands, b) Shear wave velocity in dependence of the void ratio, c) normalized shear wave velocities of the two different sands**

By the normalization, the results can be described in closed, analytical way, whereby from the measured in situ wave velocities the further initial geotechnical parameter (e.g. void ratio) can be determined by back calculation.

### 2.3.4 Theoretical applications

The final application of the wave velocity or the initial stiffness parameter has to occur in geotechnical calculations to improve the stiffness description during loading processes. The consideration is depending on the level of geotechnical task. The embedding is possible by different ways: in equivalent - linear models for more or less approximated calculations, to calculated true geotechnical problems by using initial stiffness parameter a well developed constitutive law based on the continuum mechanics has to be used. The development in this field did start in the late 1970's by implementation of kinematic yield surfaces. From the field of soil dynamics the use of stiffness-strain curves was well known. Typical models are of the Hardin-Drnevich type. These models based on the hyperbolic stress-strain description which are given by Kondner/Zelasko. Further models are the well-known bilinear Ramberg-Osgood. All these models describe the shear-strain $\gamma$ shear-stress $\tau$ space under dynamic loads

$$\text{Bilinear:}\quad \tau = \begin{cases} G_0 \gamma & \text{for} \quad \gamma < \gamma_{threshold} \\ \tau_{threshold} + G_0 \left(\gamma - \gamma_{threshold}\right) & \text{for} \quad \gamma \geq \gamma_{threshold} \end{cases}$$

$$\text{Ramberg-Osgood:}\quad \gamma = \frac{\tau}{G_0}\left(1 + \alpha \left|\frac{\tau}{\tau_{threshold}}\right|^{\kappa}\right)$$

$$\text{Kondner/Zelasko:}\quad \tau = \frac{G_0 \gamma}{1 + \left|\dfrac{\gamma}{\gamma_{threshold}}\right|}$$

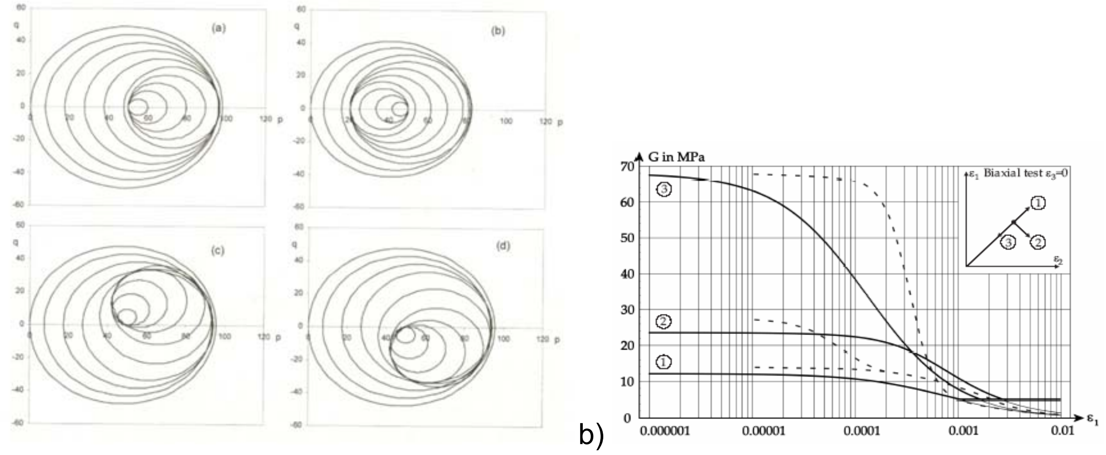
$$\text{Hardin-Drnevich:}\quad \frac{G}{G_0} = \frac{1}{1 + \left|\dfrac{\gamma}{\gamma_{threshold}}\right|}$$

By fitting the non-linear stress-strain function, Jardine defined for the first time the secant stiffness with initial small strain parameters.

$$\frac{E_u}{c_u} = A + B\cos\left\{\alpha\left[\log_{10}\left(\frac{\varepsilon_a}{C}\right)\right]^{\gamma}\right\}$$

Further developments of existing kinematic hardening models result in the extension to kinematic hardening models with multiple yield surfaces. The limitation of single surface models is obvious when the behaviour of single surface models is compared to that of real soils. The true linear elastic region is often very small and the plastic yielding starts almost immediately with straining. On of the most important feature of multi-surface models is the ability of these models to capture the recent stress history into a closed mathematical description. Inside of this class of multi-surface models are the so-called “bubble” models by Stallebass or Al-Tabbaa. The bubbles, small kinematic yield surfaces, move with change of stresses in the stress space.

Based on the multi-surface models the continuous model was developed by Houlsby & Puzrin (Figure 16a). The development of continuous models is logical by consideration the fact that the introduction of a single yield surface or several yield surfaces is artificial and doesn’t correspond to the true soil behaviour. The behaviour of the soil reflects much more a continuous field of yield surfaces. This model can reproduce a smooth transition from elastic to plastic soil behaviour. This approach is consistent with the generalized thermodynamics and hence a closed mathematical framework. By using the definitions in the thermodynamic context, there is a possibility to extent the theory for the description of more complex materials like porous continua. For the case of a continuous hyperplastic form of a small strain model, the definition of the inner elastic yield surface and the outer yield surface are controlled by two potential functionals.



a) b)

**Figure 16: a) Field of yield surfaces after different stress paths (Houlsby/ Puzrin), b) Stiffness-strain degradation by the small-strain overlay model (Benz)**

A further development to simulate the small-strain behaviour of soil was done with the Small-strain overlay model by Benz (Figure 16b). The objective of this development was the fact that models used in engineering practice have rarely more than one elastic domain, e.g. Hardening soil model. The developed small-stain overlay model is a paraelastic approach.

## 3. Outlook

The present working state is in good agreement with the planned time schedule of the project. The work will be continued accordingly the above mentioned scientific objectives and working packages.

In the next future, the application of the interface determination of laboratory tests on geophysical measurement will be a major investigation. The definitions are to be generalizing for use in conventional and advanced geotechnical applications. Additionally, from the generalization of the results simplified procedures are to be defined for the use of the given relations in practical applications.

In terms of field measurements, geotechnical investigations shall be linked in a straight line to the results of seismic tests by adaptive approaches. Further improvements of seismic landstreamers as well as of the drilling technology are to be tested and assessed according to the scientific objectives of the project.