COMEXTECH- A combined exploration technique for the delineation of subsurface structures and the assessment of rock parameters

K. Marschall[1], F. Wuttke[2], L. Karl [3],T. Fechner[3], T. Schanz[2], H.-G. Schmidt[2], P. Dietrich[1]

[1] Helmholtz Centre for Environmental Research – UFZ, Permoserstraße 15, 04318 Leipzig

[2]Bauhaus University Weimar, Faculty of Civil Engineering, Soil Mechanics, Coudraystrasse 11c, 99421 Weimar

[3]Geotomographie GmbH, Am Tonnenberg 18, 56567 Neuwied

1. Introduction and aims

The people's increasing demand for mobility requires a substantial effort in improving infrastructure, i.e. an increasing need for new traffic and transportation systems above and below ground exists. For new constructions or reconstructions, a complete description of the ground is needed including the structure and soil mechanical properties (e.g. consolidation, creeping, maturing). In this context, the prediction of ground deformation is one of the most important topics in geotechnical engineering, where the prediction requires the knowledge of soil stiffness. In most cases local site tests such as Cone Penetration Tests (CPT) and load bearing tests as well as laboratory tests are used to estimate stiffness.

The aim of the project COMEXTECH is to combine high resolution geophysics with geotechnical exploration technique in order to describe the subsurface structures and the deformation behaviour of construction ground more effectively. Seismic methods will be applied to capably and reliably imaging with a resolution of decimeters up to meters and sufficient accuracy in terms of needed soil parameters such as stiffness. This includes the development of a better understanding of the relationship between seismic and geotechnical parameters (relation shear strain – stiffness) and the combination of seismic exploration with geotechnical investigations. That includes the (further) development and assessment of measuring and interpretation methods, the evaluation of their resolution and finally the optimising of geotechnical investigations.

At the end of the project, an investigation technique should be available, which allows the common acquisition of field data for different measurement techniques (Fig. 1). The investigation technique will be suitable for the preparatory investigation of construction sites, e.g. for highways, railroads and shallow tunnels. The results of such an investigation should help to optimize the construction work and to reduce the economical risks, which arise from an incomplete knowledge of the subsurface condition. By repeated application, the investigation technique could be used for the monitoring of time dependent changes of the subsurface during the construction.

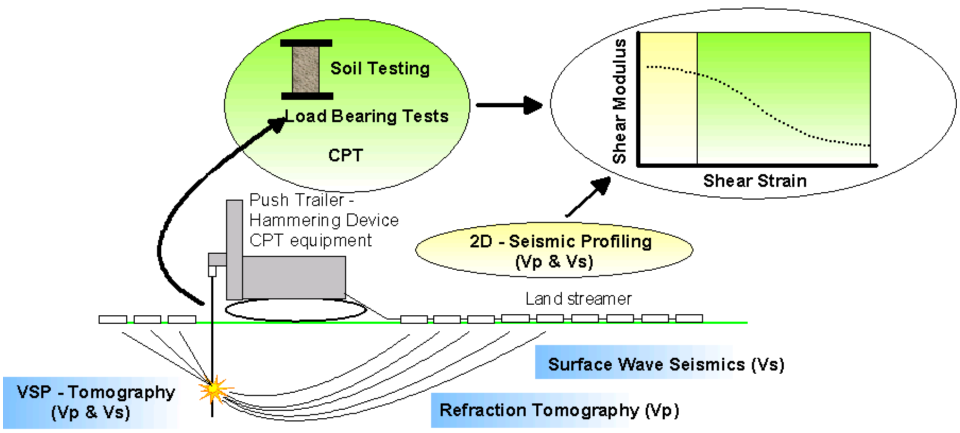

Fig.1: Combined exploration techniques – The derivation of geotechnical parameters (e.g. shear strain, shear modulus) by combination of seismic and geotechnical surveys.

2. State of the art

In order to provide soil parameters such as stiffness as input to numerical models, depth dependent stiffness profiles are needed. As these parameters are strain dependent, they have to be described for a wide range of shear strains. Among these, starting values are needed, i.e. maximum stiffness at small shear strain. Usually, starting values are obtained at small strain < 10^{-5}. These data are invariant even at different loading frequencies and they can therefore be regarded as basis for all static and dynamic considerations. Common laboratory tests are not suitable to obtain such data (Lacasse 1986, Burland 1989). Reliable data sets at small strain rates of 10^{-6} to 10^{-5} can only be obtained under laboratory conditions using Resonant-Columns-Tests, Bending elements or by direct strain measurements during triaxial tests. However, the analysis and interpretation of these tests are usually based on the assumption of undisturbed soil samples, which is in most cases not valid.

Alternatively, load bearing tests (DIN 18134) or CPTs (DIN 4094-1) can be used under field conditions. Although CPT posses a high vertical resolution, both suffer on their ability to predict lateral changes of soil parameters. Using seismic methods soil parameters may be additionally obtained without disturbing the ground and with spatial continuity. However, only a combination of all above mentioned tests may lead to a comprehensive description of the soil strain state (see Fig. 2) (Jamiolkowski et al.1995, Tatsuoka et al. 1997).

In the frame of the project, the following seismic methods will be combined and further developed: seismic tomography (refraction; 2D, 3D), vertical seismic profiling (VSP), multichannel analysis of surface waves (MASW), refraction and reflection seismics. Depending on the applied method, the shear or compressional wave velocities are determined. Commonly, the seismic methods are used individually. Although, e.g. refraction seismics can image the compressional wave velocity (Vp) distribution with depth and MASW the shear wave velocity (Vs) distribution with depth no combination is published yet although a Vp/Vs ratio map will significantly improve interpretation and reduce ambiguity.

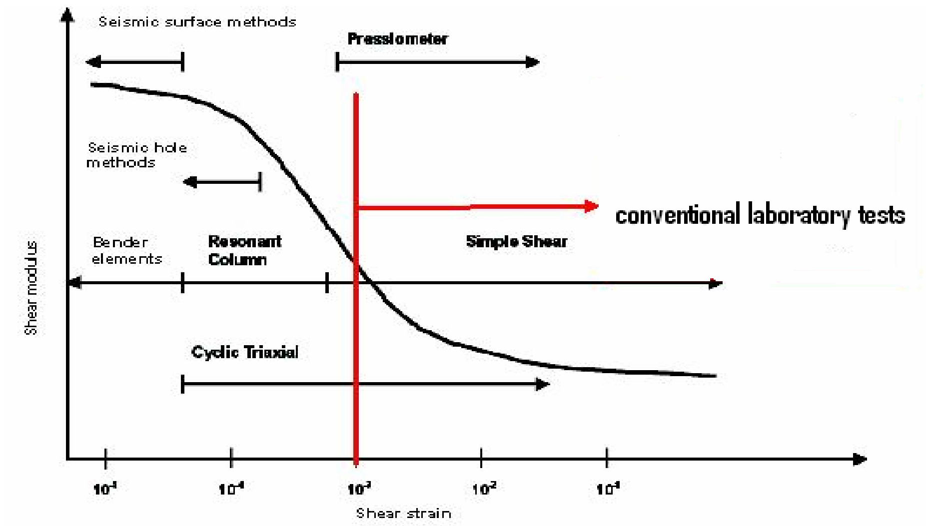

Fig. 2: Soil testing methods and typical strain ranges.

For the interpretation of the results of seismic investigations in terms of the geotechnical characterization of a site, rock physical considerations are necessary. These considerations can be based on the use of known theoretical relationships, rock physical models and/or statistical methods. If the compressional and the shear wave velocity are known then, for

example, they can be used for the calculation of elastic modules (Angenheister, 1982). But it must be considered for the geotechnical interpretation that in such a way we get dynamic elastic modules and not the required static dynamic modules (Schön, 1983 & 1996).
Also rock physical models can be used for the analysis and derivation of relationships between the seismic and the geotechnical parameters (Schön, 1996). Thereby, the complexity of the used models and the available information about the site specific conditions should be taken into account.

3. Scientific objectives and working plan

The aim of the project is the (further) development of seismic measuring devices, methods, and measuring concepts for the geotechnical site investigation (see above-mentioned). This includes the combination of seismic methods with geotechnical field and laboratory investigations. The project work is a cooperation of the Helmholtz Centre for Environmental Research (UFZ), the Professorship of Soil Mechanics of the Bauhaus-University of Weimar (BUW), and the Geotomographie GmbH (Geotom). The project management is in responsibility of the UFZ.

The planned research is divided in the following seven work packages:

1. Further development of numerical algorithms for surface wave seismic (BUW) and 2D/3D tomography (UFZ)
2. Development and testing of a seismic "land streamer" for the use with a "Push trailer" (Geotom)
3. Development and testing of seismic sources (Geotom)
4. Geotechnical laboratory (BUW) and field investigation (UFZ)
5. Investigations for the combination of geophysical, geotechnical and geological parameters (UFZ and BUW)
6. Development of a concept for the adaptive application of geotechnical tests on the base of the on-site interpretation of seismic measurement (UFZ)
7. Field investigation for testing and evaluation of the developed measuring devices, methods and concept under different site conditions (UFZ, Geotom, BUW)

Further detailed information about the project aims and working plan can be read in the project proposal (funding no. 03G0636A) or be requested from the project partners

4. Present state of the project

In the following the present state of the two major topics of the project work are presented. First the development of technologies for site characterization in the field scale is outlined and secondly the approach for the analysis and the derivation of the relationship of geotechnical and geophysical parameters is shown.

4. 1. Technologies for efficient site characterization in the field scale

To describe the subsurface structures and the deformation behaviour of construction ground more effectively the development of measuring equipment and of site characterization technologies are necessary.

4.1.1 Technical developments

4.1.1.1 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. Considering this field application some parameters and requirements of the new device are defined prior to the actual design work. The essential fixed points are a vertical orientation of the receiver axes, a changeable receiver spacing from 0.5 to 2 m and the possibility to pull the streamer by vehicle and exceptionally also by hand over paved and unpaved areas. A standard streamer should contain 24 single receivers according to the capability of most seismographs to record 24 channels.

Other design parameters need a practical evaluation in the laboratory and in situ. The most important questions concern the selection of an appropriate sensor type, the method of the mechanical coupling between sensor and ground, the tight connection between the single sensors and the coupling device for the vehicle. Furthermore a way of maintaining a sufficient vertical sensor axis on uneven surfaces needs to be found.

Until this state of the project four prototypes of the streamer have been built and compared with the performance of conventional spike mounted geophones by in situ tests.

a) Water hose streamer
A string of 24 hydrophones is placed inside a water filled hose with the size of a fire hose. A chain connects one end of the hose to the trailer hitch of a vehicle.

b) Water pocked streamer
Single hydrophones are placed in plastic bags filled with water. Several hydrophones are assembled to a string.

c) Rubber mat streamer
12 geophones are installed on a rubber mat of 40 cm width. The sensors are gimbal mounted in order to keep their axis vertical. The streamer is attachable to a trailer hitch.

d) Sledge streamer
Accelerometers are installed separately on small steel sledges. The sledges are screwed onto a textile belt connecting them to the towing vehicle.

The project is currently in the state of deciding which prototype will be developed further and which one has to be dropped. The hydrophone based streamers are able to follow the surface topography almost perfectly but the used transfer medium water has shown to affect the signal quality significantly due to reflection and resonance effects occurring inside this medium. The rubber mat streamer provides seismic signals of a similar, maybe even better, quality than conventional spike mounted geophones. It can replace the conventional geophones already in its present shape fully. The sledge streamer needs still some improvement concerning the reduction of airborne sound effects. However, the use of accelerometers has, because of their almost linear frequency response from 1 Hz up to the kHz range, great advantages for the penetration depth and resolution of surface wave methods.

The concept of the most promising prototype will be rigorously tested at different sites and environmental conditions in the further course of the project.

4.1.1.2 Development of seismic sources

The use of seismic sources in the tip of "Direct push" equipment allows the measurement of vertical profiles and tomography planes without expensive and time consuming installation of boreholes. For the practical use, robust equipment must be developed, which can also be advanced by high-performance hammering devices.
Generating seismic signals can be achieved using a permanent installed source within the hammering rod or a temporary installed one. A permanent installed source has to be shock protected to avoid destruction due to high acceleration during direct-push probing. Temporary installed sources require a probing stop to allow the lowering the source within the hammering rod. They are limited to the inner diameter of the rod whereas a permanent installed source can be designed for an individual rod type. Anyhow, a permanent installation blocks the rod and prevents further probing, i.e. groundwater sampling.

Further, source design faces challenges as seismic signals have to be generated below and above water table. Nevertheless, a SCPT-source (Seismic Cone Penetration Test) should generate also different wave types like P- and S-waves. 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) are going to be re-designed to qualify the special demands. Also, new source types like electrodynamic (ED) sources are going to be considered.

Whereas sparker sources need water coupling or a certain moisture content to work electrodynamic sources are not limited to this. Both types, sparker and ED sources, can be used to generate P- and S-waves. Geotomographie has developed prototypes of the two source types under laboratory scale. Both are currently undergoing an optimization process to find out the right balance between signal strength and installation size. It is obvious that the smaller the source is the less energy it may produce. In this content it is essential to evaluate for which rod diameter a source type is suitable.

For sparker sources it seems most promising to use the Geotomographie high voltage impulse generator (5000V). Anyhow, for ED-sources a smaller impulse generator was build working at about 800V. The smaller voltage clearly lowers the health risk. Prototypes of the sources are expected to be available within the year 2007.

4.1.2 Further development and evaluation of site characterization technologies

For the development of practical measuring devices and the evaluation of measuring methods and concepts, extensive field tests under different environmental conditions are necessary.
On base of following criteria: a: different geology, b: heterogeneous site characteristics, c: long profile, d: different covering, e: practically relevant, five different test sites are selected:

- Löbnitz -levee foreland with known channel structures in the underground (a, b, c)
- Großbrembach – deep loess soil (a)
- Klettwitz – a former open-pit mining site (a)
- Zeitz – very heterogeneous geology (a, b, c, d)
- construction site of a planned road (e)

Field investigations were already carried out on the sites in Löbnitz, Zeitz and Großbrem-bach. In the following we present the results of Löbnitz.
The field plot Löbnitz (grassland, 700 m x 6 m) is located near Leipzig, Germany. It runs parallel to a levee of the river Mulde and is characterized by channel structures of different sediment and stiffness in the underground.The starting positions of our different surveys were not identical on the test site. For a better orientation we indicated the position not by the

distance in meter but by the “levee kilometre” of the levee nearby. Its standard characterization is km+m, e.g. 2+700 km.

4.1.2.1 Cone Penetrating Test (CPT)

To find a suitable profile for our geophysical surveys 15 CPT surveys were done along a profile on the field plot into the most possible depth. All CPT surveys included Cone Resistance (qc), Sleeve Friction (fs) and the tilt angle.
The profiles of the cone resistance (Fig.3) show little resistance down to a depth of about 3 m and higher values in deeper areas. Between the levee kilometer 2+750 km and 2+875 km and between 2+925 km and 3+000 km there are higher resistance values in the shallow underground as well. Combined with the sleeve friction values (not shown) it could be concluded that in these areas there must be coarser or more compact materials (sand or gravel) whereas in the area of less cone resistance but high sleeve friction (not shown) there must be fines, i.e. clay or silt. This anomaly may be a former meander channel that has been filled with coarser bed load sediments and the fines possibly represent ‘over-bank’ flood deposits.

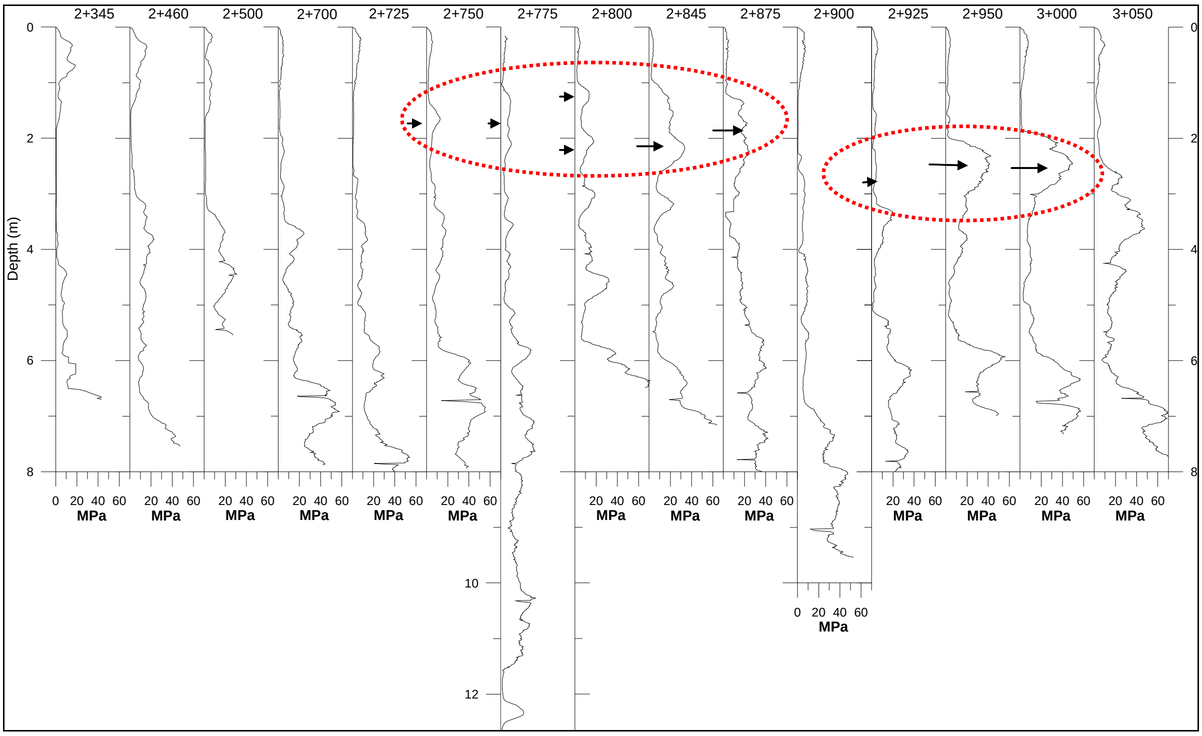

Fig. 3: Cone resistances along the profile on the test site Löbnitz. The positions of the survey points are indicated by the levee kilometer of the levee nearby. The red orbits show an area there is a coarsening of materials in the shallow underground.

4.2.1.2 Geophysics

<u>Seismics</u>
For the characterization of a construction ground, various seismic methods have to be considered: refraction and reflection seismics, multi-channel analysis of surface waves (MASW), vertical seismic profiling (VSP) and 2D/3D tomography. Thereby the joint application of various methods and the combined interpretation of the data are of peculiar interest.
At the site in Löbnitz refraction- and reflection seismics, MASW and VSP were applied. Geophones (14 Hz) along a 200 m-long profile were initially stuck in the ground. It arises that

for the survey of the shallow underground refraction- and reflection seismics are not appropriate at this site. The ground properties- the refraction layer is at great depth- do not allow sufficient signal strength whereas MASW reveals useful results.

Next a landstreamer was used for MASW. The landstreamer, designed by Geotomographie, was tipped with 24 geophones in a distance of 0.5 m. The offset was 10 m and the measuring interval 5 m. The signal was given by a 7.5 kg hammer. The data were generated into shear wave velocity profiles (Vs) by analysing the Rayleigh-type surface waves on a multichannel record (MASW) by using the program SURFSEIS.
Figure 4 is showing the interpolated shear wave velocities along the profile. The velocities are lateral layered in the subsurface and are rapidly increasing in speed in approx. 7 m depth. The increasing of the shear wave velocity corresponds very well with the increasing of CPT-cone resistance in that depth. Most CPT-cones couldn't penetrate deeper than to 7 or 8 meters (Fig.4). There is supposed to be a compacter material that leads to higher cone resistance and shear wave velocity.

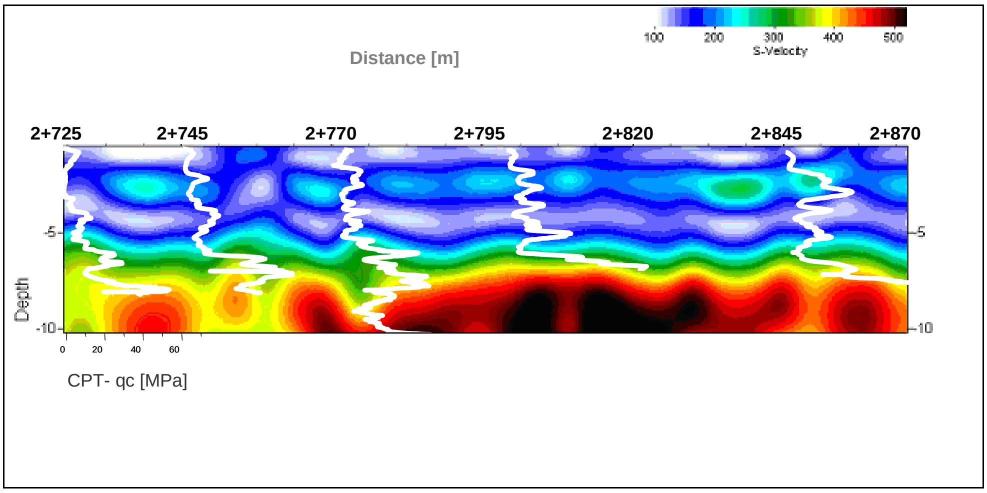

Fig. 4: Shear wave velocities analysed by MASW of the shallow underground combined with CPT-cone resistance curves (qc) at different points along the profile. The distance is indicated by levee kilometres.

Since refraction and reflection seismics are not suitable to determine the shallow underground at this site, other methods like DC Geoelectrics and GPR were tested to explore construction relevant properties of the ground.

<u>DC Geoelectrics</u>
Parallel to the seismic profile a Wenner array with 1.5 m electrode spacing was acquired on a length of 238.5 m starting from 2+700 km. We used RESECS equipment. The data were inverted by the Program Resistivityimager (Fig.5).
The pseudo-section and the inverted section show an anomaly of high resistivity in the shallow underground in the middle of the profile (2+740 km to 2+870 km). The anomaly corresponds with the area of the former meander channel.

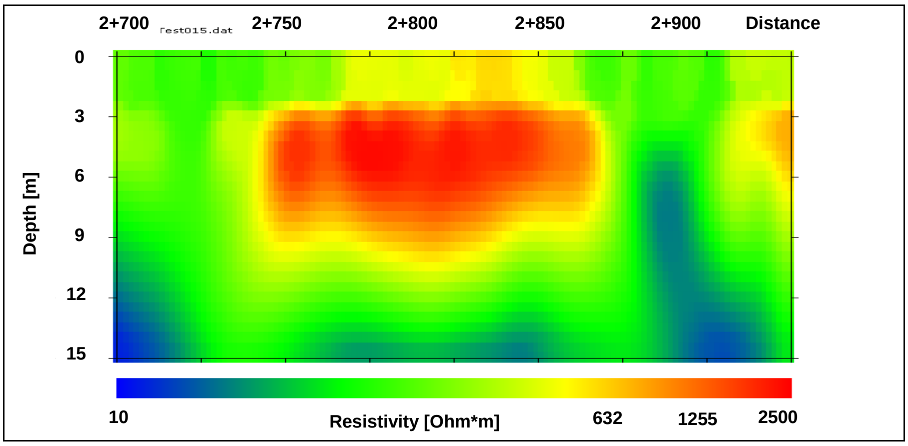

Fig. 5: DC Geoelectrics (Wenner array, 1.5 m electrode spacing). The inverted section shows an anomaly of high electrical resistivity in the shallow underground in the middle of the profile. The distance is indicated by levee kilometres.

The analysis of shear waves display the layering in the shallow underground and the changing of stiffness in the deeper ground. The DC geoelectric are more sensitive for the anomaly caused by the channel.

The results show that the applied geophysical methods are suitable to display geotechnical relevant structures at our test side. In future, geophysical investigations will be evaluated as a prerequisite for reliable and less expensive geotechnical surveys.

4.2 Approach for the analysis and the derivation of the relationship of geotechnical and geophysical parameters

For the connection of geotechnique and geophysics, the definition of the interface between both fields and basic investigations of this interface are essentially. At present, this interface can be given to the appearing shear wave velocity in situ. That means for the research network to determine the wave velocity in situ and the repeatability of this parameter in the laboratory. From this it follows, that the experimental developments have to be done in strain dependent constitutive laws, which are usually used in geotechnique. To achieve this purpose, different problems have to overcome in field and laboratory investigations. In the following, the essential results up to now are presented.

4.2.1 Field investigations

For the determination of soil parameters different geotechnical field tests have been tested and compared with regard to their applicability for soil parameter determination. The objective was the ability to predict the initial shear stiffness. At present, the ground of the test fields Löbnitz and Großbrembach are investigated. An extract of this analyses are presented in figure 6. Following techniques are compared: drilling profile, dynamic probing, cone penetration tests and seismic surface wave measurements. By using derived and available correlations (figure 6) the shear wave velocity or shear stiffness can be calculated.

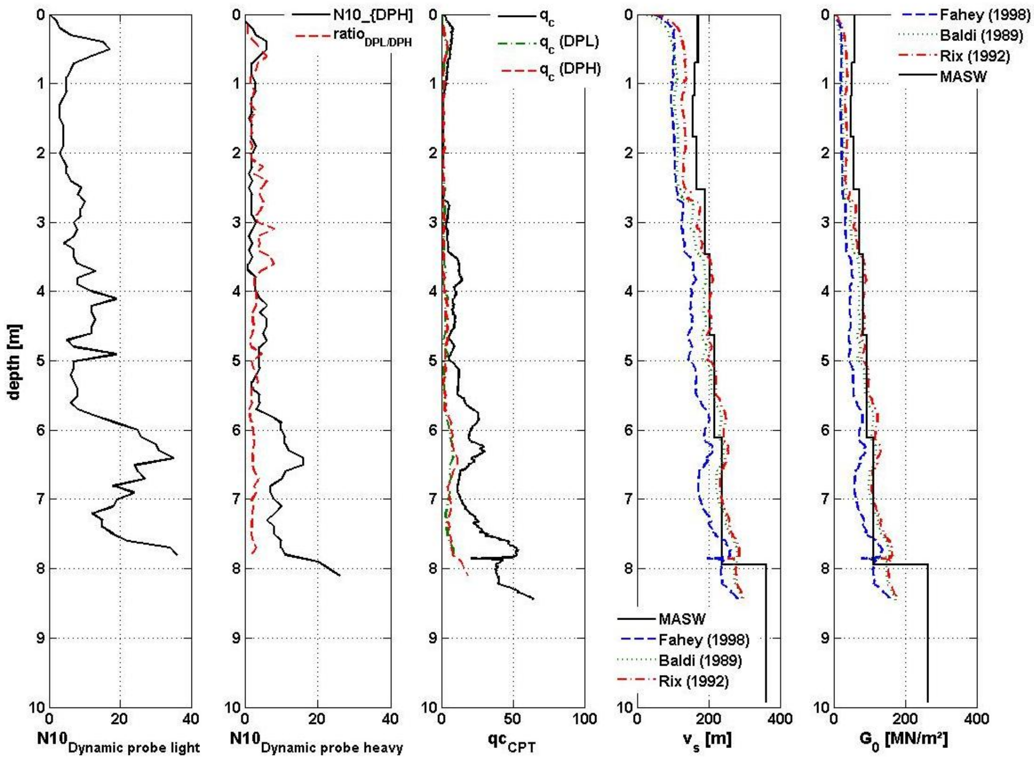

Figure 6: Field tests and correlation results at point 2-725 / Löbnitz

At the same location, different kinds of soil samples were taken. The samples play a major role in laboratory to identify the shear wave velocity and thereby the initial shear stiffness for further strain dependent descriptions during the lab experiments. At site Löbnitz, with three different methods material were extracted and analysed - disturbed material, tube sampling and block sampling (figure 7).

Figure 7: Extraction of tube sampling and block sampling at site Löbnitz:

4.2.2 Laboratory investigations

The first and essential aim of the laboratory investigations on the soil samples is the determination of the shear wave velocity and their comparison to the in situ wave velocity. To achieve this objective, piezoelectric bending ceramics were integrated in the existing triaxial cells. These bending elements are able to excite mainly shear waves in the soil sample. The sound system contains the following components: piezo transmitter and - receiver in top und base plate, a charge amplifier, a function generator (LabView) for arbitrary source functions and an oscilloscope (LabView and PicoScope). Due to the grain size and the cell geometry, the possible frequency range is limited between 1 kHz to 50 kHz, depending on the present wave velocity. There are different difficult points in this investigation: sample preparation inside the cell, contact between piezo-elements and soil, the source signal as well as the determination of the shear wave velocity. For the determination of the influence of sample preparation different techniques were analysed. The determination of time delay and the transfer function of transmitter and receiver which is important to know is determined or in work. For the determination of the shear velocity different techniques were analysed.

A widespread and often discussed technique is the using of the first arrival in time domain. The extracting of the shear wave velocity can be difficult and often ambiguous. The literature proposes often four different points (see figure 8: points A, B, C, D). In application of these four points the near field effect has to be considered. It is not exactly determinable were the near field effect starts. The consideration of the cross correlated time function of source and receiver signal in the frequency domain seems to improve the determination of the time delay. To provide the suitable source signal for the piezoelectric bending elements different waveforms were programmed and applied. Following types of impulse shapes were analysed: sinus - half, one and two periods, square, triangle, Ricker 0...2.order and step function. To detect the start of the shear wave within the seismogram in all waveforms the polarization can be changed.
Beside the essential points for determining the shear wave velocity, different investigations due to the frequency and cell pressure dependences were done. By using the time domain methods it's very difficult to avoid near field effects (figure 9), which result in a frequency dependency of the shear waves.

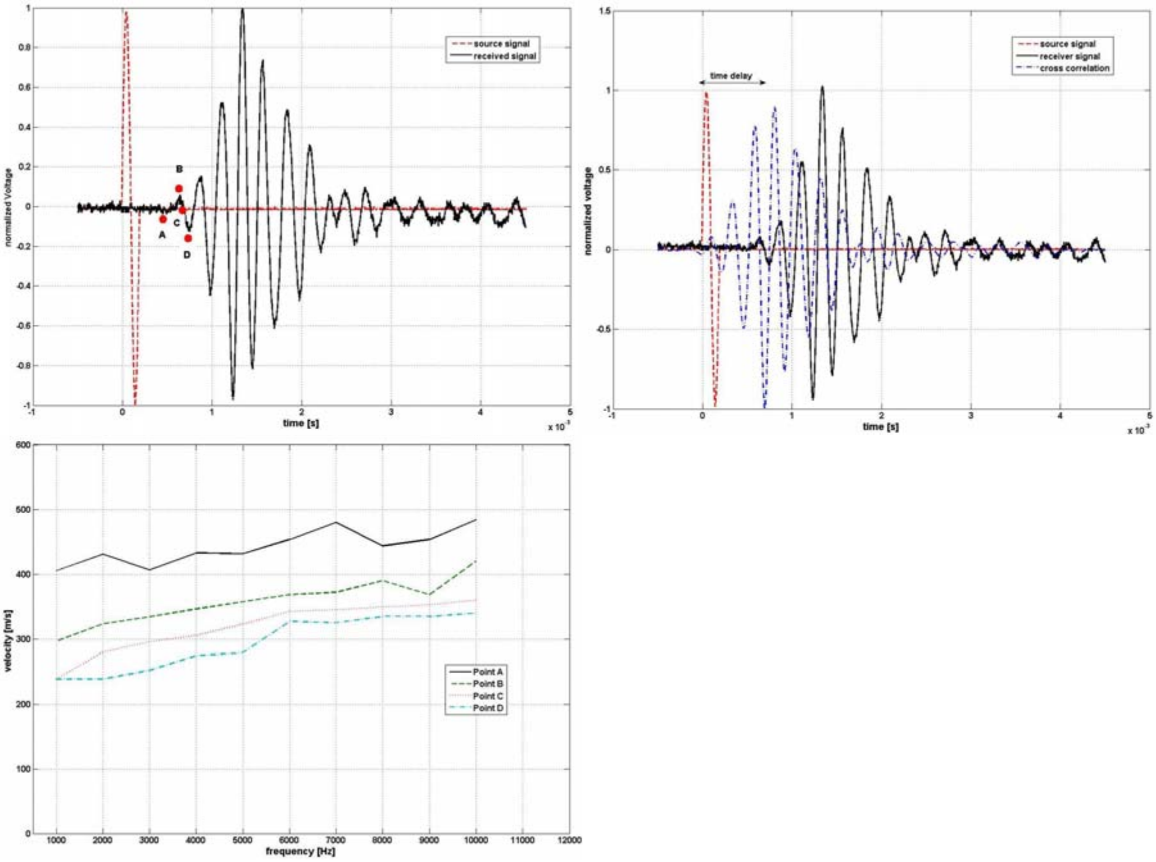

Figure 8: Extracted points (A,B, C, D) to determine the first arrival as well as the errors

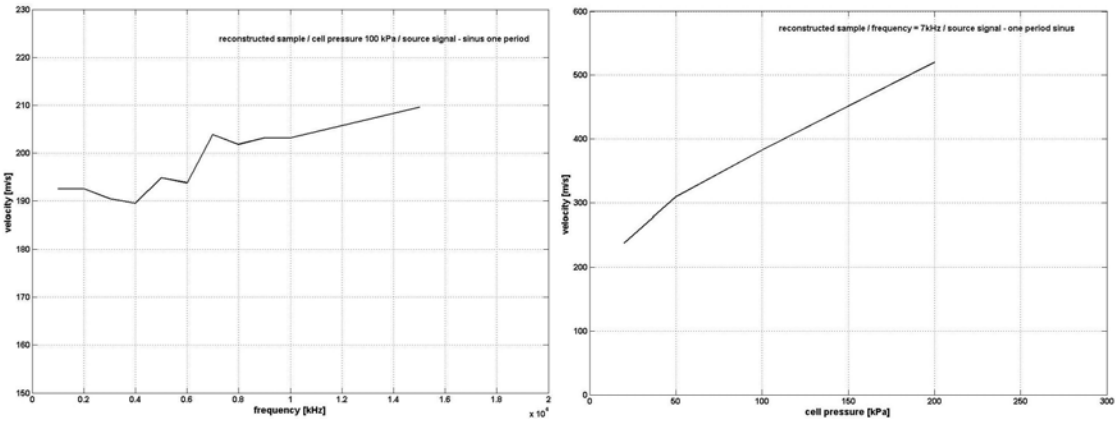

Figure 9: Frequency and stress dependency during the tests

Due to the remaining uncertainties in determination of the wave velocity, further improvements are necessary. Actually different investigations by using harmonic and sweep source excitation are done. The objective in these investigations is the ascertainment of the phase velocity in the seismogram. In figure 10 is shown, that the improvement in determining the phase function in the excitation range (1-5 kHz) is given.

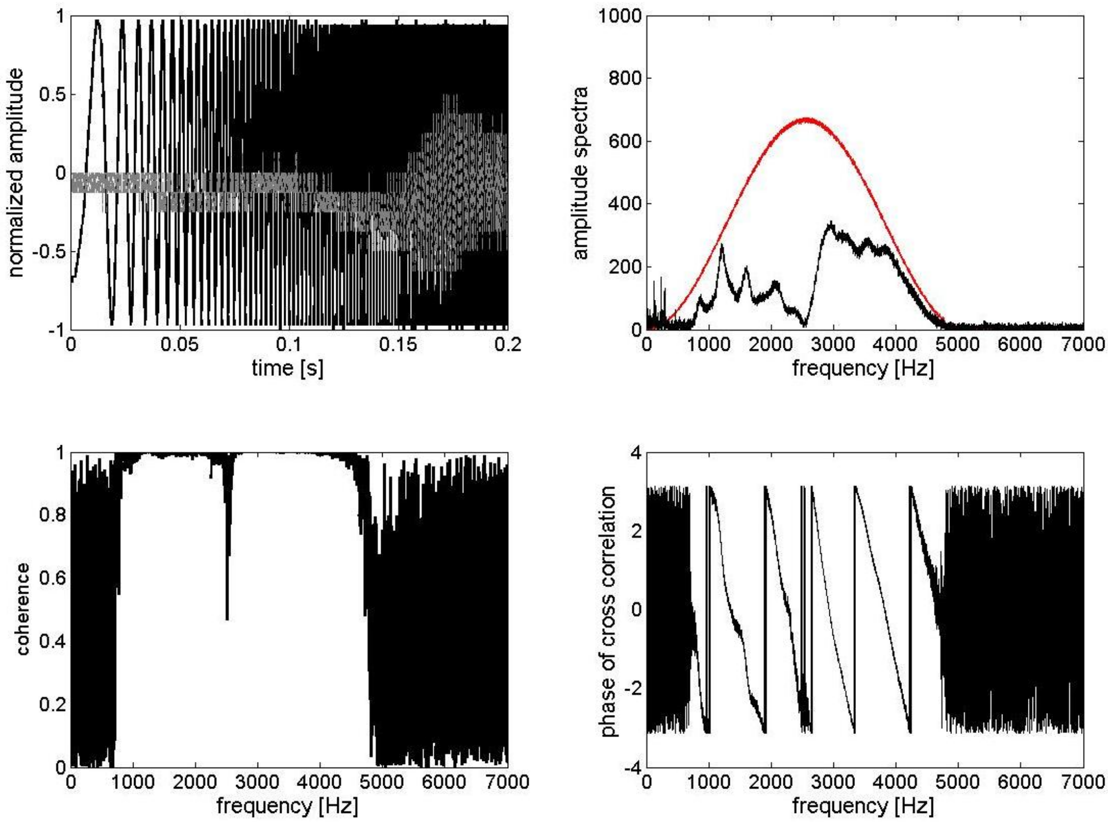

Figure 10: Application of sweep excitation, the amplitude spectra of windowed time function, the coherence and the phase spectra of the cross correlation as the base in further phase velocity calculation

The soil samples are extracted in a depth of 1.5-1.7m. To prepare the comparison of the wave velocities and stiffness between in situ and laboratory measurements different lab tests are necessary: determination of grain distribution, in situ natural water content and density, specific gravity, void ratio, the plasticity index, as well as oedometer and shear tests.

Under consideration of these soil parameters, the extraction depth with available primary stresses in the soil conform a horizontal cell pressure of 12.5 kPa and a vertical cell pressure of 25 kPa. The sample has to be prepared regarding the in situ conditions of density and water content. The preparation time for the sample need approximately 6 hours. The natural density for the site Löbnitz has a value of 1.67 g/cm³ (dry density 1.36 g/cm³). The low in situ-density makes the preparation of the sample complicate. Actually the tests in the triaxial test machine to determine the strain dependent stiffness are running.

4.2.3 Theoretical applications

To evaluate the effect of strain dependent stiffness in geotechnical design routines the strain dependent description was applied of the settlement calculation (figure 11).

The purpose of the theoretical application was a settlement comparison between conventional, usual practical calculation, the measured data and some existing strain dependent material descriptions. For this objective an adaptive settlement calculation was developed. A glimpse to the range of possible solutions shows the necessity of further developments.

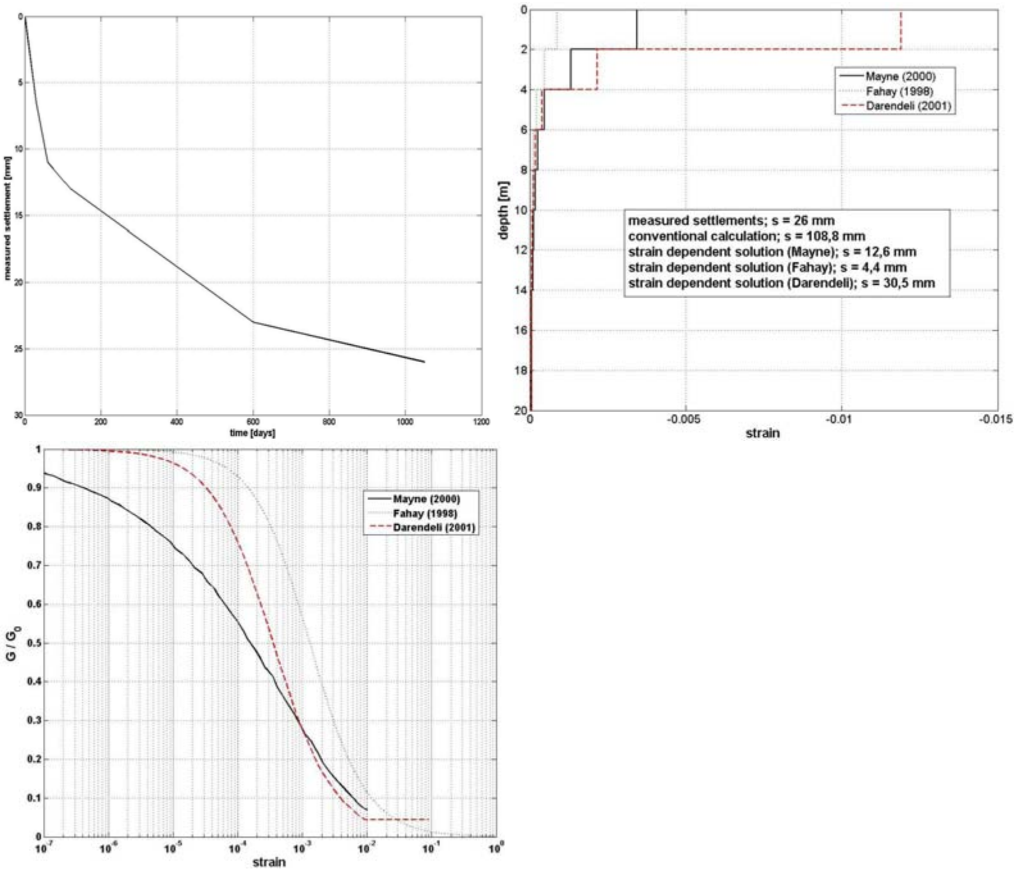

Figure 11: Application of available strain dependent descriptions to existing settlement measurements

5. 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, geotechnical measurements at the other field sites will be done on base of the existing geophysical results. The aim is to evaluate the geophysical results as a prerequisite for reliable and less expensive geotechnical surveys. For the evaluation and combination of the geophysical and geotechnical results, further investigations are in progress. To analyse site specific parameter relationships Direct Push investigations as VSP and Hydraulic Profiling will be carried out in particularly.

At the moment the analysis of measurements to compare different types of seismic receivers and signal sources is in progress. Also different receiver arrays are being evaluated and enhanced for the exploration of the shallow underground.

Further investigations in geotechnical laboratory experiments (sample preparation, testing of different soils) are in work. Additional available testing equipment will be improved regarding of new points of view. Finally, the investigation of theoretical and numerical models will be continued.

References

Angenheister, G. (1982) Physikalische Eigenschaften der Gesteine. Bd. 1a & 1b. Springer-Verlag, Berlin-Heidelberg-New York

Baldi, G., Belloti, R., Ghionna, V.N., Jamiolkowski, M., Lo Presti, D.F.C. (1989), Modulus of sands from CPTs and DMTs, Proc. 12th ICSMFE, Vol. 1, Rio de Janeiro, 165-170, Rotterdam

Burland, J.B. (1989): Small is beautiful – Soil stiffness of soils at small strains, Can.Geotechnical J. 26, 499-516.

Darendeli, M.B., (2001), Development of a New Family of Normalized Modulus Reduction and Material Damping Curves. PhD Dissertation, University of Texas at Austin

DIN 18134 (2001): Baugrund; Versuche und Versuchsgeräte - Plattendruckversuch

DIN 4094-1 (2002): Baugrund – Felduntersuchungen - Teil 1: Drucksondierungen

Fahay, M. (1998): Deformation and in situ stress measurement, Geotechnical Site Charact.., Balkema.

Jamiolkowski, M., D.C.F. LoPresti, O. Pallara (1995): Role of In-situ Testing in Geotechnical Earthquake Engineering, Proc. of Third Int. Conf. on Recent Advances in Geotechnical Earthquake Engineering and Soil Dyn.: St. Louis 1995, Vol III, 1523-1546.

Lacasse, S., Berre, T. (1986): Triaxial Testing methods for soils, Proc. of the Symp. on Advanced Triaxial Testing of soil and rock (Editors: Donaghe, Chaney, Silver): Louisville 1986, STP 977,pp. 264-289.

Mayne, P.W., Schneider, J.A., Martin, G.K. (2000): Small- and large strain soil properties from seismis flat dilatometer test, in: Pre-failure Deformation characteristics of geomaterials, Balkema, M. Jamiolkowski; R. Lancelotta: LoPresti (eds).

Rix, G. J. and Stokoe, II, K. H., (1992), Correlation of Initial Tangent Moduli and Cone Penetration Resistance, Calibration Chamber Testing, A.B. Huang, Ed., Elsevier, 351-362.

Schön, J. (1983): Petrophysik – Physikalische Eigenschaften von Gesteinen und Mineralen. Enke-Verlag, Stuttgart, 405 S.

Schön, J.H. (1996): Physical prperties of rocks – Fundamentals and principles of petrophysics. Pergamon Press, 583 S.

Tatsuoka,F; F.J. Jardine, D. LoPresti; H. di Benedetto, T. Kodaka (1997): Characterising the pre-failure deformation properties of geomaterials Theme lecture , Proc. of the 14. WCSMFE: Hamburg 1997.