APPLICATION OF NON-INVASIVE GEOELECTRICAL PROBES TO CAPTURE SUBSOIL COMPACTION

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Abstract

Due to decades of trafficking, subsoil compaction is nowadays a common phenomenon of agricultural used land. The detection of specific subsoil compaction areas is necessary to delimitate actual and future economical costs arising from additional material or nutrition input. Furthermore, ecological cost-intensive main and side effects like soil degradation, erosion, and flood magnification have to be considered.

The common verification methods for subsoil compaction such as punctual boreholes or soil pits are too time consuming, laboratory drawn, too invasive and only show the local state of the mechanical strength and are generally not suitable for regionalisation on at least the field scale. On the other hand, new approaches to image the problem by using less-invasive probes provide a good spatial resolution but cannot give a priori any information about the state of mechanical stress.

Our approach may solve this problem as we used various non-invasive geophysical sensors like EM38, Georadar, Veris 3100, and the Geophilius Electricus sensor. Data like apparent electrical conductivity [ECa] or electromagnetic reflection [EMR] were compared with the special mechanical precompaction strength factor [K_0] obtained from soil pit/ laboratory and penetration resistance [PR] measurements. Primarily we tested the validity of the underlying assumption that horizontal stress components can be used to characterise the compaction state of the soil and the significance of geophysical sensors to regionalise inhomogeneities in soils.

The results for loess soils show for various sites a strong correlation between penetration resistance [PR] and the signals of the geophysical sensors. This is mainly caused by a high response to an increased water content in the significantly compacted subsoil layers. The results indicate that in precision agriculture nearly all of the applied geophysical sensors can be used for the capture of subsoil mechanical strength. Therefore our methodology is a useful tool for the regionalisation of subsoil compaction.

Keywords subsoil compaction, regionalisation, geophysical probes, soil mechanical strength, Precision Agriculture

1. Introduction

Soil compaction is a well known problem in agricultural farming and especially the subsoil compaction can cause major problems in cultivation or tillage. This can result in permanent or non-reversible negative effects for the soil mechanical strength, soil structure, soil texture, soil life etc., and results in the worst cases in effects like e.g. enhancement of flood events. Negative economical effects are lower crop yields due to deficient plant growth or e.g. higher gasoline consumption due to the greater force needed to plough the highly compacted areas. Therefore an easy and quick access to detect and regionalise subsoil compacted areas can be a key to avoid negative impact like degradation of soil functions as well as economic losses (1).

As a matter of fact the access of the spatial distribution of soil compaction on the field scale still is an open problem. Conventional soil physical investigations are mainly provided - apart from the visual study of the plant development – by some major indicators for compaction e.g. distribution of the grain size, air and water permeability, water conductivity, soil bulk density, the mechanical strength etc.. The problem is that these soil investigations are mainly caused by selective and specific measurements done by e.g. drilling cores, soil pits etc. which represent only a punctual or a minor subarea of the soil and ignore at the same time the spatial variability of soil physical properties. Even special investigations on the mechanical strength of a soil like the pre-compression stress or shear stress are dealing with the same problems due to their lab-oriented and minor subareas based probing range. The more spatial penetration resistance measurements are only a solution for small research grids (e.g. 10 x 10 m) but are not suitable for larger areas. Lastly all of these conventional methods to regionalise subsoil mechanical strength are nowadays too work and time consuming and therefore economically inadequate.

To avoid the named methodical and spatial inadequacies, non-invasive methods like non-destructive geophysical methods offer a solution (1). So far the use of these non-invasive/ non-destructive geophysical based sensors is common in geology, archaeology, and precision farming. Within precision agriculture these sensors are widely accepted to detect various soil properties like texture variations by using the apparent electrical conductivity of the soil (2), (3), (4), (5). Factors which influence the apparent electrical conductivity (ECa) in soils are primarily soil salinity, clay content, actual water content and cation exchange capacity (6), (7), (8) . Some probes like the EM38 and the Veris 3100 soil mapping system as widely applied sensors can provide a better spatial resolution in general and allow a regionalisation for various soil characteristica (9), (10), (11), (12), (13). The measurement of the ECa with the EM38 and the Veris 3100 is e.g. sensible with respect to the variation and the thickness of clay layers in the top and subsoil (14), (15), (16) but not for the specific detection of depth-dependent material properties (2). Opposite to these sensors the new “Geophilus electricus” and the Ground Penetrating Radar (GPR) are – in addition to the detection of the variations of the soil material - able to identify a depth related variation of the soil structure, the bulk density, and the soil water content (17), (18), (19), (20), (21).

Therefore we combined conventional minimum-invasive methods e.g. the penetration resistance measurements (PR) with geophysical non-invasive methods e.g. electromagnetic induction (EMI), galvanic constant resistivity (GCR), and electromagnetic radiation (EMR) to accomplish a systematic approach for an interpretation of depth-dependent data with respect to their location in the field (1), (22).

To derive reliable data representative for soil mechanical stress from penetration resistance measurements, a new theoretical approach had to be worked out. Hartge and Bachmann (23) and later Horn (24) proposed a simple, site-specific analysis for the interpretation of subsoil mechanical strength and therefore depth-dependent penetration resistance (PR) characteristics. Results for loess profiles showed that the depth-dependent relation of PR for overburden soil can be described systematically, so that deviations from the non-compacted reference state can be detected. PR-detectable precompaction increased with duration of land use (25) or land-use intensity, i.e. changing from forest soils (reference) to agriculturally used soils. Increasing compression, e.g. by adding additional temporary loads to the soil surface, leads to a decrease of the depth-dependent void ratio, which coincides with a mean increase of the supporting grain contacts. Bachmann and Hartge (25) further reported that an observed similarity of the readings indicate that the horizontal stress component is dominant for the vertical penetration resistance as well as for the shear resistance. Readings from both measurements may be used to represent the horizontal stress component in order to estimate an equivalent of the stress-at-rest-coefficient K_0 (while K_0 is the ratio of normal compaction and precompaction). This state of precompaction and hence as well the soil mechanical strength can be detected by using results of PR measurements.

The underlying assumption is, that the vertical stress component for the lower-most layer assessed by PR measurements represents the ideal stress situation, i.e., the stress in that depth is uniform in all directions which is similar to the hydrostatic stress propagation in liquids. The procedure (Figure 1) described by Hartge and Bachmann (23) proposed that drawing a straight line from the maximum depth towards the origin of the coordinates in the depth vs. PR plot gives values of the quasi hydrostatic condition for each depth for a mechanically non-affected normally consolidated soil - i.e. values for the principal stress (σ_x) are available for each depth up to the soil surface simply by linear interpolation. To attribute a hydrostatic stress situation gives a site-specific and easily definable base, which characterises a non-preconsolidated and mechanically undisturbed soil. Deviations from the ideal (hydrostatic) condition, which serves as the reference for non-compaction, are considered to represent the depth-dependent compaction state of the soil, i.e. K_0 values >1 indicate compacted soil layers and K_0 values <1 represent labile loosened layers (25).

Using this theoretical background our main objective is to prove if non-destructive geophysical field techniques are able to detect inhomogeneities in the field, which can be used to deduce the state of soil mechanical strength and within the compaction state of the soil (1), (22).

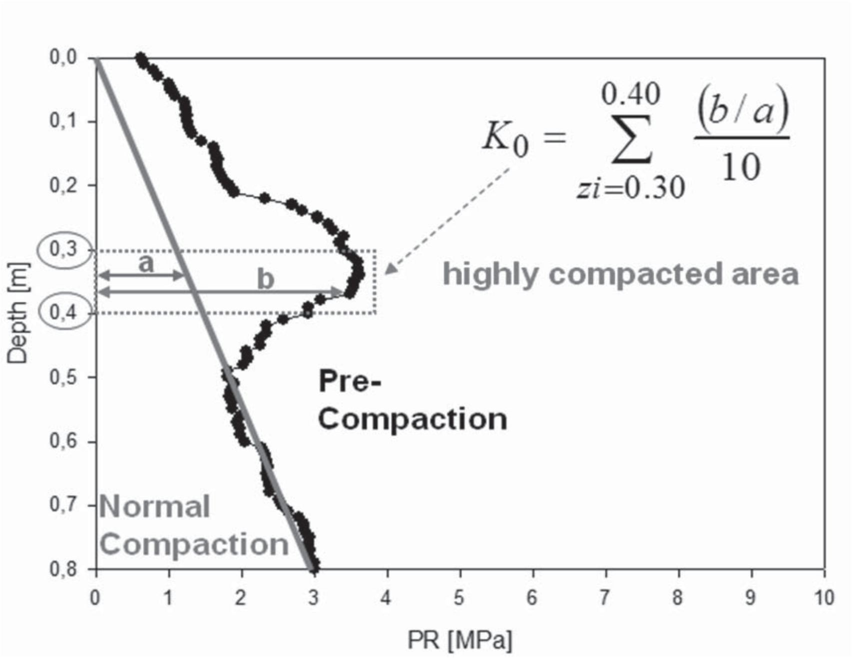

Figure 1 Hydrostatic stress depth function by Hartge and Bachmann (23), modified

2. Material and Methods

The subsoil compaction was assessed by measuring the penetration resistance (PR) with a hand-driven Penetrologger (Eijkelkamp, Giesbeek, the Netherlands) as a field reference method. The measuring range is between 0.00-10.00 MPa with a resolution of 0.01 MPa. Measuring depth is from the soil surface down to 0.8 m with a vertical resolution of 0.01 m (26).

Further we explored some soil pits including the above mentioned conventional methods to confirm the measured PR data. The used non-invasive geophysical techniques are separated by their methodical background and can be described as follows:

Measurement of the electromagnetic induction (EMI) EM38

The spatial variability of soil physical properties was assessed by measuring the apparent electrical conductivity (ECa). The electromagnetic induction meter (EM38 probe) (Geonics, Mississauga, Canada) induces an electromagnetic field in the ground with a transmitter coil and measures with a receiver coil the apparent electrical conductivity of the soil. The EM38 reaches, on average, depths of exploration of 1.5 meters in the vertical mode and of 0.75 meters in the horizontal dipole mode. The actual depth depends on the local apparent electrical conductivity of the soil. The measured quantities are the apparent electrical conductivity (ECa) in milliSiemens per meter (mS/m) (27).

Measurement of the galvanic constant resistivity (GCR) Veris 3100

The Veris 3100 (Veris Technologies, Salina, USA) as a galvanic contact resistivity meter emits an alternating voltage into the ground through metal electrodes and measures the resistance. The system works in a four equally and parallel spaced metal electrodes – in a Wenner array - which are inserted 6cm into the soil while the electrodes are replaced by six rotating coulter discs and pulled by a cart. The measurements are reaching depth sections from 0.00-0.30 m or from 0.00 0.90 m. Measured is the apparent electrical conductivity (ECa) in milliSiemens per meter (mS/m).

Geophilus electricus

The Geophilus electricus (University of Potsdam and Institute of Vegetable and Ornamental Crops, Großbeeren, Germany) as well is a galvanic contact resistivity measurement system. But instead of four (six) discs parallel in one line, six electrode pairs are pulled behind a tractor. To get a better ground contact the metal coulter electrodes have metallic spike extensions. The first electrode pair is the current electrode and the additional five electrode pairs are the potential electrodes. The current electrode pair induces an alternating voltage into the soil while the following electrodes measure the resulting voltage. This allows to determine the apparent electrical resistance in five depth sections with a maximum depth of 1 m. Measures is as well the apparent electrical conductivity (ECa) in milliSiemens per meter (mS/m). Values are expressed in specific resistivity (Rho) in Ohm per meter(Ohm/m) (19), (20), (21).

Measurement of electromagnetic radiation (EMR)
Ground Penetrating Radar (GPR)

The GPR (Geophysical Survey Systems, Salem, USA) uses electromagnetic radiation in the microwave band (UHF/VHF frequencies) of the radio spectrum and detects the reflected signals from subsurface structures. The transmitting antenna radiates short pulses of the high-frequency waves - in pico seconds or nano seconds - into the ground. The wave hits a boundary with a different dielectric constants and the receiving antenna records variations in the reflected return signal. The diffusion of the waves depend on the structure of the soil which causes the refection, scattering, diffraction, and transmission of the induced wave. The runtime, phase and amplitude of the reflected wave are logged. The GPR in use is a 400 Mhz antenna. The depth range in this case is about 2 m.

The experimental sites we investigated (Ruthe I+II) are located in Northern Germany, south of Hannover (52° 23' N, 9° 44' E) in the German loess belt with an annual precipitation around 650 mm per year and a mean annual temperature about 9 °C. The prevailing soil typ at Ruthe is classified as a typical luvisol which is derived from Weichselian loess with a development up to a depth of 1.2 m. Below the loess we found a highly permeable layer of quaternary weichselian sand and gravel of the near River Leine valley. The texture of the sites is about 10-17% clay, with a maximum of 20 % in the B_t- horizon, 70-80% silt and 10 – 15 % sand content throughout the soil profile. The first test field (Ruthe I) is under agricultural use with different types of cultivation and with a mixture of crop growing (e.g. wheat or barley) and vegetable growing (e.g. cauliflower or cabbage). The second experimental site in Ruthe (Ruthe II) (with the same climatic, soil, and cultivation conditions) was trafficked and overburdened with heavy machinery to induce an intense subsoil compaction.

The measurements were done in spring and autumn from 2005 till present. EM38 measurements were taken at about 10,000 locations on a field plot size of 42 x 70 m (Ruthe I) and 22 x 144 m (Ruthe II) with different nodal distances between 0.6 m, 1.0 m, 2.0 m, 3.0 m and 5.0 m. PR values were always measured at the same locations. Veris measurements were taken in spring 2007, Geophilus electricus measurements in spring 2008 and GPR measurements in autumn 2006, spring 2007, and 2008.

3. Results and Discussion

Results of the PR measurements show that the maximum values are in the depth compartment of 0.30-0.40 m which corresponds with the subsoil compaction beneath the plough layer.

The results of the measurements with the EM38 show a clear structure of the data, indicating areas with higher absolute values at the headland, the track wheels, and the experimental compacted areas of the field due to the intensive trafficking on those domains. The differences in the intensity and the distribution of the ECa values correlate to the average soil water content at the testing time. The measurements with the Veris 3100 are similar but with an exception on two smaller areas at the upper and lower margin of the field. These appearing "hotspots" are not detectable with all other geophysical or mechanical methods in use (Figure 2). Caused by their own methodical restriction the two geophysical methods are not able to identify the depth of the occurring high ECa values. But with the penetrologger data as a reference these results show a good correlation to the detected soil mechanical strength situation.

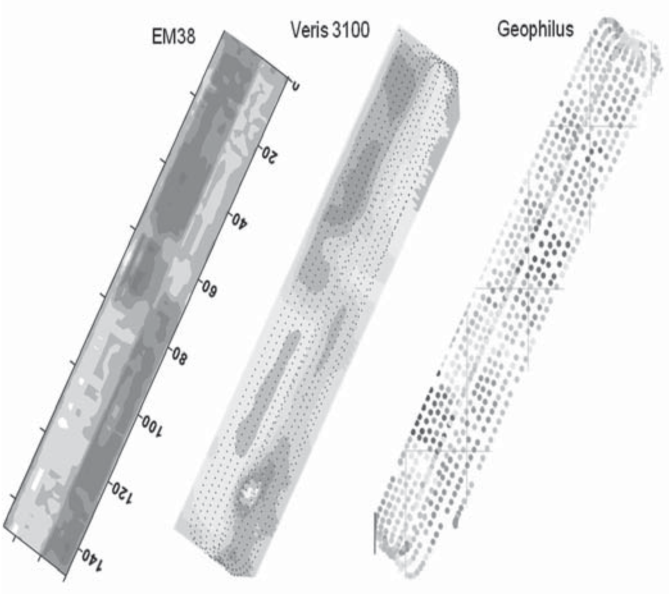

Figure 2 Comparision of sensor maps (Ruthe II)

The Geophilus electricus results show the same results as the EM38 measurements, but additionally it shows the different conductivity values of the five depth segments. They confirm the clear result that in the above mentioned area the section between 0.20-0.40 m has the highest conductivity values.

A comparable result can be identified by a look at the radargrams. The reflections are different for the headland area and experimentally compacted area caused by the induced chance of the soil strength. A comparison with Penetrologger data shows for both methods a strong correlation.

Due to technical restrictions of the Penetrologger used, the reference measurement depth is 0.8 m for all soils. However, if this basic assumption of including only one depth as a reference is considered as arbitrary, the reliability may be proved by the agreement between the postulated hydrostatic curve and measured PR at the base of the profile (0.65 to 0.8 m). Deviations are negligible near the soil surface and increase only slightly with increasing depth except for the highly compacted zone. However, no deviation occurs if the subsoil below the lower-most readings is normally compacted, as it is generally found for the subarea with the lowest ECa values.

We detected various subareas according to the state of the mechanical strength in the subsoil, which affects e.g. bulk density and hydraulic properties of the soil.

The results from the experimental sites showed a strong correlation between penetration resistance data and the signal of the various geophysical methods, especially in the areas with higher PR values. This is mainly caused by a good response of the lateral water content in the significantly compacted subsoil between 0.30-0.40 m to all geophysical methods.

4. Conclusions

Penetration resistance (PR) measurements can be performed quickly with minimal destruction of the site and the soil structure. It is the only hand-driven field method to measure soil mechanical strength directly and in situ. But as a single tool for precision agriculture it is definitely not suitable due to its marginal applicability for larger areas respectively scales.

All used geophysical methods were able to find differences in the soil bulk density and the soil water content distribution. Correlations were especially found between the reference method - the Penetrologger (PR) - and the EM38 (ECa) values, particularly in the depth 0.30-0.40 m, which generally is the depth increment with the highest penetration resistance. A reasonable agreement was found also for ECa and the precompaction state of the subsoil, K_0(PR) and therefore as well for the mechanical strength. Results show that K_0(PR) is correlated to ECa (Figure 3).

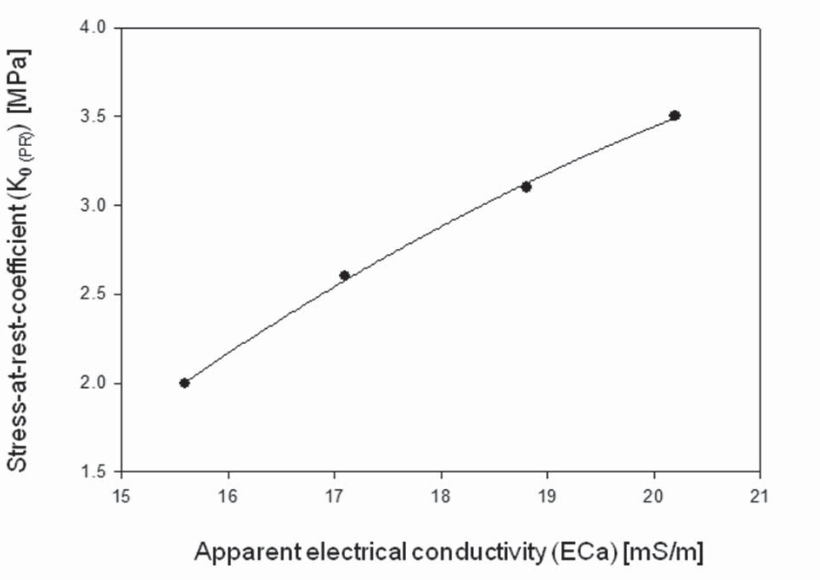

Figure 3 Relationship between $K_{0(PR)}$ and ECa

This leads us to the conclusion that the non-destructive geophysical based EM38 technique can be used for the detection of subplots with an extreme compaction or a non-compaction state but cannot give the depth or dimension. The Veris 3100 showed nearly the same results. As well like the EM38, the Veris 3100 is not suitable for depth-dependent measurements.

The reflections of the GPR profiles and the "Geophilus electricus" measurements show additionally to the detection of the soil bulk density and the soil water content distribution, a direct depth-dependent correlation with the soil stress situation, when related to the PR reference method of the Penetrologger.

Additional correlations were also found between the reference method and the "Geophilus electricus" values and results show that K_0(PR) is also correlated to Rho of the "Geophilus electricus" (Figure 4).

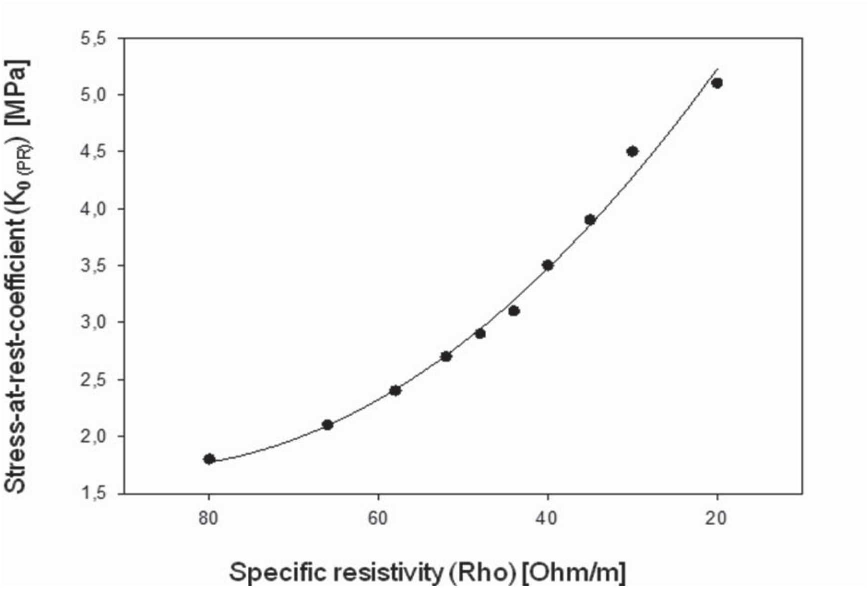

Figure 4 Relationship between $K_{0(PR)}$ and Rho

These results lead us to the conclusion that in precision agriculture nearly each of the applied geophysical based methods and sensors can be used as detectors for subsoil mechanical strength in loess derived or comparable homogenous soils. Therefore the introduced methodology can be a useful tool for the pre-screening of subsoil compaction.

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