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SOIL STRESS STATE DETERMINATION UNDER STATIC LOAD

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A b s t r a c t. Intensification of crop production by uncontrolled increasing use of agricultural machinery negatively affects soil physical properties. Heavy machinery traffic causes soil compaction, erosion and physical degradation.

In this study soil stress state under static vertical loading was predicted as a function of increasing load, soil tillage variants (plough and rototiller) as well as soil structure. Monolith samples were investigated using a SST transducer and a deformation measure device. The investigations were carried out in an Ap horizon of sandy loam Luvisol derived from glacial till (site Hohenschulen, nearby Kiel, Germany), for two tillage and structure variants.

The three major stresses, octahedral shear stress and its angle, mean normal stress as the complete stress state were determined using the SST transducer system. Soil deformations and bulk density changes were also investigated. Effects of soil structure and tillage on stress state were predicted.

K e y w o r d s: wheel-soil interaction, soil compaction, soil stress state

INTRODUCTION

Each load applied to the soil, e.g. by agricultural machinery, creates a change in an existing stress state in soil. This stress state in the soil continuum, which consists of 3 principal stresses and the octahedral shear stress as well as mean normal stress, enables us to predict and to describe the phenomena of soil compaction as well as its effects. Changes in most important soil physical properties such as bulk density, air premeability, porosity can be quantified using the stress measurement results. Soil stress state determination also allows verification of models predicting soil compaction. Besides the principal stresses, soil deformation, like volumetric change and distortion of the soil continuum, can be described as the results of mean normal and octahedral shear stress components.

In order to measure and to calculate mean normal and octahedral shear stresses, a SST transducer was used together with a displacement measuring system that allows the vertical movement of the transducer to be predicted (for more details see [4,5]). The measurements were conducted in soil monoliths, which were statically loaded. This experiment enables the continuous static stress state in loaded soil quantified and soil compaction under static or quasistatic loads to be predicted. The effect of applied loads on soil properties was predicted describing changes in bulk density.

THEORETICAL REMARKS

If a soil volume is loaded, changes in principal stresses as well as in shear stresses are created. The rigid phase and water are incompressible and if the soil bearing capacity is too small to take the load of a moving machine compared to the stress applied, soil structure is destroyed as a result of the acting forces.

A stress state at a given point in the soil is shown in Fig. 1. Normal stress S_N is perpendicular to the representative plane and shearing stress components act parallely to this plane.

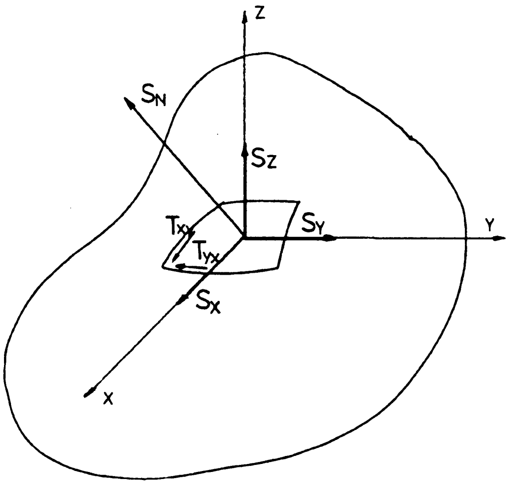

Fig. 1. Stress state in soil volume.

The SST transducer allows measurements of the axial normal stress components S_x, S_y, S_z as well as the normal stress components S_N1, S_N2, S_N3. This enables to quantify the shearing stress components at the point. The normal stress can be described as below:

$$S_N = \sum_i^{x,y,z} S_i + \sum_i^{x,y,z} T_{ij} \tag{1}$$

where S_N is normal stress, S_i - axial normal stress reducted to x, y, z axis, T_{ij} - shearing stress reducted to xy, xz, yz plane.

The axial normal and shearing stress components can be described as the stress vectors reducted to the main direction:

$$S_i = S_x \cos^2\alpha$$

$$Tij = T_{xy} \cos\alpha \cos\beta \tag{2}$$

where α - angle between the normal stress direction and the x-axle; β - angle between the normal stress direction and the y-axle.

The same calculations are valid for the remaining stress components.

The shearing stress components can be predicted as below (knowing the normal stress components and angles):

$$T_{xy} = -0.75\,(S_N2 + S_N3) + 0.5\,(S_x + S_y + S_z)\,. \tag{3}$$

So the three principal stresses as well as shearing stress components T_{xy}, T_{xz}, T_{yz} can be quantified using the results of the SST measurements: S_x, S_y, S_z *and* S_N1, S_N2, S_N3. Additionally the mean normal stress (*MNS*) can be calculated as below:

$$MNS = 1/3\,(S1 + S2 + S3). \tag{4}$$

MATERIALS AND METHODS

The Ap horizon of a sandy loamy Luvisol derived from glacial till (Hohenschulen near Kiel, Germany) was used in the experiment. Some properties of this horizon are as follows:

Specific density	Sand	Silt	Clay	Organic carbon
2.58 g/cm^3	58.5 %	25.9 %	15.6 %	0.89 %

Monolith samples (600x400x300 mm, LxWxH) were taken from the topsoil up to 300 mm depth. Two variants of soil tillage, i.e., conventional (= ploughed) and conservation system (= rototilled) were investigated. The soils were ploughed or rototilled in autumn 1993, the monolith samples were taken between February and April 1994. Each monolith was wetted up to -60 kPa pore water pressure = wettest soil conditions in spring time and drained by several ceramic cells (each 300 mm long, 30 mm diameter). Each monolith was measured at first under undisturbed conditions (= structured sample) in order to quantify the aggregate dependent stress states after complete, manually made complete homogenisation, after which the soil samples were packed in separate layers to reproduce the initial bulk density in the whole wolume. Five replicates were investigated.

The SST transducer was developed by the Institute of Plant Nutrition and Soil Science, Kiel, Germany [4]. Six pressure transducer cells of the diameter of ca.20 mm are embedded in an aluminium body, so that the placement and directions of all arbitrary planes are rigid.

The SST transducer was calibrated in air, using a triaxial chamber. A rubber diaphragm sealed the transducer to allow applying a constant pneumatic pressure during calibration. The air pressure was applied from an air compressor and set up with a valve and an air pressure calibrator. The sensitivity of the pressure calibrator was 0.1 kPa, the calibration range with the deviation of max. ±1 % was 50-400 kPa. The displacement measuring system was also developed at the same institute [5] and this system allows the determination of displacements in the horizontal and vertical directions via highly sensitive round-potentiometers. This system was calibrated using a clock length sensor with a sensitivity of ±0.1 mm. The range of the calibration was ±100 mm. Both sensors (SST and displacement sensor VDS) are connected and register the stress inducted changes of soil displacement and vice versa simultaneously at high frequency.

The SST transducer was installed at the depth of 100 mm in each monolith (Fig. 2).

A hole of approx. 70 mm diameter was excavated from the side of the monolith frame using a special drilling tool. After placing the SST transducer in the end of the hole, the remaining soil was placed again into the hole. To assure contact between the sensors and soil the transducer was pushed. When the contact was positive, the location of the loading plate was predicted to place the vertical sensor and the loading plate coaxially. The centre of a loading plate was approximately on top in the perpendicular line in the centre of the vertical stress sensor. The two dimensional displacement measuring system was connected, however, only the vertical movement of the SST transducer was measured because of the static loading.

The topsoil was compressed with a circular plate of 100 mm diameter, which was loaded with 40, 80, ... 280 kg weight, i.e., 50, 100, ... 350 kPa pressure. During the loading periods, which took 30 s each, the stresses of the six sensors were recorded every 0.1 s, as well as the vertical movement of the SST.

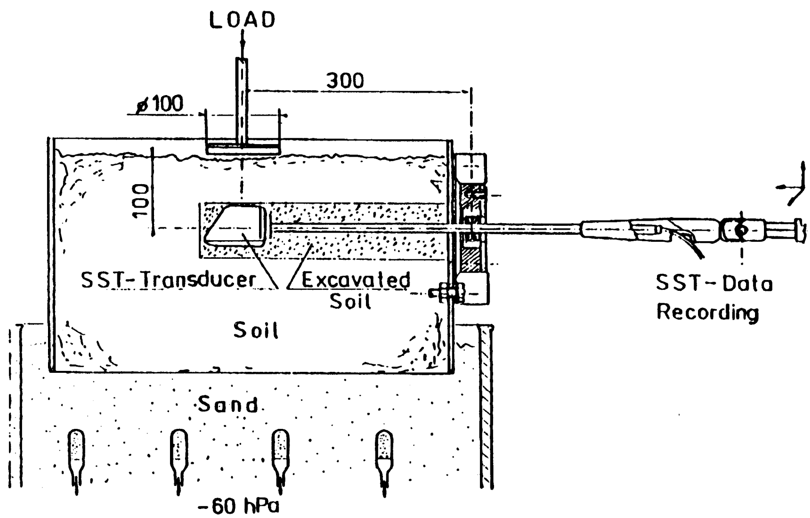

Fig. 2. Schematic diagram of the measuring system.

RESULTS

The principal stresses $S1$, $S2$, $S3$, the mean normal stress, as well as the octahedral shear stress and its angle, were calculated from the measured SST data. All the experiments were carried out fo 30 s, but only in the first ten seconds significant changes were observed.

Peak values of those parameters are summed up in Table 1 together with the values of max. vertical movement of the SST, ruth depth and bulk density (1 - initial conditions, 2 - final, after 350 kPa loading). The data represent the mean values of the five replications.

dependent settlement induces a further delay in reaching the maximum value (Fig. 4). The corresponding slopes are shown in Table 2.

With respect to the data of mean normal stress (*MNS*) and octahedral shear stress (*OCTSS*) the same trend can be defined. Especially for the variant Rototiller *OCTSS* a very pronounced alteration in the slope could be detected.

Figure 4 shows the results of the stress affected vertical movement measurements. Stresses applied, tillage variants and soil structure have shown significant effects on rut depth and vertical movement of the SST transducer. It can be seen that increasing stress applied results not only in a slight increase in rut formation, but the vertical displacement of the sensor is greater in the ploughed soil than in the rototilled one.

Table 1. Effect of wheeling on stress components and ecological parameters in structured and homogenized soil monoliths for 2 tillage treatments

Parameter	Plough				Rototiller			
	Structured		Homogenized		Structured		Homogenized	
	1	2	1	2	1	2	1	2
S_z (kPa) Vertical stress	14.82	291.94	50.43	306.9	23.46	263.46	50.64	229.28
$S1$	10.84	375.1	45.21	371.04	14.18	332.08	45.46	299.24
$S2$	10.06	7.3	16.4	24.4	13.87	19.38	12.84	4.57
$S3$	31.94	-65.86	17.63	-59.27	14.6	-86.82	13.21	-74.94
MNS	4.87	100.19	25.12	112.05	9.06	88.21	19.47	76.63
OCTSS	9.83	197.96	15.22	186.3	10.58	177.82	20.76	160.72
OCTSSA	12.54	21.65	10.45	45.87	8.62	34.62	7.51	16.2
Plate sinkage (mm)	21.8	68.6	37.2	81.6	14.0	34.8	13.9	33.4
Transducer movement (mm)	23.5	34.48	20.48	44.6	23.18	29.37	7.5	14.11
Bulk density (g/cm^3)	1.44 ±0.072	1.54 ±0.072	1.39 ±0.069	1.56 ±0.056	1.45 ±0.086	1.56 ±0.02	1.44 ±0.082	1.57 ±0.059

Table 2. Load and time dependent alteration of the measured stress ζ *T2* at 10 cm depth

Load (kPa)	50	100	150	200	250	300	350
S_z slope (s)	0.85	1.35	2.25	2.50	3.00	3.50	3.75

The three principal stresses are shown in Figs 3 and 4. It can be seen that, especially in the first seconds, the slope of the stress curves differ to a great extent, as well as the peak values between the variants. With increasing load applied, not only the vertical stress value at the depth of 100 mm increases, but the time

Bulk density values were predicted for initial conditions of each tillage as well as for

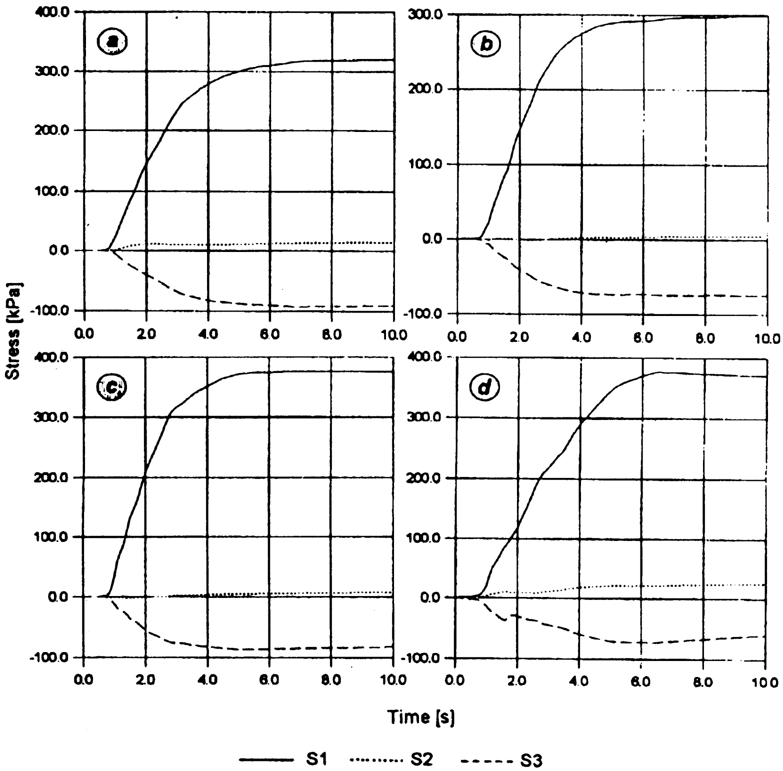

Fig. 3. Soil principal stress ($S1$, $S2$ and $S3$) as a function of time for 350 kPa load for variants: a - rototiller structured, b - rototiller homogenized, c - plough structured, d - plough homogenized.

the finally compacted soil, when soil samples were taken from under the loading plate. The relative increase of the bulk density values differs for the structured and homogenized ploughed variant 7 % and 12 %, as well as 7 % and 9 % for the rototilled variant.

DISCUSSION

Stress distribution in soils always exists as three-dimensional, but the intensity of the stress, its compositions as well as consequences on ecological parameters depend on soil structure, pore water pressure as well as tillage practices.

The higher the load is, the greater are all stress components, but the differentiations in vertical, horizontal and mean normal, or octahedral stress, have to be determined (Fig. 5). In general it can be seen that at given pore water pressure of -100 kPa the Ap horizon can only attenuate 100 kPa vertical stress, while exceeding this value results in irreversible soil compaction. It is obvious that stress distribution in this soil can reach much deeper, until the potential energy of volumetric and nondilatational strain equals the energy of the applied load.

Some interesting observations, however, were made on the peak values of the $S1$ and vertical stress for the tillage variants and for soil structure. As it was observed for load greater than 100 kPa, those stress values are higher for the homogenized ploughed soil and for structured rototilled soil. For loose soil the energy of mechanical strain in naturally smaller than for hard soil. Consequently, both variants of ploughed homogenized and structured rototilled soil are less dense, and that is why $S1$ and S_z stress components reach higher values.

In general, stress distribution in soils always occurs anisotropically. For unconfined conditions, the vertical stress component is

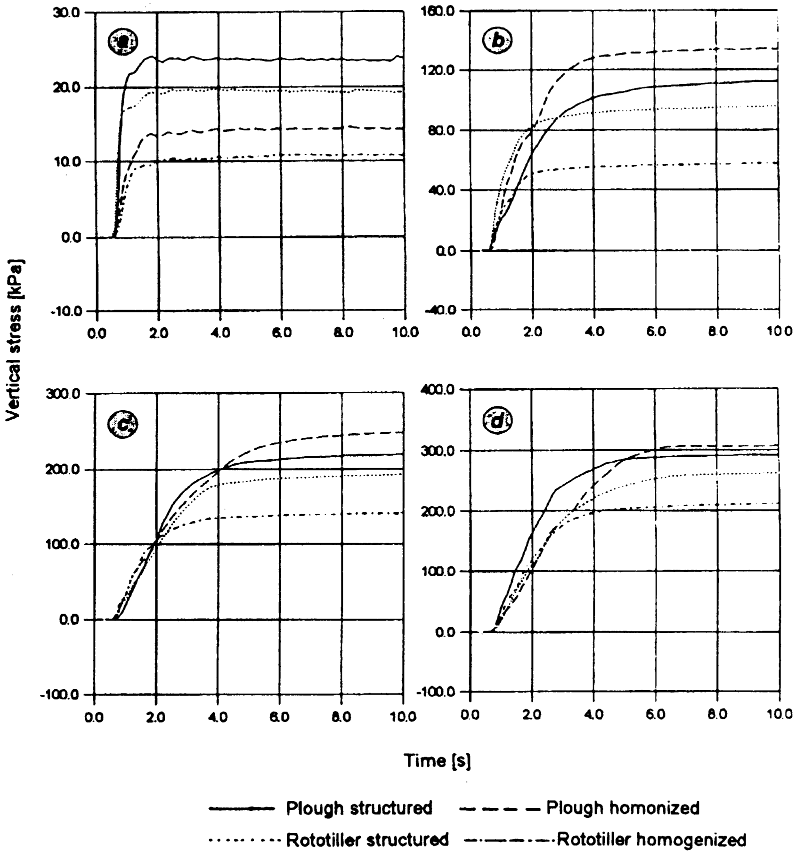

Fig. 4. Vertical stress as a function of time for 50 (a), 150 (b), 250 (c) and 350 (d) kPa load for variations: a - plough structured, b - plough homogenized, c - rototiller structured, d - rototiller homogenized.

greater and the two horizontal components are relatievly smaller, but in theory more or less identical. The proportion of these measured main stress component $S1$:$S2$:$S3$, however, as observed for all variants, was about 25:1:5, which would make it more logical to go on investigating these phenomena, even if a slight effect may be created by the soil of the plate (see also [1]).

For all the soil variants it was observed that shear stress components are higher than mean normal stress values. As the shearing stress affect non-dilatational strain and the normal stress causes volumetric strain, it can be postulated that most of the load energy was used for shear strain.

Analysing Fig. 5, which shows the results of vertical movement and rut depth measurements, it can be derived that soil strain is of higher importance for the plough variant. This is true, because a less dense soil volume finally results in a more pronounced soil compaction and failure. The effect of 'structure' on strength increase is not dominant because of a repeated aggregate deterioration during ploughing, while in the rototilled plot the effect of homogenisation on alterations in stress and strain distribution was very pronounced, if compared with the undisturbed soil monolith.

A few ideas, however, have to be mentioned with respect to displacement dependent alterations of stress distribution. Vertical moving of the SST-transducer in soil creates some inaccuracies in the stress measurements. During soil deformation the SST sensor will be translocated and results in a smaller sensor area in the perpendicular line under the loaded area.

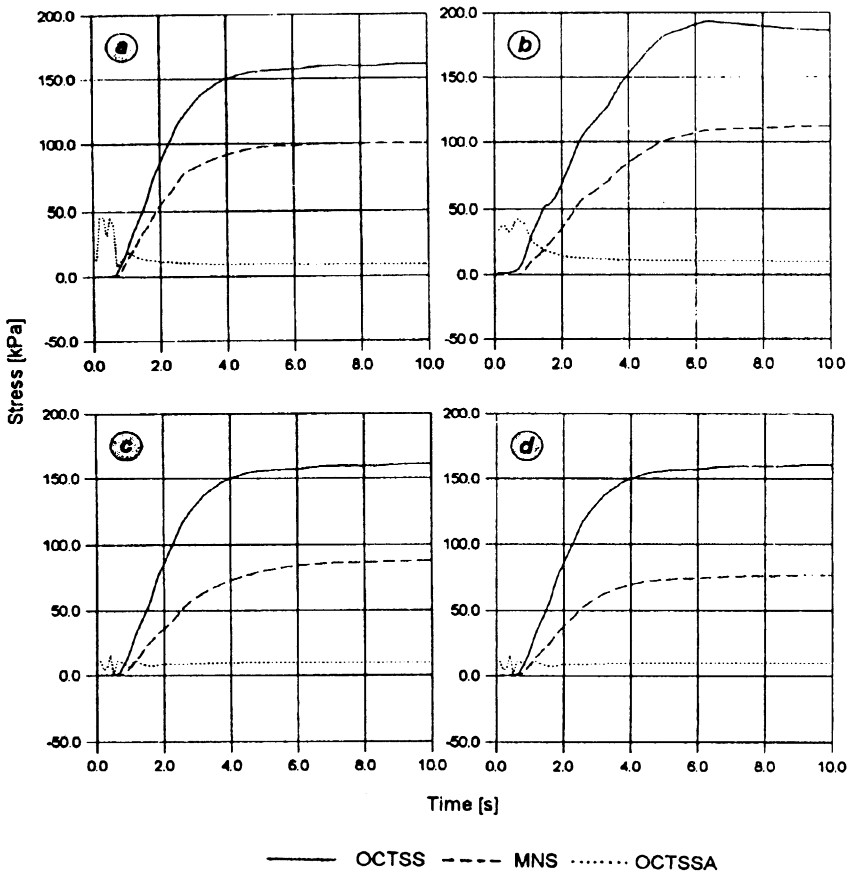

Fig. 5. Octahedral shear (*OCTSS*) and mean normal (*MNS*) stress and octahedral shear stress angle (*OCTSA*) as a function of time for 350 kPa load for variants: a - plough homogenized, b - plough structured, c - rototiller structured, d - rototiller homogenized.

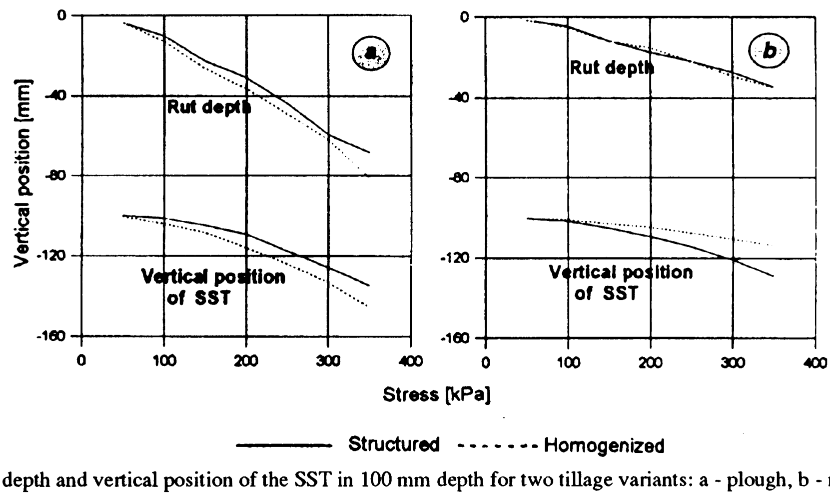

Fig. 6. Rut depth and vertical position of the SST in 100 mm depth for two tillage variants: a - plough, b - rototiller, for the structured and homogenized state at constant water pressure of -60 kPa.

Consequently, due to the geometrical relationship, this apparent diminuation of the sensing area is dependent on the lenght of the arm and the vertical displacement and affects pressure as below:

$$S_t = S_m \sqrt{1-(h/l)^2}$$

where S_t is true pressure value, S_m - measured pressure value, h - vertical movement of the SST, l - length of the arm.

However, for the length of the arm used in experiments and max. values of the vertical displacement of 40 mm the difference between S_m and S_t is not greater than 1 %.

CONCLUSIONS

Soil structure as well as tillage variants affects stress state in soil medium under static loads. All the soil variants have significant effects on peak values of all stress components and the general shape and trends are similar. For all soil variants non-dilatational strain caused mostly by shear stress components is probably relatively greater than volumetric strain, assuming that the energy of distortion is greater than the energy of compaction.

Ploughed soil has a greater trend to fail as observed by analyzing the vertical movement. Rut depth as well as vertical displacement of the SST were greater for this tillage variant. Soil structure has a small, however, significant effect. It is especially interesting that the stress and strain determination as a function of the load applied does not show the same tendency for the ploughed and rototilled soil. This can be explained by the differences in strength. The rototilled soil alternates the applied stresses more completely and therefore shows a less pronounced soil deformation at 100 mm depth. Consequently rut depth formation, stress attenuation and soil deformation can not be separated from aggregate strength, which is a very sensitive parameter to quantify each volumetric soil deformation process.

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