

Soil Stress State Under Loads of Commercial Vehicles

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Jaroslav Pytka
Lublin University of Technology

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ABSTRACT

The paper contains experimental results of soil stress state under loading of commercial wheeled vehicles. The measurements were performed with the use of SSTs (Stress State Transducers), which enable to determine soil pressures needed for calculations of stress state at a point: principal stresses and their direction cosines as well as octahedral stresses. A detailed description of the measuring method with an introductory theory of operation of the SST together with some methodology aspects of soil pressure measurements are included. The field tests were conducted on three different soil surfaces: loess, sand and turf as well as on snow surface in winter conditions. For the tests, two vehicles were used: a 5,6T 4×4 truck and a 14T 6×6 truck. The vehicles were driven at constant low speed or at different speeds. Moreover, effects of wheel loading, reduced inflation pressure, drive modes (rolling or driving) were also analyzed. The results are presented partially in a form of stress courses and as numerical data of peak maximum stresses under wheels.

INTRODUCTION

Soil stress state under loads of vehicle's wheels is a measure that describes (1) how a vehicle impacts the surface, (2) surface response to the loads. In early terramechanical studies, normal pressures in soil were determined with the use of load cells installed at a depth ([Booling, 1986](#), [Schwanghart, 1991](#), [Hetherington and White, 2002](#)). The data obtained in such experiments was useful for wheel-soil models parametrization and verification. Some methods for off-road traction examination are based on normal pressure analysis (MMP, NGP). On the other side, soil stress measurements were of high importance for description of negative effects of wheel loads on soil structure and consequently reduced crop yield in agriculture ([Horn, 1994](#),

[Akker van den, 1988](#), [Arvidsson, 1996](#)). Resuming, determining and analyzing normal stresses in soil under wheels plays an important role in multidisciplinary analysis of wheel-soil systems.

In 1987, Nichols et al have developed a SST (Stress State Transducer) [[14](#)], which enabled to determine soil pressures needed for calculations of stress state components: principal stresses, their direction cosines and the so called octahedral stresses (stresses acting in the octahedral stress system). The method was merely used in soil bin experiments on effects of different factors influencing soil stresses: reduced inflation pressure, wheel loading, etc [[1](#), [4](#), [6](#), [8](#), [13](#), [15](#), [16](#), [17](#), [18](#), [20](#)]. There are known versions of the SST by other researchers ([Harris&Bakker, 1994](#), [Horn et al 2003](#),) which were used in research for agricultural application. The author of the present paper has built his version of the SST with an attempt to apply this method for off-road traction analysis [[15](#)].

In this study, the measuring method based on SST is presented and described with some methodological problems (sensor-soil interactions, SST installation effects, etc.). A series of field experiments with wheeled commercial vehicles was performed with the use of the described measuring devices and procedures. The aim of the field tests was to determine stress state under wheel loads and to analyze effects of wheel loads, reduced inflation pressure, wheel drive mode, surface type on soil stresses.

EXPERIMENTAL METHODS

STRESS STATE TRANSDUCER

Stress state in a point of a body can be determined based upon the theory of elasticity and the algorithm of calculations is presented below.

In Fig.1 an equilibrium of a very small tetrahedron OBCD is show. The BCD is an arbitrary face, on which the contact force (or stress) is acting. Let l, m, and n denote direction cosines at which the outward normal n is inclined to the co-ordinate axes X, Y and Z respectively. The equilibrium of the tetrahedron is described in the three following equations:

$$(S - \sigma_x)l - \tau_{xy}m - \tau_{xz}n = 0 \quad (1)$$

$$- \tau_{xy}l + (S - \sigma_y)m - \tau_{yz}n = 0 \quad (2)$$

$$- \tau_{xz}l - \tau_{yz}m + (S - \sigma_z)n = 0 \quad (3)$$

where: $\sigma_x, \sigma_y, \sigma_z$ - stress components along the coordinate axes.

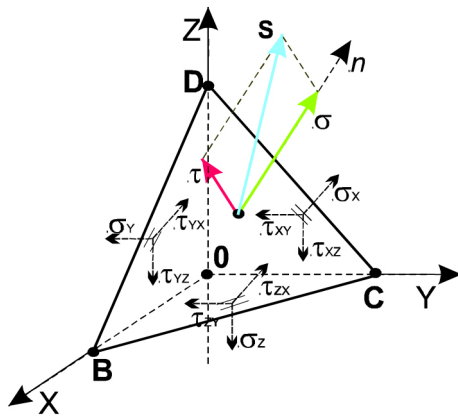


Fig.1. Equilibrium of a tetrahedron.

The above set of equations 1, 2, 3 will have one non-zero solution when the determinant equals zero:

$$S^3 - (\sigma_x + \sigma_y + \sigma_z)S^2 + (\sigma_y\sigma_z + \sigma_z\sigma_x + \sigma_x\sigma_y - \tau_{xy}^2 - \tau_{yz}^2 - \tau_{xz}^2)S - (\sigma_x\sigma_y\sigma_z + 2\tau_{yz}\tau_{zx}\tau_{xy} - \sigma_x\tau_{yz}^2 - \sigma_y\tau_{zx}^2 - \sigma_z\tau_{xy}^2) = 0 \quad (4)$$

Introduce the so called stress invariants:

• for normal stresses:

$$I_1 = \sigma_x + \sigma_y + \sigma_z = \sigma_1 + \sigma_2 + \sigma_3 \quad (5)$$

$$I_2 = -(\sigma_y\sigma_z + \sigma_z\sigma_x + \sigma_x\sigma_y) + \tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2 = -(\sigma_2\sigma_3 + \sigma_3\sigma_1 + \sigma_1\sigma_2) \quad (6)$$

$$I_3 = \sigma_x\sigma_y\sigma_z + 2\tau_{yz}\tau_{zx}\tau_{xy} - \sigma_x\tau_{yz}^2 - \sigma_y\tau_{zx}^2 - \sigma_z\tau_{xy}^2 = \sigma_1\sigma_2\sigma_3 \quad (7)$$

• for shear stresses

$$J_1 = s_x + s_y + s_z \quad (8)$$

$$J_2 = 1/6 [(\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + (\sigma_x - \sigma_y)^2] + \tau_{yz}^2 + \tau_{zx}^2 + \tau_{xy}^2 = 1/6 [(\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 + (\sigma_1 - \sigma_2)^2] = 1/3(I_1^2 - 3I_2) \quad (9)$$

$$J_3 = s_x s_y s_z + 2\tau_{yz}\tau_{zx}\tau_{xy} - s_x\tau_{yz}^2 - s_y\tau_{zx}^2 - s_z\tau_{xy}^2 = 1/27 (2I_1^3 - 9I_1I_2 + 27I_3) \quad (10)$$

Stress state transducer (see Fig.2) is built of six sensors, which are in two groupings: three sensors SX, SY, SZ are positioned as the arbitrary planes and other three sensors SN1, SN2 and SN3 as mutually orthogonal planes. The direction cosines for these planes are given in Table 1.

Table 1. Direction cosines for the arbitrary and mutually orthogonal planes in the SST

	SX	SY	SZ
SN1	0.5774	0.5774	0.5774
SN2	-0.5774	0.5774	0.5774
SN3	0.5774	-0.5774	0.5774

When the three arbitrary and mutually orthogonal pressures are determined with the use of the SST, the shear stresses can be also calculated:

$$\tau_{xy} = -0,75 (\sigma_{n2} - \sigma_{n3}) + 1/2 (\sigma_x + \sigma_y + \sigma_z) \quad (11)$$

$$\tau_{xz} = -0,75 (\sigma_{n1} - \sigma_{n3}) + 1/2 (\sigma_x + \sigma_y + \sigma_z) \quad (12)$$

$$\tau = -0,75 (\sigma_{n1} - \sigma_{n2}) + 1/2 (\sigma_x + \sigma_y + \sigma_z) \quad (13)$$

The six normal stresses SX, SY, SZ, SN1, SN2, SN3 together with the above shear stresses are the stress tensor, which describes the stress state at a point.

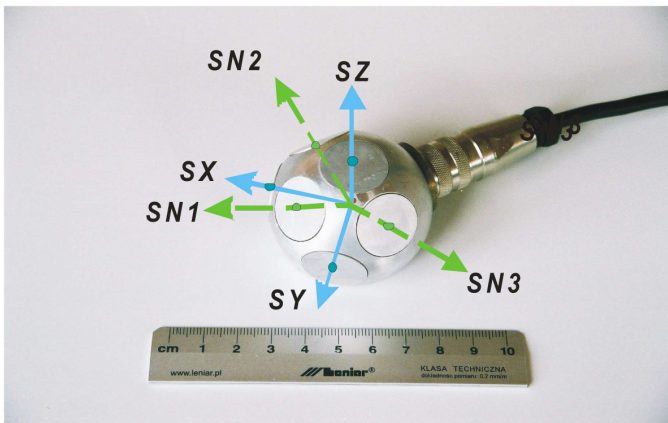


Fig.2. A schematic view of the SST with orientation of pressure sensors

Substituting the stress tensor components into Equation 1.4 we can determine principal stresses S_1 , S_2 i S_3 .

Since:

$$l^2 + m^2 + n^2 = 1 \quad (1.14)$$

it is possible to determine direction cosines of the principal stresses too.

CALIBRATION OF PRESSURE TRANSDUCERS

Precise measurements of soil pressures require the sensors to be calibrated adequately. The problem of pressure sensor calibration is concerned with direct sensor-soil interactions and, when ignored, can lead to over- or under-registration. When a sensor interacts with the soil throughout a stiffer membrane, stress concentration may occur on the surface of the membrane and the indicated pressure is higher than a real value. On the other hand, softer membranes (i.e. rubber membranes in hydraulic sensors) indicate lower pressures. Strain gage sensors based on metal membranes tend to measure with over-registrations, since the material of membranes is pronounced stiffer than soils or snow. It is needed to know, how much the indicated pressure overcomes the true value. Moreover, the effect of over-registrations may vary for different soils and at various moisture contents.

In the present study it was aimed to develop a calibration method, which enabled to determine the effect of soil and its moisture content on output signal of pressure transducers. The idea of the method is that load is applied to the transducer's membrane through a thin layer of soil, which is intended to be investigated later. In this manner, it was aimed to obtain accurate conditions of membrane-soil interactions with respect to soil effects. The intermediate soil layer should be as thin as possible (practically 2-3 mm) to minimize the

effects of energy dissipation (damping) in the soil. Moreover, it was assumed that the soil moisture content is critical for soil mechanical properties, so this parameter was also considered in calibration routines. This was proven by Harris and Bakker [8]. In this paper, they showed how soil moisture affects the calibration of their SST in soil and that there is a critical soil moisture at which the results of in-soil calibration equal in-air calibration. In the present work, gradual soil water content was applied (weight/weight) from 0 to about 20% for loess and sand, and up to 37,5% for turf, in increments (steps) of 2,5 %. In the calibration, the same soils as for the later field tests were used: loess, sand, and turf. The materials were taken directly from the sites, where off-road tests were performed.

The experimental setup for the calibration tests is depicted in Fig. 3. An external pressure is applied to a rubber coat, which covers the thin layer of soil on the

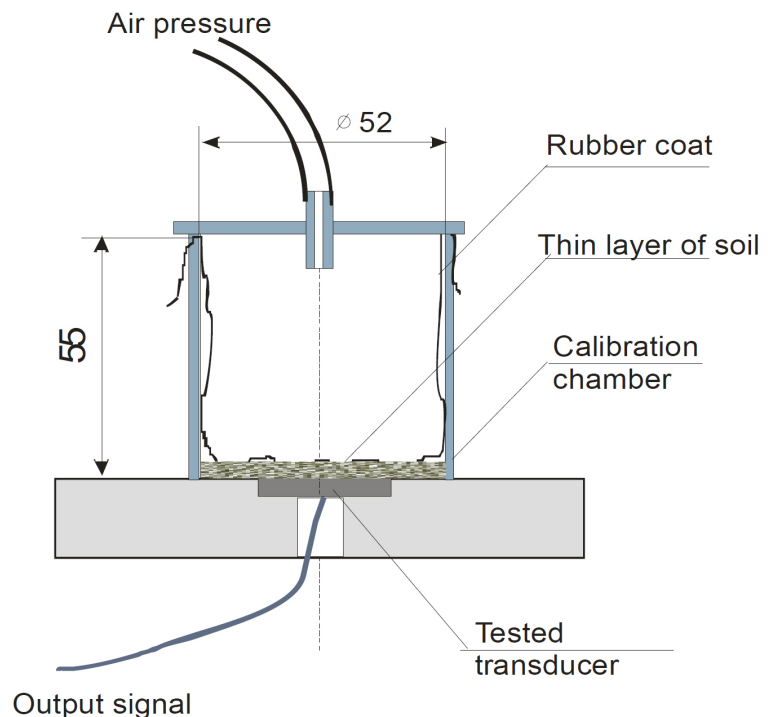


Fig.3. An experimental setup for calibration of the pressure transducers

The air pressure applied ranged from 0 to 200 kPa, with a 10-kPa step in the 0-50 kPa range and a 25-kPa step in the 50-200 kPa range. The maximum value of calibration pressure was lower than the measuring range of the transducers because of the limitation of the pneumatic system. For every combination soil-moisture content, a minimum of five replications were performed.

In Fig.4 chosen results of the calibration tests are showed. Here the output signal factor (OSF) in mV/kPa is drawn as a

function of water content for the three investigated soils together with a reference line of in-air calibration. Adding water to soils caused an increase in the OSF-the transducer became more sensitive. The effect of water in soil was the most significant in turf, while it was less significant in loess and sand. Calibration in sand showed that there is a transition between the increase and decrease of the OSF for the transducer. This transition occurred at about 7,5-12,5% WC because sand becomes a cohesive material at a certain WC, owing to the effect of water around the grains. Finally, an apparently harder material makes the transducer-soil system less sensitive.

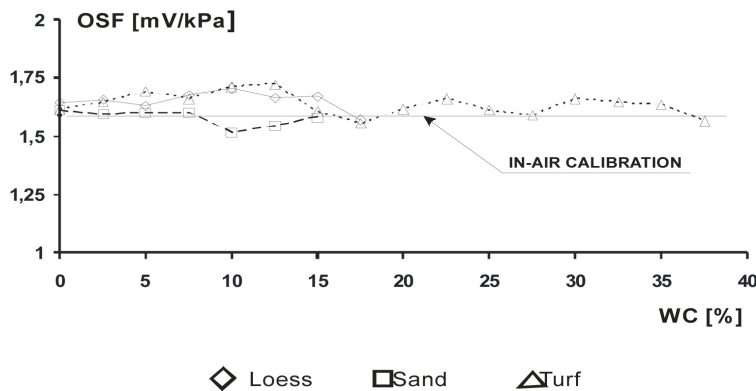


Fig.4. Effect of water content in three soils on output signal factor of the pressure transducer

INSTALLATION OF THE SST

Installation of any transducer for soil stress measurements causes a local damage of soil structure and consequently affects final results. One of the aims in this study was to develop a method for SST installation, which ensures no or minimal effect on indicated soil stresses. The field tests were done in three different soils: loess, sand, and turf and in snow cover. In order to minimize the negative effects of disturbing the soil during SST installation, various installation methods were used to place the SST at the depths. In the sandy and loess soils, simple excavation method was used. First a hole is grabbed down to the required depth, then the SST is placed and a loop of the signal cable is done in order to avoid tension or even breaking of the cable. Next, the hole is filled with the excavated soil with care to surround the SST precisely with soil - this is required to obtain good interaction between the sensors and the soil. The hole is filled to rebuild the initial density of soil surface. Such a procedure was proposed for sandy soil, which exhibits no structure. In the sandy soil, which have no structural bonds between particles, tests were done directly after the emplacing of the SST. In the loess soil, which builds a structure, the SST was installed the same manner before tests so as to let the ageing effect rebuild the damaged structure. After installation tests were postponed for approx. 3-6 hours. The installation in snow cover was similar, but without postponing. The winter tests were

performed on a settled snow cover, what simplified the installation. A cube of snow was taken off, then the SST was placed at depth and the snow was packed back. A different method of installation was performed in case of turf surfaces. Since this type of soil exhibits high content of organic matter with thin roots, the excavating method would be not suitable because of a total damage of the structure. Therefore, the SSTs were installed by drilling of a round hole in the soil profile horizontally, then pushing the transducer to a place and backfilling the hole with resting turf.



Fig.5. Installation of the SST a) in loess soil, b) in sandy soil, c) in settled snow