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Transmission of vertical soil stress under agricultural tyres: Comparing measurements with simulations

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ABSTRACT

The transmission of stress induced by agricultural machinery within an agricultural soil is typically modelled on the basis of the theory of stress transmission in elastic media, usually in the semi-empirical form that includes the "concentration factor" (ν). The aim of this paper was to measure and simulate soil stress under defined loads. Stress in the soil profile at 0.3, 0.5 and 0.7 m depth was measured during wheeling at a water content close to field capacity on five soils (13–66% clay). Stress transmission was then simulated with a semi-analytical model, using vertical stress at 0.1 m depth estimated from tyre characteristics as the upper boundary condition, and ν was obtained at minimum deviation between measurements and simulations. For the five soils, we obtained an average ν of 3.5 (for stress transmitting from 0.1 to 0.7 m depth). This was only slightly different from $\nu = 3$ for which the elasticity theory-based classical solution of Boussinesq (1885) is satisfied. We noted that the estimated ν was strongly dependent on (i) the reliability of stress measurements, and (ii) the upper stress boundary condition used for simulations. Finite element simulations indicated that the transmission of vertical stresses in a layered soil is not appreciably different from that seen in a homogeneous soil unless very high differences in soil stiffness are considered. Our results highlight the importance of accurate stress readings and realistic upper model boundary conditions, and suggest that the actual stress transmission could be well predicted according to the theory of elasticity for the conditions investigated.

1. Introduction

The transmission of stress within a soil due to agricultural machinery is of major importance since the soil can undergo deformation due to stress, resulting in changes in the soil functions. A knowledge of stress transmission is needed, among others, for two purposes: first, in order to understand the relationships between cause (soil stress due to mechanical loading) and effect (changes in soil pore functioning); and second, to develop predictive models and decision support tools that can help land users prevent soil compaction.

Stress transmission in agricultural soil is typically modelled in relation to the problem of the normal loading of the surface of a homogeneous isotropic elastic halfspace by a concentrated normal force P, for which the analytical solution was obtained by Boussinesq (1885). The vertical normal stress distribution within the soil mass is given by:

$$\hat{\sigma}_z = \frac{3P}{2\pi}\frac{z^3}{r^5} \tag{1}$$

where $\hat{\sigma}_z$ is the simulated vertical soil stress, $r = (x^2 + y^2 + z^2)^{1/2}$ is the distance from the point of action of the point load P to the desired location (x, y, z). In this paper, we shall deal only with vertical stresses, and therefore, only the equations for vertical stresses are presented. In agricultural soil mechanics the equation by Fröhlich (1934) is most often used, which allows alteration to the decay pattern of the vertical stress due to Boussinesq's solution

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Table 1
Properties and initial conditions of the soils analyzed (mean values for 0.3–0.7 m depth). F_{wheel}, wheel load; P_{tyre}, tyre inflation pressure; Clay < 2 µm; Silt 2–50 µm; Sand 50–2000 µm; ρ_0, initial bulk density; w_0, initial gravimetric water content; σ_{pc}, precompression stress.

Site	Reference[†]	F_{wheel} (kN)	P_{tyre} (kPa)	Clay (wt.%)	Silt (wt.%)	Sand (wt.%)	ρ_0 (Mg m^{-3})	w_0 (g g^{-1})	σ_{pc} (kPa)
Billeberga (SE)	1	86	100, 150, 250	30.6	40.2	29.2	1.68	0.189	92.3
Önnestad (SE)	2	82	90, 220	35.0	48.4	16.7	1.54	0.250	138.4
Strängnäs (SE)	1	32	180	61.0	30.7	8.3	1.39	0.332	129.9
Ultuna (SE)	3	11, 15, 33	70, 100, 150	60.6	23.8	15.7	1.40	0.311	73.0
Vallø (DK)	4	24	60	13.3	26.8	60.0	1.56	0.175	96.8

1: Keller and Arvidsson (2004); 2: Arvidsson et al. (2002); 3: Arvidsson and Keller (2007); 4: Keller et al. (unpublished data).

through the introduction of a "concentration factor":

$$\hat{\sigma}_z = \frac{\nu P}{2\pi} \frac{z^\nu}{r^{\nu+2}} \tag{2}$$

where ν is the concentration factor (Fröhlich, 1934). For $\nu = 3$, Eq. (2) satisfies the solution based on the classical theory of elasticity (Boussinesq, 1885; Eq. (1)).

Stress transmission under agricultural vehicles is, however, not a point-load problem; instead, the load acts over an area (i.e. the tyre-soil or track-soil contact area). Linear elasticity allows superposition, and thus the stress at any depth, z, due to distributed normal loading at the soil surface can be calculated as follows: the contact area is divided into i small elements that each have an area A_i and a normal stress, σ_i, and carry a load $P_i = \sigma_i A_i$, which is treated as a point load. Disregarding horizontal stresses in the contact area, $\hat{\sigma}_z$ is then calculated as (Söhne, 1953):

$$\hat{\sigma}_z = \sum_{i=0}^{i=n} (\hat{\sigma}_z)_i = \sum_{i=0}^{i=n} \frac{\nu P_i}{2\pi} \frac{z_i^\nu}{r_i^{\nu+2}} \tag{3}$$

For a given surface load, $\hat{\sigma}_z$ at depth z becomes a sole function of ν (Eq. (3)).

The concentration factor was introduced because the rate of decay of the stress as predicted by the classical theory of elasticity (i.e., Eq. (1)) was found to be at variance with experimental observations of vertical stress distributions in soil (Söhne, 1953; Davis and Selvadurai, 1996). The discrepancy between the simulated and measured stress was ascribed to inaccurate model predictions, while measured stress values were assumed to be correct. However, measurements of stress in soil may be biased because embedded transducers do not read true stresses (Kirby, 1999; Berli et al., 2006a). Moreover, stress simulations, e.g. using Eq. (3), are sensitive to the stress boundary conditions at the surface (upper model boundary condition), i.e. the area over which the stress is applied and the distribution of the surface stresses (Keller and Lamandé, 2010).

The aim of this paper was to measure and simulate soil stress under defined loads. Measured stress was compared with simulated stress using Eq. (3), and the simulations obtained using Eq. (3) were also compared with finite element calculations. Moreover, the sensitivity of ν (Eq. (3)) to (i) the upper model boundary condition and (ii) stress readings (stress transducer estimates of the soil stress) was investigated.

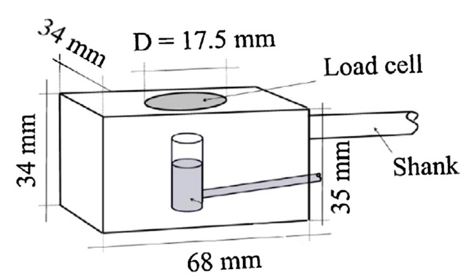
2. Materials and methods

2.1. Measurements of vertical soil stress

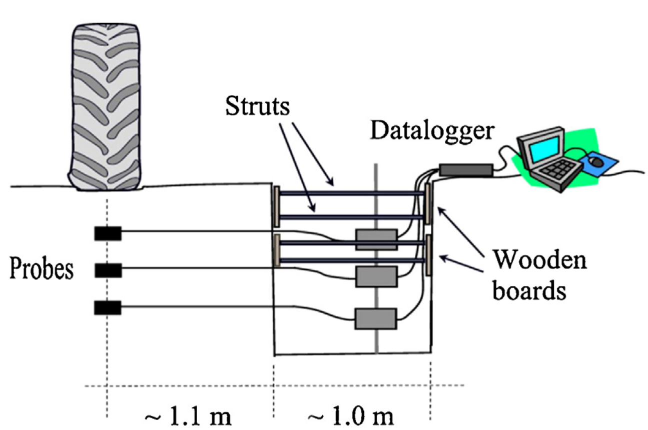
The experimental data of measured vertical soil stress from wheeling experiments performed on five soils (13–66% clay; Table 1) were used. All fields (Table 1) were conventionally tilled, including annual mouldboard ploughing to a depth of about 0.25 m. The experiments were carried out in autumn before primary tillage, or in spring (i.e. about half a year after primary tillage). Most experiments were performed with several wheel loads and/or tyre inflation pressures (Table 1). The driving speed was typically 2 m s^{-1}. The wheeling experiments reported here were carried out at a soil water content close to field capacity (Keller and Arvidsson, 2007). During wheeling experiments, the vertical stress was measured by installing probes (Fig. 1a) into the soil horizontally from a dug pit (Arvidsson and Andersson, 1997; Keller and Arvidsson, 2004) as shown in Fig. 1b. The stress was measured at three different depths, namely 0.3, 0.5 and 0.7 m. In this study, we used vertical stress measured below the centre of the loaded area.

The transducers used in this study over-predicted the vertical stress by 10% (Lamandé et al., 2014). Therefore, the transducer readings were corrected before further analysis and the vertical soil stress was assumed to be equal to 0.9 times the transducer-estimated stress (Lamandé et al., 2014).

Some of the wheeling experiments have already been reported elsewhere (Arvidsson et al., 2002; Keller and Arvidsson, 2004; Arvidsson and Keller, 2007). In the present study, we collated these data and analyzed them with respect to the stress transmission.



(a)



(b)

Fig. 1. (a) Probe (load cell and housing) used to measure vertical stress. (b) Experimental set-up for measurement of vertical stress at three depths.
Source: from Keller and Arvidsson (2004).