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# Accuracy of soil stress measurements as affected by transducer dimensions and shape

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ABSTRACT

Accurate measurements of soil stress are needed to evaluate the impact of traffic on soil properties and prevent soil compaction. Four types of transducer commonly used to measure vertical stress were calibrated in realistic traffic conditions in the field. The four transducer types differed in shape and dimensions, which are important factors influencing stress. Deviation of measured stress from true stress ranged from 15% underestimation to 18% overestimation, with transducer thickness to width ratio being the most important shape factor influencing the stress recorded. Changes in physical conditions in the soil above the transducers due to their installation did not influence the accuracy of vertical stress measurements. The results of this calibration are valid for correcting stress measurements in topsoil, but should be used with caution for vertical stress measurements in subsoil. All stress transducers should be calibrated in field conditions before use. More research is needed to characterise the stress distribution in the measuring face of transducers and better predict interactions between transducer and soil during loading.



## 1. Introduction

Prevention of soil compaction and its detrimental consequences starts with accurate quantification of the stresses imposed on the soil. Recent studies have made major advances towards more realistic description of the stress distribution at the tyre–soil interface by investigating the effects of wheel load, tyre type and tyre inflation pressure on contact stresses (Way and Kishimoto, 2004; Keller, 2005; Arvidsson and Keller, 2007; Cui et al., 2007; Mohsenimanesh and Ward, 2007; Schjønning et al., 2008; Lamandé and Schjønning, 2008; Schjønning and Lamandé, 2010). The stress distribution pattern in the soil profile has also been measured in a range of recent investigations (e.g. Arvidsson et al., 2002; Keller and Arvidsson, 2004; Arvidsson and Keller, 2007; Lamandé et al., 2007; Raper and Arriaga, 2007; Zink et al., 2010; Lamandé and Schjønning, 2011a,b,c). However, our knowledge on transducer accuracy in the field is limited. Deviations between measured and simulated values of the propagation of mechanical stresses in structured, heterogeneous, unsaturated soils (Gupta et al., 1985; Taylor and Burt, 1987; Dexter et al., 1988; Keller et al., 2007; Lamandé and Schjønning, 2011c) may be partly due to measured stress deviating from true stress (Selvadurai, 2012).

Vandenberg and Gill (1962),Blackwell et al. (1989), Arvidsson and Andersson (1997) and Lamandé et al. (2007) developed systems for measuring vertical soil stress, meaning that only one face of the transducer records a force. In contrast, Nichols et al. (1987), Horn et al. (1992) and Harris and Bakker (1994) developed a system to measure soil stress in three directions using a transducer with six measuring faces (vertical, 45°, horizontal). All factors influencing stress readings relate to the interaction between the transducer and the surrounding soil. Thus, issues concerning the accuracy of stress estimates are the same irrespective of the number of surfaces being addressed.

The stress transducers most frequently used in soil are strain gauges glued onto an aluminium, steel or titanium membrane (also called load cells), which are then accommodated in a housing of the same material (Pytka, 2013). The membrane can be in direct contact with soil, or soil stress can be transmitted to the membrane through a piston. Stress readings are affected by insertion of the transducers into the soil, among other factors. For correct stress

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readings, it is especially important to have: (i) a good contact between the transducer and the soil and (ii) minimal disturbance of soil and changes in soil strength around the measuring face(s) of the transducer. Using a finite element method, Kirby (1999a) showed that even very thin disturbed zones around the transducer alter the estimated stresses, with a zone weaker than the surrounding soil leading to underestimation of soil stress and a stronger zone leading to overestimation. Kirby (1999a) and Pytka (2013) both recommended calibration of transducers in the laboratory and in the field and theoretical simulations to estimate the response of any transducer to a stress field, as there is no general means of correcting the stress readings to match the true stress. Different calibration parameters might be obtained from these three different approaches, calibration in the field seems to be the most valid to correct transducer outputs.

Transducer height to diameter ratio, sharp angles close to the cell, diaphragm deflection, soil to cell stiffness ratio and stress–strain behaviour of the soil are factors influencing measurement of soil stress using transducers (Weiler and Kulhawy, 1982). For example, right-angled corners next to the membrane and a high height to diameter ratio are reported to lead to overestimation of soil stress (Kirby, 1999a). Transducers tend to overestimate soil stress in a strong soil (i.e. with a high shear strength and high precompression stress), but accurately estimate soil stress in a weak or wet soil (i.e. with a low shear strength and low precompression stress) (Kirby, 1999a). All studies of the accuracy of soil stress measurements lead to the same conclusions: (i) it is unrealistic to build a stress transducer that does not change the soil stress state, because soil mechanical properties change during loading and the transducer properties should then follow these changes in soil mechanical properties (e.g. Weiler and Kulhawy, 1982), and (ii) there is no universal calibration factor to account for uncertainties in stress readings. Therefore, each study using stress transducers to evaluate absolute stress values should evaluate the reliability of the measurements performed.

The accuracy of stress measurements can be evaluated by modelling (e.g. Kirby, 1999a,b), by calibration in the laboratory using remoulded soils and static loading (e.g. Harris and Bakker, 1994), or in a natural soil during wheeling. In a range of previous studies we used force sensors (load cells) embedded into housings of different shapes (e.g. Keller and Arvidsson, 2004; Keller, 2005; Schjønning et al., 2008; Lamandé and Schjønning, 2011a,b,c; Berisso et al., 2013). The linearity of the load cells embedded into housings was tested in the laboratory. The main objective of the present study was to calibrate these four types of stress transducers in a realistic wheeling situation in the field, where all transducers were installed in soil using the same method. Especially two factors potentially affecting soil stress readings were tested: (i) changes in physical conditions in the soil above and around the transducers, and (ii) shape and dimensions of the transducers.

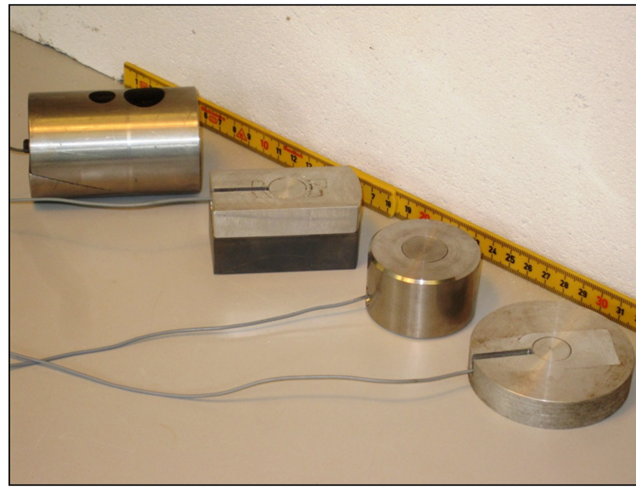

**Fig. 1.** The four types of transducers used in the study. From left to right: profile DK (load cell under the largest piston); Profile S; Surface DK; Surface S. See Table 1 for transducer dimensions.

## 2. Materials and methods

### 2.1. Stress transducers

The stress transducers tested were used in previous studies for either vertical stress measurements near the tyre–soil interface (hereafter referred to as Surface transducers) or vertical stress measurements in the soil profile (hereafter referred to as Profile transducers). One Surface- and one Profile transducer were developed in Sweden (S) and Denmark (DK), resulting in the designations Surface S, Profile S, Surface DK and Profile DK. These four types of transducers were developed and originally described by Keller (2005), Arvidsson and Andersson (1997), Schjønning et al. (2008) and Lamandé et al. (2007), respectively, and differed in dimensions and shape (Fig. 1 and Table 1). However, they contained identical load cells (DS Europe Series BC 302) and were made from materials with the same order of magnitude of stiffness (aluminium or steel). In the present study, all four transducers were tested in the same conditions, whether they were built to measure stress at the tyre–soil interface or in the soil profile.

### 2.2. Field test

The experimental field was located at Foulum Research Centre, Denmark (56°30′N, 09°34′E). The soil is a sandy loam (8% clay) and was at a water content close to field capacity during the experiment (Table 2). The specific part of the field used was the permanently grassed headland carrying the traffic when field

**Table 1**
Dimensions of the four types of stress transducers used in the study.

| Type | Shape | Length[a] (m) | Height (m) | Width[a] (m) | Aspect ratio[b] ($m\,m^{-1}$) | a/A[c] ($m^2\,m^{-2}$) |
|---|---|---|---|---|---|---|
| Profile DK | Horizontal cylinder | 0.08 | 0.052 | 0.052 | 1 | 0.024 |
| Profile S | Parallel pipe | 0.069 | 0.035 | 0.035 | 1 | 0.105 |
| Surface DK | Vertical cylinder | 0.05 | 0.032 | 0.05 | 0.64 | 0.160 |
| Surface S | Vertical cylinder | 0.07 | 0.015 | 0.07 | 0.21 | 0.059 |

[a] Length and width refer to the largest and smallest dimension in the horizontal plane, respectively.
[b] Height to width ratio.
[c] Ratio of sensitive area, *a* ($m^2$), to entire area of the measuring face of transducer, *A* ($m^2$).