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Soil stress as affected by wheel load and tyre inflation pressure

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Abstract

The relative importance of wheel load and tyre inflation pressure on topsoil and subsoil stresses has long been disputed in soil compaction research. The objectives of the experiment presented here were to (1) measure maximum soil stresses and stress distribution in the topsoil for different wheel loads at the same recommended tyre inflation pressure; (2) measure soil stresses at different inflation pressures for the given wheel loads; and (3) measure subsoil stresses and compare measured and simulated values. Measurements were made with the wheel loads 11, 15 and 33 kN at inflation pressures of 70, 100 and 150 kPa. Topsoil stresses were measured at 10 cm depth with five stress sensors installed in disturbed soil, perpendicular to driving direction. Contact area was measured on a hard surface. Subsoil stresses were measured at 30, 50 and 70 cm depth with sensors installed in undisturbed soil. The mean ground contact pressure could be approximated by the tyre inflation pressure (only) when the recommended inflation pressure was used. The maximum stress at 10 cm depth was considerably higher than the inflation pressure (39% on average) and also increased with increasing wheel load. While tyre inflation pressure had a large influence on soil stresses measured at 10 cm depth, it had very little influence in the subsoil (30 cm and deeper). In contrast, wheel load had a very large influence on subsoil stresses. Measured and simulated values agreed reasonably well in terms of relative differences between treatments, but the effect of inflation pressure on subsoil stresses was overestimated in the simulations. To reduce soil stresses exerted by tyres in agriculture, the results show the need to further study the distribution of stresses under tyres. For calculation of subsoil stresses, further validations of commonly used models for stress propagation are needed.

Keywords: Compaction; Soil stress; Subsoil; Topsoil; Tyre inflation pressure; Wheel load

1. Introduction

Soil compaction is the result of stresses acting upon the soil. One of the farmer's main options to reduce compaction is to reduce these stresses. For agricultural vehicles, this can mainly be done in two ways: by reducing the load or by increasing the contact area.

For tyres, stresses in the contact area and the topsoil are closely connected to the inflation pressure (e.g. Bailey et al., 1992; Erbach and Knoll, 1992; Raper et al., 1995; Arvidsson and Ristic, 1996). The mean contact stress can often be approximated by the inflation pressure (Plackett, 1984; Johnson and Burt, 1990; Burt et al., 1992; Van den Akker, 1994; Arvidsson et al., 2002). Koolen et al. (1992) assumed the mean normal stress in the contact surface to be 1.2–1.3 times the inflation pressure due to the stiffness of the tyre carcass. Karafiath and Nowatski (1978) presented an equation in which the mean contact pressure is calculated from the inflation pressure and tyre characteristics:

$$p_m = c_i p_i + p_c \quad (1)$$

where p_m is the mean contact pressure; c_i the tyre stiffness constant; p_i, the in flation pressure and p_c the pressure exerted by the tyre carcass when $p_i = 0$.

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Plackett (1984) measured the carcass stiffness and found it to be in the range 0.2–0.5 bar. There are also several reports in the literature where the measured average contact stress was lower than the inflation pressure (e.g. Gysi et al., 1999; Arvidsson et al., 2002; Alakukku et al., 2002). However, maximum stresses can be considerably higher than the mean contact stress, sometimes by a factor of two to four (Burt et al., 1992; Gysi et al., 2001, Alakukku et al., 2002). For a description of the stress distribution in the contact area, Söhne (1958) proposed a parabolic distribution over the tyre imprint, while Hammel (1994) suggested a trapezoidal distribution.

Whereas the effect of inflation pressure on stresses in the topsoil has been clearly demonstrated, the effect of wheel load is less clear. Stress measurements with different loads have often been carried out using the same tyre (e.g. Bailey et al., 1992; Erbach and Knoll, 1992; Burt et al., 1992; Raper et al., 1995; Way et al., 2000; Way and Kishimoto, 2003). Since increasing wheel load increases the recommended tyre inflation pressure, this means that the effect of load and inflation pressure cannot be studied independently.

Stresses in the subsoil can be calculated from the stress distribution in the contact area. Most widely used are the equations formulated by Boussinesq (1885) and later modified by Fröhlich (1934), in which the vertical stress under a point load is calculated. By dividing the contact area into subareas representing point loads, stresses beneath a tyre can be simulated (Söhne, 1958). Due to the interaction of stresses, increasing wheel load results in higher simulated stresses in the subsoil. This has also been confirmed in measurements of stresses and compaction in the subsoil (e.g. Eriksson et al., 1974, Arvidsson et al., 2001, Trautner and Arvidsson, 2003). Olsen (1994), based on calculations according to Eq. (1), stated that the soil stress in the 0.1–1 m layer depends both on the load and the contact area stress. For high wheel loads (>80 kN), Arvidsson et al. (2002) and Keller and Arvidsson (2004) demonstrated a large influence of tyre inflation pressure on soil stress and displacement at 0.3 m depth. However, at greater depths, the influence of inflation pressure was small. Danfors (1994) found no effect of inflation pressure on compaction in the subsoil. Despite a large amount of research in the area of subsoil compaction (Håkansson, 1994; Van den Akker et al., 2003), there are very few validated simulations of subsoil stresses that are based on measured contact area stresses.

The objectives of the experiment presented here were to (1) measure maximum soil stresses and stress distribution in the topsoil for different wheel loads at the same recommended tyre inflation pressure; (2) measure soil stresses at different inflation pressures for the given wheel loads; and (3) measure subsoil stresses and compare measured and simulated values.

2. Materials and methods

2.1. Stress distribution in the topsoil

Measurements of stress distribution in the topsoil were made on a loam soil (308 g kg^{-1} clay, 18 g kg^{-1} organic matter content) in Uppsala, Sweden (59.9°N, 17.6°E), in November 2002 at a water content close to field capacity (250 g kg^{-1}). Stress sensors were constructed from load cells (DS Europe Series BS 302) with a diameter of 17.5 mm, which were mounted in a circular plate, 15 mm high and 70 mm in diameter. Before the measurements, 10 cm of topsoil were removed and five stress sensors were placed at 90 mm intervals, perpendicular to the driving direction. The topsoil was then backfilled over the sensors. During wheeling, the centre of the tyre was run over the outermost sensor, and the stress distribution was assumed to be symmetrical along the centre line of the wheel track. Four separate installations were made, which were considered as replicates. For each installation, wheelings were made with all combinations of wheel loads and inflation pressures, without removing the soil between the passes. Stress measurements seem to be little influenced by the number of passes when deformations are small (Van den Akker et al., 1994; Alakukku et al., 2002). For each installation, the wheel loads were driven in a randomized order over the sensors. There was no clear difference in stress recordings due to the number of passes over the sensors.

Wheelings were made with two tractors, MF 6290 and MF 4245. The intention was to have different wheel loads, but with the same recommended tyre inflation pressure of 100 kPa. This was achieved for the front and rear tyre of the MF 4245, and the rear tyre of the MF 6290. In addition to the recommended inflation pressure of 100 kPa, wheelings were also made at tyre inflation pressures of 70 and 150 kPa. Wheel loads, tyre sizes and recommended wheel load for different inflation pressures are presented in Table 1.

2.2. Tyre contact area on hard surface

The different tyres were driven onto paper sheets lying on a concrete floor, and a spray paint was used to outline the tyre imprint onto the paper. Thereafter, the tyre imprint was cut out of the paper and weighed to