Soil & Tillage Research 111 (2010) 54–64

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Challenges in the development of analytical soil compaction models

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ARTICLE INFO

Keywords:
Soil compaction
Modelling
Stress propagation
Concentration factor
Precompression stress

ABSTRACT

Soil compaction can cause a number of environmental and agronomic problems (e.g. flooding, erosion, leaching of agrochemicals to recipient waters, emission of greenhouse gases to the atmosphere, crop yield losses), resulting in significant economic damage to society and agriculture. Strategies and recommendations for the prevention of soil compaction often rely on simulation models. This paper highlights some issues that need further consideration in order to improve soil compaction modelling, with the focus on analytical models. We discuss the different issues based on comparisons between experimental data and model simulations. The upper model boundary condition (i.e. contact area and stresses at the tyre–soil interface) is highly influential in stress propagation, but knowledge on the effects of loading and soil conditions on the upper model boundary condition is inadequate. The accuracy of stress transducers and therefore of stress measurements is not well known, despite numerous studies on stress in the soil profile below agricultural tyres. Although arable soils are characterised by distinct soil layers with different mechanical properties, analytical models rely on a one-layer approach with regard to stress propagation, an anomaly that needs further attention. We found large differences between soil stress–strain behaviour obtained from in situ measurements during wheeling experiments and those measured on cylindrical soil samples in standard laboratory tests. We concluded that the main reason was differences in loading time, and suggest that future research should concentrate on in situ stress–strain behaviour during short time, dynamic loading.

1. Introduction

Soil is subject to a series of degradation processes or threats, including soil compaction (e.g. EU, 2006). Compaction affects many physical, chemical and biological properties and processes in the soil and may result in environmental (e.g. erosion, flooding, nutrient and pesticide leaching to groundwater) and agronomic problems (decreased root growth and plant development, with an associated reduction in crop yield).

Strategies and recommendations for prevention of soil compaction often rely on simulation models (soil compaction models). Such models are able to calculate stress propagation and soil failure in the soil profile for certain mechanical loading (agricultural machinery) and soil conditions (e.g. soil moisture status), and may help farmers and advisors in planning and making decisions about specific traffic situations in the field.

Défossez and Richard (2002) divided soil compaction models into two categories: analytical and finite element models (FEM). A number of analytical models have been developed (O'Sullivan et al., 1999; van den Akker, 2004; Keller et al., 2007) and used to better understand soil compaction processes (e.g. Arvidsson et al., 2001; Défossez et al., 2003; Lamandé et al., 2007). Commercial finite element codes designed for geotechnical purposes (e.g. Brinkgreve, 2002) and FEM specifically developed for agricultural purposes (e.g. Richards, 1992; Gysi et al., 2000) have been used to simulate soil compaction due to agricultural field traffic (e.g. Gysi et al., 2000; Gysi, 2001; Berli et al., 2003; Poodt et al., 2003; Peth et al., 2006; Cui et al., 2007). Distinct or discrete element models (DEM) (e.g. Cundall and Strack, 1979) have been applied in soil science research only recently (e.g. Zhang and Li, 2006). To our knowledge, DEM have not been used to simulate soil compaction due to agricultural field traffic, but may provide a promising method for better understanding of soil deformation and stress transmission at different scales (Van Baars, 1996; Delenne et al., 2004; Zhang and Li, 2006).

In this paper, we focus on analytical soil compaction models. These models are based on the work of Boussinesq (1885), Fröhlich (1934) and Söhne (1953) for calculation of stress propagation in

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0167-1987/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.still.2010.08.004

soil (see Section 3). Although finite element models (e.g. Peth et al., this issue) and distinct element models (e.g. Shmulevich et al., this issue) are more powerful than analytical models, we still consider it worthwhile to further develop the latter because we believe analytical models are necessary in implementing soil compaction research in practice, e.g. for use by agricultural advisors and farmers. Analytical soil compaction models have the advantage that they are usually simple to use, require few input parameters and are robust. Much of what is discussed in this paper also applies to finite and distinct element models.

The structure of soil compaction models can be divided into three parts: (i) the upper model boundary condition, i.e. the contact area and the stresses at the soil surface; (ii) the propagation of stresses through soil; and (iii) the stress–strain behaviour of soil. However, these different parts are interrelated: e.g. the stress–strain behaviour of soil can influence the stresses at the soil surface. The three parts correspond to the calculation procedure of analytical soil compaction models. First, stresses at the soil surface are defined. Second, stress propagation is calculated. And third, soil deformation is calculated by applying a stress–strain relationship to the calculated stresses or it is assessed whether soil compaction has occurred by comparing the calculated stress with a critical stress (e.g. precompression stress).

Models for calculating compaction in agricultural soil suffer from drawbacks such as insufficient knowledge about the effects of soil conditions (i.e. soil type, structure, moisture, density, etc.) on stress propagation. Furthermore, soil stress–strain behaviour and soil mechanical properties relevant for short-term dynamic loading, as occurs in agricultural soils, are inadequately characterised. For example, Keller et al. (2004) and Lamandé et al. (2007) concluded that there is a need to determine soil behaviour in the field and to link in situ soil deformation behaviour to soil mechanical (laboratory) tests. There are three main reasons for this: (1) Loading time in the field (e.g. from an agricultural tyre) is much shorter than that used in laboratory tests for determination of soil mechanical properties; (2) loading in the field is dynamic (i.e. the directions of principal stresses are not constant in time) whereas loading in the laboratory is static; and (3) in contrast to loading in the field, soil samples in laboratory tests are often loaded under confined conditions.

This paper examines some issues that need further consideration in order to improve soil compaction modelling, with the focus on analytical soil compaction models. The different issues are discussed based on comparisons between experimental data and model simulations. The structure of the present paper follows the structure of analytical soil compaction models described above, so we first address the upper model boundary conditions, i.e. surface stresses and the contact area (Section 2), then stress propagation (Section 3), and finally stress–strain relationships (Section 4).

2. Upper model boundary condition: surface stresses and contact area

2.1. Accurate estimation of the upper boundary condition is crucial

The upper model boundary condition is given by the contact between tyre (or track) and soil, and consists of the contact area and the stresses at the tyre–soil interface. Here, we focus on vertical contact stresses only.

The contact area between tyre and soil can be described by an ellipse (Upadhyaya and Wulfsohn, 1990; Febo et al., 2000). The distribution of vertical stress at the tyre–soil interface has been described by power-law functions (Söhne, 1953, 1958; Johnson and Burt, 1990), by polynomials (Smith et al., 2000) and by a combination of a power-law and a decay function (Keller, 2005; Schjønning et al., 2008).

It has been shown by modelling that the stress distribution at the tyre–soil interface is highly non-uniform and largely influences soil stresses (e.g. Keller and Arvidsson, 2004; Keller, 2005; Keller et al., 2007; Schjønning et al., 2008). This is further demonstrated in Figs. 1 and 2. We compared simulated stress values obtained using the soil compaction model SoilFlex (Keller et al., 2007) with measured stress values reported by Keller and Arvidsson (2004) (Fig. 2a) and Arvidsson and Keller (2007) (Fig. 2b). We thereby calculated stress propagation for two different upper boundary conditions (Fig. 1), namely (i) assuming a circular contact area with a uniform stress distribution that equals the tyre inflation pressure, and (ii) estimating the contact area and the distribution of vertical contact stresses from tyre parameters and wheel load according to Keller (2005). Note that in both cases the same load was assumed and only the distribution of contact stress was different. The influence of the distribution of contact stresses is large near the soil surface and decreases with increasing distance from the soil surface (i.e. with increasing soil depth), as demonstrated by Taylor and Burt (1987) and Lamandé et al. (2007) and as shown in Fig. 2. Note that a uniform stress distribution, which is often used to describe the contact between a tyre and soil (e.g. Kirby et al., 1997; Poodt et al., 2003), usually underestimates stress in the upper soil layers (Fig. 2).

2.2. Important factors influencing surface stresses and contact area

2.2.1. Tyre properties and loading characteristics

Tyre construction (radial or cross-ply construction; properties of the belt and tread; lug dimensions and pattern), tyre dimensions (tyre diameter, width and aspect ratio) and tyre loading (tyre inflation pressure, wheel load) influence the contact area (e.g. Sharma and Pandey, 1996; Febo et al., 2000) and the magnitude

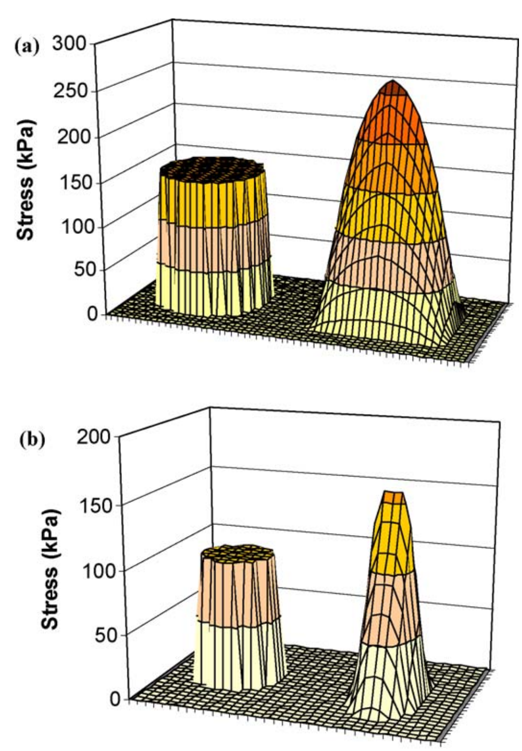

Fig. 1. Distribution of vertical stress on the soil surface (upper model boundary condition) assuming a circular contact area with a uniform stress distribution that equals the tyre inflation pressure (left) and estimating the upper model boundary condition according to Keller (2005) (right) below: (a) a tyre of size 1050/50R32 with a load of 86 kN and an inflation pressure of 150 kPa; and (b) a tyre of size 13.6R38 with a load of 15 kN and an inflation pressure of 100 kPa.