Soil Compaction and Soil Tillage – Studies in Agricultural Soil Mechanics

Thomas Keller
Department of Soil Sciences
Uppsala

Doctoral thesis
Swedish University of Agricultural Sciences
Uppsala 2004

Acta Universitatis Agriculturae Sueciae
Agraria 489

ISSN 1401-6249
ISBN 91-576-6769-1

Tryck: SLU Service/Repro, Uppsala 2004

Abstract

Keller, T. 2004. *Soil Compaction and Soil Tillage - Studies in Agricultural Soil Mechanics*
Doctoral dissertation.
ISSN 1401-6249, ISBN 91-576-6769-1

This thesis deals with various aspects of soil compaction due to agricultural field traffic, the draught force requirement of tillage implements and soil structures produced by tillage.

Several field experiments were carried out to study the mechanical impact of agricultural machines. It was shown that the stress interaction from the different wheels in dual and tandem wheel configurations is small and these wheels can be considered separate wheels with regard to soil stress. Hence, soil stress is not related to either axle load or total vehicle load. At high wheel load, tyre inflation pressure affected subsoil stresses. The maximum stress at the soil-tyre interface was greater than the tyre inflation pressure. Furthermore, the distribution of stress beneath tyres and rubber belts was highly non-uniform. This was shown to have a great influence on stress propagation in soil. Therefore, with regard to soil compaction modelling, a uniform stress distribution (as often used) is too poor an approximation of the real stress distribution and can result in underestimation of soil compaction. A model for predicting the distribution of stress below tyres using readily-available tyre parameters is proposed. With a more realistic approximation of the stress distribution at the soil surface, simulated stresses generally agreed well with measured stresses.

Both field and laboratory measurements rejected the concept of precompression stress as a distinct threshold value between reversible and irreversible compressive strain. Irreversible strain was measured at applied stresses that were lower than the precompression stress. The precompression stress was dependent on the nature of the compression test and the method of analysis.

The draught requirement of tillage implements could be related to shear vane strength for specific soil-implement combinations. Draught force and aggregate size distribution produced by tillage were strongly affected by soil water content, with the optimum tillage results being produced at water contents close to the water content at the inflection point of the water retention curve. Specific draught was calculated for comparison of the tillage efficiency of different implements. The chisel plough often worked below its critical depth, which strongly increased the energy requirement without any benefit in terms of soil break-up. Therefore, the specific draught was higher for the chisel plough compared with the disc harrow and the mouldboard plough.

Keywords: aggregates, draught force, model, precompression stress, soil compaction, soil displacement, soil strength, soil stress, soil water, tillage.

Author's address: Thomas Keller, Department of Soil Sciences, SLU, P.O. Box 7014, SE-750 07 Uppsala, Sweden. E-mail: thomas.keller@mv.slu.se

”…doch d’Wält isch so perfid, dass si sech sälten oder nie nach Bilder, wo mir vo’re gmacht hei, richtet…”

Mani Matter in *Chue am Waldrand*

”...but the world is so perfidious that it rarely or never acts in accordance with pictures that we’ve made of it…”

Mani Matter in *Cow at the Edge of the Woods*

Contents

Appendix

Papers I-VIII

This thesis is based on the following papers, which are referred to in the text by their Roman numerals:

I Arvidsson, J. & Keller, T. 2004. Soil precompression stress. I. A survey of Swedish arable soils. Soil & Tillage Research 77(1), 85-95.

II Keller, T., Arvidsson, J., Dawidowski, J.B. & Koolen, A.J. 2004. Soil precompression stress. II. A comparison of different compaction tests and stress-displacement behaviour of the soil during wheeling. Soil & Tillage Research 77(1), 97-108.

III Keller, T., Trautner, A. & Arvidsson, J., 2002. Stress distribution and soil displacement under a rubber-tracked and a wheeled tractor during ploughing, both on-land and within furrows. Soil & Tillage Research 68(1), 39-47.

IV Keller, T. & Arvidsson, J., 2004. Technical solutions to reduce the risk of subsoil compaction: Effects of dual wheels, tandem wheels and tyre inflation pressure on stress propagation in soil. Special issue of Soil & Tillage Research on Soil Physical Quality. *In press*

V Keller, T. A model for prediction of the contact area and the distribution of vertical stress below agricultural tyres from readily-available tyre parameters. *Submitted to Biosystems Engineering*

VI Keller, T., Défossez, P., Weisskopf, P., Arvidsson, J. & Richard, G. *SoilFlex*: A model for prediction of soil stresses and soil compaction due to agricultural field traffic including a synthesis of analytical approaches. *Manuscript*

VII Arvidsson, J., Keller, T. & Gustafsson, K., 2004. Specific draught for mouldboard plough, chisel plough and disc harrow at different water contents. Special issue of Soil & Tillage Research on Soil Physical Quality. *In press*

VIII Keller, T., Arvidsson, J. & Dexter, A.R. Soil structures produced by tillage as affected by soil water content and the physical quality of soil. *Manuscript*

Introduction

Soil degradation is a subject that is attracting increasing concern worldwide. The European Union has realised that there is a need to protect soils and has identified soil compaction as one of the main threats to soil that may result in the degradation of soils (COM, 2002).

Reasons for the increasing soil degradation due to soil compaction may be found in the increase in weight of agricultural machinery, in the more intense use of machinery even under unfavourable soil conditions and in bad crop rotations. Economic pressure and structural changes in modern agriculture may contribute to this development.

Soil compaction is an environmental problem (Pagliai *et al.*, 2004). It is one of the causes of erosion and flooding (Horn *et al.*, 1995; Soane & Ouwerkerk, 1995; Gieska *et al.*, 2003). In addition, it directly or indirectly increases nutrient and pesticide leaching to the groundwater and nitrous oxide (a greenhouse gas) emissions to the atmosphere (Lipiec & Stepniewski, 1995).

From an agronomic point of view, the consequences of soil compaction are decreased root growth and plant development, and consequently, a reduction in crop yield (Håkansson & Reeder, 1994). Subsoil compaction may persist for a very long time and is hence a threat to the long-term productivity of the soil (Etana & Håkansson, 1994).

Efforts to ameliorate compacted subsoil by mechanical deep-loosening are expensive and often fail. Therefore, soil compaction must be prevented. It is believed that the risk of undesirable changes in soil structure can be minimised by limiting the mechanically-applied stress to below a threshold stress (Dawidowski *et al.*, 2001), termed the precompression stress. While the concept of precompression stress as a threshold between reversible and irreversible strain (Horn & Lebert, 1994) is widely used, it has been scarcely tested in combination with wheeling experiments in the field. The impact of agricultural machinery on soil properties may be simulated by means of soil compaction models, which are an important tool for developing strategies for prevention of soil compaction.

Due to compaction, the soil not only becomes denser, but also stronger. Consequently, the soil is more difficult to till and its friability (*i.e.* ability to fragment) is decreased. As an effect of the stronger soil, draught requirement and therefore fuel consumption for tillage are increased; this increases the release of greenhouse gases that may contribute to global warming. The increased energy requirement also negatively influences the farmer's budget: the costs for fuel are high compared with the income from yield, and therefore, it is very important to minimise costs for tillage in order to optimise profit. The amount of energy consumption in tillage (especially in primary tillage) is quite high compared with other farming operations (Gill & Vandenberg, 1968; Shrestha *et al.*, 2001). Therefore, it is interesting to study the energy requirement for different tillage implements on different soils and at different soil conditions, and to compare different tillage systems.

In order to minimise the number of tillage operations and therefore total energy input for a given tillage system, tillage should be performed at optimal soil conditions. The soil structures produced by tillage are strongly affected by soil moisture. There exists a water content at which the result of tillage is optimum (*i.e.* the proportion of small aggregates produced is largest or, conversely, the proportion of clods produced smallest), termed the optimum water content for tillage. Dexter & Birkás (2004) showed that the proportion of clods produced by tillage at the optimum water content is larger for soils with lower soil physical quality, *i.e.* for degraded soils. Not only is the result of tillage worse for a degraded soil, but also the number of workable days is smaller compared with a soil of good physical quality (Dexter & Bird, 2001).

Prevention of soil compaction is a most significant measure in order to sustain or improve soil physical quality. Good soil physical quality implies good soil workability, which is a pre-condition for minimising (energy use in) soil tillage.

Objectives

The objectives of this thesis were:

(a) **Soil precompression stress and its practical significance for agricultural soil mechanics:** To compare the precompression stresses obtained by different tests and different determination procedures; to study the stress-strain behaviour of soil in the field during agricultural field traffic and relate that to the precompression stress

(b) **Stress distribution at the soil-tyre/track interface and stress propagation in soil:** To measure the distribution of stress in the ground contact area and the stress propagation in soil caused by different machines and during different field operations, and to compare measurements with model simulations

(c) **Draught requirement of different tillage implements during primary tillage:** To measure the draught requirement of different implements on different soils and at different water contents

(d) **Optimal water content for primary tillage:** To measure aggregate size distribution produced by tillage as influenced by tillage implement, soil type and soil moisture content

The following chapters contain an overview of the subject of soil compaction and tillage and put the research carried out in the present study into context. The results presented are mainly summarised from Papers I-VIII, but some are solely published in the following chapters.

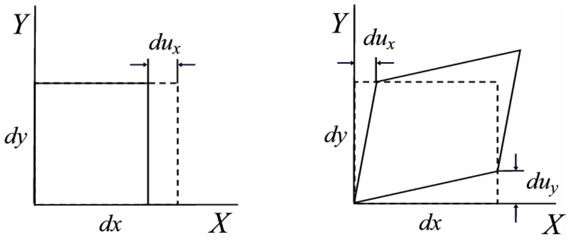
The first chapter gives definitions of some technical terms to facilitate the reading of this thesis. The second chapter deals with methodological aspects and briefly describes and discusses the main features of the methods used during field experiments to give the reader an overview. This is followed by chapters on stress propagation and mechanical behaviour of soil, which include a general discussion of stress measurements and simulations and a detailed discussion of soil precompression stress and some aspects of soil compaction modelling. The next chapter is on soil tillage including soil break-up, draught force requirement and friability. It is followed by a chapter on interactions between tillage and compaction. Finally, there is a chapter on practical solutions to reduce the risk of soil compaction. The conclusions include implications for future research.

Some definitions

Bulk density, ρ	$$\rho = \frac{total\ soil\ mass}{total\ soil\ volume}$$
Compaction or compression	Reduction of the volume of a given mass of soil, *i.e.* decrease in void ratio and porosity and, conversely, increase in bulk density. Pure compaction: the shape of a soil volume remains unchanged.
Consolidation	Compaction through the drainage of water.
Dilation, expansion or loosening	Increase in volume of a given mass of soil, *i.e.* increase in void ratio and porosity and, conversely, decrease in bulk density.
Porosity, η	$$\eta = \frac{volume\ of\ water\ and\ air}{total\ soil\ volume}$$
Precompression stress, precompaction stress, preconsolidation stress or preload	Largest overburden stress to which a soil has been exposed. Referred to as a threshold stress such that loadings inducing smaller stresses than this threshold cause little additional compaction, and loadings inducing greater stresses cause much additional compaction.
Pressure	Force or thrust exerted over a surface divided by the area of the surface. Pressure is a scalar, *i.e.* it is independent of direction. Unit: 1 Pa = 1 N m^{-2}; 1 bar = 100 kPa; 1atm = 1kp cm^{-2} ≈ 100 kPa; 1 psi = lb in^{-2}
Shear deformation	Change in the shape of a soil volume. Pure shear deformation or distortion: shear deformation at constant volume.
Specific volume, v	$$v = \frac{total\ soil\ volume}{volume\ of\ solids} = 1 + e$$

Strain

Measure of the deformation of a body. Strains can involve changes in volume, shape or both.



Normal strain, $\varepsilon_{xx} = \frac{\partial u_x}{\partial x}$

Shear strain, $\varepsilon_{xy} = \frac{1}{2}\left(\frac{\partial u_y}{\partial x} + \frac{\partial u_x}{\partial y}\right)$

Engineering shear strain, $\gamma_{xy} = \left(\frac{\partial u_y}{\partial x} + \frac{\partial u_x}{\partial y}\right)$

Strength

Stress at which a material fails; therefore, strength has the same units as stress.

Stress

Force per unit area. Stress is a vector, *i.e.* it acts in a certain direction.
Unit: 1 Pa = 1 N m^{-2}
A stress acting perpendicular to a plane is called a normal stress; a stress acting tangential to a plane is called a shear stress.
Note: In soil science, compressive stresses are usually defined as positive and tensile stresses as negative; in geotechnical engineering, compressive stresses are usually defined as negative and tensile stresses as positive.

Tension

The act or action of stretching; contrasted with compressive stress.
Tensile strength: Resistance to rupture under tension, *i.e.* the greatest tensile stress a material can bear without tearing apart.

Void ratio, *e*

$$e = \frac{volume\ of\ voids}{volume\ of\ solids} = \frac{\eta}{1-\eta} = v - 1$$

Methodological aspects

Experimental sites and machine properties

Wheeling experiments were carried out in Sweden at Billeberga (55.9°N, 13.0°E), Önnestad (56.1°N, 14.0°E), Örsundsbro (59.7°N, 17.3°E), Strängnäs (59.4°N, 17.0°E), Uppsala (59.9°N, 17.6°E), Varberg (57.1°N, 12.3°E) and Tolefors (58.4°N, 15.6°E) and in Denmark at Krenkerup (54.8°N, 11.6°E) and Vallø (55.4°N, 12.1°E) in the years 2000 to 2004. The texture of the soils ranged from sandy loam to clay. Wheeling experiments were carried out with towed trailers, wheeled and tracked tractors and sugar beet harvesters. The wheel loads were in the range 11 to 125 kN.

Tillage experiments were carried out at Ultuna and Säby in Uppsala during the years 2001 to 2003. The texture of the soils ranged from sandy loam to clay. Draught force and aggregate size distribution produced by tillage were measured for autumn primary tillage operations. The implements used were mouldboard plough, chisel plough and disc harrow.

Wheeling experiments: measurements of stress and displacement

The distribution of the vertical stress below the ground contact area of tyres (or tracks) was measured by (usually) five stress sensors that were buried in the topsoil at 0.1 m depth. Each sensor (DS Europe Series BC 302) was attached to an aluminium disc (diameter: 17.5 mm, height: 5.5 mm) embedded in the centre of a larger aluminium disc (diameter: 70 mm, height: 15 mm), see Fig. 1(a). The cells were placed on a line perpendicular to the driving direction under one half of the wheel track [Fig. 1(b)]. One cell was placed below the centre of the tyre, one below the edge of the tyre, and the remaining cells were placed in between. The set-up was similar for tracks.

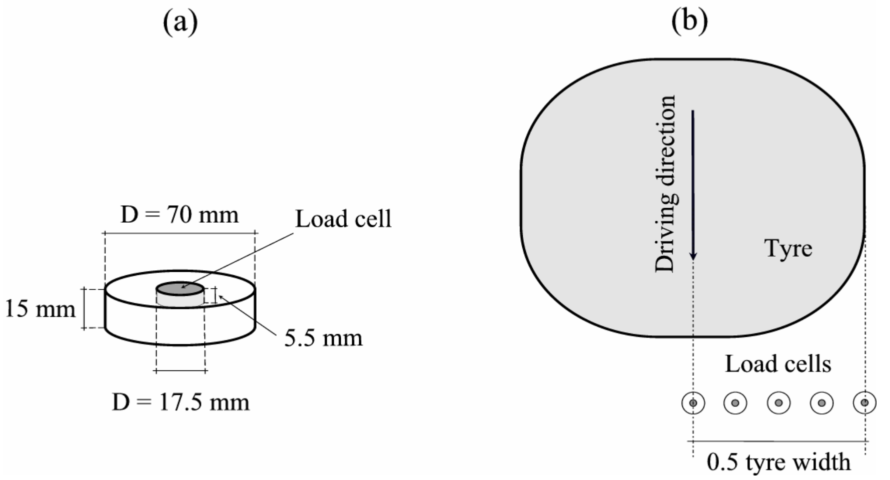


Fig. 1. (a) Stress sensor for measurements below the tyre; (b) sketch of stress measurements below the tyre (plane view).

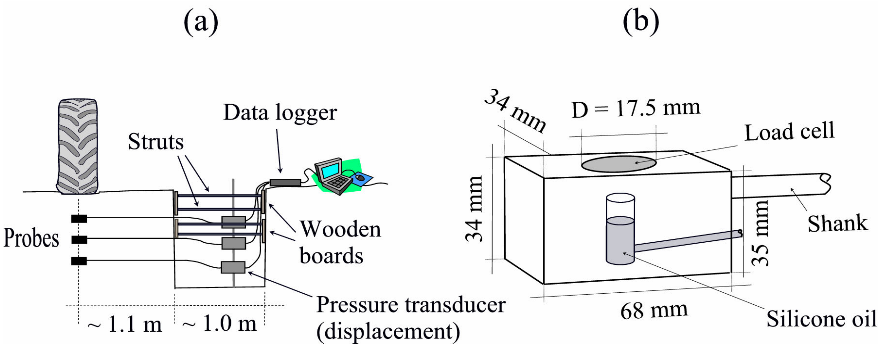


Fig. 2. (a) Experimental set-up for stress and displacement measurements in the subsoil; (b) probe for subsoil measurements.

Vertical soil stress and displacement were measured by installing probes into the soil horizontally from a dug pit that was approximately 1.5 m long, 1 m wide and 1m deep, with the walls stabilized with wooden boards [Fig. 2(a)]. The probes were installed through drilled holes that were stabilized by inserting a steel tube having the same diameter (58 mm) as the hole. For each wheeling pass, three probes were installed, typically at 0.3, 0.5 and 0.7 m depth. The distance between the pit wall and the probe head was approximately 1.1 m [Fig. 2(a)]. Stress was measured by a load cell (DS Europe Series BC 302) with a diameter of 17.5 mm [Fig. 2(b)]. Determination of the displacement is based on the physical principle that the pressure of a column of liquid (in this case silicone oil) is proportional to its height (Fig. 2). The method is described in detail in Arvidsson & Andersson (1997).

Do transducers provide accurate estimates of the true stresses in soil?

In this thesis, vertical stress was measured by load cells, also referred to as vertical transducers. Vertical transducers were also used by *e.g.* Blunden *et al.* (1994) and Kirby *et al.* (1997). Measuring only vertical stress may be a serious limitation, since it is not only vertical stresses that are of importance for soil reaction in terms of soil deformation and soil compaction, but also horizontal stresses and shear stresses. Several researchers including Bailey *et al.* (1988), Bakker *et al.* (1995), Way *et al.* (1995), Wiermann *et al.* (1999), Pytka & Dabrowski (2001), Abu-Hamdeh & Reeder (2003) and Horn *et al.* (2003) measured stresses with a transducer with six measuring faces; such a transducer is called a stress state transducer. Gysi *et al.* (1999), Gysi *et al.* (2000) and Diserens & Steinmann (2002), measured soil stress with Bolling pressure probes (Bolling, 1987). Gysi *et al.* (2000) showed that the stress measured by Bolling probes is a good indicator of the mean normal stress.

Measuring stress in soil with stress transducers is accompanied by several problems, as discussed by Trautner (2003). A pre-condition for reliable stress measurements is to have a good contact between the stress transducer and the surrounding soil. This may be difficult, especially under very dry conditions or in sandy soils (Trautner, 2003). Obtaining good contact between transducer and soil is probably more difficult with a stress state transducer (with six faces) than with a vertical transducer (with one face).

The stress estimate provided by the transducer is influenced by the stiffness of the transducer in comparison with its surrounding soil (Kirby, 1999a, b). The size of the transducer is another factor affecting the measurements. Trautner (2003) observed that the measured stress was much higher when the stress sensors were placed on a wooden board compared with when the stress sensors were placed directly in the soil. According to Kirby (1999a, b), the stress sensors used here might rather overestimate the stresses in soil, as they have a greater stiffness than the soil.

Kirby (1999a, b) analysed the stress fields around transducers by means of FE modelling. He concluded that absolute values of stress measurements should be treated with caution. Furthermore, he concluded that stress state transducers may overestimate stresses more than vertical transducers and that the magnitude of the overestimate is not necessarily the same on each face. This implies that the derived quantities such as the octahedral shear stress, τ_{oct}, and the mean normal stress, p, may be inaccurate not just in magnitude, but also relative to one another (Kirby, 1999a, b).

An idea of the accuracy of the stress measurements can be gained when the stress is measured with a high spatial resolution (in a plane parallel to the soil surface). For the stress measured directly below a tyre, the following equation must be satisfied:

$$F_{wheel} = \int_A \sigma_v dA \qquad (1)$$

where F_{wheel} is the wheel load, A the contact area and σ_v the measured vertical stress. For the 29 combinations of loading and tyre characteristics analysed in Paper V, F_{wheel} was on average within 3% of the weighed wheel load. Similar results were reported by van den Akker & Carsjens (1989).

Therefore, it may be concluded that the vertical transducers used in this thesis provide adequate estimates of the true vertical stress in soil. This is supported by the fact that measured values can be reproduced by models for stress propagation (see section 'Soil compaction modelling').

Methods to measure soil displacement

In this thesis, vertical soil displacement was measured as described in Arvidsson & Andersson (1997). From the measurements of vertical displacement at two different depths, vertical strain may be calculated. However, we cannot measure soil compaction, nor can it be calculated from the measurements of vertical displacement since we do not know how large the horizontal strains are.

However, by measuring vertical soil displacement, we can observe if 'something is happening' in the soil due to field traffic. This 'something' may either be compressive deformation, or it may be shear deformation, or (most likely) a combination of both. Therefore, the measurement of vertical displacement may potentially be an indicator of a change in soil function. Finding a relationship between vertical soil displacement/strain and soil function may be the subject of future research.

Gliemeroth (1953) tracked soil particles in a vertical plane parallel to the driving direction by filming. Kühner (1997) used a purely mechanical principle for measuring both vertical and horizontal displacement in a similar plane. With this method, it is possible to observe soil shearing. Shearing may affect the quality of a soil more negatively than pure compaction, especially in the topsoil (Horn, 2003). Compaction is not measured, nor can it be calculated with this method.

In order to observe compaction, it is necessary to measure displacements in three dimensions. This was done by Way *et al.* (2005), who measured soil strains with three mutually orthogonal soil strain transducers (*i.e.* one vertical, one lateral and one longitudinal). From these strains, volume change can be calculated. However, unless the transducers are anchored in some way, their absolute positions and directions and their positions and directions relative to one another may change due to the passage of a wheel, which makes the calculation of volume change highly erroneous.

Another method for measuring displacements is to use accelerometers, as did Ristolainen *et al.* (2003). From the measured acceleration, displacement can be calculated by two-fold integration over time. A difficulty of that method is that accelerations due to vertical movement can *a priori* not be distinguished from accelerations due to rotation of the accelerometer.

Measurements of draught force

Draught force was measured for different implements pulled by a four-wheel-drive tractor (Paper VII). The tractor had equipment to measure fuel consumption, which was calibrated so that the power at the power take-off (PTO), P_{PTO}, could be calculated for any combination of fuel consumption and engine speed (revolutions per minute). A technical description of the measuring system is given in Pettersson *et al.* (2002). P_{PTO} was assumed to be the same as the power available at the tractor wheels. The power available for pulling an implement, P_{pull}, was calculated as:

$$P_{pull} = P_{PTO}(1 - s) - fGv_{radar} \quad (2)$$

where s is the wheel slip, f the coefficient of rolling resistance, G the weight of the tractor and v_{radar} the velocity of the tractor measured by radar. Wheel slip, s, was calculated from wheel and tractor speed, respectively, whereas f was obtained by driving the tractor without pulling any implement. From P_{pull}, the draught force, D, is calculated as:

$$D = \frac{P_{pull}}{v_{radar}} . \quad (3)$$

Before tillage, bulk density of the topsoil was determined by taking core samples in the tillage layer. After tillage, a frame was inserted into the soil, and all soil loosened by tillage within the frame was collected and weighed. From the weight of the loosened soil and the bulk density, the actual average working depth (in relation to the original soil surface), $d_{working}$, can be calculated. Specific resistance (specific draught), $D_{specific}$ (kN m^{-2}), is then calculated as:

$$D_{specific} = \frac{D}{d_{working} w_{implement}} \qquad (4)$$

where $w_{implement}$ is the width of the implement.

Methods to measure draught force

Draught force can be measured in two ways. Firstly, and most used, is the direct measurement with (strain gauge) force transducers (*e.g.* Payne, 1956; Godwin *et al.*, 1985; Hadas & Wolf, 1993; Onwualu & Watts, 1998; Aluko & Seig, 2000; Berntsen & Berre, 2002; Kheiralla *et al.*, 2004). Secondly, as used in this thesis, draught force can be measured indirectly via fuel consumption (Paper VII). Fuel consumption for tillage operations was measured by *e.g.* Serrano *et al.* (2003) and Kheiralla *et al.* (2004), but they did not use the data to calculate draught force.

The direct method may provide the most accurate estimates of the true draught force. Both horizontal and vertical forces can be measured, which may provide interesting data on how implements perform. The set-up of transducers may be implement-specific and different for mounted and drawn implements.

The indirect method via measurement of fuel consumption may be more flexible, since irrespective of the linkage of the implement, the measuring system is the same for all implements. The errors that may be made in the calculation (*e.g.* due to power loss in transition to the wheels, tractor rolling resistance, *etc.*) are approximately constant. Therefore, this method may be favourable for comparisons of different implements and tillage systems.

Stress propagation in soil

Theoretical background

Stress state in soil

The stress state of an infinitely small cubic soil element can be described with normal stresses, σ_i (perpendicular to a plane), and shear stresses, τ_{ij} (tangential to a plane) as shown in Fig. 3. The stress state can be written in a matrix, termed the matrix of the stress tensor (Koolen & Kuipers, 1983). Due to equilibrium of all force couples (Fig. 3), the matrix of a stress tensor is always symmetrical, implying $\tau_{xy} = \tau_{yx}$, $\tau_{xz} = \tau_{zx}$ and $\tau_{yz} = \tau_{zy}$.

A very important property is that there are always positions of the co-ordinate system that simplify the numbers in the stress tensor. For a given stress state it is always possible to choose a co-ordinate system (ξ, ψ, ζ) in such a way that all shear stresses are zero at the same time. The stress state is then fully described by three normal stresses, σ_1, σ_2 and σ_3, which are referred to as major, intermediate and minor principal stress. For $\sigma_1 = \sigma_2 = \sigma_3$ (isotropic compression), the stress state does not have any shear stress components.

Another property of the stress tensors is the existence of invariants. Stresses acting on a soil element can be described by mechanical invariants, which are independent of the choice of reference axes. The three invariants, I_1, I_2 and I_3, yield:

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3 = \sigma_x + \sigma_y + \sigma_z \tag{5}$$

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

$$I_3 = \sigma_x\sigma_y\sigma_z + 2\tau_{xy}\tau_{xz}\tau_{yz} - \sigma_x\tau_{yz}^2 - \sigma_y\tau_{xz}^2 - \sigma_z\tau_{xy}^2 = \sigma_1\sigma_2\sigma_3 \tag{7}$$

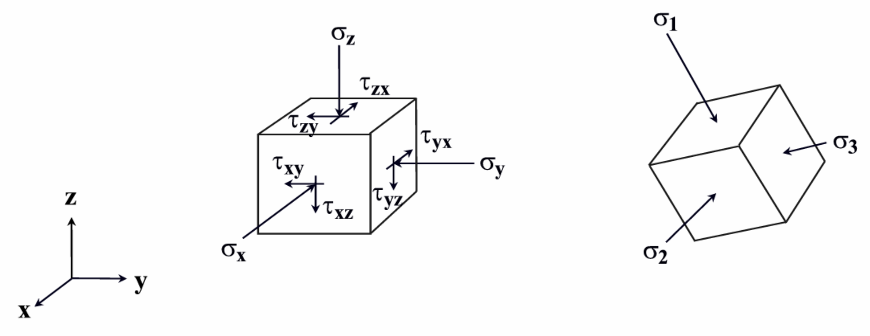


Fig. 3. Stress tensor components (adapted from Koolen & Kuipers, 1983).

It is useful to define stress measures that are invariant. Such stresses are the octahedral normal stress, σ_{oct}, and the octahedral shear stress, τ_{oct}:

$$\sigma_{oct} = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) = \frac{1}{3} I_1 \tag{8}$$

$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2} = \sqrt{\frac{2}{9}(I_1^2 - 3I_2)} \tag{9}$$

Critical state soil mechanics terminology uses the mean normal (or isotropic) stress, p, and the deviator stress, q. Whereas $p = \sigma_{oct}$ [Eq. (8)], q is given as:

$$q = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2} = \sqrt{(I_1^2 - 3I_2)} \tag{10}$$

The shear stress, q, has the important property that it reduces to $q = \sigma_1 - \sigma_3$ for triaxial stress states with $\sigma_2 = \sigma_3$.

In saturated soils, total stress, σ, is divided into effective stress, σ', and the pore water pressure, u_w (Terzaghi, 1936):

$$\sigma' = \sigma - u_w \tag{11}$$

In saturated soils, stress is transmitted via the solid phase (*i.e.* particles) and the liquid phase.

In unsaturated soils, the pore air pressure, u_a, has to be considered too. The effective stress is then described in terms of the net stress, $(\sigma - u_a)$, and the water tension, $(u_a - u_w)$ (Bishop, 1959):

$$\sigma' = \sigma - u_a + \chi(u_a - u_w) \tag{12}$$

where χ is a factor that depends on the degree of saturation (for completely dry soil, $\chi = 0$; while for fully saturated soil, $\chi = 1$). Stresses in unsaturated soils are transmitted via the solid, liquid and gaseous phase.

Modelling stress propagation in soil

There are mainly two different approaches for calculation of the propagation of stress through soil (Défossez & Richard, 2002): a pseudo-analytical procedure or a numerical calculus based on the finite element method (FEM).

Pseudo-analytical models are based on the work of Boussinesq (1885), Fröhlich (1934) and Söhne (1953). Boussinesq (1885) established an analytical solution for the propagation of σ_1 under a vertical point load, P, acting on a semi-infinite, homogeneous, isotropic, ideal elastic medium:

$$\sigma_1 = \frac{3P}{2\pi r^2}\cos^3\theta \tag{13}$$

where r is the radial distance from the point load to a desired point and θ is the angle between the normal load vector and the position vector from the point load to the desired point (Fig. 4).

Fröhlich (1934) suggested applying Eq. (13) to soil. He introduced the so-called concentration factor, v, because he noticed that stresses measured in soil deviate from stresses calculated according to Eq. (13) in such a way that they are greater under the load axis and smaller further outside. Fröhlich (1934) calculated σ_1 as:

$$\sigma_1 = \frac{vP}{2\pi r^2}\cos^v\theta \tag{14}$$

Note that for $v = 3$, Eq. (14) is equal to Eq. (13).

Söhne (1953) calculated the vertical stress under the centre of a tractor tyre using Eq. (14). He divided the contact area, A, into i small elements with an area A_i and a normal stress, σ_i, carrying the load $P_i = \sigma_i A_i$, which is treated as a point load. The vertical stress, σ_z, at a certain depth, z, is then calculated by summation:

$$\sigma_z = \sum_{i=0}^{i=n}\left(\sigma_z\right)_i = \sum_{i=0}^{i=n}\frac{vP_i}{2\pi r_i^2}\cos^v\theta_i \tag{15}$$

Calculation of other stress components is given in the Appendix of Paper VI.

The concentration factor, v, is a parameter that is not directly measurable. Söhne (1953) assumed v to be related to the bulk density and the water content of soil in such a way that v is greater the softer (weaker) the soil. Horn (1990b) showed that v is greater the smaller the precompression stress (*i.e.* the weaker the soil) and the greater the applied load. This implies that v is not only dependent on soil properties, but also on the loading intensity. However, Trautner (2003) found an opposite behaviour, *i.e.* that v is greater the harder the soil.

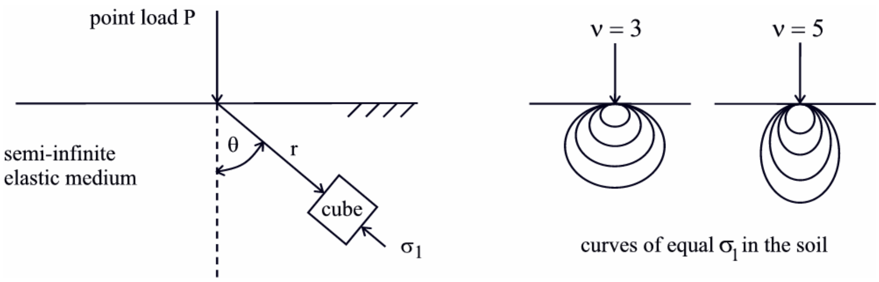


Fig. 4. Soil stresses due to a vertical point load (left-hand side) and modification to match agricultural conditions (right-hand side) (adapted from Koolen & Kuipers, 1983).

Obviously, soil is not a homogeneous, isotropic, ideal elastic medium. This is in conflict with the assumptions made by Boussinesq (1885) for his model for stress propagation. Fröhlich (1934) partly compensated for that by introducing the concentration factor. Since soil does not behave as an elastic material, soil strength influences the stress propagation (Koolen & Kuipers, 1983). This can be accounted for in numerical models. Unlike pseudo-analytical models, models based on the FEM use the limit conditions at the soil surface (*i.e.* contact area and surface stresses) and the stress-strain relationships simultaneously to calculate the distribution of displacement within the soil. Both strain and stress fields are then deduced from the displacement field (Défossez & Richard, 2002).

Measurements and simulations of stress in soil due to agricultural field traffic

Distribution of stress at the tyre/track-soil interface

When a vehicle runs over soil, the soil surface is exposed to mechanical stresses from the tyre or track of the vehicle. The stresses at the tyre/track-soil interface are a function of tyre/track and loading characteristics, as well as soil conditions. Obviously, the stresses in the soil profile are a function of these surface stresses.

The ground contact stress is often assumed to be approximately equal to the tyre inflation pressure. In soil compaction modelling, the contact stress distribution is often assumed to be uniform (Kirby *et al.*, 1997; Gysi *et al.*, 2000; Arvidsson *et al.*, 2002; Poodt *et al.*, 2003). However, this is in conflict with the findings of several researchers including Burt *et al.* (1992), Gysi *et al.* (2001) and Way & Kishimoto (2003), who have shown that the stress in the contact area is not uniformly distributed and that maximum stress may be several times the tyre inflation pressure. This is due to the carcass stiffness, the tread and lug pattern of the tyre and the dynamic forces acting when the tyre is operating in the field.

Hammel (1994) and van den Akker (1992) showed in model calculations that the distribution of surface stress markedly affected the stress in the topsoil. Consequently, it is important to have a good estimation of the vertical stress distribution over the tyre print (van den Akker, 2004). Therefore, it is important to be able to predict not only the area of contact, but also the distribution of the stresses at the tyre/track-soil interface.

Söhne (1953), Johnson & Burt (1990) and Smith *et al.* (2000) described the stress distribution by a power-law function or a polynomial. Söhne (1953) assumed the order of the power-law function to be dependent upon the soil hardness in such a way that the ratio of maximum stress to average stress is smaller the drier and harder the soil. However, none of these approaches allows for a direct prediction of the distribution of stress from tyre parameters and/or soil conditions. Van den Akker (2004) described the fact that the estimation of the shape of the stress distribution is based on rules of thumb as a weak point of his soil compaction model (SOCOMO).

Stress distribution beneath tracks

The stress distribution below rubber tracks was studied in Paper III. Two main conclusions could be drawn. Firstly, the stresses below the rubber tracks were unevenly distributed, both in the driving direction and perpendicular to the driving direction. Vertical stress was high under the sprocket ('drive wheel'), idler and the supporting rollers, and considerably lower in between the wheels and rollers. In addition, vertical stress decreased from the centreline of the track to the edge of the track. Secondly, the distribution of stress longitudinally to the driving direction was strongly influenced by the draught force induced by a tillage tool (the experiment was carried out during ploughing with a mouldboard plough). The maximum contact stress was minimised by balancing the tracked tractor through adjusting the vertical position of the point of application of the draught force.

The first conclusion implies that even if a rubber-tracked tractor is well-balanced, the stresses are unevenly distributed at the soil-track interface. Therefore, the maximum contact stress is larger than the ratio of tractor mass to contact area, which is often not considered in advertisements and catalogues of manufacturers. In Paper III, the maximum measured contact stress was 304 kPa with initial setting of the linkage between the tillage implement and the tractor and 158 kPa with adjusted setting, while the average ground contact stress was 43 kPa. Hence, the ratio of maximum to average stress was nearly four when the tractor was balanced.

The second conclusion has implications for the prevention of soil compaction and for vehicle performance. The draught force is affected not only by the nature of the tillage implement and the tillage depth, but also varies with driving speed, soil type and soil conditions. Therefore, the linkage between the tillage implement and the tractor may need a different setting for different conditions in order to maintain an optimal stress distribution below the tracks. Considering that the soil type and the soil conditions may not be homogeneous in space within a field, the setting would need to be changed continuously. Similarly, the draught force affects the weight distribution between the front and rear wheels of wheeled tractors.

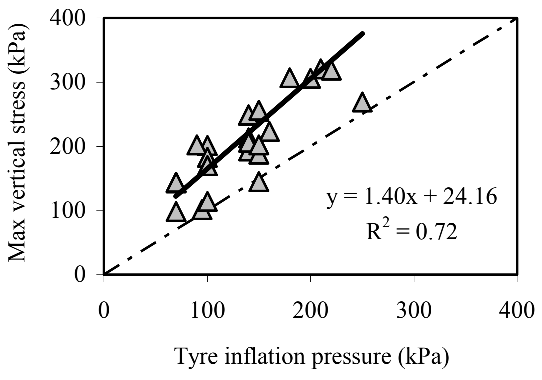


Fig. 5. Maximum vertical stress below the tyre as a function of tyre inflation pressure.

Stress distribution beneath tyres

During the years 2000-2003, distributions of vertical stress below tyres (at a depth of 0.1 m) were measured for a total of 29 different combinations of tyre characteristics and wheel load. Examples of stress distributions are shown in Papers IV and V. The two main conclusions from these measurements are in accordance with other studies (Burt *et al.*, 1992; Gysi *et al.*, 2001; Way & Kishimoto, 2003). Firstly, the vertical stresses were unevenly distributed both in the driving direction and perpendicular to the driving direction. Secondly, the maximum stress was generally higher than the tyre inflation pressure (Fig. 5).

The maximum stress perpendicular to the driving direction was in most cases measured under or close to the tyre centre, but in some cases it was measured close to the tyre edge (Paper V). This may depend on the construction of the tyre and on loading characteristics. In the investigated data set, the position of maximum stress was strongly dependent on tyre width. The maximum stress in the driving direction was generally measured under the transverse axis of the tyre, *i.e.* under the centre of the axle (Paper V).

A model for prediction of stress distribution below agricultural tyres

Paper V presents a model for prediction of the contact area and the distribution of vertical stress beneath agricultural tyres. The key characteristics of the model are that the shape of the stress distribution in the driving direction and perpendicular to the driving direction can be different from one another, and that the parameters used to generate the contact area and the stress distribution are directly calculated from readily-available tyre parameters.

The stress distribution perpendicular to the driving direction is described by a decay function:

$$\sigma(y) = C\left(\frac{w(x)}{2} - y\right) * e^{-\delta\left(\frac{w(x)}{2} - y\right)};\ 0 \le y \le \frac{w(x)}{2} \tag{16}$$

where C and δ are parameters and $w(x)$ is the width of contact, whereas the stress distribution in the driving direction is described by a power-law function:

$$\sigma(x) = \sigma_{x=0,y}\left\{1 - \left(x\left(\frac{l(y)}{2}\right)^{-1}\right)^{\alpha}\right\};\ 0 \le x \le \frac{l(y)}{2} \tag{17}$$

where $\sigma_{x=0,y}$ is the stress under the tyre centre, $l(y)$ is the length of contact and α is a parameter. Eq. (16) is powerful, as it is able to describe different cases of stress distribution, *e.g.* maximum stress under the tyre centre or maximum stress under the tyre edge. The parameters of Eqs. (16) and (17) are calculated from wheel load, tyre inflation pressure, recommended tyre inflation pressure at given wheel load, tyre width and overall diameter of the unloaded tyre. All these parameters are easy to measure or readily available from *e.g.* tyre catalogues.

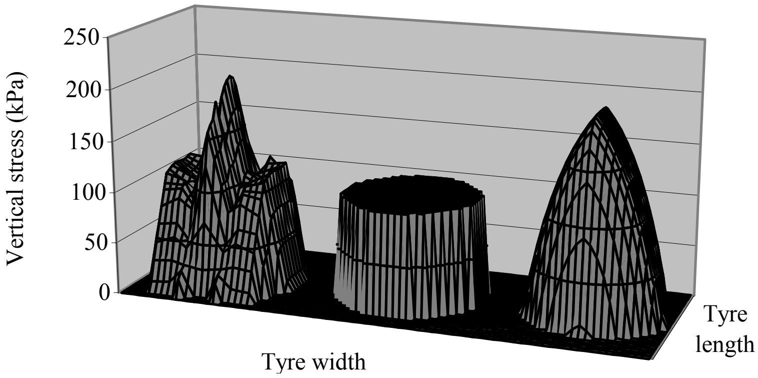


Fig. 6. Measured stress (left), uniform stress distribution (centre) and stress distribution generated with the model presented in Paper V (right) below a tyre of size 1050/50 R32 with a tyre inflation pressure of 100 kPa and a wheel load of 86 kN on a moist loam soil.

The model provides significantly improved input data for soil compaction models (Fig. 6) and hence increases the accuracy of predictions of stresses [*e.g.* as calculated according to Eq. (15)] in soil (Fig. 8), and therefore also increases the accuracy of predictions of soil compaction due to agricultural field traffic.

Measurements and simulations of stress propagation in soil

Stress interaction from wheels in dual wheel and tandem wheel configurations

The wheel load of a given vehicle is reduced by increasing the number of wheels, *e.g.* by using dual wheels or tandem wheels. However, the effects of different wheel arrangements on stress propagation in soil is subject to controversy among researchers. It is often believed that subsoil stresses are a function of axle load and hence the use of *e.g.* dual wheels would not reduce stresses and compaction in the subsoil compared with single wheels.

We measured stresses below dual wheels and tandem wheels (Paper IV) and could conclude that such wheels can be considered separate wheels in terms of soil stress, *i.e.* the stress interaction from the different wheels in these constellations does not lead to higher stresses between the wheels.

Simulations using Eq. (15) supported these findings (Paper IV); the stress interaction from different wheels in dual or tandem wheel arrangements was adequately reproduced by the model. Therefore, a general conclusion on stress propagation in soil is that the stress may be propagated 'straighter down' than what is normally anticipated, as also discussed by Trautner (2003).

However, in the discussion on stress interaction from dual wheels, we must not forget that agricultural tyres have been significantly developed during recent decades. Tyres have become larger (especially wider) and allow lower tyre inflation pressures to be used. Fig. 7 shows the simulated stress propagation [using Eq. (15)] below single and dual wheels with wheel loads of 40 kN. Simulations were made for narrow tyres (tyre width = 0.4 m) with an inflation pressure of 300

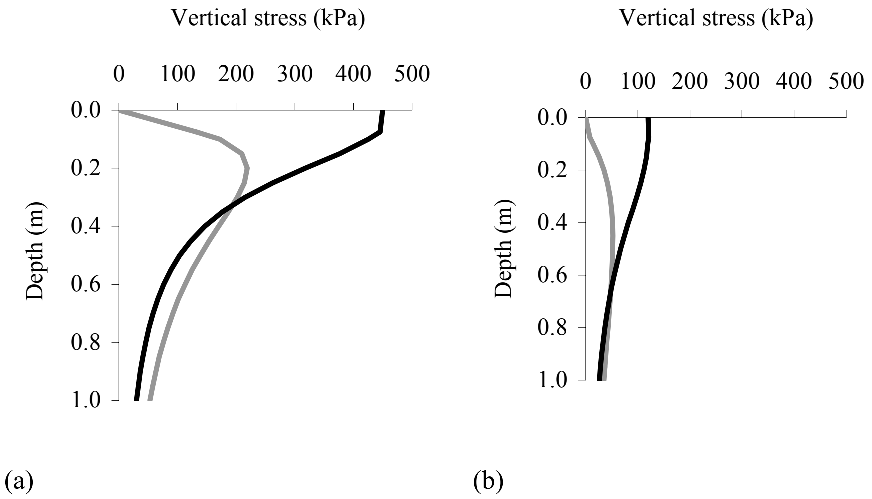


Fig. 7. Predicted vertical stress beneath a single wheel (black curve) and the centre of dual wheels (grey curve) with a wheel load of 40 kN for (a) narrow tyres with an inflation pressure of 300 kPa and (b) wide tyres with an inflation pressure of 80 kPa.

kPa and tyres with a width of 0.7 m and an inflation pressure of 80 kPa. For narrow tyres with high inflation pressure, the stress beneath the centre of duals is slightly larger than that beneath the single wheel at depths greater than about 0.3 m, *i.e.* in the subsoil [Fig. 7(a)]. For wide tyres with low inflation pressure, the stress beneath the single wheel is larger than that beneath the centre of duals at depths shallower than about 0.7 m [Fig. 7(b)]. At greater depths, the stress beneath the single wheel is the same as that beneath the dual wheels. Therefore, such dual wheels can be considered separate wheels with regard to soil stress. This is in accordance with the results presented in Paper IV.

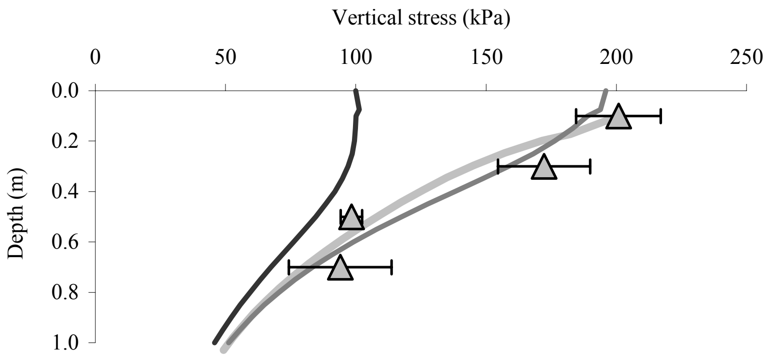


Fig. 8. Measured stress (triangles) and calculated stress below a tyre of size 1050/R32 with a tyre inflation pressure of 100 kPa and a wheel load of 86 kN on a moist loam soil. Calculated stress with a distribution of the stresses on the soil surface that is uniform (black curve), generated with the model presented in Paper V (dark grey curve) and measured (light grey curve).

Effect of tyre inflation pressure and contact stress distribution on stress propagation

In Paper IV, we studied the effect of tyre inflation pressure (at constant wheel load) on stress propagation. The tyre inflation pressure significantly affected the vertical stress in the topsoil and at 0.3 m depth (*i.e.* subsoil) in such a way that the stress was lower the lower the tyre inflation pressure. At 0.5 and 0.7 m depth, there was no effect of tyre inflation pressure.

Simulations of stress propagation were performed using Eq. (15). It was demonstrated that the stress distribution (again, at constant load) strongly affects the propagation of stress in soil (Papers IV, V), as shown in Fig. 8: a uniform stress distribution is a poor approximation of the true stress distribution. Hence, the distribution of the stress on the soil surface is of great importance for accurate prediction of stress propagation. Therefore, the above-described model was developed for prediction of the distribution of the vertical stress below agricultural tyres (Paper V).

The impact of stress distribution is also demonstrated in Fig. 9. The peak stresses that were measured at 0.15 m depth below the sprocket, idler and supporting rollers of a rubber-tracked chassis (of the tractor described in Paper III) are clearly visible at 0.5 m depth, too. It is interesting that the relative stress (defined as the ratio of stress to maximum stress) changes only little with depth. The measurements shown in Fig. 9 were made when the tractor was not balanced. The fact that the highest stress was measured under the sprocket both at 0.15 and at 0.5 m depth demonstrates once again the importance of balancing the tractor.

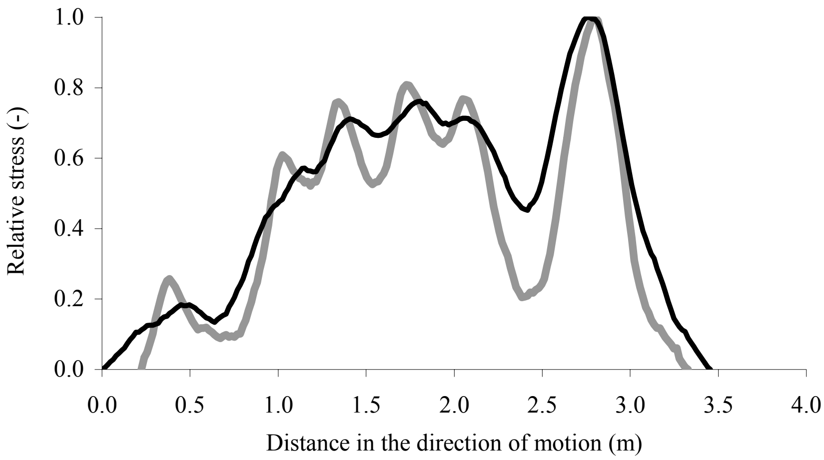


Fig. 9. Relative stress at 0.15 (grey curve) and 0.5 m depth (black curve) below a rubber-tracked tractor on a moist silt loam soil. The relative stress is the ratio of measured stress to the maximum measured stress at the respective depth.

Mechanical behaviour of soil

When mechanical stresses are imposed on a material, corresponding strains are produced. For soil, the relationships between stresses and strains are measured on soil samples in the laboratory or directly in the field. The stress-strain relationships are given by constitutive equations. Together with the yield conditions, they constitute the mechanical properties of soil. The stress at which a material fails is called strength.

Compaction is a reduction of the volume of a given mass of soil. When a soil is compacted, the void ratio and porosity are decreased and, conversely, the bulk density is increased. If the shape of a soil volume changes, then we talk about shear deformation. It can occur at constant volume (pure shear deformation or distortion), or it can be accompanied by compaction or expansion.

Soil cannot be deformed to any extent, but will break or start to flow at a certain stress or strain; this is called breaking or failure. A soil can fail under compression, tension or shear. The combinations of stresses that give rise to failure represent a surface in the (σ_1, σ_2, σ_3) co-ordinate space. This surface is called yield surface or state boundary. If the stress state reaches this surface, the yield condition is reached and the material is yielding. Mathematically, a yield surface can be represented by: if $f(\sigma_1, \sigma_2, \sigma_3)$ = a certain constant $\rightarrow$ failure occurs (Koolen & Kuipers, 1983).

In soil science, compaction and shearing are two processes that are not strictly separated. This is not correct by definition; however, compaction and shearing rarely occur as separate processes. Soil compaction is sometimes even used as a collective term for ‘physical degradation due to field traffic’ by soil scientists. In German the expression ‘Schadverdichtung’, which is a combination of the two words ‘harm’ and ‘compaction’, is widely used.

Compressive behaviour of soil – soil precompression stress

The compressive behaviour of soil is usually measured in a tri-axial or uniaxial compression apparatus. The latter is also referred to as an *oedometer* [Fig. 10(a)]. When using tri-axial compression tests, the applied compressive stress is usually expressed in terms of the mean normal stress, p, whereas when using uniaxial compression tests, the applied stress is expressed in terms of the first principal stress, σ_1. Uniaxial compression tests are widely used, as they are easier to conduct compared with tri-axial tests. A uniaxial strain state appearing during uniaxial testing on soil cores is assumed to be a sufficiently good approximation of the strain state in the subsoil under a running wheel (Koolen & Kuipers, 1983). In an *oedometer* test, the horizontal strain is fully prevented by a cylindrical stiff ring in which the sample is enclosed, which means that under increasing load, there is no final fracture state in the soil as would be the case under a fundament or a plate in field conditions (Lang *et al.*, 1996).

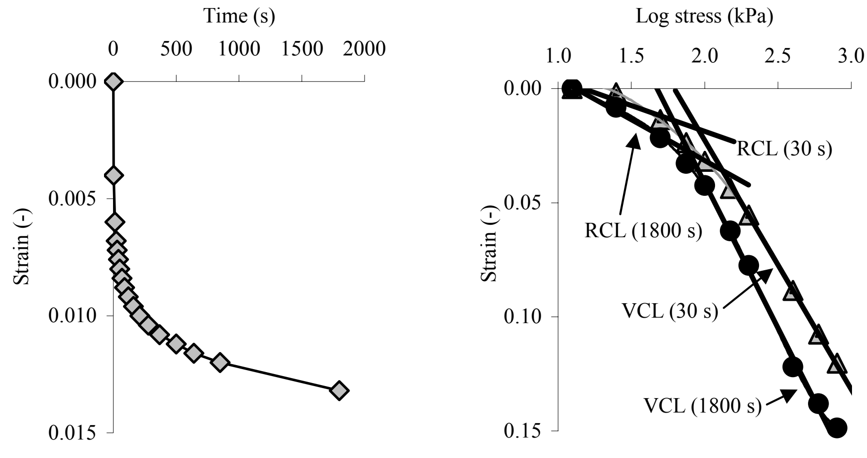
When a soil has been compacted by field traffic or has settled owing to natural factors, a threshold stress is believed to exist such that loadings inducing smaller stresses than this threshold cause little additional compaction, and loadings inducing greater stresses cause much additional compaction (Dawidowski & Koolen, 1994). In the literature, various names are used for this threshold: **precompression stress**, preconsolidation stress, precompaction stress and preload (Dawidowski & Koolen, 1994). In principle, the risk of undesirable changes in soil structure due to agricultural field traffic could be minimised by limiting the mechanically applied stress to below the precompression stress (Dawidowski *et al.*, 2001). The precompression stress is one of the most important input parameters for soil compaction models (Poodt *et al.*, 2003).

The precompression stress is derived from the compressive behaviour of soil, which is expressed graphically in the relationship between the logarithm (both the natural logarithm, ln, and the base 10 logarithm, log, are used) of applied stress, σ (either σ_1 or p), and some parameter related to the packing state of the soil, *e.g.* strain, ε; void ratio, e; specific volume, v; or bulk density, ρ. It has to be noted here that the precompression stress derived from log σ-e data differs from the precompression stress derived from log σ-ρ data as shown by Mosaddeghi *et al.* (2003). (However, the relationships between ε, e and v are linear, meaning that these parameters are interchangeable for the determination of the precompression stress).

In order to obtain the stress-strain relationship of soil, the stress is usually applied stepwise (sequential loading). For construction engineering purposes, the load is typically applied for 24 hours (or longer) per load step. In agricultural soil mechanics research, the load is often applied for 30 minutes per step only. This might be justified by a much shorter loading time of the soil in the field, and by purely practical reasons. However, the loading time during wheeling in the field is in the order of magnitude of a second, *i.e.* extremely short. Stafford & De Carvalho Mattos (1981) found that compaction increases with increasing loading time for soils drier than the plastic limit but not for those that are wetter.

(a) (b)

Fig. 10. (a) *Oedometer* and (b) *in situ* plate sinkage test.



(a) (b)

Fig. 11. (a) Strain as a function of loading time for a silty clay loam; (b) examples of the compressive behaviour of a sandy loam with a loading time of 1800 s (grey triangles) and 30 s (black circles); the precompression stress is the intersection of the respective VCL and RCL.

Fig. 11(a) shows the strain as a function of the loading time. Lebert *et al.* (1989) showed that the precompression stress increases with decreasing loading time [see also Fig. 11(b)], and that the effect of loading time on precompression stress is larger the more fine-textured the soil. In general, soil is stronger as the loading rate is higher, but weaker at repeated loading (Koolen & Kuipers, 1983). Bakker *et al.* (1995) point out that it is crucial to establish soil mechanical parameters with loading rates similar to those expected in the field.

There are several methods known for the determination of the precompression stress (for an overview, see *e.g.* Dias Junior & Pierce, 1995). The graphical procedure developed by Casagrande (1936) is regarded as a standard method. He developed this method empirically from a large number of tests on different types of soils and used it to derive the pre-consolidation load with a satisfactory degree of accuracy. Fig. 12 demonstrates Casagrande's procedure using data from a uniaxial compression test. "One determines first the position of the virgin compression line with a sufficient number of points. Then one determines on the preceding branch the point *T* that corresponds to the smallest radius of curvature, and draws through this point a tangent to the curve, and a horizontal line. The angle between these two lines is then bisected, and the point of intersection of this bisecting line with the virgin line determined, which approximately corresponds to the pre-consolidation load of the soil in the ground." Casagrande (1936) determined the point corresponding to the smallest radius of curvature visually. The visual determination is very subjective and scale-dependent. An objective determination is obtained with a mathematical procedure as described by Dawidowski & Koolen (1994) or as given in Paper I.

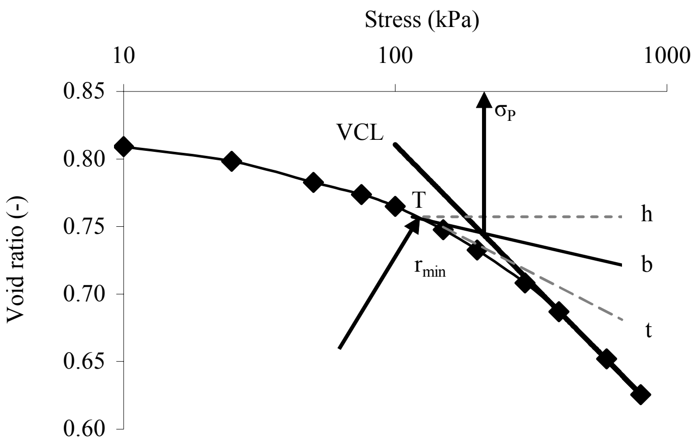


Fig. 12. Graphical method (Casagrande, 1936) for determination of the precompression stress. Measured data (black dots); recompression line (grey dashed line); VCL (grey line); point *T* corresponding to the smallest radius of curvature; tangent *t* and horizontal line *h* through point *T* and bisecting line *b* through *T*. The intersection of the virgin compression line and the bisecting line *b* corresponds to the precompression stress (σ_P).

Soil sampling in the field is time- and work-intensive, and marginal destruction of the soil cores cannot be avoided, even with careful handling (Casagrande, 1936; Dawidowski *et al.*, 2001). There are mainly three (partly counter-effective) sources of error that affect the result of compression tests: non-suit of the soil at the cylinder walls, unevenness and disturbance of the free upper and lower surface, and friction of the soil at the ring walls (Muhs & Kany, 1954; Leussink, 1954; Schmidbauer, 1954). An important factor that influences the magnitude of these errors is the cylinder dimensions.

A method to avoid these sources of errors is to subject the soil to compression *in situ* by a plate sinkage apparatus [Fig. 10(b)]. The soil is thereby subjected to compression at the desired depth with a circular plate. Alexandrou & Earl (1995) showed that the plate sinkage test can be applied for determining the precompression stress. For small deformations, data from confined compression tests are similar to those from plate sinkage tests (Earl, 1997). It is believed that the precompression stress is identified within this range of deformation (Dawidowski *et al.*, 2001). At greater deformations, the further movement of the plate is mainly caused by lateral deformation and not by compaction, whereas in a confined test, the deformation is caused by compaction (Earl, 1997).

Influence of compression test, determination method and sample size on precompression stress

The influences of compression test and determination method (*i.e.* the procedure for estimating the precompression stress from soil compression curves) on the precompression stress were studied in Papers I and II. In Paper I, five different determination methods were compared. In Paper II, precompression stress was measured using an *in situ* plate sinkage test, and by compressing soil cores in the laboratory with sequential loading or at constant strain speed. The influence of sample size on the precompression stress was studied for an Ultuna clay.

Different methods for determination of the precompression stress are not interchangeable (Papers I and II). The precompression stress value was generally greater when determined according to Casagrande (1936) compared with when determined with other methods. Bölling (1971) determined the precompression stress using different graphical procedures and found values ranging from 0.38 to 0.71 kg cm^{-2}. Hence, there is already a large uncertainty in the analysis, which makes the precompression stress rather a range than an exact value. Precompression stress is in many cases not easy to determine according to Casagrande (1936), as log stress-strain curves do not show a clear bend (Paper I). This was also reported by other researchers, *e.g.* Berli (2001) who stated that 'the precompression stress is usually not evident as a sharp bend in the compression curve but rather an operationally defined point in an often rather gradual transition between recompression curve and virgin compression line'.

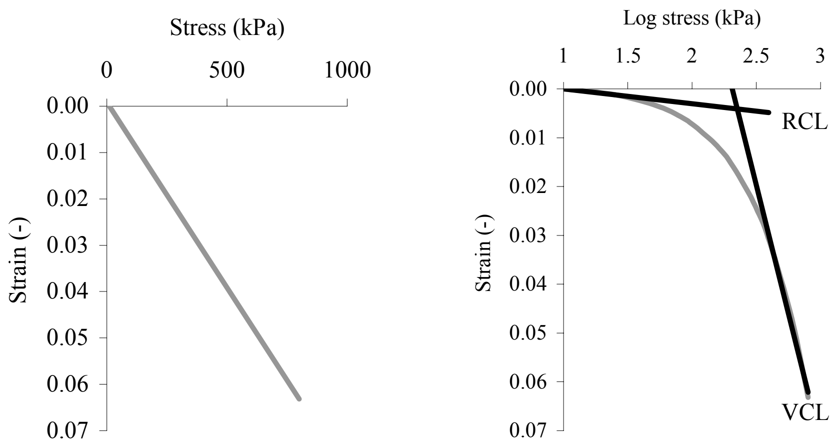
Precompression stress values derived from the *oedometer* and the *in situ* plate sinkage test generally did not differ from one another, despite the different mechanisms involved (Paper II). Precompression stress derived from the constant speed test was either higher (silty clay loam) or lower (clay) compared with the other two tests, which is probably due to differences in the initial soil water potential (Paper II).

The precompression stress is further dependent on sample height (at constant sample diameter) as shown for an Ultuna clay in Keller & Arvidsson (2003). However, there was no clear relationship between the precompression stress and the sample height. With increasing sample height, friction of the soil at the cylinder walls increases. As a consequence, strain is under-estimated and therefore the slope of both the RCL and VCL is underestimated, which usually results in an overestimation of the precompression stress. However, the errors due to non-suit of the soil at the cylinder walls and unevenness and disturbance of the free upper and lower surface are usually larger, the smaller the sample height. Therefore, high cores should be avoided because of the effect of sidewall friction, while small cores should be avoided because of sample disturbance. Berli (2001) concluded that the influence of sample dimension on the compressive behaviour of a structured soil originates from soil spatial variability and sampling disturbance rather than from sidewall friction. Koolen (1974) measured sidewall friction and concluded that samples for *oedometer* tests of a ratio of diameter (d) to height (h) of about d/h = 2-3 are reasonable in restricting sidewall friction effects and permitting an acceptable accuracy. Muhs & Kany (1954) concluded based on a calculation of errors that a ratio of d/h = 1 would yield a minimum of errors. As practical points of view (*e.g.* consolidation time) have to be taken into account as well, they suggest a ratio of d/h = 5 as still functional, as errors should be within reasonable limits.

Some remarks on the use of the logarithm of applied stress for expressing the compressive behaviour of soil

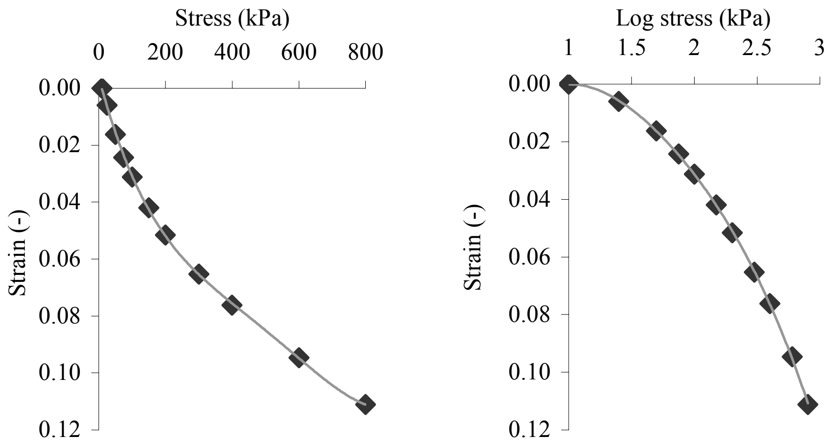
Let us consider an elastic, homogeneous, isotropic material that behaves according to Hooke's law. If such a material is compressed, strain is proportional to the applied stress. An example of such a compression curve is shown in Fig. 13(a). The same stress-strain relationship is now plotted in a semi-logarithmic diagram [Fig. 13(b)], as is used for determination of the precompression stress. With the logarithmic scale on the stress axis, the stress-strain relationship of the material seems to have changed its characteristics; now a 'recompression line' and a 'virgin compression line' can easily be distinguished and one may determine the precompression stress (*e.g.* as the intersection of the two lines mentioned). In doing so, the precompression stress is 234 kPa in the given example. However, there is obviously no change in material behaviour at a stress level of 234 kPa, nor at any other stress level [Fig. 13(a)]. The semi-logarithmic diagram can obviously lead to misinterpretation of a material's behaviour. However, there are reasons for using the semi-logarithmic diagram, which will be explained later.

A natural soil behaves as shown in Fig. 14. In a stress-strain diagram [Fig. 14(a)], the ratio of strain/stress at low stresses is greater (*i.e.* the slope of the curve is greater) compared with the strain/stress at high stresses, where the curve starts to flatten (*i.e.* the slope of the curve becomes smaller). Plotting the same curve in a log stress-strain diagram [Fig. 14(b)], the opposite seems to be true; of course, in this case we are looking at ratios of strain/**log** stress, which has to be remembered. It is interesting to note that the bend of the log stress-strain curve in Fig. 14(b) is less distinguished compared with the bend of the curve in Fig. 13(b).



(a) (b)

Fig. 13. Compressive behaviour of a linear elastic material in (a) stress-strain space and (b) log stress-strain space.



(a) (b)

Fig. 14. Compressive behaviour of a natural, undisturbed silty clay soil measured in an *oedometer* in (a) stress-strain space and (b) log stress-strain space.

The semi-logarithmic diagram for analysing the compressive behaviour of soil is questionable, as it can lead to misinterpretation of a material's behaviour (Fig. 13). Terzaghi (cited in Casagrande, 1936) used log σ as he could find a linear relationship between log σ and e (or ε) at high stresses, *i.e.* on the VCL. However, the VCL is only a line within a limited stress interval, as the compaction curve has to asymptotically reach a line that is parallel to the stress axis: e obviously cannot become negative. However, the stress interval where the compaction curve is a line is rather large and usually within the range of applied stresses, which justifies the use of log σ. Volume change caused by mechanical stresses actually results in an S-shaped function and can be modelled by *e.g.* a van Genuchten-type equation, as shown by Baumgartl & Köck (2004). In principle, it does not matter in what kind of diagram the compressive behaviour of soil is analysed as long as it can be described (mathematically). It may be more interesting to describe the (log) stress-strain relationship with a mathematical function, rather than trying to determine the precompression stress, and to develop pedo-transfer functions to estimate the parameters of such a mathematical function. The compaction curve may be described by a hyperbolic (*e.g.* Koolen, 1974), logarithmic (*e.g.* Bailey *et al.*, 1986) or S-shaped (Baumgartl & Köck, 2004) function. Dexter & Tanner (1973) described the relationship between particle packing density and the applied stress by an equation with two exponential terms, where one describes the deformation of soil crumbs and the other the rearrangement of individual particles.

Soil behaviour during wheeling in relation to precompression stress

During the years 2000-2004, a relatively large number of wheeling experiments and measurements of vertical stress and vertical displacement in natural arable soil have been conducted in Sweden and Denmark. In addition, the precompression stress at field moisture was determined for different depths at the same sites. From the measurements of vertical displacement at two different depths, vertical strain could be calculated.

In Fig. 15, measured strain at 0.3–0.5 and 0.5-0.7 m depth is plotted against the ratio of measured stress to precompression stress, $R_{\sigma/PreComp}$, at the respective depth, the data being from the above-mentioned experiments. A ratio smaller than 1 implies that the measured stress is smaller than precompression stress, a ratio greater than 1 implies that the measured stress exceeds the precompression stress. Strain increased with increasing $R_{\sigma/PreComp}$. However, there is no clear transition from the range $R_{\sigma/PreComp} \leq 1$ to the range $R_{\sigma/PreComp} > 1$, as could be expected if the precompression stress was a distinct limit between reversible and irreversible strain. Irreversible strain was measured even when measured vertical stress was smaller than precompression stress, *i.e.* when $R_{\sigma/PreComp} < 1$, which was also observed in Paper II and by Trautner (2003). In Fig. 16, measured strain is shown as a function of measured stress. The measured strains are approximately zero as long as the applied stress is smaller than about 50 kPa. If the stress is greater than that, irrecoverable strains could be measured. Therefore, the following rule of thumb could be proposed: soil compaction can be avoided if the applied stress is below 50 kPa. This makes sense in line with practical experience. For practical purposes, this would imply rather low wheel loads and low tyre inflation pressures.

It is certainly true that applying a higher stress to a soil will compact the soil more than applying a lower stress, as also shown in Fig. 16. However, considering the precompression stress a threshold value, σ_T, implies that a major difference in soil reaction is expected when applying a stress $\sigma_T + \Delta\sigma$ compared with when applying a stress $\sigma_T - \Delta\sigma$, where $\Delta\sigma$ is a stress increment.

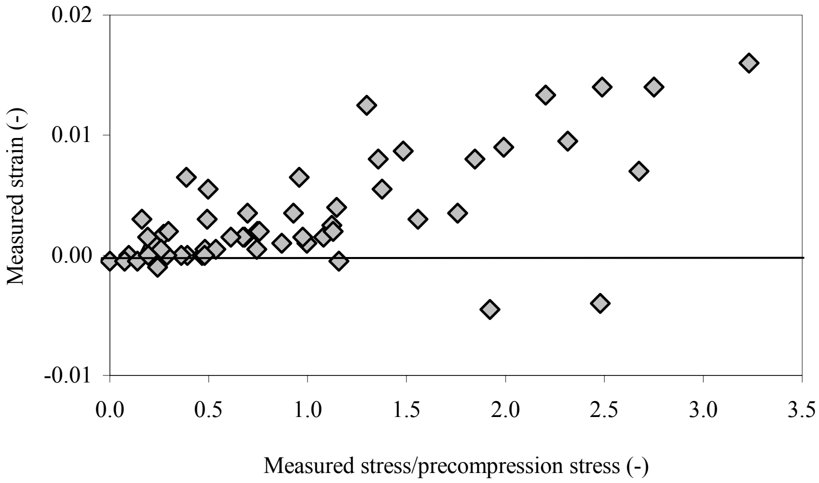


Fig. 15. Measured strain plotted against the ratio of measured stress/precompression stress from experiments made at 11 different sites in Sweden and Denmark.

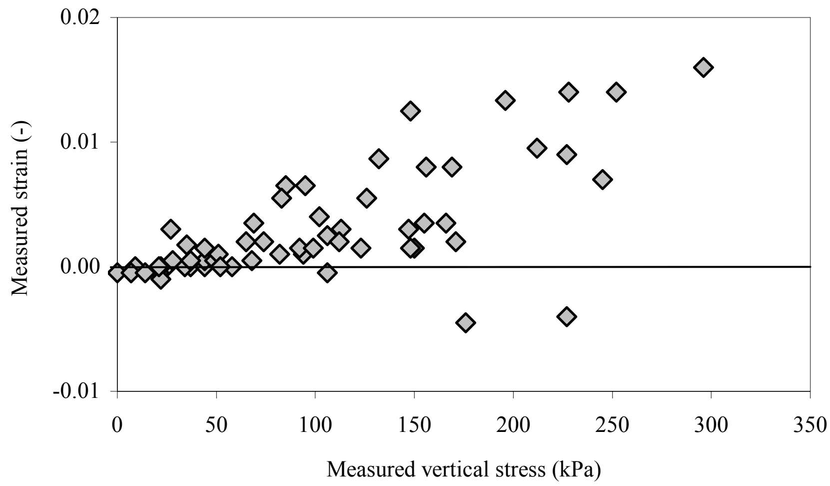
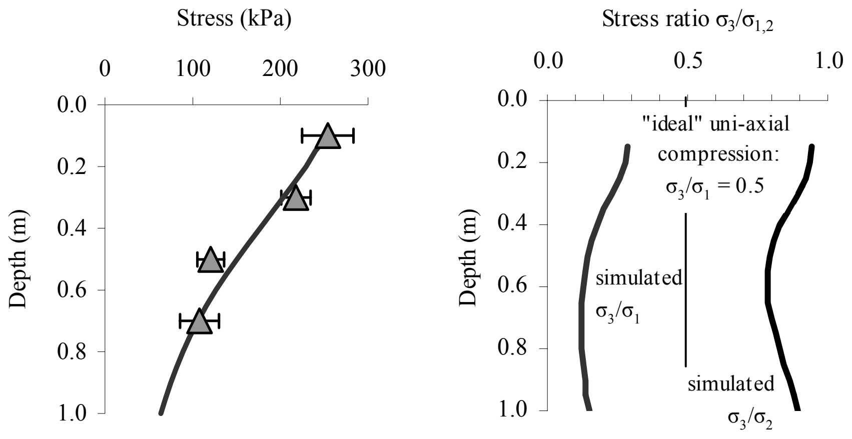


Fig. 16. Measured strain plotted against measured stress from experiments made at 11 different sites in Sweden and Denmark.

Some reservations to the data presented in Figs. 15 and 16 must be made, as discussed in the section 'Methodological aspects'. Firstly, volume change was not measured, only vertical strain. However, it is probably safe to assume that lateral strains are negligible in the subsoil (Koolen & Kuipers, 1983). Secondly, the uncertainty of the absolute values of stress measurements has to be considered. However, the measured stresses generally agree well with simulated stresses (*e.g.* Fig. 8).

There may be several reasons for the data being as shown in Figs. 15 and 16. Stresses in the field are dynamic. Horn (1990a) concluded that during wheeling, dynamic forces would reduce the soil strength more intensely than the forces due to static loading because of the homogenisation of particle arrangement. Furthermore, large (weak) soil structures may not be captured in soil cores but collapse first in the field. Larger compound particles (of higher hierarchical order) are weaker than smaller compound particles (Dexter, 1988). According to Kirby (1991), compaction damage is to be expected when the normal stress exerted by the tyre or track exceeds a value somewhat less than the precompression stress, since shear stresses will cause more compression than the normal stress alone. Bakker *et al.* (1995) found that a static load generates a poor representation of the stress state produced by a rolling tyre. Hartge & Sommer (1980) stated that it should be remembered that the compression test used is much different from what happens in the field when a heavy load is applied by a moving tractor.



(a) (b)

Fig. 17. (a) Measured (triangles) and calculated (curve) σ_1 below the centre of a tyre of size 1050/50 R32 with an inflation pressure of 150 kPa and a wheel load of 86 kN; (b) simulated ratios of σ_3/σ_1 and σ_3/σ_2, respectively.

In a uniaxial compression test, horizontal movement is restricted. This does not hold true for the situation in the field. As a consequence of that, the stress state in the field (beneath agricultural machines) may differ from the stress state in a uniaxial compression test. Fig. 17 shows the simulated vertical stress in comparison with measured stress [Fig. 17(a)] and the simulated ratios of σ_3/σ_1 and σ_3/σ_2, respectively [Fig. 17(b)] below a tyre with a wheel load of 86 kN. As shown in Fig. 17(b), the ratio of σ_3/σ_1 is not constant with depth and smaller than $\sigma_3/\sigma_1 = 0.5$, which is the ratio of an 'ideal' uni-axial compression (Tschebotarioff, 1951; Koolen & Kuipers, 1983). Fig. 17(b) also shows that $\sigma_3 \approx \sigma_2$, *i.e.* the stress state is approximately cylindrical.

According to Atkinson (1993), stress-strain behaviour inside the state boundary surface (*i.e.* at stresses smaller than the precompression stress) is essentially elasto-plastic and not purely elastic. In other words, the stress range below the precompression stress is **not completely elastic** and recoverable, as often assumed in theories. The range of pure elastic, recoverable volume change is very small (Atkinson, 1993).

O'Sullivan & Robertson (1996) suggest a soil compaction model which takes into consideration the fact that there is irreversible volume change even if the applied stress is smaller than the precompression stress (Fig. 18). Rebound takes place along the recompression line (RCL). Recompression takes place along the RCL until the so-called yield line is reached. Recompression then follows a steeper line (referred to as 'plastic recompression line' or 'steeper recompression line, RCL'') until the virgin compression line (VCL) is reached. In fact, the model proposed by O'Sullivan & Robertson (1996) with three lines (RCL, RCL' and VCL) is a closer approximation to the real compaction curve compared with the commonly-used models with two lines only (RCL and VCL).

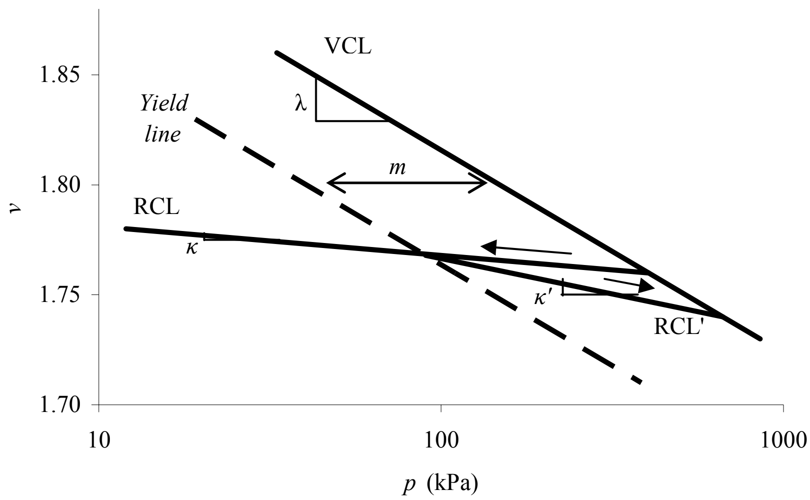


Fig. 18. Model of rebound and recompression (O'Sullivan & Robertson, 1996) in terms of specific volume, *v*, and mean normal stress, *p*. Adapted from O'Sullivan *et al.* (1999).

The model also simulates multi-passes of a vehicle more realistically: if a soil is loaded or wheeled several times (with the same load), compaction does not stop after the first loading, but is continuous at every loading event (Koolen & Kuipers, 1983). Field experiments show that the additional compaction becomes less with every additional wheeling, but total compaction increases with increasing number of wheel passes (Arvidsson *et al.*, 2001; Horn *et al.*, 2003; Trautner, 2003). For these reasons, it cannot be expected that the precompression stress measured at a certain depth after wheeling corresponds to the measured stress during wheeling at the same depth.

Whether soil compaction is detected in the field is further strongly dependent on the accuracy of the measuring method. Small volume changes cannot be detected by bulk density sampling unless a huge amount of replicates (or very large samples) are used. Additionally, problems with spatial variability and with determining the sampling depth arise (one has to know the amount of displacement of the soil profile, *i.e.* the 'same' soil layer before and after wheeling has to be sampled). This problem can be overcome by calculating a mass balance, which is very time-consuming and therefore rarely done. Measuring vertical soil displacement during wheeling is much more sensitive at the same effort. However, in this case soil compaction as such is not measured, as discussed in the section 'Methodological aspects'.

Nevertheless, the precompression stress gives some information on the soil's strength and hardness. The precompression stress increases with increasing soil water tension (*e.g.* Cully & Larson, 1987; Horn, 1993; Berli, 2001; Paper II), *i.e.* the soil gets stronger as it dries, which is a general characteristic of soil mechanical properties. Furthermore, the precompression stress may be used as a parameter describing the load transfer through soil as speculated by Trautner

(2003). Casagrande (1936) stated that the most important practical application of the pre-consolidation load is in connection with settlement analyses and geological investigations. The assumption that there is no soil compaction if the applied stress is smaller than the precompression stress is an acceptable approximation for engineering purposes. However, for soil protection purposes this approximation may not be good enough.

Shear strength, tensile strength and penetrometer resistance

Shear strength is measured in the laboratory in tri-axial cells or in shear apparatus (most widely used are direct shear boxes). There are several methods to measure shear strength *in situ*, among which is the vane shear apparatus that was used in this thesis (Paper VII). A general model for shear failure is Coulomb's law:

$$\tau_f = c + \sigma_n \tan \phi \tag{18}$$

where τ_f is shear stress at failure (= shear strength), c the bonding force per unit area, called cohesion, σ_n the normal stress on the failure plane, and ϕ the angle of internal friction. The cohesion, c, and the friction angle, ϕ, depend on soil type and soil conditions, and can therefore be regarded as soil properties.

In tillage and field traffic, boundary surfaces occur between soil bodies and other materials like steel and rubber. For driven wheels shear stresses in the contact surface should be as high as possible to maximize pull. In other cases such as tines and plough bodies, low values of the shear stresses in the contact surface are desirable (Koolen & Kuipers, 1983). In accordance with Coulomb's law, a shear stress, τ_s, that is exerted by a material on a soil body can be written as:

$$\tau_s = a + \sigma_n \tan \delta \tag{19}$$

where a is the adhesion and δ is the angle of soil-material friction. It is possible to get shearing either at the material-soil interface or within the soil; if $\tau_s > \tau_f$, shearing within the soil will occur. If $\tau_s < \tau_f$ or:

$$\sigma_n < \frac{a - c}{\tan \phi - \tan \delta}, \tag{20}$$

shearing at the material-soil interface will occur.

Tensile strength of soil is most often measured in indirect tension tests. These are called indirect because the tensile stress is produced by applying a compressive stress in another direction. For spherical particles of incompressible material, the tensile strength, Y, can be calculated by (Dexter & Kroesbergen, 1985):

$$Y = 0.576 \frac{F}{d^2} \tag{21}$$

where F is the compressive force at failure and d is the diameter of the spherical particle.

Penetrometer resistance is often used as a measure of soil strength in soil compaction research (Arvidsson, 1997). Here, the force required to push a steel cone into the soil is measured. A problem is that the resistance to probe penetration arises from a number of factors including shear strength, compressibility, friction and adhesion. Different proportions of these components operate in different soils and in the same soil at different water contents (Dexter, 2002). Therefore, the interpretation of penetrometer readings may not be easy. These problems may also apply to readings from shear vane apparatus.

On six different soils in Uppsala, we measured shear strength by a shear vane apparatus and penetration resistance by a soil penetrometer at different, naturally-obtained water contents. The correlation between vane shear strength and penetrometer resistance is generally poor, but may be good for a specific soil, as shown in Fig. 19. The correlation was generally higher for clay loam soils compared with clay soils.

Impact of soil type and soil conditions on mechanical properties

The mechanical properties of soil are affected by soil type and soil conditions. For example, the soil precompression stress is dependent on the soil texture and the soil water potential (Papers I and II). For a given texture, the mechanical properties of soil may be strongly influenced by soil moisture and bulk density. Soil moisture is the soil property that undergoes the fastest changes. Furthermore, soil strength increases with time (this effect is known as age-hardening) (Dexter *et al.*, 1988; Horn & Dexter, 1989), with increasing number of wetting-drying cycles (Horn, 1993) and with decreasing loading time (Dexter & Tanner, 1974; Stafford & De Carvalho Mattos, 1981; Koolen & Kuipers, 1983; Lebert *et al.*, 1989).

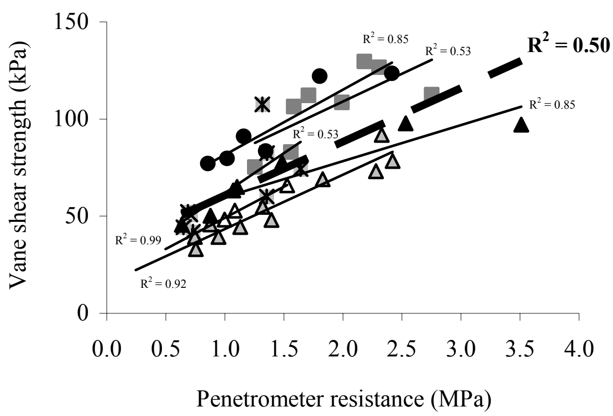


Fig. 19. Penetrometer resistance versus vane shear strength; linear regressions (solid lines) for three clay soils at Ultuna (squares and circles) and three clay loam soils at Säby (triangles), and linear regression for all soils together (dashed line).

Modelling stress-strain relationships

Compressive behaviour of soil

There exist different approaches for the description of the compressive behaviour of agricultural soils. Gupta & Larson (1982) describe volume change with a relationship between the bulk density and the logarithm of the major principal stress:

$$\rho = \left[\rho_k + \Delta_T \left(S_1 - S_k\right)\right] + C \log\left(\frac{\sigma_a}{\sigma_k}\right) \tag{22}$$

where ρ is the compacted (final) density corresponding to an applied stress σ_a, ρ_k a reference bulk density corresponding to a reference stress σ_k on the virgin compression line (VCL), Δ_T is the slope of the bulk density versus degree of water saturation curve at σ_k, S_1 is the desired degree of saturation at σ_k, S_k is the degree of saturation corresponding to ρ_k and σ_k, and C is the compression index, *i.e.* the slope of the VCL.

The model by Bailey & Johnson (1989) was developed for cylindrical stress states and is, in terms of bulk density, ρ, given by:

$$\ln \rho = \ln \rho_0 - \left[\left(A + B\sigma_{oct}\right)\left(1 - e^{-C\sigma_{oct}}\right) + D\left(\frac{\tau_{oct}}{\sigma_{oct}}\right)\right] \tag{23}$$

where ρ_0 is the initial bulk density, σ_{oct} is the octahedral normal stress, τ_{oct} is the octahedral shear stress and A, B, C and D are compactibility coefficients. For D = 0, the model by Bailey & Johnson (1989) reduces to the model of Bailey *et al.* (1986).

O'Sullivan & Robertson (1996) describe volume change as illustrated in Fig. 18. The VCL, the recompression line (RCL) and the steeper recompression line (RCL') are given by:

$$VCL: v = N - \lambda_n \ln p \tag{24}$$

$$RCL: v = v_{init} - \kappa \ln p \tag{25}$$

$$RCL': v = v_{YL} - \kappa' \ln p \tag{26}$$

where v is the specific volume, p is the mean normal stress, N is the specific volume at p = 1 kPa, λ_n is the compression index, v_{init} is the initial specific volume, κ is the recompression index, v_{YL} is the specific volume at the intersection of the yield line and the RCL and κ' is the slope of the RCL'.

Obviously, there is some controversy as to whether soil compaction is related to the major principal stress, σ_1 (Gupta & Larson, 1982), or to the mean normal stress, p (O'Sullivan & Robertson, 1996). Bailey & Johnson (1989) also include a shear stress component in their model [Eq. (23)].

Since any deformation can be expressed as the sum of (pure) compressive deformation and (pure) shear deformation, it seems to be useful to describe compaction as a function of p. Because lateral strains are small in the subsoil, it is justifiable to express subsoil compaction as a function of σ_1.

Critical state soil mechanics

The behaviour of soil due to applied stresses may be described in terms of critical state soil mechanics, which were developed for saturated soils (Schofield & Wroth, 1968; Atkinson, 1993). A short overview on the theories of critical state soil mechanics is given here. For further reading, see Schofield & Wroth (1968), Britto & Gunn (1987) or Atkinson (1993).

The critical state concept considers that a continuously deformed material will come to a critical state (defined by a unique line in stress-void ratio space, the critical state line, CSL) at which infinite shear deformation with no change in stress or volume occurs (Kirby, 1989). A soil can exist in a stress state on or within a defined yield surface (Fig. 20). Within the yield surface, behaviour is assumed to be fully elastic, and can be described by 'elastic walls'. Note that the intersection of an elastic wall with the *e*-*p* plane is a curved line that corresponds to the recompression line (RCL) in the *e*-ln *p* plane. On the yield locus to the right (Fig. 20) of the CSL, called the Hvorslev surface, shear is strain-softening and accompanied by a volume increase. On the yield locus to the left (Fig. 20) of the CSL, called the Roscoe surface, shear is strain-hardening and accompanied by a volume decrease. An example of a critical state constitutive model is 'Cam clay' (Schofield & Wroth, 1968).

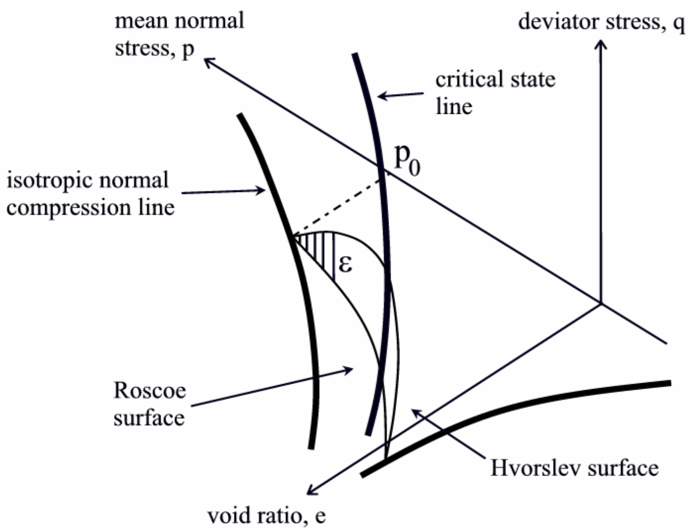


Fig. 20. State boundary surface in critical state soil mechanics. ε: elastic wall; p_0: precompression stress.

In critical state soil mechanics, the elastic material parameters are usually the slope of the RCL, κ, and the shear modulus, G (alternatively Young's modulus of elasticity, E, and Poisson's ratio, v). The plastic stress-strain behaviour is usually described by the slope of the virgin (or normal) compression line, λ, and the slope of the critical state line, M. The precompression stress, p_0, marks the transition from the elastic to the plastic compressive behaviour. The shear parameters are the cohesion, c, the angle of internal friction, ϕ, and the angle of diletancy, ν. The plastic behaviour is specified by a yield surface (separates states of stress which cause only elastic strains from states of stress which cause both plastic and elastic strains, *c.f.* Fig. 20), a flow rule (relates the direction of the vector of the plastic strain increment to the yield surface) and a hardening law (relates the magnitude of a plastic strain to the magnitude of an increment of stress as the state of stress traverses the yield surface and the material strain hardens/softens) (Atkinson & Bransby, 1978).

Remarks on critical state soil mechanics

Atkinson (1993) defines three ranges of mechanical soil behaviour: very small strains (< 0.001%), small strains and large strains (for states on the state boundary surface). For states on the state boundary surface the strains are large and can be modelled reasonably using Cam clay or a similar elasto-plastic model. For very small strains the stress-strain behaviour is approximately linear. For small strains the soil is highly non-linear and hence the stress-strain behaviour inside the state boundary surface (*i.e.* at stress states below the precompression stress) is essentially elasto-plastic and not purely elastic as assumed in the Cam clay theories. For numerical modelling, Atkinson (1993) suggests either regarding the soil behaviour inside the state boundary surface as elastic, but non-linear, or including additional yield surfaces within the state boundary surface (*i.e.* adapting for example the Cam clay model by including additional yield surfaces). The latter approach was chosen by O'Sullivan & Robertson (1996), as illustrated in Fig. 18.

Impacts of agricultural field traffic on soil properties

Soil compaction due to agricultural field traffic is almost always accompanied by shear deformation (Koolen & Kuipers, 1983). Tyres, wheels and rollers induce relatively high stresses which, since the affected soil can move away rather easily, may induce large deformations. As shown by several researchers, compaction and shearing due to field traffic affect many soil properties and processes and lead to soil physical degradation (Pagliai *et al.*, 2003).

A property that is often measured in order to quantify the effects of field traffic is the saturated hydraulic conductivity, k_{sat} (*e.g.* Horn *et al.*, 1995; Alakukku, 1996; Marsili *et al.*, 1998). It is a more sensitive parameter than bulk density to study the effects of traffic (Arvidsson, 1997). Of course, an increase in bulk density itself is not an indicator of soil degradation, but only the negative alteration of properties that describe the function of soil are evidence of negative effects of field traffic.

Alteration of the hydraulic properties of soil may have several implications. Reduced water infiltration may cause flooding during intensive rainfall. Reduced drainage capability implies that the soil is wetter for a longer time, which decreases the number of days available for tillage. Mechanical impacts may cause local water ponding on the soil surface, which can enhance preferential flow (Kulli *et al.*, 2003).

Within the framework of this thesis, the change in saturated hydraulic conductivity, k_{sat}, due to field traffic was measured in two experiments; k_{sat} was measured on cylindrical soil cores that were sampled at a depth of 0.05-0.1 m below the original soil surface. Results of both experiments are published in Bölenius (2002).

One experiment was carried out at Örsundsbro with a wheeled tractor (the same tractor as described in Paper IV). The objective was to study the effect of traction on k_{sat}. Whereas k_{sat} of the control plot was 5.6 cm h^{-1}, it was reduced to 2.5 cm h^{-1} due to a single passage of a tractor. When the tractor was pulling a chisel plough, k_{sat} was still lower, 0.4 cm h^{-1}. Note that k_{sat} was measured in the wheel track between the rear wheel of the tractor and the chisel plough, *i.e.* the implement did not directly affect the measurements, but only indirectly via draught force.

The other experiment was conducted at Krenkerup, with a wheeled tractor and a rubber-tracked tractor pulling a mouldboard plough (as described in Paper III). In the control plot, k_{sat} was 13.4 cm h^{-1}, which was significantly ($p < 0.05$) decreased to 0.3 cm h^{-1} due to the passage of the rubber-tracked tractor and to 0.2 cm h^{-1} due to the passage of the wheeled tractor.

The reduction in k_{sat} is the result of both shear deformation and compaction. The former may even have more severe consequences on k_{sat} because of distortion of originally vertical pores (Horn, 2003). Additionally, soil becomes weaker due to shear straining.

When soil is compressed, there is not only a change in porosity but also in pore size distribution. The structural pores tend to be eliminated preferentially on compression. The modification of the pore geometry during compaction results not only from a decrease in volume of structural pores but also from a change in the relationship between textural pores and the remaining structural pores (Richard *et al.*, 2001). This changes the pore size distribution and hence the water retention characteristics. Dexter (2004a, b, c) showed that several important soil physical properties can be estimated from the slope of the water retention curve (WRC) at its inflection point. This slope is defined as the soil physical parameter S (Dexter, 2004a). Soil physical degradation occurs when soil is compacted, and this reduces the slope of the WRC at the inflection point, *i.e.* S decreases with increasing bulk density (Dexter, 2004a), as illustrated in Fig. 21.

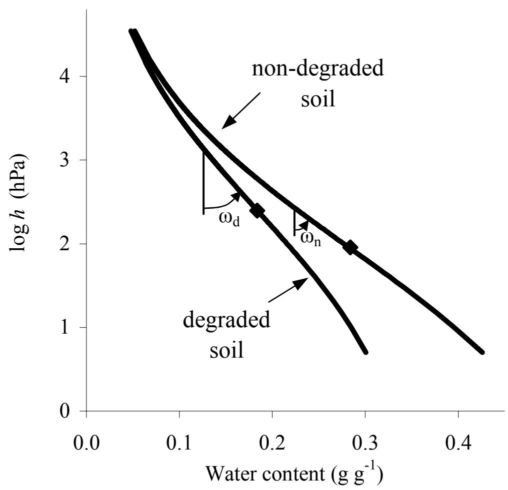


Fig. 21. Water retention curves of the same soil at two different bulk densities. Soil physical degradation occurs when the soil is compacted, and this reduces the slope of the WRC at the inflection point (indicated by rhombi on the respective curves). Adapted from Dexter (2004a).

Soil compaction modelling

The structure of soil compaction models can be divided into two parts (Défossez & Richard, 2002): Firstly, the propagation of stress through soil including the description of stress on the soil surface; and secondly, the modelling of the stress-strain behaviour. The main difference between the existing models lies in the procedure used to calculate the propagation of stress through soil, a pseudo-analytical procedure or a numerical calculus based on the finite element method (FEM). A review of soil compaction models and their evaluation can be found in Défossez & Richard (2002).

In Paper VI, we discuss the soil compaction models by Gupta & Larson (1982), van den Akker (1986, 2004), Johnson & Burt (1990) and O'Sullivan *et al.* (1999). These models have in common that stress propagation is calculated analytically based on the work by Boussinesq (1885), Cerruti (1888), Fröhlich (1934) and Söhne (1953) as described in the section 'Stress propagation in soil' and in Papers IV, V and VI. Soil compaction is only calculated in the models of Gupta & Larson (1982) and O'Sullivan *et al.* (1999); while the former use Eq. (22), the latter use Eqs. (24-26) to calculate volume change (change in bulk density) due to an applied stress.

The choice of the stress-strain relationships used in these models [Eq. (22) and Eq. (24-26), respectively] has implications for the effect of the concentration factor, v, on soil compaction. The greater v, the more concentrated are the stresses under the load and the deeper the stresses extend, as shown in Fig. 4. This is true for the major principal stress, σ_1, and for the vertical stress. However, horizontal stresses reach deeper in the soil at smaller values of v. Therefore, the effect of v on soil compaction is dependent on whether soil compaction is described as a function of σ_1 (Gupta & Larson, 1982) or a function of p (O'Sullivan & Robertson, 1996).

Models using the FEM apply continuum mechanics. According to the FEM a continuum is divided into a number of (volume) elements. Each element consists of a number of nodes. Each node has a number of degrees of freedom that correspond to discrete values of the unknowns in the boundary value problem to be solved. In the case of deformation theory the degrees of freedom correspond to the displacement components. Numerical procedures are used to calculate displacements at each nodal point. Strains and stresses are deduced from the displacements by satisfying the equilibrium condition that a difference between the external forces and the internal reactions should be balanced by a stress increment. Since the relationship between stress increments and strain increments is usually non-linear, strain increments generally cannot be calculated directly, and global iterative procedures are required to satisfy the equilibrium condition for all material points. Hence, unlike the pseudo-analytical models, FE models use the limit conditions at the soil surface (*i.e.* contact area and surface stresses) and the stress-strain relationships simultaneously to calculate the distribution of displacement within the soil (Défossez & Richard, 2002). For further reading on the theory of FEM in soil mechanics, the reader is referred to *e.g.* Britto & Gunn (1987).

Limitations of the different model approaches

While analytical models usually contain fewer parameters (for stress calculation, the only parameter is the concentration factor) and may often be easier to use than FE models, the latter have the potential to describe the mechanical behaviour of soil more accurately, but require a certain number of soil mechanical parameters, which may be difficult to measure. Therefore, in the field of agricultural soil compaction, analytical models may rather be used for practical purposes, while FE models may rather be used for extending knowledge in the soil deformation processes.

Analytical models for stress propagation are based on theories for elastic, homogeneous, semi-infinite materials. Obviously, these properties do not apply to soil. However, they may be a good-enough approximation for many practical applications. It was shown in Fig. 7 of Paper VI that the stress calculated with a FE model did not differ significantly from the stress calculated with an analytical model.

A drawback of the analytical stress calculation is the concentration factor, v. As mentioned elsewhere, v cannot be measured directly with standard laboratory equipment and may therefore often be considered as a fitting parameter. However, $4 \leq v \leq 6$ yielded good results for the simulations done within the work of this thesis. Within this relatively small range of v, the influence of v on calculated stresses at a certain depth is rather small and of the same order of magnitude as the standard error of stress measurements (Paper IV).

As shown in Papers IV, V and VI, the stress in soil can be calculated according to Söhne (1953). A pre-condition is, however, that the stresses in the contact area are accurately predicted. This is equally important for FE models, too. Often however, FE models assume either axi-symmetrical or plane strain problems; therefore, the choice of shape of the contact area and contact stress distribution is limited.

Certainly, the stresses predicted according to Söhne (1953) **will never exactly agree with measured stresses**, as the model does not account for *e.g.* heterogeneity (*c.f.* Fig. 8). On the other hand, many factors influence the stresses measured by stress transducers, and therefore absolute values should be treated with caution when comparing measured stresses with predicted stresses.

However, I think it is probably in many cases most important to accurately predict the **general pattern** of the stress propagation. If that holds true, the model can be used to analyse the stress propagation below different agricultural machinery and for the study of factors such as wheel load, tyre inflation pressure, tyre dimensions, number of wheels, wheel constellation, *etc.*

It may be the subject of future research to define the conditions under which analytical models produce useful predictions and the conditions under which such models fail. I believe this to be a very important aspect.

SoilFlex – *A* Soil *compaction model that is* Flex*ible*

In Paper VI, a new soil compaction model is proposed, the main characteristics of which are summarised here. The model is written in Visual Basic and implemented in an Excel file. Therefore, it is easy to use for farmers, advisers, students, *etc*. We use the name *SoilFlex*, because it is a *Soil* compaction model that is *Flex*ible in terms of the description of the stresses on the soil surface, the stress-strain relationship and the estimation of soil properties using pedo-transfer functions, and because the user can easily modify and *e.g.* add pedo-transfer functions to the model. With the model, the mechanical *Flex*ibility of *Soil* may be studied.

The model calculates the stress state in soil below agricultural machinery and predicts the changes in volume due to field traffic. Calculations are made in two dimensions, in a plane perpendicular to the driving direction and/or in a plane in the driving direction. The model contains three main components. Firstly, stress on the surface is described; both normal and shear stresses are considered. Secondly, stress propagation through soil is calculated analytically. Thirdly, soil deformation is calculated as a function of stress. With *SoilFlex*, the passage of machinery and machinery combinations that are used in practice, including dual/triple wheels and tandem wheels, can be simulated, which is an important aspect for the control of soil compaction in practice. This may sound trivial, but is actually not dealt with in previous models.

The distribution of vertical stress on the soil surface can either be uniform, parabolic (Söhne, 1953), or modelled as described in Paper V. Horizontal stress (shear stress) on the soil surface can be either calculated from a given traction or from soil strength; different shapes for the distribution can be chosen. It is also possible for users to define their own distributions of the surface stresses. Stress propagation through soil is calculated according to Söhne (1953). We calculate the complete stress state, including the invariant stress measures $\sigma_{oct} = p$, τ_{oct} and q.

Three different sub-models for description of the stress-strain behaviour are integrated, namely the models by Gupta & Larson (1982), Bailey & Johnson (1989) and O'Sullivan & Robertson (1996), which were all developed for agricultural soils. The model allows for a direct comparison between these soil deformation models. Shear failure is calculated according to the Mohr-Coulomb failure criterion. The soil mechanical parameters used in these models can be estimated by means of pedo-transfer functions.

Model input and model output (both in table form and as graphs) can be chosen according to requirements. For example, for an *a priori* comparative assessment of the impact of different machinery, the calculation of the vertical stress may be sufficient, which reduces the numbers of input parameters and computational time. In a second step, site-specific calculations using the most suitable machine may be performed by calculating stress propagation, soil deformations and soil displacements.

Soil tillage

The main reasons for tillage of the topsoil (also referred to as the ‘tilled layer’ or ‘plough layer’) are: soil loosening, weed control, burial of crop residues, preparation of a seedbed, preparation of a level surface to facilitate other operations, improvement of water infiltration, reduction of evaporative water loss and incorporation of manure. A distinction is made between primary tillage and secondary tillage (seedbed preparation). In the following, the focus is on primary tillage.

Deep tillage (‘deep loosening’ or ‘subsoiling’) is carried out to loosen, fracture and rearrange compact subsoils and subsurface pans, to improve drainage and aeration and to reduce resistance to root penetration.

During primary tillage, the soil is loosened from an initial compact state by dragging a metal implement through it. For loosening to occur, the soil must reach either shear failure or tensile failure (Hettiaratchi, 1988). Because tillage implements may compress the non-tilled soil ahead of them, it is possible that the resulting aggregates are denser than they were in the original soil, even though the porosity of the tilled layer is increased (Arvidsson & Dexter, 2002).

Due to tillage, the aggregates are exposed to the weather which accelerates the effect of wetting-drying and freezing-thawing cycles on soil structure formation. This is a very significant effect of primary tillage on soil fragmentation.

Tillage implements

Tillage implements are of mainly three different basic forms: tines, plough bodies and discs.

A **tine** is pulled through soil at a certain angle called the rake angle, α, which is the angle between the rake and the horizontal (Fig. 22). With increasing rake angle (especially if $\alpha > 90°$), the compressive forces exerted on the soil are increased (Koolen & Kuipers, 1983), which may increase fragmentation and create a finer seedbed compared with small rake angles. Therefore, tines with $\alpha \geq 90°$ are used in seedbed preparation. Draught force requirement decreases with decreasing α (Payne & Tanner, 1959; Olson & Weber, 1966; Godwin & Spoor, 1977). Therefore, tines with small rake angles are used in primary tillage and deep-loosening. Soil disturbance is dependent upon the tine spacing, *i.e.* the distance between the tines. The most effective soil loosening occurs with winged tines. The practical spacings recommended for good soil loosening are approximately 1.5 and 2.0 times the depth of work for simple and winged tines, respectively (Godwin, 2003).

A **plough body** loosens the soil in an area that is approximately equal to its width (Arvidsson & Dexter, 2002). The most widely used plough body is the mouldboard plough, which has a curved, concave shape for reversing the soil and thereby burying plant residues and weeds. The mouldboard plough is mainly used in primary tillage.

The main applications of **discs** are for primary tillage, either in the form of disc ploughs or disc harrows (Godwin *et al.*, 1987). Discs are often incorporated in implements in combination with tines. For any disc, the working depth, the tilt angle (*i.e.* the angle between the disc circumferential plane and the plumb line) and the sweep angle (*i.e.* the horizontal angle between the disc circumferential plane and the direction of motion) are the factors that determine the areas of the front and rear surfaces of the disc engaging the soil and the balance of the net forces acting on discs (O'Dogherty *et al.*, 1996). O'Dogherty *et al.* (1996) found that for the range of disc angles (35° to 55°) and tilt angles (15° to 25°) used in practice, there was no scuffing on the rear spherical surface.

Soil break-up and implement performance

Soil break-up and deformation by tillage occur mainly by three different mechanisms (Aluko & Seig, 2000): shear failure, brittle failure and plastic flow (Fig. 22). The three failure mechanisms correspond to the three types of intake by a plough body discussed by Koolen & Kuipers (1983): shear-plane failure, open crack formation and steady cutting.

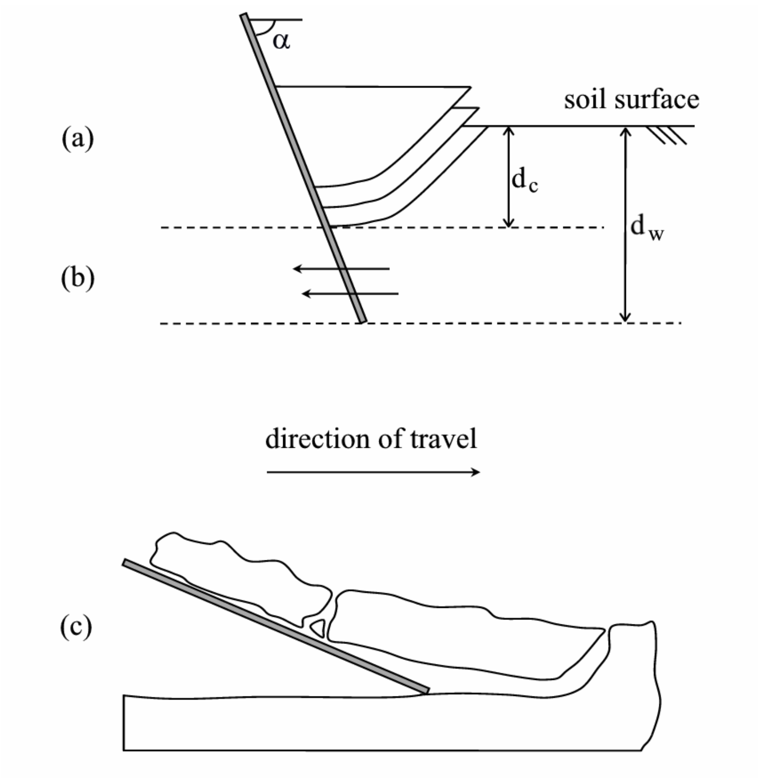


Fig. 22. A schematic illustration of typical failure patterns in soil cutting: (a) shear failure; (b) plastic flow; (c) tensile failure. *α*: rake angle; d_c: critical depth; d_w: working depth. Adapted from Aluko & Seig (2000).

It is possible to distinguish between two- and three-dimensional soil cutting. In two-dimensional soil cutting, the width of soil cut corresponds almost entirely to the width of the cutting tool, while in three-dimensional soil cutting the width of the soil cut is much wider than the tine width (Aluko & Seig, 2000).

Brittle failure (or tensile failure) occurs (mainly for relatively wide blades, *i.e.* in two-dimensional soil cutting) under certain soil conditions at low rake angles (Aluko & Seig, 2000). The formation of a crack is initiated by the penetration of the blade tip into the soil. The crack propagates towards the soil surface at a much faster rate than tool speed. As the blade advances, the crack opens further and separates a soil clod, which begins to move up the blade surface. With further blade movement, cutting is again initiated, a new crack starts to propagate and a new clod is separated. The deformation within separated soil clods is negligible. Aluko & Seig (2000) showed that at low rake angles, brittle failure occurs, while at higher rake angles, shear failure occurs. The angle, α_t, at which the transition from brittle to shear failure occurs is dependent on shear strength in such a way that α_t is larger the higher the shear strength.

Shear failure (also called crescent failure) occurs mainly due to compressive stresses; the soil fails when the applied stress overcomes the shear strength of the soil, and soil blocks with a crescent form are sheared off. This only occurs when the shearing resistance for upward soil flow from any particular depth is less than that for lateral flow, the two resistances being equal at a certain depth, termed the critical depth (Godwin & Spoor, 1977). At shallow working depths, the soil is displaced forwards, sideways and upwards, failing along well-defined rupture planes (Fig. 22). The performance of a tine may be simulated on a sandy beach, as shown in Fig. 23. The formation of crescent cracks can be clearly observed, successive blocks of sand are sheared off, and layers are piled up and slide up the foot, *i.e.* the 'face of the tine'. Fig. 23 is similar to Figs. 2 and 9 in Payne (1956), with the foot simulating a wide tine.

Crescent failure continues with increasing depth until at the critical depth, the soil at the tine base begins to flow forwards and sideways only (lateral failure or **plastic flow**) creating compaction at depth (Spoor & Godwin, 1978), *i.e.* soil is not uplifted nor loosened. Therefore, deep loosening can only have a positive result if the tine used for deep loosening is working above its critical depth (Spoor & Godwin, 1978). Plastic flow may also occur when the soil is not in a friable state (Arvidsson & Dexter, 2002).

The **critical depth** is dependent on the soil conditions, the tine width and the rake angle (Spoor & Godwin, 1978). Under given soil conditions, the wider the tine, the smaller its rake angle and the looser the soil surface, the greater the critical depth. The wetter and more plastic a soil the shallower the critical depth. Using shallow tines to loosen the soil surface layers ahead of a deep tine reduces the upward flow resistance, but only marginally changes that for lateral flow, and so effectively increases the critical depth. The use of wings or sweeps additionally increases the critical depth (Spoor & Godwin, 1978).

Fig. 23. Performance of a ‘tine’ in sand. Sunshine Beach, Queensland, Australia (Photo: Thomas Keller).

Draught force requirement and specific resistance

Draught force of a tillage implement is a direct measure of the energy requirement and hence fuel consumption for tillage, which is an important variable when analysing different tillage systems. The draught requirement for pulling a tillage implement through soil is dependent on implement parameters, tillage depth, driving speed and soil mechanical strength (Payne, 1956).

Isolated analysis of the draught force may be of limited value if the amount of soil disturbed is not considered (Godwin *et al.*, 1985). Therefore, it is useful to relate draught to the area of soil loosened by the implement by calculating the ratio of draught to the cross-sectional area of soil disturbance, termed the specific resistance or specific draught (Spoor & Godwin, 1978).

According to Payne (1956), the draught force of a wide tine is approximately proportional to the total passive earth pressure, E_p:

$$E_p = \frac{1}{2}\gamma H^2 K_p + 2cH\sqrt{K_p} = \frac{1}{2}\gamma H^2 \tan^2\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) + 2cH \tan\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) \qquad (27)$$

where: γ is the soil density, H is the working depth, K_p is the coefficient of passive earth pressure, c is the cohesion and φ is the angle of internal friction. The first component of Eq. (27) is usually small.

Therefore, the draught force is expected to be proportional to H if c and φ [Eq. (27)] are kept constant. Nevertheless, this may not hold true in real soils, as the soil conditions cannot be expected to remain constant with depth. It was shown in Paper VII that the draught increased approximately linearly with depth for the mouldboard plough. However, for the chisel plough, the increase in draught with depth was larger, probably because the chisel plough was working below its critical depth.

On the other hand if *H* and *φ* [Eq. (27)] are kept constant, draught force is expected to be proportional to *c*. This is believed to be true because the adhesion, the angle of soil-metal friction and the angle of internal friction vary over a small range compared with cohesion (Payne, 1956). However, draught force did not correlate with *c* in the experiments of Olson & Weber (1966). They argue that the methods for measuring shear strength do not give an adequate description of the properties of arable soil for dynamic conditions (a similar problem arises for the measurement of the compressive behaviour of soil as discussed in section 'Compressive behaviour of soil – soil precompression stress').

Energy requirement and draught force increase with increasing implement velocity (Payne, 1956; Olson & Weber, 1966; Wheeler & Godwin, 1996; Onwualu & Watts, 1998; Al-Jalil *et al.*, 2001). In Fig. 24, specific resistance as a function of implement velocity is shown for a mouldboard plough, chisel plough and disc harrow on two different soils at Ultuna. The specific resistance generally increased with increasing speed, the correlation being high for the mouldboard plough and the disc harrow. The correlation was weaker for the chisel plough, especially on the clay soil, where specific resistance did not increase with speed [Fig. 24(a)]. This is explained by reduced penetration at higher speeds, which resulted in a lower working depth and hence in both lower draught and smaller area of disturbance.

The speed effect has been attributed to an increase in shear strength with speed, increase in length of the failure path, and acceleration of the soil (see *e.g.* Olson & Weber, 1966). The latter effect is not likely to be of importance with the range of

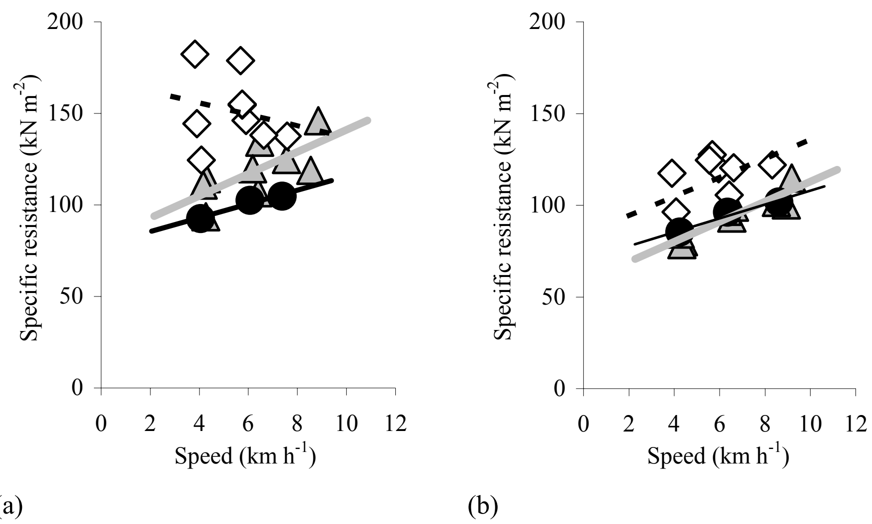


Fig. 24. Specific resistance as a function of implement velocity for mouldboard plough (triangles), chisel plough (rhombi) and disc harrow (circles) on (a) a clay soil and (b) a sandy clay loam soil at Ultuna.

speed encountered in agriculture (Payne, 1956), nor was it observed by Olson & Weber (1966). According to Olson & Weber (1966) the most important factor is that mechanical properties of soil are dependent on the loading time. Wheeler & Godwin (1996) found that the effect of speed on draught force is insignificant at speeds below $\sqrt{5g(w+0.6d)}$, where g is the acceleration due to gravity, w the tine width and d the working depth.

Draught force increases with increasing rake angle, α, especially at $\alpha > 50°$, while draught is lowest at $\alpha \approx 20°$ (Payne & Tanner, 1959; Godwin & Spoor, 1977; Aluko & Seig, 2000). At low rake angles brittle failure may occur, while at higher rake angles shear failure occurs (Aluko & Seig, 2000). However, Aluko & Seig (2000) could not measure a drastic change in the draught at the transition between brittle and shear failure. Payne & Tanner (1959) found that changes in draught due to the rake angle were closely correlated with changes in the length of the shear path in the direction of travel.

Compared with a tine working above the critical depth, the specific resistance for a tine with wings is decreased (Spoor & Godwin, 1978). Because wings increase the critical depth a tine with wings may still work above critical depth, while the conventional tine (without the wings) works below critical depth for a given working depth under given soil conditions. Comparison of specific resistance values then shows that the specific resistance of the winged tine is significantly lower than that of the conventional tine.

With regard to the draught force of a mouldboard plough, the furrow depth (working depth) has a much greater influence than the furrow width and the implement velocity (Godwin, 2003).

In addition to working depth, disc dimensions and rake angle, the draught for discs is a function of the sweep angle. Godwin *et al.* (1985) found that the minimum draught occurred at sweep angles in the range 20° to 30°, and that the minimum specific resistance occurred at sweep angles marginally higher than those for the minimum draught.

In Paper VII, we measured and compared the draught force requirement and the specific resistance of a mouldboard plough, a chisel plough and a disc harrow. The draught force requirement was highest for the mouldboard plough and lowest for the disc harrow. However, specific resistance was lowest for the mouldboard plough and the disc harrow, and highest for the chisel plough. This is due to great differences in the area of disturbed soil, which was much higher for the mouldboard plough compared with the chisel plough (Fig. 25). The disc harrow works at shallow depth only, which explains the lower total energy requirement.

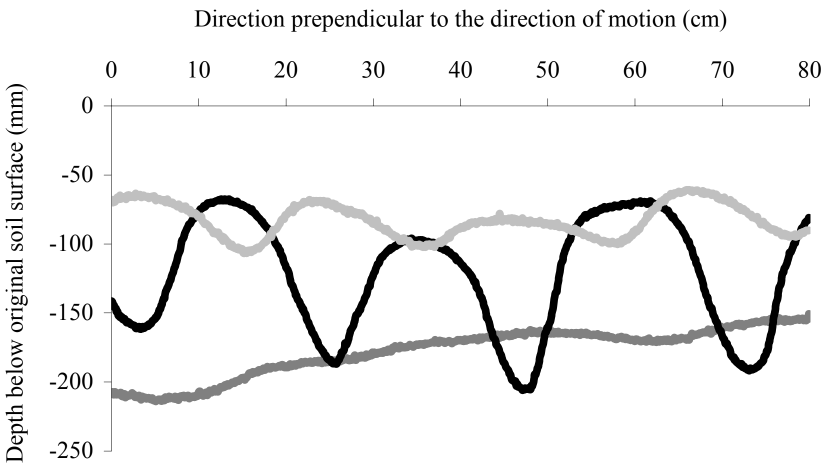


Fig. 25. Relief of the bottom of the tilled layer after tillage with a mouldboard plough (dark grey curve), a chisel plough (black curve) and a disc harrow (light grey curve) on a sandy loam at Ultuna.

Predicting draught force

Analytical models (*e.g.* Godwin *et al.*, 1984; Godwin *et al.*, 1985; Hettiaratchi, 1997; Shrestha *et al.*, 2001) are usually based on classical soil mechanics theory, which relies upon Mohr-Coulomb soil properties (Desbiolles *et al.*, 1997). Brittle failure in soil cutting is principally an elastic problem (Aluko & Seig, 2000) and can be modelled using methods of fracture mechanics for elastic-brittle materials (Aluko & Chandler, 2004).

Empirical methods typically correlate the draught of a specific implement with relevant parameters such as working depth, velocity, soil moisture content, density, cohesion or penetration resistance (*e.g.* Dawidowski *et al.*, 1988; Mouazen & Ramon, 2002; Kheiralla *et al.*, 2004; Paper VII). Such models cannot be used to predict the draught of other, different soil types or of other, different tillage implements. However, they give an indication of the force requirements for specific soil-implement combinations. We found that for three soils at Ultuna, the draught was better correlated to the cohesion obtained from a shear vane apparatus than to the penetrometer resistance (Paper VII). One reason may be that the tine draught sensitivity to soil moisture content is different from that of the cone penetration resistance (Desbiolles *et al.*, 1997).

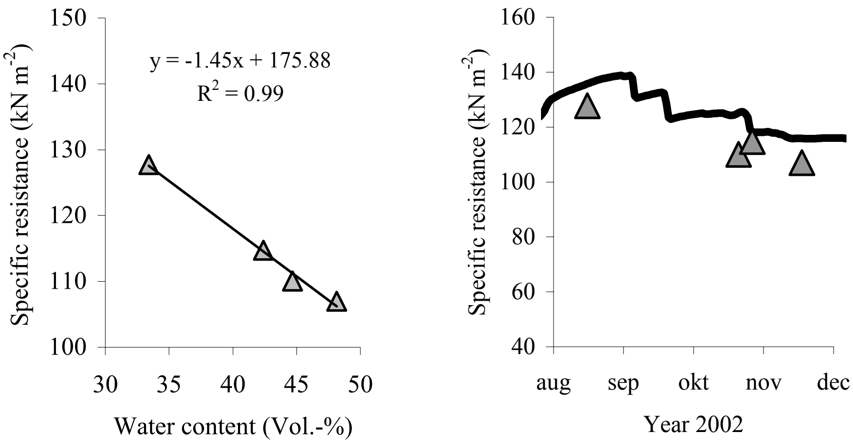
For a given soil, draught requirement of a given implement may change as a function of water content, since soil strength itself depends on the soil water content. Therefore, draught force requirement can be modelled as a function of water content, while water content can be modelled by means of a soil-water-atmosphere-transport (SWAT) model. This is shown in Fig. 26, where with the help of the correlation between specific resistance for mouldboard ploughing to a depth of 0.2 m and water content [Fig. 26(a)] and with the water content as a function of time simulated by means of the SWAT model COUP (Jansson &

Karlberg, 2001), the specific resistance for mouldboard ploughing to a depth of 0.2 m could be modelled as a function of time [Fig. 26(b)].

However, this procedure is restricted to time periods without any tillage operations and without any changes in the WRC due to *e.g.* freezing-thawing cycles. Such a period occurs between harvest in autumn and the beginning of the winter (as in Fig. 26). The accuracy of the predicted specific resistance [as shown in Fig. 26(b)] is directly dependent on the quality of the correlation between specific resistance and the water content [Fig. 26(a)] and the accuracy of the water content predicted by means of the SWAT model. For more details, see Gustafsson *et al.* (2003) and Myrbeck *et al.* (2003).

Desbiolles *et al.* (1997, 1999) developed an empirical approach for prediction of draught of different tools and for different soil conditions. They interpreted the draught as the product of two components, namely a soil strength factor and a standard tine geometrical factor. The draught of an implement operating in field conditions can be estimated from the draught of a standard tine measured in those field conditions (soil strength factor) and from a comparative draught relationship between the standard tine and another tillage implement. The soil strength factor may also be estimated from the soil moisture content, the working depth and the cone index (Desbiolles *et al.*, 1999).

Multi-tool tillage implements (*i.e.* tillage implements used in practice) can be considered as an association of *n* single tillage tools. The implement draught can be approximated as *n* times the draught of a single tool, minus a force reduction that accounts for the tool interactions within the implement, plus an additional draught due to any additional attachment or accessory fitted (*e.g.* scrapers, wheels) (Godwin *et al.*, 1984; Desbiolles *et al.*, 1999).



(a) (b)

Fig. 26. (a) Specific resistance for mouldboard ploughing to a depth of 0.2 m as a function of water content, and (b) as a function of time on an Ultuna clay; measurements (triangle) and simulations (black curve).

Friability and workability

Friability has been defined as the tendency of a mass of soil to crumble into a certain size range of smaller fragments under the action of an applied stress (Utomo & Dexter, 1981). Soil workability can be defined in terms of the sizes of the soil aggregates that exist after tillage (Dexter, 2004b).

Soil structures produced by tillage strongly depend upon the initial soil conditions (Dexter, 1979; Berntsen & Berre, 2002). This has to be accounted for when comparing aggregate size distributions produced on different soils or produced from implements working to different depths. The soil conditions cannot be expected to be constant with depth. Therefore, aggregates produced by disc harrowing may be finer than those produced by a mouldboard plough, as the latter has a larger tillage depth (Paper VII). Dexter (1979) predicted the soil structures produced by tillage as a function of implement type, number of implement passes, tillage depth, soil management, crop, soil water content and soil compaction.

Average aggregate diameter after tillage decreases with increasing specific energy (J kg^{-1}) supplied (by the implement). Berntsen & Berre (2002) showed that on four soils with clay contents ranging from 15 to 45%, an energy input of about 50 J kg^{-1} caused a substantial reduction in the initial aggregate size and a final aggregate size in the range that is considered a good seedbed. Greater energy input caused very little further aggregate size reduction. For analysis of the energy efficiency in fragmentation, initial soil state can be taken into account by relating the increase in aggregate surface to the initial surface, and by relating the specific energy supply to the specific fracture energy needed to crush a clod or to shear the soil, as demonstrated by Berntsen & Berre (2002).

Consequently, the energy efficiency in fragmentation of implements, and the efficiency of different implements relative to one another, may strongly depend upon the initial soil state (Hadas & Wolf, 1983; Berntsen & Berre, 2002).

Optimum water content for tillage

For a given soil, the soil structures produced by tillage are strongly affected by the soil moisture content. There exists a water content at which the result of tillage is optimum, termed the optimum water content for tillage, θ_{OPT}. It is defined as the water content at which the proportion of small aggregates produced is largest, or, conversely, the proportion of clods produced is smallest (Dexter & Bird, 2001; Dexter, 2004b). In Paper VIII, we define θ_{OPT} as the water content at which the specific surface area of the aggregates produced by tillage is maximal. (Here, the symbol θ is used for gravimetric water content, which may be different from conventional notation).

It was found in several studies that θ_{OPT} corresponds to a water content slightly below the lower plastic (or lower Atterberg) limit, θ_{PL}. Ojeniyi & Dexter (1979) found maximum production of small aggregates when tillage was performed at $0.9\theta_{PL}$. However, de Toro & Arvidsson (2003) measured an increase in the proportion of small aggregates with decreasing soil water content down to about $0.5\theta_{PL}$ during seedbed preparation in spring. Barzegar *et al.* (2004) found that θ_{OPT} in terms of θ_{PL} was affected by both tillage system and soil type. In their experiments, θ_{OPT} was between $0.7\theta_{PL}$ and $0.8\theta_{PL}$. Friability of soil was also found to be maximum at a water content close to θ_{PL} (Utomo & Dexter, 1981).

However, as argued by Dexter & Bird (2001), this has the limitations that θ_{PL} is a property of moulded soil, and not of undisturbed real soil in the field. Furthermore, many sandy soils are not plastic and therefore do not have a plastic limit (Dexter & Bird, 2001). Therefore, Dexter & Bird (2001) define θ_{OPT} in terms of the water retention curve (WRC). They found that θ_{OPT} corresponds to the water content at the inflection point of the WRC, θ_{INFL}, when this is plotted as the logarithm of the water tension, log *h* (hPa), against the gravimetric water content, θ (g g^{-1}). This was supported in the present study for four different Uppsala soils with clay contents ranging from 22 to 53% (Paper VIII). Müller e*t al.* (2003) found that at θ_{INFL}, the soil is often too wet for tillage. However, they did not measure the aggregate size distribution produced by tillage, but estimated workability using a field scoring method that includes pressing, remoulding and rolling of a soil sample by hand.

Dexter & Bird (2001) also define a lower (dry) and an upper (wet) tillage limit that can be calculated from parameters of the WRC. The difference between the upper and lower tillage limit is the range of water contents over which tillage may satisfactorily be carried out. Fig. 27 shows the range of water contents for tillage of the topsoil of an Ultuna clay. Water content was simulated by means of COUP (Jansson & Karlberg, 2001); the upper and lower tillage limit and θ_{OPT} were determined according to Dexter & Bird (2001). In the example shown (Fig. 27), θ_{OPT} was on 11 September, while tillage was expected to be satisfactory between 28 August and 8 October. For modelling details, see Gustafsson *et al.* (2003) and Myrbeck *et al.* (2003).

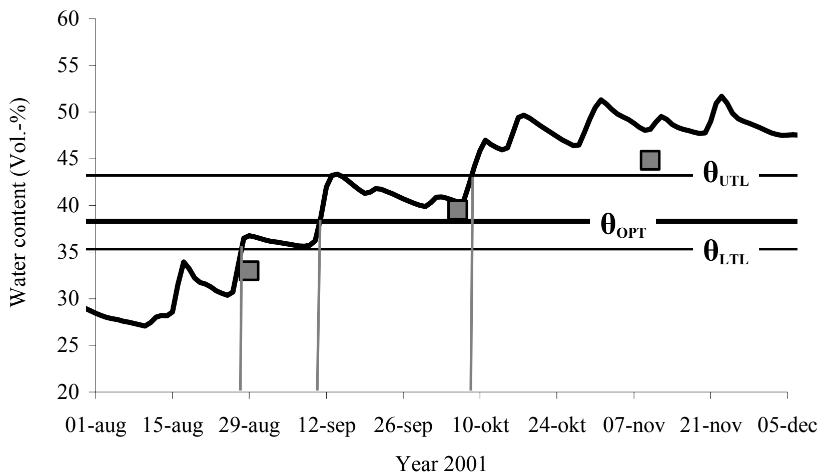


Fig. 27. Measured (squares) and simulated development of water content (black curve), upper and lower tillage limit (θ_{UTL} and θ_{LTL}, respectively), and optimal water content for tillage (θ_{OPT}) for the topsoil of an Ultuna clay.

Friability was found to be strongly correlated with the index of soil physical quality, *S* (Dexter, 2004b). This is because both depend on the soil microstructure (Dexter, 2004b). Dexter & Birkás (2004) found a good correlation between the proportion of clods produced by tillage at θ_{OPT} and *S*, such that the proportion of clods produced was larger for smaller *S* values, *i.e.* for soils with a lower soil physical quality. This could be confirmed for four Uppsala soils (Paper VIII). In Paper VIII, we additionally show that the specific surface area (*i.e.* the surface area per volume soil) of the aggregates produced by tillage is strongly positively correlated with the value of *S* (Fig. 28).

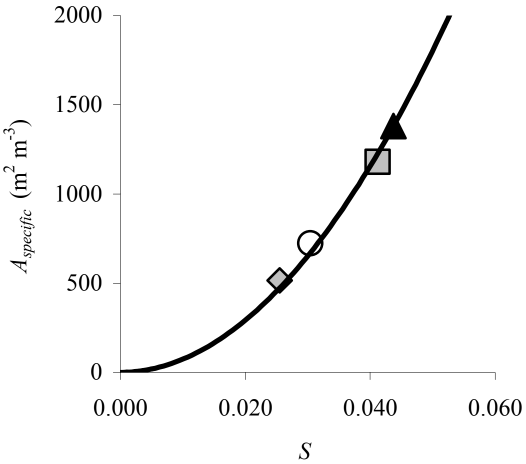


Fig. 28. Specific surface area produced by tillage, $A_{specific}$, of four Ultuna soils at the optimum water content as a function of *S*.

Interactions between tillage operations and soil compaction

There are a number of interactions between tillage operations and soil compaction. These are discussed in the following paragraphs. Obviously, soil compaction may occur during a tillage operation, as explained by Gupta & Larson (1982). During tillage, a part of the soil is broken up into various size clods by the implements and a part is compacted by traffic. Soil compaction is in turn one of the reasons for the need for tillage.

We can distinguish between traffic-induced compaction (due to field traffic) and tillage-induced compaction (due to both traffic and tillage implements). The latter may result in the formation of a 'tillage pan' (Fig. 29), also termed 'plough pan' (due to mouldboard ploughing) or 'disc pan' (due to disc harrowing). Birkás *et al.* (2004) observed that annual shallow discing and ploughing causes subsoil compaction at the depth of tillage within three years. The surfaces of tillage pans are often smeared due to the passage of the implement, which drastically reduces the pore continuity between the topsoil and the subsoil. This may have a major negative effect on soil quality.

Effect of compaction on draught requirement

It has been shown that the draught force of a tillage implement increases with increasing bulk density (*e.g.* Mouazen & Ramon, 2002). This holds true because the soil strength usually increases with increasing bulk density (Horn, 1993).

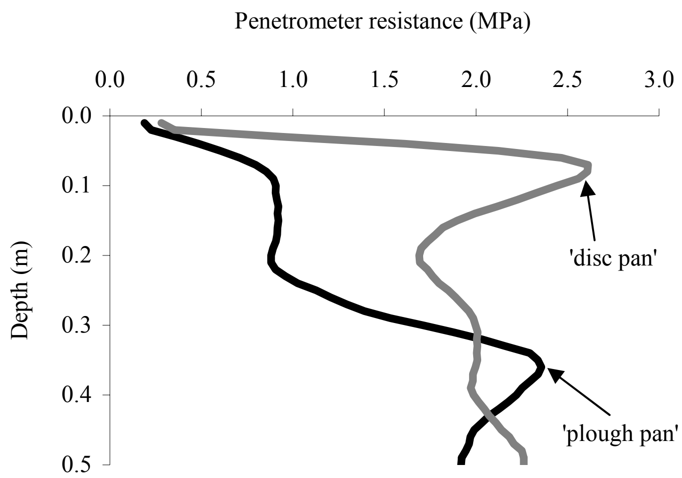


Fig. 29. Examples of penetration resistance as a function of depth; plough pan and disc pan are clearly visible. Data: Svantesson (unpublished).

Tullberg (2000) showed that compaction due to tractor and/or implement wheels that precede tillage implements can increase total implement draught by more than 30%. This is termed the 'traffic penalty' of the operation. The traffic penalty can be reduced by minimizing the proportion of the width trafficked by the tractor to the implement width, *e.g.* by using rubber belts instead of wheels. In controlled traffic farming, tractors are fitted with tyre equipment of minimal width or with rubber belts, load-bearing implement wheels are confined to permanent tracks, and traffic penalties do not occur when trafficked soil is neither tilled nor planted (Tullberg, 2000). Furthermore, the tractive efficiency is increased in controlled traffic farming due to the firmer surface provided by permanent lanes, which additionally increases the energy efficiency of that system.

Effect of draught force on soil stress and soil properties

The distribution of vertical stress below a tracked tractor was shown to strongly depend on the draught force induced by a tillage implement (Paper III). It was shown that at constant draught force, the stress distribution is very sensitive to the horizontal position of the point of application of the draught. This is assumed to be true also for wheeled tractors, although in that case, the major effect is on the weight distribution between front and rear wheel.

In Papers IV and V, it was demonstrated that the stress distribution at the tyre-soil interface strongly affects the propagation of stresses in the soil, especially at depths shallower than about 0.5 m, *i.e.* at depths that are susceptible to subsoil compaction.

The draught not only affects the distribution of stress, but also increases shear stresses at the soil surface. These shear stresses are built up to produce the traction needed to pull an implement. They may have a two-fold effect: Firstly, a direct effect on the soil structure near the soil surface; and secondly, an effect on the propagation of stresses, as can be understood from Eq. (14) in Paper VI. The latter effect may only be small. As shown by Johnson & Burt (1990), the traction mainly causes p and τ_{oct} to be skewed in the direction of driving, while the absolute values are scarcely affected. Bakker *et al.* (1995) found that increasing the draught force by pulling a cultivator through the soil did not alter the stress state at 0.2 m depth. This is in accordance with measurements made at Örsundsbro, where the effect of increased traction (induced by a chisel plough) on vertical stress, displacement and saturated hydraulic conductivity was studied (see Bölenius, 2002). Neither stress nor displacement at 0.15, 0.3 and 0.5 m depth was affected by the increased traction, which was confirmed by simulations (not shown). However, as mentioned elsewhere, saturated hydraulic conductivity in the wheel track was about seven times smaller after the passage of the pulling tractor compared with the non-pulling tractor. The soil was probably sheared to a greater extent below the wheels of the pulling tractor, which resulted in disconnection of pores, as illustrated by Horn (2003).

The slip of tracked devices is normally lower than that of wheels at similar traction (Okello *et al.*, 1994). This is the result of the longer area of ground contact under the track. However, the total displacement may be similar for a track compared with a wheel. Consequently, in the experiment at Krenkerup (Bölenius, 2002), k_{sat} measured after the passage of the wheeled tractor was not different from k_{sat} measured after the passage of the rubber-tracked tractor. The slip of a wheeled tractor is reduced by using wider tyres or dual tyres.

Effect of compaction on workability and friability

As illustrated by Dexter (2004a), bulk density affects the water retention curve (WRC) of a given soil in such a way that at higher densities, the slope of the WRC at the inflection point, *i.e.* the value of *S*, is smaller (Fig. 21). Therefore, the range of water contents over which tillage may satisfactorily be performed as defined by Dexter & Bird (2001) is also smaller for a higher density of a given soil. For practical purposes, this means that the number of days available for successful tillage is smaller for a more compacted soil.

The quality of the soil structures produced by tillage depends on the friability of the soil (Utomo & Dexter, 1981; Watts & Dexter, 1998; Dexter & Bird, 2001). Dexter (2004b) was able to show that the friability is positively correlated to *S*. Consequently, the quality of the soil structure produced is worse for a soil with a low value of *S*, *i.e.* for a soil with a poor soil physical condition. This was supported by Dexter & Birkás (2004) and in Paper VIII, where the proportion of clods produced by tillage at the optimum water content was negatively correlated with *S*, while no clods were produced on soils with good physical quality.

Practical solutions to reduce the risk of subsoil compaction

The risk of subsoil[1] compaction can be reduced by several measures. These are presented in the following paragraphs in a hierarchical way, meaning that the first mentioned measure is the easiest to implement and should therefore be applied first.

The easiest way to avoid soil compaction, at least theoretically, is to avoid field operations under soil conditions that are susceptible for compaction. This would mean avoiding field operations when the subsoil is wet. It is important to stress that the situation may be more complex than this, as discussed by Trautner (2003). Caution is necessary because even when the topsoil is dry and hardly any ruts can be observed after the passage of a vehicle, the subsoil can still be wet and hence compacted. Dry, hard topsoil cannot prevent the stresses propagating into the subsoil; on the contrary, the stress propagation may even be faster and more direct (Trautner, 2003). Of course, it may not always be possible to avoid field traffic under wet subsoil conditions in practice, for example when a crop has to be harvested.

Certain field operations can be avoided and replaced by others. With regard to tillage operations, conventional ploughing is the operation involving the highest risk of subsoil compaction. Conventional ploughing involves the wheels on one side of the tractor running in the furrow, *i.e.* directly on the subsoil. As a consequence, stresses in the subsoil are very high (Paper III), as is the risk of subsoil compaction. In addition, the plough pan may be smeared, which may result in pore discontinuity and a decrease in water infiltration. Conventional ploughing can be replaced by on-land ploughing (or of course, by reduced tillage). On-land ploughing considerably reduces the risk of subsoil compaction compared with conventional ploughing (Paper III). Another field operation that may involve high risks of subsoil compaction is transport traffic with trailers bringing the crops from the field. To avoid this, the harvester could be unloaded at the head of the field. This is of course only possible in practice when the capacity of the harvester is adjusted to the dimensions of the field or vice versa.

If transport traffic cannot be avoided, then at least the tractors and trailers used for such transport should have good tyre equipment. This problem is often not taken care of, especially for trailers. Trailers used for transporting crops are often equipped with old tyres, sometimes even with lorry tyres. Good tyre equipment (large tyres that are constructed for agricultural use and that allow for low tyre inflation pressure in order to reduce contact stress) should of course be used on all agricultural machinery.

[1]It is important to remember that subsoil is the soil deeper than about 0.25 m (for conditions in Swedish and many other European countries). This implies that when we talk about subsoil compaction, we mean compaction of all soil layers at depths greater than about 0.25 m. Subsoil compaction is most likely to occur in the layers just below the tillage depth, down to maybe 0.5 m depth; subsoil compaction due to agricultural field traffic is not associated with depths of one or two metres (which may be a common understanding of 'subsoil'). With the trends towards shallower ploughing and reduced tillage, subsoil may even include shallower depths in future.

In Paper IV, the effect of tyre inflation pressure on soil stress was investigated. Whereas the stress was lower with lower tyre inflation pressure at 0.3 m depth (= subsoil), there was no difference in stress due to tyre inflation pressure at greater depths. For several reasons, a tyre should be used with the tyre inflation pressure that is recommended by the manufacturers. This implies that low wheel load is a pre-condition for low tyre inflation pressure.

Wheel load can be reduced by dividing the machinery load onto more wheels, which is obtained with dual (or triple) wheels or tandem wheels. In Paper IV, it was shown that the wheels from such wheel constellations can (for practical purposes) be considered as separate wheels with regard to soil stress.

Another potential way to reduce contact stress is to use tracks instead of wheels. Tracked tractors usually have a greater contact area than wheeled tractors with equivalent power ratings (Brown *et al.*, 1992). Rubber tracks have a great potential to provide better tractive performance than wheels either over a wider range of drawbar pull with a tractor of the same weight or over the same range with a much lighter tractor (Okello *et al.*, 1994). The stress distribution below the tracks may be very uneven (Paper III), resulting in high maximum stress and hence a high risk of compaction (Fig. 9). However, in cases where the rubber-tracked tractor is well-balanced (the maximum stress is as small as possible) the risk of subsoil compaction may be lower than with wheeled tractors of similar size.

Controlled traffic is a system to reduce compaction by limiting compaction to designated areas of the field, *i.e.* the wheel tracks or 'tramlines'. All machinery is then adjusted to *e.g.* 3 m wheel base and 9 m implement width, while the width of the tyres or tracks is kept relatively small. While this concept is very appealing, it is probably limited to large farms that have more or less rectangular fields. It is also difficult to apply in tillage systems that include mouldboard ploughing.

Tractor driving speed is of little importance for practical purposes, although there is a trend towards smaller stress and displacement with increasing speed (Stafford & De Carvalho Mattos, 1981; Horn *et al.*, 1989; Keller *et al.*, 2004). In all these studies, small differences in stress and strain were found between extreme speeds, *e.g.* between 1 and 20 km h^{-1}. In practice, it may be possible to increase speed for a given tillage operation from (say) 10 to 15 km h^{-1}, which is unlikely to have any significant effect on soil compaction. In addition, at high speeds the vehicle may start to bounce, which may result in locally very high stresses. Parameters other than tractor speed, such as tyre inflation pressure and wheel load, are much more important for controlling traffic-induced compaction.

Conclusions and implications for future research

In contrast to the common belief that the stress at the tyre-soil interface is approximately equal to the tyre inflation pressure, it was shown in Papers IV and V that the maximum stress is greater than the tyre inflation pressure, and that the distribution of stress beneath tyres and rubber belts is highly non-uniform. Furthermore, the distribution of stresses is strongly influenced by the draught force induced by a tillage implement (Paper III). This underlines the importance of studying the mechanical impact of machinery during relevant field operation in practical agriculture.

The distribution of stress on the soil surface was shown to have a great influence on stress propagation in soil (Papers IV and V). This has the following implications. Firstly, tyre and machinery manufacturers are addressed and challenged to develop tyres that produce a uniform distribution of stresses at low tyre inflation pressures, and machinery that allows for the use of tyres at low inflation pressure. Secondly, with regard to soil compaction modelling, a uniform stress distribution (as often used) is too poor an approximation of the real stress distribution and can result in serious underestimation of soil compaction. Therefore, a model for the prediction of the distribution of stress below tyres from readily-available tyre parameters is proposed in Paper V. It was shown that this model produces significantly improved input data for soil compaction models and hence increases the accuracy of prediction of soil compaction.

Stress is propagated in soil 'straighter down' than what may be commonly believed. For example, the stress interaction from the different wheels in dual and tandem wheel configurations is rather small, *i.e.* for practical purposes, these wheels can be considered separate wheels with regard to soil stress (Paper IV). Hence, soil stress is not related to either axle load or total vehicle load. This underlines again the strong effect of the distribution of stress on the soil surface on stress propagation. For example, the peak stresses that are measured in the topsoil below a rubber belt are also clearly visible in the subsoil (Fig. 9).

It was possible to simulate stress propagation in soil by means of an analytical model (Papers IV, V and VI), provided that the stresses in the contact area were accurately predicted. Analytical models may be restricted to conditions of relatively small strains. However, such conditions are encountered when field operations are avoided under conditions of high susceptibility for soil compaction. Under conditions resulting in large strains, numerical models (*e.g.* based on the finite element method) may provide better predictions. It is of great importance to define the limits of application of analytical models.

Further refinements of soil compaction models should include the development of pedo-transfer functions for prediction of the soil mechanical parameters that are required in soil compaction models, as well as coupling with *e.g.* plant growth models, soil-water-atmosphere-transfer models, erosion models or models that describe the development of the soil structure.

The precompression stress is widely used in soil compaction research and included in soil compaction models. It marks the transition from the elastic to the plastic compressive behaviour of a soil. This transition is more gradual than sharp in practice, as shown in Papers I and II. The precompression stress is not an exact value, but depends *inter alia* on the compression test, the determination method and the sample dimensions. It is not a distinct threshold between the elastic and the plastic part; plastic deformation was measured in the field even when the precompression stress was not exceeded. The stress-strain behaviour at stress states below the precompression stress is not purely elastic, as often assumed in theory. A subject of future research should be to show how and whether the strains at stress states below the precompression stress affect physical properties of soil.

Interactions between soil tillage operations and soil compaction obviously do exist. In Paper III, it was shown that the draught force induced by a tillage implement affects the stress distribution below a rubber-tracked tractor, which in turn affects stress propagation and hence soil compaction. On the other hand, soil compaction affects the draught requirement as well as the aggregate size distribution produced by tillage.

It was shown in Paper VII that the draught requirement of tillage implements has to be related to the cross-sectional area of soil disturbance by calculating the specific resistance for comparison of the tillage efficiency. The draught could be related to shear vane strength for specific soil-implement combinations.

Chisel ploughs often work below their critical depth, which strongly increases the energy requirement (*i.e.* fuel consumption) without any benefit in terms of soil break-up (Paper VII). Therefore, tillage to depths greater than about 10-15 cm with a chisel plough that has narrow tines without wings is not recommended. The disc harrow was shown to be energy efficient for soil fragmentation. The mouldboard plough is energy efficient for loosening soil and therefore, shallow mouldboard ploughing may be an interesting concept for reducing the energy requirement while maintaining the benefit of a mouldboard plough (*e.g.* incorporation of crop residues). Future research should include analysis of the energy requirement of all operations within tillage systems.

The optimum water content for tillage, θ_{OPT}, was found to correspond closely to water content at the inflection point of the water retention curve, when this is plotted as the logarithm of the water tension against the gravimetric water content (Paper VIII). Furthermore, a strong correlation was found between the specific surface produced by tillage at θ_{OPT} and the value of Dexter's index S of soil physical quality. The specific surface was larger, the better the soil physical quality, *i.e.* the greater S. Both θ_{OPT} and S are properties of the water retention curve, which is strongly affected by tillage operations and soil compaction. The changes of the water retention characteristics over time in different tillage systems could be the subject of future research.

References

Abu-Hamdeh, N.H. & Reeder, R.C. 2003. Measuring and predicting stress distribution under tractive devices in undisturbed soil. *Biosystems Engineering* 85, 493-502.

Alakukku, L. 1996. Persistence of soil compaction due to high axle load traffic. II. Long-term effects on the properties of fine-textured and organic soils. *Soil and Tillage Research* 37, 223-238.

Alexandrou, A. & Earl, R. 1995. In situ determination of the pre-compaction stress of a soil. *Journal of Agricultural Engineering Research* 61, 67-72.

Al-Jalil, H.F., Khdair, A. & Mukahal, W. 2001. Design and performance of an adjustable three-point hitch dynamometer. *Soil and Tillage Research* 62,153-156.

Aluko, O.B. & Chandler, H.W. 2004. Characterisation and modelling of brittle fracture in two-dimensional soil cutting. *Biosystems Engineering* 88, 369-381.

Aluko, O.B. & Seig, D.A. 2000. An experimental investigation of the characteristics of and conditions for brittle failure in two-dimensional soil cutting. *Soil and Tillage Research* 57, 143-157.

Arvidsson, J. 1997. *Soil Compaction in Agriculture – From Soil Stress to Plant Stress*. Doctoral Thesis. Agraria 41, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Arvidsson, J. & Andersson, S. 1997. Determination of soil displacement by measuring the pressure of a column of liquid. In: *Proceedings of the 14th International Conference of ISTRO*, Puławy, Poland, pp. 47-50.

Arvidsson, J. & Dexter, A.R. 2002. Tillage. Course in agricultural soil mechanics, *Swedish University of Soil Sciences,* Uppsala, Sweden.

Arvidsson, J., Trautner, A. & Keller, T. 2002. Influence of tyre inflation pressure on stress and displacement in the subsoil. In: Pagliai, M., Jones, R. (Eds), *Sustainable Land Management – Environmental Protection. A Soil Physical Approach*. Advances in Geoecology 35, Catena Verlag, Reiskirchen, pp. 331-338.

Arvidsson, J., Trautner, A. & Sjöberg, E. 2001. *Alvpackning av tunga betupptagare. Slutrapport från försök 1995-2000.* Report 102, Division of Soil Management, Department of Soil Sciences, Swedish University of Agricultural Sciences, 56 pp.

Atkinson, J. 1993. *An Introduction to the Mechanics of Soils and Foundations through Critical State Soil Mechanics*. McGraw-Hill International Series in Civil Engineering, London, 337 pp.

Atkinson, K.H. & Bransby, P.L. 1978. *The Mechanics of Soils – An Introduction to Critical State Soil Mechanics*. McGraw-Hill, London, 375 pp.

Bailey, A.C. & Johnson, C.E. 1989. A soil compaction model for cylindrical stress states. *Transactions of the American Society of Agricultural Engineers* 32, 822-825.

Bailey, A.C., Johnson, C.E. & Schafer, R.L. 1986. A model for agricultural soil compaction. *Journal of Agricultural Engineering Research* 33, 257-262.

Bailey, A.C., Nichols, T.A. & Johnson, C.E. 1988. Soil stress state determination under wheel loads. *Transactions of the American Society of Agricultural Engineers* 31, 1309-1314.

Bakker, D.M., Harris, H.D. & Wong, K.Y. 1995. Measurement of stress path under agricultural vehicles and their interpretation in critical state space. *Journal of Agricultural Engineering* 61, 247-260.

Barzegar, A.R., Hashemi, A.M., Herbert, S.J. & Asoodar, M.A. 2004. Interactive effects of tillage system and soil water content on aggregate size distribution for seedbed preparation in Fluvisols in southwest Iran. *Soil and Tillage Research* 78, 45-52.

Baumgartl, T. & Köck, B. 2004. Modelling volume change and mechanical properties with hydraulic models. *Soil Science Society of America Journal* 68, 57-65.

Berli, M. 2001. *Compaction of Agricultural Subsoils by Tracked Heavy Construction Machinery*. Doctoral Thesis. ETH Diss. No. 14132, Swiss Federal Institute of Technolgy, ETH Zurich, Switzerland, 105 pp.

Berntsen, R. & Berre, B. 2002. Soil fragmentation and the efficiency of tillage implements. *Soil and Tillage Research* 64, 137-147.

Birkás, M., Jolankai, M., Gyuricza, C. & Percze, A. 2004. Tillage effects on compaction, earthworms and other soil quality indicators in Hungary. *Soil and Tillage Research* 78, 185-196.

Bishop, A.W. 1959. The principle of effective stress. *Teknisk Ukeblad* 106(39), 859-863.

Blunden, B.G., McBride, R.A., Daniel, H. & Blackwell, P.S. 1994. Compaction of an earthy sand by rubber tracked and tyred vehicles. *Australian Journal of Soil Research* 32, 1095-1108.

Bölenius, E. 2002. *Packning av jordbruksmark – inverkan av dubbelmontage, banddrift och dragkraftsuttag*. Report 41, Division of Soil Management, Department of Soil Sciences, Swedish University of Agricultural Sciences, 33 pp.

Bolling, I. 1987. *Bodenverdichtung und Triebverhalten bei Reifen – neue Mess- und Rechentechniken.* Forschungsarbeit Agrartechnik des Arbeitskreises Forschung und Lehre der Max-Eyth-Gesellschaft. Doctoral thesis, University of Munich, Germany, cited by Gysi *et al.* (2000).

Bölling, W.H. 1971. *Zusammendrueckung und Scherfestigkeit von Böden*. Springer-Verlag, Wien New York, 103 pp.

Boussinesq, J. 1885. *Application des Potentiels à l'étude de l'équilibre et du Mouvement des Solides Élastiques*. Gauthier-Villars, Paris, 30 pp.

Britto, A.M. & Gunn, M.J. 1987. *Critical State Soil Mechanics via Finite Elements*. Ellis Horwood, Chichester, 488 pp.

Brown, H.J., Cruse, R.M., Erbach, D.C. & Melvin S.W., 1992. Tractive device effects on soil physical properties. Soil and Tillage Research 22, 41-53.

Burt, E.C., Wood, R.K. & Bailey, A.C. 1992. Some comparison of average to peak soil-tire contact pressures. Transactions of the American Society of Agricultural Engineers 35, 401-404.

Casagrande, A. 1936. The determination of pre-consolidation load and its practical significance. Proceedings of the International Conference of Soil Mechanics and Foundation Engineering, 22-26 June. Harvard University. Cambrigde. USA. Vol. 3, 60-64.

Cerruti, V. 1888. Sulla deformazione di un corpo elastico isotropo per alcune speciali condizioni ai limiti. Mathematica Acc. r. de'Lincei, Rom.

COM (Commission of the European Communities). 2002. Communication from the Commission to the Council, the European Parliament, the Economic and Social Committee and the Committee of the Regions – Towards a Thematic Strategy for Soil Protection. Brussels, 35 pp.

Cully, J.L.B. & Larson, W.E. 1987. Susceptibility to compression of a clay loam Haplaquoll. Soil Science Society of America Journal 51, 562-567.

Dawidowski, J.B. & Koolen, A.J. 1994. Computerized determination of the precompression stress in compaction testing of field core samples. Soil and Tillage Research 31, 277-282.

Dawidowski, J.B., Morrison, J.E. & Snieg, M. 2001. Measurement of soil layer strength with plate sinkage and uniaxial confined methods. Transactions of the American Society of Agricultural Engineers 44, 1059-1064.

Dawidowski, J.B., Worona, M. & Hencel, A. 1988. The determination of plow draught from soil penetration resistance. In: *Proceedings of the 11th International Conference of ISTRO on Tillage and Traffic in Crop Production*, Edinburgh, Scotland, Vol. 2, 457-462.

de Toro, A. & Arvidsson, J., 2003. Influence of spring preparation date and soil water content on seedbed physical conditions of a clayey soil in Sweden. *Soil and Tillage Research* 70, 141-151.

Défossez, P. & Richard, G. 2002. Models of soil compaction due to traffic and their evaluation. *Soil and Tillage Research* 67, 41-64.

Desbiolles, J.M.A., Godwin, R.J., Kilgour, J. & Blackmore, B.S., 1997. A novel approach to the prediction of tillage tool draught using a standard tine. *Journal of Agricultural Engineering* 66, 295-309.

Desbiolles, J.M.A., Godwin, R.J., Kilgour, J. & Blackmore, B.S. 1999. Prediction of tillage implement draught using cone penetrometer data. *Journal of Agricultural Engineering* 73, 65-76.
Dexter, A.R. 1979. Prediction of soil structures produced by tillage. *Journal of Terramechanics* 16, 117-127.
Dexter, A.R. 1988. Advances in characterization of soil structure. *Soil and Tillage Research* 11, 199-238.
Dexter, A.R. 2002. Soil mechanical notes. Course in agricultural soil mechanics, *Swedish University of Soil Sciences,* Uppsala, Sweden.
Dexter, A.R. 2004a. Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. *Geoderma* 120, 201-214.
Dexter, A.R. 2004b. Soil physical quality: Part II. Friability, tillage, tilth and hard-setting. *Geoderma* 120, 215-225.
Dexter, A.R. 2004c. Soil physical quality: Part III. Unsaturated hydraulic conductivity and general conclusions about S-theory. *Geoderma* 120, 227-239.
Dexter, A.R. & Bird, N.R.A. 2001. Methods for predicting the optimum and the range of water contents for tillage based on the water retention curve. *Soil and Tillage Research* 57, 203-212.
Dexter, A.R. & Birkás, M. 2004. Prediction of the soil structures produced by tillage. *Soil and Tillage Research*, in press.
Dexter, A.R., Horn, R. & Kemper, W.D. 1988. Two mechanisms for age-hardening of soil. *Journal of Soil Science* 39, 163-175.
Dexter, A.R. & Kroesbergen, B. 1985. Methodology for determination of tensile strength of soil aggregates. *Journal of Agricultural Engineering* 31, 139-147.
Dexter, A.R. & Tanner, D.W. 1973. The response of unsaturated soils to isotropic stress. *Journal of Soil Science* 24, 491-502.
Dexter, A.R. & Tanner, D.W. 1974. Time dependence of compressibility for remoulded and undisturbed soils. *Journal of Soil Science* 25, 153-164.
Dias Junior, M.S. & Pierce F.J. 1995. A simple procedure for estimating preconsolidation pressure from soil compression curves. *Soil Technology* 8, 139-151.
Diserens, E. & Steinmann, G. 2002. Calculation of pressure distribution in moist arable soils in Eastern Switzerland: a simple model approach for the practice. In: Vuillet, L., Laloui, L., Schrefler, B. (Eds.), *Environmental Geomechanics,* EPFL Lausanne, Switzerland, pp. 413-421.
Earl, R. 1997. Assessment of the behaviour of field soils during compaction. *Journal of Agricultural Engineering* 68, 147-157.
Etana, A. & Håkansson, I. 1994. Swedish experiments on the persistence of subsoil compaction caused by vehicles with high axle load. *Soil and Tillage Research* 29, 167-172
Fröhlich, O.K. 1934. *Druckverteilung im Baugrunde.* Springer Verlag, Wien, 178 pp.
Gieska, M., van der Ploeg, R.R., Schweigert, P., Pinter, N., 2003. Physikalische Bodendegradierung in der Hildesheimer Börde und das Bundes-Bodenschutzgesetz. *Berichte über Landwirtschaft* 81, 485-511.
Gill, W.R. & Vandenberg, G.E. 1968. *Soil Dynamics in Tillage and Traction.* U.S.A. Department of Agriculture, Handbook 316, USA, Washington D.C., cited by Makanga *et al.* (1996).
Gliemeroth, G. 1953. Untersuchungen über Verfestigungs- und Verlagerungsvorgänge im Ackerboden under Rad- und Raupenfahrzeugen. *Zeitschrift für Acker- und Pflanzenbau* 96, 219-234.
Godwin, R.J. 2003. A review of the effect of tillage implement geometry on soil failure and implement forces. In: *Proceedings of the 16th International Conference of ISTRO on Soil Management for Sustainability*, 14-18 July 2003, Brisbane, Australia, pp. 471-483.
Godwin, R.J., Seig, D.A. & Allott, M. 1985. The development and evaluation of a force prediction model for agricultural discs. In: *Proceedings of the International Conference on Soil Dynamics,* Auburn, AL, USA, pp. 250-265.
Godwin, R.J., Seig, D.A. & Allott, M. 1987. Soil failure and force prediction for soil engaging discs. *Soil Use and Management* 3, 106-114.

Godwin, R.J. & Spoor, G. 1977. Soil failure with narrow tines. *Journal of Agricultural Engineering* 22, 213-228.

Godwin, R.J., Spoor, G. & Soomro, M.S. 1984. The effect of tine arrangement on soil forces and disturbance. *Journal of Agricultural Engineering* 30, 47-56.

Gupta, S.C. & Larson, W.E. 1982. Chapter 10 - Predicting soil mechanical behaviour during tillage. In: *Predicting Tillage Effects on Soil Physical Properties and Processes*. American Society of Agronomy, Special Publications 44, pp. 151-178.

Gustafsson, K., Arvidsson, J. & Keller, T. 2003. *Dragkraftsbehov för plog, kultivator och tallriksredskap vid olika vattenhalter.* Rapport 106, avdelningen för jordbearbetning SLU, Uppsala, 41 pp.

Gysi, M., Klubertanz, G. & Vulliet, L. 2000. Compaction of an Eutric Cambisol under heavy wheel traffic in Switzerland – field data and modelling. *Soil and Tillage Research* 56, 117-129.

Gysi, M., Maeder, V. & Weisskopf, P. 2001. Pressure distribution underneath tires of agricultural vehicles. *Transactions of the American Society of Agricultural Engineers* 44, 1385-1389.

Gysi, M., Ott, A. & Flühler, H. 1999. Influence of single passes with high wheel load on a structured, unploughed sandy loam soil. *Soil and Tillage Research* 52, 141-151.

Hadas, A. & Wolf, D. 1983. Energy efficiency in tilling dry clod-forming soils. *Soil and Tillage Research* 3, 47-59.

Håkansson, I. & Reeder, R.C. 1994. Subsoil compaction by vehicles with high axle load – extent, persistence and crop response. *Soil and Tillage Research* 29, 277-304.

Hammel, K. 1994. Soil stress distribution under lugged tires. *Soil and Tillage Research* 32, 163-181.

Hartge, K.H. & Sommer, C. 1980. The effect of geometric patterns of soil structure on compressibility. *Soil Science* 130, 180-185.

Hettiaratchi, D.R.P. 1988. Theoretical soil mechanics and implement design. *Soil and Tillage Research* 11, 325-347.

Hettiaratchi, D.R.P. 1997. Prediction of soil forces acting on concave agricultural discs. *Journal of Agricultural Engineering* 68, 51-62.

Horn, R. 1990a. Aggregate characterization as compared to soil bulk properties. *Soil and Tillage Research* 17, 265-289.

Horn, R. 1990b. Structure effects on strength and stress distribution in arable soils. In: *Proceedings of the International Summer Meeting of the American Society of Agricultural Engineers,* June 24-27, 1990, Columbus, Ohio, pp. 8-20.

Horn, R. 1993. Mechanical properties of structured unsaturated soils. *Soil Technology* 6, 47-75.

Horn, R. 2003. Stress-strain effects in structured unsaturated soils on coupled mechanical and hydraulic processes. *Geoderma* 166, 77-88.

Horn, R., Blackwell, P.S. & White, R. 1989. The effect of speed of wheeling on soil stresses, rut depth and soil physical properties in an ameliorated transitional red-brown earth. *Soil and Tillage Research* 13, 353-364.

Horn, R. & Dexter, A.R. 1989. Dynamics of soil aggregation in an irrigated desert loess. *Soil and Tillage Research* 13, 253-266.

Horn, R., Domzal, H., Slowinska-Jurkiewicz, A. & van Ouwerkerk, C. 1995. Soil compaction process and their effects on the structure of arable soils and the environment. *Soil and Tillage Research* 35, 23-36.

Horn, R. & Lebert, M. 1994. Soil compactibility and compressibility. In: Soane, B.D., van Ouwerkerk, C. (Eds.), *Soil Compaction in Crop Production.* Elsevier, Amsterdam, pp. 45-69.

Horn, R., Way, T. & Rostek, J. 2003. Effect of repeated tractor wheeling on stress/strain properties and consequences on physical properties in structured arable soils. *Soil and Tillage Research* 73, 101-106.

Janson, P.-E. & Karlberg, L. 2001. *Coupled Heat and Mass Transfer Model for Soil-Plant-Atmosphere Systems.* Royal Institute of Technology, Department of Civil and Environmental Engineering, Stockholm, 321 pp.

Johnson, C.E. & Burt, E.C. 1990. A method of predicting soil stress state under tires. *Transactions of the American Society of Agricultural Engineers* 33, 713-717.

Keller, T. & Arvidsson, J. 2003. Some remarks on the use of the soil precompression stress as a limit for applied stress to reduce soil compaction. In: *Abstracts from the International Workshop on Soil Physical Quality,* 2-4 October 2003, Pulawy, Poland, pp. 83-86.

Keller, T., Grimm, M. & Arvidsson, J. 2004. Effekt av körhastighet på tryck och deformation i marken. In: Arvidsson, J. (Ed.), *Jordbearbetningsavdelningens årsrapport* 2003. Report 107, Division of Soil Management, Department of Soil Sciences, Swedish University of Agricultural Sciences, Uppsala, Sweden, pp. 58-60.

Kheiralla, A.F., Yahaya, A., Zohadie, M. & Ishak, W. 2004. Modelling of power and energy requirements for tillage implements operating in Serdang sandy clay loam, Malaysia. *Soil and Tillage Research* 78, 21-34.

Kirby, J.M. 1989. Measurements of the yield surfaces and critical state of some unsaturated agricultural soils. *Journal of Soil Science* 40, 167-182

Kirby, J.M. 1991. Strength and deformation of agricultural soil: measurement and practical significance. *Soil Use and Management* 7, 223-229.

Kirby, J.M. 1999a. Soil stress measurement: Part 1. Transducer beneath a circular loaded area. *Journal of Agricultural Engineering* 72, 151-160.

Kirby, J.M. 1999b. Soil stress measurement: Part 2. Transducer in a uniform stress field. *Journal of Agricultural Engineering* 72, 141-149.

Kirby, J.M., Blunden, B.G. & Trein, C.R. 1997. Simulating soil deformation using a critical-state model: II. Soil compaction beneath tyres and tracks. *European Journal of Soil Science* 48, 59-70.

Koolen, A.J. 1974. A method for soil compactibility determination. *Journal of Agricultural Engineering* 19, 271-278.

Koolen, A.J. & Kuipers H. 1983. *Agricultural Soil Mechanics:* Advanced Series in Agricultural Sciences, Vol. 13. Springer, Heidelberg, 241 pp.

Kühner, S. 1997. *Simultane Messung von Spannungen und Bodenbewegungen bei statischen und dynamischen Belastungen zur Abschätzung der dadurch induzierten Bodenbeanspruchung*. Schriftenreihe, Institut für Pflanzenernährung und Bodenkunde, Universität Kiel, no. 39, 231 pp, cited by Wiermann *et al.* (1999).

Kulli, B., Gysi, M. & Flühler, H. 2003. Visualizing soil compaction based on flow pattern analysis. *Soil and Tillage Research* 70, 29-40.

Lang, H.-J., Huder, J. & Amann, P. 1996. *Bodenmechanik und Grundbau. Das Verhalten von Böden und Fels und die wichtigsten grundbaulichen Konzepte*. Springer-Verlag Berlin, Germany, 320 pp.

Lebert, M., Burger, N. & Horn, R. 1989. Effects of dynamic and static loading on compaction of structured soils. In: Larson, W.E., Blake, G.R., Allmaras, R.R., Voorhees, W.B., Gupta, S. (Eds.), *Mechanics and Related Processes in Structured Agricultural Soils.* NATO ASI Series E, Applied Science 172. Kluwer Academic Publishers, Dordrecht, pp. 73-80.

Leussink, H. 1954. Das seitliche Nichtanliegen der Bodenprobe im Kompressions-Apparat als Fehlerquelle beim Druck-Setzungs-Versuch. In: *Fortschritte und Forschungen im Bauwesen. Grundbau* – Vorschriften und Versuche, Heft 17, Franckh'sche Verlagshandlung, Stuttgart, Germany, pp. 153-160.

Lipiec, J. & Stepniewski, W. 1995. Effects of soil compaction and tillage systems on uptake and losses of nutrients. *Soil and Tillage Research* 35, 37-52.

Marsili, A., Servadio, P., Pagliai, M. & Vignozzi, N. 1998. Changes of some physical properties of a clay soil following passage of rubber- and metal-tracked tractors. *Soil and Tillage Research* 49, 185-199.

Mosaddeghi, M.R., Hemmat, A., Hajabbasi, M.A. & Alexandrou, A. 2003. Pre-compression stress and its relation with the physical and mechanical properties of a structurally unstable soil in central Iran. *Soil and Tillage Research* 70, 53-64.

Mouazen, A.M. & Ramon, H. 2002. A numerical-statistical hybrid modelling scheme for evaluation of draught requirements of a subsoiler cutting a sandy loam soil, as affected by moisture content, bulk density and depth. *Soil and Tillage Research* 63, 155-165.

Muhs, H. & Kany, M. 1954. *Einfluss von Fehlerquellen bei Kompressionsversuchen. In: Fortschritte und Forschungen im Bauwesen.* Grundbau – Vorschriften und Versuche, Heft 17, Franckh'sche Verlagshandlung, Stuttgart, Germany, pp 125-152.

Müller, L., Schindler, U., Fausey, N.R. & Lal, R. 2003. Comparison of methods for estimating maximum soil water content for optimum workability. *Soil and Tillage Research* 72, 9-20.

Myrbeck, Å., Arvidsson, J. & Keller, T. 2003. *Plöjningstidpunktens inverkan på markstruktur, växtproduktion och kväveutlakning på lerjord.* Slutrapport från försök 1999-2002. Rapport 105, avdelningen för jordbearbetning SLU, Uppsala, 44 pp.

O'Dogherty, M.J., Godwin, R.J., Hann, M.J. & Al-Ghazal, A.A. 1996. A geometrical analysis of inclined and tilted spherical plough discs. *Journal of Agricultural Engineering* 63, 205-218.

O'Sullivan, M.F., Henshall, J.K. & Dickson, J.W. 1999. A simplified method for estimating soil compaction. Soil and Tillage Research 49, 325-335.

O'Sullivan, M.F. & Robertson, E.A.G. 1996. Critical state soil parameters from intact samples of two agricultural topsoils. *Soil and Tillage Research* 39, 161-173.

Ojeniyi, S.O. & Dexter, A.R. 1979. Soil factors affecting the macrostructures produced by tillage. *Transactions of the American Society of Agricultural Engineers* 22, 339-343.

Okello, J.A., Dwyer, M.J. & Cottrell, F.B. 1994. The tractive performance of rubber tracks and a tractor driving wheel tyre as influenced by design parameters. *Journal of Agricultural Engineering* 59, 33-43.

Olson, D.J. & Weber, J.A. 1966. Effect of speed on soil failure patterns in front of model tillage tools. *Transactions of the Society of Automotive Engineering.* 74, 298-310.

Onwualu, A.P. & Watts, K.C. 1998. Draught and vertical forces obtained from dynamic soil cutting by plane tillage tools. *Soil and Tillage Research* 48, 239-253.

Pagliai, M., Marsili, A., Servadio, P., Vignozzi, N. & Pellegrini, S. 2003. Changes in some physical properties of a clay soil in Central Italy following the passage of rubber tracked and wheeled tractors of medium power. *Soil and Tillage Research* 73, 119-129.

Pagliai, M., Vignozzi, N. & Pellegrini, S. 2004. Soil structure and the effect of management practices. *Soil and Tillage Research* (in press).

Payne, P.C.J. 1956. The relationship between the mechanical properties of soil and the performance of simple cultivation implements. *Journal of Agricultural Engineering* 1, 23-50.

Payne, P.C.J. & Tanner, D.W. 1959. The relationship between rake angle and the performance of simple cultivation implements. *Journal of Agricultural Engineering* 4, 312-325.

Pettersson, O., Norén, O., Hansson, P.A. & Lindgren, M. 2002. A system for onboard determination of engine power by measuring fuel consumption at 1 Hz. *International Conference of the European Society of Agricultural Engineers,* 30 June-4 July 2002, Budapest, Hungary, paper No. 02-PM-024.

Poodt, M.P., Koolen, A.J. & van der Linden, J.P. 2003. FEM analysis of subsoil reaction on heavy wheel loads with emphasis on soil preconsolidation stress and cohesion. *Soil and Tillage Research* 73, 67-76.

Pytka, J. & Dabrowski, J. 2001. Determination of the stress-strain relationship for sandy soil in field experiments. *Journal of Terramechanics* 38, 185-200.

Richard, G., Cousin, I., Sillon, J.F., Bruand, A. & Guérif, J. 2001. Effect of compaction on the porosity of a silty soil: influence on unsaturated hydraulic properties. *European Journal of Soil Science* 52, 49-58.

Ristolainen, A., Ahokas, J. & Alakukku, L. 2003. Using acceleration sensors to measure soil displacement. In: *Proceedings of the 16th International Conference of ISTRO,* Brisbane, Australia, pp. 1003-1008.

Schmidbauer, J. 1954. Fehlerquellen und deren Ausschaltung beim Druck-Setzungsversuch (Kompressionsversuch). In: *Fortschritte und Forschungen im Bauwesen*. Grundbau – Vorschriften und Versuche, Heft 17, Franckh'sche Verlagshandlung, Stuttgart, Germany, pp. 162-174.

Schofield, A.N. & Wroth, C.P. 1968. *Critical State Soil Mechanics*. McGraw-Hill, London.

Serrano, J.M., Peca, J.O., Pinheiro, A., Carvalho, M., Nunes, M., Ribeiro, L. & Santos, F. 2003. The effect of gang angle of offset disc harrows on soil tilth, work rate and fuel consumption. *Biosystems Engineering* 84, 171-176.

Shrestha, D.S., Singh, G. & Gebresenbet, G. 2001. Optimizing design parameters of a mouldboard plough. *Journal of Agricultural Engineering* 78, 377-389.

Smith, R., Ellies, A. & Horn, R. 2000. Modified Boussinesq's equations for nonuniform tire loading. *Journal of Terramechanics* 37, 207-222.

Soane, BD. & van Ouwerkerk, C. 1995. Implications of soil compaction in crop production for the quality of the environment. *Soil and Tillage Research* 35, 5-22.

Söhne, W. 1953. Druckverteilung im Boden und Bodenverformung unter Schlepperreifen. *Grundlagen der Landtechnik* 5, 49-63.

Spoor, G. & Godwin, R.J. 1978. An experimental investigation into the deep loosening of soil by rigid tines. *Journal of Agricultural Engineering* 23, 243-258.

Stafford, J.V. & De Carvalho Mattos, P. 1981. The effect of forward speed on wheel-induced soil compaction: laboratory simulation and field experiments. *Journal of Agricultural Engineering* 26, 333-347.

Terzaghi, K. 1936. The shearing resistance of saturated soils. *1st International Conference on Soil Mechanics and Foundation Engineering,* Harvard University, Cambridge, Massachusetts, pp. 54-56.

Trautner, A. 2003. *On Soil Behaviour During Field Traffic*. Doctoral Thesis. Agraria 372, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Tschebotarioff, G.P. 1951. *Soil Mechanics, Foundation and Earth Structures*. McGraw-Hill, New York, cited by Koolen & Kuipers (1983).

Tullberg, J.N. 2000. Wheel traffic effects on tillage draught. *Journal of Agricultural Engineering* 75, 375-382.

Utomo, W.H. & Dexter, A.R. 1981. Soil friability. *Journal of Soil Science* 32, 203-213.

van den Akker, J.J.H. 1986. SOCOMO: Een model voor de berekening van de spanningsverdeling en de daaruit volgende verdichting van de grond onder wielen. Deel 1: De spanningsverdeling in de grond. *ICW nota 1729, Instituut voor cultuurtechniek en waterhuishounding*, Wageningen, The Netherlands, pp. 22.

van den Akker, J.J.H. 1992. Stresses and required soil strength under terra tyres and tandem and dual wheel configurations. In: *Proceedings of the International Conference on Soil Compaction and Soil Management,* 8-12 June, Tallinn, Estonia. Estonian Research Institute of Agriculture and Land Improvement, Saku, Estonia, pp. 23-26.

van den Akker, J.J.H. 2004. SOCOMO: a soil compaction model to calculate soil stresses and the subsoil carrying capacity. *Soil and Tillage Research* 79, 113-127.

van den Akker, J.J.H. & Carsjens, G.J. 1989. Reliability of pressure cells to measure traffic-induced stress in the topsoil-subsoil interface. In: *Proc. 4th European Conf. ISTVS*, 21-23 March 1989, Wageningen, Vol. 1, 1-7.

Watts, C.W. & Dexter, A.R. 1998. Soil friability: theory, measurement and the effects of management practices and organic carbon content. *European Journal of Soil Science* 73-84.

Way, T.R., Bailey, A.C., Raper, R.L. & Burt, E.C. 1995. Tire lug height effect on soil stresses and bulk density. *Transactions of the American Society of Agricultural Engineers* 38, 669-674.

Way, T.R., Erbach, D.C., Bailey, A.C., Burt, E.C. & Johnson, C.E. 2005. Soil displacement beneath an agricultural tractor drive tire. *Journal of Terramechanics* 42, 35-46.

Way, T.R. & Kishimoto, T. 2003. Interface pressures of a tractor drive tyre on structured and loose soils. *Biosystems Engineering* 87, 109-120.

Wheeler, P.N. & Godwin, R.J. 1996. Soil dynamics of single and multiple tines at speeds up to 20 km/h. *Journal of Agricultural Engineering* 63, 243-250.

Wiermann, C., Way, T.R., Horn, R., Bailey, A.C. & Burt, E.C. 1999. Effect of various dynamic loads on stress and strain behaviour of a Norfolk sandy loam. *Soil and Tillage Research* 50, 127-135.

Acknowledgements

Many people have contributed in one or another way to this work. In particular, I would like to express my gratitude to:

Johan Arvidsson, for accepting me as a new member of the 'Compaction-Mafia' a few years ago, for letting me dig holes in Swedish soils, for highly supporting me in establishing and maintaining international contacts and for many more things; in brief: for being an excellent supervisor;

Tomas Rydberg, for being a wonderful boss;

Tony Dexter, for teaching me a lot about soil (*S*tructure), for useful discussions and valuable comments on manuscripts, and for showing me all the restaurants that serve lamb in the vicinity of Pulawy; Ewa Czyz, for delicious buns and for many more things during my visits to Pulawy;

Guy Richard, for letting me work in his group in Laon for some weeks, for many helpful discussions and for beautiful jogging tours in the Fôret de Saint-Gobain; Pauline Défossez, for valuable discussions on soil mechanics and soil compaction modelling; Hubert Boizard, for showing me Δ-zones in France, Australia and Sweden, and for interesting discussions on French (and Australian) wine;

The staff of the Division of Soil Management for great help and for a very pleasant working atmosphere. Special thanks to Elisabeth, for lovely discussions on models; Urban, for kindly providing Fig. 29 and for reminding me in every situation that things could be worse; Andreas, for long discussions on soil over many beers during the many field trips; Ararso, for being such a happy person; Åsa, for being so considerate; Mulle, for accepting my Swedish from the very first day; Bibbi, for help with administrative things;

Christina Öhman and Einar Larsson, for enormous help with the laboratory work;

Mary McAfee for improving the English of the manuscripts;

Ragnar Persson for solving computer problems;

Inge Håkansson, for sharing the office with me, for valuable discussions and valuable comments on manuscripts;

Peter Weisskopf, for many valuable discussions and for keeping me up-to-date with Swiss soil compaction research;

Jos Koolen, for helping me to conduct some of my experiments in his lab in Wageningen;

Bronek Dawidowski for helpful discussions on the precompression stress; Jacek and his colleague, for excellent cooperation during field work in a rainy, cold and dark Swedish autumn;

Olof Andrén, Martin Larsson and Ingvar Nilsson, for improving the manuscript of this thesis;

Rupert Gorm Reventlow-Grinling, Sören Jespersen, Hugo Jørgensen, Kurt Rasmussen (Krenkerup Estate, Denmark), M. Worre-Jensen and René Borggreen (Vallø Estate, Denmark), Stefan Karlsson and his family (Staby Säteri, Örsundsbro; now at Björksund, Nyköping kommun), Ove Sjöberg and Mats Persson (experiments in Strängnäs), Sten Segerslätt (Billeberga), Roland Johnson (Kungagården, Varberg) and Axel Lagerfeld (Tolefors), for interest and support during the field experiments;

All my friends out there. Special thanks to Manfred, for teaching me some basic Swedish and for bringing me into contact with SLU a few years ago; Dani, Jürg and Roland, for new challenges every winter and for nice trips to *Vasaloppet* and *Birkebeinerrennet* and Maria, for never giving up believing that I'm going strong; Martin, for supplying *Chrüter* and *Williams*; Florian, for a multitude of e-mails on the really important aspects of life; Annica and Tommy, for memorable crayfish parties; all the football players at SLU, for fair games; Teet, Taavo and Mart, for accepting a Swiss into the Estonian community of Uppsala; special thanks to Teet, for innumerable pool and snooker games, and for letting me win sometimes;

My parents, my brother, and my sister and her family for support;

Villem, for being a good boy and for introducing me into the world of computer games and PS2 ;-));

Annika, for love.

Financial support was received from the Swedish Farmers Foundation for Agricultural Research (SLF), the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas) and the Royal Swedish Academy of Agriculture and Forestry (KSLA), which is gratefully acknowledged.