On Soil Behaviour during Field Traffic

Andreas Trautner
Department of Soil Sciences
Uppsala

Doctoral thesis
Swedish University of Agricultural Sciences
Uppsala 2003

Acta Universitatis Agriculturae Sueciae
Agraria 372

ISSN 1401-6249
ISBN 91-576-6404-8

Tryck: SLU Service/Repro, Uppsala 2003

Abstract

This thesis summarizes and discusses results of subsoil stress, strain and strength measurements during field traffic with several load intensities on five sites in Sweden during the growing season. Vertical subsoil stress and displacement were measured by installing sensors horizontally 1 m into the soil at 0.3, 0.5 and 0.7 m depth through holes drilled from a pit whereby the soil flanking the sensors was left undisturbed. The soil precompression stress was determined on each occasion by sequential loading of soil samples in the laboratory.

The topsoil properties had a large impact on the vertical subsoil stress, and the concentration of stress below a loaded surface appears to be affected by topsoil characteristics quite different than normally anticipated. The stress was clearly transmitted more directly and undiminished in relatively dry soil than in relatively wet soil.

The precompression stress as determined by classical, uniaxial compression tests was a poor measure of soil ability to sustain non-recoverable deformation. The study showed that plastic deformation occurred at stress levels far below that predicted by the precompression stress. A linear correlation between elastic (recoverable) and plastic (non-recoverable) soil deformation indicates that soil should be regarded as an assemblage of soil elements with a stochastic distribution of the strength of the contact points. The practical implication of the observed soil behaviour is that the subsoil appears to be vulnerable to plastic (non-recoverable) deformation at lower wheel loads than normally anticipated. Furthermore, it is important that the stress in the contact area is as evenly distributed as possible to avoid unnecessarily high peak stresses. This calls for relatively fast and reliable methods that enable the land-users to optimise the stress distribution below tyres or tracks for specific soil types, water content and field operation. Furthermore, the results suggests an urgent need for engineering developments in vehicles with small load intensities.

Keywords: arable land, field traffic, field measurements, soil stress, subsoil displacement, load transmission, soil strength, models.

Author's address: Andreas Trautner, a@trautner.com

”Was man weisst, das sieth man erst”.

Goethe

Contents

Appendix

Papers I-IV

This thesis is based on measurements of soil strength, stress and displacement during experimental field traffic applied in 1999-2001 on five Swedish soils. Of the first part of the thesis, only results from 1999 have previously been published (Paper I).

The following papers can be found in this thesis and will be referred to in the text by their Roman numerals.

I. Trautner, A and J. Arvidsson. 2002. Special Issue on subsoil compaction. In print. Subsoil compaction caused by machinery traffic on a Swedish Eutric Cambisol at different soil water contents. *Special Issue of Soil & Tillage Research on soil compaction.*

II. Trautner, A., J.J.H van den Akker, H. Fleige, J. Arvidsson, R. Horn. 2002. Special Issue on subsoil compaction. In print . A subsoil compaction database: its development, structure and content. *Special Issue of Soil & Tillage Research on soil compaction.*

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, 39-47*

IV. Arvidsson, J., Trautner, A., van den Akker, J.J.H., & Schjønning, P. 2000. Subsoil compaction caused by heavy sugar beet harvesters in southern Sweden. II. Soil displacement during wheeling and model computations of compaction. *Soil & Tillage Research 60*, 79-89.

Introduction

The soil below vehicles presently used in agriculture may be subjected to load intensities that are not even allowed on paved public roads. Wheel loads as high as 15 Mg have been reported (Håkansson & Reeder, 1994). Field traffic may reduce the amount of air-filled pores and cavities in the soil thus affecting a large range of physical soil properties and processes, such as infiltration, soil water flow and water retention (Horton *et al*., 1994). Furthermore, compaction of the soil may increase the mechanical strength of the soil and thereby impede root growth. Arvidsson *et al.* (Paper IV) found that wheel loads of 8-10 Mg caused vertical residual (permanent) deformation on both a clay soil and a sandy soil to at least 0.7 m depth. At depths > 0.4 m, soil compaction may persist for decades or even permanently, so soil compaction is a serious threat to the long-term productivity of arable soils (Håkansson & Reeder, 1994).

Kulli *et al.* (2000) found that topsoil compaction reduced the infiltration and caused water to pond on the soil surface. Hence, the water may redistribute horizontally to open pores or cracks, and via preferential flow bypass a large part of the soil matrix. Hence, agrochemicals may be transported rapidly from the biologically active zone to the groundwater. A practical implication of a reduction in the infiltration rate of a given field is that the number of days with adequate workability may decline, especially in soils with potentially low hydraulic conductivity. Whereas ploughing may loosen the plough layer, i.e. the topsoil, amelioration of the subsoil structure is more difficult and costly. Furthermore, subsequent field traffic may re-compact the subsoil extensively (Soane *et al*., 1986).

Consequently, there is a need to understand better how to minimize subsoil compaction during field traffic, a task that has been addressed using many different approaches.

Boussinesq (1885) suggested a mathematically exact solution for calculating the stress propagation in elastic material. Measurements showed that the theory of elasticity did not predict stresses in soil satisfactorily, so Fröhlich (1934) introduced a "concentration factor" to Boussinesq's equations to allow for conditions of non-elastic behaviour. The concentration factor is based on the assumption that the stress is more concentrated around the load axis (higher concentration factor) and propagates deeper the wetter the soil. Söhne's (1958) illustration of stress distributions calculated with this method is often cited in scientific papers and textbooks. However, the basic assumptions for the theory of elasticity, i.e. a homogeneous, linear elastic, semi-infinite, isotropic, weightless space below a static load are never fulfilled in natural soils during field traffic (Gupta & Raper, 1994; Ullidtz, 1998).

Traditional mathematical relationships developed for uses in geotechnical engineering are based on equilibrium state stress-strain, while wheel traffic induces a very different stress regime that typically operates for only a fraction of a second.

Considering the rheological properties of structured topsoils, Or & Ghezzehei (2002) showed that soil deformation and compaction strongly depends on the duration of the load and soil water content. However, measurements of the behaviour of undisturbed subsoil during field traffic are very scarce, so there is a strong need for further studies in order to create a reliable tool for prediction of subsoil compaction. Ullidtz (1998) stated that "the only way to evaluate the existing models is by measuring the stresses, strains and displacements… and compare the measured values to those predicted by the theory".

On dynamic soil behaviour and soil strength during loading – theory and reality

Behaviour of an elastic continuum during loading

Several approaches to calculate the soil bearing capacity and soil stresses induced by external loading have been suggested in the literature. Many models of dynamic soil behaviour use elastic properties of soil, and when the soil is represented by a linearly elastic, homogenous, isotropic, weightless material, the elastic properties required to fully account for the behaviour of the material are Young's modulus (E), shear modulus (G), and Poisson's ratio (ν). According to the theory, any soil element in the medium is subjected to vertical (σ_z), horizontal (σ_h) and tangential (σ_t) normal stresses and vertical (τ_z) and horizontal (τ_h) shear stresses (fig 1). Young's modulus (E) is the ratio of vertical stress (σ_z) to vertical strain ($\varepsilon_z = dz/l_z$) and is a constant of a linearly elastic medium. This proportionality between stress and deformation, $\sigma = E\varepsilon$, is known as Hooke´s law, formulated by Hooke in 1678 as "Ut tensio sic vis". The positive value of the ratio between the horizontal strain and the vertical strain is known as Poisson's ratio. The shear modulus, G, is the ratio of a shear stress to the double shear strain resulting from the former.

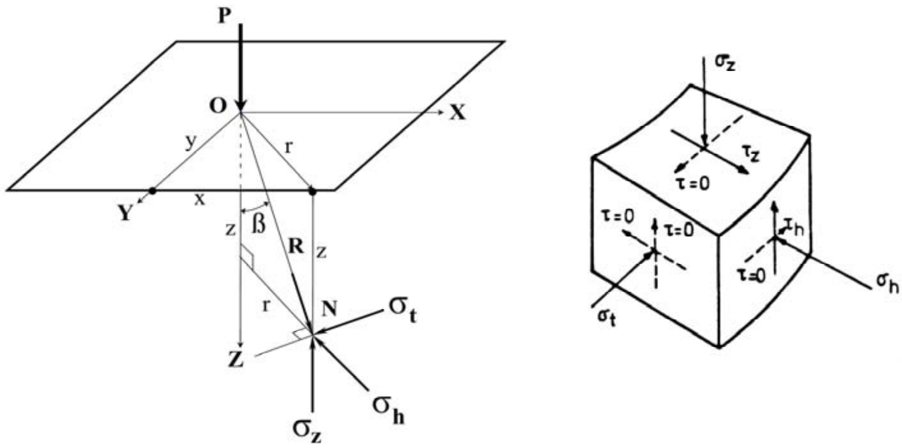


Fig.1. Load and stresses in a cylindrical coordinate system.

Boussinesq's equation for calculating the vertical stress

Several models are based on the equations of Boussinesq (1885, cited by Frölich, 1934), who described the distribution of stresses in an elastic, homogenous, isotropic, weightless, semi-infinite solid medium due to a force applied to a point in that medium.

Boussinesq's vertical stress component (σ_z) on point N (Fig. 1) is given by:

$$\sigma_z = \frac{3P}{2\pi}\frac{z^3}{R^5} = \frac{3P}{2\pi R^2}\cos^3\beta \qquad (1)$$

where P is the vertical point load, z is the depth below the surface, and R and β are polar coordinates. Since $R^2 = r^2 + z^2$ (where x, y and z are coordinates of point N since $r^2 = x^2 + y^2$) (fig 1), the stress at the centre line of the load can be expressed as:

$$\sigma_z = \frac{3P}{2\pi z^2} \qquad (2)$$

The normal vertical stress component, $\sigma_{z,}$ on point N can be expressed as:

$$\sigma_z = \frac{3P}{2\pi z^2}\frac{1}{\left[1+(r/z)^2\right]^{5/2}} \qquad (3)$$

The Boussinesq vertical stress coefficient (K) is given by:

$$K = \frac{3}{2\pi}\frac{1}{\left[1+(r/z)^2\right]^{5/2}} = \frac{0.478}{\left[1+(r/z)^2\right]^{5/2}} \qquad (4)$$

whereby Eq. (2) can be written as:

$$\sigma_z = K(P/z^2) \qquad (5)$$

The K-values can be presented graphically for different values of z and r since (K=f(r/z)), whereby Eq. 5 may be used to calculate the vertical, normal stress caused by a point load P at any point N in the medium restricted by the assumptions (Jumikis, 1967).

Frölich (1934) introduced the concentration factor (ν) into the Boussinesq equation for the vertical stress component (Eq. 1) to account for the non-elastic behaviour of soil, because measurements showed that the theory of elasticity did not predict the stress distribution in a satisfactory manner:

$$\sigma_z = \frac{\nu P}{2\pi r^2} \cos^{\nu} \beta \tag{6}$$

where ν = 3 describe the distribution in a perfect elastic isotropic mass according to Boussinesq. The concentration factor does not represent a soil physical property, but is related to the soil type, soil moisture content (Söhne, 1958), precompression stress (Horn, 1991) soil structure, contact area of the applied load and contact stress (Horn & Lebert, 1994). Söhne (1953) assigned ν-values of 4, 5 and 6 for dry (hard), average (relatively dry) and soft (wet) soil, thus assuming that the more plastic the soil, the more the stress will be concentrated around the load axis and propagate to a greater soil depth (Fig.2).

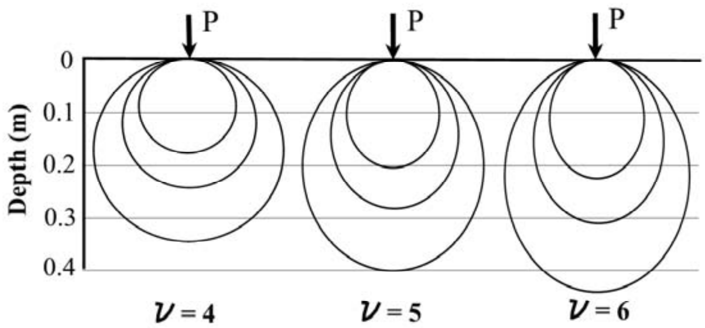


Fig. 2. Calculated principal stress distribution for different concentration factors under a point load (P) (After Söhne, 1958).

Söhne (1958) stated that wet soil would yield at the edge of the contact area whereby the stress would propagate deeper into the soil than when the soil was dry. By implication, Söhne assumed that dry soil would not yield at the edge of the contact area.

The principal stress distribution as shown in Fig. 2 is often referred to and may be found in a number of textbooks as "stress distribution in soil". However, it must be kept in mind that the principal stress distribution is calculated in a medium restricted by the assumptions of Boussinesq's equations, which are never fulfilled in a natural soil.

By using Eq. 6, the total stress on a point below a loaded area has formerly been calculated by dividing the contact area into a number of elements where a point load acts in each centre (Söhne, 1958; van den Akker & Wijk, 1987).

Behaviour of natural soil during loading

In natural soil several types of deformation may be observed (Fig. 3). Viscous-plastic deformation, or flow, has also been reported, but this is probably mostly limited to the upper part of the soil.

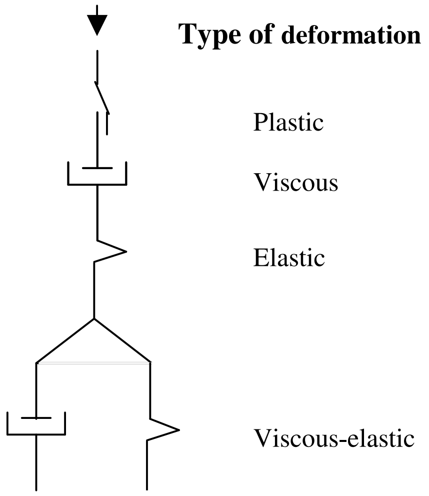


Fig. 3. Types of deformation observed in natural soils (after Ullidtz, 1998).

Fig. 4 shows the three-dimensional path of a soil particle at 0.2 m depth below a two axles vehicle during a single pass (Gliemeroth, 1953).

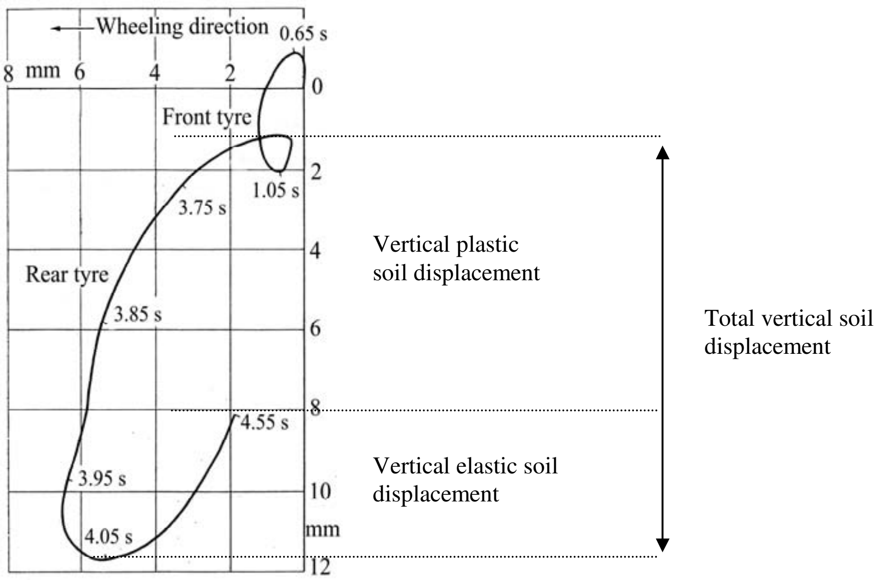


Fig 4. The photographically recorded path of displacement of a soil particle 0.2 m below a tractor (after Gliemeroth, 1953). Plastic and elastic soil displacement caused by the rear tyre is illustrated.

The soil was dynamically loaded for 4.55 seconds, first the front wheel and then the rear wheel, which caused both horizontal and vertical soil displacement. When the vehicle had passed and the soil therefore unloaded, a part of the deformation was recovered.

Soil deformation resistance

Non-recoverable soil deformation results in soil compaction and/or shear. Compaction is defined as an increase in soil bulk density whereby the soil porosity is reduced, whereas soil shearing does not necessarily reduce soil porosity, but may instead destroy the continuity of macro-pores (Horn, 2001). The ability of soil to resist non-recoverable deformation during loading is often defined as the soil strength.

Soil precompression strength

Several methods for determining the soil strength have been proposed. The determination of the precompression stress is based on the stress-strain relationship of soil during compression. By plotting the void ratio, or another soil property related to soil volume reduction, against the logarithm of the applied stress (Fig. 5), the stress range where the soil behaves plastically is often determined graphically as the virgin compression line (I) (Casagrande, 1936). According to the theory, if the soil has been subjected to compaction, reloading of the soil with a smaller stress will result in relatively small and, largely recoverable deformation (Lebert & Horn, 1991). If a stress larger than the previous maximum stress is applied, the soil will be compacted along the virgin compression line. The precompression stress may be determined by the method suggested by Casagrande (1936), as the stress (P_o) corresponding to the intersection (C) of the virgin compression line (I) and the line (c) in Fig. 5.

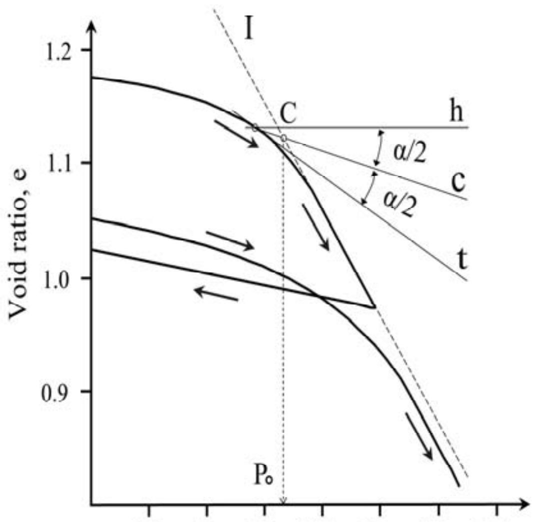


Fig. 5. Determination of the precompression stress of a soil sample (After Casagrande, 1936).

Factors influencing soil strength

Soil strength is a dynamic soil property since it changes when the soil is loaded and deformed (Gill & Vanden Berg, 1967). The strength of the soil is influenced by several factors such as texture, structure, organic matter content and in particular the soil water content/soil water potential (Horn, 1988). Therefore, consistency limits for a given soil based on moisture content may be useful to predict the behaviour of soil during loading at a given soil water content. The Atterberg limits (Fig. 6) express the state of the soil in relation to the soil moisture content. The shrinkage limit may be defined as the moisture content at which the change in soil water content is no longer proportional to the change in volume. The liquid and plastic limit may be determined by standardized laboratory tests. The plastic limit is the minimum moisture content at which the soil can be rolled into a 3 mm diameter thread without breaking and crumbling, whereas the liquid limit is the soil water content at which a groove cut in a soil sample in a standard liquid limit device is closed after 25 taps.

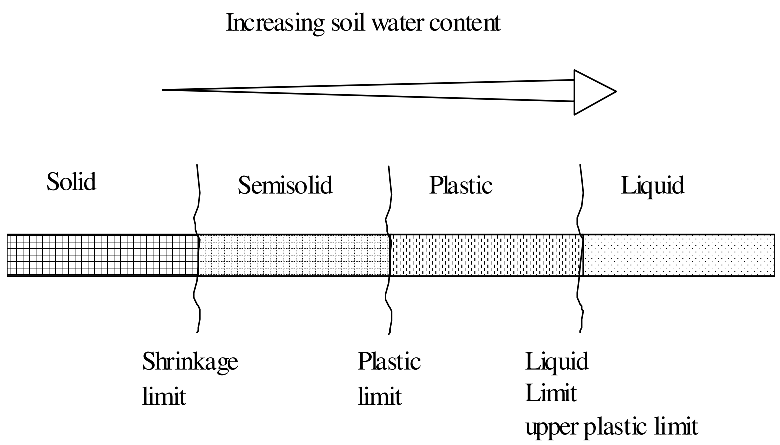


Fig. 6. Atterberg limits of soil (After Young & Warkentin, 1966).

Load application during field traffic

Since the load application during field traffic is dynamic, and the deformation event in natural soil is time dependent, we need information about both the soil deformation characteristics, *e.g.* soil strength, the load application in terms of load intensity (maximum contact area stress), the loading time as well as number of loading events.

The contact area depends on external factors such as the load and the properties of the tyre. Furthermore, the contact area is influenced by the soil strength. The stresses at the tyre-soil interface are often unevenly distributed, so knowledge abut the maximum contact stress is required in order to successfully predict the soil deformation.

When the velocity of the vehicle is increased, the duration of the load is reduced. However, a high velocity is not necessarily desirable from a soil deformation point of view, because this may cause the vehicle to bounce, which in turn may cause high stress peaks (Danfors, 1974).

The number of loading events is important for the deformation of the soil. Usually, most of the total plastic deformation is observed already after the first pass. The additional plastic deformation of the soil caused by each traffic application is gradually reduced due to increasing soil strength.

Objectives

The aim of the present study was to evaluate soil behaviour in the field during traffic by agricultural machinery. For this purpose, simultaneous measurements of stress and soil displacement were carried out on various occasions at five sites in Sweden when applying traffic with wheel loads from 2 to 7 Mg. Furthermore, the usefulness of the soil precompression stress as a measure of soil resistance of non-recoverable deformation was studied. The intention was to construct and test a model to predict the vertical subsoil stress.

Materials and methods

Experimental sites

Five experimental sites were selected in arable fields on three Swedish farms: Ultuna (1999), Tolefors (2000) and Kungagården (2001) (Table 1).

Sites 2 and 3 were located at Tolefors near Linköping, and situated 200 m apart. Sites 4 and 5 were located at Kungagården near Varberg and situated about 300 m apart. The farmers tilled and sowed the fields using their ordinary practices and equipment.

Table 1. Basic soil characteristics of the five experimental sites

Site	Depth (m)	Soil type	Particle size distribution ($g\ kg^{-1}$) Clay	Silt	Sand	Org. matter ($g\ kg^{-1}$)
1 Ultuna	0.1	Clay Loam	400	397	184	20
	0.3	Clay	533	386	79	2
	0.5	Clay loam	454	469	78	0
	0.7	Clay loam	435	442	122	0
2 Tolefors	0.1	Silt Loam	270	536	168	26
	0.3	Silt clay loam	297	533	156	14
	0.5	Clay loam	316	637	47	0
	0.7	Clay loam	194	718	88	0
3 Tolefors	0.1	Clay	491	357	121	31
	0.2	Clay	537	405	52	6
	0.5	Silty clay	534	418	48	0
	0.7	Silty clay	364	605	31	0
4 Kungagården	0.1	Sandy loam	173	186	575	66
	0.2	Sandy loam	131	197	652	20
	0.5	Sandy loam	118	166	716	0
	0.7	Loamy sand	69	113	818	0
5 Kungagården	0.1	Clay loam	298	265	369	68
	0.2	Clay	487	248	248	17
	0.5	Clay	646	263	91	0
	0.7	Clay	626	274	100	0

Parts of the fields with a potentially high degree of soil compaction caused by previous traffic, *e.g.* the headland, were avoided. Before each experimental traffic application, the small area where the measurements and sampling were made was harvested by hand.

At all sites, traffic treatments and measurements were carried out at the prevailing soil water content. The soil profile at site 1 was comparatively wet in the early spring (Table 2). During summer, the profile dried out and the topsoil in particular became very dry and rigid. The soil water content in the lower part of the soil profile was higher than in the topsoil. The soil water content below 0.4 m at site 2 was relatively high and stable throughout the year, while the soil above this depth dried out in late June. At site 3, the desiccation in June included most of the profile, while the water content was comparatively high for all the profile in May and September. Site 4 had approximately the same vertical distribution of water content profile at all three traffic events (May, August and September). The May and September experiments at site 5 were conducted at a comparatively high water content, while the experiment in August was performed under drier conditions.

Due to the mouldboard ploughing in autumn, and a single harrowing of site 5 the day before traffic application in May, a significantly different topsoil structure than for all other traffic experiments was created. The depth of the bed of loosely arranged aggregates created by the plough and the single harrowing varied through time. On May 13, the day after harrowing, its depth was estimated at 0.32 m, and at 0.25 m in August.

Table 2. Sites and times of trafficking and tillage, soil water content and crop grown

Site/date	Soil water content (w/w%)				Crop	Tillage operation
	0.1m	0.3m	0.5m	0.7m		
Site 1					*Triticum aestivum* L.	Mouldboard ploughed in the
May 11	21	27	23	29	spp. *vulgare*	Autumn 1998. Harrowed and
June 8	18	22	22	24		sown primo May
July 15	11	16	20	19		
Aug.14	12	15	15	19		
Sept.10	11	16	18	19		
Oct. 27	25	24	21	20		
Dec. 1	24	25	21	26		
Site 2					*Avena sativa* L.	Mouldboard ploughed in the
May 5	17	22	21	23		autumn 1999. Harrowed and
June 5	15	16	22	19		sown in the end of March
Sept. 1	22	18	23	25		
Site 3					*Avena sativa* L.	Mouldboard ploughed in the
May 5	23	28	26	27		autumn 1999. Harrowed and
June 5	21	21	23	20		sown in the end of March
Sept. 1	28	27	29	29		
Site 4					*Triticum aestivum* L.	Harrowed in the autumn 2000
May 13	27	32	19	16	spp. *vulgare*	and sown with winter wheat
Aug. 6	22	27	16	23		
Sept.15	28	23	12	15		
Site 5					*Vicia Faba* L.	Mouldboard ploughed in the
May 13	28	42	29	29		autumn 2000. Harrowed on
Aug. 6	23	24	24	28		May 12, sown on May 14

The loose structure of the topsoil at site 5 on May 13 was found only at this particular site and date, probably because the site was harrowed only once the day before the experimental traffic application and was not sown until after to May 13. For later traffic applications at site 5, the topsoil was more compacted due to the harrowing, sowing, and by natural processes.

Experimental traffic

A tractor-towed trailer was constructed to apply traffic with controlled wheel loads (Fig. 7) on the right wheel, which was equipped with a Trelleborg TWIN 700-26.5 tyre. This wheel ran outside the rut created by the tractor tyres to avoid compacting the soil before the passage of the trailer tyre. At each traffic experiment, wheel loads of 2, 3, 4, 5 and 7 Mg were applied, except on site 1, where the 4 Mg load was excluded. Each tyre load was applied on soil not disturbed by previous traffic treatments. The tyre inflation pressure was 140 kPa with wheel loads of 2, 3, 4 and 5 Mg and 240 kPa with 7 Mg tyre load. The speed was approximately 4 km/h. Measurements of repeated applications of field traffic were made by reversing the direction of travel.

Fig.7. Tractor-towed trailer used to apply experimental traffic. Site 1, June 8.

The contact area on a hard surface was measured by parking the wheel on cloth and spraying paint around the tyre. The contact area was thereafter cut out of the cloth, and transferred to a piece of paper, which was weighed for calculation of the contact area.

Measurements of soil displacement and stress

Soil vertical displacement during traffic was measured as described by Arvidsson & Andersson (1997). The technique is based on the principle that the pressure of a liquid column is proportional to its height. The probe contains a Plexiglas body (length 70 mm, width 35 mm, height 36 mm) with a reservoir filled with silicone-oil (Fig. 8). The oil is connected through a hose to a pressure transducer. Vertical movement of the cylinder changes the height of the oil column and the output signal of the pressure transducer. The transducer can measure a displacement of

102 mm with a repeatability of 0.1 mm (Arvidsson & Andersson, 1997). A stress transducer (DS Europe Series BC 302) was mounted on top of the probe cylinder to measure the normal vertical soil stress. The probe-head was attached to a 1095 mm long steel rod.

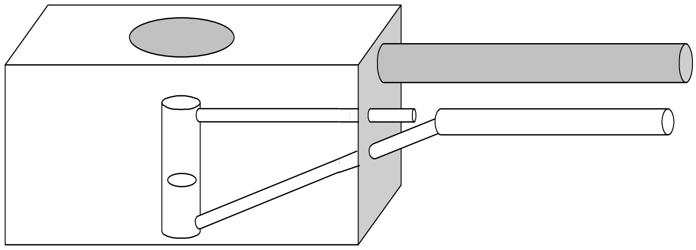


Fig. 8. Displacement sensor with a stress transducer attached on top. The probe was installed horizontally into the soil and registered vertical soil stress and displacement simultaneously.

Each probe was installed into the soil through a borehole approximately one metre long with a diameter of 60 mm drilled horizontally. A steel tube with the same diameter as the hole was inserted to stabilise the hole. At the end of the hole, a square reamer (35x35mm) removed 100 mm of soil so that the probe would be firmly embedded in soil relatively undisturbed by the installation procedure. Before each traffic treatment, probes were installed at 0.3 m, 0.5 m and 0.7 m depth under the centre line of the wheel rut. Care was taken so that the probes were not installed above each other.

The measurements on sites 2-3 and 4-5 were carried out by shifting the same equipment between the pits at the adjacent sites during the measurements.

On September 2, 2001 on site 5, the horizontal distribution of the vertical stress below the ground contact area of the trailer was measured using seven stress transducers buried in the topsoil layer at a depth of 0.1 m. Each transducer (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). Two transducers were placed under the centre line of the rut 0.1 m apart to determine the velocity of the vehicle during the measurements. The remaining transducers were placed perpendicular to the driving direction at intervals of 0.1 m. The sampling rate was 100 hertz. Each transducer was calibrated individually.

Laboratory determination of soil precompression stress and soil water content

At 0.3, 0.5 and 0.7 m depth, two to six cores (25 mm in height, 72 mm in diameter) were sampled per depth at the time of each traffic treatment for determination of precompression stress. Uniaxial loading of the soil cores from sites 2, 3, 4 and 5 was carried out at ambient soil water content in an oedometer described by

Eriksson (1974). Stresses of 12.5, 25, 50, 100, 150, 200, 400 and 800 kPa were applied sequentially during 30 minutes each, after which the strain was determined. The soil cores sampled at site 1 on September 10, 1999, were tested in a slightly different way by using a "Universal-Prüfpresse" UP 100, by courtesy of Dr. Berli, the Swiss Federal Institute of Technology. Stresses of 13, 50, 75, 100, 150, 200, 400, 800, 1000, 1600, 3200 and 4800 kPa were applied sequentially. Each stress was applied for 30 minutes before the amount of strain was determined. The precompression stress was determined from the stress-strain relationship according to Casagrande (1936).

For each wheeling treatment, the gravimetric soil water content was determined to 1 m depth by sampling soil at intervals of 0.1 m. The topsoil plastic limit was determined according to the British Standard 1377 (1975) with five replicates per depth.

Model prediction of stress propagation

The elastic model

The elastic model applied in this thesis uses the work of Fröhlich (1934), which is based on the formulae given by Boussinesq (1885) for calculating stresses in a homogeneous, isotropic, weightless, linear elastic semi-infinite space below a point load. Standard values of ν were adopted for the calculations, i.e. $\nu=4$ for relatively dry soil, $\nu=5$ for intermediate water contents, and $\nu=6$ for wet soil as suggested by Söhne (1953). In this thesis, the contact area of the tyre was divided into small squares of 3.5x3.0 cm each, where the force vectors acted as a point load in the middle of each square within the surface contact area. The stress at a given point in the soil was found by summation of the vertical stress contribution from each force vector.

A parabolic surface load was assumed, where the power for the parabolic load in the driving direction and in the cross section was set to 2 and 3, respectively, and the ratio of the maximum stress under the sides of the tyre footprint to the maximum stress at the centre of the tyre footprint was 0.8 (Paper I).

The Distinct Element Method

To illustrate the topsoil stress distribution as affected by topsoil water content and density, a Distinct Element Model (Dem2d) was used. The model is based on the method suggested by Cundall (1978), but uses a Constant Average Acceleration Method for integrating the equations of motion (Ghaboussi *et al*., 1993). The Dem2D programme makes it possible to consider the non-linear relationships between stress and elastic and plastic strain in the same process (Ullidtz, 1998). Furthermore, viscous or viscous-elastic as well as inertial effects during deformation may be considered (Ullidtz, 1998). The model was used for a computer simulation of the stress distribution in three different types of topsoil: a) loose soil with very low aggregate stiffness, b) loose soil with low aggregate stiffness and c) soil with large aggregates of high stiffness. The sample representing loose soil consisted of 3346 disks with radii between 4 and 6 mm, placed in a box (400 x 300 mm), whereas the sample representing the soil with large aggregates contained 276 disks with radii between 4 and 200 mm. The soil sample was compacted at 20 kPa, and thereafter loaded with 250 kPa using a 40 mm wide "piston".

Results

Horizontal distribution of vertical stress below applied loads

The vertical stress measured on one occasion 0.1 m below the ground contact area of the trailer was unevenly distributed (Fig. 9). The shape of the peak stresses suggested that they were associated with the tyre lugs. The measured maximum peak stress below wheel loads of 2, 3, 4 and 5 Mg (tyre inflation pressure 140 kPa) were 197, 250, 227 and 215 kPa, respectively. With 7 Mg wheel load and tyre inflation pressure of 240 kPa, the peak stress was 300 kPa.

In general, the contact areas were larger than those measured on a hard surface, and at the same tyre inflation pressure (140 kPa), and they increased with the wheel load. The largest contact area was measured below a 5 Mg wheel load, 140 kPa inflation pressure. The calculated average ground pressures below wheel loads of 2, 3, 4 and 5 Mg were 128, 152, 137 and 146 kPa, respectively. With a 7 Mg wheel load and a tyre inflation pressure of 240 kPa, the calculated average ground pressure was 246 kPa.

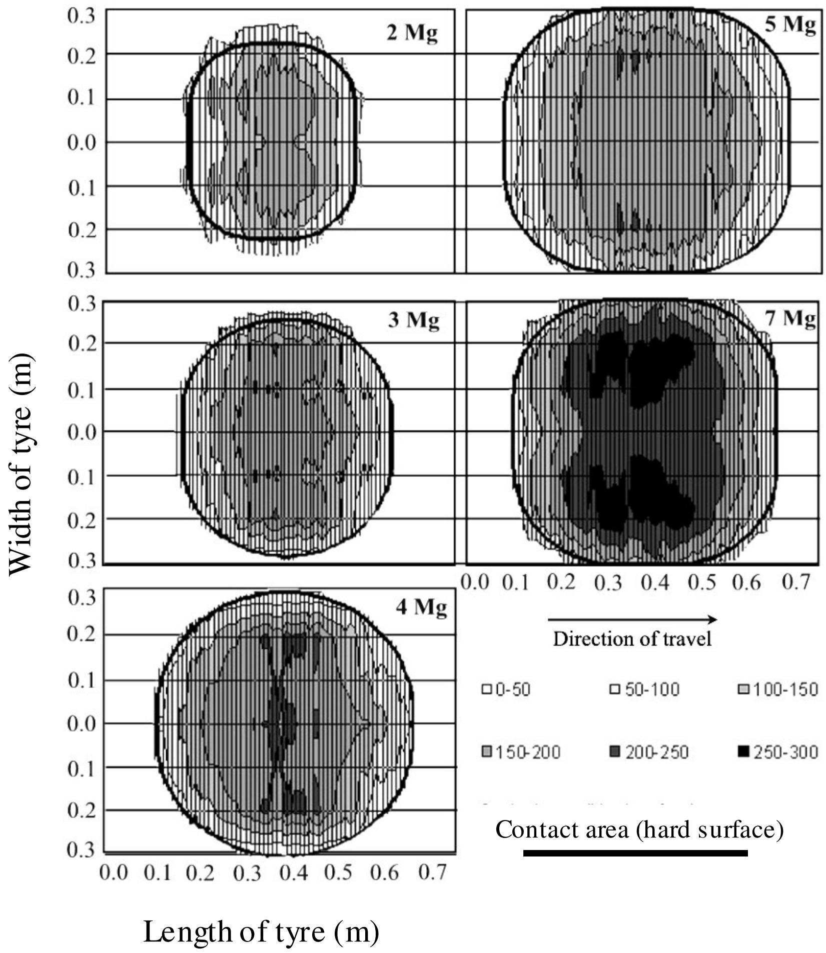


Fig 9. Horizontal distribution of the vertical stress measured in the soil 0.1 m below the trailer tyre at site 5 on September 2, 2001.

Stress propagation in the subsoil during wheeling

A typical result of the individual measurements of vertical soil stress is shown in Fig. 10. During wheeling, the peak stress at 0.3 m depth was reached in approximately 0.5 s, and was very distinct. The difference between the peak stresses at 0.5 and 0.7 m depth was in most cases not as large as between 0.3 and 0.5 or 0.7 m depth. In general, the peak stress was reached fastest at 0.3 m depth, whereas no clear difference between the stress time at 0.5 and 0.7 m depth could be found.

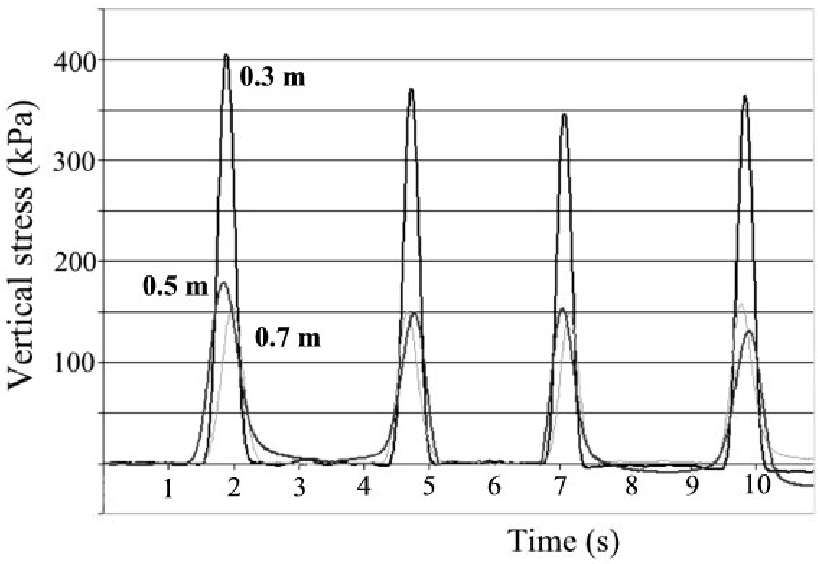


Fig. 10. Result of soil vertical stress measured at three depths simultaneously during 4 traffic applications (forward, backward, etc.) with 7 Mg wheel load, 240 kPa tyre inflation pressure, at site 1, October 27).

The maximum soil stress generally decreased with depth and increased with increasing wheel load, but showed large variations, especially at 0.3 m depth. At site 1 (Fig. 11), the stress measured below 7 Mg wheel loads ranged from 390 to 650 kPa at 0.3 m depth. At this depth, wheel loads of 5 Mg induced stresses between 290 and 520 kPa. In 29% of the total number of measurements, no vertical stress was registered, and in 55% of these cases, vertical stress was registered in soil layers below. The likely explanation is that this was due to insufficient contact between the soil and the stress transducer.

The highest soil stresses at 0.3, 0.5 and 0.7 m depth were measured when the soil precompression stress was relatively high. The soil stress exceeded the soil precompression stress in less than 30% of the measurements where soil stress was greater than zero. In most cases this occurred at 0.3 m depth.

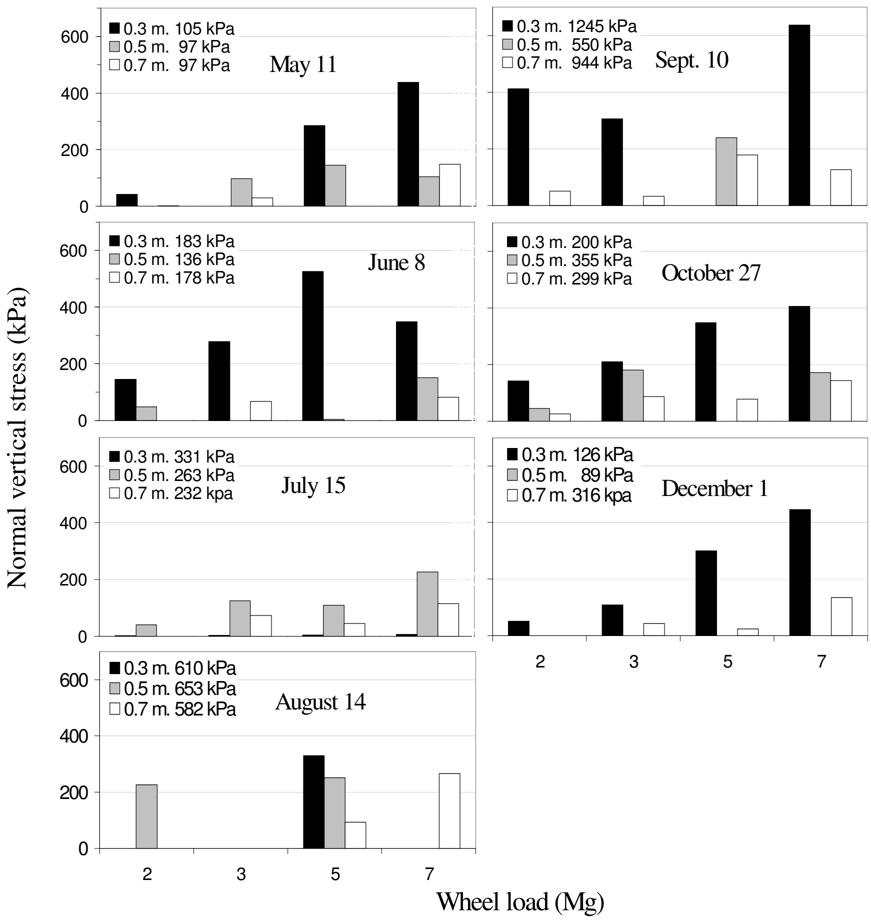
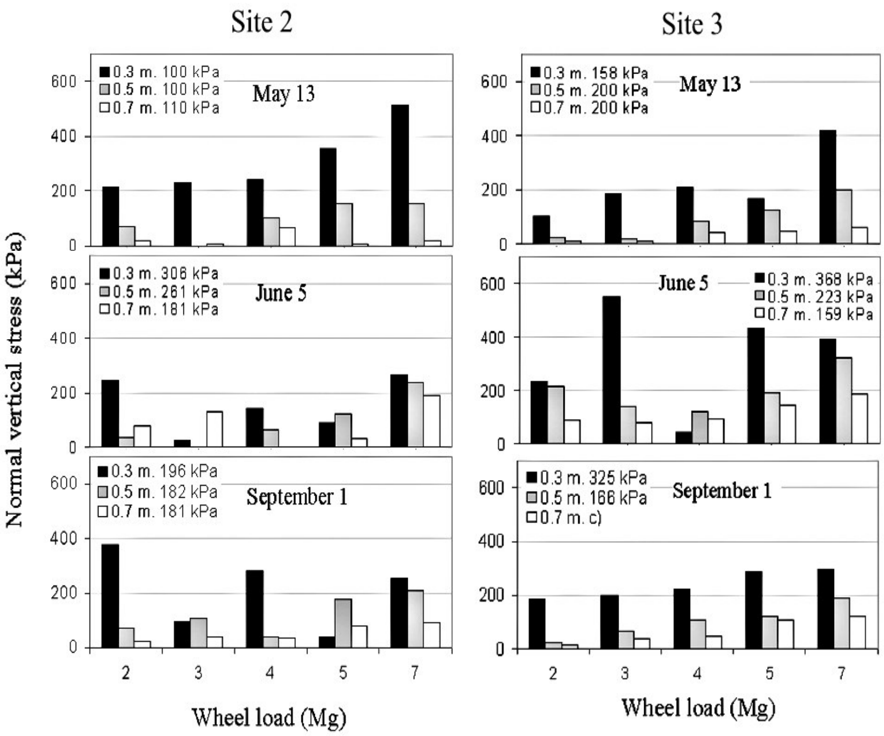


Fig 11. The maximum normal vertical stress measured at three depths on seven occasions during field traffic with four different wheel loads on site 1. The precompression stresses at three depths are also presented.

At site 2 (Fig. 12), no vertical stress was registered in 7% of the measurements. There was a tendency in May, when the soil precompression stress was lowest (approximately 100 kPa at all three depths), for the stress measured at 0.3 m depth to be higher than in June and September, whereas the stress measured at 0.7 m depth was highest when the soil precompression stress was high. The measured vertical stress at 0.7 m depth was lower than the precompression stress on all but one occasion (7 Mg wheel load on June 5). On June 5, the measured stress was in most cases lower than the soil precompression stress at 0.5 m depth.

At site 3 (Fig. 12), on June 5, the precompression stress at 0.3 and 0.5 m depth was higher than in May and September, and the measured stress at 0.3, 0.5 and 0.7

m depth was higher. The stress at 0.3 m depth was 230, 550, 420 and 390 kPa with wheel loads of 2, 3, 5, and 7 Mg respectively. Even at 0.7 m depth, the stress was relatively high: 90, 80, 95 145 and 190 kPa. The stresses measured in May and September did not differ noticeably. With wheel loads less than 7 Mg, the precompression stress exceeded the measured soil stress at 0.5 m depth.

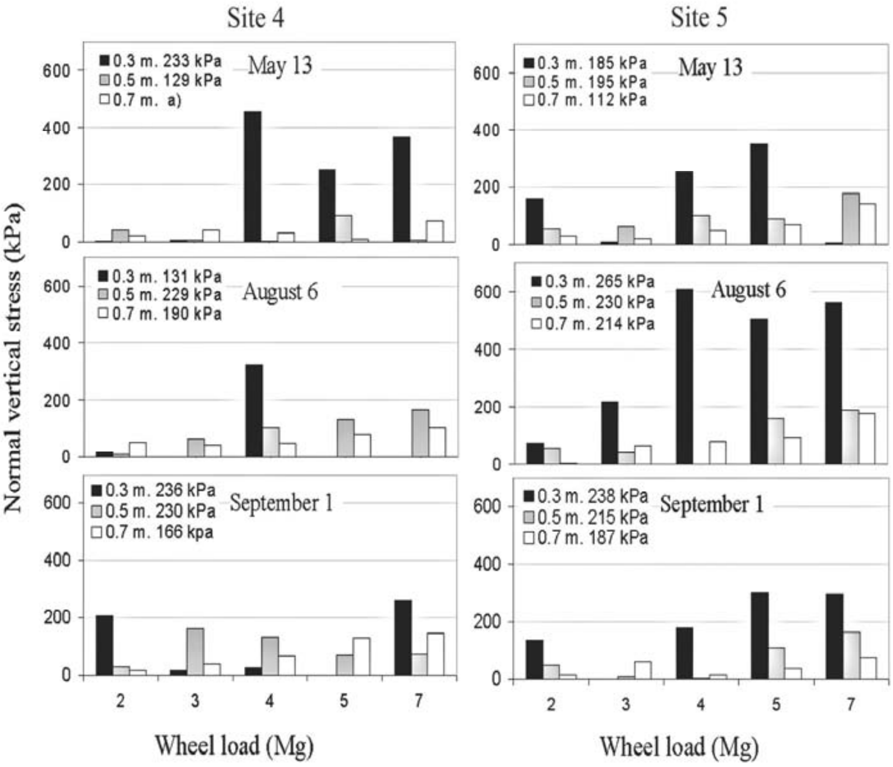


c) Missing value at 0.7 m depth

Fig 12. The normal vertical stress measured at three depths on three occasions during field traffic with five different wheel loads on sites 2 and 3. The soil precompression stress at three depths is also presented.

At site 4 (Fig. 13), a soil stress less than 10 kPa was measured for 60% of the loadings. On May 13, the precompression stress could not be determined at 0.7 m depth. The measured soil stress did not exceed the precompression stress at 0.5 or 0.7 m depth. The stress at 0.5 and 0.7 m depth was lowest on May 13.

At site 5 on August 6, the vertical soil stresses at 0.3 m depth were 611, 510 and 564 kPa during wheeling with wheel loads of 4, 5 and 7 Mg, respectively. This was considerably higher than on May 13 or September 1, when the highest soil stress was 350 and 300 kPa, respectively. At 0.5 and 0.7 m depth, the precompression stress exceeded the measured soil stress on all but one occasion (7 Mg wheel load on May 13).



a) Missing value at 0.3 m depth

Fig 13. The normal vertical stress measured at three depths on three occasions during field traffic with five different wheel loads on sites 4 and 5. The soil precompression stress at three depths is also presented.

Vertical soil displacement

Displacement patterns

The vertical soil displacement showed some typical features during the traffic applications (Fig. 14):

a) a maximum of soil displacement (peak) occurred at the moment of wheel pass

b) the peak soil displacement consisted of a recoverable and a non-recoverable (residual) part

c) the recoverable displacement was more or less constant with each traffic application, and larger than the non-recoverable deformation

d) the residual soil displacement increased with the number of traffic applications

e) each wheeling caused less residual deformation than the previous wheeling

f) the soil displacement decreased with the soil depth

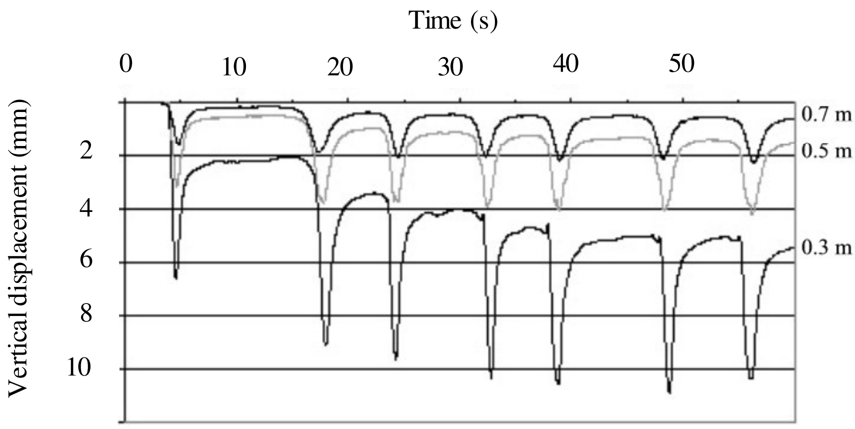
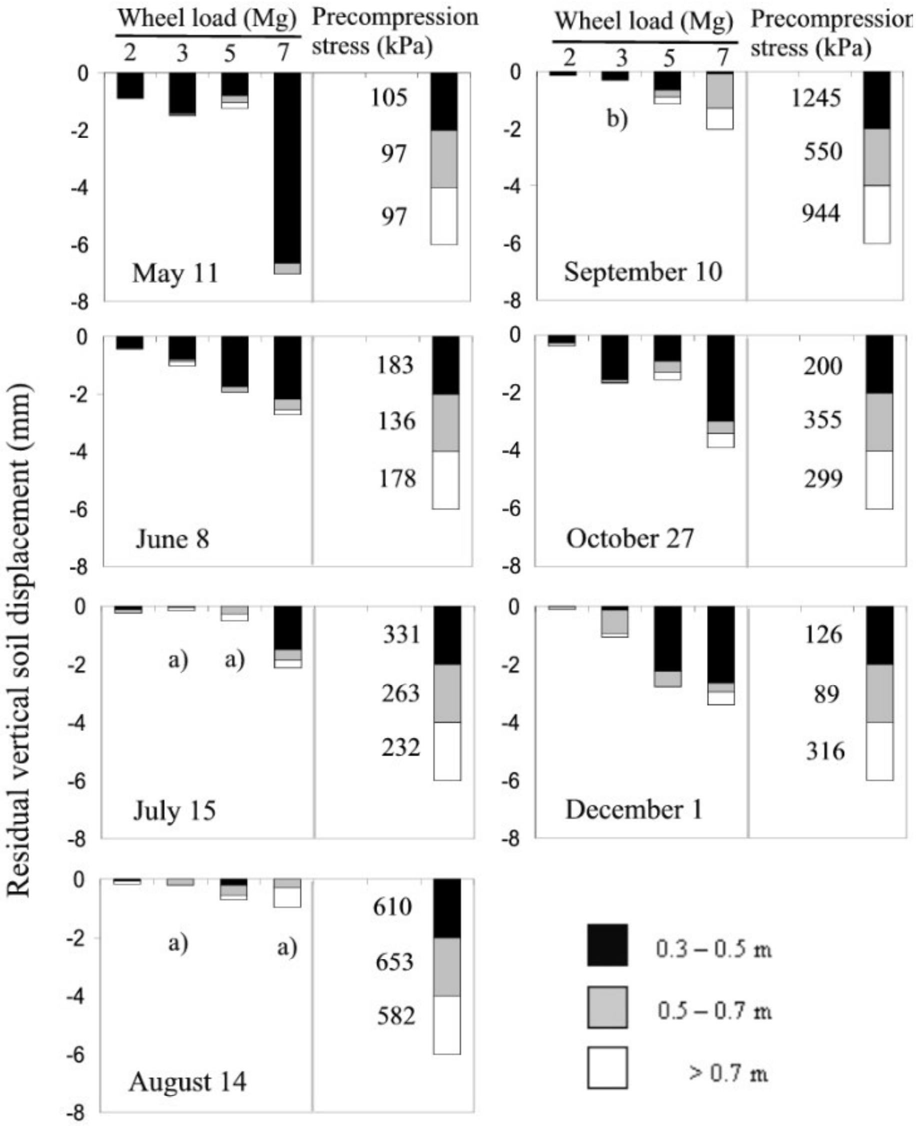


Fig. 14. Vertical soil displacement measured simultaneously at three depths during seven passes with a tyre with 7 Mg load, 240 kPa inflation pressure. Site 1, July 15.

Residual displacement

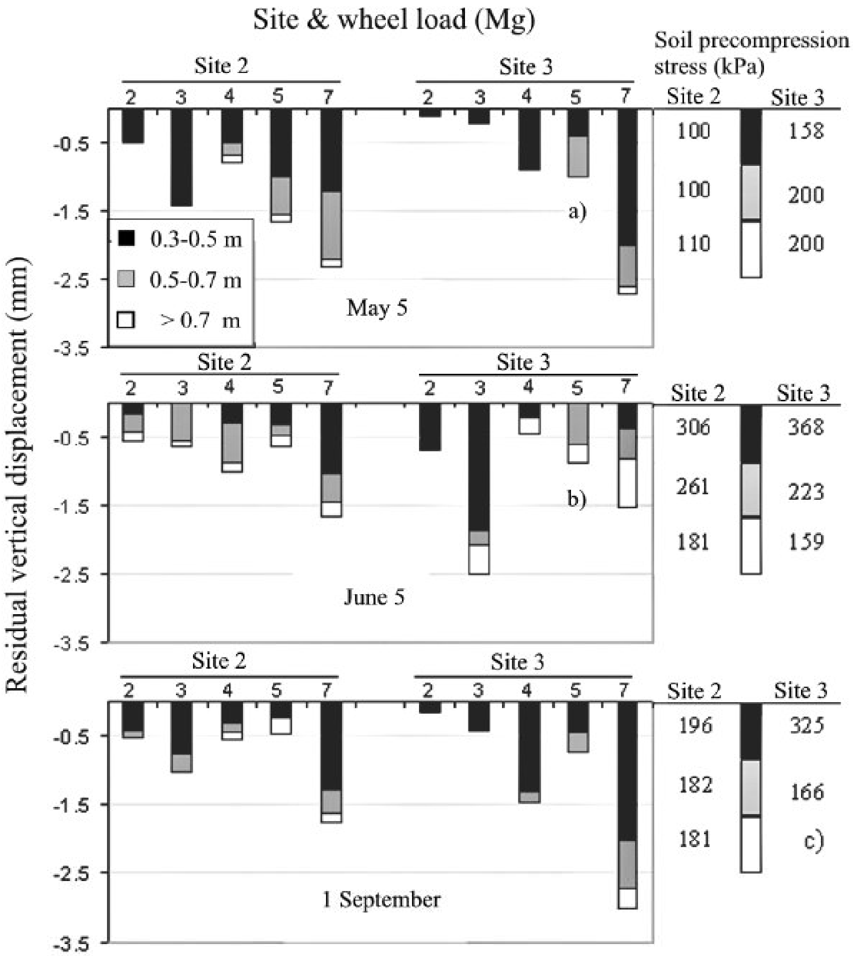
At all sites, the residual vertical soil displacement usually increased with the wheel load. At site 1 regardless of wheel load and precompression stress, all traffic applications resulted in soil displacement to at least 0.3 m depth (Fig. 15). In 70% of the traffic applications with 2 Mg wheel load, the soil layer at 0.5-0.7 m depth was displaced. The vertical displacement at 0.5 m depth was 0.1 mm. Field traffic with 7 Mg wheel load resulted in soil displacement below 0.7 m depth in all cases except on May 11, when the soil was displaced at 0.5 – 0.7 m depth. The soil precompression stress was very high during the dry summer: In August it was above 500 kPa in all layers, and in September even above 1000 kPa at 0.3 m depth. In May and in December, the soil had the lowest strength, close to 100 kPa at 0.3 and 0.5 m depth. When the precompression stress was relatively low (May, June and December), the amount of displacement at 0.3-0.5 m depth was generally higher than when the soil precompression stress was high. However, there was a tendency for the displacement below 0.5 m depth to be greatest when the soil had high strength.



a) missing values at 0.3m; b) at 0.5 m depth.

Fig. 15. Residual vertical soil displacement in three layers after field traffic with four different wheel loads on seven occasions on site 1, presented with the soil precompression stress at the upper boundary of the layer.

At sites 2 and 3 (Fig. 16) regardless of wheel load and precompression stress, all application of field traffic resulted in soil displacement to at least 0.3 m depth. Field traffic with 7 Mg wheel load and 240 kPa tyre inflation pressure resulted in soil displacement below 0.7 m depth in all cases.



a) Missing value at a) 0.7 m; b) 0.3 m. c): The precompression stress could not be determined from the stress/strain-curve

Fig. 16. Residual vertical soil displacement in three soil layers after field traffic with five different wheel loads on three occasions on sites 2 & 3, presented with the soil precompression stress at the upper boundary of the layer.

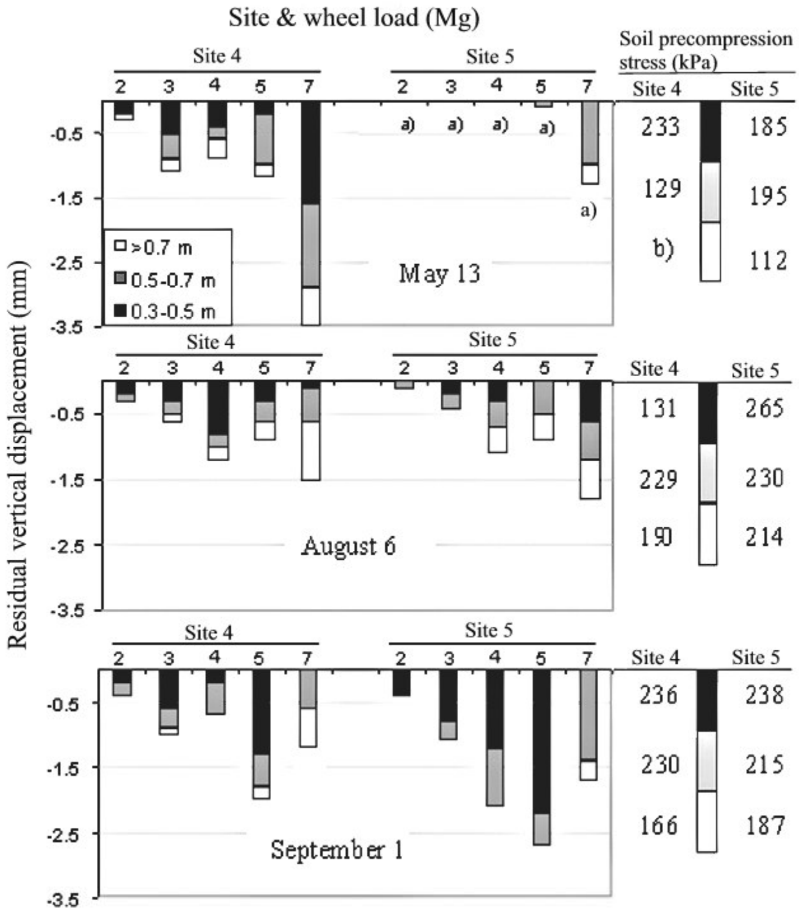
The soil precompression strength on both sites was highest on June 5; at both sites it was above 300 kPa at 0.3 m depth. On this date, the soil was displaced below 0.7 m depth by field traffic with 3, 4, 5 and 7 Mg wheel loads. On site 2, the soil below 0.7 m depth was displaced 0.2 mm with 2 Mg wheel load. When the soil precompression stress was high, a larger amount of soil displacement was measured below 0.7 m depth than when the soil precompression strength was low. This was observed on both sites, but most pronounced on site 3. On May 13 and

September 1, the soil displacement measured in the 0.3-0.5 m layer was generally larger than when the soil was strong.

On site 4 (Fig. 17) the soil had a low bearing capacity since all applications of field traffic resulted in soil displacement of the 0.5-0.7 m layer and with wheel loads of 3 Mg and above, the soil was displaced below 0.7 m depth. Traffic with 2 Mg wheel load resulted in displacement of the 0.5-0.7 m layer in all cases. Field traffic with 7 Mg wheel load resulted in soil displacement below 0.7 m depth in all cases. The results from site 4 did not show any clear relationship between the soil strength and the depth of displacement.

Site 5 was harrowed on May 12, the day before the first experimental traffic application. Hence, the depth of the plough layer was approximately 0.32 m compared to 0.25 m in August, where the soil was naturally compacted. Because the sensors were always installed at 0.3, 0.5 and 0.7 m depth, on May 13 the displacement sensors at 0.3 m depth were installed in the plough layer, and not in the subsoil, which otherwise was the normal procedure. Therefore, these measurements were disregarded.

The precompression stress was lowest on May 13, but did not differ much between either depths or dates (Fig. 17). Nevertheless, the residual soil displacements showed that the soil behaviour during traffic applications differed on the three occasions. On May 13, there was no residual soil displacement at 0.5 and 0.7 m depth after field traffic with 2, 3, 4 and 5 Mg, whereas traffic applied in August and September resulted in soil displacement to at least 0.5 m depth. On September 1, field traffic with 2, 3, 4 and 5 Mg wheel load resulted in more displacement of the 0.3-0.5 m soil layer, and less displacement below 0.5 m depth compared to August 6. Field traffic with 7 Mg wheel load resulted in soil displacement (0.3-0.6 mm) below 0.7 m depth in all cases. The residual (Fig. 17) as well as the recoverable (data not shown) vertical deformation differed on the three occasions.



a) Missing value at 0.3 m depth.
b) The precompression stress could not be determined

Fig. 17. Residual vertical soil displacement in three soil layers after field traffic with five different wheel loads on three occasions on sites 4 & 5, presented with the soil precompression stress at the upper boundary of the soil layer.

Recoverable and residual deformation

Generally, the recoverable and the residual vertical soil displacement were linearly correlated (Fig. 18). Apart from site 4, the correlation was reasonably linear. The best linear correlation between the recoverable and residual displacements was found at site 1 (R^2= 0.68). At sites 2, 3 and 5, the linear model accounted for 49, 59 and 56%, respectively, of the variability. At site 4, where the linear model only accounted for 22% of the variability. One reason for this was that the ratio between recoverable and residual soil deformation during field traffic with 7 Mg wheel load was smaller than with lower wheel loads. When these data were omitted, the R^2-value for the regression (y4b) was 0.56 (Fig. 18).

If the recoverable vertical displacement is interpreted as an elastic soil deformation and the residual displacement as a plastic deformation, the soils could endure only a relatively small amount of elastic deformation before being deformed plastically. The regression lines intercepted the abscissa at relatively low values of elastic deformation, indicating the transition between purely elastic and elastic/plastic soil layer deformation happened at very small deformations, i.e. 0.13, 0.03, 0.08, 0.16 and 0.17% deformation, respectively for site 1-5. The largest amount of measured elastic deformation that did not result in plastic deformation in the given soil layer was 0.5%, 0.37%, 0.5%, 0.37% and 0.5 % for sites 1, 2, 3, 4 and 5, respectively.

The correlation lines were expected to intercept the abscissa at much higher values, but the soil layers could sustain almost no recoverable soil deformation before being permanently deformed. The amount of recoverable subsoil deformation during field traffic was in all cases larger than the amount of permanent subsoil deformation. On the heavier soil types (site 1, 3 and 5), the non-recoverable soil deformation was 40-50% of the recoverable deformation, and somewhat smaller (29-35%) at site 2 and 4.

The largest plastic deformation at any site in any layer was 3.4% measured at site 1 during field traffic with 7 Mg wheel load. The second largest plastic deformation at site 1 was 1.5%. For sites 2, 3, 4 and 5, the largest plastic deformations were 0.75%, 1.0%, 0.75%, and 1.5 %, respectively.

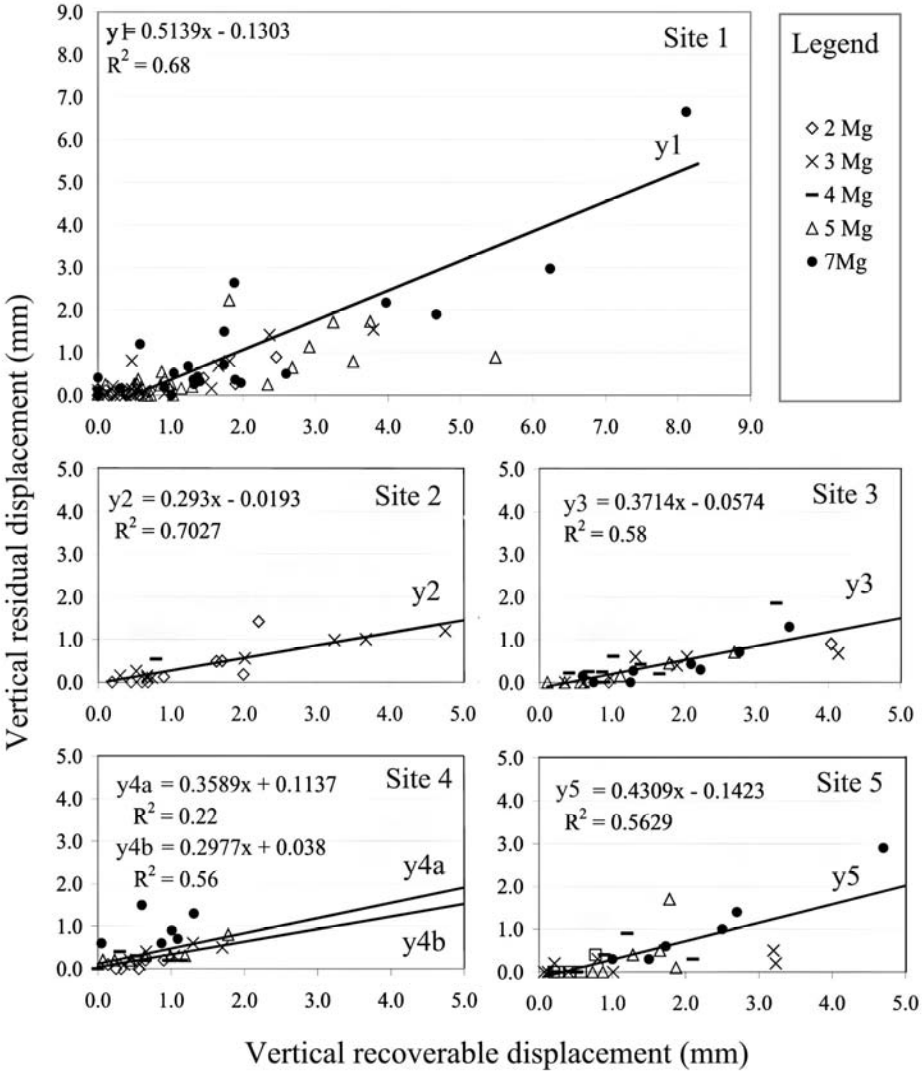


Fig. 18. The relationships between recoverable and residual soil displacement on the five experimental sites. Values for all wheel loads, date of traffic applications, and soil layers (0.3-0.5, 0.5-0.7 and below 0.7 m depth) are plotted for each site. At site 4, 'y4a' represents the linear correlation line of all measurements, whereas 'y4b' represents the linear correlation line for all data minus 7 Mg.

Discussion

Methodological aspects

As expected, the stress measurements at 0.1 m depth showed that the vertical soil stress was horizontally unevenly distributed below the tyre with maximum peak stresses of 197, 250, 227, 215 and 300 kPa for wheel loads of 2, 3, 4, 5 and 7 Mg, respectively. The difference was small compared with results reported by Burt *et al*. (1992), who found that the maximum ground pressure measured on the tyre surface was sometimes as high as four times the calculated average ground pressure. In my investigation, the peak stresses were 50-100 kPa higher than the tyre inflation pressure. However, it is important to emphasize that relatively few measurements of the peak "surface" stress were made, and the vertical stress across the whole tyre/soil interface was not measured. The results of e.g. Vanden Berg & Gill (1962) and Burt *et al.* (1992) clearly showed that high peak stresses might be found very locally in the contact area, so maximum stresses considerably higher than those reported may have passed unobserved.

The soil stress did not vary to the same extent at 0.5 and 0.7 m depth as at 0.3 m depth. The vertical subsoil stress measured during field traffic showed large inconsistencies and variability, especially at 0.3 m depth: the vertical soil stress ranged from 5 to 400 kPa at all five sites, and sometimes even exceeded 600 kPa. In some cases, the measured stress was very low (0-5 kPa) when clearly higher stresses were expected because higher stress was measured at lower load intensity. The problem seemed to be largest when the soil was very dry or very sandy. This was probably caused by insufficient contact between the soil and the stress transducer. A precondition for reliable stress measurements is that the stress transducer has good contact with the soil, and this may not always be obtained when the stress transducer is installed laterally into the soil. An uneven stress distribution below the tyre may also account for some of the variation, since the area of the stress transducer was only 2.4 cm^2 and may not have coincided with the main areas of vertical stress. Due to these circumstances, the data collected had a bias in terms of some observations obviously being too low. This has to be considered when interpreting the data. In the sections below, the geometric mean or median values are generally used in order to prevent erroneous results from biasing the whole dataset. It is clear that to analyse the stress propagation in soil, a large number of measurements are needed.

Furthermore, the rigidity of the soil may also influence the stress measurements when types stress transducers are used where the membrane is in direct contact with the soil, as opposed to stress transducers with two membranes. According to Ullidtz (1998), "the signal often varies non-linearly with the stress in the surrounding media, and tends to be a function of the stiffness of the media, and thus of the loading history". Unpublished data collected at the Department of Soil Science, Swedish University of Agricultural Sciences, have shown that when the stress sensors were placed on a wooden board 0.1 m below the soil surface, the vertical soil stress values recorded were five times higher than when the same sensors were placed directly in the soil. However, the large number of simultaneous stress and strain measurements in this study allows for analysis of the general soil behaviour during field traffic.

Due to its application of a very simple physical principle, the method used for measuring vertical soil displacement should be very reliable.

Taken together, the data on vertical stress and displacement can be considered reliable and applicable for evaluation of the mechanical behaviour of the soils tested.

Stress propagation in soil

It is generally assumed that the high strength of a soil in dry conditions will protect the soil profile from compaction. However, the results presented here clearly showed that the deformation mechanics involved were much more complex. On several occasions, the soil was displaced despite having low water content and high precompression stress (Figs. 15-17). It was evident from the results that the load transmission in soil may be more concentrated, or direct, in dry soil compared to wet soil.

A literature review revealed the existence of an institute report at the Swedish Institute of Agricultural Engineering by Danfors (1974), who conducted a large series of field measurements on soil deformation during field traffic. Probes were inserted vertically into the soil at 0.3, 0.5, 0.8 and 1.2 m depth through drilled holes. The probes were fixed in the soil with "anchors" and the deformation measured with micrometers fixed at the soil surface on a reference beam. The measurements were performed during field traffic in the early spring, and in the autumn. The soil profiles were at field capacity in the spring and relatively dry in the autumn.

Using a methodology different from the one used in this study, Danfors (1974) found a similar trend (Fig. 19), with the vertical displacement at 0.3 and 0.5 m depth being smaller in dry conditions in the autumn than when the soil was wet in the spring. However, at 1.2 m depth, soil deformation was highest when the soil was dry.

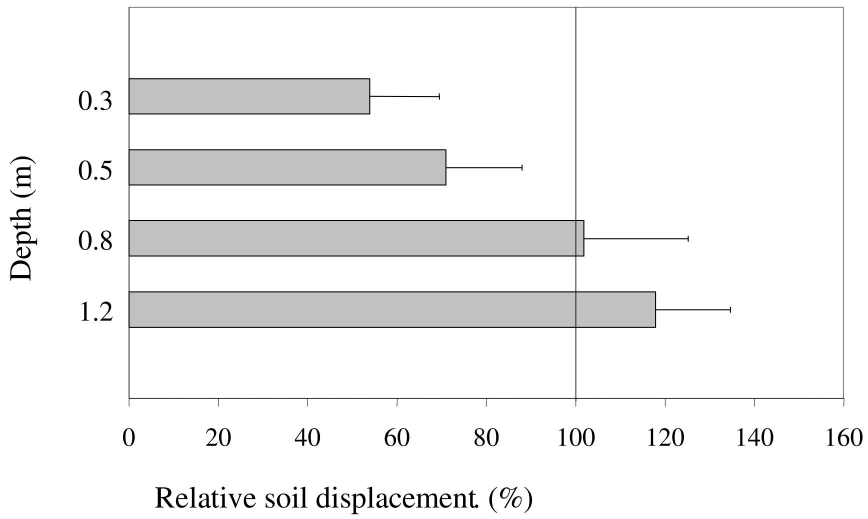


Fig 19. Average relative vertical soil displacement (n = 22) measured in the field at 0.3, 0.5, 0.8 and 1.2 m depth during wheeling on natural soils in the spring (wet conditions) and autumn (dry conditions) with several wheel loads. The values along the abscissa indicate the soil deformation in the autumn relative to that in the spring (%). The bars indicate standard deviation. Adapted from Danfors (1974).

The present investigation as well as the results presented in Fig.19 suggests that the stress propagation in soil may in some cases be viewed as a concentrated transmission of the surface load to deeper layers. This will be discussed in the following sections.

Topsoil structure effects

The effect of the topsoil properties on the subsoil stress could be studied at site 5, where the structural conditions of the topsoil clearly differed on the three traffic occasions. On May 13, the topsoil consisted of a loose bed of relatively weak aggregates and clods created by autumn ploughing, and harrowing of the soil on the previous day. At the August and September measurements, the topsoil had regained structural strength, but the topsoil water content on August 6 was very low due to a dry summer, and the topsoil was very heterogeneous with large, dense clods. The subsoil precompression stress was lowest on May 13. The subsoil precompression stress on August 6 was slightly higher than on September 1, but the differences may be considered to be within the precision with which the soil precompression stress was determined.

On May 13, no residual soil displacement was found below 0.3 m depth after field traffic with 2, 3 and 4 Mg wheel load, and only 0.1 mm residual displacement at 0.5 m depth with 5 Mg wheel load. In comparison, soil displacement was measured to at least 0.5 m depth at the same site on August 6 for all wheel loads. Apparently, the loose plough layer on May 13 limited the depth of subsoil displacement as compared to a rigid and strong plough layer. However, this was not supported by the measured stresses, which were more or less similar in the two cases. Nevertheless, the displacement measurements cannot be disregarded since the method is more reliable than stress measurements. The displacement sensor is installed tightly in the soil, and when the soil moves vertically, the sensor invariably moves as well. The possibility of a general malfunction of the displacement sensors on May 13 is highly unlikely since measurements were made with the same equipment, which was shifted between site 4 and site 5 during the measurements.

The stress measured at 0.3 m depth had its greatest value on August 6, and there was a tendency that the stress at lower soil depths also had its greatest value on the same date. This implies that the structure of the plough layer had a considerable impact on the stress propagation in the subsoil, i.e. there was more direct load transmission in August than by the weakly aggregated topsoil in May.

That topsoil, and not subsoil, properties had the largest impact on the subsoil stress may be inferred from the fact that the subsoil stress was generally higher on August 6 than September 1. The vertical displacement measurements showed that the soil behaviour on August 6 than on September 1: when the topsoil was dry, the soil was displaced at greater depths whereas the amount of displacement was less at 0.3 m depth.

The effect may have been partly due to an increased tyre/soil contact area in the loose soil. Furthermore, the bow wave in front of the wheel (Meltzer, 1983) may have contributed to an increase of the contact area, as well as the stress distribution in the topsoil. However, the results strongly suggest that different mechanisms governed the deformation event during field traffic on the three occasions. I suggest that the most important cause of the observed effect was changed load transmission characteristics of the topsoil. In the next sections, this soil behaviour will be discussed.

Load transmission in a structured medium

The Dem2D Distinct Element Model (Ullidtz, 2001) allows for simulation of the stress propagation in a bed of distinct elements. The stress distribution was modelled in three different types of topsoil: a) loose soil with very low aggregate stiffness, b) loose soil with moderate aggregate stiffness and c) soil with large aggregates of high stiffness (Fig. 20). In all three cases, the cohesion and the cohesive strength of the contact points were similar. In the rigid soil (c) with stiff and large aggregates, the stress was distributed rapidly and concentrated through the sample. In the stronger of the loose samples (b), the load transmission was fast and more dispersed compared with the dry and rigid sample, even if there was a stress peak centred below the piston after 0.3 s. When a soil is loaded with an external force large enough to cause plastic deformation, the weak contact points near the contact area are destroyed first and the volume of the compacted zone increases as contact points are destroyed at an increasing distance from the contact area. Hence, the load may be transmitted to a larger area in the subsoil. In relatively dry soil, a large amount of contact points may be strong enough to resist destruction, such that the deformation process may be concentrated at relatively few contact points. As strong parts of the soil are displaced downwards, the load may be transmitted to the subsoil more directly, and to relatively small areas in the subsoil.

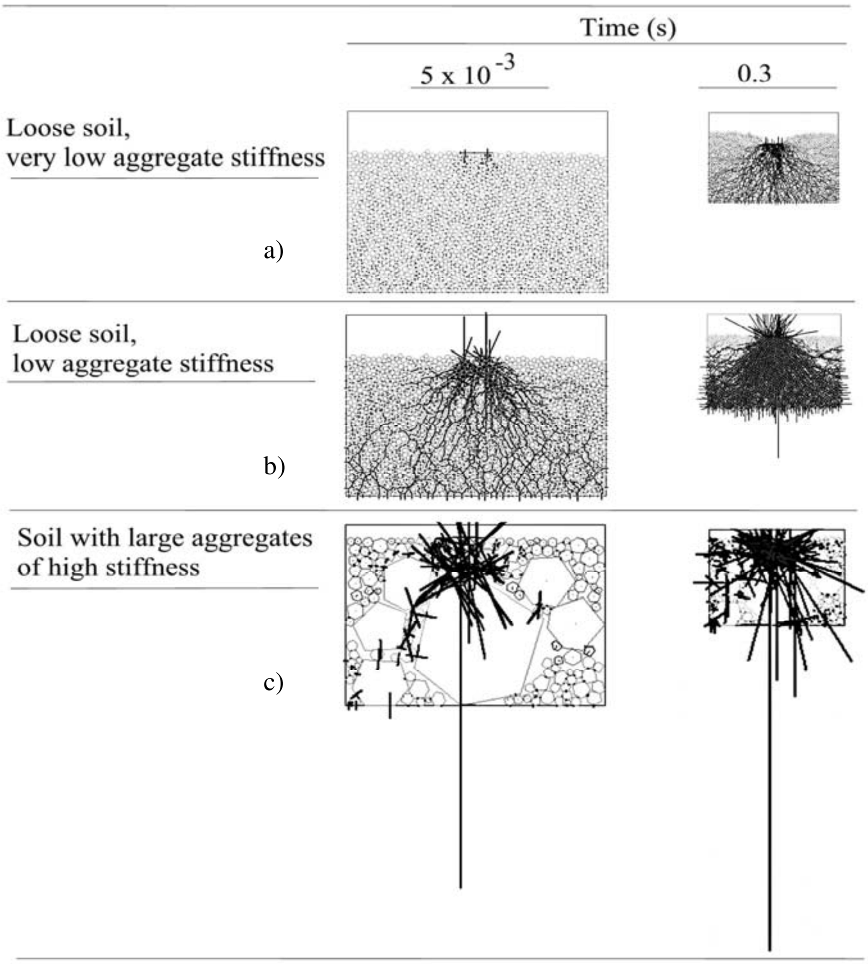


Fig. 20. Simulation with the Dem2D Distinct Element Model illustrating the forces on elements and contact points in a) loose soil with very low aggregate stiffness, b) loose soil with moderate aggregate stiffness and c) soil with large aggregates of high stiffness, immediately after loading with 220 kPa and after 0.3 s.

The suggested load transmission process in soil also provides an explanation as to why the measured vertical stress tended to be highest when the soil was dry, sometimes even exceeding 600 kPa. An implication of this is that there is a need to quantify or describe the topsoil structure to successfully model the stress propagation in natural soil. Furthermore, the simulation indicates that the horizontal distribution of the vertical soil stress at 0.3 m depth during field traffic may be highly uneven, and may in distinct contact points be many times higher than the calculated average stress in the contact area. From Fig. 20, it is clear that direct, or unstable, load transmission may have a huge impact on the subsoil stress levels.

An important implication of the different load transmission abilities as affected by topsoil properties is that if the "true" peak stress is to be measured, the sensors must be installed without destroying the structure of the adjoining soil. It is also clear that when measuring the vertical peak stress in the soil profile, the lateral location of the stress sensors below the tyre may be very important, since the propagation of the vertical peak stress may occur very locally. Clearly, it cannot merely be assumed that the vertical peak stress is located below the centreline of the tyre.

Construction of the LOTRA model

One objective of the thesis work was to construct a model to calculate the vertical peak stress in the soil during loading. The model was calibrated with data from site 1 (Paper I). A criterion for the model was that it should be as simple as possible to use. Only if a clear improvement in the predictions is found should complex solutions be preferred to simpler ones. In the following paragraphs, the construction of the LOTRA model (LOad TRAnsmission) and the principles that it was based on will be discussed.

Vertical peak stress

To calculate the soil stress propagation in the soil profile, information about the load intensity is needed. The average contact area stress may be calculated from the total wheel load and the contact area. However, since tyres are not perfectly flexible, the stress distribution at the soil-tyre interface is often non-uniform. To account for this, assumptions are often made about the contact area stress distribution, e.g. that the stress is parabolically distributed. However, this is not true in all cases: At great tyre deflections, e.g. when the tyre inflation pressure is low, the bearing surface may become concave due to the stiffness of the sides of the tyre (*e.g.* Ageikin, 1987). Hence, the position of the vertical peak stress must be located. However, it is not trivial to measure the stress distribution at the tyre/soil interface. One reason is that due to the tyre lugs, the stress distribution at the contact area depends on whether it is measured on rigid or soft surfaces: if the surface is rigid, the vertical stress between the lugs may be zero. It was decided that the LOTRA model should use as input the vertical peak stress measured at 0.1 m below the homogenized soil surface since it is relatively easy to measure compared with making measurements at the tyre/soil interface.

The load transmission factor

The model is based on the hypothesis that the load is transmitted more directly in the soil profile - and to relatively small areas - when the soil is relatively dry compared with when it is relatively wet (Paper I). To account for this behaviour, the load transmission factor was constructed, the function of which is directly opposed to the function of the concentration factor that Frölich (1934) suggested for the theory of elasticity. The load transmission factor was suggested as the ratio $w_{LPL}/w_{act.}$ of the topsoil water content at the lower plastic limit (w_{LPL}) to the topsoil water content at the time of traffic application ($w_{act.}$). Hence, the load transmission factor, WR, expresses the consistency of a given soil in a relatively simple and objective way. However, even if the soil water content may have a large impact on the soil structure, there are other factors of importance on the structure of arable soil, e.g. tillage operations. Hence, the SR-factor, which is a calibration factor accounting for topsoil structure, was introduced. The SR factor was set to 0.9 for relatively loose topsoil with small aggregates, to 1.0 for normally aggregated and naturally compacted soil, and to 1.1 for strongly aggregated topsoil with large aggregates and clods. In this thesis, the structure-factor was simply determined from the WR: for intervals of WR < 1, WR = 1 - 1.2 and WR > 1.2, structure factor values of 0.9, 1, and 1.1 were assigned. As a matter of principle, the SR-factor was not incorporated into the WR-factor, but remained separate. In this thesis, the product of WR and SR is referred to as the load transmission factor, or LOTRA-factor.

The next task was to determine whether the observed load transmission was an effect of topsoil or subsoil water content, or a combination of both. Whereas the results clearly indicated that the topsoil structure and consistency had an impact on the subsoil stress levels, there was no clear indication that the model would be improved by implementing the load transmission factor into the model below 0.3 m depth. For example, even when the soil water contents at 0.5 m depth were similar (Table 2), the vertical soil stresses at 0.7 m depth were not. Hence, the load transmission factor was applied for the topsoil only (Eq. 7). This made the practical use of the LOTRA model easier, since the load transmission factor only had to be determined for the upper 0.3 m. I suggest that more research is done to establish a load transmission factor for the subsoil.

The LOTRA Model

In Eq. 7, the LOTRA model for calculating the peak vertical stress at 0.3 m depth is presented:

$$\sigma_{0.3(pred.)} = \sigma_{0.1(meas.)} \text{ WR SR} \quad (7)$$

where σ_z is the predicted (pred.) or measured (meas.) vertical peak stress at depth z (meter), WR is the ratio $w_{LPL}/w_{act.}$ of the topsoil water content at the lower plastic limit (w_{LPL}) to the topsoil water content at the time of traffic application ($w_{act.}$), and SR is a calibration factor accounting for topsoil structure. The WR factor in Eq. 7 ranges for the particular soil from 1.0-1.9. The SR factor was set to 0.9, 1.0 or 1.1 as described above. As can be seen from Fig. 20, the vertical peak stress may be found very locally.

Below 0.3 m depth, the vertical peak stress calculated with the LOTRA model was used as input in Eq. 8, which was derived directly from the Boussinesq's

(1886) equation for a vertical stress below a point load, which in this case was calculated with Eq.7:

$$\sigma_{z>0.3(pred.)} = \sigma_{0.3(pred.,Eq.7)} / (z/0.3)^2 \qquad (8)$$

where z is the depth in metres.

A practical implication of the LOTRA model is, that since the load transmission factor only rarely will be lower than 1, the predicted vertical maximum stress at 0.3 m depth in structured soil will in most cases exceed the vertical peak stress measured in homogenized soil at 0.1 m depth.

Model calculations and load transmission in natural soil during field traffic

Predictions made with the LOTRA model were compared with calculations made with an elastic model. The two approaches to calculate the vertical peak stress are based on fundamentally different principles of soil stress propagation. First, the function of the concentration factor is diametrically opposed to the load transmission factor. Second, the elastic model makes use of an analytical solution for calculating the stress profile along a vertical axis through the centre of a given contact area. The LOTRA model is not analytical, but calculates the stress along a vertical axis below the vertical peak stress. The elastic model is based on the assumption that the contact area must be taken into account, whereas the LOTRA is based on the assumption that the lateral stress propagation is negligible, and consequently, only the vertical peak stress should be considered. In reality, this may not be true in all cases. On the other hand, the lateral stress propagation as indicated by the theory of elasticity probably rarely or never occurs in natural structured soils.

In Table 3 the maximum vertical stress at the surface calculated by the elastic model, i.e. that the load is parabolically distributed as described in the "Materials and methods" section, is shown with the measured peak stress at 0.1 m depth used as input in the LOTRA model.

Table 3. Vertical peak stress at the surface below tyre loads of 2-7 Mg calculated by the elastic model, and the measured peak stress at 0.1 m depth used as input in the LOTRA model

Model	Depth (m)	Vertical peak stress (kPa)				
		2 Mg	3	4	5	7
Elastic model	0	178	231	186	233	364
LOTRA	0-0.1	197	250	227	215	300

The elastic model (Fig. 21, left) generally underestimated the stress at 0.3 m depth. The stress measurements showed large variability at 0.3 m depth compared to 0.5 and 0.7 m depth. This may be taken as an indication of the uneven stress distribution below the topsoil as affected by soil structure.

The LOTRA model predicted the general trend of the soil stress at 0.3 m depth better than the elastic model (Table 4). When the concentration factor values in the elastic model were reversed (*i.e.* ν=6, 5 and 4 for dry, moist and wet soil respectively) the correlation between measured and predicted stress was improved in all five cases (data not shown). Hence, it seems as if the theoretic soil behaviour on which the concentration factor is based, i.e. the higher the soil water content, the more the compressive stress will concentrate around the load axis, and the deeper the stresses will propagate into the soil profile, is not valid for natural soil. Instead, I suggest that the stress may be transmitted more directly and undiminished in relatively dry soil than in relatively wet soil, whereby the underlying soil layer is subjected to a relatively higher peak stress. This load transmission theory is further supported by the comprehensive dataset from strain measurements in natural soil presented in this study.

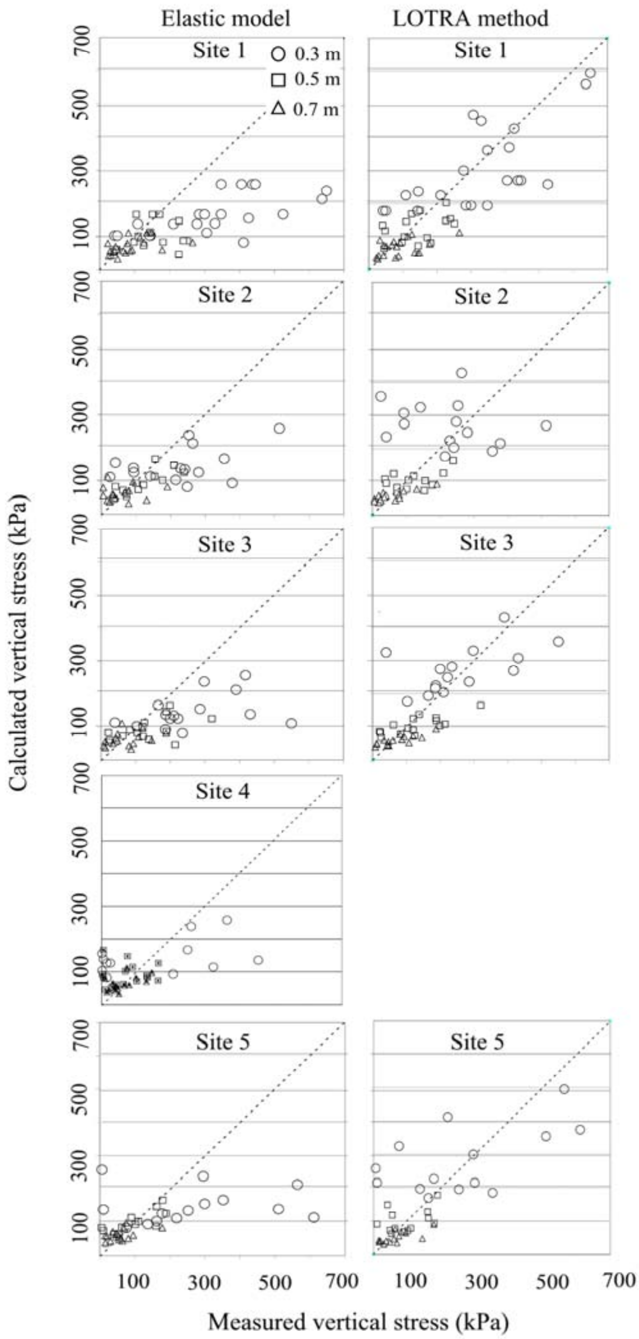


Fig. 21. Measured and predicted vertical stress at 0.3, 0.5 and 0.7 m depth. The elastic model was used with the'classical' concentration factor values (4, 5 and 6 for dry, moist and wet, respectively; left) and the LOTRA model (Eq. 7-8; right).

The poor stress prediction by the model of elasticity, especially at high stress levels at 0.3 m depth, may be taken as a falsification of the theory that stress propagation in the structured topsoils is similar to that in a linearly elastic, homogeneous, isotropic, weightless medium.

Table 4. The difference between geometric means of measured and predicted values of soil stress shown in Fig 22. The circles indicate differences larger than 10 % relative to geometric predicted means

		Elastic model			LOTRA		
	Depth (m)	0.3	0.5	0.7	0.3	0.5	0.7
Site 1	n (number of pairs)	21	15	21	21	15	20
	Maximum (%)	398	387	234	104	125	200
	Minimum (%)	21	3	2	0	5	3
	Geometric mean	87	36	39	22	37	38
Site 2	n (number of pairs)	15	13	14	15	13	14
	Maximum (%)	302	89	204	93	106	102
	Minimum (%)	6	6	3	2	1	27
	Geometric mean	62	28	42	34	25	53
Site 3	n (number of pairs)	15	15	15	15	15	15
	Maximum (%)	391	360	166	88	97	116
	Minimum (%)	0	9	20	3	0	1
	Geometric mean	44	44	60	20	23	27
Site 4	n (number of pairs)	11	14	15			
	Maximum (%)	237	121	88			
	Minimum (%)	9	1	7			
	Geometric mean	77	38	31			
Site 5	n (number of pairs)	14	13	13	14	13	14
	Maximum (%)	434	87	115	112	114	245
	Minimum (%)	9	7	14	2	3	4
	Geometric mean	78	20	42	33	32	39

If the stress propagation mechanism described by the load transmission theory presented above is correct, then it is a fundamental soil characteristic. Surely, one may argue, it must have been described before. In fact, it has. The general soil behaviour found in this thesis was measured by Semmel (1993), who measured the soil stress as affected by number of traffic applications. The measured stress decreased at 0.3 m depth but increased at 0.6 m depth with the number of traffic applications. Horn & Rostek (2000), explaining the effect of consecutive traffic events, stated that the increased elasticity of the topsoil induces “an additional plastic deformation of the still weaker subsoil”. Obviously, this is a description of the different load transmission characteristics of relatively strong (elastic) and weak (plastic) soil layers. The speed effect may also be explained as a consequence of the soil’s load transmission characteristics: According to Horn (1993), the higher the vehicle speed, the smaller the vertical soil stress. The transient stresses during passage of farm vehicles act on the subsoil for too short a time for the pore water flow in the subsoil to be of any significance, especially in clay soils. According to Ageikin (1987), a dense core is formed during loading, which moves in the direction of the load, compacting adjoining soil layers. These explanations were supported by the stress measurements in this study: The vertical peak stresses at 0.5 and 0.7 m depth were in most cases higher during the third than during the first traffic application. Clearly, the explanations provided above of observed soil behaviour during field traffic certainly do not encourage the application of the theory of elasticity to calculate stresses in natural soil. Furthermore, the soil behaviour observed at the five sites falsified the soil stress propagation theory upon which the concentration factor, ν, is based (Eq. 6).

The factor accounting for the water content effect, WR, provided a precise and objective figure to be used as an input value. A disadvantage with the WR factor was that it could not be calculated for non-cohesive sandy soils. Hence, the LOTRA model was not used to predict the vertical stress at site 4. Alternative methods to determine the lower plastic limit must be applied, preferably a method where the soil is not completely homogenized.

The results showed that the vertical load transmission ability of the topsoil had a very clear impact on the level of subsoil stress, and as implied by the calculations with the LOTRA model, the impact of subsoil water content and structure may be comparably small. Even if the assumptions for the theory of elasticity were not fulfilled, the use of Eq. 8 to calculate the subsoil stress may perhaps be justified in this case: since the residual displacements measured in the subsoil were relatively small, the disagreement between the predicted and the real stress may be relatively small compared with the variability of the measured stress. However, work is needed in order to establish the effect of subsoil properties on subsoil stress.

Clearly, the wheel load had an impact on the peak stress, but clearly did not provide enough information to predict the soil stress accurately. Nevertheless, the wheel load is often used to estimate the soil stress because information about the wheel load is relatively easy to acquire. Alas, assumptions about the contact area stress distribution have to be made, e.g. that it is parabolic, and this makes the validity of the calculated soil stress an open question. A practical implication of the assumption of a parabolic stress distribution is that the sensors must be placed in the soil below the vertical axis through the centre of the contact area in order to measure the maximum stress. However, if the stress distribution is not parabolic, the maximum peak stress is not measured. This may be very important when studying the effect of tyre inflation pressure on the subsoil stress. While reducing the tyre inflation pressure in order to increase the contact area, the stress distribution in the contact area is also likely to change. For example, where the vertical peak stress at high tyre inflation pressure was positioned below the centre of the tyre, it may be positioned below the edges of the tyres when the inflation pressure is low due to the rigidity of the tyres (Gill & Vanden Berg, 1967). Van den Akker *et al.* (1994) measured the soil penetration resistance after traffic with normal and low inflation pressure, respectively, and concluded that “measuring the penetration resistance in the centre of the rut would lead to incorrect conclusions”.

Hence, if the sensors in both cases are installed directly below the centre of the contact area, the soil stresses are clearly not comparable.

Hence, in order to install the sensors correctly in the subsoil, the vertical stress below a tyre must be determined for the whole contact area, and not merely at a few positions. If not, then the experimental data simply cannot be used to falsify the theory that the wheel load determines the subsoil stress levels. This theory is based on the stress propagation in a linearly elastic, homogeneous, isotropic medium. However, there are good reasons not to exaggerate the importance of lateral stress propagation in naturally structured soil. First, and most important, in natural soil where concentrated or unstable load transmission occurs, not every point at the loaded area contributes to the vertical stress on a given point in the soil, just as unstable or direct load transmission is not possible in a medium that completely complies with the assumptions of the theory of elasticity. Furthermore, if the stress distributions below the tyre used in this research are considered (Fig.18), it is clear that the vertical stress decreased rapidly towards the edges. The contribution from areas of low stress intensity to the vertical subsoil stress must be very small, probably even negligible, compared with the contribution from areas of high load intensity. The size of the contact area may simply be regarded as one of several factors that have an impact on the vertical peak stress. Furthermore, due to the high stochastic variability and low precision, i.e. the relatively low reproducibility of stress measurements in natural soil, it is often very difficult to find any statistically significant difference (*e.g.* Paper III). Hence, only with a large amount of data may the stress propagation in natural soils be properly analysed.

A practical implication of the above is that the soil stress below vehicles may be reduced with the proper tyre equipment, or through the use of tracks, regardless of the axle load.

More measurements are urgently needed to establish a relationship between the maximum surface peak stress and the stress levels in the soil profile. One challenge is that the stress distribution in the entire contact area must be determined to ensure that the position of the vertical peak stress is known. A practical solution to this problem could be that tyre manufactures supply information on the stress distribution of tyres as affected by wheel load and inflation pressure.

Elastic and plastic soil deformation

Within the given load intensities and soil water contents, the results suggested a linear relationship between elastic and plastic soil deformation for four of the sites (Fig. 18). On the light-textured site 4, field traffic with wheel loads of 7 Mg did not follow the general linear relationship, but resulted in a larger fraction of plastic deformation. It may be speculated that this was caused by plastic flow.

The intersects of the regression lines indicated that the transition between purely elastic and elastic/plastic soil layer deformation took place at very small deformations, i.e. 0.13, 0.03, 0.08, 0.16 and 0.17% deformation for sites 1-5, respectively. The largest measured elastic deformation that did not result in plastic deformation in the given soil layer was 0.5%, 0.37%, 0.5%, 0.37% and 0.5 % for sites 1- 5, respectively. Obviously the soils generally had a low ability to support the wheel during field traffic without permanently deforming the subsoil.

Field traffic with 2, 3 and 4 Mg wheel load (inflation pressure of 140 kPa) yielded soil deformation to at least 0.3 m depth regardless of soil texture and soil water content (Fig. 22). In more than 60% of the cases, the subsoil was deformed at 0.5-0.7 m depth after traffic with 2 Mg wheel load, and in more than 70% of the cases with wheel loads of 3 and 4 Mg, respectively (Fig. 22). Field traffic with 5 and 7 Mg wheel load deformed the soil at 0.5 – 0.7 m depth in all cases.

destruction of the weakest contact points in the soil layers. Higher load intensities may destroy stronger contact points so more deformation of a permanent nature occurs.

Field traffic with 7 Mg wheel load and 240 kPa tyre pressure resulted in large deformations on all soils. Clearly, this load intensity displaced the soil to large depths irrespective of the soil water content, and even if the soils were traditionally regarded as relatively strong. In modern agriculture, this load intensity is often exceeded.

Soil deformation related strength expressions

The soil precompression stress, as it was determined in this study, was not a very useful indicator of the ability of the soil profile to resist permanent deformation during field traffic. Even when the subsoil precompression stress was higher than the measured stress at 0.1 m depth, the soil was in many cases deformed permanently by the applied traffic. This agrees with Berli (2001), who questioned the suitability of "the soil precompression stress as a regulatory criterion to prevent soil compaction under real-world conditions". It underlines the fact that the precompression stress is not a threshold value between recoverable and non-recoverable soil deformation, which is obvious from the stress-strain curve. Casagrande (1936), who suggested the method used in this experiment, stated that if the load did not exceed the precompression stress, there would not be much deformation. However, it must be kept in mind that Casagrande (1936) was concerned with problems related to civil engineering and not those encountered by soil scientists working in agriculture.

An implication of the suggested soil deformation event is that since soil strength only exists as an average value over a large number of contact points, a strength definition with zero permanent deformation tolerance of the subsoil would be so low as to have little practical use.

Instead, the solution could be to supply information about the deformation caused by a given stress. For example, if the stress that would permanently deform the soil by 1% were 100 kPa, it could be given as $\sigma_{(1\%)}= 100$. To include the time-factor, the rate of decrease in layer modulus could be supplied.

For this to make any sense, the strength/deformation-value should reflect the stress-strain relationship in the field, since laboratory measurements cannot exactly reproduce the mechanical stress or the air and water drainage conditions encountered in the soil during field traffic (Berli, 2001). Richards (1977) wrote: "…the numeric value of shearing strength to be included in analytic studies of dynamic soil motions must be determined for conditions likely to be encountered in the field".

The rigid confinement of the soil sample during laboratory testing has been reported to give stress-strain relationships during compression that may differ from those obtained during compression with less rigid confinement (Richards, 1977).

The size of the soil sample may also be of importance for the stress-strain relationship during loading. The soil precompression stress in this study was determined by uni-axial deformation of 25 mm high and 72 mm wide confined soil samples. It is likely that because of the small size of the samples, the precompression stress represented the strength of compound particles or soil elements of a hierarchical order of soil structure lower than needed to describe the strength of the soil profile. According to Dexter (1988), compound particles or soil elements of a lower hierarchical order are denser and have higher strength than those of higher hierarchical order.

An important implication of the observed soil behaviour and the suggested load transmission mechanism is that a soil layer or soil element cannot be considered isolated because the behaviour of each soil layer will be strongly influenced by the load transmission characteristic of the soil layers above and the reaction to the applied load offered by the soil below. Ingles (1974) stated that “where a layer of saturated soil or other soil of low bearing capacity underlies the layer to be compacted, it is obvious that no real compaction can be achieved, because the soft layer will offer no reaction to the load and will deform so as to negate much of the applied compactive effort”. The ability of a soil layer or a soil element to resist permanent deformation during loading seemed to be linked closely to the load transmission characteristic or ability of that soil layer or element, as well as to its ability to offer a reaction to the applied load.

Consequently, the concept of soil strength is problematic. Soil strength is often defined as the soil’s ability to resist permanent compaction, but clearly this definition is imprecise, and may be wrongly interpreted. The strength of single aggregates in a given soil layer is very unlikely to reflect the soil layer strength, and the strength of a soil sample cannot be presumed to reflect the soil profile strength. In a medium that fulfilled the assumptions of the Boussinesq (1886) theory of elasticity, any sample would represent the whole medium perfectly. However, natural soil is a different medium. Already the existence of soil aggregates is a clear indication of this. Soil aggregates consists of particles bound together, so the average contact point strength of an aggregate cannot be taken as representative for the average contact point strength of a larger soil volume.

It is difficult to argue for the soil precompression stress, as measured in this study, to be used as a value describing the transition between elastic and plastic soil deformation. However, in this study, the soil precompression stress was useful in comparing the local soil conditions at the time of traffic application, whereas the soil water content does not provide enough information to compare different soil types. Furthermore, and most importantly, soil sample strength seems to provide useful information on local load transmission ability.

More research is urgently needed to identify a soil strength parameter that realistically reflects the ability of a soil to resist permanent deformation during field traffic, and to study the use of soil sample strength for predicting the load transmission characteristic in soil profiles during field traffic.

Models, measurements and reality

The problems, or challenges, faced by soil compaction scientists and soil engineers working with pavement design and response have obvious similarities, i.e. both groups are trying to understand the response to transient stresses applied by tyres. Obviously, the problems faced by engineers concerned with building more or less permanent structures are different. Nevertheless, soil scientists often apply solutions constructed to be used by soil engineers. According to pavement engineer Ullidtz (1998), "We simply cannot trust that elastic layer theory will produce the correct stresses or strains in the materials, or that laboratory fatigue testing will predict cracking of an asphalt layer".

A general problem associated with the analysis of stress distribution in natural soils is that their true mechanical properties are too complicated to be used as a basis for theoretical analysis (Terzaghi, 1943). Some may argue that this statement was made before computers were available, so consequently, it is not valid anymore. However, it cannot be assumed that the deformation process and stress propagation in natural soil can be accurately predicted merely because computers and very sophisticated models, like the Distinct Element Method or the Finite Element Model, capable of considering elastic, plastic, viscous and viscous-elastic soil deformation, are now available. The reason for this is that these models require a complete description of the system in order to accurately predict the stress distribution below tyres in that particular system. The task of giving a complete description of every system for each simulation would be extremely difficult, or impossible, because not only would we have to know exactly which properties and parameters should be included in such a description, and how they interacted with each other, we should also know how to measure or describe these parameters or properties. Additionally, the transient load application during field traffic is very complex, and would have to be described and incorporated into the model.

As discussed above, concentrated or direct load transmission is a fundamental feature of natural soils, and must therefore be considered. To quote Scott (1985): "There has been a good deal of debate about unstable behaviour that develops in association with volume expansions. Loading of such a soil is accompanied by local inhomogeneities in the form of slip lines, shear bands, or "bifurcations", as they are now commonly called. Thus, the single-element behaviour referred to in the foregoing breaks down as strains and displacements become localised in the shear zone…. It occurs in real soils in nature very frequently, is the source of many engineering problems, and so far is not represented in a single soil model. At present, it is also difficult to see how a suitable model could be implemented in a finite element code, since each individual element must have the opportunity of developing shear bands as the loading progresses. Their position cannot be predicted in advance".

Due to the complexity of the soil-tyre system, simplifying assumptions must be made for it to be modelled. However, there are some problems related to this. First, these simplifications may obviously make the validity of the soil behaviour analysis an open question, so they must be used with caution. According to Terzaghi (1943), "… no theory should be presented without a complete and concise statement of the assumptions on which the theory is based. Otherwise, the results are likely to be applied in cases which are beyond the range of their validity". Nevertheless, however complex and sophisticated, models are still only models, and only their predictive capability can justify their use. For this, measurements on the system that they describe are a prerequisite. According to Timoshenko (1953, p.383), "… materials sometimes deviate considerately from perfect homogeneity and perfect elasticity, and it becomes of practical importance to verify formulas derived for ideal materials". However, accurate field measurements of the stress distribution in - and the deformation of - natural soil profiles during field traffic are scarce, in particular those suited for studying the different load transmission characteristics of soils as affected by soil structure, water content and loading intensity. Measurements of soil stress distribution have mostly been performed on soils where the structure has been destroyed, i.e. the soil is homogenized, pulverized or even "over-pulverized". According to Horn & Lebert (1994) "the strength of structured agricultural soils differs to a great extent from that of homogenized soil samples". Consequently, it may be argued that our perception of the deformation event of natural soils during field traffic has been based largely on studies of over-simplified systems, and that it may therefore not be valid for natural soils.

There can be little doubt that there is a strong need for accurate field measurements on the behaviour of natural soils during loading. The database described by Trautner *et al.* (Paper II) contains only about 25 experiments where the stress or/and strain had been measured during field traffic. Clearly, not all available data has been reported, *e.g.* the data reported in this thesis, but this nevertheless emphasizes the need for accurate stress/strain-measurements.

Furthermore, how to define a successful model prediction needs to be considered. One problem is that since field measurements are time-consuming and their success to a large degree depends on the weather conditions, it is often difficult to obtain the number of measurements needed for statistical data analysis. Hence, there is a risk that lack of agreement between measured and predicted values may be compensated for by wishful thinking. For example, measured and predicted values have been reported to agree well or reasonably well, even if the relative difference was more than 50 or even 100%.

Finally, since the aim is to predict soil deformation, any model for predicting soil stresses must eventually be linked to some soil parameter reflecting the resistance of the soil profile to permanent deformation. This is indeed a great challenge, which can only be accomplished by accurate field measurements.

Conclusions and implications for further studies

The comprehensive dataset collected in this study reveals that much has to be learned about stress distribution and stress-provoked soil deformation. The topsoil properties had a large impact on the vertical subsoil stress, and that the concentration of stress below a loaded surface appears to be affected by topsoil characteristics quite different than normally anticipated. Further studies on the concept of load transmission in natural soils are encouraged. My investigations also call for studies integrating the effect of loading time.

The precompression stress as determined by classical, uniaxial compression tests appeared to be a poor soil failure criterion. The study showed that plastic deformation occurred at stress levels far below that predicted by the precompression stress. A linear correlation between elastic (recoverable) and plastic (non-recoverable) soil deformation indicates that soil should be regarded as an assemblage of soil elements with a stochastic distribution of the strength of the contact points. One implication of this is that no existing, practical soil parameter expresses the threshold value between recoverable and non-recoverable deformation, because non-recoverable soil deformation will occur even from small loads. I suggest the use of a strength parameter where information about the amount of deformation caused by a given stress, as well as the rate of modulus decrease, is supplied. There are many indications that the deformation value must be determined in conditions similar to the stress-strain relationship encountered in the field to be of practical use. The practical implication of the observed soil behaviour is that the subsoil appears to be vulnerable to plastic (non-recoverable) deformation at lower wheel loads than normally anticipated. This suggests an urgent need for engineering developments in vehicles with small wheel load intensities. Not only should the wheel load be as low as possible, but the stress in the contact area must also be as evenly distributed as possible.

An important implication of the suggested soil behaviour is that the strength of a soil layer cannot be considered isolated because the behaviour of each soil layer will be strongly influenced by the load transmission characteristic of the soil layers above and below. Furthermore, considering only one soil layer at a time will not reveal the mechanics involved in the deformation of the soil profile.

The results strongly suggest that models based on analysis of oversimplified systems cannot be relied upon to predict the stress distribution in soil successfully. We clearly need to identify exactly what is governing the deformation event, using accurate stress-strain measurements during field traffic on natural soils, so that the analysed system is not over-simplified.

References

Ageikin, Ia.S. 1987. Off-the-road mobility of automobiles [Translated from Russian: Prokhodimost' Avtomobilei]. Oxonian Press Pvt. Ltd., New Delhi.

Arvidsson, J. & Andersson, S. 1997. Determination of soil displacement by measuring the pressure of a column of liquid. *Proceedings of the 14th ISTRO Conference, Pulawy, Poland.*

Berli, M. 2001. Compaction of Agricultural Subsoils by Tracked Heavy Construction Machinery. Diss. ETH No. 14132. Institute of Technology Zürich.

Boussinesq, J. 1885. *Application des potentials à l'étude de l'equilibre et du mouvement des solides élastique.* Gauthier-Villais, Paris. Cited by Frölich, 1934.

British Standard 1377. 1975. *Methods of testing soils for civil engineering purposes*. British Standards Institute, London, 134pp.

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

Casagrande, A. 1936. The determination of pre-consoildation load and its practical signifigance. *Proc. Int. Conf. Soil Mech. Found., Eng. 22-26 June*. Harvard University. Cambridge. USA. Vol 3, pp 60-66.

Cundall, P.A. 1978. BALL – A program to model granular media using the Distinct Element Method. Dames & Moore, Advanced Technology Group*, Technical Note No. TN-LN-13*.

Danfors, B. 1974. Packning i alven [Subsoil compaction]. *Report S 24*. Swedish Inst. Agric. Eng., Uppsala, Sweden. 91 pp. (In Swedish, summary in English).

Dexter, A.R. 1988. Advances in characterization of soil structure. *Soil & Tillage Research 11*, 199-238.

Eriksson, J., 1974. Markpackning och rotmiljö. (Soil Compaction and Root Environment). Report 126, Division of Agricultural Hydrotechnics, Department of Soil Sciences, Swed. Univ. Agric. Sci., Uppsala, Sweden.

Frölich, O. K., 1934. Drückverteilung im Baugrunde. 1934. Wien

Ghaboussi, J., Basole, M.M. & Ranjithan, S. 1993. Three Dimensional Discrete Element Analysis on Massively Parallel Computers*. Proceedings of the 2nd International Conference on Discrete Element Methods (DEM).* The Massachusetts Institute of Technology, March 1993.

Gill, W.R & Vanden Berg, G.E. 1967. *Soil dynamics in tillage and traction.* Agriculture Handbook no. 316. Agricultural Research Service. United Department of Agriculture.

Gliemeroth, G. 1953. Untersuchungen über Verfestigungs-und Verlagerungs-vorgänge im Acherbodenunter Rad- und Raupenfahrzeugen.[Investigations of compaction and displacement phenomena in the soil under wheel and track vehicles]. *Zeitschrift. für Acker und Pflantzenbau 96,* 218-234.

Gupta, S.C & Raper, R.L. 1994. Prediction of soil compaction under vehicles. In: B.D. Soane & C. van Ouwerkerk (Eds.) *Soil compaction in crop production*. Elsevier Science. ISBN 0-444-88286-3.

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

Horn, R. 1991. Structure effect on strength and stress distribution in arable soils. *Proc. 12th Conf. Of Int Soil & Tillage Research Org. (ISTRO), Ibadan, Nigeria, 8-12 July*. Ohio State University, Columbus, OH pp. 204-218.

Horn, R. 2001. Die verformung von Böden – Ursachen und Folgen für eine nachhaltige Landnutzung [Soil deformation – causes and conquences fore a sustainable landuse]. In: Prof. Dr. G.W. Brümmer (Ed.). *Schadverdictung in Ackerböden.* 14. Wissenschaftliche Fachtagung, 5. Dezember 2001. Landwirtschaftliche Fakultät der Rheinischen Friedrich-Wilhelms-Universität Bonn. ISBN 0943-9684

Horn, R. 1988. Compressibility of arable land. In: J. Drescher, R. Horn and M. De Boodt (Eds.) *Impact of Water and External Forces on Soil Structure*. Catena Supplement 11. Catena-Verlag, Cremlingen_Destedt, pp. 53-71

Horn, R. & Rostek, J. 2000. Subsoil Compaction Processes – state of knowledge. . In: R. Horn, J.J.H. van den Akker and J. Arvidsson (Eds). *Subsoil Compaction: Distribution, Processes and Consequences*. Reiskirchen, Cartena Verlag 2000. Advances in GeoEcology 32. ISBN 3-923381-44-1. pp 44-54.

Horn, R & Lebert, M. 1994. Soil compactability and compressibility. In: B.D. Soane and C. van Ouwerkerk (Editors). *Soil Compaction in crop production.* Elsevier science B.V. pp 45-69.

Horton, R., Ankeny, M.D. & Almaras, R.R. 1994. Effects of compaction on soil hydraulic properties. In: B.D. Soane & C. van Ouwerkerk (Eds.) *Soil compaction in crop production*. Elsevier Science. ISBN 0-444-88286-3.

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

Ingles, O.G. Compaction. In: Lee, I.K. (Ed). *Soil Mechanics – New Horizons.* Butterworth & CO Ltd. London, 88 Kingsway, WC2B 6AB. ISBN 0408705434.

Jumikis, A.R. 1967. *Introduction to Soil Mechanics.* D. Van Nostrand Company Inc. Princeton, New Jersy.

Karafiath, L.L., & Nowatzki, E.A. 1978. *Soil mechanics for off-road vehicle engineering*. Series on Rock and Soil Mechanics, vol. 2 (1974/77) NO. 5. Trans Tech Publications, Clausthal, Germany. ISBN 0-87849-020-5

Kulli, B. Berli, M. Gysi, M. Schulin, R & Flühler, H. 2000. Subsoil compaction on agricultural land by heavy construction machinery – soil physical aspects. In: R. Horn, J.J.H. van den Akker and J. Arvidsson (Eds). *Subsoil Compaction: Distribution, Processes and Consequences*. Reiskirchen, Cartena Verlag 2000. Advances in GeoEcology 32. ISBN 3-923381-44-1. pp 278-283.

Lebert, M., & Horn, R. 1991. A method to predict the mechanical strength of agricultural soils. *Soil and Tillage Res. 19*, 275-286.

Meltzer, K.J. 1983. Possibilities of evaluating the traction of tyres for off-road transportation vehicles. *Position paper for the 2nd European Conference on Terrain Vehicle Systems*, Ferrara, Italy, 1983.

Or, D & Ghezzehei,T.A. 2002. Modeling post-tillage soil structural dynamics: a review. Soil&TillageResearch 64, 41-59

Richards, F.E, Jr. 1977. Field and laboratory measurements of dynamic soil properties. In: Prange, B (ed.) Vol 1. *Dynamic response and wave propagation in soils*. Proc. of Dynamic Methods in Soil and Rock Mechanics. Karlsruhe, 5-16 September 1977. A.A. Balkema. Rotterdam. 1978. ISBN 9061910242

Scott, R.F. 1985. Plasticity on skid resistance at the Transport and road research laboratory (1927 to 1977), *Transportation Research Record 622*, Transportation Research Board, Washingrton, D.C.

Semmel, H. 1993. *Auswirkungen kontrollierter Bodenbelastungen auf das Druckfortpflanzungverhalten und physikalisch-mechanische Kenngrössen von Ackerböden*. Schriftenreihe Institut für Pflanzenernährung und Bodenkunde. Universität Kiel, nr. 26, ISSN 0933-680 X.

Soane, G.C., Godwin, R.J., & Spoor, G. 1986. Influence of deep loosining techniques and subsequent wheel traffic on soil structure. *Soil & Tillage Research, 8*, 231-237.

Söhne, W., 1958. Fundamentals of pressure distribution and soil compaction under tractor tires. Agricultural engineering, May.

Söhne, W. 1953. *Druckverteilung im Boden und Bodenverformung unter Schlepperreifen*. Grdlgn. Landtechn., 5, 49-63

Terzaghi, K. 1943. *Theoretical Soil Mechanics.* London: Chapman and Hall, Ltd. John Wiley and Sons, inc. New York.

Timoshenko, S.P. 1953. *History of strength of materials*. McGraw-Hill Book Company, Inc. Library of congress catalog card number: 52-10341.

Ullidtz, P. 1998. *Modelling Flexible Pavement Response and Performance*. Polyteknisk Forlag. pp 205. ISBN 87-502-0805-5

Vanden berg, G.E. & Gill, W.R. 1962. Pressure distribution between a smooth tyre and the soil. *Amer. Soc. Agr. Engin. Trans. 5*, 105-107.

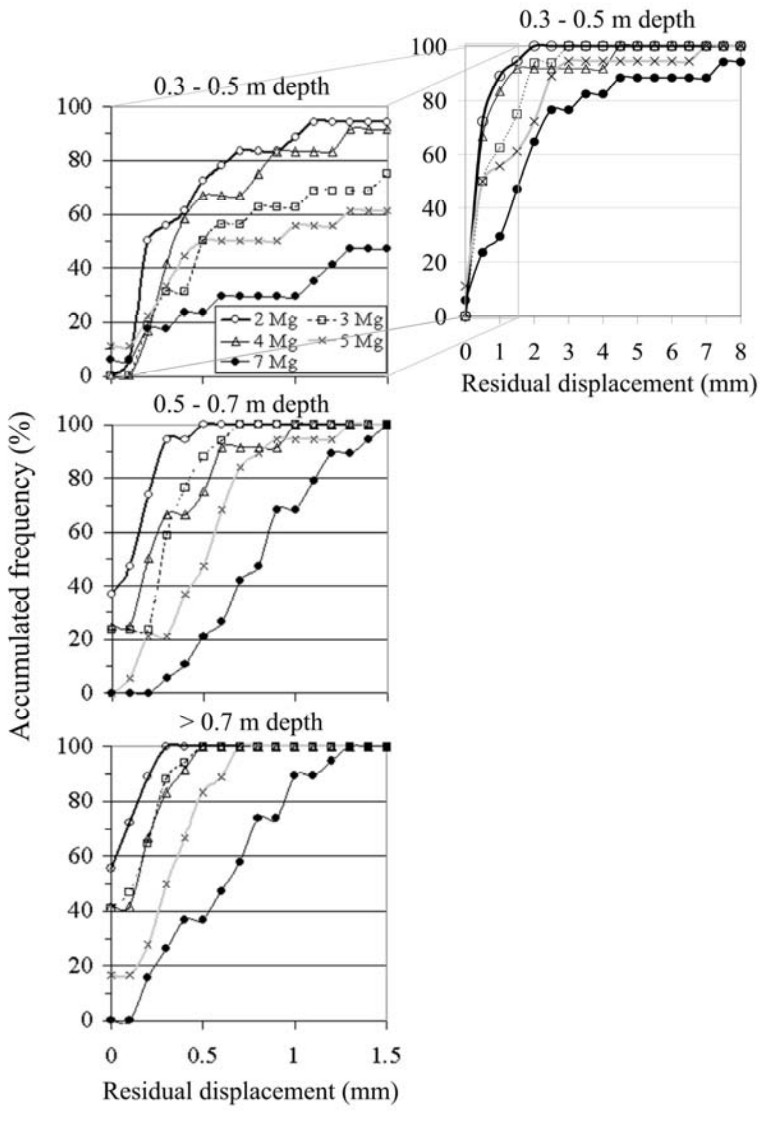


Fig. 22. Accumulated frequency (%) of vertical displacement measurements in intervals of 0; 0-0.1; 0.1-0.2 mm, etc. at three depths. Data from all sites and occasions.

This may simply be explained as a consequence of the structure of natural soils. Soil is an assemblage of a large number of particles, which make up the soil skeleton (Karafiath & Nowatzki, 1978). The strength of the contact points between these particles varies from almost zero to relatively high, i.e. the soil is anisotropic with regard to soil strength. According to Ullidtz (1998), "stresses" and "strains" only exist as average values over a large number of grains. This anisotropy is a characteristic of most natural soils and will be present in both wet and dry soils. Relatively small loads may therefore cause small, permanent displacements via

Van den Akker, J.J.H., & van Wijk, A.L.M. 1987. A model to predict subsoil compaction due to field traffic .In: G. Monnier and M.J. Goss (eds.) *Soil compaction and regeneration*. Proc. on the Workshop on soil compaction: *Consequences and structural regeneration precesses*. Avignon 17-18 Sept. 1985. Published for the Commission of the European Communities by A.A. Balkema/Rotterdam,/Boston/1987.
Young, R.N. & B.P. Warkentin. 1966. *Introduction to soil behaviour*. The Macmillian Company, N.Y. Library of Congress catalogue card number 66-11691

Acknowledgements

Many people have been involved in this thesis work, and without their help and effort, this thesis would never have been written. In particular, I would like to thank the following:

Johan Arvidsson: Thanks for lots of things. This thesis would not have been without you, and in the process, we truly had a lot of great times together.

Thomas Rydberg for all his support, both personal as well as professional.

Tony Dexter for teaching me many things about soil. Soil is indeed very strange.

John Lövkvist, Urban Svantesson, Bert “Mulle” Mårtensson, Fredrik Sassner, Emmanuel Puymoying, and last, but not least, Thomas Keller, for enormous help with the many field measurements.

Axel Lagerfeld (Tolefors) and Roland Johnsson (Kungagården), for allowing me to conduct experiments on their soils, and giving me invaluable help during the measurements.

My good friend Per Schjønning for all his support, brilliant ideas and great mind storming sessions which often send me to cloud seven or for a long soothing walk.

Inge Håkansson for his interest in the project, and for the frequent discussions that helped me interpreting the data and getting a grasp on the deformation process. Your dedication has been an inspiration for me.

Per Ullidtz for his enormous encouragement. Our discussions on soil deformation and stress propagation were eye-openers.

Bibbi for being such a wonderful and happy person.

Mary McAfee, Nick Jarvis and Ingvar Nilsson for improvement of manuscripts.

Rainer Horn, for interesting discussions and for putting my attention to several very useful papers.

Henry Jensen, Carsten Petersen and Kurt Pedersen for introducing me to soil science.

The dedicated people at the estates of Krenkerup, Bregentved and Vallø, (Denmark) who have played an important role in this thesis work.

The Swedish Farmers Foundation for Agricultural Research (SLF) and The Royal Swedish Academy of Agriculture and Forestry (KSLA) for financial support.