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Use of Finite Element Method to Determine the Influence of Land Vehicles Traffic on Artificial Soil Compaction

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1. Introduction

It is known that the soil is an heterogenous, polyphasic, disperse, structured and porous material, whose non-linear behaviour at the interaction with the rolling bodies of land vehicles is difficult to be modeled mathematically, being necessary to use simplifications and idealizations. The compaction phenomenon of agricultural soil can be defined as an increase of its dry density and the closer packing of solid particles or reduction in porosity (McKyes, 1985), which can result from natural causes, including rainfall impact, soaking and internal water tension (Gill & Vandenberg, 1968; Arvidsson, 1997). Knowing the behaviour of soil under the action of such rolling bodies is an important element, because, by optimizing the pressures applied on the soil, the negative effects of soil compaction can be diminished, both at the surface and in depth.

Agricultural soil is a particularely important case, being the development environment of plant roots, for which artificial compaction is very important. Soil compaction reduces water permeability, favoring water runoff on soil surface, causing erosion and preventing proper restoration of soil moisture. Soil aeration is also reduced, with direct consequences on the metabolic processes occurring in plant roots. Another negative effect for agriculture is the increase caused by compaction of mechanical resistance, thus the development of roots being delayed. All those mentioned effects may reduce the quantity and quality of agricultural products (Koolen & Kuipers, 1983).

Between land vehicles traffic and soil compaction, between soil compaction and the parameters characterizing the development environment of plants and between this environment and the level of crop production, there are direct qualitative relations, of cause-effect type. This raises the following two problems: the soil may be too compact to be actually used for agricultural production, requiring the prevention and reduction of this phenomenon; on the other hand, soil may not be compact enough to be used for road construction, dams or building foundations. In this last case, the problem is to obtain the maximum degree of compaction, with minimum effort (Gill & Vandenberg, 1968).

Compaction phenomenon must be described mathematically, by equations that take into account the forces causing it. From this point of view, there are two categories of forces: in the first category enter the mechanical forces generated by the traffic of land vehicles. These forces are applied for short periods of time and can be measured relatively easily (Gill &

Vandenberg, 1968). Second category is that of forces generated by natural phenomena. For example, drying has as effect soil compaction. Forces in this category are acting for long periods of time, are difficult to define and hard to measure. Estimating the degree of compaction can only be made by using precise equations, which describe soil behaviour at compaction. In the attempt to developing these equations, outstanding scientific efforts have been made.

Soil degradation is a worldwide topic of actuality (Keller, 2004). The European Union noticed that it is necessary to protect soil and has identified soil compaction as one of the most important threats for soil, which leads to its degradation (COM, 2002). Soil compaction in an environmental problem (Pagliai et al., 2004). It is also one of the causes of erosion and land flooding (Horn et al., 1995; Soane & Ouwerkerk, 1995; Gieska et al., 2003). In addition, it contributes directly or indirectly to crop growth and pesticides leaching in ground water and to the emission of nitrogen oxides in the atmosphere (Lipiec & Stepniewski, 1995). Efforts to improve depth compaction by deep loosening are expensive and often ineffective. Therefore, soil compaction must be prevented. It is believed that the risk of unwanted changes in soil structure can be decreased by limiting the applied mechanical stresses (Dawidowski et al., 2001), and by limiting the precompression tensions.

The most important factors, which have a significant influence in the process of artificial compaction of agricultural soil, are: the type of soil, moisture content of the soil, intensity of external load, area of the contact surface between the soil and the tyre or track, shape of the contact surface, and the number of passes (Biriş, 2003).

The impact of land vehicles on soil properties can be simulated using compaction models (Bailey et al., 1986; O'Sullivan et al., 1999), which are an important instrument in the development strategy for soil compaction prevention. The traffic of land vehicles on soil in inappropriate moisture conditions is one of the most important causes of soil degradation by artificial compaction (Trautner, 2003). The value of soil moisture must be taken into account when referring to the traffic of a land vehicle which develops soil works, crops maintenance, harvest or transport. It is known that, for proper processing of agricultural soil, its normal moisture in the processed layer must be 18-22 % (Biris et al., 2007; Biris et al., 2009). Too dry soil compacts less, deforms less, but the resistance to processing is higher. For optimum moisture soils, the area of maximum pressures is found in the plough area, while soil deformations are reasonable, the resistance at mechanical processing being minimum. In case of too wet soil, maximum stresses are concentrated near the rolling bodies, soil strains are very high, shear stresses are high, and soil processing under these conditions is not recommended (Arvidsson, 1997).

Soil moisture influences the deforming pattern and the size of soil strains at the contact with the rolling bodies of land vehicles (Bakker et al., 1995; Way, 1995). Strains are very low for dry soils, but, under these conditions, agricultural works of soil processing are not recommended, because friction forces between soil particles and working bodies are very large, leading to large mechanical resistances, and abrasion wear phenomena for these working bodies are emphasized. Transport works, traffic, phytosanitary treatments applying, harvesting, etc. is recommended to be performed at smaller moisture values.

At the present moment, one of the most advanced methods for modelling the phenomenon of stresses propagation into soil is the Finite Element Method (FEM), which is a numerical method for obtaining approximate solutions of ordinary and partial differential equations of this distribution (Biris et al., 2003; Biris et al., 2007, Biris et al., 2009; Britto & Gunn, 1987; Gee-Clough et al., 1994; Van den Akker, 2004).

This paper presents a model for prediction of the stress state in agricultural soil below agricultural tyres in the driving direction and perpendicular to the driving direction, which are different from one another, using the Finite Element Method. It was created a general model of analysis using FEM, which allows the analysis of equivalent stress distribution and the total displacements distribution in the soil volume, making evident both of the conditions in which the soil compaction is favoured and of the study of graphic variation of equivalent stress and the study of shifting in the depth of soil volume.

This work has theoretical and obvious practical importance, because it allows that, by running the program of analysis through Finite Elements Method, to determine in a short period of time how are distributed in the soil the stresses that generate soil compaction at the interaction with the rolling bodies of land vehicles, for all traffic conditions and for any physical and mechanical properties of soil, no matter what value its moisture has.

2. Modelling the soil artificial compaction

2.1 Modelling the soil stress spreading

Because the agricultural soil is not a homogeneous, isotropic, and ideal elastic material, the mathematical modelling of stress propagation phenomenon is very difficult. Many mathematical models of stress propagation into the soil under different traction devices are based on the Boussinesq equations, which describe the stress distribution under a load point (Figure 1) acting on a homogeneous, isotropic, semi-infinite, and ideal elastic medium (Hammel, 1994). Frohlich developed equations to account for stress concentration around the application point of a concentrated load for the problem of the half-space medium subjected to a vertical load (Kolen, 1983).

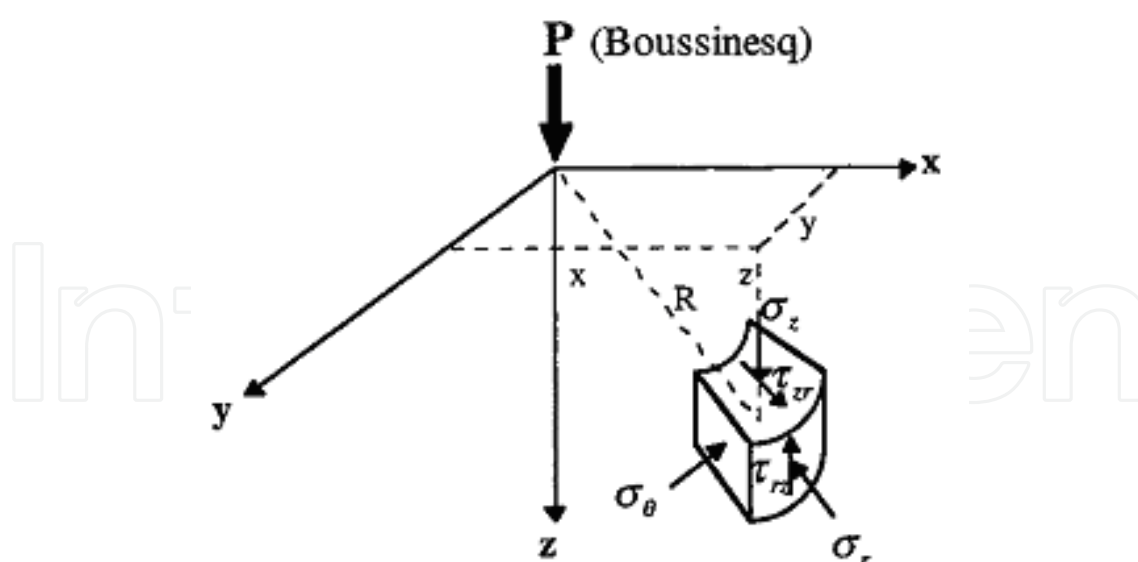


Fig. 1. Stress state produced by a concentrated vertical load (Upadhyaya, 1997)

Many models of dynamic soil behaviour are using elastic properties of soil, and when the soil is represented by a linear-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).

For agricultural soils, the relationships between stresses and strains are measured on soil samples in the laboratory or directly in the field. The stress-strain relationships are given by constitutive equations (Gee-Clough, 1994).

The Drucker-Prager plasticity model can be used to simulate the behaviour of agricultural soil. The yield criteria can be defined as:

$$F = 3 \cdot \alpha \cdot \sigma_m + \bar{\sigma} - k = 0 \quad (1)$$

where a and k are material constants which are assumed unchanged during the analysis, σ_m is the mean stress and $\bar{\sigma}$ is the effective stress, a and k are functions of two material parameters (Φ and c) obtained from the experiments, where Φ is the angle of internal friction and c is the material cohesion strength.

Using this material model, the following considerations should be noted: strains are assumed to be small; problems with large displacements can be handled providing that the small strains assumption is still valid; the use of NR (Newton-Raphson) iterative method is recommended; material parameters Φ and c must be bounded in the following ranges: $90^\circ \geq \Phi \geq 0$ and $c \geq 0$.

The required input parameters for the constitutive model of the agricultural soil of wet clay type are (Gee-Clough, 1994):

- Soil cohesion (c): 18.12 kPa
- Internal friction angle of soil (ϕ): 30°
- Soil density (γ_w): 1270 kg/m³
- Poisson's ratio (ν_s): 0.329
- Young's modulus (E): 3000 kPa

The stress levels under a point load as shown in figure 1 are given in cylindrical coordinates as follows (Upadhyaya, 1997):

$$\sigma_z = \frac{3 \cdot P \cdot z^3}{2 \cdot \pi \cdot R^5} \quad (2)$$

$$\sigma_r = \frac{P \cdot z^3}{2 \cdot \pi} \cdot \left[\frac{3 \cdot z \cdot r^2}{R^5} - \frac{1 - 2 \cdot \nu}{R \cdot (R + z)} \right] \quad (3)$$

$$\sigma_\theta = \frac{P \cdot (1 - 2 \cdot \nu)}{2 \cdot \pi} \cdot \left[\frac{1}{R \cdot (R + z)} - \frac{z}{R^3} \right] \quad (4)$$

$$\tau_{rz} = \frac{3 \cdot P \cdot r \cdot z^2}{2 \cdot \pi \cdot R^5} \quad (5)$$

where P -is the point load, ν -Poisson's ratio, $\sigma_{z,r,\theta}$ -normal stress components, and τ_{rz} -shear stress component.

Figure 2 shows the stress state in soil, of an infinite cubic soil element, which can be written in a matrix, named the matrix of the stress tensors (Koolen, 1983; McKyes, 1985). Stresses acting on a soil element can be described by mechanical invariants, which are independent of the choice of reference axes. The invariants yields are (Keller, 2004):

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3 = \sigma_x + \sigma_y + \sigma_z$$

(6)

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

(7)

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

(8)

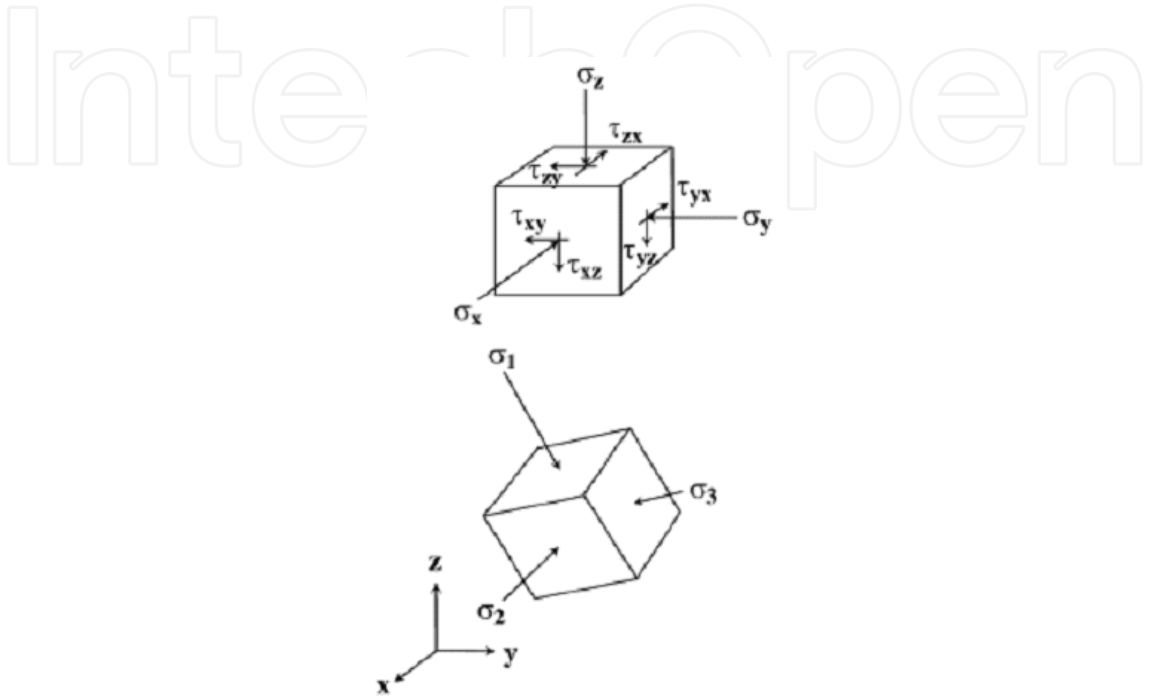


Fig. 2. Stress tensor components (Koolen, 1983)

It is useful to define the stress measures that are invariant. Such stress is the octahedral normal stress and the octahedral shear stress (Keller, 2004):

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

(9)

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

(10)

The critical state soil mechanics terminology uses the mean normal stress p and the deviator stress q . If $p = \sigma_{oct}$ (Eq. 9), q is given as (Keller, 2004):

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

(11)

2.2 Utilization of incremental methods for studying the soil non-linear behaviour

The incremental methods are used to deal with material and geometrically non-linear problems. The basis of the incremental procedure is the subdivision of the load into many small increments. Each increment is treated in a piecemeal linear behaviour with the stiffness matrix evaluated at the start of the increment. The tangent stiffness, E_t (Figure 3) for

each element is calculated from the stress-strain curves according to the current stress level of that element. The Finite Element Method (FEM) is proving to be very promising into modelling this propagation phenomenon. In a FEM calculation when the coordinates are continually updated, the strain increment $d\epsilon$, has the mean of a ratio between an incremental length and the current length.

The relationship between ϵ and $\bar{\epsilon}$ has the form (Gee-Clough, 1994):

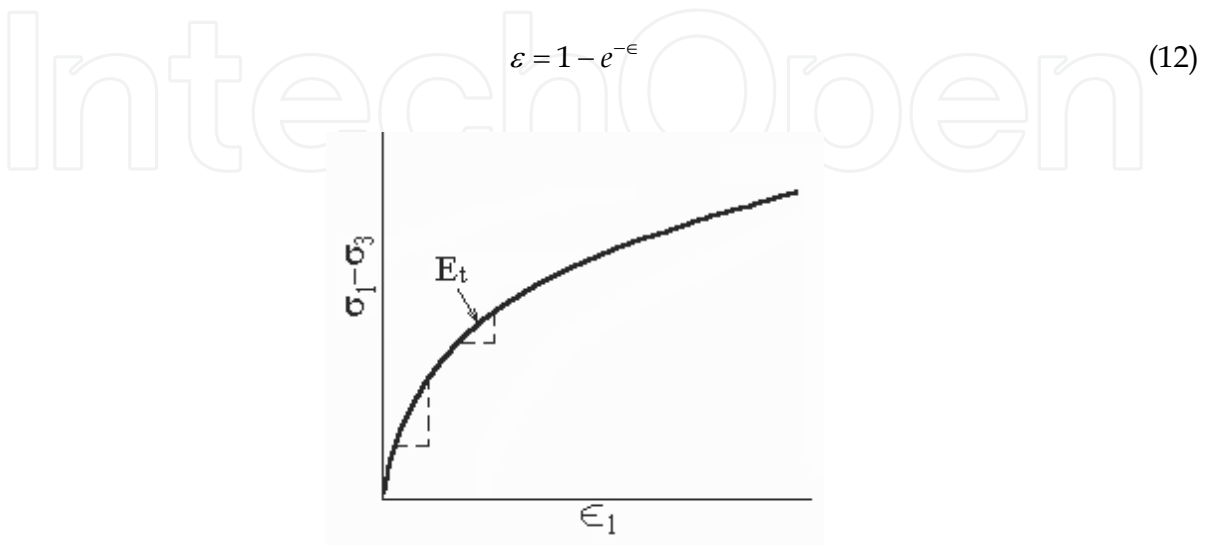


Fig. 3. Stress-strain curve for agricultural soil

According to the relationship between ϵ and $\bar{\epsilon}$ the following revised stress-strain and tangent stiffness formulae were derived and used in the calculation (Gee-Clough, 1994):

$$\sigma_1 - \sigma_3 = \frac{1 - e^{-\epsilon_1}}{a + b \cdot (1 - e^{-\epsilon_1})} \tag{13}$$

$$E_t = \frac{1}{a} \cdot [1 - b \cdot (\sigma_1 - \sigma_3)] \cdot [1 - (b + a) \cdot (\sigma_1 - \sigma_3)] \tag{14}$$

For saturated soil under an un-drained condition, the volume change is generally considered to be negligible. But for FEM calculation purposes, it is common to assume a constant Poisson’s ratio slightly less than 0,5 (Gee-Clough, 1994). In terms of the concept of the incremental method, for a soil with nonlinear properties when increments are very small, Hooke’s law in which the Young’s modulus, E_t , and Poisson’s ratio, ν_t , are variables (depending on current stress and strain values) is valid. On this basis, for a plane strain problem, a formula for the volume modulus, K_t , can be derived:

$$K_t = \frac{d(\sigma_x + \sigma_y)}{d(\epsilon_x + \epsilon_y)} = \frac{E_t}{(1 - \nu_t - 2 \cdot \nu_t^2)} \tag{15}$$

where: ϵ_x, ϵ_y are strains in x and y directions; σ_x, σ_y are stresses in x and y directions.

If ν_t is constant, as E_t decreases (soil failure), K_t also decreases. This means that soil volume changes can be large. Assuming K_t is constant, and the initial values of E_t and ν_t are E_0 and ν_0 , respectively, then the Poisson’s ratio formula can be derived as in eq. (15) in which a

maximum ν_t and a minimum E_t may be specified to avoid the calculation problem (Gee-Clough, 1994):

$$\nu_t = 0,25 \cdot \left(\sqrt{9 - \frac{8 \cdot E_t}{E_0} \cdot (1 - \nu_0 - 2 \cdot \nu_0^2)} - 1 \right) \tag{16}$$

2.3 Tyre deformation at running path interaction

Under the action of an external load (weight per wheel), a tire deforms as it is shown in figure 4. According to Hedekel’s equation, tire deformation is given by the following relationship:

$$f = \frac{F}{2 \cdot \pi \cdot p_i \cdot \sqrt{R \cdot r}} \quad [\text{mm}] \tag{17}$$

where: F – vertical load acting on the wheel, [N]; p_i – air pressure inside the tire, [MPa]; R – free radius of the wheel, [mm]; r – radius of tire running path in cross section, [mm].

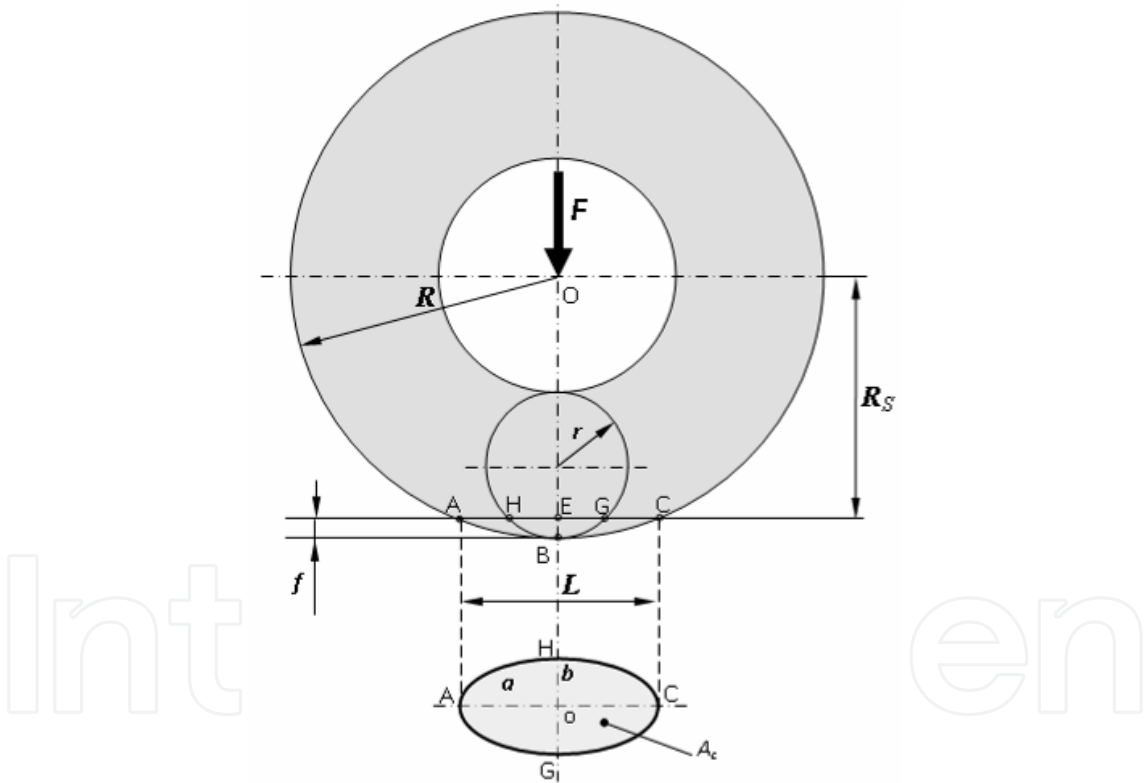


Fig. 4. Tire deformation under the action of an external load

Static tire radius is given by:

$$R_s = R - f \quad [\text{mm}] \tag{18}$$

and the length of the contact chord is:

$$L = 2 \cdot \sqrt{R^2 - R_s^2} \quad [\text{mm}] \tag{19}$$

Figure 5 shows the influence of tire pressure on the dimensional characteristics of the wheel (figure 4), respectively tire deformation (Eq. 17), static radius R_s (Eq. 18) and the length of contact chord L (Eq. 19), for the rear wheel.

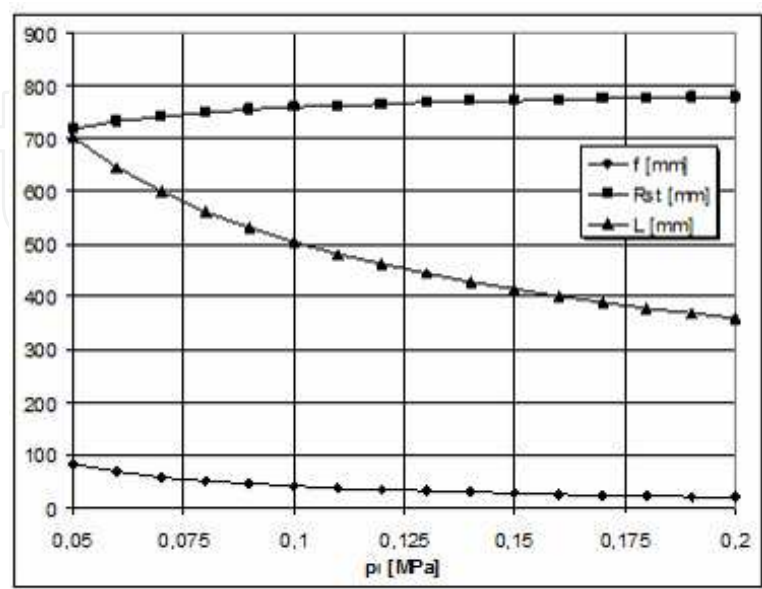


Fig. 5. Influence of tire pressure on the dimensional characteristics of the wheels

2.4 Contact surface between tyre and running path

The calculation of the contact surface between tyre and running path is rather complicate due to this interface complexity which depends on soil variaible parameters and tyre parameters. It is usually necessary to make simplifying assumption of the true contact area. Surface of contact can be approximated by a circle, in case of rigid running paths and tyres with high pressure. In case of low inflation pressures, the more elliptical the contact area becomes. Low tire inflation pressure and high axle loads lead to high tire deflection and the contact area is no longer elliptical, but rectangular with curved ends (Upadhyaya & Wulfsohn, 1990). Figure 6 shows the theoretial shape of contact area between the soil and agricultural tyres. The pressure distribution along the width of tyre is described by a decay function (Keller, 2004):

$$p(y) = C \cdot \left[\frac{w(x)}{2} - y \right] \cdot e^{-\delta \cdot \left[\frac{w(x)}{2} - y \right]}; 0 \leq y \leq \frac{w(x)}{2} \tag{20}$$

and the pressure distribution in the driving direction is described by a power-law function:

$$p(x) = p_{x=0,y} \cdot \left\{ 1 - \left[\frac{x}{\frac{l(y)}{2}} \right]^a \right\}; 0 \leq x \leq \frac{l(y)}{2} \tag{21}$$

where C , δ and a are parameters, $w(x)$ is the width of contact between the tyre and soil, $p_{x=0,y}$ is the pressure under the tyre centre and $l(y)$ is the length of contact between the tyre and soil.

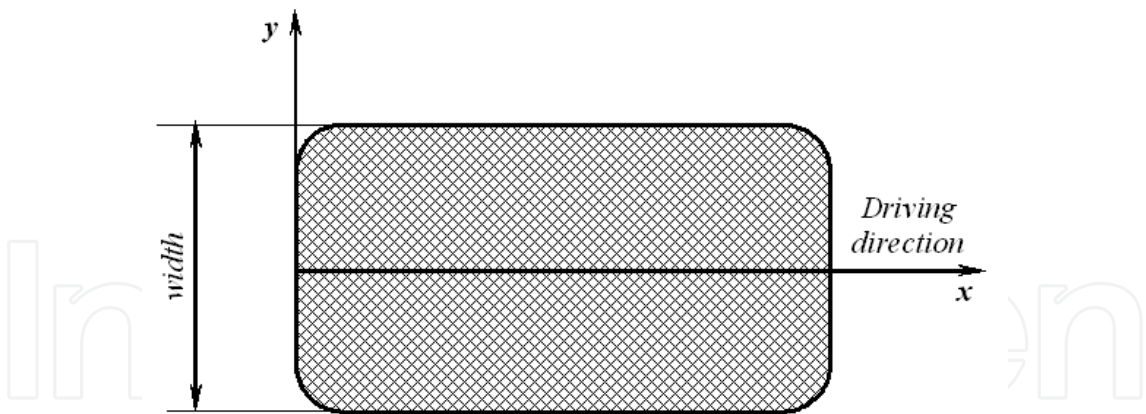


Fig. 6. Shape of the contact surface between the soil and the tyre

Figure 7 shows the vertical load distribution in the contact area beneath agricultural tyres for three considerations: the real distribution with measured values (left), a model with uniform load distribution (centre), and a better model with irregular load distribution (right).

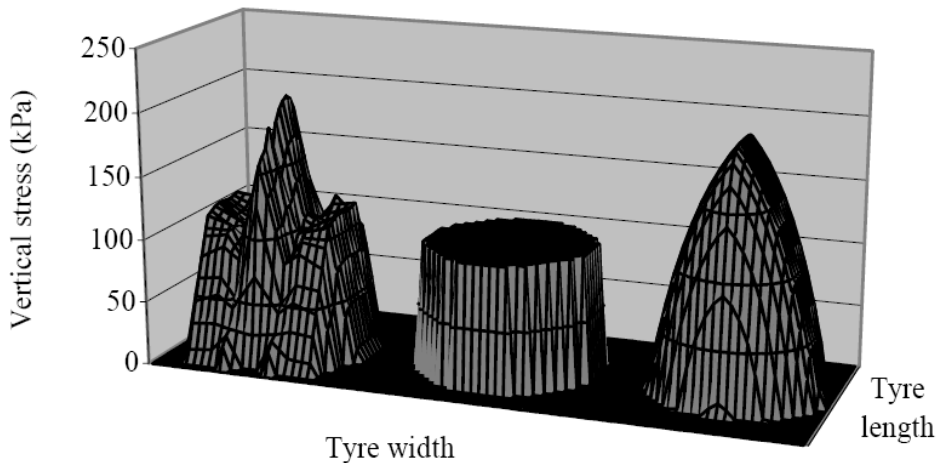


Fig. 7. Distribution of the vertical load in the contact area (Keller, 2004)

Equation (20) can describe different cases of pressure distribution, e.g. maximum pressure under the tyre centre or pressure under the tyre edge. The parameters C , δ and a are calculated from wheel load, tyre inflation pressure, recommended tyre inflation pressure at given wheel load, tyre width and overall diameter of the unloaded tyre. All these parameters are easy to measure or readily available from e.g. tyre catalogues.

2.5 FEM model for studying the distribution of soil strains and stresses

For the modelling using the finite element method it was considered a soil volume with the depth of 1 meter, the width of 3 meter and length of 4 meter (Figure 8) under the action of different tractors and harvester-threshers (Table 1). The structural nonlinear analysis was made on the ideal model, the soil being considered a homogeneous and isotropic material. It was used the COSMOS/M 2.95 Programme for FEM modelling.

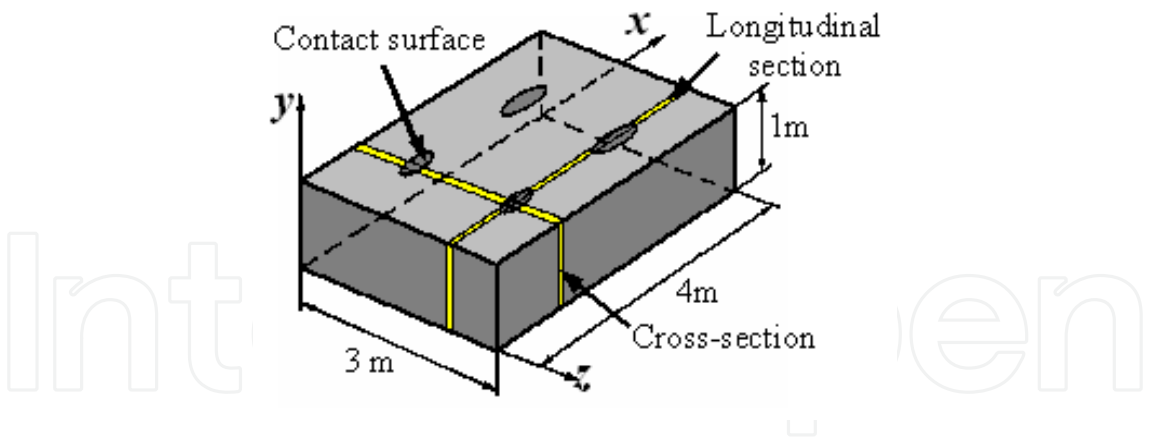


Fig. 8. Analyzed soil volume

Applicant	Soil interaction elements	Gauge [mm]	Mass (total / deck) [kg]		The active width for load [mm]	Pressure on the soil [kPa]
Romanian tractor U-445 (45 HP)	The front wheels	1500	1920	720	170	82.5
	The back wheels			1200	315	44.2
Romanian tractor U-650 (65 HP)	The front wheels	1600	3380	1170	180	110
	The back wheels			2210	367	57.3
Romanian Caterpillar SM-445 (45 HP)	Track	1300	2600		360	31
Harvester-thresher NH-TX66	The front wheels	2950	14000	11000	615	106.5
	The back wheels			3000	408	103.2
Romanian harvester-thresher Sema-140	The front wheels	2850	11033	9033	587	115
	The back wheels			2000	317.5	148.5

Table 1. The principal characteristics of the rolling devices used in modelling

The static radius of tire and length of contact chord are computed, thus providing the contact area between the wheel and the soil and the value of the pressure applied by the rolling body on the soil.

Figures 9, 10 and 11 show the results of FEM analysis in cross-section and figures 12, 13, 14 and 15 the results of FEM analysis in longitudinal section for two 45 HP tractors with tires and with caterpillar (U-445 and SM-445), respectively for two harvester-threshers (New Holland TX-66 and SEMA-140). These results are: the stresses distribution in soil and the

graphical variation of stresses along the vertical-axial direction and along to the longitudinal direction.

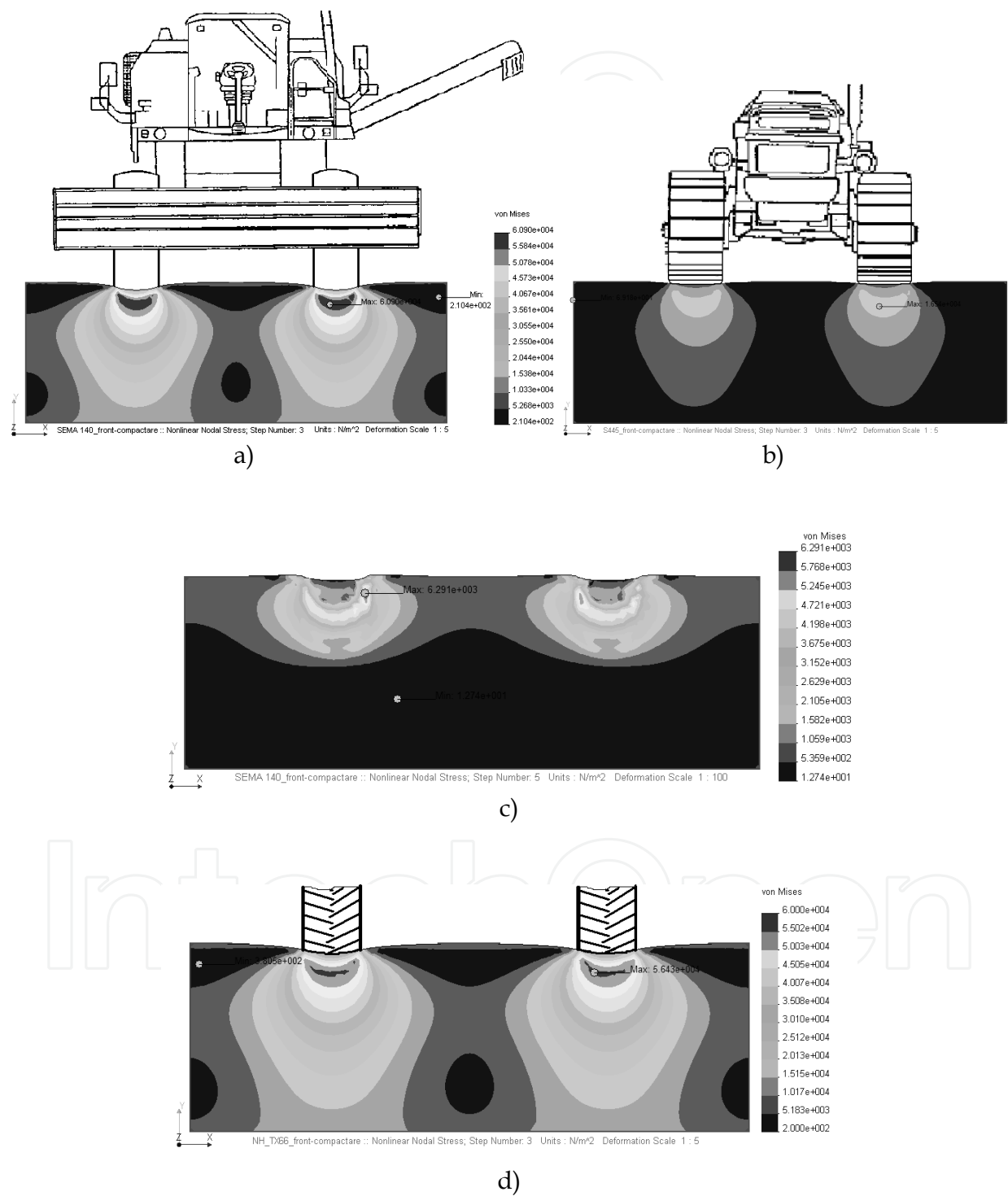


Fig. 9. Stresses distribution in cross-section for: a) SEMA 140 harvester-thresher, b)SM-445 caterpillar tractor, c) SEMA 140 harvester-thresher after the first transit, d) New Holland TX-66 harvester-thresher (Units: Pa)

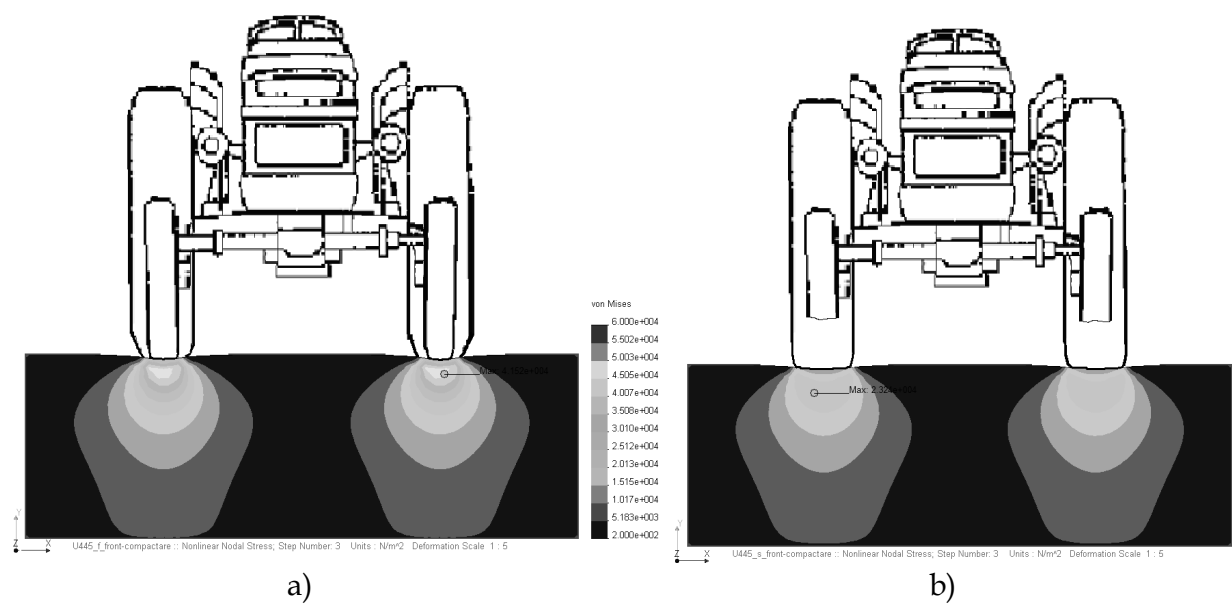


Fig. 10. Stresses distribution in cross-section for: a) front wheels of U-445 tractor (U-445_f) (Units: Pa), b) back wheels of U-445 tractor (U-445_b) (Units: Pa)

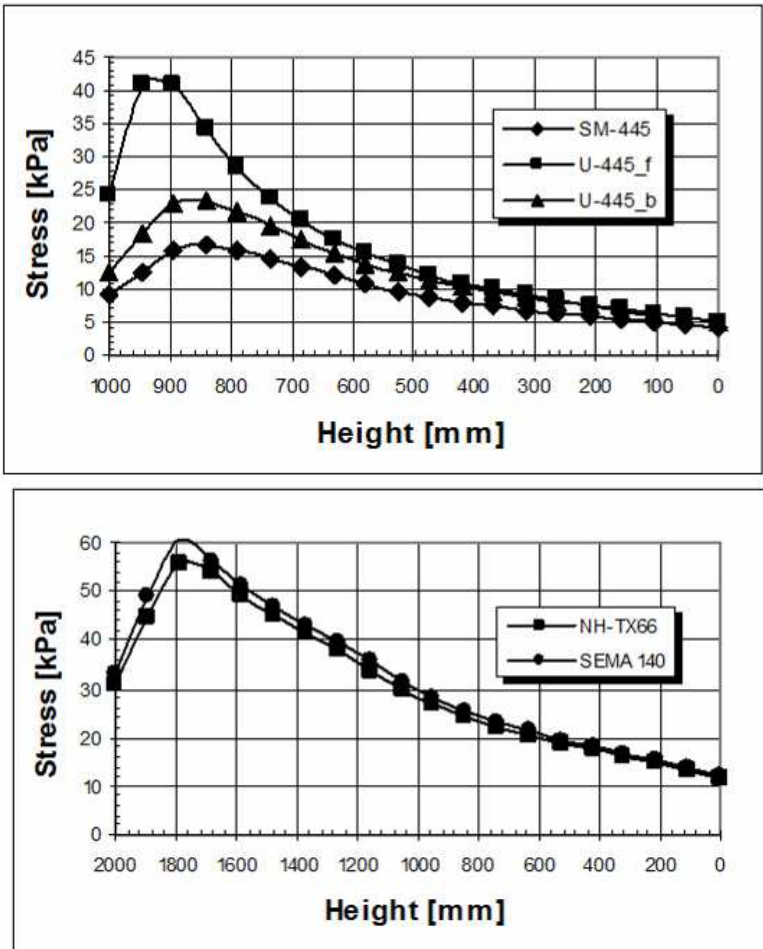


Fig. 11. Graphical distribution along the axial-vertical direction

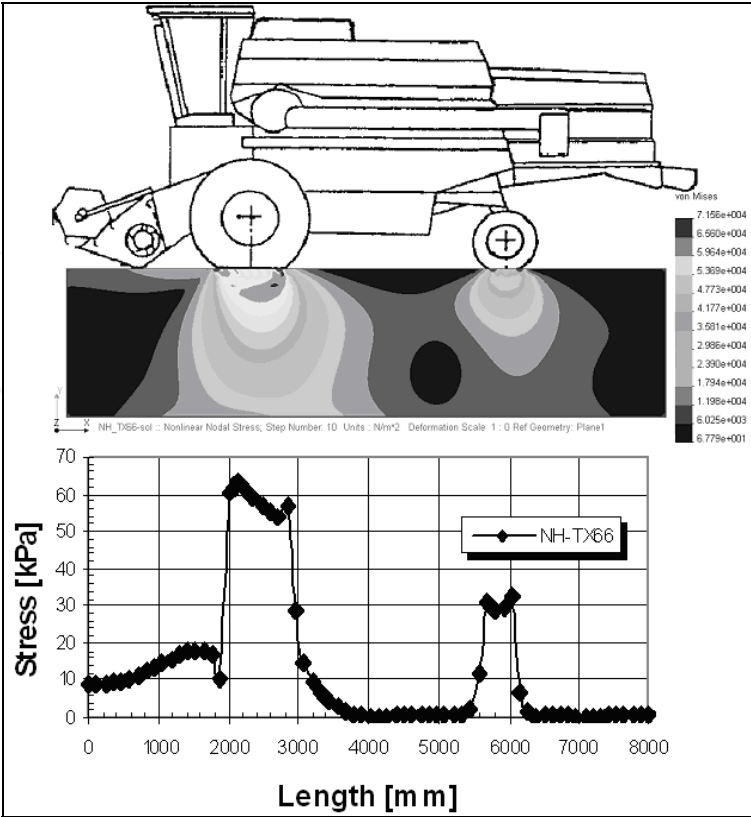


Fig. 12. Stresses distribution and graphical variation along the longitudinal direction to the top layer of the soil in longitudinal section for New Holland TX-66 harvester-thresher

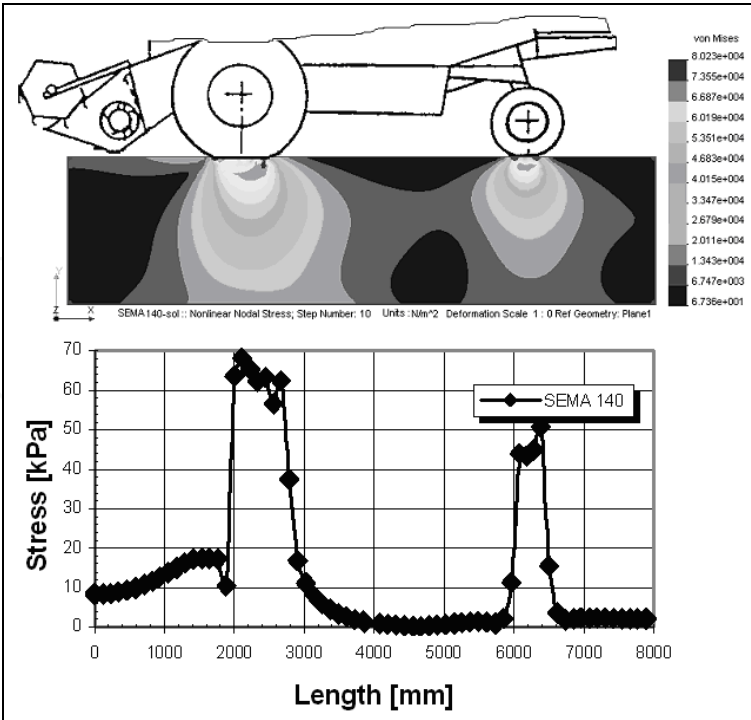


Fig. 13. Stresses distribution and graphical variation along the longitudinal direction to the top layer of the soil in longitudinal section for SEMA 140 harvester-thresher

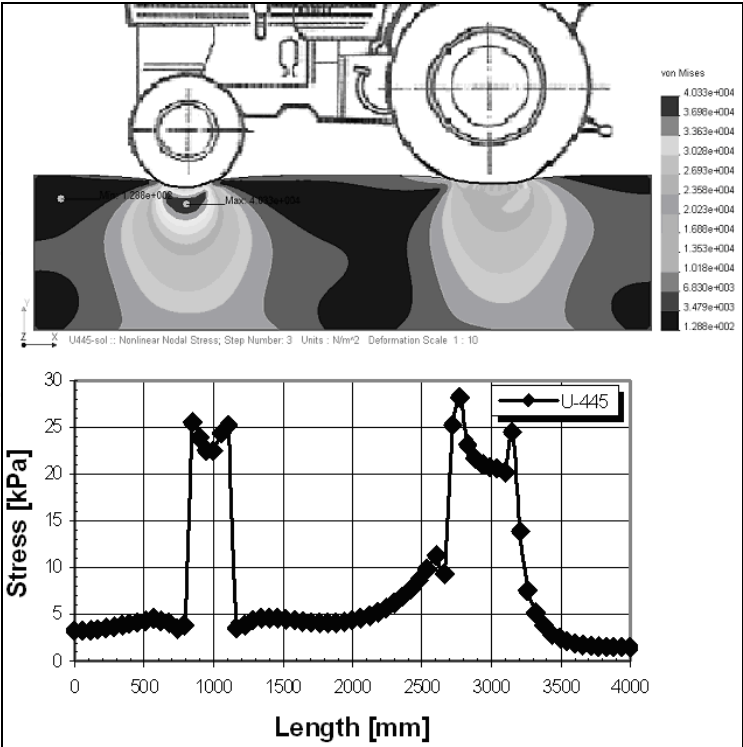


Fig. 14. Stresses distribution and graphical variation along the longitudinal direction to the top layer of the soil in longitudinal section for U-445 tractor, b) SM-445 caterpillar tractor

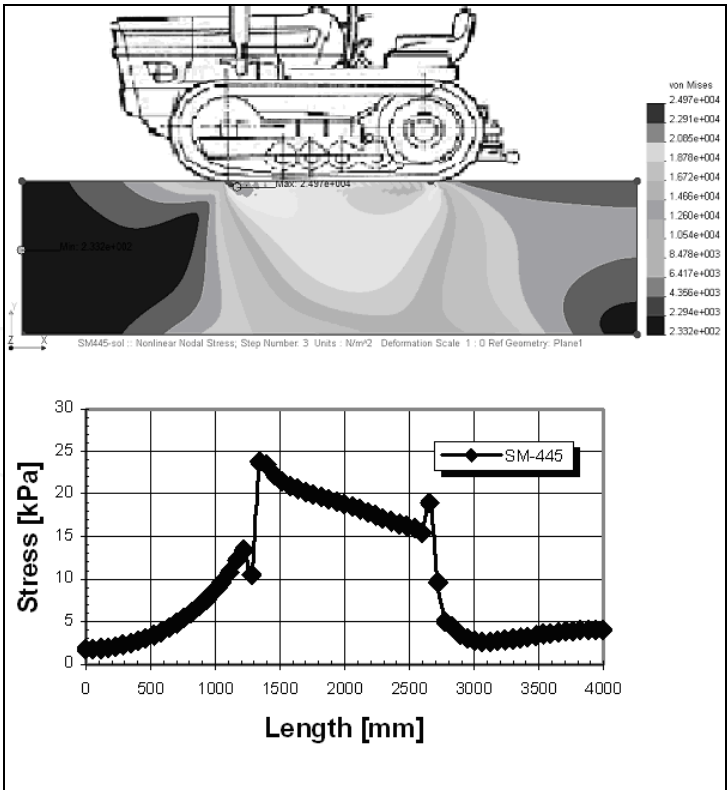


Fig. 15. Stresses distribution and graphical variation along the longitudinal direction to the top layer of the soil in longitudinal section for SM-445 caterpillar tractor

Figure 16 shows the results of FEM analysis in cross-section for a “1/2 symmetrical model” which consists in equivalent stresses distribution in agricultural soil under the action of a uniform load in the case of back wheel of U-650 tractor. Figure 17 shows the distribution of equivalent stresses in agricultural soil in cross-section for the same “1/2 symmetrical model” under the action of an un-uniform load (Decay function, Eq. 20) in the case of back wheel of U-650 tractor.

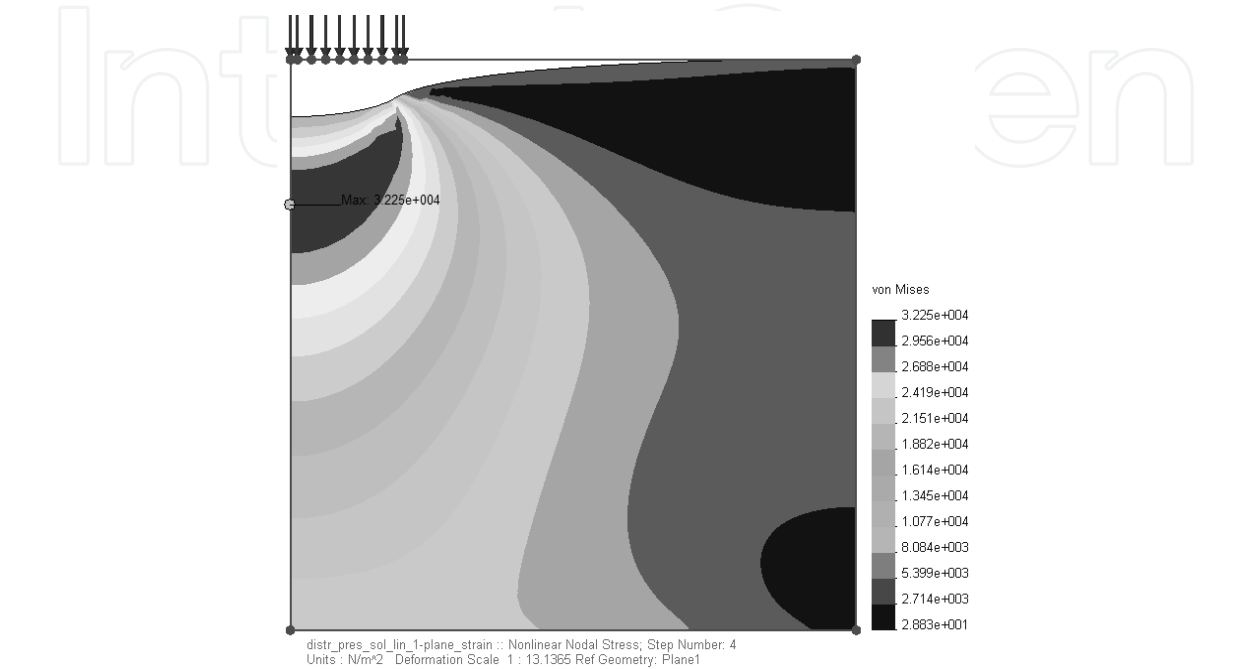


Fig. 16. Distribution of equivalent stresses for uniform load in the case of back wheel of U-650 tractor (Units: Pa)

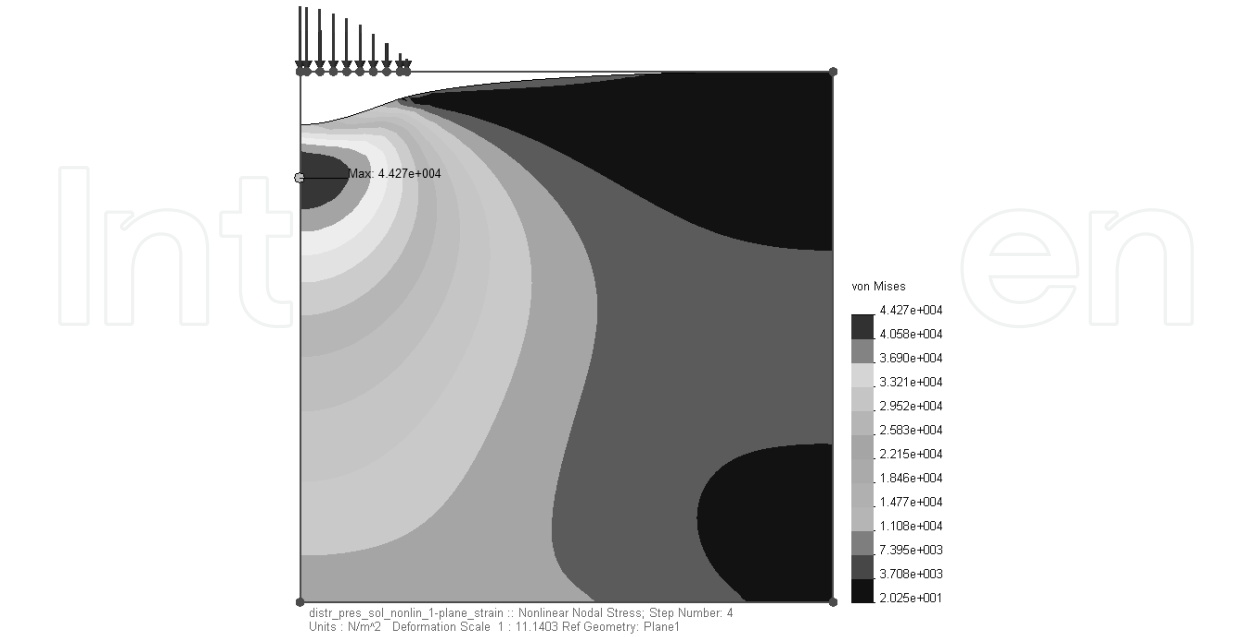
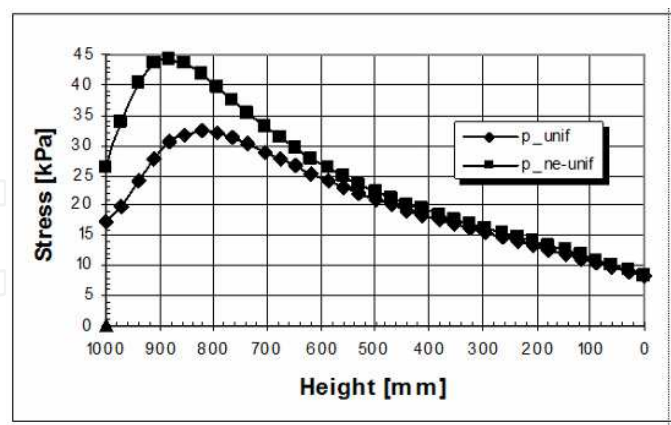


Fig. 17. Distribution of equivalent stresses for un-linear load in the case of back wheel of U-650 tractor (Units: Pa)

Figure 18 shows the graphical variation of equivalent stresses along the vertical-axial direction for the two cases of loading.



(p_unif: uniform load; p_ne-unif: un-linear load)
Fig. 18. Graphical variation of stresses along the vertical-axial direction

2.6 Laboratory tests for studying the stress and strain distribution into the soil

In order to check the model elaborated using FEM, laboratory tests were taken using a data acquisition system (Figure 19). The system was connected to Flexi Force Tekscan W-B201-L force sensors (Figure 20), vertically mounted in the soil, at 10 cm distance, in a metallic container with 1x1x1 m dimensions (Figure 21). The load on the wheel (of different types) in statically state was applied using the Hydropulse equipment (Figure 22).

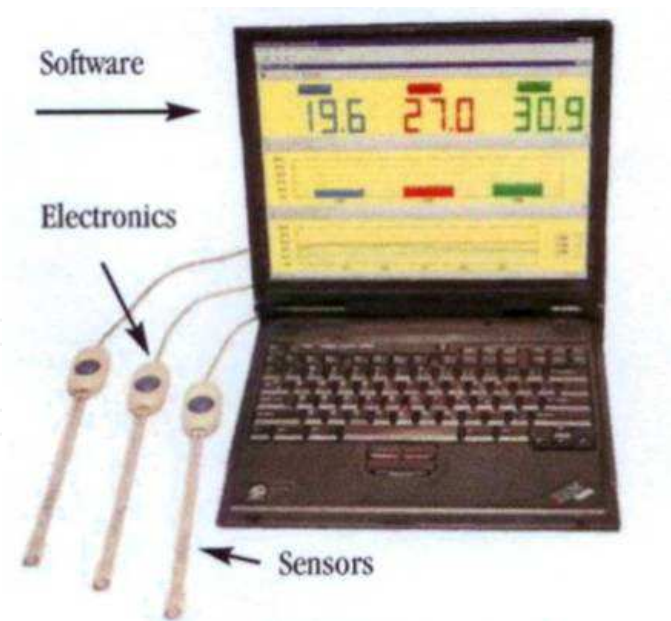


Fig. 19. Data acquisition system



Fig. 20. Flexi Force Tekscan W-B201-L force sensors



Fig. 21. Metallic container



Fig. 22. Test stand in Hydropulse laboratory

2.7 Comparative analysis of results measured and calculated, using FEM model

In figures 23 and 24 are comparatively presented the variation curves of the equivalent stresses with the points obtained by FEM calculus and by experimental tests for different depths along the tire's vertical axis in the case of the U-445 tractor.

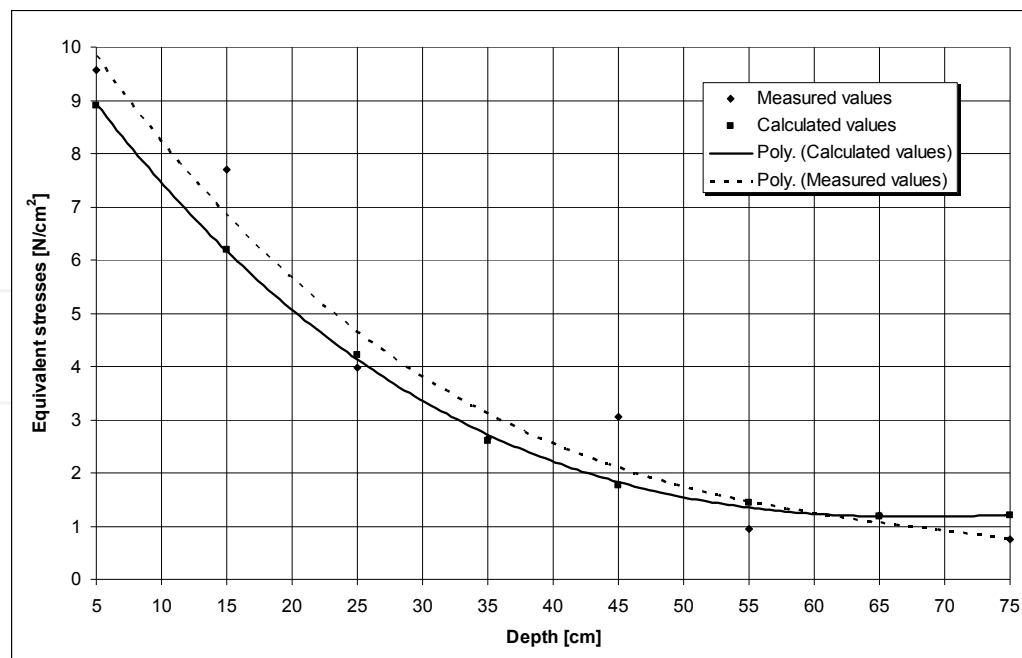


Fig. 23. Equivalent stresses calculated and measured for the front deck of U-445 tractor

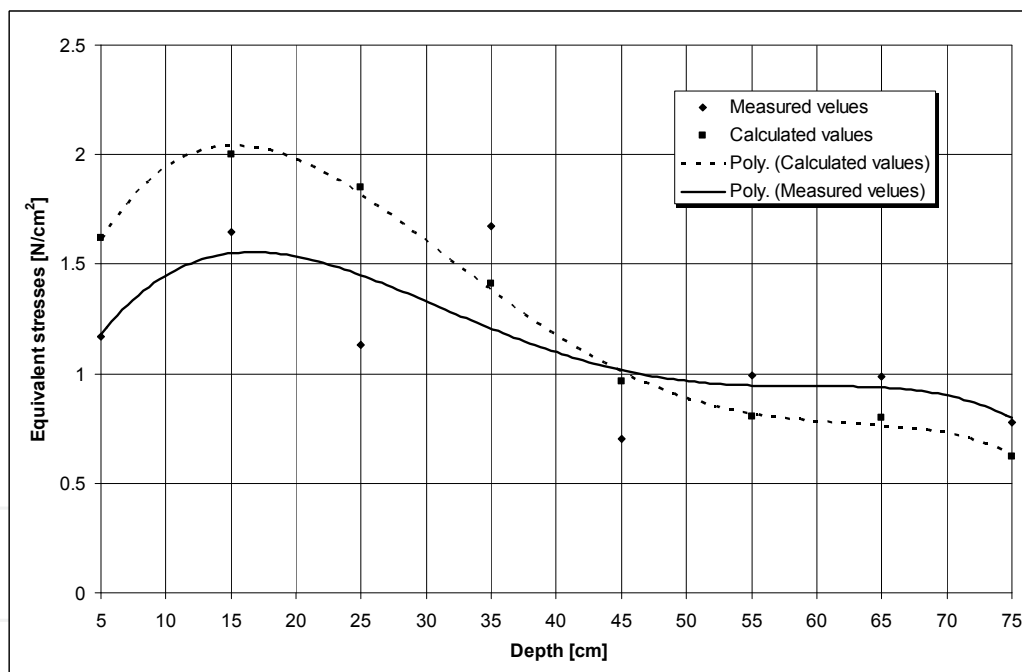


Fig. 24. Equivalent stresses calculated and measured for the back deck of U-445 tractor

3. Conclusions

The Finite Element Method is at the present the most advanced mathematical tool which can be used for the study of agricultural soil artificial compaction process. For mathematical modelling the soil is considered as a homogeneous and isotropic material, and the Drucker-Prager plasticity model can be used to simulate the behaviour of agricultural soil.

This study shows that from these analysed tractors and harvester-threshers, the highest artificial compaction of soil was caused by the front wheels of SEMA-140 harvester-thresher (see Figure 13), when the equivalent maximum stress in soil is approx. 60 kPa, and in the case of the front wheels of NH TX-66 harvester-thresher (Fig. 12), when the maximum equivalent stress is higher than 55 kPa. In these cases it is recommended to extend the contact area between the wheel and the soil.

In the case of the front wheels of U-445 tractor (see figure 10.a), the equivalent maximum stress in soil is approx. 42 kPa (Fig. 11). We can see that the equivalent maximum stress in soil in the case of analyzed caterpillar tractor (SM-445) is less than 20 kPa (Figure 11 and 15). This study represents a supplementary argument for using the caterpillar for the reduction of artificial soil compaction. The present researches are directed to using the rubber caterpillar, and also to using the reduce-pressure tyres with largest contact area with the soil.

We can see from the figures 16, 17, and 18, that the distribution of equivalent stresses in soil volume is strongly influenced by the loading distribution in the contact area.

As we can see in figure 23 and 24, between the calculated and measured results is a difference of 8% for the front wheel and 12% for the back wheel of U-650 tractor. There is a true development possibility of the pseudo-analytical procedures for the modelling of the stress propagation in agricultural soil, based on the work of Boussinesq, Fröhlich and Söhne, using the numerical calculus procedures, respectively the finite element method.

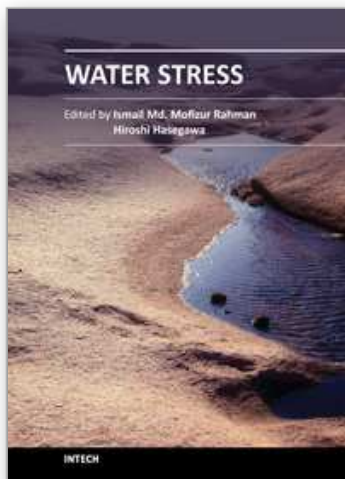
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Plants experience water stress either when the water supply to their roots becomes limiting, or when the transpiration rate becomes intense. Water stress is primarily caused by a water deficit, such as a drought or high soil salinity. Each year, water stress on arable plants in different parts of the world disrupts agriculture and food supply with the final consequence: famine. Hence, the ability to withstand such stress is of immense economic importance. Plants try to adapt to the stress conditions with an array of biochemical and physiological interventions. This multi-authored edited compilation puts forth an all-inclusive picture on the mechanism and adaptation aspects of water stress. The prime objective of the book is to deliver a thoughtful mixture of viewpoints which will be useful to workers in all areas of plant sciences. We trust that the material covered in this book will be valuable in building strategies to counter water stress in plants.

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