MODELLING OF SOIL COMPACTION UNDER HEAVY-DUTY TRACTORS / *MODELAREA COMPACTĂRII SOLULUI SUB ACȚIUNEA TRACTOARELOR DE MARE PUTERE*

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ABSTRACT

This paper presents a theoretical model for prediction of the stress state in agricultural soil under the agricultural tires of a heavy-duty tractor, using the Finite Element Method. Using an acquisition data system and pressure sensors, the theoretical model was experimentally verified in the laboratory. This study highlights the major advantage of using FEM models, which consists mainly in the spectacular reduction of costs for experimental testing and a considerable reduction in the time needed to analyse the possibility of the occurrence of artificial compaction phenomenon in the agricultural soil under heavy-duty tractors.

REZUMAT

Lucrarea prezintă un model teoretic pentru estimarea stării de tensiune în solul agricol sub acțiunea roților unui tractor de mare putere, utilizând metoda elementelor finite. Cu ajutorul unui sistem de achiziție de date și a senzorilor de presiune, modelul teoretic a fost verificat experimental în laborator. Acest studiu evidențiază avantajul major, în cazul utilizării modelelor FEM, care constă, în principal, în reducerea spectaculoasă a costurilor necesare încercărilor experimentale și a timpului necesar analizării posibilității de apariție a fenomenului de compactare artificială a solului agricol sub acțiunea tractoarelor de mare putere.

INTRODUCTION

At the moment, the heavy-duty tractors are increasingly used in intensive farming and especially where conservative technology for seedbed preparation is applied, because it offers the possibility of working with a minimum number of passes on agricultural soil, thus conserving it and avoiding the risk of artificial soil compaction. The heavy-duty tractors are characterized by the fact that they provide great powers which ensure great traction forces and allow the towing of complex equipment that performs more agricultural works for seedbed preparation in a single-pass. The weight of these tractors is distributed on the two axles (front and rear), respectively the wheels, and transmitted to the soil by means of the footprint, producing soil stress.

Wheel passage on agricultural soil, which for most vehicles is usually of short duration, results in the artificial compaction of soil (*Gill and Vanden Berg, 1968*). The phenomenon of agricultural soil compaction is defined as an increase in soil dry density and the closer packing of solid particles or reduction in porosity (*Kuhwald et al., 2018; McKyes, 1985*), which can result from natural causes including rainfall impact, soaking and internal water stress (*Arvidsson, 1997*). New methods of mechanisation, associated with increasing weight and size of machinery, have the potential to cause undesirable soil compaction to a depth below that of normal tillage operation (*Bennett et al., 2019; Javadi and Spoor, 2006; Martínez-Ramírez et al., 2017; Mohsenimanesh and Laguë, 2017*).

The most important factors that have a significant influence on the artificial compaction of soil are: soil type, soil moisture content, size of external load, area of contact surface between the soil and tire, the shape of contact surface and the number of passages (*Augustin et al., 2019; Cueto et al., 2016; Kuhwald et al., 2018*). Tillage systems influence the physical, chemical and biological characteristics of the soil, which in turn can change the characteristics, growth and development of the roots (*Augustin et al., 2019; Hajabbasi, 2001*).

Since the agricultural soil is not a homogeneous, isotropic and ideal elastic material, the mathematical modelling of the phenomenon of stress distribution is very difficult. Many mathematical models of stress distribution in the soil under various traction devices are based on Boussinesq's equations describing stress distribution below a loaded point (Fig. 1) acting on a homogeneous, isotropic, semi-infinite, and ideal elastic medium (*Hammel, 1994*). Frohlich has developed equations to take into account stress concentration around the application point of a concentrated load for the semi-space medium subjected to a vertical load (*Koolen and Kuipers, 1983*). The Finite Element Method (FEM) proves to be very promising in modelling this distribution phenomenon (*Cueto et al., 2013*). For agricultural soils, the relations between stresses and deformations are measured on soil samples in the laboratory or directly in the field. The stress-strain relations are given by the constitutive equations (*Gee-Clough et al., 1994; Keller and Lamandé, 2010*). A non-linear finite elements model could be a useful tool in developing a predictive method of soil pressure-sinkage behaviour and can be used to investigate and analyse soil compaction (*Rashidi et al., 2007; Silva et al., 2018*). Other researchers (*Cueto et al., 2013; Khodaei et al., 2016*) developed a three-dimensional model of the soil, and they represented soil properties by an Extended Drucker-Prager material model.

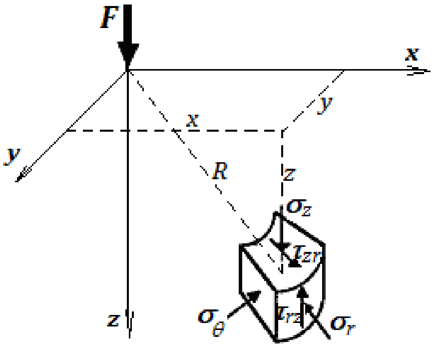


Fig. 1 - Stress state produced by a concentrated vertical load
(*Upadhyaya and Rosa, 1997*)

Validation of the mathematical model of soil stress distribution can be done using special sensors, either in the laboratory - on prepared volumes of soil or in-situ, by comparing the values predicted by the model with those resulting from the measurements. As shown in some studies (*Rashidi et al., 2007*), the statistical analysis of verification confirmed the validity of the FEM model and demonstrated the potential use of FEM in predicting soil pressure-sinkage behaviour. However, experimental verification of the model is required before the model can be recommended for extensive use.

Some researchers (*Loghavi and Khadem, 2006*) developed sensors to detect the location and depth of the hardpans in real time. In their study, a soil compaction profile sensor equipped with four horizontally operating penetrometers was developed and tested, for on-the-go detection and mapping of the site and intensity of the hardpans artificially formed in a soil bin.

Another researcher (*Keller, 2004*) used five stress sensors that were buried in the topsoil at a depth of 0.1 m for measuring of the vertical stress. Each sensor (DS Europe Series BC 302) was attached to an aluminium disc (diameter: 17.5 mm, height: 5.5 mm) embedded in the centre of a larger aluminium disc (diameter: 70 mm, height: 15 mm). The cells were placed on a line perpendicular to the direction of travel below one half of the wheel track.

The main objective of this paper is to find and certify a simulation model for prediction of stress in agricultural soil under the tires of heavy-duty tractors, using the most advanced mathematical tools, such as the Finite Element Method.

MATERIALS AND METHODS

To simulate the behaviour of agricultural soil, the Drucker-Prager plasticity model can be used. The yield criteria can be defined as (*Kushwaha and Shen, 1995*):

$$\mathcal{F} = 3 \cdot \alpha \cdot \sigma_m + \bar{\sigma} - k = 0 \tag{1}$$

where α and k are material constants assumed unchanged during the analysis, σ_m is the mean stress and $\bar{\sigma}$ is the effective stress, α 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, provided that the assumption of small strains 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: $90 \geq \Phi \geq 0$ and $c \geq 0$.

The input parameters required for the constitutive model of wet clay type agricultural soil are (*Gee-Clough et al., 1994*): soil cohesion (c): 18.12 kPa; internal friction angle of the soil (φ): 30°; soil density (γ_w): 1270 kg/m^3; Poisson's ratio (υ_s): 0.329; Young's modulus (E): 3000 kPa.

The stress levels under a point load, as shown in Fig. 1, are given in cylindrical coordinates as follows (*Upadhyaya and Rosa, 1997*):

$$\sigma_z = \frac{3\cdot F\cdot z^3}{2\cdot\pi\cdot R^5} \tag{2}$$

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

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

$$\tau_{rz} = \frac{3\cdot F\cdot r\cdot z^2}{2\cdot\pi\cdot R^5} \tag{5}$$

where F –is the point load, ϑ –Poisson's ratio, $\sigma_{z,r,\theta}$ – components of normal stress, and τ_{rz} –shear stress component.

A volume of soil, 2-meter deep, 4.5 meters wide and 6 meters long (Fig. 2) was considered to be under a heavy-duty tractor (Massey Ferguson, range 8700) (Table 1). The nonlinear structural analysis was made on the ideal model, the soil being considered a homogeneous and isotropic material. The QuickFieldTM 6.3 program was used for FEM modelling in planar strain state (Fig. 3).

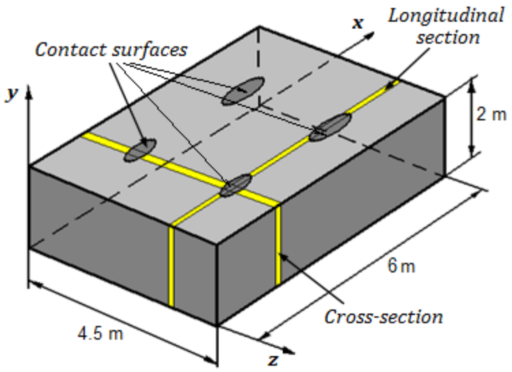


Fig. 2 - Analyzed volume of soil

Table 1

Main characteristics of MF-8700 tractor

Tractor	Soil interaction part	Type of tire	Gauge (mm)	Weight (total / per axle) (kg)	
MF-8700	Front tire	620/75R30	2000	18000	6000
	Rear tire	650/85R42			12000

Fig.3 - Meshed model of soil used to analyze the distribution of stresses and strains in the longitudinal-vertical plane

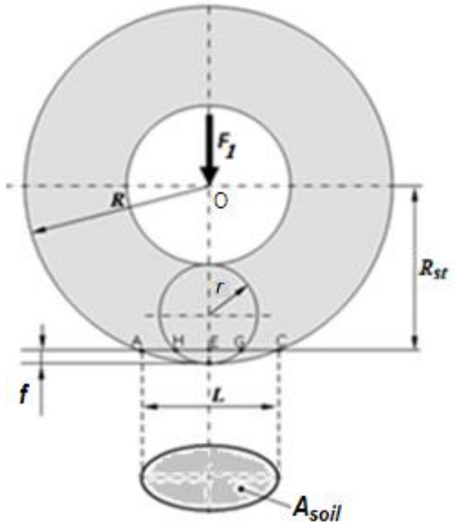


Fig. 4 - Tire deformation under the action of an external load

According to Hedekel's equation, the deformation of the tire in contact with the rolling surface (Fig. 4) is given by the relation (*Koolen and Kuipers, 1983*):

$$f = \frac{F_1}{2 \cdot \pi \cdot p_i \cdot \sqrt{R \cdot r}} \tag{6}$$

where: F_1 – is vertical load on the wheel, (N); p_i – tire inflation pressure, (MPa); R – free radius of the wheel, (mm); r – radius of tire rolling path in cross section, (mm).

Static tire radius is given by:

$$R_{st} = R - f \tag{7}$$

and the length of the contact chord is:

$$L = 2 \cdot \sqrt{R^2 + R_{st}^2} \tag{8}$$

The empirical model for calculating the contact area between soil and agricultural tires (Komandi, 1976) is:

$$A_{soil} = c \cdot F_1^{0.7} \cdot \sqrt{\frac{b}{D}} \cdot p_i^{-0.45} \quad (\mathrm{m}^2) \tag{9}$$

where: c –constant; *F1*–wheel load, (kN); *b* –tire width, (m); *D* –tire diameter, (m); p_i –inflation pressure, (kPa). Constant *c* for different substrates has the following values (*Komandi, 1976*): *c*=0.3-0.32 for rather bearing soil, *c*=0.36-0.38 for sandy field, and *c*=0.42-0.44 for loose sand.

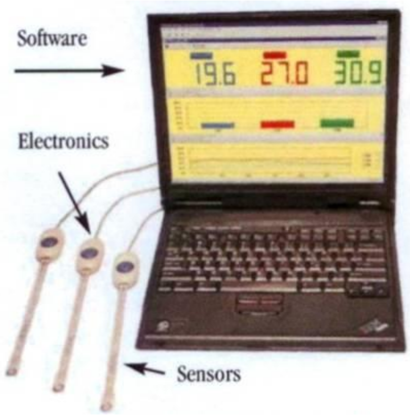


Fig. 5 - Data acquisition system

In order to check the model developed using Finite Element Method (FEM), laboratory tests were conducted using a data acquisition system (Fig. 5) connected to Flexi Force Tekscan W-B201-L force sensors (Fig. 6), vertically mounted in the soil, at 10 cm distance, in a metallic container with 1x1x1 m dimensions (Fig. 7). Fig. 8 shows the testing stand on the Hydropulse installation. The corresponding load on the wheel was applied using the hydraulic cylinder of the Hydropulse.

Fig. 6 - Flexi Force Tekscan W-B201-L force sensor

The soil inside the testing bin is cohesive and has been compacted by compression as the bin has been filled, to reproduce the clayey soil as accurately as possible. By water spraying, soil moisture was brought to the value of 20%, corresponding to the most common case of soil processing, when the contact with the rolling bodies (wheels) of the tractors or agricultural machines occurs.

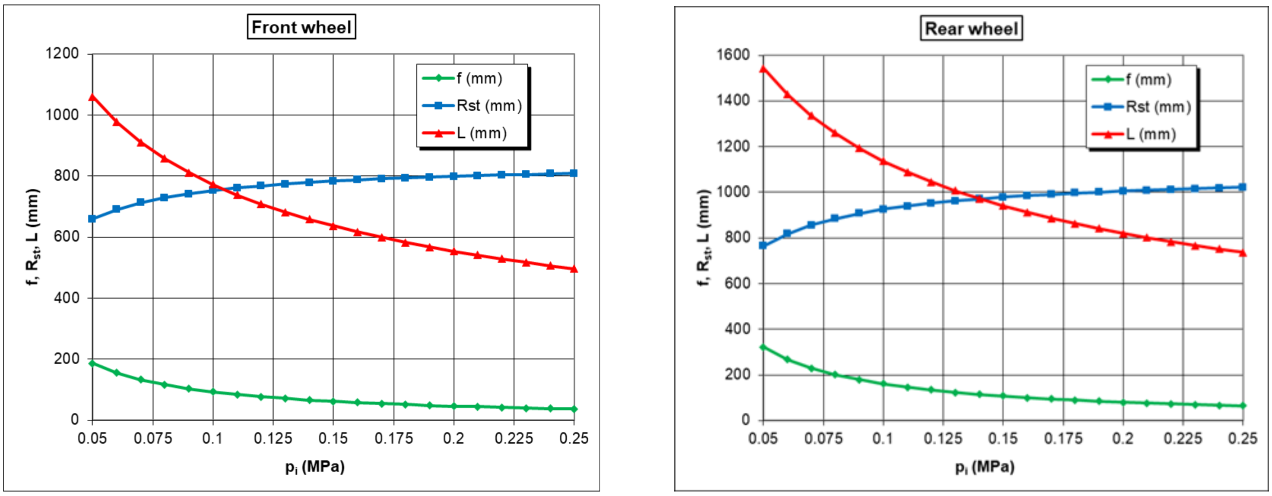
Fig. 7 - Sensors mounted in the soil bin

Fig. 8 - Test stand in Hydropulse laboratory

On the experimental stand of the Hydropulse installation (Fig. 8) was mounted a wheel from the front axle of MF-8700 tractor, for 3 different tire inflation pressures (0.1 MPa, 0.15 MPa, and 0.2 MPa). With the help of a controlled hydraulic cylinder, the load on wheel was reproduced, according to Table 1, of 3000 kg (30 kN) after a cycle consisting of three distinct phases, namely: 1 second of linear loading up to the maximum value (30 kN), 1 second to maintain this maximum load and 1 second to linear discharge the compression force to the value of 0 N, for each of three different tire inflation pressures. The maximum values of equivalent stress in the soil were recorded by the acquisition system, using the 10 Flexi Force Tekscan W-B201-L pressure sensors disposed vertically in the soil on the symmetry axis of the bin. These experiments are intended to validate the model of soil stress distribution using the Finite Element Method (FEM).

RESULTS

The figures below (Fig. 9, a and b) show the influence of tire inflation pressure on the dimensional characteristics of the MF-8700 tractor wheels (according to Fig. 4), respectively tire deformation *f* (Eq. 6), static radius R_{st} (Eq. 7) and the length of contact chord *L* (Eq. 8), for the front (a) and rear (b) wheel.

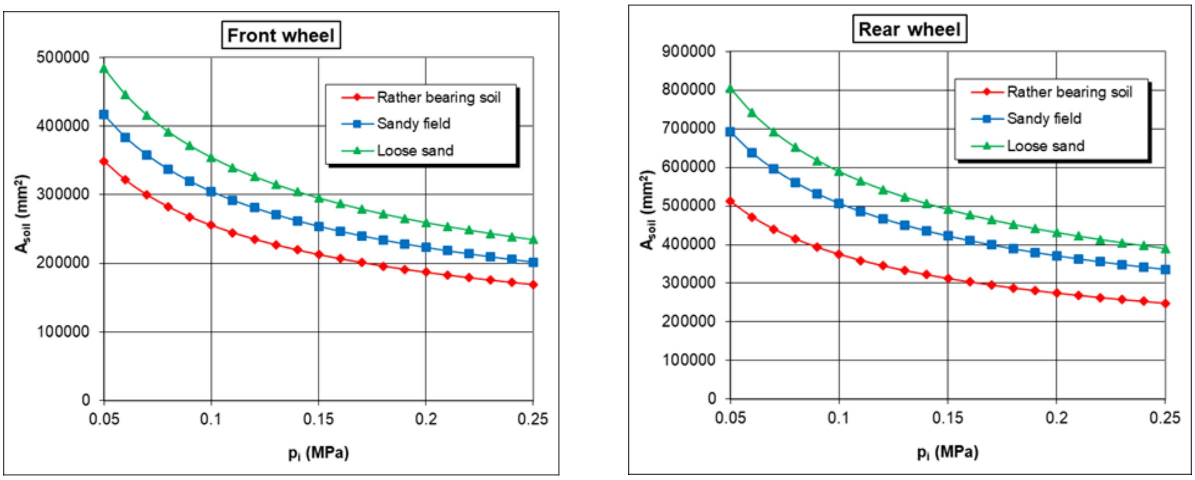


a) b)

Fig. 9 - Influence of tire inflation pressure on the dimensional characteristics of the wheels (front and rear)

From the two graphs it can be observed the importance of the tire inflation pressure on the dimensional characteristics of the wheel, respectively on the size of tire deformation. Thus, for the front wheel (Fig. 9.a), for the same loading force, tire deformation depending on the value of tire inflation pressure, reaches: 93 mm (for p_i=0.1 MPa), 62 mm (for p_i=0.15 MPa), and 46 mm (for p_i=0.2 MPa). For the rear wheel (Fig. 9.b), for the same loading force, tire deformation depending on the value of tire inflation pressure, reaches: 160 mm (for p_i=0.1 MPa), 107 mm (for p_i=0.15 MPa), and 80 mm (for p_i=0.2 MPa).

The figures below (Fig. 10, a and b) show the variation curves of the contact area A_{soil} (Eq. 9) depending on tire inflation pressure for three different types of substrates, for the front wheel (a) and rear wheel (b) respectively. It can be seen that for both wheels (front and rear), the contact area decreases significantly with increasing tire inflation pressure, regardless of the nature of the rolling surface.



a) b)

Fig. 10 - Influence of tire inflation pressure on the contact area for different substrates of the wheels

The pressure applied by the tractor, through the wheels, on the soil (*p*), is calculated as the ratio between the vertical load on the wheel (F_1) and the contact area (A_{soil}), for each wheel. This dependency is shown in Fig. 11, for the front and rear wheels of the MF-8700 tractor, in the case of a cohesive soil. As it can be seen, tire inflation pressure influences the tire pressure applied on the soil.

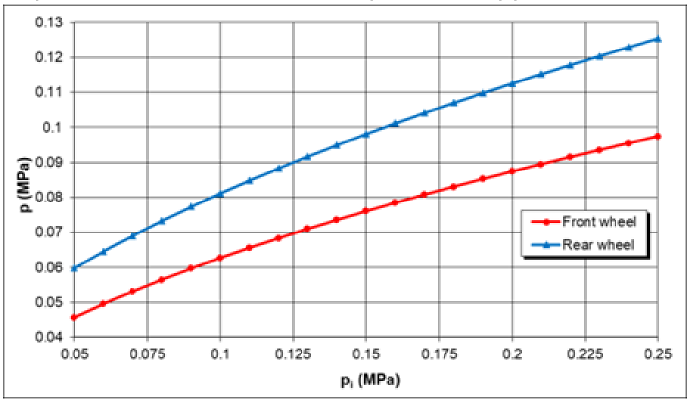
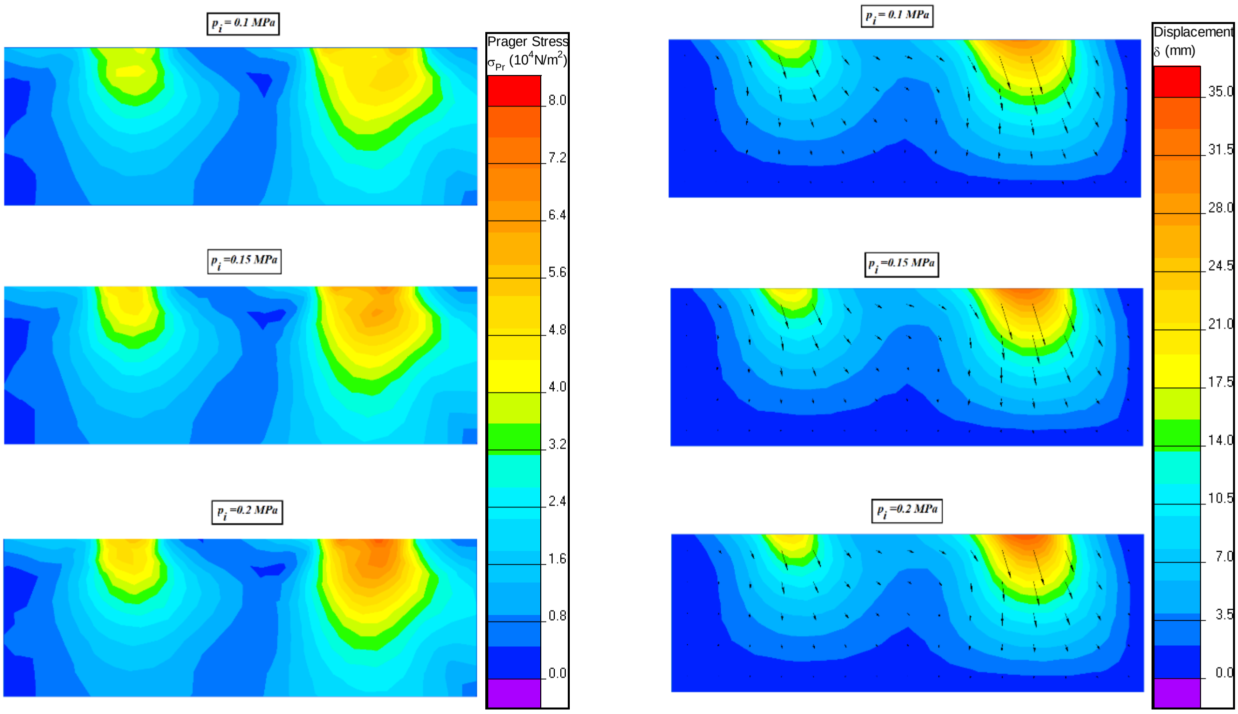


Fig. 11 - Influence of tire inflation on the contact pressure between wheel and soil

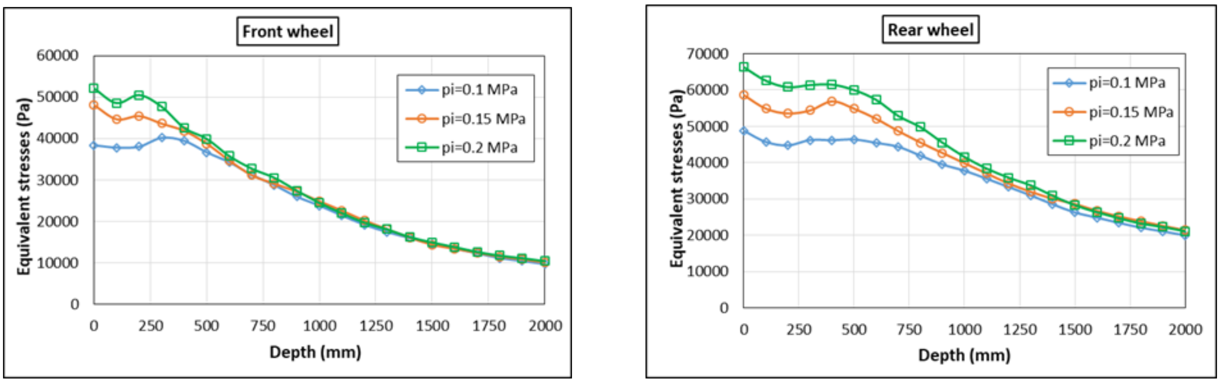
By running the simulation model using the Finite Element Method (according to Fig. 3), the results shown in the following figures are obtained. Thus, Fig. 12-a shows the distribution of equivalent stresses in the soil, according to Drucker-Prager yield criteria for the same cohesive soil (clayey), for three different tire inflation pressures (0.1 MPa, 0.15 MPa, 0.2 MPa). It can be observed that the higher the tire inflation pressure, the more the equivalent stresses propagate in the soil at higher depth and they have higher values, especially in the surface (arable) layer. The simulation model allows highlighting the distribution of stresses in the soil and their values, making it possible to highlight situations in which the soil is artificially compacted, usually when the value of equivalent stress exceeds 80 kPa. Analysing Fig. 12-a, it results that if tire inflation pressure is 0.2 MPa, the susceptibility of superficial compaction occurs in the superficial layer, especially in the case of the rear wheel, hence it is recommended to limit the value of this tire inflation pressure to maximum 0.15 MPa.



a) b)

Fig. 12 - Distribution of equivalent stresses (a) and of total displacements (b) in the soil for different tire inflation pressures

Fig. 12.b shows the distribution of total displacements in the soil, at the interaction with the wheels of MF-8700 tractor, for the same cohesive soil (clayey) for three different tire inflation pressures (0.1 MPa, 0.15 MPa, 0.2 MPa). It can be observed that the higher the tire inflation pressure, the deformation of agricultural soil increases and the total displacements are distributed in the soil at a higher depth and have higher values, especially in the surface layer (arable).



a) b)

Fig. 13 - Variation of the equivalent stress distribution in the soil after vertical-axial direction for different inflation pressures of the front tire (a), and rear tire (b)

In Fig. 13-a and Fig. 13-b there are presented the variation graphs of the distribution of equivalent stresses in the soil after vertical-axial direction, resulting from the numerical simulation, for different inflation pressures (0.1 MPa, 0.15 MPa, 0.2 MPa) of the front tire, respectively rear tire, depending on the depth. Analysing Fig. 13-b in particular, it is observed that if tire inflation pressure is 0.2 MPa, the susceptibility of superficial compaction occurs in the superficial layer, hence it is recommended to limit the value of this tire inflation pressure to a maximum of 0.15 MPa.

Fig. 14 shows the variation graphs of the distribution of vertical displacement in the soil after vertical-axial direction, resulting from the numerical simulation, for different inflation pressures (0.1 MPa, 0.15 MPa, 0.2 MPa) of the front tire, respectively rear tire, depending on soil depth. It can be seen that the largest vertical displacements, respectively the largest deformations, occur in the superficial (arable) layer of soil.

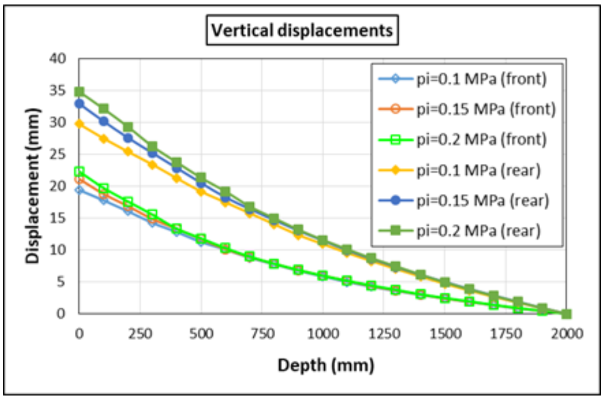
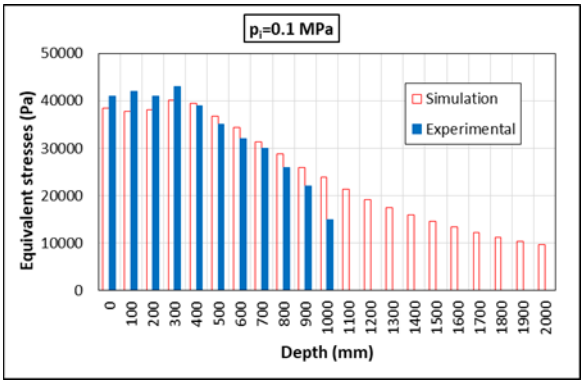
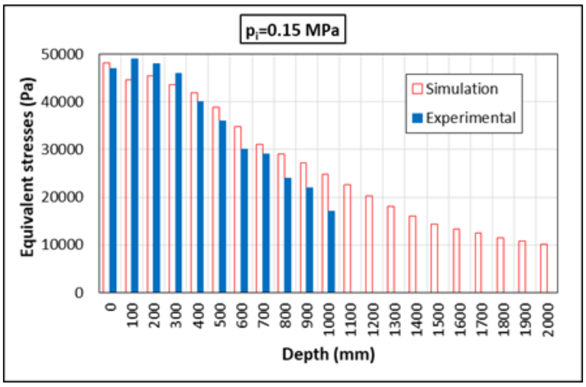


Fig.14 - Variation of distribution of the total displacement in the soil after vertical-axial direction for different inflation pressures of the two tires

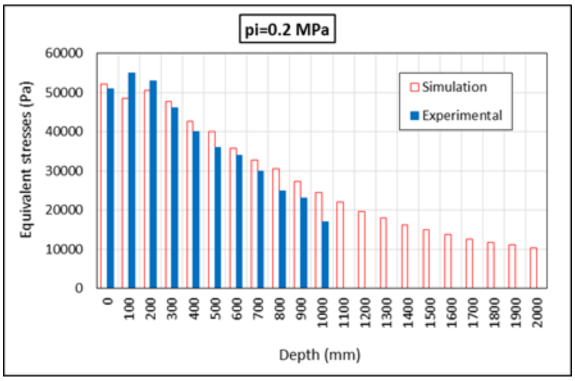
In order to validate the model of analysis using the Finite Element Method, Fig. 15 (a, b, and c) presents comparatively the values of the equivalent stresses in the soil after vertical-axial direction in the case of front wheel of the MF-8700, values obtained by numerical simulation using the FEM model developed and those obtained by experimental testing, down to a depth of 1 meter (Fig. 8) for different tire inflation pressures (0.1 MPa, 0.15 MPa, 0.2 MPa).



a)



b)



c)

Fig.15 - Equivalent stresses obtained by FEM simulation and experimentally

Comparative statistical calculations were performed for the absolute deviation (**ε**) of the values of equivalent stress obtained by simulation (S_s) compared to those obtained experimentally (S_e), for the depth of 1 meter of the analysed soil layer, applying the relation:

$$\varepsilon = \frac{\sum_{i=1}^{n}|S_e - S_s|}{\sum_{i=1}^{n} S_e} \cdot 100 \quad (\%) \tag{10}$$

where n is the number of points (10 points) in which experimental values were recorded by means of the Flexi Force Tekscan W-B201-L force sensors placed vertically in the soil in the experimental stand bin (in increments of 10 cm) and of the data acquisition system (Fig. 5).

Following the calculations, the following deviations of the values given by the simulation model from the experimentally obtained values for the front MF-8700 tractor are obtained, for the three different tire inflation pressures: ε=9.23 % (Fig. 15-a), ε=10.31 % (Fig. 15-b) and ε=9.79 % (Fig. 15-c). These relatively small deviations, taking into account the complexity of agricultural soil behaviour at the interaction with the wheels of tractors and agricultural machines, justify us to appreciate that the simulation model using the Finite Element Method can be validated and can be used in assessing the phenomenon of artificial compaction of soil under the action of heavy-duty tractors.

CONCLUSIONS

The Finite Element Method is currently the most advanced mathematical tool that can be used to modelling the process of artificial compaction of soil under the action of rolling bodies of tractors and agricultural machinery. For mathematical modelling, the soil can be considered a homogeneous and isotropic material, and the Drucker-Prager plasticity model can be used to simulate the behaviour of agricultural soil. The simulation model, using the Finite Element Method (Fig. 12-a), allows highlighting the distribution of stresses into the soil and their values, making it possible to highlight situations in which soil is artificially compacted, usually when the value of equivalent stress exceeds 80 kPa.

As it can be seen in Fig. 15, between simulated and experimental results there is a difference of approximately 10% for the front wheel of the MF-8700. These relatively small deviations encourage us to appreciate that the simulation model using the Finite Element Method, developed in the present paper, can be validated and used in assessing the phenomenon of artificial compaction of soil under the action of heavy-duty tractors.

This study highlights the major advantage of using models of stress distribution in the soil by the Finite Element Method (FEM), namely reducing dramatically the costs associated with experimental testing and reducing considerably the time required to analyse the possibility of occurrence of artificial compaction phenomenon of the agricultural soil under the action of heavy-duty tractors. This simulation model can be extremely useful to both manufacturers of tractors and agricultural machinery, but also to those who exploit such machinery and aim to limit the phenomenon of artificial compaction of agricultural soil by properly choosing the rolling bodies and by setting the appropriate tire inflation pressure.

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