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FEM modelling of soil behaviour under compressive loads

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Abstract. Artificial compaction is one of the most dangerous forms of degradation of agricultural soil. Recognized as a phenomenon with multiple negative effects in terms of environment and agricultural production, soil compaction is strongly influenced by the size of external load, soil moisture, size and shape of footprint area, soil type and number of passes. Knowledge of soil behavior under compressive loads is important in order to prevent or minimize soil compaction. In this paper were developed, by means of the Finite Element Method, various models of soil behavior during the artificial compaction produced by the wheel of an agricultural trailer. Simulations were performed on two types of soil (cohesive and non-cohesive) with known characteristics. By applying two loads (4.5 kN and 21 kN) in footprints of different sizes, were obtained the models of the distributions of stresses occuring in the two types of soil. Simulation results showed that soil stresses increase with increasing wheel load and vary with soil type.

1. Introduction

In the actual context of continuously increasing world population, it became necessary the development of mechanized agriculture, which requires the use of heavy agricultural machinery, often on soils with high moisture content. This practice increases the risk of degradation of agricultural soil through artificial compaction, a phenomenon with multiple negative effects on the environment and on crop yields. The first paragraph after a heading is not indented.

According to Soil Science Society of America (1996), soil compaction is the process by which soil particles are rearranged so that is reduced the volume of voids, and solid particles are put into contact, thereby contributing to the increase of bulk density [1].

Soil compaction is a reduction of soil volume [2] under the action of compressive loads (external forces forming soil stress) applied on soil surface by the agricultural machinery [3], [4].

Soil compaction can be produced by natural phenomena such as rainfall impact, soaking, freeze-thaw cycles, internal tensions of soil water, rooting system of plants, soil drying. Among the artificial causes, a certain influence has the trampling of grazing animals, but the most important factor is traffic intensity of tractors and agricultural machinery, often performed on inadequate moisture conditions, with high wheel loads and high tire inflation pressures.

From an environmental point of view, soil compaction leads to: erosion, landslides, leakage of pesticides and nutrients intro groundwater, reduced capacity of water infiltration into the soil, ncreased emanations of N_2O, CH_4 and CO_2, forming of ruts. In agronomic terms, in compacted soils were reported negative effects such as: increased penetration resistance, inhibition of root development and plant growth, followed by reduced yield of agricultural crops, increased resistance to plowing and therefore, higher fuel consumption.

The most important factors influencing the artificial compaction of soil are: size of external load (wheel load), type of soil, tire inflation pressure, moisture content, footprint area between the soil and tire, shape of footprint, and the number of passes of agricultural machinery.

Stresses applied by the agricultural machinery are transmitted to different soil depths, through the footprint between the soil and tire, resulting in topsoil compaction and/or subsoil compaction.
Topsoil compaction has a significant effect on crop yield and may last for some years, but is can easily be alleviated by tillage, drying-wetting and freeze-thaw cycles, and by the action of soil biota [5]. Subsoil compaction (occurring on layers of soil below 25 cm depth) is particularly persistent [5] and the compacted layer cannot be removed by conventional tillage [6].

Distribution of stresses into the soil is influenced by factors such as: surface of contact area (footprint area) between the rolling body and soil, wheel load, tire inflation pressure, soil moisture and tire design. According to [7], the vertical stress down to 1 m depth depends both on soil contact stress (contact pressure) and wheel load.

Artificial compaction of soil is very difficult to alleviate and it became of special concern because the weight of tractors and agricultural machinery has increased significantly [8]. Hence, various modeling techniques have been used to predict the response of soil to the traffic of agricultural vehicles. The modeling predicts the distribution of stresses in the soil profile, giving informations about the depth at which the compaction takes place, and is also useful in making recommendations to farmers and designers about which agricultural machinery to use in order to minimize soil compaction [9].

Agricultural soil is not a homogeneous, isotropic and elastic ideal material, and the mathematical modeling of stress distribution is quite difficult. The Finite Element Method (FEM) is a numerical method for obtaining approximate solutions of ordinary and differential equations that describe the distribution of stresses and strains into the soil, being extremely useful for the modeling of this phenomenon [10].

However, the soil can be idealized as an elastic-plastic material, and in FEM modeling it is necessary to define some parameters, such as: Young's modulus and Poisson's ratio, which describe the elasticity, respectively the cohesion and the angle of internal friction, describing soil plasticity.

2. Methods

The aim of this FEM study was to simulate behavior of agricultural soil under the influence of wheel loads applied by an agricultural trailer equipped with tires model Danubiana 11.5/ 80-13.5 profile D179 (width 290 mm, diameter 845 mm).

The distribution of equivalent stress in the soil by FEM was performed in the QUICKFIELD Student program. The analysis was carried out on the 2D geometric model of plane load. A volume of soil with dimensions of 1 m x 1 m x 1 m was considered, and on its surface was applied a pressure plate with the area equal to the area of footprint between the soil and tire. Over the pressure plate was applied a uniformly distributed load (located in the upper corner of the meshed section in Figure 1).

By meshing the physical model of soil through FEM, was obtained the meshed half model presented in Figure 1. To obtain high precision of results, the model was meshed in maximum 250 nodes, with smaller discrete elements in the area where stresses are concentrated.

The simulation was performed for the two types of soil, whose characteristics are presented in Table 1. Besides the characteristics of the two types of soil, other parameters used for the modeling of wheel load effect on the soil were the width of the footprint between the soil and tire, respectively the contact pressure applied on the contact surface between soil and tire, for two wheel loads (4.5 kN and 21 kN). For each wheel load, tire inflation pressure was varied (180 kPa, 240 kPa, and 300 kPa), thereby obtaining different footprint areas. Contact pressures were computed as ratio between wheel load and footprint area. The values of these parameters are presented in Table 2.

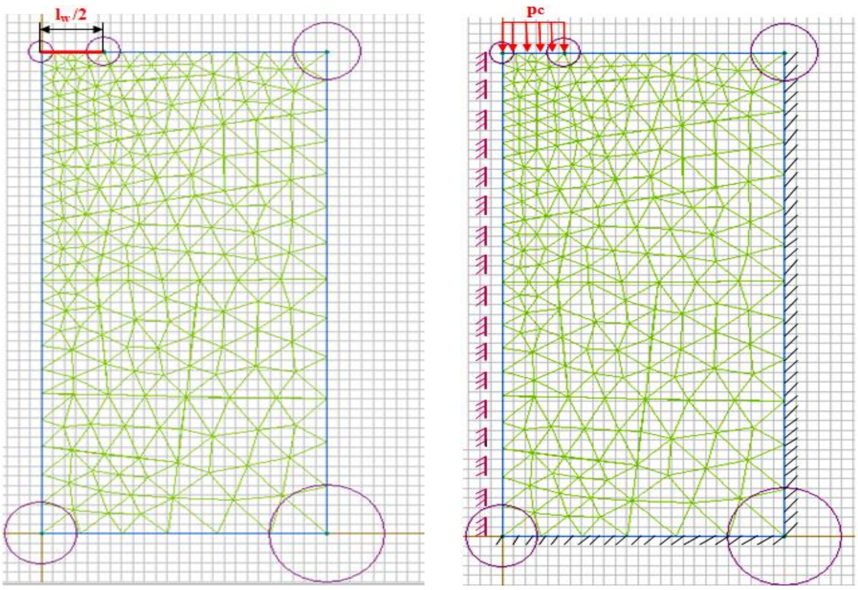

Figure 1. Meshed model of the analyzed soil (half model)

Table 1. Characteristics of cohesive soil [11] and non-cohesive soil [12] used in FEM modeling

Soil characteristic	Cohesive soil (clay)	Non-cohesive soil (sandy-loam)
Young's modulus of elasticity, E [kPa]	3000	13000
Poisson's ratio, ν	0.329	0.3
Cohesion, c [kPa]	18.12	2
Angle of internal friction, φ [°]	30	32
Density, ρ [kg/m^3]	1270	2040
Moisture, w [%]	24	6.5

Table 2. Other parameters used in FEM modeling

Wheel load, Q [kN]	Tire inflation pressure, p_i [kPa]	Footprint area, A [m^2]	Footprint width, l_w [m]	Contact pressure, p_c [kPa]
4.5	180	0.03	0.206	150
	240	0.028	0.190	161
	300	0.023	0.156	196
21	180	0.099	0.248	212
	240	0.077	0.238	273
	300	0.073	0.220	288

For each simulation, footprint width was fixed on the surface of the analyzed soil volume. The force applied to the soil by the agricultural machinery (contact pressure) was considered uniformly distributed in the footprint.

By applying different loads on the meshed model of the agricultural soil, were obtained various distributions of equivalent stresses in the two types of soil, during the artificial compaction caused by the tire of agricultural machinery.

3. Results and discussions

Figures 2 and 3 show the distribution of equivalent stress by the von Mises criterion, occurring in the two types of soil, for a wheel load of 4.5 kN and tire inflation pressure of 180 kPa.

These half-models correspond to contact pressure p_c = 150 kPa, uniformly distributed in a footprint area A= 0.03 m^2 (footprint width l_w = 0.206 m).

In the cohesive soil (Figure 2), the maximum stress of 88.2 kPa was concentrated in the topsoil at a depth of 10-12 cm, and the minimum stress was 1.91 kPa. Referring to Figure 3, it can be seen that in non-cohesive soil (sandy-loam) the highest stress had a value of 90.6 kPa and the minimum stress was 1.88 kPa.

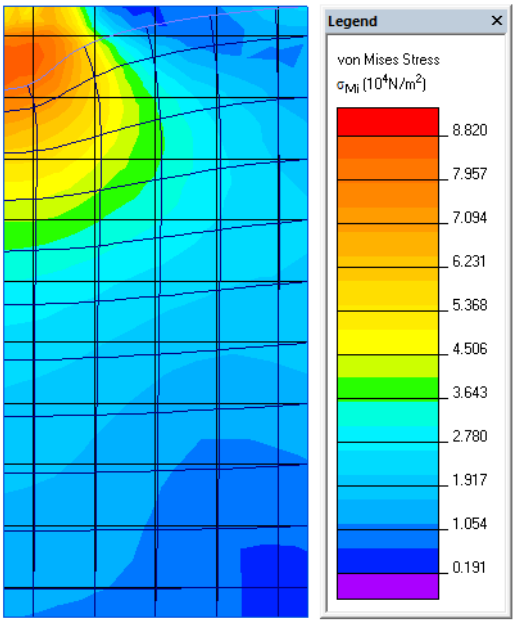

Figure 2. Distribution of equivalent stress in the cohesive soil, for p_c = 150 kPa and l_w = 0.206 m

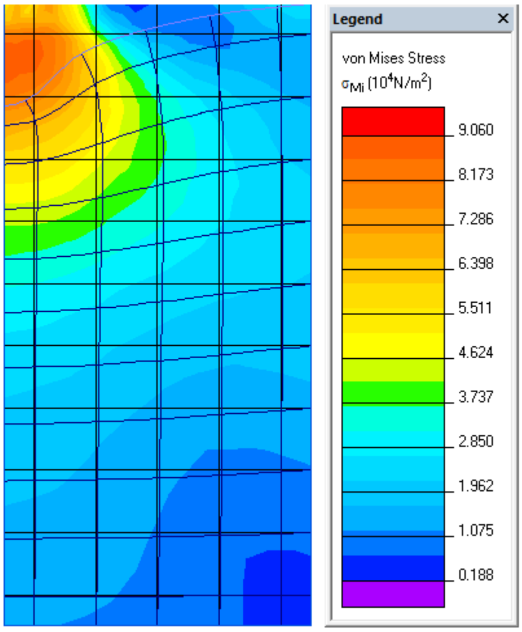

Figure 3. Distribution of equivalent stress in the non-cohesive soil, for p_c = 150 kPa and l_w = 0.206 m

In Figure 4 and Figure 5 are presented the distributions of equivalent stresses by von Mises criterion in the two types of soil, obtained by simulation, considering a wheel load of 4.5 kN at tire inflation pressure 240 kPa. Contact pressure p_c = 161 kPa is considered to be uniformly distributed in a footprint of area A= 0.028 m^2 (with footprint width l_w = 0.190 m). By analyzing the half-models it can be noted that in the cohesive soil (Figure 4), the maximum stress was 97 kPa and the minimum stress was 1.97 kPa. In the non-cohesive soil (Figure 5), the highest stress was 99.81 kPa and the minimum stress was 1.94 kPa.

In Figures 6 and 7 are presented the distributions of equivalent stresses by von Mises criterion, considering a wheel load of 4.5 kN at tire inflation pressure 300 kPa. These half- models correspond to a contact pressure of 196 kPa, uniformly distributed in the footprint with area of 0.023 m^2 (footprint width l_w = 0.156 m).

From the analysis of Figure 6 it can be seen that in the cohesive soil (clayey), the highest stresses were recorded to about 10-12 cm depth under the wheel and they had a value of 96.11 kPa, while the minimum stress was 1.63 kPa.

Figure 7 shows that in the non-cohesive soil (sandy-loam) for a wheel load of 4.5 kN, the highest stress had a value of 98.6 kPa and the minimum stress was about 1.6 kPa, similar to that occuring in the clayey soil.

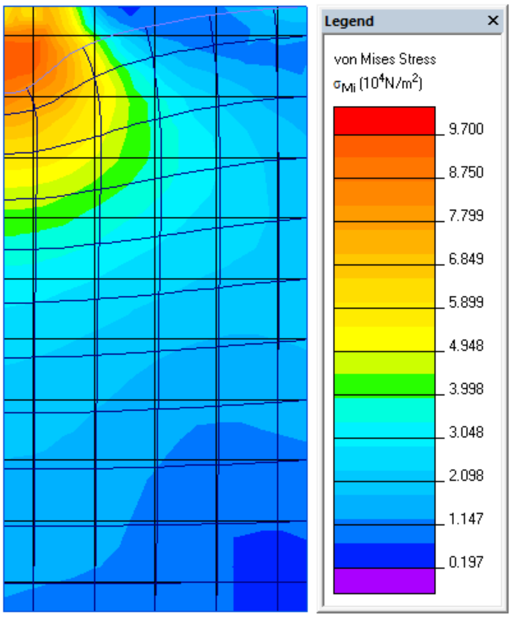

Figure 4. Distribution of equivalent stress in the cohesive soil, for p_c = 161 kPa and l_w = 0.190 m

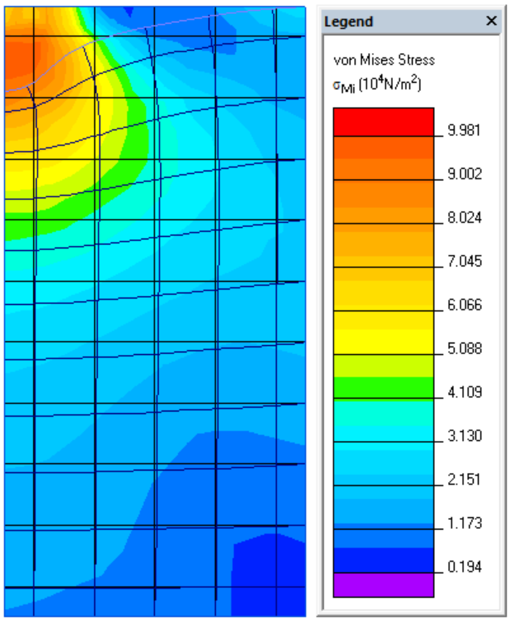

Figure 5. Distribution of equivalent stress in the non-cohesive soil, for p_c = 161 kPa and l_w = 0.190 m

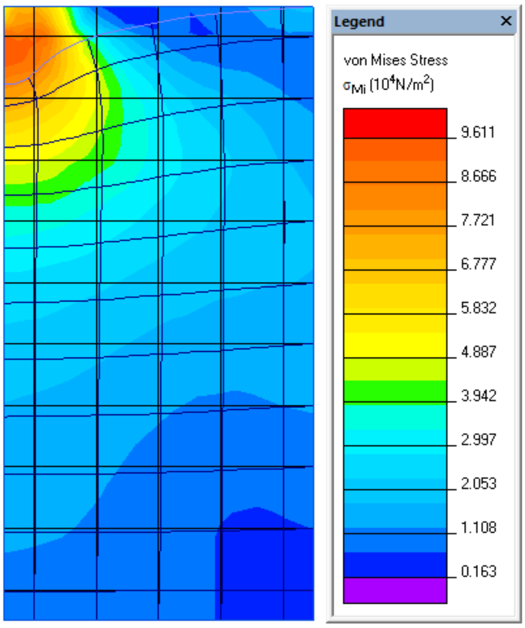

Figure 6. Distribution of equivalent stress in the cohesive soil, for p_c = 196 kPa and l_w = 0.156 m

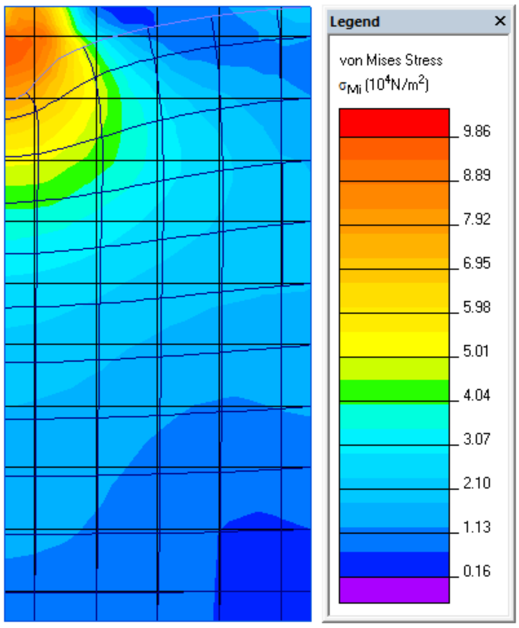

Figure 7. Distribution of equivalent stress in the non-cohesive soil, for p_c = 196 kPa and l_w = 0.156 m

Table 3 presents some values of equivalent stresses obtained by FEM modeling, in the two analyzed types of soil, from soil surface to 1000 mm depth, considering a wheel load of 4.5 kN.

Table 3. Distribution of equivalent stress for 4.5 kN wheel load, for different footprint widths

Soil depth [mm]	l_w = 206 mm	l_w = 190 mm	l_w = 156 mm
Equivalent stress in the cohesive soil (clayey), σ_{Mi} [N/m^2]			
0	58927	53951	53675
200	72682	70936	62337
400	38739	36911	30942
600	24138	22847	18966
800	17643	16724	13825
1000	12818	11998	9905
Equivalent stress in the non-cohesive soil (sandy-loam), σ_{Mi} [N/m^2]			
0	58928	62596	62214
200	72682	72980	63946
400	38740	38348	32126
600	24138	23777	19734
800	17643	17333	14329
1000	12818	12587	10392

From the analysis of Figures 2-7 and data presented in Table 3 it can be observed that the maximum equivalent stresses are generally concentrated in the layer of soil located between 50 -150 mm depth, in both types of soil. This is due to flow and agglomeration phenomenon of soil particles under the action of wheel load, resulting in a denser layer of soil.

The value of stress that propagates under this layer decreases with soil depth, and at the same soil depth, the value of equivalent stress decreases with decreasing footprint width. Hence, the two types of soil will compact in the arable layer at depths up to 400 mm, where the equivalent stresses exceed 27.5 kPa (as noted in various studies in the literature).

Half-models obtained for a wheel load of 21 kN at different footprint widths are presented next.

Figures 8 and 9 present the distribution of equivalent stress by von Mises criterion in the two types of soil, for a wheel load of 21 kN and tire inflation pressure of 180 kPa. These half-models correspond to a contact pressure p_c = 212 kPa, uniformly distributed in a footprint whose area is 0.099 m^2 (footprint width l_w = 0.248).

Study results showed similar values for the two types of soil. Thus, in the cohesive soil, maximum stress was 133 kPa and minimum stress 3.4 kPa, while in the non-cohesive soil were obtained maximum stresses of 137 kP and minimum stresses of 3.3 kPa.

Figures 10 and 11 show the distribution of equivalent stress by von Mises criterion, obtained by simulation for the two types of soil, considering a wheel load of 21 kN and tire inflation pressure of 240 kPa. These half-models correspond to a contact pressure p_c = 273 kPa, uniformly distributed in a footprint area of 0.077 m^2 (footprint width l_w = 0.238). In the cohesive soil, the highest stress was 167 kPa and the minimum stress was 4.1 kPa, while in non-cohesive soil the highest stress was 172 kPa and the minimum stress was 4 kPa.

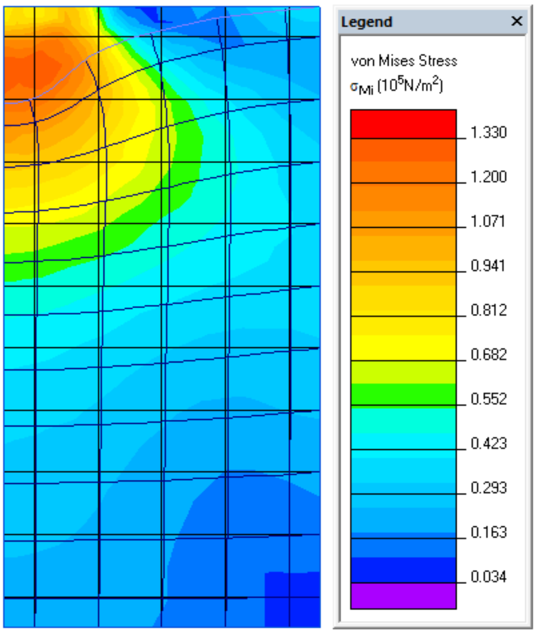

Figure 8. Distribution of equivalent stress in the cohesive soil, for p_c = 212 kPa and l_w = 0.248 m

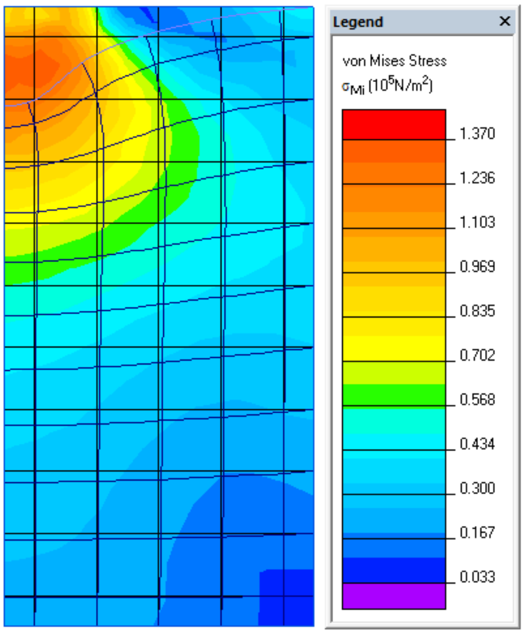

Figure 9. Distribution of equivalent stress in the non-cohesive soil, for p_c = 212 kPa and l_w = 0.248 m

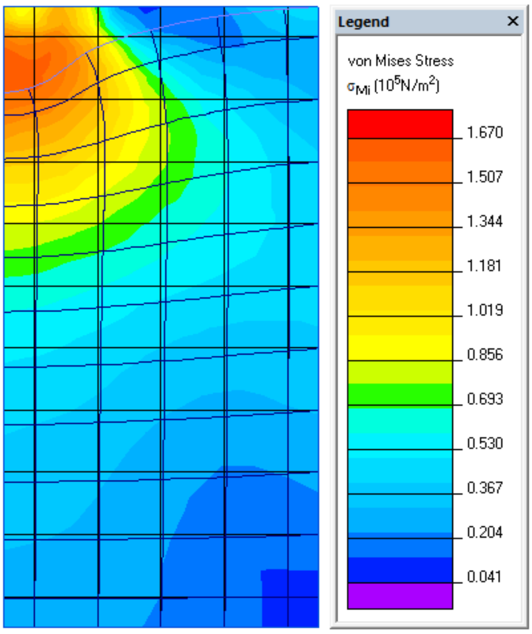

Figure 10. Distribution of equivalent stress in the cohesive soil, for p_c = 273 kPa and l_w = 0.238 m

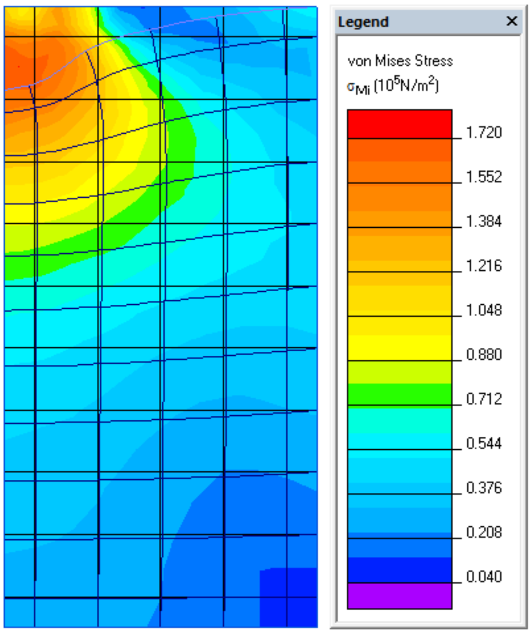

Figure 11. Distribution of equivalent stress in the non-cohesive soil, for p_c = 273 kPa and l_w = 0.238 m

Figures 12 and 13 present the distribution of equivalent stress by von Mises criterion, considering a wheel load of 21 kN and a tire inflation pressure of 300 kPa. These half-models correspond to a contact pressure p_c = 288 kPa, uniformly distributed in a footprint whose area is 0.073 m^2 (footprint width l_w = 0.220). In the cohesive soil, the highest stress of 175 kPa was concentrated in the topsoil, and in the non-cohesive soil the highest stress was 180 kPa. In both types of soil, the minimum stress was 4 kPa.

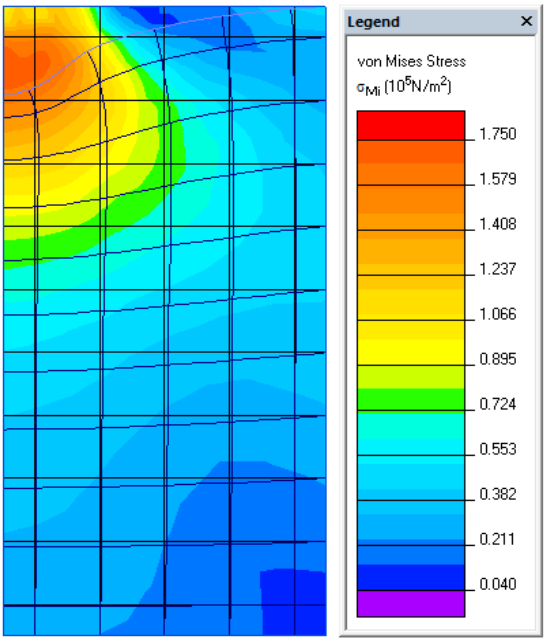

Figure 12. Distribution of equivalent stress in the cohesive soil, for p_c = 288 kPa and l_w = 0.220 m

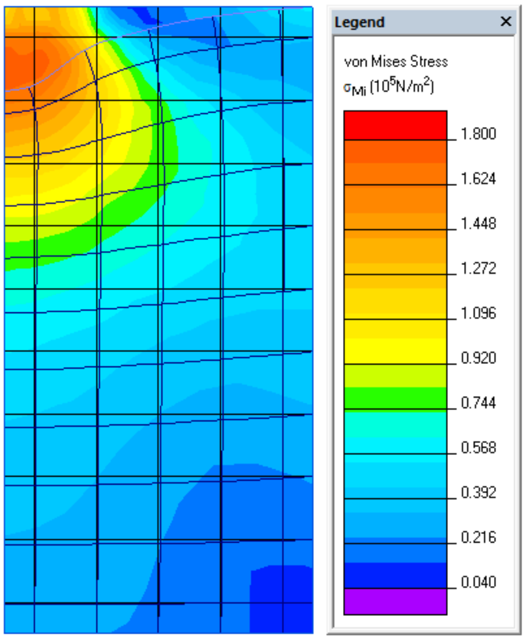

Figure 13. Distribution of equivalent stress in the non-cohesive soil, for p_c = 288 kPa and l_w = 0.220 m

In Table 4 are given some values of equivalent stresses obtained by FEM modeling, in the two analyzed types of soil, from soil surface to 1000 mm depth, considering a wheel load of 21 kN.

Table 4. Distribution of equivalent stress for 21 kN wheel load, for different footprint widths

Soil depth [mm]	l_w = 248 mm	l_w = 238 mm	l_w = 220 mm
Equivalent stress in the cohesive soil (clayey), σ_{Mi} [N/m^2]			
0	71201	104739	95477
200	110757	136984	138082
400	61038	75110	74331
600	38469	47119	46425
800	28384	34714	34144
1000	20414	24956	24524
Equivalent stress in the non-cohesive soil (sandy loam), σ_{Mi} [N/m^2]			
0	82583	117989	110775
200	113940	140968	142135
400	63503	78086	77273
600	40059	49057	48335
800	29417	35977	35386
1000	21413	26176	25724

From the analysis of Figures 8-13 and data presented in Table 4 it can be observed that at a load of 21 kN applied in footprint areas of various sizes, on two types of soil, compaction will occur in the arable layer, but also under this layer, on depths at equivalent stresses in the soil exceed 27.5 kPa, determined empirically in the literature.

Thus, we can recommend the use of agricultural trailers equipped with tires having large width and diameter, because this would increase the footprint in which the loads are applied, and therefore stresses will propagate at shallower depths in the soil, which is much easier to alleviate compared to deep compaction.

FEM analysis was verified by laboratory tests and test results proved that FEM is an accurate method for predicting stress distribution in soil depth.

4. Conclusions

Numerical methods such as the Finite Element Method require the generation of a large number of finite elements to achieve a high accuracy of the results, but they can be successfully applied to simulate the phenomenon of soil compaction.

The results obtained by FEM simulation showed that the values of stresses occurring in the soil increase with increasing the wheel load and they vary depending on soil characteristics.

By comparing the results obtained for the same load, it was found that the clayey soil (cohesive) has the highest predisposition to compaction, while the sandy-loam soil (non-cohesive) is less predisposed to compaction.

In agricultural soil, due to higher tire inflation pressures, smaller footprint areas are formed, the soil deforms more and the stresses are distributed deeper into the soil, requiring remedial works such as deep loosening. At lower tire inflation pressures, the tire deforms more, footprint area is greater, contact pressure is lower, the soil deforms less and stresses are transmitted at shallower depths.

The increase of the footprint area not necessarily leads to lower stress intensity in the soil, but rather to limiting the distribution of high stresses on soil depth, respectively to their expansion in horizons closer to soil surface.

FEM simulation models of the behavior of the two types of soil can be useful to farmers and designers of agricultural machinery, for optimizing wheel loads and tire inflation pressure, in order to reduce the risk of artificial compaction of agricultural soil.

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