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Study and simulation of the effective factors on soil compaction by tractors wheels using the finite element method

Kazem Jafari Naeimi[1*], Hossein Baradaran[2], Razieh Ahmadi[3] and Malihe Shekari[3]

1. Assistant Professor, Department of Mechanical Engineering of Biosystems, Faculty of Agriculture, Shahid Bahonar University of Kerman, Kerman, Iran

2. Associate Professor, Department of Mechanical Engineering, Faculty of Engineering, Shahid Bahonar University of Kerman, Kerman, Iran

3. M.S. Student, Department of Mechanical Engineering of Biosystems, Faculty of Agriculture, Shahid Bahonar University of Kerman, Kerman, Iran

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Abstract

Soil is a nonrenewable source that needs considerable management to prevent physical deterioration by erosion and compaction. Compacted soil causes low fertility and yield. The purpose of this study is to investigate the effect of viscoelastic properties of soil and to determine important factors on compaction. Furthermore, stress distribution, prediction of soil compaction and simulation of its effect under tractor wheels using ANSYS software were also studied. Predicted results using ANSYS software are compared with laboratory and field results. Simulations were carried out by changing and measuring effective factors on soil compaction. These factors consist of wheel parameters which include: number of wheel passes, speed and load; and the soil parameters such as soil bulk density and Young's modulus. The predicted results indicated that maximum soil compaction in the first traffic with 512 mm was induced by viscoelastic properties of soil and the minimum soil compaction in the sixth traffic was 8 mm caused by soil elasticity properties. Variation in soil bulk density was negligible. Also at each wheel pass, e maximum stress was in the soil surface and this decreased with increase in depth. The maximum vertical stress on the soil in the sixth traffic was 120.477 kPa at 2.52 km/h and the minimum was 117.46 kPa at 5 km/h.

Keywords: *soil bulk density, soil compaction, soil Young's modulus, simulation, viscoelastic properties.*

1. Introduction

Soil is a three-part system which includes solid, liquid and gas. The solid part of a soil is a complex set of organic and inorganic materials whose arrangement, quantity and quality determine its physical characteristics such as porosity, structure and bulk density (Shahidi, 2005). Soil is a nonrenewable resource that requires considerable management to prevent

* Corresponding Author Emai: jafarinaeimi@uk.ac.ir

physical deterioration by erosion and compaction (Kibblewhite et al., 2008; Horn, 2009). Soil compaction is one of the major issues in modern agriculture (Hamza and Anderson, 2005). Agricultural production yield depends on farm machinery traffic within the field. In modern agriculture, operations such as planting and harvesting are impossible without tractors and combine harvesters. Traffic damages might occur on the surface or in lower layers of soil (Raper, 2005). Soil compaction is the quantitative expression of soil behavior under stress and pressure which is usually expressed as a variation in bulk density, degree of porosity, total porosity, ventilated porosity, rate of water infiltration and soil strength (Soane, 1990). Results of a study in 1974 showed that with the same moisture content and bulk density, plowed soil compacts faster than undisturbed soil. It was also determined that undisturbed soil suffers less compaction especially at higher speeds of tractor passes (Tanner and Dexter, 1974).

One of the factors that affect soil compaction is the size its constituent particles. Hard pans, which are created by soil compaction, are often observed in loam, sandy loam and silt loam soils (Minaei, 1984). Compaction increases bulk density by binding soil particles below the soil critical moisture level to each other. Soil specific gravity depends on the percentage of clay and organic matter and it changes during tillage operations (Chen et al., 1998). Another study showed that after compacting soil by nine passes of sprocket wheel tractor, bulk density of a silt clay soil is inversely proportional to its clay percentage and is directly proportional to its silt percentage (Hatchell et al., 1970).

Below the wheel at various depths, soil stress increases with pressure caused by the tractor's weight or wheels track. Increase in soil stress depends on the load per wheel-soil contact area, depth and distance of a studied point from the tractor wheel. Meanwhile, increase in tractor wheel passes on the soil causes compressive stresses in the soil layers. Due to nonlinear and viscoelastic behavior of soil, investigation of the effects of tractor wheel passes on agricultural soils and simultaneous evaluation of soil stresses and deformations is complicated. The term viscoelastic is used for materials that have two parts: elastic (reversible) and viscose (irreversible). Quick loading leads to elastic deformation while viscose deformation needs a longer time.

One of the most important effects of soil compaction is increased shear strength due to increased bulk density. In general, soil strength at a certain level of moisture is increased by increasing bulk density. The amount of soil cohesion and internal friction angle are increased by reduced water content (Gill and W.R., 1971). The appeared soil compaction is directly proportional to applied force. Soil compaction is inversely related to the contact area between the machine wheel and soil surface (Lancas et al., 1998; Burger et al., 1984). The amount of load has the greatest effect on soil compaction. The maximum increase in soil specific gravity usually occurred during the first time of loading or passing (Steinbrenner, 1995). Based on Minaei's (1984) research, maximum compaction is created in 0 to 15 cm of the soil surface and its rate is directly proportional to the number of tractor passes. The maximum change in bulk density of clay soil is created at depths of 12 to 16 cm below the wheel center (Raghavan et al., 1977). Becerra and his colleagues evaluated the vertical distribution of soil compaction induced by traffic of two tractors with different weights. Their study showed that soil compaction resulting from tractor traffic increases bulk density and decrease total soil porosity. Furthermore, their results showed that up to the fifth pass of each tractor, ground pressure is responsible for topsoil compaction (Botta et al., 2012). In order to reduce soil compaction risk, it was suggested to use the tractor with the lowest possible load and tire inflation pressure. In addition, if wheel slippage is less than 30%, soil pore spaces decrease and therefore soil compaction increase with tractor passes. If wheel slippage is around 30%, pure shear occurs and the effect of wheel passes remains within deep layers of soil (Lencas et al., 1998).

In recent years, researches have been published comparing various methods of identifying soil characteristics after compression. Variations in soil structure were investigated by standard soil sampling at various depths with drill sampler and non-destructive methods based on electrical resistivity thermography (Besson et al., 2013). In 2007, Jafari Naeimi presented a method to calculate soil characteristics and effective parameters based on wheel passes in certain points of a field. In this mathematical model, soil deformation was presented as viscoelastic differential equation which could precisely calculate soil deformation based on theoretical models. Shahgholi and Abuali used 3 transducers to measure soil compaction under the rear tire of an MF285 tractor. The soil behavior results showed that the soil compacted vertically during tractor tire passage and expanded laterally. In the longitudinal direction, the soil compacted later it was expanded and ultimately it was compacted again (Shahgholi and Abuali, 2015).

In this study, factors affecting stress distribution and compaction in soil under tire tracks were studied by simulation process using ANSYS software and comparing the results with those of the experiments. A survey of the literature revealed that there is a lack of reports on the simulation of soil visco-elastic behavior under the tractor wheel using finite element method. The achieved visco-elastic model for prediction of soil compaction could be applied to other soil forms.

2. Materials and Methods

In this study, wheel effect on soil is considered as a massive compressive load. Since wheel pass is a time dependent parameter, dynamic analysis and soil depth of 0 to 10 cm are assumed as complete viscoelastic material. Elastic behavior is shown by the linear elastic model and soil viscoelastic behavior by Peroni model while ANSYS Software was used for all simulations. Simulations were performed by changing the effective factors on soil compaction which include tractor and wheel related factors such as number of passes, tractor weight and speed; and soil related parameters such as bulk density and modulus of elasticity numerical simulation was done by using ANSYS finite element software in transient dynamic analysis. With this analysis, which is sometimes called the time-dependent analysis; it is possible to calculate the dynamic response of a structure influenced by time-dependent loading. Researches and experimental results were obtained in order to study soil compaction process in medium soil texture with average moisture content of 13 to 16%. Viscoelasticity changes were determined by the differential Equation (1) as result of tractor wheel passes (Jafari naeimi, 2007).

$$\dot{\sigma}_T + p\sigma = q\dot{\varepsilon}_T \tag{1}$$

The experiments confirmed that the viscoelastic expression of soil properties can be expressed by differential Equation (1) that is based on the vertical stress on the soil, stress change rate and soil particles displacement ratio (Jafari Naeimi, 2007). Viscose properties arise from adhesion and cohesion forces. p and q are dependent variables on factors such as wheel rotational speed (w), moisture content and soil density. These parameters were measured in the field and calculated by using the equations according to Jafari et al. (2007). Among the available models in the ANSYS software related to viscoelastic materials, Prony model or the generalized Maxwell model was used for soil simulation soil in this study. According to this model, mechanical soil behavior was simulated by the set of spring and damper (Fig. 1). This model consists of two parallel branches; the first branch includes the spring E_1 and the damper η_1 while the second branch consists of the spring E_e.

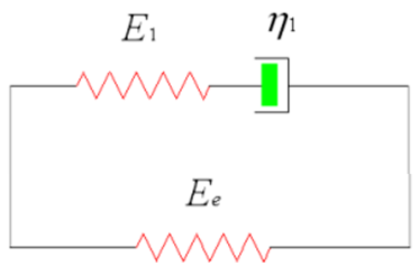


Fig. 1. Prony model used in simulation

Since total strain ε_T is identical for both branches, Equation (2) is inferred.

$$\dot{\varepsilon}_T = \dot{\varepsilon}_S + \dot{\varepsilon}_D \tag{2}$$

$$\sigma_S = E.\varepsilon_S \rightarrow \varepsilon_S = \frac{\sigma_S}{E} \rightarrow \dot{\varepsilon}_S = \frac{1}{E}.\frac{d\sigma_S}{dT}$$

$$\sigma_D = \eta.\dot{\varepsilon}_D \rightarrow \dot{\varepsilon}_D = \frac{\sigma_D}{\eta} \tag{3}$$

$$\frac{d\varepsilon_T}{dt} = \frac{\sigma_D}{\eta} + \frac{1}{E}.\frac{d\sigma_S}{dt}$$

where $\dot{\varepsilon}_T$: strain time rate of spring in first branch, $\dot{\varepsilon}_D$: strain time rate of damper, $\frac{d\sigma_s}{dt}$: the stress time rate, η: damper coefficient and E: spring modulus (Pa).

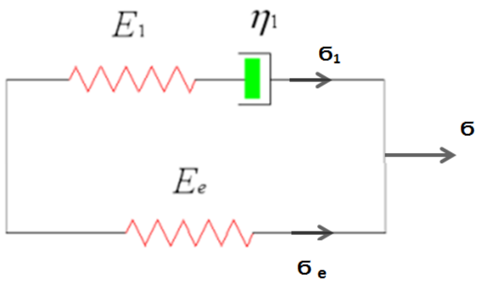


Fig. 2. Stress distribution of Prony model in loading

$$\begin{aligned} &\sigma_1 = E_1.\varepsilon \quad , \quad \sigma_e = E_e.\varepsilon \\ &\sigma = E_0\varepsilon = \sigma_1 + \sigma_e \rightarrow \sigma = (E_1 + E_e).\varepsilon \qquad (4) \\ &E_0 = E_e + E_1 \end{aligned}$$

In slow loading equation can be written as:

$$\sigma_1 = 0, \quad \sigma_2 = \sigma = E_e.\varepsilon$$

E_0 is fast modulus and E_e or E_∞ are called slow soil modulus and the relationship between them using the Prony model is shown in Equation (4). To simulate tire and soil, SOLID185 elements was used for the determination of visco-elastic properties using ANSYS software having 8 nodes with three degrees of freedom for each one. The selected element supports viscoelastic properties in different scales (small and large) deformations. Soil properties were determined after selecting the element type. Since bulk density and modulus of elasticity are different in each soil layer, therefore in this simulation, soil was modeled in four layers of (0-10), (10-20), (20-30) and (30-100) after which the properties of each layer were defined. Soil was considered as a viscoelastic material at 0 to 10 cm depth and an elastic material at other depths. To achieve reliable results, soil dimensions were considered large enough to obviate fracture probability of soil segment during loading. Underside nodes of soil segment were bound in the x.y.z resolution and creeping did not occur. Meshing was carried out at 0 to 10 cm depth. Manual meshing was used because of its high accuracy in this soil layer while in the other layers, automatic meshing with intermediate grade was used.

In order to model soil depths from as a viscoelastic material using Prony model, bulk modulus and quick shear modulus (K_0, G_0) were required. By using slow loading, modulus of elasticity (E_0) and Poisson ratio (V_0) that were measured in the field were introduced to the software for above mentioned depths (0 to 10 cm). The software automatically used these parameters to calculate viscoelastic parameters of soil according to Equations (5) and (6).

$$G_0 = \frac{E_0}{2(1+2\nu_0)} \qquad (5)$$

$$K_0 = \frac{E_0}{3(1-2\nu_0)} \qquad (6)$$

The values of a_1 and t_1 (tranquility time) which are related to viscoelastic properties of soil, were defined for the software in the form of Equations (7) and (8).

$$a_1 = \frac{G_1}{G_0} = \frac{E_1}{E_0} \qquad (7)$$

$$t_1 = \frac{\eta_1}{E_1} = \frac{1}{p} \qquad (8)$$

According to Equation (4):

$$E_0 \rangle E_1 \rightarrow a_1 \langle 1$$

After determining soil properties, mesh was used. Speed as a variable parameter at different levels, was considered in soil compaction simulation. In this simulation, soil compaction was analyzed at four speed levels of 2.52, 4.5, 4.71 and 5 Km/h.

3. Results

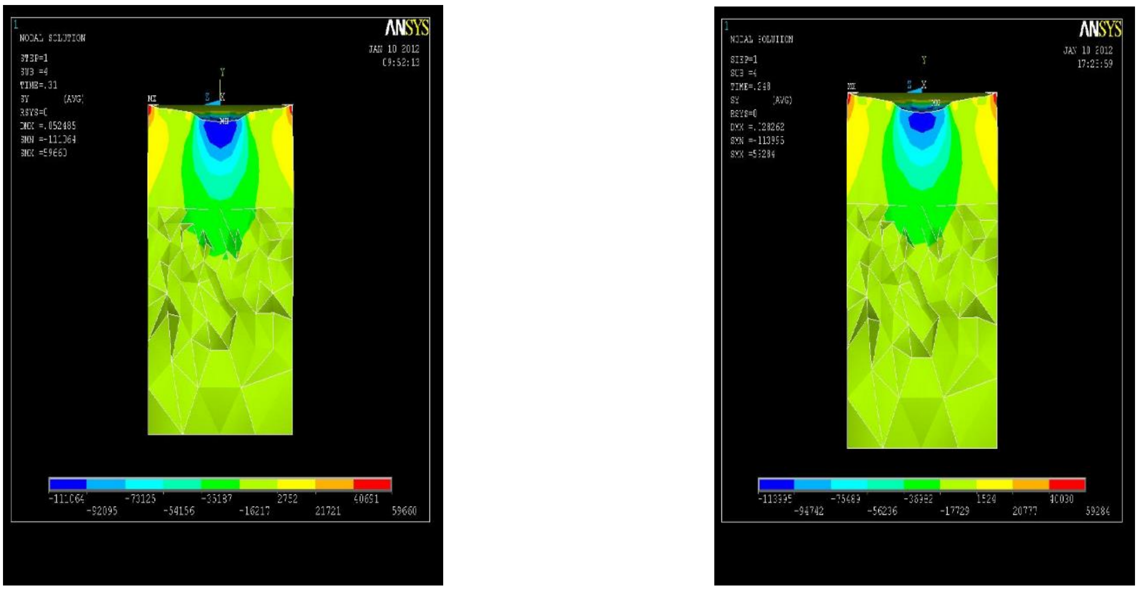
To assess the wheel pass effect on soil compaction, soil compaction simulations were performed in various tractor (MF-285) passes. Table-1 shows the factors that depend on the number of tractor passes.

Table 1. Factors depend on number of tractor passes during simulation experiments

The number of tractor passes	Load on wheel G_d (kN)	Pressure in tire P_w (MPa)	Tractor speed V_0 (km/h)	Tractor wheel angular velocity W (1/s)	Measured stress in experiments σ (MPa)	Measured soil density P (gr/cm^3)	Soil constant factor Q (MPa)
0	*	0.18	2.52	*	*	1.25	3.20
1	8.1	0.18	2.52	1.40	0.131	1.48	4.70
6	8.1	0.18	2.52	1.37	0.150	1.63	6.39

According to Figure 3, the maximum soil sinkage was 512 mm in the first wheel pass due to viscoelastic properties of soil and the minimum was 8 mm in the sixth pass due to elasticity properties of soil. Thus, soil sinkage decreased with increasing wheel passes. In other words, after six tractor passes, soil sinkage was almost reciprocating which indicated the soil property change of viscoelasticity to elasticity. Also, according to diameter and wheel width, stress distribution in soil under the tractor wheel, as obtained in previous researches, was seen as a parabolic (U- shape) under the wheel center.

The results showed that in each wheel pass, the maximum stress was increased in soil surface and stress decreased with increasing depth (Lamande and Schjonning, 2010). In addition, soil vertical stress increased with increasing number of wheel passes thus, the soil became more compact. The results obtained in the experiments and software simulation are in agreement. The maximum stress of σ_{max}=12.477 Kpa was observed in the sixth wheel pass by comparing created stress. The mentioned results are shown in Figures 4 and 5.



(a) (b)

Fig. 3. Simulation of the number of wheel passes on soil compaction, the rate of soil compaction and stress distribution in soil influenced by tractor wheel passes by ANSYS software (a) after the first pass (b) after the sixth pass.

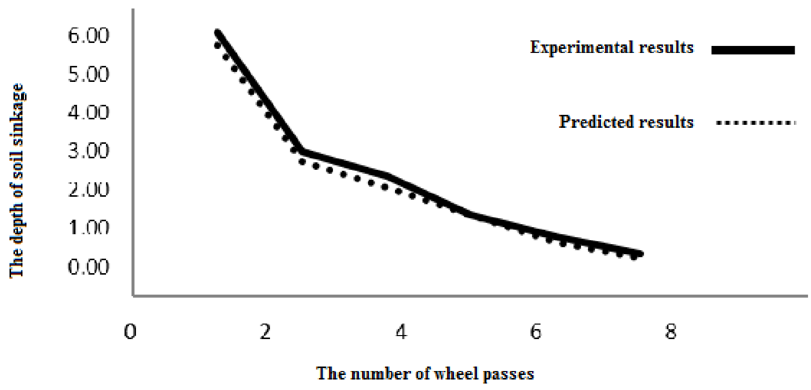


Fig. 4. Wheel passes effects on soil sinkage comparing the simulation results by ANSYS software with experimental results

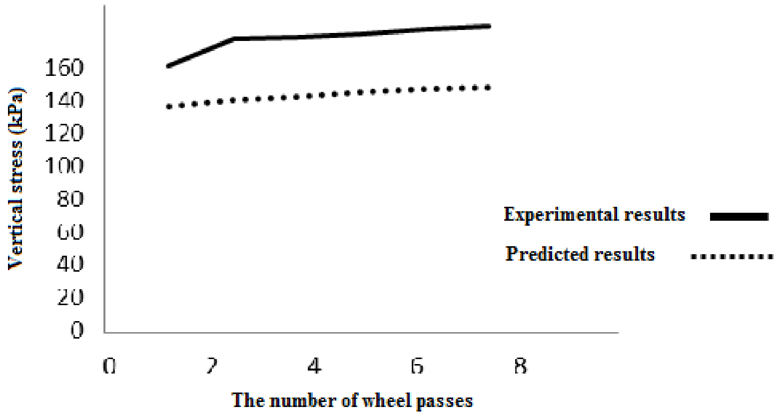


Fig. 5. Wheel passes effects on vertical stress comparing the simulation results by ANSYS software with experimental results

The most increase in soil bulk density usually occurs in the first loading (Minaei, 1984; Steinbrenner, 1995). Slight compaction occurs with increasing number of wheel passes because since the soil is in a viscoelastic area, there is a lot of reversible deformation (Jafari et al., 2007). Soil bulk density changes at 0 to 10 cm depth and different wheel passes were simulated as shown in Figure 6. According to Figure 6, the most increase in soil bulk density usually occurred in the first time loading and generally with increasing wheel passes, soil bulk density increased.

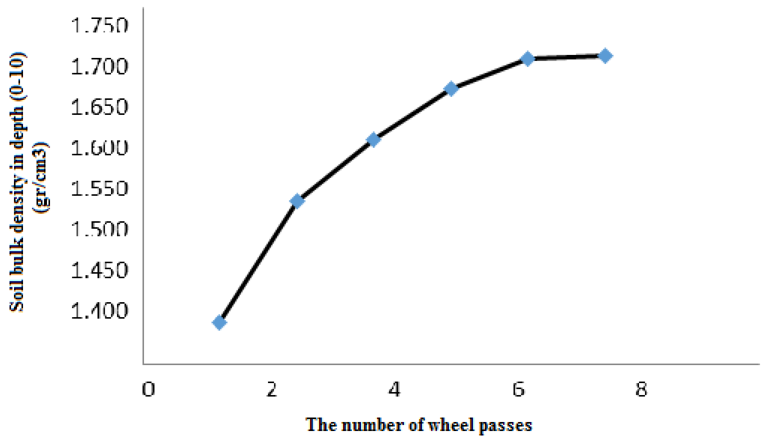


Fig. 6. Soil bulk density in depth (0- 10) cm in different tractor wheel passes by soil compaction simulation

When the viscoelastic materials were loaded fast, they showed more stress. In, comparing vertical stresses at different speeds as shown in Figures 7 and 8, observed σ_{max} and reversible deformation increased with increasing tractor speed.

If the soil is considered as a viscoelastic material, stress and strain changes are described according to Equation (1) where soil permanent deformation decreases and its reversible deformation or elastic deformation increases with increasing wheel passes. In this case, (q) in Equation (1) tends to soil modulus (E) which corresponds with Jafari (2007) results.

Soil viscoelastic properties depend on tractor speed. According to Figure 7, soil sinkage and volumetric strains decreased with increasing tractor speed. Also in Figure 8, by comparing vertical stress at different speeds, it was observed that σ_{max} and soil reversible deformation increased with increasing tractor speed.

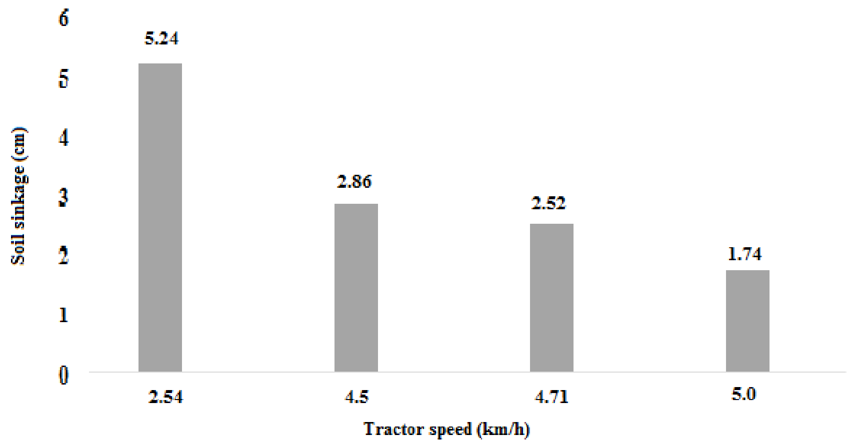


Fig. 7. Tractor speed effect on soil sinkage depth in soil compaction simulation

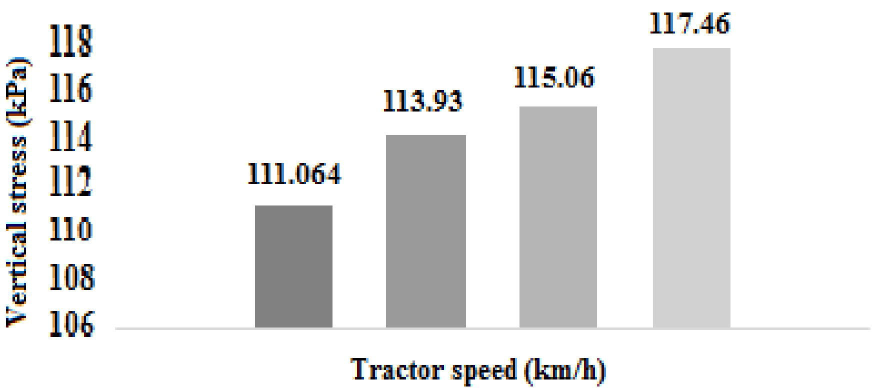
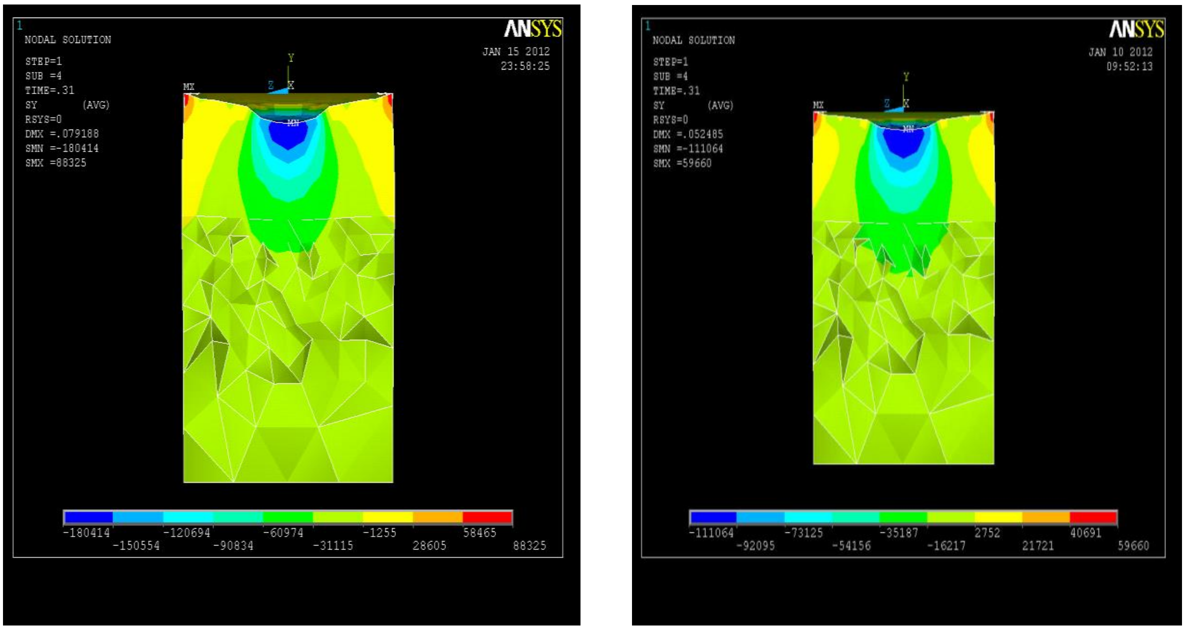


Fig. 8. Tractor speed effect on vertical stress of soil in soil compaction simulation

Soil compaction is directly proportional to the applied force. Heavier tractor causes more soil compaction (Lull, 1959; Hassan, 1978). The result of loading simulation on soil compaction (tire pressure of 180 Kpa at two loads 7.1 and 8.4 kN with other factors remaining constant) is shown in Figure 9. By increasing the applied force and increasing pressure load on the soil in simulation, soil sinkage, volumetric strains and soil bulk density increased and therefore soil compaction increased. Also, generated vertical and lateral stresses increased with increasing load and these stresses were distributed at greater soil depths. By increasing the load, lower layers of soil had more sinkage and soil became more compact (Arvidsson and Keller, 2007).



(a) (b)

Fig. 9. The effect of wheel loading on soil compaction at the tire pressure 180 kPa by simulating in (a) 8.4 kN, (b) 7.1 k N

Since in this simulation soil at depth 0 to 10 cm was considered as a viscoelastic material, modulus of elasticity and bulk density were noted as parameters that affect the viscoelastic properties of soil. In checking the effect of these parameters on soil compaction, soil compaction simulation was done at different values of soil modulus of elasticity and bulk density.

According to Table 2, soil sinkage depth decreased while the stress increased with increasing modulus of elasticity. Any soil texture has a unique modulus of elasticity and heavier soil textures have higher modulus of elasticity (Shahidi and Ahmadi, 2005). Therefore, with heavier soil textures, soil sinkage decreased while its stress increased. Soil sinkage and vertical stress changed a little with increasing soil bulk density.

Table 2. The effect of elasticity modulus changes on soil subsidence and vertical stress

E (MPa)	Soil sinkage (cm)	Vertical stress (Pa)
3.55	5.24	1.5596
3.75	4.95	1.6591
4.20	4.41	1.8464
5.40	3.40	111859
6.40	2.86	113672

4. Conclusions

In the present study, soil visco-elastic behavior was studied using ANSYS software. The simulation results showed that farming machines and tractors passes, loading, tractor speed, soil bulk density and soil elasticity modulus affect soil compaction. The results also indicated that with increasing wheel passes, soil bulk density increased. The soil vertical stress increased with increasing number of wheel passes and there is a lot of reversible deformation. Further more, soil sinkage and volumetric strains reduced with increasing tractor speed and soil reversible deformations increased with increasing tractor speed. Soil sinkage depth decreased and the stress increased with increasing the modulus of elasticity.

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