Determination of agricultural soil compaction affected by tractor passing using 3D finite element

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Abstract: Recently, soil compaction is one of the main problems of farmers and the main parameters of efficiency reduction of crops in some areas due to increasing in weight and size of agricultural tractors and passing of them in the field. In this research, for determining of soil compaction after tractor passing, the numerical and empirical methods were used. In empirical method, a Massy Ferguson tractor with a 3 moldboard mounted plough was used. The experiment was carried out in the university of Urmia farmland. The soil's physical properties were measured in three portions, front of wheels before transmission, after transmission frontal wheel and after transmission hinder wheel in depth of 0-5, 5-10 and 10-15 cm respectively. The resistance of soil was determined using penetrometer and determination of cone index (CI). In numerical method, the finite element was utilized for simulation of soil and penetrometer interaction. Since the penetration of penetrometer rod is as a function of time, the dynamic analyze and ABAQUS software was used for simulation. In this research, the soil was supposed as Elastic-perfectly plastic material and linear elasticity and Drucker-Prager plasticity model was applied for indicating the elastic and plastic behavior of soil, respectively. Finally, the necessary force for penetration in the soil was determined and compared with field experiments. Results of finite element analysis in initial depth were near the field experiments results. But in lower depth, results of the compacted soil layers demonstrated that the field results were higher than finite element results.

Keywords: soil, finite element, cone index, interaction

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1 Introduction

Preservation ratio among solid, liquid and gas phases of soli is an important problem. Through, during trafficking of machines and tractors in farmland, the soil solid phase is increased and the gas phase is decreased. Compaction of soil is an index that indicates the physical structure destruction of soil. Compaction is defined as increase in apparent density of soil or decrease in porosity.

From agricultural machinery engineering view, the compaction causes an increase in soil mechanical resistance and as a result, increases drafting force, fuel consumption, time of farming operations and implements abrasion. Referring to previous researches, about 60% of consumed energy in mechanized agriculture is used in tillage operation (Davies et al., 1993).

Barbosa et al. (1997) reported that for commercial and Zero tillage, the apparent density have not varied significantly and increased from 1 t m^{-3} to 1.2 t m^{-3}. But the soil penetration resistance increased from 0.8 MPa to 5 MPa and from 1.9 MPa to 3.2 MPa for sandy-loam and clay-loam, respectively.

Gupta and Allmaras (1987) believed when the soil compaction will be noticeable that the porosity of soil is less than 10% and the penetration resistance is more than

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2 MPa which is a critical pressure for plant root penetration.

Increasing the apparent density or decreasing of moisture content increases soil penetration resistance. The density of particles varies based on the clay ratio and type of the soil minerals specially iron minerals ratio and possibly influences the compatibility of soil (Cullet, 1993). Hakanson and Reeder (1994) reported that the crop performance decreased about 14% due to tractor passing in the next year. The mentioned researches indicated the importance of soil compaction.

Recently, with advancement of computer science and technology, numerical methods have been developed and the finite element tool is widely used in studying and prediction of soil behavior and soil-implement interaction.

Alavi and Hojati (2012) modeled the soil cutting process in rotary tillers using finite element method considering the effect of forward speed, rotary speed and soil moisture content on stress rate applied to the soil. They reported that forward speed increase led to the applied stress decrease and increasing the rotary speed and soil moisture content led to increasing of the applied stress on soil. They compared stress rate in different conditions with the allowed stress in soil and also the additional stress that led to powdering aggregation computed.

Zhong et al. (2010) investigated a finite element of the tillage of compacted soil, using the modified Drucker-Prager plasticity material model. They analyzed three different blade shapes by the finite element model. They reported that reverse-rotational rotary tool can work for the cutting of compacted soil and proper structural parameters of rotary blades can reduce the power consumption. The simulation results were also compared with classical soil mechanics theories for blades (the McKyes approach). A good correlation was between the simulation results and McKyes approach.

For a shear implement with width to depth ratio less than 10 (a narrow implement) the two dimensional space analysis is not proper. Because soil beside movement to up, has a simultaneous motion from lateral edge of blade (McKyes, 1985).

This paper aimed to simulate the soil-implement interaction and determine penetration resistance of soil and verify it with field experiment.

2 Materials and methods

This research was to implement in a farmland of Urmia University with 48.5% clay, 30.6% silt and 20.9% sand. The type of soil was determined as clay soil using USDA soil texture triangle. A Massey Ferguson 285 tractor made in Iran (2,540 kg) with a mounted three-bottom moldboard plough was used to simulate the tractor passing in the farmland.

2.1 Determination of soil properties

Physical properties of soil in 0-5 cm, 5-10 cm and 10-15 cm were determined in front of tractor before passing (A), after passing of frontal wheel (B) and after passing of rear wheel (C). An aluminum cylindrical container with 40 mm diameter and 54 mm height was used for sampling preparation. The experiment was set up in two factors with three repetitions and the average value of repetitions was reported.

2.2 Penetration resistance measurement

A penetrometer (model Rimik Cp20, made in UK) was used to measure the penetration resistance (cone index). The penetrometer is composed of a cone, penetrating rod, force transducer and a microprocessor (Figure 1). The speed of penetration was set on 0.02 m s^{-1} and cone index (CI) was obtained up to 150 mm depth and at each 15 mm the CI value was saved.

Figure 1 The used penetrometer set (model: Rimik Cp20) for CI measurement

2.3 Model description

In this paper, soil was assumed as a granular material. The behavior of granular materials can be modeled as an elastic-plastic material. In shallow layers of soil, including agricultural soil, the hardening properties of soil are ignored. In investigation of shear forces of interaction between soil and blade, the goal is shear force determination in plastic zone and also linear elasticity is not suitable for modeling in this case. Therefore, in this study soil was assumed as an elastic-plastic-perfectly that the linear elasticity and linear yield criterion of the Drucker–Prager model $\beta \neq \psi$ were utilized for describing of soil elastic and plastic behavior, respectively (β = angle of friction, ψ = dilation angle). Because only the elastic and Coulomb parameters of soil are available, (Young's modulus (E) and Poisson's ratio (υ)), the soil internal friction angle and cohesion must be determined. These parameters are obtained by Eq. (1), Eq. (2) and Eq. (3) as a function of Mohr–Coulomb parameters. In this research, the needed parameters were calculated from Mohr–Coulomb curvature. The following equations were used for calculation of Drucker–Prager parameters.

$$\tan\beta = \frac{6\sin\varphi}{3-\sin\varphi} \tag{1}$$

$$d = c\cdot\frac{6\cos\varphi}{3-\sin\varphi} \tag{2}$$

$$\sigma_y = \frac{2c\cos\varphi}{1-\sin\varphi} \tag{3}$$

where, φ is internal friction angle; β is angle of friction for the linear yield function of the Drucker–Prager; c is cohesion of material and d is the cohesion coefficient of Drucker–Prager model.

The need parameters were obtained:

$\beta = 43.26°$

$\sigma_y = 49.27$ kPa

$d = 33.82$ kPa

The numerical simulation was performed using Abaqus/Explicit that enables simulating of large deformations using Lagrangian-Eulerian analysis. The Abaqus/Explicit has ability of dynamic solution. In this feature, the penetrometer rod and soil were modeled using Lagrangian and Eulerian feature, respectively. In ABACUS/Explicit, the Mohr-Coulomb failure condition has been approximated by modified Drucker-Prager failure condition. The Drucker-Prager condition conforms to Mohr-Coulomb condition in three axial pressure and tension.

In this research, soil was supposed as Elastic-perfectly plastic material. The linear elasticity and Drucker-Prager plasticity model were used to describe the elastic and plastic behavior of soil, respectively. Drucker-Prager Elastic-perfectly plastic material model was adopted with the flow rule of associated plasticity. In order to simulate soil material the Young's Modulus (E), Poisson's ratio (υ), friction angle (φ), Cohesion (c) and Dilation angle (ψ) were necessary. These values were obtained in the laboratory.

The penalty algorithm was used for contact definition of soil and penetrometer rod surface. Furthermore the rod was modeled as a rigid material with a reference point in cone point.

2.4 Finite element mesh and boundary conditions

Because the influence of loading force on soil decreases with increasing in distance from loading point, the total of soil space was not modeled and a part of soil that penetrometer had significant effect on, was modeled. But the modeling was performed with a proper boundary condition.

A 3D 8-node linear brick continuum element C3D8 was used to represent both clay soil and the penetrometer in the finite element model. The dimensions of models are presented in Table 1.

Table 1 Dimensions of soil and penetrometer

Parameter	Soil	Penetrometer
Length/mm	100	-
Width/mm	100	-
Height/mm	250	200
Diameter/mm	-	9

Approximately, 14594 elements were used to simulate the clay soil, and 19965 elements were used to simulate the penetrometer which was defined as a rigid body with a reference point. Simulating the blade using the *RIGIDBODY* feature in Abaqus enables the calculation of the resultant reaction forces acting on the entire blade at a single node called "the reference point for the rigid body". Due to the symmetric geometry of the model, quarter-half of the model was simulated but all the results considered the complete model. Relative motion was allowed with friction along the soil–blade interface surfaces. The model was meshed in a manner that increased the mesh density near the blade and the predefined failure surfaces as shown in Figure 2. Boundary conditions of the model are also shown in Figure 3 and can be listed as follows.

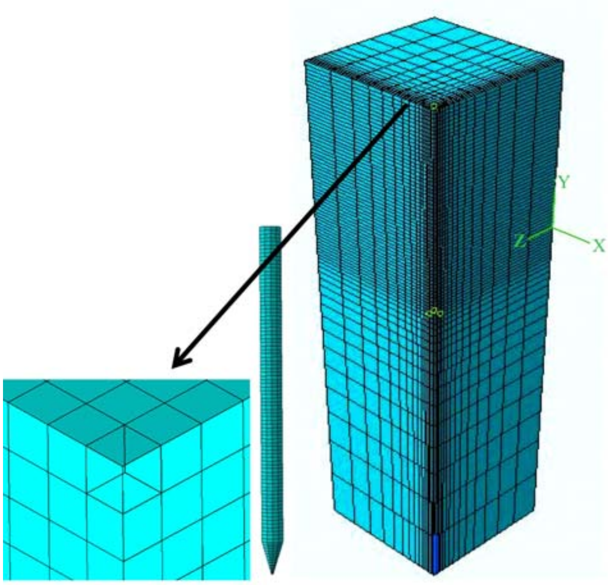

Figure 2 Finite element mesh of soil and penetrometer

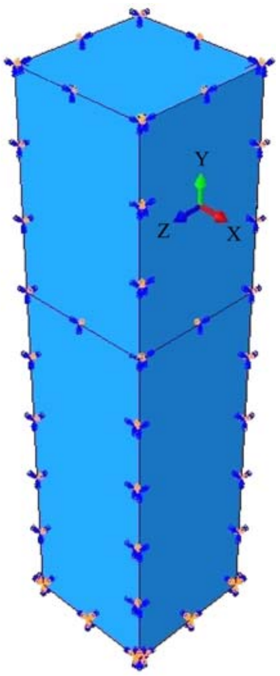

Figure 3 Soil boundary conditions

In this research, the modeling was performed based on Abo-Elnor et al. (2003) method that the mesh density increased near force effect point.

The physical concept of boundary condition creation is that a substance can have free motion if the substance is bounded with constraints. Therefore in finite element problems, boundary conditions and backrest constraints must be defined. The following boundary conditions were used to constrain the soil and penetrometer models.

a) The lower nodes in base of soil model are fully constrained.

b) Nodes on vertical boundaries parallel to the Y–Z plane are constrained in the horizontal direction along X-axis.

c) Nodes on vertical boundaries parallel to the X–Y plane are constrained in the horizontal direction along Z-axis.

d) The penetrometer is constrained in any rotation in X-axis and Z-axis but it is free to displace in the Y direction.

3 Results and discussion

The average value of soil physical properties is presented in Table 2. Also the soil coulomb's properties are showed in Table 3.

Table 2 Average of soil physical properties in 3 areas

Area	Wet density /g cm^{-3}	Dry density /g cm^{-3}	Porosity	Void ratio	Degree of saturation/%
A	1.425	1.339	0.495	0.98	17.1
B	1.572	1.51	0.43	0.76	14.7
C	1.488	1.404	0.47	0.89	18.3

Table 3 Soil coulomb's properties

δ	v	E/MPa	C/kPa	φ
23°	0.3	2	16	24°

The simulation of penetrometer and soil interaction in Abaqus were compared with field data and validated. Figure 4, Figure 5, Figure 6, and Figure 7 show the result of simulation and field experiment, respectively.

The initial penetrometer resistance obtained in beginning of contact between cone and soil, had the highest value. This phenomenon was due to point type contact that resulted stress concentration. To eliminate this phenomenon, two steps were assumed for cone penetration. At the first 0.1 s and in the second step 7.4 s was selected as penetrating time and only the obtained value of CI in second step was saved and used.

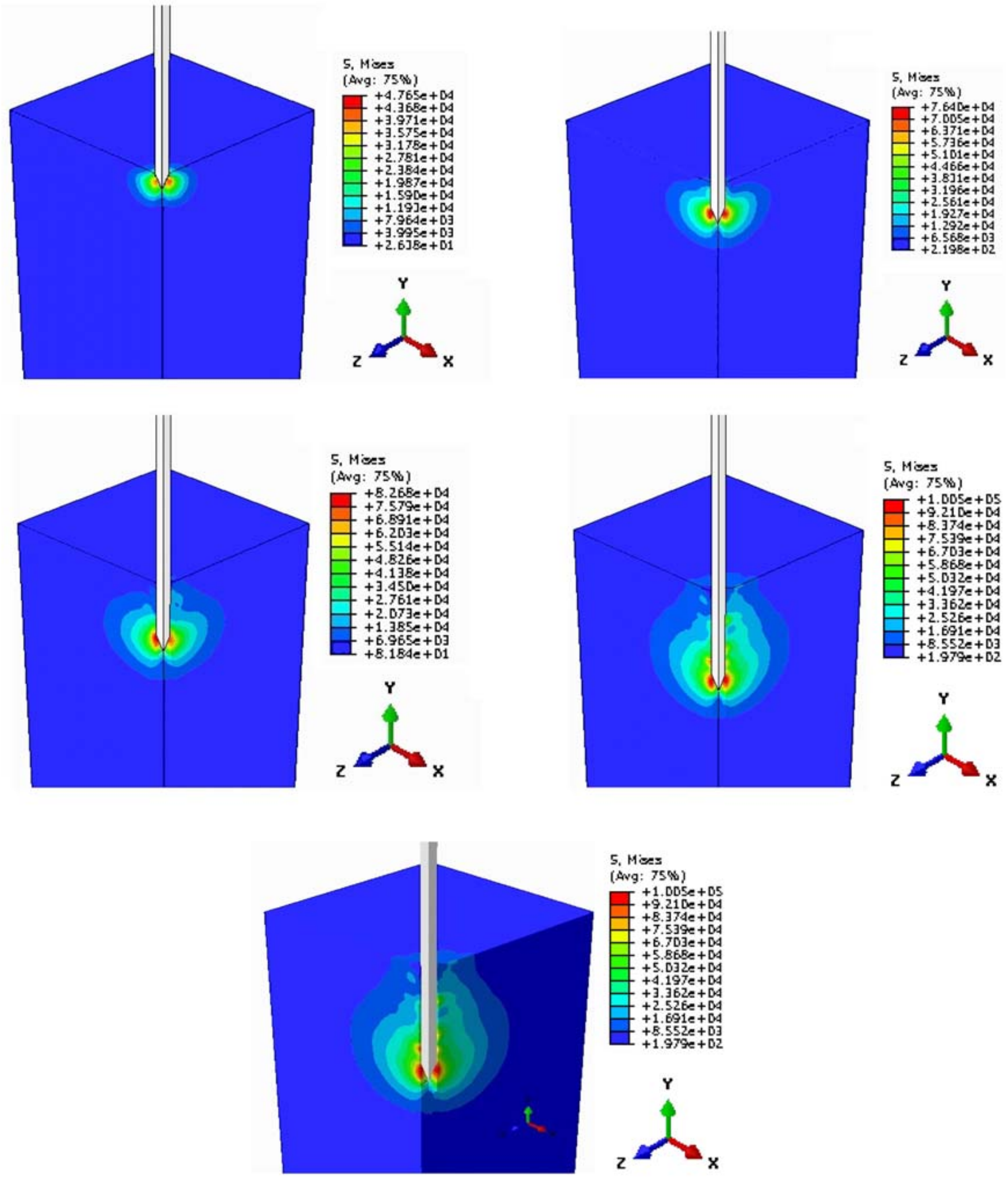

Figure 4 The soil- penetrometer interaction

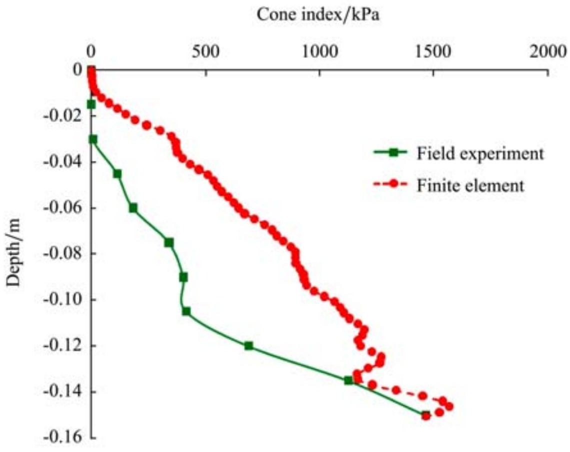

Figure 5 Comparison of penetration resistance of soil in an area

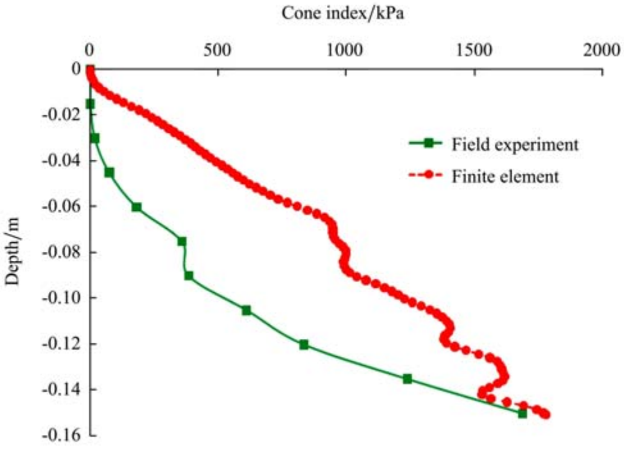

Figure 6 Comparison of penetration resistance of soil in C area

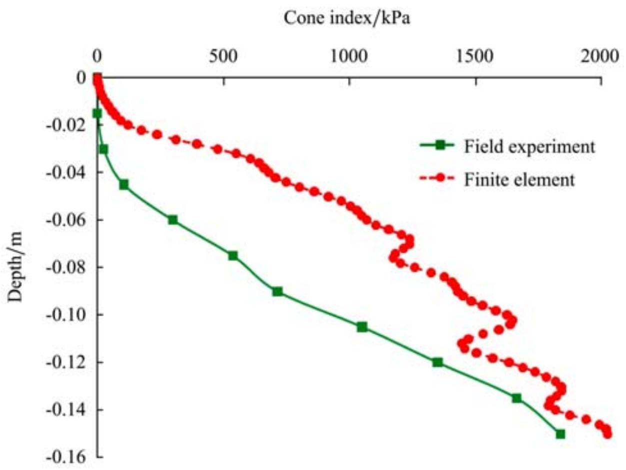

Figure 7 Comparison of penetration resistance of soil in B area

As perceived from Figure 4, Figure 5, Figure 6, and Figure 7, the results obtained from FEM had a higher value than field experiment results in upper layers of soil. Also in higher depth, the difference between FEM and field experiment results decreased. Because the beneath layers of soil usually is more compacted than upper layers so the physical properties of soil vary with variation of depth. But in FEM, soil was assumed as homogeneous material with stationary physical properties. In FEM, the CI approximately increases linearly with increase in depth, but in farmland, increasing of CI is unsteady. Totally, the FEM yields acceptable result in lower soil layers.

4 Conclusions

In this research, 3D finite element analysis has been performed for simulation of soil-penetrometer interaction and studying of tractor passing on soil compaction. Based on results, the numerical method seems to be appropriate for analyzing of soil-penetrometer reaction or other agricultural implements, but the studied components must be simulated perfectly and boundary conditions must be indicated precisely. This method can be used as a replacement for field experiments.

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