https://doi.org/10.17221/58/2022-RAE

3D finite element analysis of tine cultivator and soil deformation

Muhammad Hashaam[1], Muhammad Waqar Akram[1]*, Moaz Ahmad[2], Muhammad Zuhaib Akram[3], Muhammad Faheem[1], Muhammad Maqsood[4], Muhammad Aleem[5]

[1]Faculty of Agricultural Engineering and Technology, University of Agriculture Faisalabad, Pakistan
[2]Department of North Surgery, King Edward Medical University Lahore, Pakistan
[3]State Key Laboratory of Automobile Safety and Energy, School of Vehicle and Mobility, Tsinghua University, China
[4]National Institute of Food science and Technology, University of Agriculture Faisalabad, Pakistan
[5]College of Environment, Hohai University, China

*Corresponding author: waqarakram@uaf.edu.pk

Citation: Hashaam M., Akram M.W., Ahmad M., Akram M.Z., Faheem M., Maqsood M., Aleem M. (2023): 3D finite element analysis of tine cultivator and soil deformation. Res. Agr. Eng.: 69: 107–117.

Abstract: For effective tillage, design and selection of tillage tool according to soil type and condition is very important. The present study is carried out for in-depth investigation of different types of shovels of tine cultivator and behavior of soil in response to loads subjected during tillage using finite element analysis. Different types of shovels like reversible, duck foot, seed drill and cultivator shovel are simulated with different types of soil like sand, clay and loam. The origination, level and distribution of stresses and deformations in shovels experienced in different types of soils are probed. Furthermore, high stressed and crack sensitive regions are identified. The stresses of 18, 53, 64 MPa are generated in reversible shovel of tine cultivator during ploughing in sandy, clay and loamy soil respectively. In addition, results of different shovels are compared, and it is found that the duck foot type shovel experiences highest stress and deformation. The duck foot shovel experiences about 20 and 71% higher stresses in loam compared to that in clay and sand respectively. Moreover, the study of soil mechanical behavior shows that the soil block (clay soil) experiences maximum stress of 34 MPa while tilling with reversible shovel. The statistical analysis is also conducted that shows high significance of simulation results.

Keywords: finite element method; soil deformation; stresses; tillage implement; tine cultivator shovel

Tillage is an important practice in agriculture for the mechanical manipulation of soil for the purpose of crop production. It can help in the enhancement of soil structure using bio-tillage practices, which are considered important for sustainable agriculture production (Zhang and Peng 2021). An effective and reliable tillage operation has a great impact on sustainability and productivity of soil, and it is of high significance in terms of achieving tillage objectives with conservation of energy and other resources (Zein El-Din et al. 2021). The tillage operations consumed a large portion of energy available at farms

https://doi.org/10.17221/58/2022-RAE

due to high frictional and wear losses in tillage implements. The development of durable and efficient tillage implements is important in this context. The actual soil-working component in tillage operation is a tillage tool, whose efficiency and reliability depend upon various factors such as cutting speed, soil type, soil condition, tillage tool design/geometry, and tool material (Mustafa et al. 2015; Okoko and Ajav 2021).

Tine cultivator is one of the common secondary tillage implements used for breaking clods and pulverizes the soil, making the soil condition favorable for optimum production of particular crop. The actual soil-working and most important part in the cultivator is shovel that pierce the soil as it is dragged through it linearly; however, farmers face several problems during its operation like high energy losses, wear and damage i.e. breakage of shovel tip or cracking, etc. leading to higher operational cost, poor soil tillage and productivity, and reduced implement field capacity and durability (Aramide et al. 2021). To overcome this problem, specific type of shovel could be used in specific type (and condition) of soil (Šařec and Šařec 2015; Askari et al. 2017). Furthermore, for effective tillage, design and selection of tillage tool (shovel) according to soil type and condition is very important (Yezekyan et al. 2021). Research in this area has significant importance.

Several studies on different tillage tools (shovels and others) have been conducted for investigating their behavior and force/power requirement. The study (Abbaspour-Gilandeh et al. 2020) investigated the effects of forward speed, moisture content of the soil, and tillage depth on energy and force requirement of different cultivators. Shinde et al. (2011) and Tagar et al. (2015) investigated the effect of tool shape on soil disruption. In these studies, different shapes of tillage tool were analyzed in single soil type. Another study (Abu-hamdeh and Reeder 2003) investigated the forces acting on a disk using finite element modelling technique. In this study, the tillage tool (disk) was examined in clay and sandy loam soils at different speed and tilt angles. Umesh et al. (2016) studied the failure investigation of agricultural nine-tine cultivator (Galat and Ingale 2016). Du et al. (2013) studied the design and conducted finite element analysis of rotary tillage blades (Du et al. 2013). This study analyzed the basic working principle of rotary cutter by designing 3D modelling of rotary tillage blade using the SolidWorks software. The analysis of results shows that the parts near the assembling hole have the largest stress, and the area around blade tip has the largest deformation. Sumit et al. (2016) studied the design, and analyze the shaft of two-furrow reversible shovel (Balwani et al. 2016). The main objective of this study was to optimize the design of shaft as it gets bend or fails after some uses. After the analysis it has been found that whenever there is sudden impact on the plough the shaft gets bend thus for efficient working the shaft is redesigned to withstand the different forces along with static and dynamic load. Sadek et al. (2021) predicted the draft force for a high-speed disc implement using discrete element modelling (Sadek et al. 2021). Draft forces were measured for an individually mounded disc using soil bin tests at low speeds in a sandy loam soil. Raut et al. (2014) studied the finite element method (FEM) analysis of nine-tine medium duty cultivator (Raut et al. 2014). The main objective of this analysis was to increase the life of shovel by simply changing the material of shovel from EN45 (spring steel) (spring steel) to boron steel that have more allowable stress than the material EN45. Chirende et al. (2019) studied the application of finite element analysis in modeling of bionic harrowing discs (Chirende et al. 2019). The main objective of this study was to find out the effects of different biomimetic surface designs on reducing soil resistance. Selvi et al. (2017) investigated the structural deformation behavior of the sub-soiler and para-plow tines using finite element method. In this study, static stress-deformation analysis (in terms of material strengths) were presented. Another study (Hoseinian et al. 2022) analyzed soil deformation and reaction forces to dual sideway share during plowing using simulation and physical experiments. The study (Ananyev et al. 2021) carried out simulation study on duck-foot tines of different materials i.e. steel and isotropic fiberglass and found that fiberglass tine experiences less deformation relatively. The study (Kshetri et al. 2021) investigated soil-tool interaction for a vertical tine (mounted on a disk) working at different rotational and linear velocities. The study (Sher et al. 2021) used discrete element modeling approach for analysis of soil-tool interaction of grouser shoe and clay soil. The simulations are carried out at different moisture contents and Hertz Mindlin contact model was used. The study (Changbin et al. 2023) proposed a model for draft force prediction in shank type tillage tine. Validation experiments were also carried out in soil bin

https://doi.org/10.17221/58/2022-RAE

to check the prediction accuracy. The study (Kesner et al. 2021) modeled stresses experienced by chisel shank during soil tilling. The discrete element method (DEM) and FEM methods were used and strain gauges were also used for experimental validation. There are several studies related to modeling of soil behavior using Drucker prager yield criterion (Li et al. 2013; Armin et al. 2014; Tagar et al. 2015; Chirende et al. 2019; Orlando et al. 2019). The existing related studies mostly focused on tool and soil behavior, and force/power requirement for simple cases of specific tool type and/or condition.

A comprehensive existing study considering different types of shovels and its analysis in different types of soils (tool-soil interaction and soil deformation) is not available. There is lack of related in-depth and comprehensive knowledge and understanding. With the advent of high-end computational hardware resources and the availability of numerical modeling tools, it is possible to simulate the entire machine-soil system for probing into the deeper details. The computer modeling can provide deeper details at the element/unit level to understand the origination and distribution of stresses. The large use of tine cultivator worldwide and high losses and failure rates demands a comprehensive study in this context, that can enable us to reduce or avoid wear and tear in tillage implements through the use of enhanced designs and optimization strategies, and appropriate tillage tool selection.

In this light, the present study is conducted, in which finite element analysis of shovels of tine cultivator during plowing is carried out in different types of soils to probe into the origination, level, and distribution of stresses. In addition, soil failure pattern is also studied. The main objectives of this study are to analyze the mechanical behavior of different types of tillage tools like reversible, seed drill, duck foot, and cultivator shovel of tine cultivator in response to loads experienced during plowing in different types of soil, and the behavior of different soil types like sand, clay and loam soil during plowing by tine cultivator. The stresses and displacements experienced in different shovels and soils are compared. The statistical analysis of simulation results is also conducted at the end. This study can help in designing and tillage tool selection according to soil type and condition leading to reduced losses and damages, less operational cost, enhanced soil tillage and productivity, and increased implement field capacity and durability.

MATERIALS AND METHODS

This section deals with details about geometrical modeling, materials, meshing, and simulation methodology. Geometrical models of different types of shovels i.e. reversible, seed drill, duck foot, and cultivator shovel are created in Design Modeler (ANSYS 16.0) and simulated in different soil types. Finite element analysis [(static structural dealing with steady load and response conditions (ANSYS 2015)] is carried out to analyze the mechanical behavior of shovels in response to forces experienced during soil cutting. Moreover, soil failure pattern is also studied. Boundary conditions and loads are applied as in real field condition. The FEM is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. In simple terms, FEM is a discretization method for dividing a very complicated problem into small elements that can be solved in relation to each other (ANSYS 2015).

After discretization and assembling the elements at nodes, the unknown parameters/quantities are obtained by minimizing energy functional, consisting of all associated energies of the FE model. The minimum functional can be found according to the following Equation (1), where derivative of the energy functional with respect to unknown gird point potential is zero.

$$\frac{\partial F}{\partial P} = 0 \tag{1}$$

where: F – the energy functional; P – unknown grid point potential i.e. displacement in solid mechanics. This works on the principle of virtual work.

The governing equations for rigid body can be attained by minimizing total potential energy, which can be expressed as below.

$$\pi = \frac{1}{2}\int_{\Omega} \varsigma^{T} \varepsilon dV - \int_{\Omega} d^{T} b dV - \int_{\Gamma} d^{T} q ds \tag{2}$$

where: Ω – the stress component; ε – the strain component; d – displacement vector at any point; b – force component; q – surface traction component; s – bounding surface.

The surface and volume integrals are defined over entire structure region Ω and that boundary part subjected to Γ load. The first term in the Equation shows strain energy, second term shows potential energy

https://doi.org/10.17221/58/2022-RAE

of body force, and third term represents potential energy of distributed surface loads. For FE displacement method, within one element, $d = Nu$ whereas, N – matrix of interpolation functions; u– vector of displacements at nodes. The strains within element can be expressed as $\varepsilon = Bu$, whereas B is strain displacement matrix. Moreover, the stresses can be expressed as $\Omega = E\varepsilon$, whereas E – young's modulus of elasticity.

The total potential energy of a meshed (discretized) structure is the sum of energy of all elements.

$$\Pi = \sum_e \Pi_e \tag{3}$$

whereas Π_e shows potential energy of each element, given below:

$$\Pi_e = \frac{1}{2}\int_{\Omega_e} (B^T EB)^T u dV - \int_{\Omega_e} U^T N^T p dV - \\ - \int_{\Gamma} N^T q ds = 0 \tag{4}$$

By taking derivative of above equation:

$$\frac{\partial \Pi_e}{\partial u} = \frac{1}{2}\int_{\Omega_e} (B^T EB)^T u dV - \int_{\Omega_e} N^T p dV - \\ - \int_{\Gamma} N^T q ds = 0 \tag{5}$$

From above, the element equilibrium equation can be written as:

$$ku - f = 0 \tag{6}$$

Where:

$$f = \int_{\Omega_e} N^T p dV + \int_{\Gamma} N^T q ds; \; k = \frac{1}{2}\int_{\Omega_e} (B^T EB)^T u dV$$

K is known as element stiffness matrix. The vector f and u varies according to the physical system and application under study. For problems of solid mechanics (as in our case), displacement is state (degree of freedom) vector (d) and mechanical force is forcing vector (f).

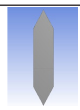
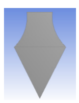
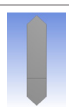
The details of present analysis are discussed in following subsections.

Types of shovel studied. The most important part of the cultivator is a shovel that pierces the soil, as it is dragged through it linearly. The following types of shovels are studied. (*i*) Reversible shovel: It is made of carbon steel and used for loosening and stirring the soil, (*ii*) duck foot shovel: It is also made of carbon steel and used for destruction of weeds and retention of soil moisture, (*iii*) seed drill shovel: It is wide range shovel for deeper tillage than reversible and duck foot shovel and also used to cover the seed. It is also made of carbon steel, (*iv*) cultivator shovel: It is also a common type of shovel used to cut the soil.

Geometrical/FE model and meshing. The geometrical models of shovels are drawn in ANSYS Design Modeler (ANSYS 16). The geometrical models, dimensions and brief description of shovels are shown in Table 1.

After building models of shovels in Design Modeler, face split function is used to split the bottom face of shovel to simulate the real field loading process. The split face is the part of a shovel that experiences soil penetration resistance force in actual. Following above, in ANSYS Mechanical, 3-D 10-Node Tetrahedral Structural Solid elements (Solid 187) are used to simulate the FE model of shovels and soil block. The degree of freedom for this element is UX, UY,

Table 1. Different types of shovels

Sr. No#	Shovel type	Geometry	Dimensions (mm)	Description
01	reversible		thickness: 4 width: 50 length: 254	It is a common type of shovel used for loosening and stirring the soil
02	duck foot		thickness: 4 width: 150 length: 250	It is used for destruction of weeds and retention of soil moisture
03	seed drill		thickness: 4 width: 40 length: 300	It is a comparatively long shovel for deep tillage to cover the seed
04	cultivator		thickness: 4 width: 50 length: 254	It is also a common type of shovel used to cut the soil

https://doi.org/10.17221/58/2022-RAE

UZ (ANSYS 2013). Such elements are well suited to model irregular meshes as in our case. The meshing is carried out using tetrahedrons. Mesh refinement is carried out to attain the best results and to prevent convergence problems. Mesh refinement of soil block is also performed with great care. Beginning from a coarse mesh, finer and finer meshes are successively selected and results of different meshes are compared.

The number of elements and nodes in reversible, duck foot, seed drill and cultivator type shovel models are 3782 and 5807, 6222 and 10751, 5020 and 8417, and 4028 and 6183 respectively. The element size used for meshing in shovels is 2 mm, and in soil block is 5 mm. The meshed models of shovels and soil block are shown in Figure 1.

Afterwards, different types of shovels models are simulated with FEM, a numerical method for solving complex problems or dividing complex problems into small elements that can be solved in relation to each other.

Materials. The material used in shovel is carbon steel. The physical and mechanical properties of carbon steel are given in Table 2.

We simulate shovels with three type of soils that is sandy, clay and loam. The resistance values of these soils, that are used in our analysis are given below in Table 3.

Simulation Methodology. Boundary conditions are applied to the model to simulate real field loading process. Fixed support is applied to the upper part of a shovel (other than split face). The boundary conditions for shovels are shown in Figure 2. For clay soil block, Drucker prager elastic perfectly plastic material model is used. Drucker prager model is widely used for soil in several existing studies (Li et al. 2013; Armin et al. 2014; Tagar et al. 2015; Chirende et al. 2019; Orlando et al. 2019). It is a pressure-dependent model used for determination of plastic yielding (deformation) of soil. Soil block is constrained in all directions from bottom side as shown in Figure 3. While, shovel load is applied on the other side to the bottom side of the soil block. It demonstrates how the clay soil deforms during tilling operations in response to the applied load. On the

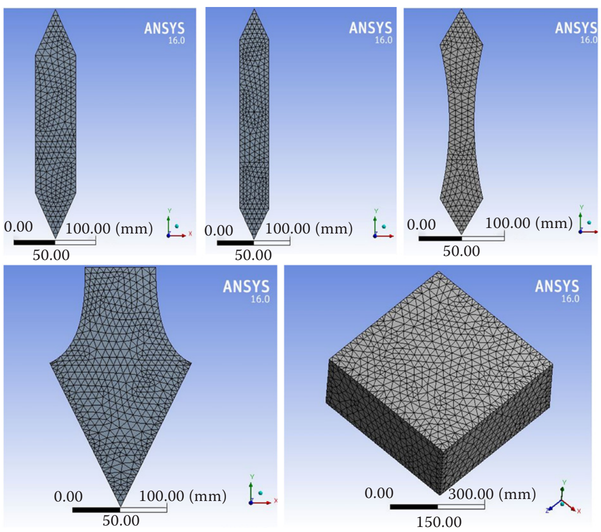


Figure 1. Meshing of shovels and soil block model

Table 2. Mechanical properties of carbon steel

Material property	Value and unit
Density	7 870 kg·m^{-3}
Young's modulus	200 GPa
Poisson's ratio	0.29
Bulk modulus	158 GPa
Shear modulus	77 GPa
Tensile yield strength	415 MPa
Tensile ultimate strength	540 MPa

Table 3. Soil types and their resistance

Type of soil	Soil resistance (kg·cm^{-2})	Optimum moisture content (%)
Sandy	0.20	3.50
Clay	0.40–0.56	7.18
Loamy	0.50–0.70	13.30

Source: Topakci et al. 2010; Raut et al. 2014

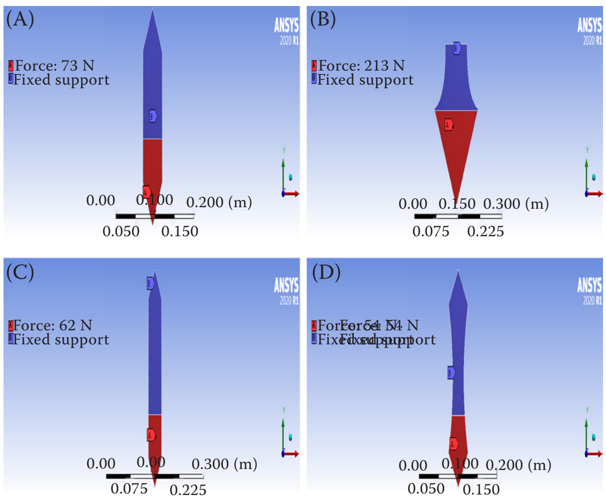


Figure 2. Boundary conditions applied to the shovel: (A) reversible shovel analysis (B) duck foot shovel analysis (C) seed drill shovel analysis and (D) cultivator shovel analysis

https://doi.org/10.17221/58/2022-RAE

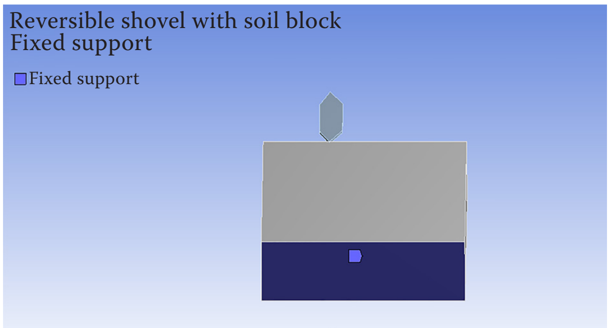


Figure 3. Boundary conditions applied to the soil

other hand, 0.2, 0.56, 0.7 kg·cm^{-2} loads are applied separately for sandy, clay and loamy soil, respectively to the bottom side of the shovels (split face) to simulate soil loads during tillage operation. In ANSYS Mechanical, static structural analysis is considered; and inertial and damping effects are ignored because this type of analysis deals with static loads only.

Statistical Analysis. The modeling results of these simulation experiments were also compared by using statistical tool (Statistic software, version 8.1). Statistical results were analyzed at 5% significance level and their means were also compared at least significance design (LSD) test. These simulation experiments are carried out in ANSYS. In ANSYS, "level of significance" refers to the level of confidence that a user has in the results obtained from a simulation. The level of significance is used to determine the level of accuracy required in a simulation, that the results of the simulation will fall outside of the desired level of accuracy. It also can affect the computational cost of the simulation. For tradeoff between accuracy and computational cost, this probability value is 0.05 (5 %) in ANSYS.

RESULTS AND DISCUSSION

In this section mechanical behavior of different types of shovels against different soils is discussed. Furthermore, the behavior of soil block (clay soil) during tillage operation with reversible shovel of tine cultivator is also discussed.

Behavior of shovel

Reversible shovel with sandy soil. The distribution of Von-Mises stress in reversible shovel while tilling in sandy soil is shown in Figure 4(A). At the bottom side, 1/3rd part of the shovel (fixed with tine) experiences maximum stress of 18.9 MPa. The total deformation in reversible shovel during tilling

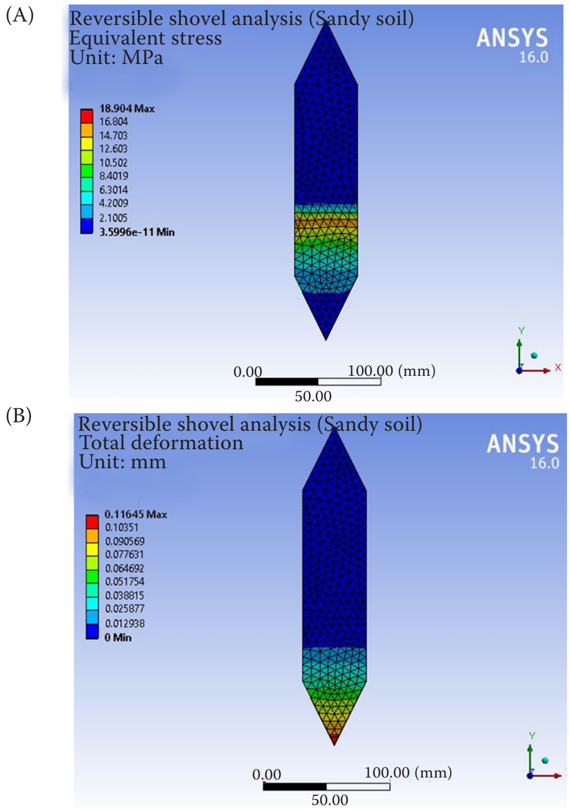


Figure 4. Reversible shovel analysis with sandy soil (A) Von-Mises stress distribution and (B) total deformation

in sandy soil is shown in Figure 4(B). The bottom side of a shovel (subjected to soil) experiences maximum deformation of 0.116 mm. The minimum and maximum safety factor observed for the reversible shovel with sandy soil is 15. The safety factor (SF) is the ratio of the stress at which failure occurs to the stress that actually occurs in the part. Therefore, a SF of 15 means that the loads causing the stress could be increased by a factor of 15 before failure occurs. In case of sandy soil, the soil resistance is too small to affect the shovel.

Duck foot shovel with sandy soil. The distribution of Von-Mises stress in duck foot shovel while tilling in sandy soil is shown in Figue 5(A). Middle part of the shovel (fixed with tine) experiences maximum stress of 28 MPa. The total deformation in duck foot shovel during tilling in sandy soil is shown in Figure 5(B). The bottom side of a shovel (subjected to soil) experiences maximum deformation of 0.38 mm. The minimum and maximum safety factor observed for the duck foot shovel in loamy soil is 4.8 and 15 respectively.

Seed drill shovel with sandy soil. The distribution of Von-Mises stress in seed drill shovel during tilling in sandy soil is shown in Figure 6(A).

https://doi.org/10.17221/58/2022-RAE

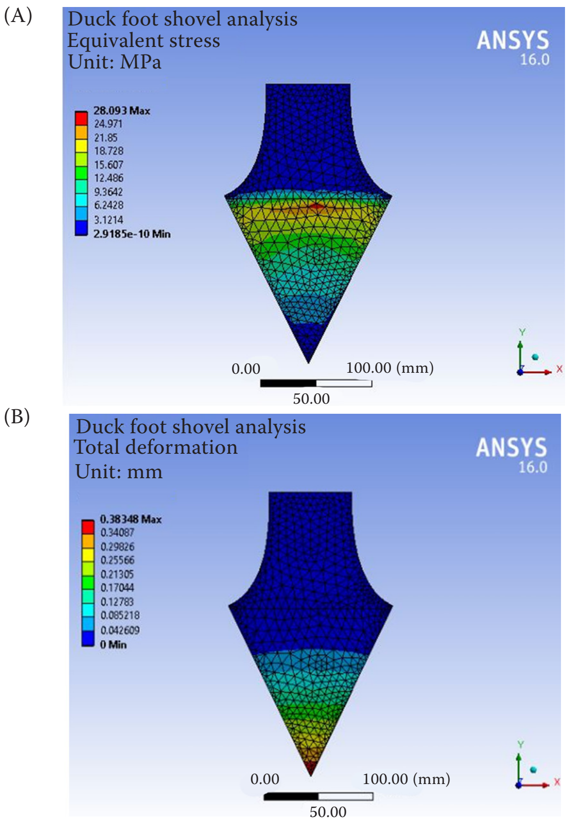


Figure 5. Duck foot shovel analysis with sandy soil (A) Von-Mises stress distribution (B) Total deformation

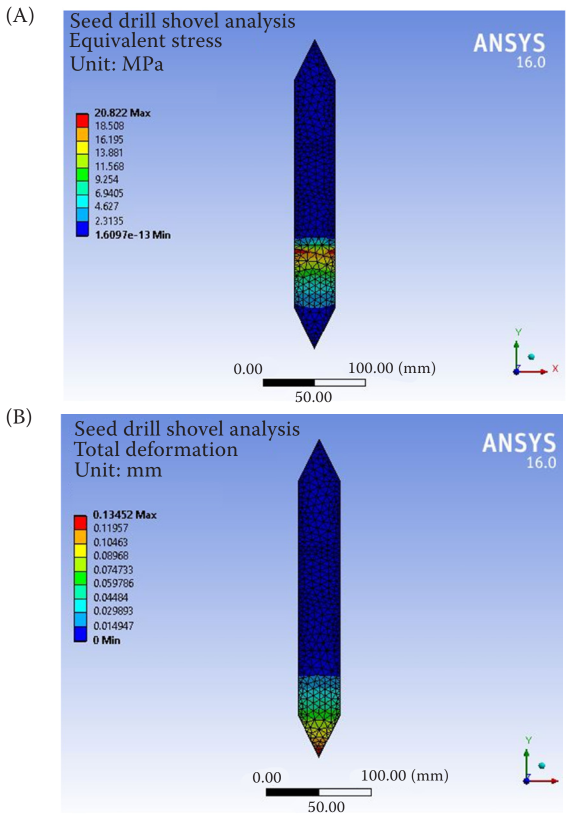


Figure 6. Seed drill shovel analysis with sandy soil (A) Von-Mises stress distribution (B) total deformation

At the bottom side, 1/3rd part of the shovel (fixed with tine) experiences maximum stress of 21 MPa. The total deformation in seed drill shovel during tilling in sandy soil is shown in Figure 6(B). The bottom side of shovel (subjected to soil) experiences maximum deformation of 0.13 mm. The minimum and maximum safety factor observed for the seed drill shovel in loamy soil is 6.7 and 15 respectively.

Cultivator shovel with sandy soil

The distribution of Von-Mises stress in cultivator shovel during tilling in sandy soil is shown in Figure 7(A). At the bottom side, 1/3rd part of the shovel (fixed with tine) experiences maximum stress of 17 MPa. The total deformation in cultivator shovel during tilling in sandy soil is shown in Figure 7(B). The bottom side of shovel (subjected to soil) experiences maximum deformation of 0.07 mm. The minimum and maximum safety factor observed for the cultivator shovel in loamy soil is 12 and 15 respectively.

Behavior of soil

The distribution of Von-Mises stress in soil block (clay soil) during tilling with reversible shovel is

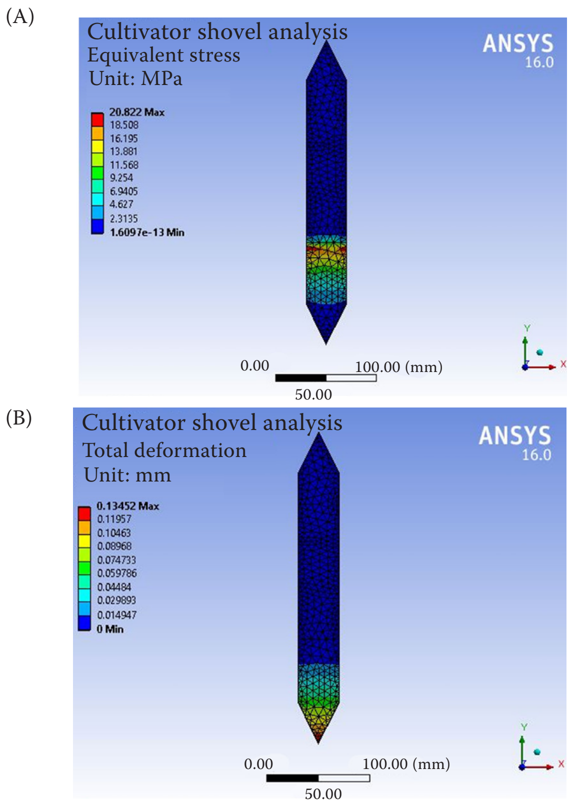


Figure 7. Cultivator shovel analysis with sandy soil (A) Von-Mises stress distribution (B) total deformation

https://doi.org/10.17221/58/2022-RAE

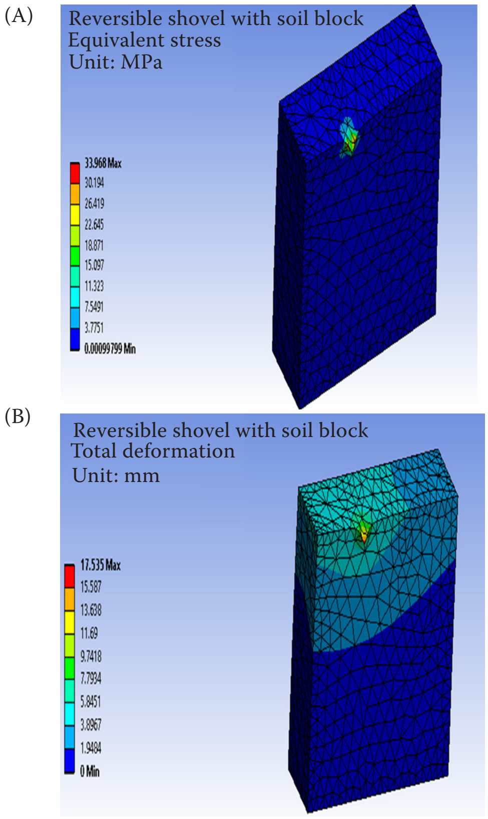


Figure 8. Behavior of soil block against reversible shovel (A) Von-Mises stress distribution in soil block (clay soil) and (B) total deformation in soil block (loamy soil)

shown in Figure 8(A). The soil block (clay soil) experiences maximum stress of 34 MPa while tilling with reversible shovel. The maximum deformation experienced by the soil block (loamy soil) is of 17.5 mm. The total deformation in soil block during tilling with reversible shovel is shown in Figure 8(B).

Comparison

This section deals with comparison of maximum stresses and deformation generated in different types of shovels i.e., reversible, duck foot, seed drill and cultivator, due to forces subjected by different soil types i.e., loam, clay, and sand. Maximum

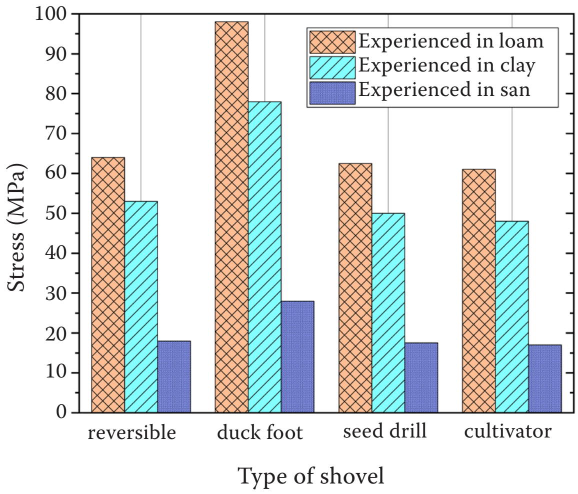


Figure 9. Maximum stresses generated in different types of shovels, due to forces subjected by different soil types

stresses generated in different types of shovels, due to forces subjected by different soil types are shown in Figure 9. The duck foot type shovel experiences higher stresses as compared to other shovel types; while the loam is subjected to higher stresses on shovels as compared to other soil types. The duck foot shovel experiences about 20% higher stresses in loam compared to that clay, about 64% higher in clay compared to sand, and about 71 % higher in loam compared to that in sand. There are almost similar results for other shovel types in these soils. These results are summarized in Table 4. The comparison of stresses within different types of shovels for different soils is summarized in Table 5.

Maximum deformation generated in different types of shovels, due to forces subjected by different soil types are shown in figure 10. The duck foot type shovel experiences larger deformation as compared to other shovel types; while the loam subjected larger deformation on shovels as compared to other soil types. The duck foot shovel experiences about 15% larger deformation in loam compared to that in clay, about 72% larger in clay compared to that in sand, and

Table 4. Comparison of maximum stresses (% age) generated in shovels for different soil types

Sr. No.	Duck foot shovel	Reversible shovel	Seed drill shovel	Cultivator Shovel
		compared to clay		
1	20.408 higher in loam	17.187 higher in loam	21.324 higher in loam	20.505 higher in loam
		compared to sand		
2	64.102 higher in clay	66.037 higher in clay	64.681 higher in clay	65.000 higher in clay
		compared to sand		
3	71.428 higher in loam	71.875 higher in loam	72.213 higher in loam	72.105 higher in loam

https://doi.org/10.17221/58/2022-RAE

Table 5. Comparison of maximum stresses (% age) within different types of shovels

Sr. No.	Loam soil	Clay soil	Sandy soil
		compared to reversible shovel	
1	35 higher in duck foot shovel	32 higher in duck foot shovel	36 higher in duck foot shovel
		compared to seed drill shovel	
2	36 higher in duck foot shovel	36 higher in duck foot shovel	37.5 higher in duck foot shovel
		compared to cultivator shovel	
3	38 higher in duck foot shovel	38 higher in duck foot shovel	39 higher in duck foot shovel
		compared to seed drill shovel	
4	2.5 higher in reversible shovel	5.5 higher in reversible shovel	3 higher in reversible shovel
		compared to cultivator shovel	
5	5 higher in reversible shovel	9 higher in reversible shovel	5.5 higher in reversible shovel
		compared to cultivator shovel	
6	2.4 higher in seed drill shovel	4 higher in seed drill shovel	2.8 higher in seed drill shovel

about 77% larger in loam compared to that in sand. The comparison results in percentage (% age) for other shovels are shown in Table 6. The comparison of deformation within different types of shovels for different soils is summarized in Table 7.

In this section, the obtained results are compared for different cases; but cannot be compared with other studies due to unavailability of existing results. There are several existing studies related to different tillage tools and operations, as mentioned earlier in introduction section. But there is no existing experimental or modeling based study available on tine cultivator shovel thermo-mechanical analysis. The experimental work on this topic is an important research direction. The possible continuation of the present study can be experimental thermo-mechanical measurements.

At present, to ensure maximum reliability of the models, the following measures are taken into consideration:

(*i*) 3D geometrical models (of shovels under study) with maximum details are simulated to obtain high solution accuracy.

(*ii*) Real field conditions are simulated/considered to obtain the best results.

(*iii*) Mesh convergence experiments are performed to verify that meshing is sufficiently accurate.

(*iv*) The material model and type are selected according to recommendations by previous studies.

(*v*) Element selection is carefully carried out according to recommendations by previous studies.

Statistical analysis

The modeling results were also compared by using statistical tool (statistic 8.1). Statistical results were analyzed at 5% significance level and their means were also compared at LSD test. Mean values for the shovels (duck foot shovel, reversible shovels, seed drill shovel, cultivator shovel) varies in range from 0.93 ± 0.05, 0.28 ± 0.05, 0.22 ± 0.05, and 0.09 ± 0.05 for deformation and 60.50 ± 2.17, 43.13 ± 2.17, 42.57 ± 2.17, and 23.70 ± 2.17 for stresses respectively. Standard error (SE) for deformation was found as 0.07; whereas for stress, it was found as 3.07. ANOVA test was conducted for the stress and deformation which indicates that the results are highly significant for all the types of soil (loam, clay and sand) and shovels (duck foot shovel, reversible shovels, seed drill shovel, cultivator shovel). The results support the modeling studies and revealed highly significant results; which also makes evident that the

Table 6. Comparison of maximum deformation (% age) experienced by shovels in different soil types

Sr. No.	Duck foot shovel	Reversible shovel	Seed drill shovel	Cultivator Shovel
			compared to clay	
1	15.3 larger in loam	20 larger in loam	23 larger in loam	20 larger in loam
			compared to sand	
2	72.72 larger in clay	68.7 larger in clay	67 larger in clay	65 larger in clay
			compared to sand	
3	77 larger in loam	75 larger in loam	75 larger in loam	72 larger in loam

https://doi.org/10.17221/58/2022-RAE

Table 7. Comparison of maximum deformation (% age) within different types of shovels

Sr. No.	Loam soil	Clay soil	Sandy soil
1		**compared to reversible shovel**	
	69 larger in duck foot shovel	71 larger in duck foot shovel	66 larger in duck foot shovel
2		**compared to seed drill shovel**	
	70 larger in duck foot shovel	73 larger in duck foot shovel	68 larger in duck foot shovel
3		**compared to cultivator shovel**	
	81 larger in duck foot shovel	82 larger in duck foot shovel	76 larger in duck foot shovel
4		**compared to seed drill shovel**	
	2.5 larger in reversible shovel	6 larger in reversible shovel	3 larger in reversible shovel
5		**compared to cultivator shovel**	
	38 larger in reversible shovel	37.5 larger in reversible shovel	30 larger in reversible shovel
6		**compared to cultivator shovel**	
	36 larger in seed drill shovel	33 larger in seed drill shovel	28 larger in seed drill shovel

shovel types have different stress and deformation results for each kind of soil.

These simulation experiments are carried out in ANSYS. In ANSYS, "level of significance" refers to the level of confidence that a user has in the results obtained from a simulation. The level of significance is used to determine the level of accuracy required in a simulation, and the results of the simulation will fall outside of the desired level of accuracy. It also can affect the computational cost of the simulation. For the tradeoff between accuracy and computational cost, this probability value is 0.05 (5 %) in Ansys.

CONCLUSION

The results in this work give understanding about mechanical behavior of shovels and soil block during tillage operation, which can aid the development of enhanced design strategies and appropriate tillage tool selection; leading to reduced losses and damages, less operational cost, enhanced soil tillage and productivity, and increased implement field capacity and durability. The obtained results show that the duck foot shovel experiences about 20% higher stresses in loam compared to that in clay, about 64% higher in clay compared to sand, and about 71% higher in loam compared to that in sand. There are almost similar results for other shovel types in these soils. On the other hand, the duck foot shovel experiences about 15% larger deformation in loam compared to that in clay, about 64% larger in clay compared to that in sand, and about 69% larger in loam compared to that in sand. The overall conclusions for different cases are:

(*i*) 1/3rd part of the shovels experiences maximum stress as it is fixed with tine of cultivator.

(*ii*) The bottom tip of the shovel experiences maximum deformation.

(*iii*) Overall in the case of loamy soil, shovels experience high stresses and displacements.

(*iv*) In the case of sandy soil, shovels experience less deformation and stress.

(*v*) The duck foot type shovel experiences the highest stress and deformation among all scenarios.

(*vi*) Drucker prager elastic perfectly plastic material model can be used for soil tilling simulation.

(*vii*) The statistical analysis shows a high significance of simulation results.

The experimental work on this topic is an important research direction. The possible continuation of the present study can be experimental thermomechanical measurements.

REFERENCES

Abbaspour-gilandeh Y., Fazeli M., Roshanianfard A. (2020): Effect of different working and tool parameters on performance of several types of cultivators. Agriculture, 10: 1–19.

Abu-hamdeh N.H., Reeder R.C. (2003): A nonlinear 3D finite element analysis of the soil forces acting on a disk plow. Soil Tillage Research, 74: 115–124.

Ananyev M., Ishkov A. V., Malikov V.N., Karpov N. (2021): Study of 3D models of composite duck-foot tines. Materials Science Forum, 1031: 209–215.

ANSYS (2013): ANSYS Mechanical APDL Element Reference. USA.

ANSYS (2015): Workbench User's Guide. USA.

Aramide B., Pityana S., Sadiku R., Jamiru T., Popoola P. (2021): Improving the durability of tillage tools through surface

https://doi.org/10.17221/58/2022-RAE

modification-a review. International Journal of Advanced Manufacturing Technology, 116: 83–98.

Armin A., Fotouhi R., Szyszkowski W. (2014): On the FE modeling of soil-blade interaction in tillage Operations. Finite Elements in Analysis and Design, 92: 1–11.

Askari M., Shahgholi G., Abbaspour-Gilandeh Y. (2017): The effect of tine, wing, operating depth and speed on the draft requirement of subsoil tillage tines. Research in Agricultural Engineering, 63: 160–167.

Balwani S.N., Gulhane U.D., Shu A.R. (2016): Design, modification and analysis of shaft of two furrow reversible plough. International Journal of Engineering, Science and Technology, 3: 108–116.

Changbin H., Yanying G., Xudong G., Hongchao S. (2023): A mathematical model for predicting the draft force of shank-type tillage tine in a compacted sandy loam. Soil and Tillage Research, 228: 105642.

Chirende B., Li J.Q., Vheremu W. (2019): Application of finite element analysis in modeling of bionic harrowing discs. Biomimetics, 4: 61.

Du X.W., Jia S.T., Jiang-Tao, Xiu J., Yu F., He Z.T., Zheng Z.H., He Y.K., Liu J.J. (2013): Design and finite element analysis of rotary tillage blade based on solidworks. International Conference on Advanced Mechatronic Systems. Lyoyang, China, September 25–27, 317–321.

Galat U.N., Ingale A.N. (2016): Failure investigation & analysis of agricultural 9 tyne cultivator used in various soil condition. International Journal on Recent and Innovation Trends in Computing and Communication, 4: 173–179.

Hoseinian S.H., Hemmat A., Esehaghbeygi A., Shahgoli G., Baghbanan A. (2022): Development of a dual sideway-share subsurface tillage implement: Part 1. Modeling tool interaction with soil using DEM. Soil Tillage Research, 215: 105201.

Kešner A., Chotěborský R., Linda M., Hromasová M., Katinas E., Sutanto H. (2021): Stress distribution on a soil tillage machine frame segment with a chisel shank simulated using discrete element and finite element methods and validate by experiment. Biosystems Engineering, 209: 125–138.

Kshetri S., Steward B.L., Tekeste M.Z. (2021): Modeling soil forces on a rotary tine Tool in artificial soil. Transactions of the ASABE, 64: 1693–1704.

Li M., Chen D., Zhang S., Tong J. (2013): Biomimeitc design of a stubble-cutting disc using finite element analysis. Journal of Bionic Engineering, 10: 118–127.

Mustafa U., John M., Fielke C.S. (2015): Defining the effect of sweep tillage tool cutting edge geometry on tillage forces using 3D discrete element modelling. Information Processing in Agriculture, 2: 130–141.

Okoko P., Ajav E. (2021): Modeling of tillage operation parameters for draft and power requirement for three tillage implements in a loamy soil. Agricultural Engineering, 4: 10–29.

Orlando L., Cabrera M., Eloy C.A., De G., Costales F. (2019): Model of soil –tillage tool interaction using finite element method. Revista Ciencias Técnicas Agropecuarias, 28: 40–50.

Raut M.P.M., Thakre G. V., Thakre P.R.D., Gulhane P.U.D. (2014): Fem analysis of nine tyne medium duty cultivator. IORD Journal of Science & Technology, 1: 58–65.

Sadek M.A., Chen Y., Zeng Z. (2021): Draft force prediction for a high-speed disc implement using discrete element modelling. Biosystems Engineering, 202: 133–141.

Šařec P., Šařec O. (2015): Employment characteristics of tine cultivators at deeper soil loosening. Research in Agricultural Engineering, 61: 80–86.

Selvi K.Ç. (2017): Investigation of the structural deformation behaviour of the subsoiler and paraplow tines by means of finitie element method. Turkish Journal of Agriculture, 5: 1482–1487.

Sher A.S., Yaoming L., Zheng M., Farman A.C., Mazhar H.T., Zhenwei L. (2021): Discrete element method (DEM) simulation of single grouser shoe-soil interaction at varied moisture contents. Computers and Electronics in Agriculture, 191: 106538.

Shinde G.U., Badgujar P.D., Kajale S.R. (2011): Experimental analysis of tillage tool shovel geometry on soil disruption by speed and depth of operation. International Conference on Environmental and Agriculture Engineering. Singapore, July 28–30.

Tagar A.A., Changying J., Adamowski J., Malard J., Shi C., Qishuo D., Abbasi N.A. (2015): Finite element simulation of soil failure patterns under soil bin and field testing conditions. Soil Tillage Research, 145: 157–170.

Topakci M., Celik H.K., Canakci M., Rennie, A.E.W., Akinci I., Karayel D. (2010): Deep tillage tool optimization by means of finite element method: Case study for a subsoiler tine. Journal of Food, Agriculture and Environment, 8: 531–536.

Yezekyan T., Benetti M., Armentano G., Trestini S., Sartori L., Marinello F. (2021): Definition of reference models for power, mass, working width, and price for tillage implements. Agriculture, 11: 197.

Zein El-Din A., Youssef Taha R., Abdel Hamied R. (2021): Mathematical models for predicating draft forces of tillage tools: A review. Journal of the Advances in Agricultural Researches, 26: 48–52.

Zhang Z., Peng X. (2021): Bio-tillage: A new perspective for sustainable agriculture. Soil Tillage Research, 206: 104844.

Received: August 13, 2022
Accepted: March 20, 2023
Published online: September 1, 2023