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Research article

Determination of the Force Analysis of Subsoiler Plow Tines Using Finite Element Method

Mahmood N. Al-Irhayim, Ghazwan A. Dahham, Khalid E. Al-Mistawi* and Arkan M. Sedeeq

Department of Agricultural Machines and Equipment, College of Agriculture and Forestry, University of Mosul, Iraq

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Abstract

Farmers in the north part of Iraq still practice traditional ways in agriculture, and often perform in multi passes for land preparation with heavy tools generating hardpanning which can become a serious problem.One of the most effective and fast methods to control plough pan is subsoiler. Subsoiling is one of the most agricultural operations that needs power. Tines of subsoiler are main working part, and it has a significant effect in working type, energy consumption and soil resistance. Farmers in Iraq are restricted on using subsoiler due to limitation of tractor horse power.The goal of this study was to modify tine shape to enhance subsoiling operation and minimize draft force. The study was conducted using two types of subsoiler tines: traditional (T) and modified (M) type. The tines were tested in two types of soil texture, clay and silty loam and under different soil humidity, to evaluate tine work efficiency. The following traits were adopted as comparison parameters: stress, draft force (DF), soil loss efficiency (SLE), and depth stability ratio (DS). Finite element method was used to analyse stress forces on the tines in field experiments. The results showed that the modified tine was superior in performance for stress, DF, SLE and DS, recording the best values for these traits: 1312 Mpa, 4.95 kN, 215.79 cm2/kN and 98.91%, respectively. The algorithms for stress, DF, SLE and DS showed acceptable performance because their R2 scores were recorded as 0.989, 0.991, 0.991, and 0.998 as predictor variables. The modified tine revealed higher efficiency performance under different soil humidities ranging 10.24% to 19.11% in the silty loam and clay soil texture. From the field results and observation, modifying the tines shape had significant impact on the field performance of the subsoiler.

Keywords: tines; traditional; modified; depth stability

*Corresponding author: E-mail: khalid.allaf@uomosul.edu.iq

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1. Introduction

Tillage is one of the most effective tools for soil aggregate improvement and crop production. Tillage increases soil prosity and mixing in plant residue. However, continuious use of tillage equipment and tractor traffic over years may cause hardpan, which limit water and plant rooting systems to penetrate through soil layers (Bandalan et al. 1999; Ovchinnikov et al., 2017). In many types of soil hardpan or plough pan, layers are established after heavy trucks pass (soil compaction) on soil surface, or long term tillage at shallow depths (Hang et al., 2018; Wang et al., 2023), and subsoiler is a tool using for breaking up such layers without turning it to the surface (Bo et al., 2016). The use of subsoiler can keep soil in good condition and improve crop productivity (Jiang et al., 2020). Subsoiler can be defined as a one type of tillage equipment which can work under soil surface at depths of 450-750 mm. Due to the harsh conditions and significant depth, subsoiler faces different forces that impact on tines. In some case, subsoiler materials (shank or tin) may fail to cope with work conditions because of plastic deformation, corrosion or breakage (Topakci et al., 2010). The use of subsoiler can also be limited because of high energy requirments (Tong et al., 2020). It is crucial for agricultural equipment designers and manufacturers to predict and determine forces that affect equipment during farm operation. This can help them to manufacture optimal equipment for farmer use. Many computer programs are used to detect and analyze the forces which affect subsoilers during field operation. These programs can save time and are very helpful to solve complicated problems in design operations without expensive field test. In addition, subsoiler design can have a significant effect on draft force, which directly affects fuel consumption. Many studies proposed different methods to minimize the forces on subsoiler during tillage operation. Included were the use of lubrication, wobbling, line element design and so on. Some of these were found effective in some conditions and others helped to some extent but were not developed because of high cost or power requirements (Wang et al., 2023). Tines and shank are the main parts of subsoiler that are exposed to working resistance, leading to increases in fuel consumption and reducing working life of these parts. Many studies have been conducted on shank and tines to minimize soil resistance through inspired geometrical properties and making changes on shank and tine (Wang et al., 2020; Zhang et al., 2021). Other studies added wing to tines with different bent angle to minimize draft force.Tines of subsoiler were made in several shapes. Tines has a significant effect on power requirements and the type of tillage. Many researchers noted that shape of subsoiler tines showed different effect on draft and tillage force (Tong et al., 2020; Song et al., 2022). In this study, a local tine was modified to minimize draft force and enhance subsoiler performance in comparison with an ordinary tine.

2. Materials and Methods

2.1 Field and soil test

The field experiment was performed in different soil types at Al-Rshidia fields (longitude: 34º 2 N and latitude: 36º 22 E), in Mosul north Iraq.The first field was located inside the Al-Rshidia, which had a texture of silt loam, The field had been exploited in the previous season to grow vegetable crops, and the total area was 30000 m^2 with 4050 m^2 for the experiment. The second field was located north of Al-Rshidia. The soil was of clay texture, and the field had been exploited over the preceding seasons in the cultivation of barley crops. The total area of 25000 m^2 and 4050 m^2 were used for the experiment. The soil texture of Al-Rshidia fields is shown in Table 1. The fields feature the flatness of their surfaces and the presence of a hardpan subsurface layer appearing at a depth of 15-35 cm. In addition, the soil samples had high values of bulk density and penetration resistance but low soil hydraulic conductivity values. The sites were irrigated by surface irrigation method. Samples were taken to analyze the texture of the soil and some of its physical properties at five soil depths. Soil moisture content and soil bulk density were calculated using the methods mentioned by Dane and Topp (2020). The soil hydraulic conductivity was measured by the drop-pressure method in the laboratory described by Klute and Dirksen (1986). A hydraulic penetrometer tool was used for measuring the soil penetration index according to method of Gill and Van den Berg (1968). The results are illustrated in Figure 1.

Table 1. Soil texture at Al-Rshidia fields

Field Test	Soil Texture	Clay (g kg^{-1})	Silt (g kg^{-1})	Sand (g kg^{-1})
The first field	Silt loam	210.75	518.57	270.50
The second field	Clay	526.00	383.34	90.67

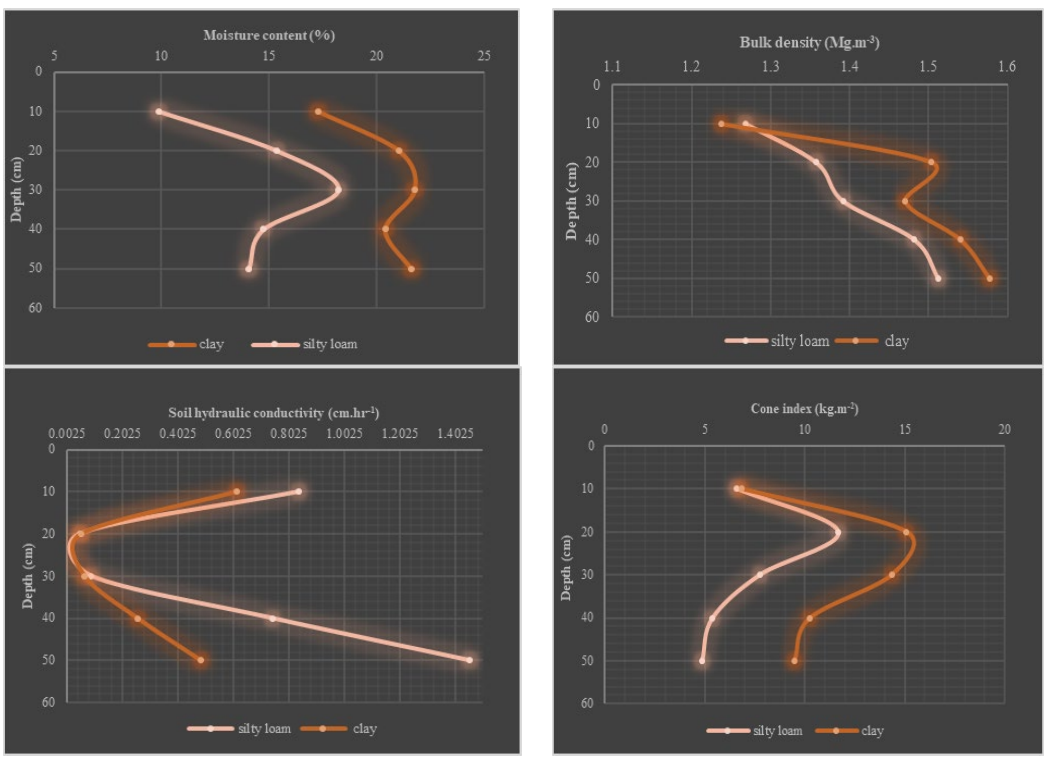

Figure 1. Soil physical properties at the study site

2.2 Subsoiler tines

The local subsoiler consisted of frame, shank and tine as shown in Figure 2. The traditional tine (flat surface tine) shown in Figure 3 was widely used in north Iraq and had technical specification as mentioned in Table 2. Tine of subsoiler has significant impact on tillage force (Tong et al., 2020),changing in tine geometry shape has an effective roll in field performance for tillage equipment (Ramin et al., 2011). After surveying for the types and dimensions for the subsoiler tines which were manufacture by different company the new tine (pointed surface with fixed width). Accessories used to recorded stress are presented in Figure 4. The dimension of modified tine was identical to the traditional but it has different external appearance, as shown in Figure 5.

Figure 2. A traditional subsoiler

Figure 3. Flat surface tine (traditional)

Table 2. The dimensions of traditional and modified tines

Type of Tine	Length (mm)	Maximum Width (mm)	Maximum Thickness (mm)	Thickness at Penetration Point (mm)	Weight (kg)
Traditional	300	68	38	1	4.440
Modified	300	68	38	1	3.130

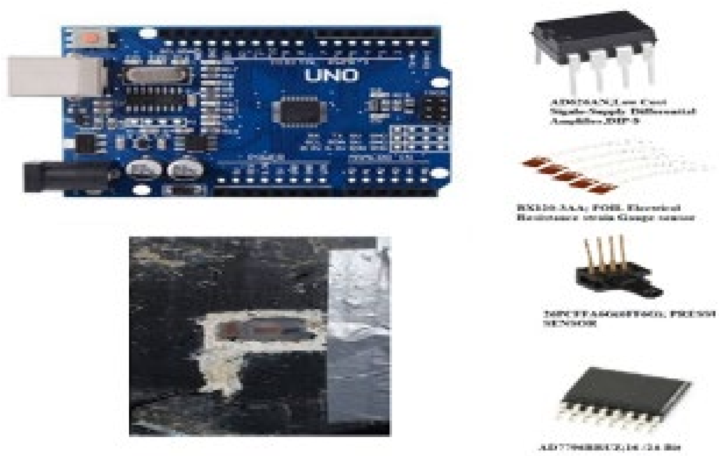

Figure 4. Accessories used to recorded stress

Figure 5. Pointed surface with fixed width (modified)

Perfect tine design, computer and simulation programs were used for predicting parameters that affected tines efficiency. Inventor (1.2023) with AUTODECK was used to predict stress distribution according to the finite element method. The harsh work conditions that subsoiler tines are exposed to may lead to tine failure, displacement and breakage. Due to sudden Obstacles in field so selecting alloy type for tine manufacturing critical to cope with those conditions. The properties for selected alloy (type of metal for manufacturing subsoiler tines) are showed in Table 3.

Table 3. The chemical and mechanical properties for tine alloy

Alloy	Chemical Composition (%)				Mechanical Properties		Classification AISA
	C	Si	Mn	Cr	Hardness HD	Stress Resistance N/mm^2	
C	0.5	0.3	1.0	1.1	310	1370	6150

The effective field stress was calculated using stress sensors that were fixed by special adhesive and covered by silicone to protect them. The sensors were attached at several points to the rear surface of the tine and stress was measured by a voltmeter. The sensors were connected to an Arduino board and laptop.

2.3 Depth stability rate (DSR)

The DSR for subsoiler tines were measured by digging a cross section for subsoiler and manually removing the disturbed soil. The sure depth was measured and the DSR was calculated using equation 1 (Hilal et al., 2021). This measurement were repeated for all treatments and sites.

$$DSR=\frac{Sure\ Depth}{Adjusted\ Depth}\ 100\% \quad (1)$$

2.4 Soil loosening efficiency (SLE) cm^2/kN

Soil loosening or soil disturbance can be defined as the area of disturbance between the soil surface and inner soil disturbance profile divided by draft force, as seen in Figures 6 and 7 (Wang et al., 2021). The following equation was used to calculate it (Salar et al., 2021).

$$SLE = \frac{A}{D} \quad (2)$$

Where A is a loosened area (cm^2), and D is a draft force.

Figure 6. Side veiw of soil loosening efficiency

Figure 7. Top veiw of subsoiling line through soil

2.5 Draft force

Draft force is a crucial parameter for tillage equipment and is related to power consumption. Draft force depends on type and engineering of the tools, and field and operating conditions (Sadek et al., 2021). The draft force was measured by a Dynamometer device (Dillon) with a highest value recorded at 3500 kg.N. It is a special part of equipment used to calculate the draft force of towing equipment. The device can be used by fixing it between two tractors; the front tractor draws the rear tractor and the subsoiler is attached to the rear tractor. The dynamometer measures the power draft for the rear tractor and subsoiler and the following equation (Al-Mastawi et al., 2022) was used to calculate the draft force.

Draft force = Dynamometer record when subsoiling – Dynamometer record for rear tractor only no subsoiler attached (3)

3. Results and Discussion

The Von-Mises stress and deflection of the traditional and modified tines were determined by using finite element method with Inventor Auto Deck computer program to evaluate the ability of the manufactured tines working under the same field conditions. In Figures 8 and 9, the modified tine recorded the lowest Von-Mises stress 875.4 MPa and defection of 0.788 mm compared with the traditional tine, which were shown in Figures 10 and 11, which were 1430 MPa for stress and 1.348 mm for deflection.

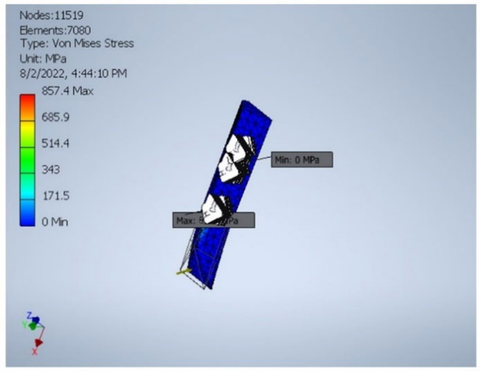

Figure 8. Von Mises Stress for modified tine

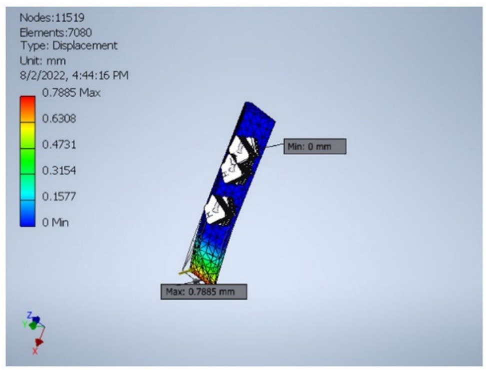

Figure 9. Deflection for modified tine

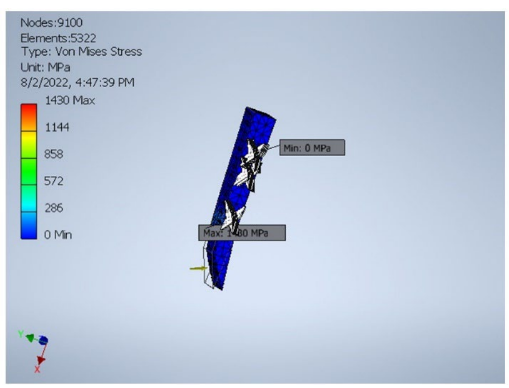

Figure 10. Von Mises Stress for traditional tine

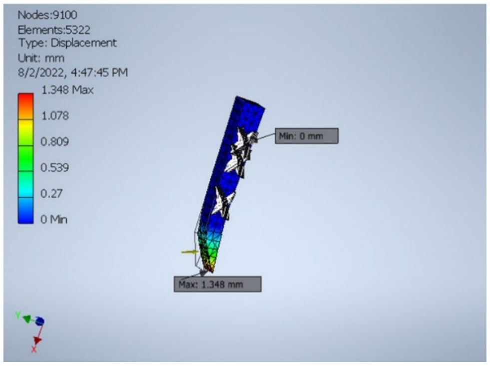

Figure 11. Deflection for traditional tine

The practical results in field operation where the subsoiler experiences different forces due to soil conditions can be different from the theoretical results generated by computer programs because when a subsoiler reaches into deeper soil layers, it comes under high stress forces (Allaie et al., 2020). The stress values varied according to soil texture, which played a significant role in the degree of forces on the subsoiler. At the clay soil site, the traditional tine was exposed to highest stress value, which started form 2105 MPa at 19.11% and increased to 2980 MPa at 10.24% soil moisture content, whereas the modified tine was recorded at 1312 MPa at 19.11% and 2241 MPa at 10.24 % (Figures 12, 13 and Table 4). At the silty loam soil site, the modified tine (M) recorded values started from 1162 MPa at 19.11% soil humidity to 2011 MPa at 10.24% soil humidity whereas the traditional tine recorded higher values for stress started from 1986 MPa at 19.11% until 2831 MPa at 10.24 %. The results were in line with (Ramin et al., 2011). The soil moisture content had significant effects on stress force. In general, when soil water content increases, the soil cutting force decreases. In the two locations, the soil moisture content played a significant role in stress. There is an opposite relation between soil humidity and stress volume as soil humidity increased the stress volume decrease.

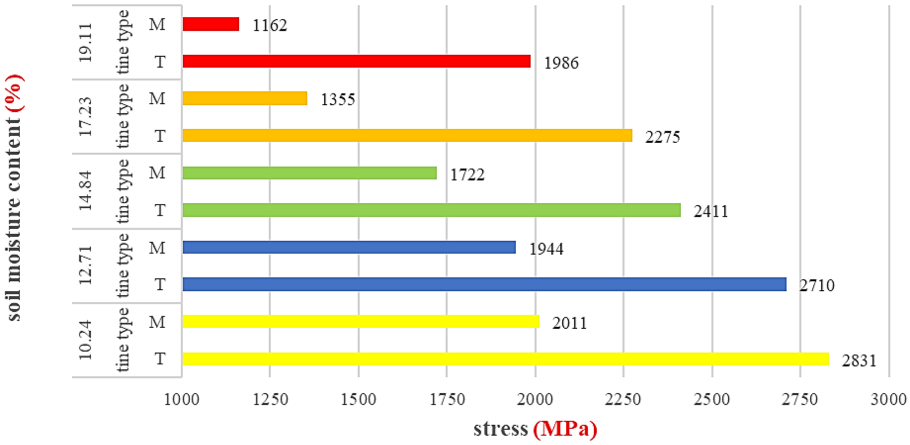

Figure 12. Site with silty loam soil texture

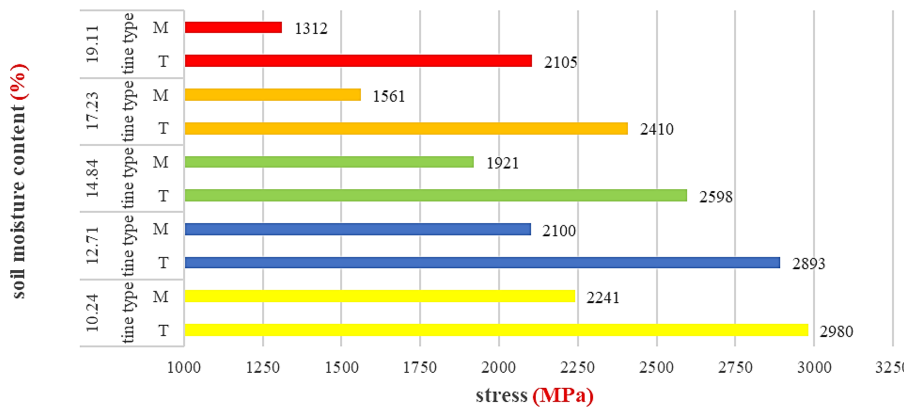

Figure 13. Site with clay soil texture

Table 4. ANOVA for stress

Source	Sum of Squares	df	Mean Square	F-value	p-value*
Block	177.70	2	88.85		
Model	1.589E+07	11	1.445E+06	3200.96	< 0.0001
A-Soil type	4.249E+05	1	4.249E+05	941.42	< 0.0001
B-SMO	6.179E+06	4	1.545E+06	3422.60	< 0.0001
C-Tine type	9.217E+06	1	9.217E+06	20423.81	< 0.0001
AC	5940.15	1	5940.15	13.16	0.0007
BC	63965.10	4	15991.27	35.43	< 0.0001
Residual	20760.30	46	451.31		
Cor Total	1.591E+07	59			

*Significant difference

The main goal of any new design for subsoiler tine is to reduce the required draft forces, which can be used as an indicator to distinguish tillage equipment (Song et al., 2022). Draft forces are affected by many factors such as tillage depth, speed and tine types (Askari & Abbaspour-Gilandeh, 2019). Draft forces also reflect energy requirements as draft forces increase operation cost. Figures 14 and 15 and Table 5 show the effect of soil moisture content on draft force under the two types of soil texture for the traditional and modified tines. The modified tine showed superiority in achieving lower draft forces (16.3% and 18.7%) than the traditional tine in silty loam and clay soil, respectively, under the entire range of soil humidity levels. As soil moisture content decreases, soil becomes harder to penetrate with tillage equipment and more draft force required. The two types of tine showed the same behavior with soil humidity; the highest draft forces reached 17.99 kN and 15.80 kN in clay soil for the traditional and modified tines, respectively, whereas they recorded lower value in silty loam soil at 12.84 and 14.56 kN for the modified and traditional tines, respectively, at the same moisture content. These results were in agreement with Marakoğlu and Çarman (2010), who mentioned that soil type and condition were by far the most important factors influencing tool draft force.

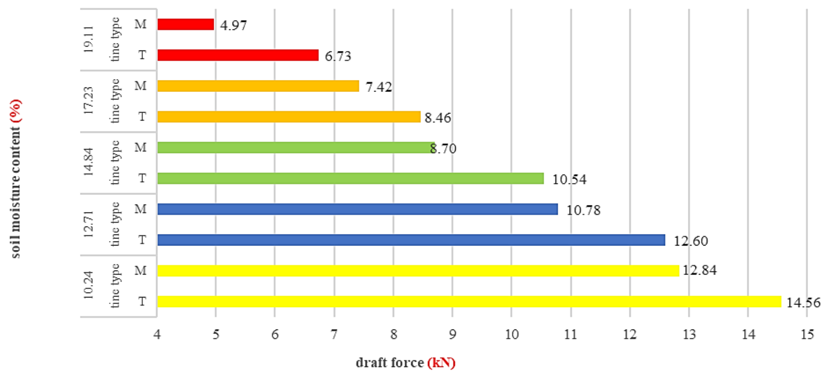

Figure 14. Site with silty loam soil texture

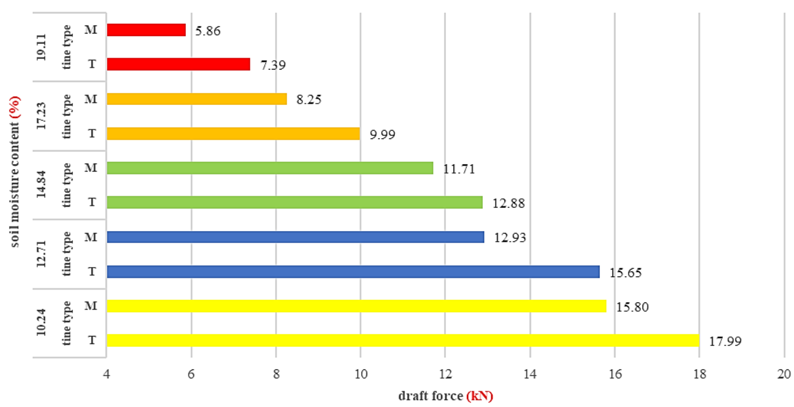

Figure 15. Site with clay soil texture

Table 5. ANOVA for draft force

Source	Sum of Squares	df	Mean Square	F-value	p-value*
Block	0.1234	2	0.0617		
Model	709.71	10	70.97	432.29	< 0.0001
A-Soil type	60.94	1	60.94	371.21	< 0.0001
B-SMO	595.07	4	148.77	906.14	< 0.0001
C-Tine type	42.59	1	42.59	259.41	< 0.0001
AB	11.12	4	2.78	16.93	< 0.0001
Residual	7.72	47	0.1642		
Cor Total	717.55	59			

*Significant difference

As the subsoiler moves through soil layer, the tine loosens the soil, and the efficiency of soil loosening can be defined as disturbance divided by the tractor draft force required and it is an important criteria to assess work efficiency for tillage tools (Salar et al., 2021). One of criteria for effective subsoiling tool is good soil loosening efficiency which may increase or decrease according to tools adjustment (Wang et al., 2022).The results in Figures 16 and 17 and Table 6 revealed that the modified tine was superior in soil loosening efficiency in silty loam and clay soil texture. Under different soil moisture contents, the modified tine surpassed the traditional tine by achieving the highest values for soil loosening efficiency by a factor of 42.97%, whereas the difference rate in clay soil site reached 34.38% in favor of modified tine. These results were due to the difference in shape of the modified and traditional tines, the central pointed surface with two sliding side edges may be a better loosening effect on the upper soil surface compared to the traditional tine which had a flat surface.

Figures 18, 19 and Table 7 show the results of the depth stability test. Depth stability is another critical evaluation indicator for tillage equipment. Generally, the depth stability of a subsoiler or other type of tillage equipment depends on different factors such as land leveling, working speed and working depth (Wang et al., 2017). As a result, during subsoiling operations where working conditions varied, tillage depth may be needed to adjust several times to get uniform work rate (Lou et al., 2021).The modified tine recorded the highest depth stability ratio for all levels of soil humidity; DS ratio started from 98.91% to 92.16% compared to the traditional tine which recorded values from 96.11% to 90.69% under same soil humidity in silty loam soil, and likewise in the clay soil texture. There were remarkable differences among those values. The results proved that depth stability was influenced by soil humidity and soil type more than other factors, which was in agreement with Wang et al. (2017), who mentioned tillage stability depth was influenced through its relation with soil resistance.

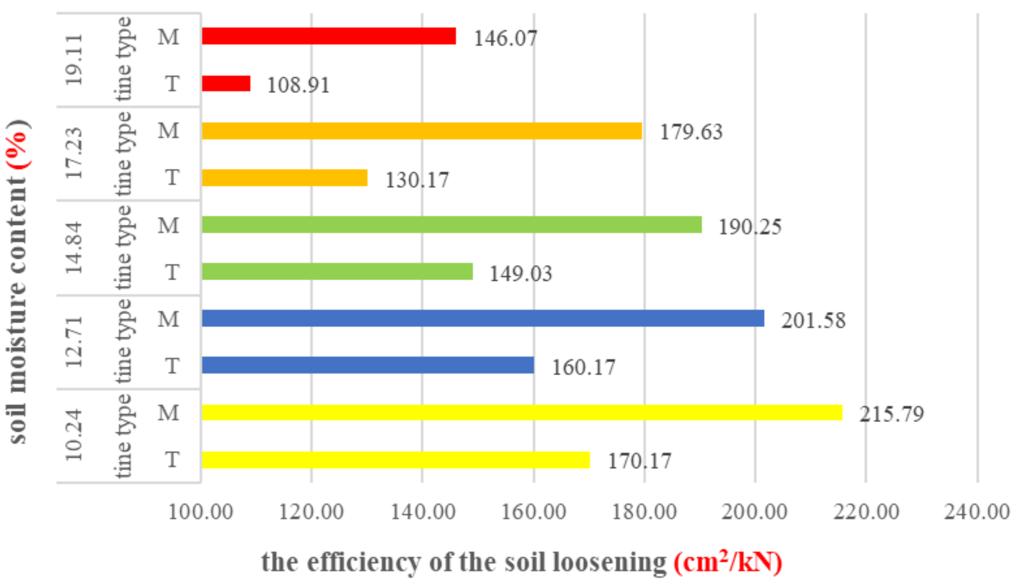

Figure 16. Site with silty loam soil texture

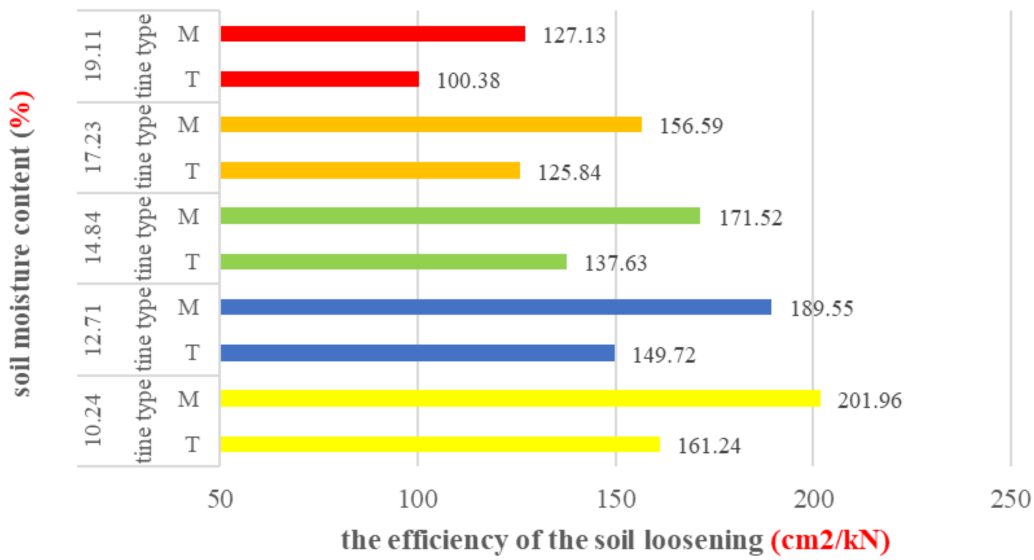

Figure 17. Site with clay soil texture

Table 6. The ANOVA for efficiency of the soil loosening

Source	Sum of Squares	df	Mean Square	F-value	p-value*
Block	55.93	2	27.97		
Model	1.623E+05	15	10820.90	320.36	< 0.0001
A-Soil type	31958.11	1	31958.11	946.14	< 0.0001
B-SMO	40174.30	4	10043.58	297.35	< 0.0001
C-Tine type	61149.35	1	61149.35	1810.36	< 0.0001
AB	1980.43	4	495.11	14.66	< 0.0001
AC	1868.36	1	1868.36	55.31	< 0.0001
BC	25182.91	4	6295.73	186.39	< 0.0001
Residual	1418.66	42	33.78		
Cor Total	1.638E+05	59			

*Significant difference

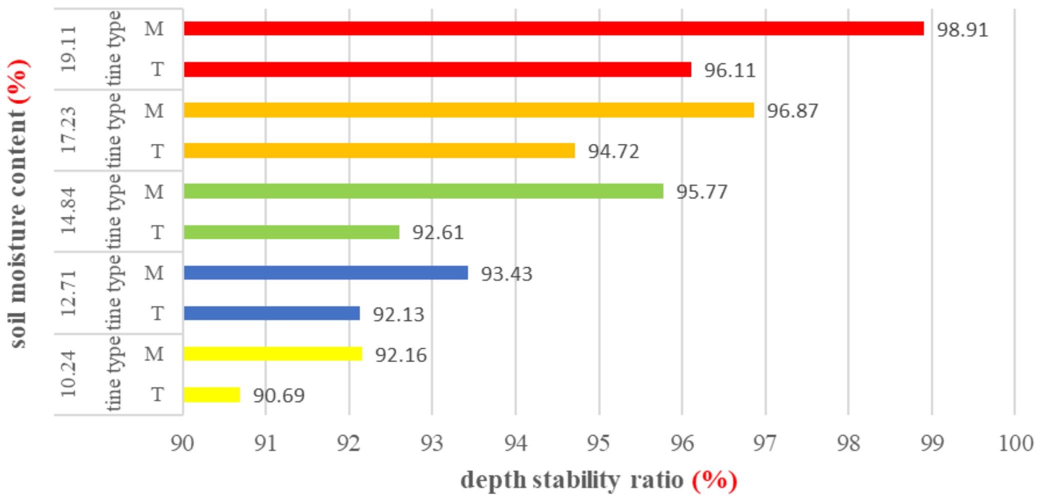

Figure 18. Site with silty loam soil texture

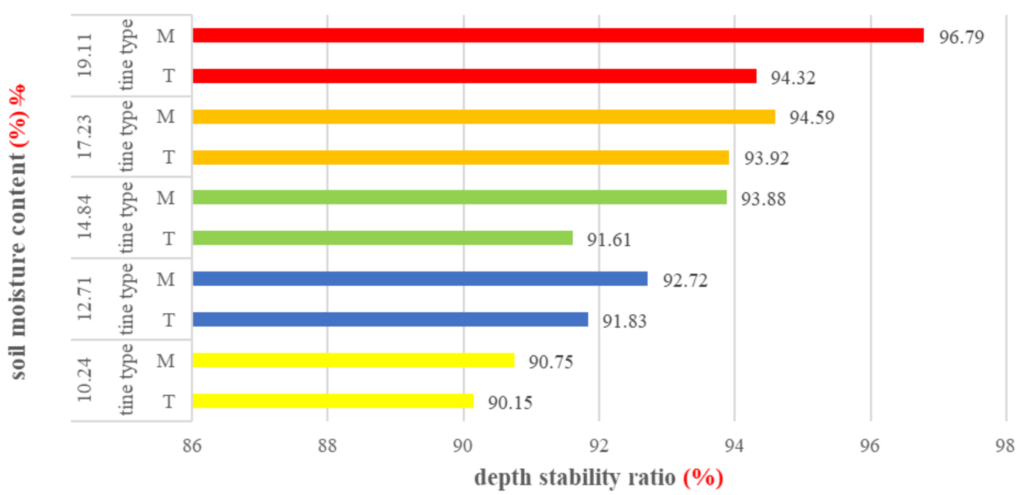

Figure 19. Site with clay soil texture

Table 7. The ANOVA for depth stability

Source	Sum of Squares	df	Mean Square	F-value	p-value*
Block	0.0352	2	0.0176		
Model	301.98	15	20.13	310.59	< 0.0001
A-Soil type	22.74	1	22.74	350.87	< 0.0001
B-SMO	217.51	4	54.38	838.93	< 0.0001
C-Tine type	44.65	1	44.65	688.88	< 0.0001
AB	4.39	4	1.10	16.92	< 0.0001
AC	3.05	1	3.05	47.00	< 0.0001
BC	9.64	4	2.41	37.18	< 0.0001
Residual	2.72	42	0.0648		
Cor Total	304.73	59			

*Significant difference

4. Conclusions

The main goal of this study was to design and test a new shape for local subsoiler tine for better farm performance and compared it with traditional tine. The comparison was made on the basis of the following indicators: stress on tine, draft force, soil loosening efficiency and depth stability ratio. The study was conducted in two sites of different soil texture. From the obtained results, it can be concluded that the tine shape has significant effect on stress and tractor draft force. The modified tine with its pointed surface and fixed width achieved lower stress and draft force values, and the modification had a positive effecte on soil loosening efficiency. Moreover, it was remarkable that soil moisture content and soil texture had pronounced effects on the depth stability ratio. Soil moisture content increase facilitated tillage operation stabilization. On the other hand, as soil moisture content increased, soil became more coherent and opposed to loosening by subsoiler. Overall, the results indicate that tine shape had a direct effect on subsoiler performance. The modified tine, with its altered shape or surface, had the ability to penetrate the soil layer more smoothly and the subsoiler works easier.

5. Acknowledgements

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6. Conflicts of Interest

The authors declare that there are no conflicts of interest.

ORCID
Mahmood N. Al-Irhayim https://orcid.org/0009-0007-7521-8353
Ghazwan A.Dahham https://orcid.org/0000-0001-7059-7787
Khalid E. Al-Mistawi https://orcid.org/0000-0002-0326-5907

References

Al-Mastawi, K. E., Dahham, G. A., & Yahya, L. M. (2022). Effects of soil moisture content, tire inflation pressure, and tillage speed on tractive performance of 2WD tractor in Northern Iraq. *Transactions of the Chinese Society of Agricultural Machinery,* 53(8), 132-139.

Allaie, S. P., Tripathi, A., Dsouza, P. M., & Parvaze, S. (2020). Topology optimization of a straight subsoiler through computer mathematical modelling. *Current Journal of Applied Science and Technology,* 39(33), 35-46. https://doi.org/10.9734/cjast/2020/v39i3331016

Askari, M., & Abbaspour-Gilandeh, Y. (2019). Assessment of adaptive neuro-fuzzy inference system and response surface methodology approaches in draft force prediction of subsoiling tines. *Soil and Tillage Research,* 194, Article 104338. https://doi.org/10.1016/j.still.2019.104338

Bandalan, E. P., Salokhe, V. M., Gupta, C. P., & Niyamapa, T. (1999). Performance of an oscillating subsoiler in breaking a hardpan. *Journal of Terramechanics,* 36(2), 117-125. https://doi.org/10.1016/S0022-4898(98)00035-4

Bo, L., Rui, X., Fanyi, L., Jun, C., Wenting, H., & Bing, H. (2016). Determination of the draft force for different subsoiler points using discrete element method. *International Journal of Agricultural and Biological Engineering,* 9(3), 81-87.

Dane, J. H., & Topp, C. G. (2020). *Methods of soil analysis, part 4: Physical methods* (Vol. 20). John Wiley & Sons.

Gill, W. R., & Van den Berg, G. E. (1968). *Soil dynamics intillage and traction*. Agricultural Research Service, US Department of Agriculture.

Hang, C., Gao, X., Yuan, M., Huang, Y., & Zhu, R. (2018). Discrete element simulations and experiments of soil disturbance as affected by the tine spacing of subsoiler. *Biosystems Engineering,* 168, 73-82. https://doi.org/10.1016/j.biosystemseng.2017.03.008

Hilal, Y. Y., Al-rajabo, S. A. J., & Dahham, G. A. (2021). The effects of vibrating wings subsoiler plow on driver's seat of agricultural tractors and mechanization performance. *Soil and Tillage Research,* 205, Article 104806. https://doi.org/10.1016/j.still.2020.104806

Jiang, X., Tong, J., Ma, Y., & Sun, J. (2020). Development and verification of a mathematical model for the specific resistance of a curved subsoiler. *Biosystems Engineering,* 190, 107-119. https://doi.org/10.1016/j.biosystemseng.2019.12.004

Klute, A., & Dirksen, C. (1986). Hydraulic conductivity and diffusivity: Laboratory methods. In A. Klute (Ed.). *Methods of soil analysis: Part 1 physical and mineralogical methods.* (2nd ed., pp. 687-734). American Society of Agronomy. https://doi.org/10.2136/sssabookser5.1.2ed

Lou, S., He, J., Lu, C., Liu, P., Li, H., & Zhang, Z. (2021). A tillage depth monitoring and control system for the independent adjustment of each subsoiling shovel. *Actuators,* 10(10). Article 250. https://doi.org/10.3390/act10100250

Marakoğlu, T., & Çarman, K. (2010). Fuzzy knowledge-based model for prediction of soil loosening and draft efficiency in tillage. *Journal of Terramechanics,* 47(3), 173-178. https://doi.org/10.1016/j.jterra.2009.10.001

Ovchinnikov, A. S., Mezhevova, A. S., Novikov, A. E., Fomin, S. D., Pleskachev, Y. N., Borisenko, I. B., Zvolinsky, V. P., Tyutyuma, N. V., & Vorontsova, E. S. (2017). Energy and agrotechnical indicators in the testing of machine-tractor units with subsoiler. *ARPN Journal of Engineering and Applied Sciences,* 12(24), 7150-7160.

Ramin, J., Seyyed, H. K., & Seyyed, A. H. (2011). The effect of geometry and motion characteristics of narrow tillgae tool on soil Disturebance Efficiency. *Journal of Agricultural Machinary Science,* 7(3), 253-258.

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. https://doi.org/10.1016/j.biosystemseng.2020.12.009

Salar, R. M., Karparvarfard, H. S., Askari, M., & Kargarpour, H. (2021). Forces and loosening characteristics of a new winged chisel plough. *Research in Agricultural Engineering,* 67(1), 17-25. https://doi.org/10.17221/71/2020-RAE.

Song, W., Jiang, X., Li, L., Ren, L., & Tong, J. (2022). Increasing the width of disturbance of plough pan with bionic inspired subsoilers. *Soil and Tillage Research,* 220, Article 105356. https://doi.org/10.1016/j.still.2022.105356

Tong, J., Jiang, X.-H., Wang, Y.-M., Ma, Y.-H., Li, J.-W., & Sun, J.-Y. (2020). Tillage force and disturbance characteristics of different geometric-shaped subsoilers via DEM. *Advances in Manufacturing,* 8(3), 392-404. https://doi:10.1007/s40436-020-00318-x

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 & Environment,* 8(2), 531-536.

Wang, X., Li, P., He, J., Wei, W., & Huang, Y. (2021). Discrete element simulations and experiments of soil-winged subsoiler interaction. *International Journal of Agricultural and Biological Engineering,* 14(1), 50-62.

Wang, X., Zhou, H., & Ji, J. (2022). Effect of mounting angle on bending subsoiling tool-soil interactions using DEM simulations. *Agriculture,* 12(11), Article 1830. https://doi.org/10.3390/agriculture12111830

Wang, X., Zhou, H., Wang, S., Zhou, H., & Ji, J. (2023). Methods for reducing the tillage force of subsoiling tools: A review. *Soil and Tillage Research,* 229, Article 105676. https://doi.org/10.1016/j.still.2023.105676

Wang, Y., Li, N., Ma, Y., Tong, J., Pfleging, W., & Sun, J. (2020). Field experiments evaluating a biomimetic shark-inspired (BioS) subsoiler for tillage resistance reduction. *Soil and Tillage Research,* 196, Article 104432. https://doi.org/10.1016/j.still.2019.104432

Wang, Y., Yang, L., Zhang, D., Cui, T., Han, D. D., & Zhang, T. (2017). Experimental study on loosening depth stability for self-excited vibrating subsoiler. In *2017 ASABE annual international meeting.* https://doi.org/10.13031/aim.201700040

Zhang, Z., Gan, S., Zuo, G., Zhao, L., Chen, Z., & Carr, S. (2021). Bionic design of Sandfish (*Scincus scincus*) head inspired subsoiler tine and its performance evaluation by DEM. In *2021 ASABE annual international virtual meeting*. https://doi.org/10.13031/aim.202100223