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Forces and loosening characteristics of a new winged chisel plough

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Abstract: This study was devoted to verifying the performance of various configurations of a winged chisel plough (WCP) in a soil bin. The performance of the new tool was assessed at three wing depths (5, 10 and 15 cm), three bend angles (10, 20 and 30 °), and three rake angles (7.5, 15 and 22.5 °) with three replications using a completely randomised design at a constant depth and speed of 30 cm and 1 $m \cdot s^{-1}$, respectively. The draught and vertical forces, soil disturbed and upheaved areas plus the efficiency of the soil loosening were measured during the tests. The results revealed that the draught and vertical forces were significantly increased by increasing the wing depth, bend and rake angles. The soil disturbance area increased with an increase in the wing depth, bend and rake angles. While the soil upheaving was decreased by increasing the wing depth and bend angle, the effect of the rake angle on the soil upheaving area was not significant. The maximum efficiency of the soil loosening of 268.1 $cm^2 \cdot kN^{-1}$ was achieved for a wing depth of 10 cm, a bend angle of 20 °, and a rake angle of 15 °. A significant improvement in the efficiency of the soil loosening along with maintaining a considerable portion of the residue on the soil surface suggest that the WCP should be adopted for conservation tillage.

Keywords: bend angle; draught force; loosening efficiency; wing; rake angle

A good tillage operation can exploit the soil and water in the best way if it is selected according to the crop and soil conditions plus the proper tillage results in the optimum growth and yield. Recently, different tillage tools have been designed to fulfil the main purposes of tillage operations. The efficient use of soil and water resources, a lower and efficient energy consumption, less evaporation and a desire for higher yield calls for the development of new tillage tools.

Conservation tillage has been gradually introduced to alleviate the problems associated with conventional tillage and its special tools, such as a chisel plough, sweeps and a cultivator, reduces the soil erosion, increases the water infiltration rate into, and reduces the water evaporation (Griffith et al. 1986; Subbulakshmi et al. 2009). Moreover, conservation tillage causes less soil disturbance and maintains a higher percent of plant residue on the soil surface when compared to conventional tillage (Askari et al. 2017).

A high draught and obtaining the desired soil disturbance at depths are the limiting factors in using conservation tillage tools. The soil moisture content, speed of the travel, blade depth and width, and various blade angles are the parameters that influence the tillage tool performance (Liu and Kushwaha 2006; Askari et al. 2016). Decreasing the draught force of tillage tools has always been one of the most important goals of researchers (Godwin 2007). Previous studies have indicated that a bent leg plough is more energy efficient than a subsoiler and paraplough for both semi-deep and deep tillage operations. A great deal of research has been conducted on the bent leg plough and the effect of different operation parameters, like the soil properties, tillage depth and speed on the interaction between the soil and bent leg (Durairaj and Balasubramanian 1997; Jafari et al. 2008, 2011; Salar et al. 2013; Askari et al. 2016).

Wings could be attached to the sides of the subsoiler and paraplough with a view to improve their performance in increasing the soil loosened area and decreasing the specific resistance (Ramadhan 2014; Askari et al. 2017). Many authors reported the effect of adding wings on the draught increment and other effects (Godwin et al. 1981; Ahmed and Godwin 1983; Desbiolles et al. 1997; Arvidsson et al. 2004; Ramadhan 2014). Wings cannot be attached to a bent leg plough due to its different design.

Furthermore, Iranian and other third world farmers commonly use a chisel plough as a subsoiler and do not use a bent leg plough or a paraplough plus wings as a supplement for subsoiling operations. Consequently, very little research on the effects of adding wings to the subsoil tines on the draught and other soil properties were conducted in the regional countries (Askari et al. 2017), thus, it is necessary to conduct research on a winged chisel plough in the local conditions of Iran.

With regard to the mentioned matters, the aim of this study was to design and evaluate a new winged chisel plough that could be used in conservation tillage operations with the expectation of having a low energy consumption and high soil loosening efficiency. The study plans to find the optimum geometry of this tool and the attached wings.

MATERIAL AND METHODS

Development of a new winged chisel plough. A new winged chisel plough (WCP) was designed and built by a combination of the properties of the dual bent blade subsurface introduced by Salar et al. (2013) and a chisel plough. It was designed in CATIA software (version V5R20). Forward type wings were chosen because the soil fragmentation and disturbance area were more in the forward type compared to the backward type ones according to previous studies (Salar et al. 2013; Askari et al. 2016). Previous studies also revealed that the least amount of draught force occurred at the rake angle of 30 ° for chisel ploughs (McKyes and Maswaure 1997; Aluko and Seig 2000). Therefore, a rake angle of 30 ° was used in this work also. In this research, the effective wing geometry was determined. The levels of the rake and bend angles of the tine were chosen based on the optimum angles of previous studies (Durairaj and Balasubramanian 1997; Majidi Iraj and Raoufat 1997; Esehaghbeygi et al. 2005; Jafari et al. 2008; Salar et al. 2013). The independent variables were related to the wing as three depths (5, 10, and 15 cm from the soil surface), three bend angles (10, 20, and 30 °), and three rake angles (7.5, 15, and 22.5 °) which were tested in a soil bin. Nine holes were created in the tine and wings to change the wing depth and rake angle. CK30 steel (Isfahan steel Co., Iran) was used to build the different components. The tine and wings were laser-cut and assembled (Figure 1).

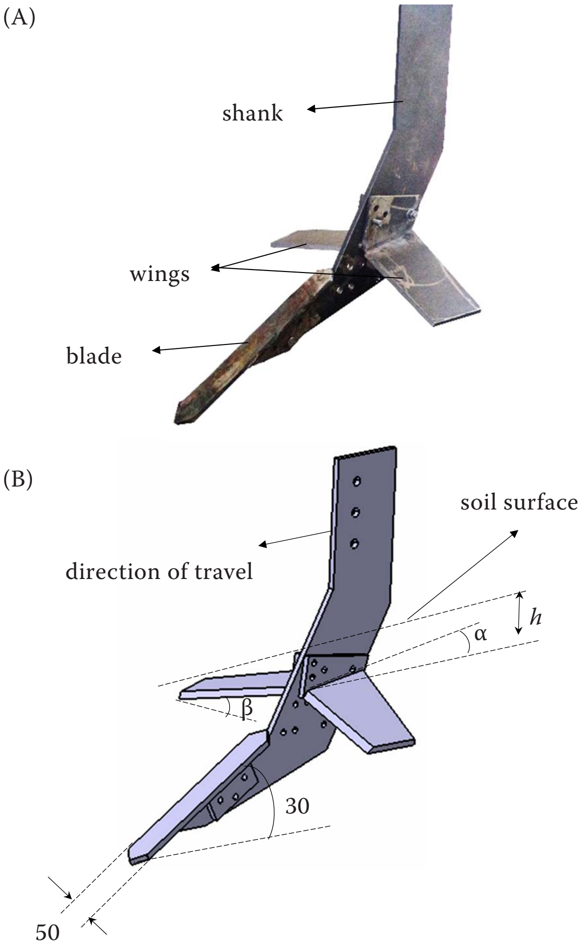

Figure 1. (A) The new tool and (B) the schematic of the newly developed winged chisel plough

h – depth of the wing; α – rake angle of the wing; β – bend angle of the wing (mm)

Table 1. Analysis of the soil at the experiment site

Property	Clay (%)	Sand (%)	Silt (%)	Plastic limit (%)	Moisture (d.b., %)	Bulk density (g·cm^{-3})
Amount	33.3	45.8	20.9	21.3	10.4 ± 0.4*	1.45

*The value indicates the standard deviation; d.b. – dry base

Experimental design. A completely randomised design (CRD) was used for the experiment layout. The treatments consisted of the combination of the three wing depths of 5, 10, and 15 cm, the three wing bend angles of 10, 20, and 30 °, and the three wing rake angles of 7.5, 15, and 22.5 °. Also, each treatment consisted of three replicates. Thus, a total of 81 tests were conducted. For all of the tests, a constant working depth of 30 cm and travel speed of 1 m·s^{-1} were used. The draught and vertical forces, the soil disturbance and upheaved area plus the efficiency of the soil loosening were the measured traits.

Soil bin. The experiment was conducted in the laboratory soil bin of the Iranian Agricultural Engineering Research Institute (IAERI) in Karaj, Iran. The bin is 24 m in length, 1.7 m in width and 1 m in depth. The bin was equipped with a tool carrier, power transport system and soil processors. The soil preparation was undertaken by a bucket for the soil movement plus smooth and spike tooth rollers to compact the soil. The moisture content, bulk density, soil texture and soil strength (Sahu and Raheman 2006a) are the soil properties that contribute to the tillage energy and loosening characteristics. The soil texture in the bin was a clay loam based on the soil texture triangle defined by the United States Department of Agriculture's (USDA) textural classification. The combined particles and other soil properties are shown in Table 1. A RIMIK digital penetrometer (CP20, RIMIK Co., Australia) was utilised to measure the soil penetration resistance. Randomly, the soil cone index was measured at 20 points in the bin before the tests over a 0–40 cm depth range and the obtained data are presented in Figure 2. Also, the mean of the cone index after the tillage treatments are presented in this figure to evaluate the effect of the tillage on the soil loosening and plant root development.

Measurements and data acquisition system. To measure the draught and vertical forces, an extended octagonal ring transducer (EORT) was used along with the relevant data acquisition system. The EORT was mounted on the tool carrier (Figure 3) and the carrier was connected to the three-point hitch of a Massey Ferguson 285 tractor (ITM Co., Iran) to provide the required pull force. The forward speed of the tractor was adjusted to 1 m·s^{-1} for all the tests. The limiting factor for a higher forward speed was the length of the soil bin. A 10-meter motion route along 10–20 meter of the soil bin's length was used for the data collection. When considering the forward speed of 1 m·s^{-1}, only 10 seconds were left for the data collection and higher forward speed was not possible.

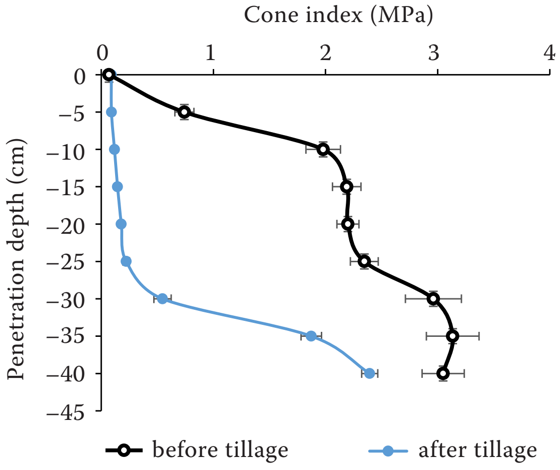

Figure 2. Results of the penetrometer tests on the bin soil before and after tillage

Figure 3. The used winged chisel plough, extended octagonal ring transducer and carrier in the study

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The tine was attached to the implement's frame and penetrated until a soil depth of 30 cm. A data logger (CR23X, CAMPBELL, UK) was used in order to save and record the data of the EORT. The data logger was programmable with PC208 software (version 7.0). The set was connected to a laptop computer through an RS-232 port to provide the data transfer and analysis.

To ensure the accuracy of the EORT measurements, the equipment was calibrated before the actual tests. The dead weight method was used for the calibration in the range of the force experienced in the draught and vertical measurements (Manuwa 2009).

The soil disturbance and upheaved areas were measured using image processing techniques. In all the treatments after the tool passed over the soil, a cross-section was created to measure the soil loosening area. After emptying the loosened soil, a white rope was placed around the soil disturbance and upheaved areas. Images with a resolution of 2 592 × 4 608 pixels were taken by a digital camera (DSC-W710, Sony, China) at a constant distance of 1 meter from the section. The colour of the rope was then changed to green for better diagnosis by the Photoshop software (version 16.1). The captured RGB (red, green, and blue) images were transferred to the computer and inserted into the image processing part of Matlab software (version $R2013_b$). After extracting the colour components of green, red and blue from the primary images, the images were transferred to the YCrCb colour space using Equation (1) and the green colour difference (Cg) was derived from the images using Equation (2) (Bulanon et al. 2004).

$$Y = 0.3R + 0.6G + 0.1B \tag{1}$$

$$C_g = G - Y \tag{2}$$

Applying an appropriate threshold on the green image difference, the rope was completely extracted from the image and the image was changed to black and white. The upheaved soil and the disturbed parts were separated from each other in the black and white image and the area of each part was calculated using the "region props" command in the Matlab software (Figure 4).

The efficiency of the soil loosening (*ESL*) is defined as the disturbed soil at the draught force unit in each treatment. It can be calculated by the following Equation (3):

$$ESL = \frac{A}{D} \tag{3}$$

where: ESL – the efficiency of the soil loosening; A – the loosened soil area (cm^2); D – the draught force (kN).

Figure 4. (1) The soil disturbance and (2) soil upheaved area tilled by the new winged chisel plough

Statistical analyses. ANOVA was performed using SAS statistical software (version 9.4M6) to determine the main effects of the experimental factors (depth, bend angle and rake angle of the wing) as well as their interactions. Moreover, the means were compared using the least significant difference (LSD) tests with a significance level of $P < 0.05$.

RESULTS AND DISCUSSION

The field data were analysed for three wing depth levels, three bend angle levels and three rake angle levels in order to determine the effect of the mentioned parameters on the draught and vertical forces, disturbance and upheaved area plus loosening efficiency of the new winged chisel plough. The ANOVA is presented in Table 2. The results show that the depth, bend and rake angle of the wing and the interaction effect among them are effective on the draught, vertical, disturbance area, upheaved area and loosening efficiency excluding the effect of the rake angle and the interaction effect of the rake and the bend angle on the upheaved area plus the effect of the rake angle and the interaction effect of the rake angle and the wing depth on the loosening efficiency.

Analysis of the draught force data. The working depth of the wing had a significant effect on the draught force (Table 2), the draught force significantly increased with an increment in the wing depth (Table 3). Studies on other tillage tools have indicated similar results (Sahu and Raheman 2006a;

Table 2. Analysis of variance of the field data with the studied variables

Source of variation	*df*	Mean square				
		draught	vertical	disturbance	upheaved	loosening efficiency
Wing depth	2	9.668^{**}	3.991^{**}	$181\,697.236^{**}$	$62\,925.055^{**}$	$17\,168.002^{**}$
Bend angle	2	6.967^{**}	2.289^{**}	$157\,752.468^{**}$	$18\,456.693^{**}$	$2\,407.827^{*}$
Rake angle	2	2.204^{**}	0.292^{**}	$181\,023.707^{**}$	$1\,707.908^{ns}$	$1\,002.307^{ns}$
Wing depth × bend angle	4	1.514^{**}	0.557^{**}	$65\,953.985^{**}$	$8\,314.195^{**}$	$3\,920.786^{**}$
Wing depth × rake angle	4	0.496^{**}	0.021^{*}	$28\,427.840^{*}$	$5\,304.624^{**}$	699.623^{ns}
Rake angle × bend angle	4	1.069^{**}	0.371^{**}	$30\,065.960^{*}$	$1\,257.842^{ns}$	$3\,983.199^{**}$
Wing depth × bend angle × rake angle	8	1.521^{**}	0.547^{**}	$20\,300.400^{*}$	$2\,322.666^{*}$	$2\,374.741^{**}$
Error	54	0.15	0.006	9 531.107	997.864	504.604
Corrected total	80					

*, **Significant difference at 0.5 and 0.01 level, respectively; ns – not significant, *df* – degree of freedom

Aboukarima 2007; Al-Suhaibani and Ghaly 2010; Akbarnia et al. 2014).

When the tool moved in the soil, the blade loosened the soil simultaneously and a part of the wings length (x) moved in the undisturbed soil. As the wings depth increased, the amount of "x" increased also, which resulted in a higher draught force (Figure 5).

The mean values of the draught force were significantly increased with the increment in the bend angle (Table 3) which is in line with the findings of Harrison and Licsko (1989). An increment in the bend angle caused an increase in the wing's contact area with the soil, which led to an increase in friction and eventually boosted the draught force of the tillage tool. Another reason for the increase in the draught force from bend angle enhancement, could be due to the higher required force to upheave more soil with the increased bend angle.

The effect of the rake angle was significant on the draught force and had direct effect on it (Table 3). Also, previous findings showed the draught force was significantly affected by the wing rake angle plus a lower draught occurred with a smaller rake angle and vice versa (Majidi Iraj and Raoufat 1997; McKyes and Maswaure 1997; Godwin 2007; Jafari et al. 2008). Moreover, some of the researchers reported that the least amount of draught of the studied tines occurred at wing rake angle of 7.5 ° (Majidi Iraj and Raoufat 1997; Jafari et al. 2008). For any increase

Table 3. Mean comparison of the experiment variables on the studied parameters of the new winged chisel plough

Variables	Draught force (kN)	Vertical force (kN)	Disturbance area (cm^2)	Upheaved area (cm^2)	Loosening efficiency ($cm^2 \cdot kN^{-1}$)
Depth of wing (cm)					
5	4.38^{c*}	-1.82^{a}	$1\,115.8^{b}$	296.1^{a}	258.3^{a}
10	4.82^{b}	-2.23^{b}	$1\,277.5^{a}$	246.6^{b}	268.1^{a}
15	5.56^{a}	-2.59^{c}	$1\,220.9^{a}$	199.6^{c}	220.3^{b}
Bend angle (°)					
10	4.53^{c}	-2.00^{a}	$1\,131.2^{c}$	274.3^{a}	249.1^{b}
20	4.74^{b}	-2.10^{b}	$1\,199.1^{b}$	245.9^{b}	259.0^{a}
30	5.50^{a}	-2.55^{c}	$1\,283.8^{a}$	222.1^{c}	238.0^{c}
Rake angle (°)					
7.5	4.67^{c}	-2.10^{a}	$1\,120.5^{c}$	255.0^{a}	242.1^{b}
15	4.87^{b}	-2.27^{b}	$1\,209.6^{b}$	239.1^{a}	257.9^{a}
22.5	5.23^{a}	-2.29^{b}	$1\,284.0^{a}$	248.2^{a}	246.5^{b}

*Means with the same letters have no significant differences based on the LSD test at a 5% confidence level

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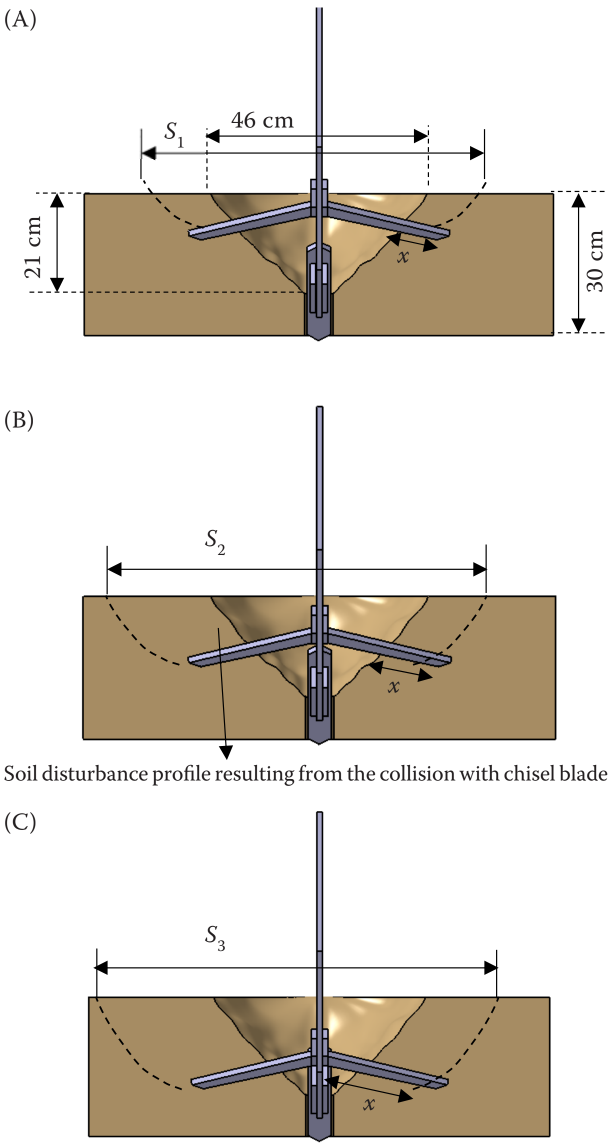

Figure 5. The back view of the soil failure caused by the new winged chisel plough and the collision of the wing with the undisturbed area at a wing depth of (A) 5 cm, (B) 10 cm, and (C) 15 cm

Direction of movement is normal to the page, S– width of wing effect; x – distance between wing edge and soil failed area

in the rake angle, the cross-sectional area of the blade on the vertical surface would be increased which led to an increase in the friction force. Similarly, a higher volume of soil resulted in a higher draught force.

Analysis of the vertical force data. A higher vertical force causes the deeper penetration into the soil for the tillage tool (Askari et al. 2016). Increasing the wing depth resulted in a more downward vertical force (Table 3) which was in line with previous research (Al-Suhaibani and Ghaly 2010; Ibrahmi et al. 2015). The increased depth of the wing caused the wing to move a higher volume of soil that led to an increase in the tool penetration into the soil.

Increasing the bend angle caused that the wings were placed deeper which resulted in a boost in the downward vertical force of the tool (Table 3). Similar results were reported by other researchers (Godwin 2007; Ramadhan 2014). In some research, a significant difference in the subsoiler vertical force at a constant wing rake angle of 15 ° and with different bend angles (10 and 20 °) was not seen (Askari et al. 2016). The difference between the results could be due to the differences in the used tools and dimensions, operating conditions, soil properties and so on.

Furthermore, the results revealed that an increase in the rake angle led to an increase in the downward vertical force (Table 3), this is in line with the results of other researchers (Harrison and Licsko 1989; Jafari et al. 2011), but it is in contradiction to the results of Ibrahmi et al. (2015) because of the difference in the tillage tools. On the other hand, the friction between the wing and soil increased as the rake angle increased. Consequently, more soil would be loosened that caused greater draught and vertical forces.

Analysis of the soil disturbance area. The results indicated that the soil disturbance area was increased by the increment of the wing's rake and bend angles (Table 3). The effect of increasing the tillage depth on the increment of the soil disturbance area has been reported by many researchers (McKyes and Maswaure 1997; Sahu and Raheman 2006b; Manuwa 2009; Ramadhan 2014; Askari et al. 2017), however, a different trend was seen in this study. The increment of the wing's depth from 5 to 10 cm caused an increase in the disturbance area, but the increment in the wing's depth from 10 to 15 cm caused a decrease in the disturbance area and the maximum disturbance area occurred with a 10 cm wing depth. It showed that the high and low distances between blade and wings had a negative effect on the soil disturbance area and an optimum disturbance area would be achieved at an optimum distance.

Because of the symmetric shape of the winged tool, the soil failure due to the collision of the wings followed a fixed curve in the left and right side of the tool. When the wing was located at a larger depth as with the increase in the bend angle, the development of the soil failure was extended to the sides of the tool (the width of the soil failure increased, $S_1 < S_2 < S_3$) that resulted in a boost in the soil disturbance area (Figure 5).

Salar et al. (2013) stated that the wing bend angle did not have a significant effect on the soil disturbance area. Askari et al. (2016) reported that the wing bend angle had a significant effect on the soil disturbance area. They found that a bend angle of 10 ° had more disturbance than 20 °. The difference between the results of this research and mentioned research is due to the differences between the tine and wing specifications and operating test conditions.

Increasing the rake angle from 7.5 to 22.5 ° caused a significant increase in the soil disturbance area, (Table 3). With an increment in the rake angle, the wing contact area with the soil increased which enhanced the soil disturbance area. Some researchers reported that a change in the wing rake angle did not have a significant effect on the soil disturbance area (McKyes and Maswaure 1997; Esehaghbeygi et al. 2005; Jafari et al. 2008).

On the contrary, Salar et al. (2013), stated that an increase in the rake angle enhanced the soil disturbance area. The variations in the research results might be due to the differences in the tool's geometry, especially the dimensions of the tools and wings.

Soil upheaved area. The soil upheaved indicates the reduction in the soil compaction after the tillage operation (Salar et al. 2013; Askari et al. 2016). The magnitude of the soil upheaved area significantly decreased due to the increase in the wing depth, (Table 3). It was found that the lack of necessary power to push the underneath soil toward the ground surface led to a decrease in the soil upheaving.

The increment in the bend angle caused a significant decrease in the soil upheaved area (Table 3) which could be because of the lower ability of the tool to move the soil upward. Increasing the bend angle caused the wing tip to be deeper. A similar result was reported by Askari et al. (2016). However, Salar et al. (2013) stated that the effect of the wing bend angle was not significant on the soil upheaved area.

Increasing the wing's rake angle from 7.5 to 15 ° and from 15 to 22.5 ° did not cause a significant decrease and increase in the upheaved area, respectively (Table 3), while Salar et al. (2013) reported that increasing the rake angle led to an increase in the soil upheaving. This could be because of the difference in the type of soil failure in the two types of tools and tested rake angles.

Table 3 shows that the upheaved area had an inverse relation with the downward vertical force, thus, with increasing the tendency of the tool to penetrate into the soil, the soil upheaving power decreased. It was in contrary to the results of Askari et al. (2016) with the different tools and dimensions.

Efficiency of the soil loosening. The efficiency of the soil loosening (ESL) is an important criterion for the selection of the working conditions of a tillage tool. Increasing the amount of the ESL (the ratio of the soil disturbed area to the draught force) for a tool is more important than reducing the draught force (Godwin 2007). In this study, the effect of the wing depth was significant on the ESL (Table 2).

Increasing the wing depth from 5 to 10 cm and 10 to 15 cm resulted in an increase and a decrease in the ESL, respectively (Table 3) which could be due to the increase in the soil bulk density at a higher depth than 10 cm. This finding was in line with the results of other researchers (Arvidsson et al. 2004; Manuwa 2009; Al-Suhaibani and Ghaly 2010). In this research, the maximum ESL occurred at a10 cm wing depth.

The effect of the bend angle was significant on the ESL of the new winged chisel plough (Tables 2 and 3). The results showed that the maximum ESL occurred at a bend angle of 20 °. By increasing the bend angle of the wing from 10 to 20 °, the rate of increasing the soil disturbance area was more than the rate of increasing the draught force of the tool that led to an increase in the ESL. An increment of the bend angle from 20 to 30 ° caused a decrease in the ESL.

The effect of the rake angle was not significant on the ESL (Tables 2 and 3). The maximum ESL was observed at a rake angle of 15 ° (Table 3). Increasing the rake angle of the wing from 7.5 to 15 ° and from 15 to 22.5 ° caused an increase and decrease in the ESL, respectively (Table 3). The maximum ESL occurred at a rake angle of 15 °. A similar result was reported by Jafari et al. (2008), while Arvidsson and Hillerström (2010) stated that increasing the rake angle led to a decrease in the ESL. The differences were due to the variety in the types of tillage tools and tested rake angles.

CONCLUSION

The purpose of this study was to develop and evaluate of a new winged chisel plough to be used in conservation tillage. The effects of the depth, bend angle, and rake angle of the wing on draught and vertical forces, soil disturbance and upheaved area plus the efficiency of the soil loosening were studied. The results revealed that:

The draught and vertical forces of the new winged chisel plough were significantly affected by the depth, bend and rake angle of the wing. The least amount of these forces of about 4.53 and –2.00 kN were found at a wing depth of 5 cm, a bend angle of 10 °, and a rake angle of 7.5 °.

Increasing the depth of the wing led to an increase in the soil disturbance area and a decrease in the soil upheaved.

The efficiency of the soil loosening was greater for the wing depths of 5 and 10 cm, bend angle of 20 °, and rake angle of 15 °.

To increase the efficiency of the soil loosening and deeper penetration into the soil for conservation tillage purposes, the new winged chisel plough with a wing depth of 10 cm, a bend angle of 20 °, and a rake angle of 15 ° is recommended.

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