Design steps of narrow tillage tools for draught reduction and increased soil disruption – a review

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Abstract: Design steps of narrow tillage tools for draught reduction and increased soil disruption was reviewed. Narrow tillage tools are the main components of conservation tillage and soil compaction alleviation equipment. Literature regarding dynamic behaviour and step-by-step design of narrow tillage tools is scarce. A better understanding of soil dynamic behaviour and designing steps will help in the design of new tool shapes which will reduce tool draught, energy demand and increased soil disruption over a wide speed range. At the same time, narrow tools disturb less soil, ideally only the minimum necessary to establish a crop. Narrow tillage tools such as subsoilers have gain much ground in their application for alleviating soil compaction; and are attracting awareness in their utilization for conservative tillage practices. There is a great amount of variability in depth and thickness of hardpan layers from field to field and also within the field. Applying uniform-depth tillage over the entire field may be either too shallow or too deep and can be costly. There is very little to gain from tilling deeper than the compacted layer and in some cases it may be detrimental to till into the deep clay layer. Hence the need for more studies on development of narrow tillage tools for site specific and in-row tillage practices for the enhancement of agriculture. A steps-wise study of the design process of narrow tillage tools will help the designers and producers to improve on the quality of their work for efficient application in agriculture. The purpose of this article is to bring to light the design steps and the various expressions involve in the effective design and construction of narrow tillage tools.

Keywords: design, draughts, soil disruption, subsoiler shanks

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1 Introduction

Development and evaluation of tillage tools performance, and their energy requirements during operation has been of great concern to engineers and farmers as this has very important effect on the efficiency of tillage operations. Tillage tools are mechanical devices used for applying forces to the soil to cause one or more of cutting, movement, fracturing, loosening, overturning and pulverization of the soil to prepare a seed bed. Friction between soil bodies, cohesion between the soil particles and friction between soil and tool are the most important elements in the mechanical study of the tilled soil body. These are the major effects that the external force has to overcome to break the soil into smaller aggregates. Some studies have been useful in calculating the force that the tool will have to apply to the soil to cut and to determine the shape and volume of soil cut. These models have shown the relation between the tool geometry, force requirements and the total cut soil volume. Studies have also shown that energy requirements increase with tool width at a fixed depth, and specific energy efficiency for cutting alone increases with tool width (Godwin, 2007).

1.1 Draughtand energy requirements for narrow tools

Draught is an important parameter for measurement and evaluation of implement performance (Grisso *et al.*, 1994). The specific draught of agricultural tools and implements varies widely under different conditions, being affected by such factors as the soil type and condition, ploughing speed, plough type, shape, friction characteristics of the soil-engaging surfaces, share sharpness, and shape, depth of ploughing, width of furrow

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slice, type of attachments, and adjustment of the tool and attachments. A great deal of work has been done in evaluating these various factors and investigating possible means for reducing draught (Manuwa and Ademosun, 2007). Rational design must be based on knowledge of tool performance and soil parameters (Stafford, 1984). For efficient tillage, both must be considered with the aim of minimizing specific resistance, which is draught per unit area of soil disturbance (Godwin et al., 1984; Godwin, 2007). Quantification of force response relations for the soil cutting process can be used by the equipment designer for improving cutting element design, and for mathematically simulating whole vehicle performance. Traditional tools have been designed in the light of empirical experimentation based on low speed tests and quasi-static theory of soil cutting. Experimental results cannot be directly extrapolated for use with high speed tools because the results would be unrealistic.

The recent emphasis, placed on energy conservation, has strengthened the need for improving the efficiency and reducing the energy requirements for tillage tools. This can be effectively accomplished only if the complex interaction between the soil and the tillage tool is understood clearly. The developed concepts in soil dynamics depend on controlled experiments. In a tillage operation, the energy requirement is the most important factor in characterizing and evaluating the operation of any tillage tool. It can be expressed in terms of energy per unit area or per volume of disturbed soil (Panwar and Siemens, 1972; Mehrez et al., 2014). Soil-bin facilities are usually employed for such controlled studies. The use of microcomputer based data acquisition and control system has greatly enhanced data collection and processing and ensured better monitoring of the parameters varied during the experiments in the soil-bins (Ademosun, 2014). A high-energy input is required to disrupt hardpan layer to promote improved root development and increased draught tolerance. Significant savings in tillage energy could be achieved by site-specific management of soil compaction. Site-specific variable-depth tillage system can be defined as any tillage system which modifies the physical properties of soil only where the tillage is needed for crop growth objectives.

1.2 Subsoilershapes and their effects on draught and soil disturbance

Godwin (2007) revealed that aspect ratio (depth/width) and rake angle (α) are two major variables in the design and selection of the appropriate geometry for given tillage implements such as subsoiler. Wide blades and narrow tines with depth/width ratios less than 5 and rake angles less than 90^0 tend to fail the soil in crescent manner, with the wide blade creating a wide slot and narrow blade, narrow slot especially when the aspect ratio increases. As the depth/width ratio increases the soil failure changes such that there is a small crescent close to the soil surface but the soil at depth is forced laterally to produce a slot. Godwin (Godwin, 2007) further revealed that implements designed with rake angles less than 90^0 ($\alpha<90^0$) tend to cut, loosen, invert and smoothen the soil while implements with rake angles equal to or greater than 90^0 ($\alpha = > 90^0$) tend to consolidate, disintegrate and compact the soil during operation. He concluded Minimising the draught force is not the main issue because reducing the magnitude of the specific resistance (draught force/disturbance) is much more significant as it is a better indicator of overall tillage efficiency.

There exists different shapes of shank designs in subsoiler. Shank design affects subsoiler performance, shank strength, surface and residue disturbance, effectiveness in fracturing soil, and the horsepower required to pull the subsoiler (Sakai et al., 1993; Kees, 2008). Such shapes are Swept shank, Straight shank, angled or curved (semi-parabolic) shank, Parabolic shank, Winged type, rotary or oscillating, Vibration and non-vibration types, Coulter subsoiler, Coulter with blades subsoiler, Coulter with blades and reversing subsoiler. Thus, subsoilers are designed with various shapes depending on the form of subsoiling operation that will be performed. An important consideration concerning subsoiling is the amount of soil disruption for different soil conditions to increase the long-term benefits of subsoiling (Raper and Sharma, 2004). Celik and Raper (2012) reported that many subsoilers have been designed and tested, using a number of subsoiling techniques for alleviating compacted layers of various types and conditions of soils.

The objective of this research is to consider design steps of narrow tillage tool shanks for effective soil disruption, reduced specific draught and energy requirements.

2 Materials and methods

2.1 Design of subsoilershanks - parameters and steps: briefly first paragraph

Development of subsoilers have been carried out by several researchers such as Nichols and Reaves (1958); Hettiaratchi, *et al.* (1966); Hettiaratchi and Reece (1974); McKyes and Ali (1977); Spoor and Godwin (1978); McKyes and Desir (1984); Upadhyaya *et al.* (1984); Smith and Williford (1988); Sakai *et al*. (1988); Ademosun (1991); Sakai *et al*. (1993); Reeder *et al*. (1993); Kooistra and Boersma (1993); Tupper, (1994); Allaby and Allaby (1999); Bandalen *et al.* (1999); Agbetoye (2000); Rahman *et al*. (2001); Manuwa (2002); Slattery and Desbiolles (2002); Chen and Hepner (2002); Ashrafizadeh and Kushwaha (2003); Pullen *et al.* (2004); McLaughlin and Campbell (2004); Raper and Sharma (2004); Kumar and Thakur (2005); Miszczak (2005); Raper (2005, 2007); Kumar *et al*. (2006); McLaughlin *et al*. (2005); Williams *et al*. (2006); Manuwa and Ademosun (2007); Godwin (2007); Kasisira and DuPlessis (2009); Manuwa (2009); Sakai (2009); Mollazade *et al*. (2010); Mandale and Thakur (2010); Celik and Raper (2012); Li *et al*. (2012) and other relevant works.

Thus for purpose of clear understanding of the various parameters use in the design of subsoilers, the illustration of basic tillage implement geometry arepresented in Figures 1 and 2. The respective parameters are defined in subsequent sections.

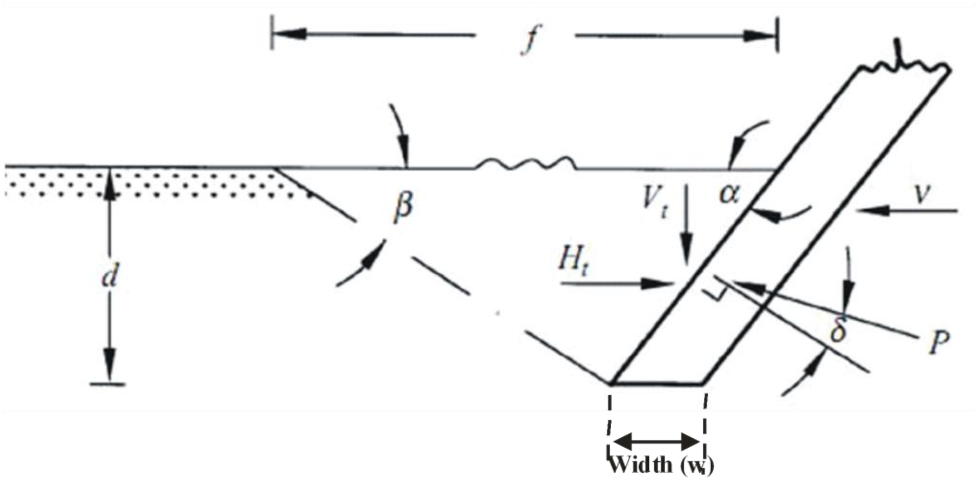

Figure1 Schematic diagram of tine in digging position (Odey, 2015)

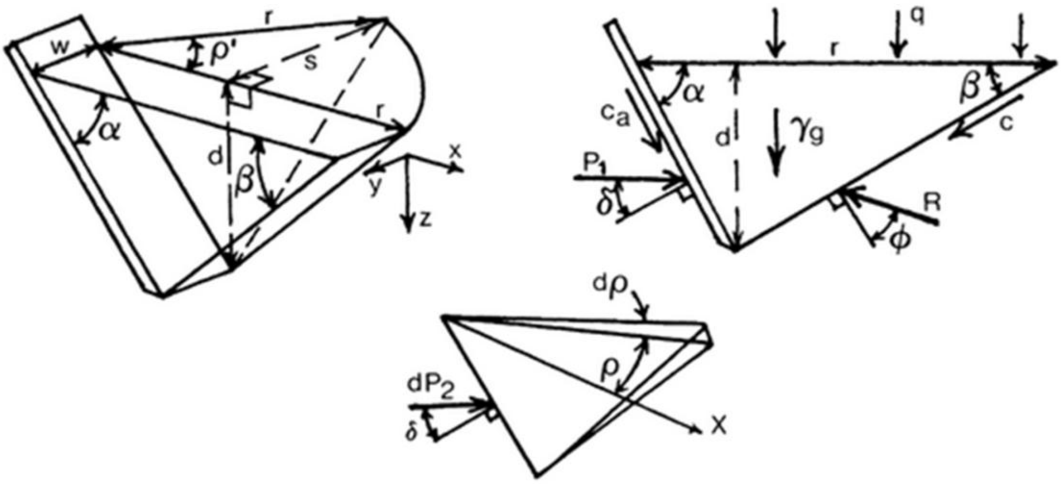

Figure 2 Three dimensional soil cutting model, Mckyes and Ali (1977) used by Ashrafizadeh and Kushwaha (2003) and Mollazade *et al*., (2010)

First the values of mechanical characteristics of agricultural soils as reported by Agbetoye, 2000 are:

Angle of shearing resistance, $\phi = 22^\circ$, angle of soil metal friction, $\delta = 10^\circ$, soil cohesion, $C = 5.2$ kN/m^2, bulk unit weight of soil, $\gamma = 17.4$ kN/m^3, adhesion, Ca = 2.6 kN/m^2. Rake angles varies from 16° to 58° (inclined tine) in previous works (Rahman *et al*., 2001). The larger the rake angle, the thicker the sweep. Increasing the rake angle causes a rapid rise in the draught force (Pullen *et al*., 2004).

Select appropriate rake angle for the tool say 27°. Choose maximum depth of operation of shank based on common practices say 50 cm (Rahman et al., 2001; Pullen *et al*., 2004; Manuwa and Ademosun, 2007). Thus most soils around the globe have hard pans at 25-50 cm depth (Kumar and Thakur, 2005).

2.2 Determination of the width of the subsoiler

For a conventional subsoiler working at depths of between 30 and 50 cm, aspect ratio of between 5 and 7 canbe used based on Spoor and Godwin (1978) as reported by Kumar and Thakur (2005). Aspect ratio of 6.5 can be selected.

$$6.5 = \frac{\text{Depth}}{\text{Width}} \quad (1)$$

6.5 = 40 / width

Tine width = 6.15 cm

2.3 Determination of angle between the tine face and the soil failure plane at working depth (ϴ)

According to Hettiaratchi and Reece (1974), the angle, ϴ is given by,

$$\Theta = \frac{90^\circ + \phi + \delta + \text{Sin}^{-1}(\frac{\text{Sin}\delta}{\text{Sin}\phi})}{2} \quad (2)$$

Substituting the given values in the above equation,

$$\Theta = \frac{90^\circ + 22^\circ + 10^\circ + \text{Sin}^{-1}\,(\text{Sin }10^\circ/\text{Sin }22^\circ)}{2}$$

$$\Theta = \frac{90^\circ + 22^\circ + 10^\circ + \text{Sin}^{-1}\,(0.173648/0.374607)}{2}$$

$$\Theta = \frac{90^\circ + 22^\circ + 10^\circ + \text{Sin}^{-1}\,(0.4635)}{2}$$

$$\Theta = \frac{90^0 + 22^0 + 10^0 + 27.61^0}{2}$$

$$\Theta = \frac{149.61^0}{2}$$

$$\Theta = 74.805^0$$

$$\Theta \approx 74.80^\circ$$

2.4 Determination of critical rake angle (α_c)

$$\alpha_c = 135^0 + \phi/2 - \Theta \quad (3)$$

$$\alpha_c = 135^0 + \frac{22^0}{2} - 74.8^0)$$

$$\alpha_c = 71.2^0$$

2.5 Determination of tine inclination factor (K)

The transition point between wide and narrow tine failure occurs at a working depth Z as a function of tine width b and rake angle α (Hettiaratchi and Reece, 1974).

Ratio of wedge formation transition $K = \frac{Z^1}{b}$

K depends on rake angle.

(i) For small rake angle, $\alpha \leqslant \alpha_c$

$$k = \frac{z}{b} = \frac{\tan(45^0 + \phi/2)\,\mathrm{Sin}\,(\alpha + \square)^0}{2\mathrm{Sin}\square} \qquad (4)$$

(ii) For larger rake angle when $\alpha > \alpha_c$

$$K = \frac{Z^1}{b} = \frac{\tan\left(45^0 + \frac{\phi}{2}\right)\mathrm{Sin}\left(\alpha + \theta + \frac{\phi}{2} - 45^0\right)}{4\,\mathrm{Sin}\theta\,\mathrm{Sin}\left(45^0 + \frac{\phi}{2}\right)} \qquad (5)$$

Since the actual rake angle (27^0) is less than the critical rake angle ($\alpha \leqslant \alpha_c$) equation 3.4 was used to find K.

$$k = \frac{z}{b} = \frac{\tan(45^0 + \phi/2)\,\mathrm{Sin}\,(\alpha + \square)^0}{2\mathrm{Sin}\square}$$

$$K = \frac{Z}{b} = \frac{\tan\left(45 + \frac{22}{2}\right)^0 \mathrm{Sin}(27 + 74.8)^0}{2\,\mathrm{Sin}\,74.8^0}$$

$$K = \frac{Z}{b} = \frac{\tan(45 + 11)^0\,\mathrm{Sin}(101.80)^0}{2\,\mathrm{Sin}\,74.8^0}$$

$$K = \frac{Z}{b} = \frac{\tan(56)^0\,\mathrm{Sin}(101.80)^0}{2\,\mathrm{Sin}\,74.8^0}$$

$$K = \frac{Z}{b} = \frac{1.4826 \times 0.9789}{1.9300}$$

K = 0.75

2.6 Determination of tine category

Manor and Clark (2001) reported that many soils around the globe have average hard-pan at about 15 to 36 cm deep and thickness of up to 5-15 cm. According to Kumar and Thakur (2005), soil profile pit examination at a number of locations in Tarai region of Uttaranchal (India) revealed the presence of Hard pans/compacted layers at depths varying from 30 to 60 cm.

The following parameters can be taken as initial dimension of the blade:

Highest working depth (d)= 0.50 m, blade width (b) = 0.0615 m, rake angle (α) = 27^0 and K = 0.75

To determine whether shank falls into wide or narrow tine category, the following steps should be taken:

Determine the category of tine according to the submission of Hettiaratchi and Reece (1974).

Thus, when

Z < Kb (wide tine)

Z = Kb (transition)

Z > Kb (narrow tine)

From the initial parameters given,

Kb =0.046125

Since the working depth, d = 0.50 m

Thus, d > 0.046125

The tine category is said to be narrow tine, but if d < Kb the tine would be wide category.

2.7 Determination of sectional area of soil loosened behind a tine

The sectional area loosened behind a tine as reported by (Pullen et al., 2004),

$$A_i = d^2 \mathrm{Cot}\beta + dW \qquad (3.6)$$

Where:

Sectional area of loosened soil, A_i (m^2)

Tine working depth in meter, d = 0.50 m

The angle subtended by the line joining the soil rupture and the edge of the tine,

β (deg).

Cot β is given to be 0.59

Tine width (W) = 0.0615 m

A_i = $(0.0615)^2$ (0.59) + 0.4 x 0.0615

A_i = (0.00378) (0.59) + 0.0246

A_i = 0.0022315 + 0.0246

= 0.02683 m^2

≈ 2.683 x 10^{-2} m^2

2.8 Determination of void (v) created by the Shank

New voids (v) in m^3/m created per m length are:

$$V = \frac{A_i(\gamma_i - \gamma_f)}{\gamma_f} \qquad (7)$$

Where: V = new voids in m^3/m

γ_i =initial soil density in kg/m^3

γ_f = final soil density in kg/m^3

Typically, $\frac{\gamma_i - \gamma_f}{\gamma_f}$ ranges from 0.10 – 0.50 according to (Pullen *et al*., 2004) To determine for maximum void,

$\frac{\gamma_i - \gamma_f}{\gamma_f} = 0.45$ was selected

V = 2.683 x 10^{-2} (0.45) m^3/m

$V = 1.20735 \times 10^{-2}\ m^3/m$

$V \approx 1.2074 \times 10^{-2}\ m^3/m$

2.9 Determination of soil shear plane angle (β) in degree

Aikins and Kilgour (2007) gave soil shear plane angle (β) as:

$\beta = \arctan\left(\frac{1}{m-\cot\alpha}\right)$ (8)

Where:

Rupture distance ratio, m = 1.85 (from graph) (Godwin and Spoor, 1977)

α = rake angle

$$\beta = \arctan\left(\frac{1}{m-\cot\alpha}\right)$$

$$\beta = \arctan\left(\frac{1}{1.85-\cot 27^0}\right)$$

$$\beta = \arctan\left(\frac{1}{1.85-0.700}\right)$$

β =arctan (0.8695652)

β =arctan (0.8695652)

$\beta = 41^0$

$m = \frac{\text{Rupturedistance (r)}}{\text{Workingdepth (d)}}$ (9)

$$1.85 = \frac{\text{Rupturedistance (r)}}{0.50}$$

$\text{Rupturedistance(r)} = 0.93\ m$

2.10 Determination of side crescent(s)

Side crescent (s) according to Abo Al-Kheer (2010) is given by,

$S = d\sqrt{\cot^2(\beta) + 2\cot(\alpha)\cot(\beta)}$ (10)

Depth of cut, d = 0.50 m

Rupture angle, $\beta = 41^0$

Rake angle of the tool, $\alpha = 27^0$

$$S = 0.50\sqrt{\cot^2(41^0) + 2\cot(27^0)\cot(41^0)}$$

$$S = 0.50\sqrt{1.3233 + (2 \times 0.7002)\, 1.1504}$$

$$S = 0.50\sqrt{2.9343}$$

$S = 0.50 \times 1.7130\ m$

$S \approx 0.857\ m$

2.11 Determination of maximum crescent angle, (ℓ)

Godwin and Spoor (1977) and Ashrafizadeh and Kushwaha (2003) gave maximum crescent angle, (ℓ) as,

$\ell = \cos^{-1}\left(\frac{\cot\alpha}{m}\right)$ (11)

According to Godwin and Spoor (1977) rupture distance ratio, m = 1.85

$\ell = \cos^{-1}\left(\frac{\cot 27^0}{1.85}\right)$

$\ell = \cos^{-1}\left(\frac{0.70002}{1.85}\right)$

$\ell = \cos^{-1}(0.3785)$

$\ell = 67.759^0$

$\ell \approx 68^0$

2.12 Determination of N-factors

The N-factors are:

N_γ=soil reaction component due to gravity

N_c=soil reaction component due to soil cohesion

N_{ca}=soil reaction component due to soil-metal adhesion

N_q = soil reaction component due to surcharge

N_{sc} ,$N_{s\gamma}$= soil reaction component due to side failure

As stated earlier, $\delta = 10^0$, $\phi = 22^0$, $\alpha = 27^0$.

Values of N factors in the Universal Earthmoving Equation for narrow flat blades cutting soil in a passive failure are taken from graphs. Soil to metal angle, δ, is two thirds of internal friction angle, Φ. Which ranges from 0-45^0, and tool rake angle, α̇, from the 0 – 90^0 (Hettiaratchi and Reece, 1974; Mckyes and Ali, 1977; Mckyes and Desir, 1984).

When $\delta = 0$; $N_\gamma = 0.84$, $N_{ca} = 3.4$, $N_c = 1.09$, $N_q = 1.65$, $N_{sc} = 2.90$, $N_{s\gamma} = 1.06$, When $\delta = \phi = 22$, $N_\gamma = 1.11$, $N_{ca} = 3.40$, $N_c = 3.40$, $N_q = 2.30$, $N_{sc} = 40.40$, $N_{s\gamma} = 2.90$

Values of the factors for intermediate values of δ, N_δ can be calculated from the following equation by Ademosun (1991) and Aikins and Kilgour (2007):

$$N_\delta = {}_0\left[\frac{N_{\delta=\phi}}{N_{\delta=0}}\right]^{\delta/\phi} \quad (12)$$

Using Equation (12) above and the N values calculated when δ= 0 and δ = ϕ to find N_γ, C_a, q, sc, s_γ

(i) $N_\gamma = (0.84)x(\frac{1.11}{0.84})^{10/22}$

$= (0.84) \times (1.32)^{0.45}$

$= 0.95178$

$N_\gamma \approx 0.95$

(ii) $N_{ca} = (1.09)x(\frac{3.40}{1.09})^{10/22}$

$= (1.09) \times (3.119)^{0.45}$

$= 1.8186$

≈ 1.82

(iii) $N_c = (1.09)x(\frac{3.40}{1.09})^{10/22}$

$= (1.09 \times (3.12)^{0.45}$

$= 1.8188$

≈ 1.82

(iv) $N_q = (1.65)x(\frac{2.30}{1.65})^{22/10}$

$= (1.65) \times (1.39)^{0.45}$

$=1.1597$

≈ 1.16

(v) $N_{sc} = (2.9)x(\frac{40.40}{2.9})^{10/22}$

$= (2.9)x(13.93)^{0.45}$

$= 9.4880$

≈ 9.49

(vi) $N_{s\gamma} = (1.06)x(\frac{2.90}{1.06})^{10/22}$

$= (1.06)x(2.74)^{0.45}$

$= 1.6683$

≈ 1.67

2.13 Calculationof total tool force on shank (F)

According to Terzaghi's theory, the following equation was proposed as universal earthmoving equation (UEE) for describing the force required in cutting the soil by a tool and it has been used by several investigators (Reece, 1965; Hettiaratchi and Reece, 1966 as reported by Ashrafizadeh and Kushwaha, 2003):

$$F = (\gamma g d^2 N_\gamma + CdN_c + qdN_q)\, w \quad (13)$$

Where:

Total tool force required to cut the soil by a tool, F(N)

Total soil density, $\gamma = 17400\ N/m^3$

Acceleration due to gravity, $g = 9.81\ m/s^2$

Total working depth below the soil surface, d = 0.50 m

Soil cohesion, $C = 5200\ N/m^2$

Adhesion, $Ca = 2600\ N/m^2$

Tool width, W = 0.0615m

The surcharge (q) was estimated by calculating the maximum weight of roots/unit cross-sectional area of soil $\approx 0.31\ kN/m^2$ (Agbetoye, 2000).

$F\ (\gamma g d^2 N_\gamma + CdN_c + C_a Z N_a + qdN_q)\, w$

$F = [17.4 \times 10^3 \times 9.81 \times (0.50)^2 \times 0.95 + (5.2 \times 10^3 \times (0.50) \times 1.82) + (2600 \times 0.50 \times 1.82) + 310 \times 0.50 \times 1.16]\ 0.0615$

$= [40539.825 + 4732 + 179.8 + 2366]\ 0.0615$

F= 2940.7840 N

F = 2.941 kN

For winged subsoiler with a total width of 0.18 m,

F = [40539.825 + 4732 + 179.8 + 2366] x 0.18

F = 9,563.525 N

F = 9.564 kN

2.14 Calculation of forward failure force (F_f)

Forward failure force (F_f) reported by Ashrafizadeh and Kushwaha (2003):

$F_f = (\gamma d^2 N_\gamma + CdN_c + C_a dN_a + qdN_q)\ w$ (14)

$F_f = [(17.4 \times 10^3 \times (0.5)^2 \times 0.95) + (5.2 \times 10^3 \times (0.5) \times 1.82) + (2.6 \times 10^3 \times 0.5 \times 1.82) + (310 \times 0.5 \times 1.16)]\ 0.615$

$= (4132.5 \times + 4732 + 2366 + 179.8) \times 0.615$

$= (11{,}410.3) \times 0.0615$

$= 701.733$ N

= 0.702 kN

For winged subsoiler with a total width of 0.18 m,

$F_f = (11{,}410.3) \times 0.18$

$F_f = 2{,}053.854$ N

F_f = 2.054 kN

2.15 Calculation of sideways failure force (F_s)

The sideways failure force (F_s) reported by Ashrafizadeh and Kushwaha (2003):

$$F_s = \{\gamma(d_e + \frac{q}{\gamma})^2 W N_{s\gamma} + CWd_e N_{sc}\}\ K_\alpha \quad (15)$$

Where:

d_e is effective wedge depth.

$$d_e = Z - \frac{Kb}{2} \quad (16)$$

$$d_e = 0.5 - \frac{0.59 \times 0.5}{2}$$

$= 0.3525$ m

Now calculating the sideways failure force

Where:

$C = 5.2 \times 10^3\ N/m^3$,

$\gamma = 17.4 \times 10^3\ N/m^3$,

$K_\alpha = 0.59$ as earlier calculated.

Using equation $P_s = \{\gamma(d_e + \frac{q}{\gamma})^2 W N_{s\gamma} + CWd_e N_{sc}\}\ K_\alpha$

$F_s = \{17400(0.106 + \frac{310}{17400})^2 0.0615 \times 1.67 + 5200 \times 0.0615 \times 0.106 \times 9.49\}\ 0.59$

$F_s = (27.396 + 321.6996)\ 0.59$

$F_s = 349.096 \times 0.59$

$F_s = 205.966$ N

2.16 Calculation of draught force (H)

Draught requirements depend on soil type and condition, manner of tool movement and tool shape (Gill and Vanden Berge, 1968; Upadhyaya et al., 1984). Draught requirements of a subsoiler may be represented in the following functional form (Freitaget al., 1971):

$D = f_1(\rho_w, C_1, d, S, w, \varrho_1, \alpha, \vartheta)$ (17)

Where,

D = Draught force, F

ρ_w = Wet bulk density, $FL^{-4}T^2$

C_1 = Cone index, F/L^2

d = Depth of operation, L

S = Speed of operation, L/T^2

w = width of subsoiler cutting edge, L.

ϱ_1 = all other length related subsoiler parameters such as the curvature, length, shank width, etc., L

α =Subsoiler cutting angle (lift angle)

ϑ = acceleration due to gravity, L/T^2

But the simplified equation by (Ademosun, 1990; Ashrafizadeh and Kushwaha, 2003) can be used to calculate the draught force:

$H = F_f \sin(\alpha + \delta) + F_s \sin\alpha + C_a d \cos\alpha$ (18)

Where,

F_f = forward failure force

$H = 701.766 \sin(27 + 10)^0 + 205.966 \sin 27^0 + 2.6 \times 10^3 \times 0.5 \cos 27^0$

H = 123.953 + 529.72 + 1,158.31

H = 1,811.98 N

H = 1.812 kN

Considering afactor of safety of n = 3.0 (safe load for locally available material of good strength) can be chosen to ensure that a sudden surge of forces due to dynamic loading will be taken care of, so that the soil engaging parts do not fail. It accounts for the uncertainties that may occur in the strength of a part and the uncertainties that may occur when the load acting on the part.

Hence,

H = 3 x 1.812 = **5.436 kN**

2.17 Calculation of vertical force (V)

The vertical force (V) is reported by Ashrafizadeh and Kushwaha (2003) as:

$V = F_f \cos(\alpha + \delta) + F_s \cos\alpha + C_a d$ (19)

Where: d= depth of tine or blade

$V = 701.733 \cos (27 + 10)^0 + 205.966 \cos 27^0 + 2.6 \times 10^3 \times 0.5$

$V = 560.4298 + 183.5170 + 1300$

$V = 2{,}043.95$ N

V = **2.044 kN**

2.18 Determination of resultant force acting on shank (R_F)

Hall et al.(1980) gave the resultant force acting on tine as:

$$R_F = \sqrt{H^2 + V^2} \quad (20)$$

H= D = the horizontal force = 1811.98 N

V = the vertical force = 2043.95 N

$R_F = \sqrt{1811.98^2 + 2043.95^2}$

$R_F = \sqrt{3283271.52 + 4177718.52}$

$R_F = \sqrt{7460990.04}$

$R_F = 2731.4813$

R_F = 2731.48 N

R_F = 2.731 kN

2.19 Determination of bending moment on the shank (M_b)

The bending moment on the shank (M_b) calculated by Ademosun (1991) is:

$$M_b = \tfrac{2}{3} \times V (\cos \alpha) d \quad (21)$$

Vertical force (V)= 2,043.95 N

Rake angle (α) = 27^0

Length (d) =0.50 m

$M_b = \tfrac{2}{3} \times 2043.95 \times \cos 27^0 \times 0.50$

M_b =607.06 Nm

The bending moment for the blade is **607.06 Nm**

2.20 Determination of thickness of the shank blade (t)

Material selected was high grade structural carbon steel

Working depth =0.5 m

Width of blade (W) =0.0615 m

Allowable steel stress $\delta_n = 210 \times 10^6$ N/m^2

Bending moment on blade (M_b) ≈ 607.06 Nm

Thickness of blade is given by the expression, according to (Ademosun, 1991):

$$t = \sqrt{\frac{12\, M_b}{2\delta_n W}} \quad (22)$$

tis thickness

$$t = \sqrt{\frac{12 \times 607.06}{2 \times 189 \times 10^6 \times 0.0615}}$$

$$t = \sqrt{\frac{7284.69}{23247000}}$$

$t = 3.13 \times 10^{-3}$ m

t = 3.13 mm

Factor of safety of n = 3.0 (safe load for locally available material of good strength) can be chosen.

Actual thickness (t) = 3.13 x 3.0 ≈9.39 mm

Thickness of blade 9 mm designed is similar to thickness of experimental blades reported in Manuwa and Ogulami (2010). Steel plate of 8 mm thickness design is readily available locally inthe markets.

2.21 Calculation of power requirement to pull the shank (P)

Using the formula by (Agbetoye, 2000):

$$P = (D \times S \times W) \quad (23)$$

Where: P = power requirement.

Draught force, D = 1,811.98 N

Width of implement, W = 0.0.0615 m

But width at which implement will disturb the soil according to Godwin (2007) = 1.5 x depth of operation for narrow tillage tools and 2.0 x depth of operation for wide tine.

Hence, for subsoiler shank (narrow tine) width of disturbance,w = 1.5 x 0.5 = 0.75

Select speed of the implement as desired say 5 km/h or more.

P = (1811.98 x 5 x 0.75)

P =6794.92W = 6.795 kW

Considering factor of safety in the event of shock, mechanical faults and other environmental influences on material of the implement, we can multiply the calculated power by a factor of 3 (Agbetoye, 2000).

P = 6794.92 x 3) W

= 20384.78 W

P = **20.385 kW**

3 Conclusions

This work presents a step-by-step approach towards design of narrow tillage tools. Determination of tool width (w), angle between the tine face and the soil failure plane at working depth (ϴ), rake angle **(**α_c**)**, inclination factor (K), tine category, area of soil disruption, void (v) created by tine, tool forces and power requirement; and other major soil and tool parameters have been identified and defined for researchers to follow and improve on in subsequent development of subsoilers for effective agricultural production. More attention should be given to design process that tends towards reduction in the magnitude of specific draught for overall benefits of tillage process.

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