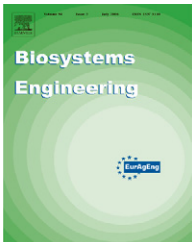
BIOSYSTEMS ENGINEERING 97 (2007) 27–39

Available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110



Research Paper: PM—Power and Machinery

Design of the Ethiopian *ard* plough using structural analysis validated with finite element analysis

S. Gebregziabher[a,b,c,*], A.M. Mouazen[a,d], H. Van Brussel[b], H. Ramon[a], F. Meresa[c], H. Verplancke[e], J. Nyssen[f,g], M. Behailu[f], J. Deckers[g], J. De Baerdemaeker[a]

[a]Department of Agro-Engineering and Economics, Katholieke Universiteit Leuven, Kasteelpark Arenberg 30, B-3001 Heverlee, Belgium
[b]Department of Mechanical Engineering, Katholieke Universiteit Leuven, Celestijnenlaan 300B, B-3001 Heverlee, Belgium
[c]Department of Mechanical Engineering, Mekelle University, P.O.Box 231, Mekelle, Ethiopia
[d]Department of Rural Engineering, University of Aleppo, P.O.Box 12214, Aleppo, Syria
[e]Department of Soil Management and Soil Care, Coupure links 653, 9000 Gent, Belgium
[f]Department of Land Resource Management and Environmnetal Protection, Mekelle University, P.O.Box 231, Mekelle, Ethiopia
[g]Department of Soil and Water Management, Katholieke Universiteit Leuven, Vital Decosterstraat 102, 3000 Leuven, Belgium

ARTICLE INFO

Article history:
Received 5 September 2005
Accepted 30 January 2007
Available online 12 April 2007

The Ethiopian *ard* plough 'Maresha' is a tillage tool that most farmers still use for land preparation. The production of the wooden structure is based on experience, culture, and trial and error methods. In this paper, the basic design of the *ard* plough is presented. The mathematical descriptions (traditional force analysis) are based on static analysis at equilibrium of the structure. The forces considered were the pulling forces provided by a pair of draught animals, the operator input force, gravitational weight of the implement, the normal and tangential interfacial forces acting on the ploughshare and wooden side-wings and the inertial force. The draught, vertical, tangential interfacial and normal interfacial forces of the implement were determined. Moreover, sensitivity of draught and vertical forces to different pulling angles and sensitivity of normal and tangential interfacial forces to different rake angles were investigated. The force analysis was validated by means of the finite element (FE) analysis using the ABAQUS package. It was confirmed that draught force on the ploughshare increased with pulling angle. Similarly, the tangential interfacial force of the implement was higher than the normal interfacial capacity at lower pulling angles. The output of the FEM and traditional calculation resulted in small errors of less than 3% for draught and 5% for vertical forces for small pulling angles $\leqslant 30^\circ$. This study integrates the previous research experiences with theory and computer-based analysis and simulations. The design guidelines and considerations for improving or developing small-scale tillage implements are presented.

1. Introduction

The history of animal traction in eastern and southern Africa, with the exception of Ethiopia and South Africa, started with the introduction of the ox–plough by the missionaries and white settlers in the early 1920s (Starkey, 1995). While in Ethiopia, animal power has been used for thousands of years, in South Africa it dates back to the 1600s (Starkey, 1995).

---

*Corresponding author.
E-mail address: sgher1@yahoo.com (S. Gebregziabher).

doi:10.1016/j.biosystemseng.2007.01.012

Nomenclature

a_1	height of the tip of handle (where the operator apply force) from horizontal, m
a_2	height of the yoke from horizontal, m
b_1	horizontal projected distance between the tip of the handle 'M' and the centroid of the ploughshare 'O', m
b_2	horizontal projected distance between the middle of the yoke 'B' and the centroid of the ploughshare 'O', m
c_1	horizontal distance between the centre of the yoke and the position of the right draught animal, m
c_2	horizontal distance between the centre of the yoke and the position of the left draught animal, m
d	depth where forces assumed to be concentrated on the ploughshare, m
e	depth where forces assumed to be concentrated on side-wings, m
F_b	pulling force acting on the beam top position, N
F_n	pulling force acting at the junction of the beam and the handle, N
F_O	applied force by the operator, N
F_p	pulling force transferred from the wooden pin to the side-wing, N
F_x	draught force, N
F_{t1}	pulling force by the right draught animal, N
F_{t2}	pulling force by the left draught animal, N
F_z	vertical force, N
F_1	tangential interfacial force of the ploughshare, N
F_2	tangential interfacial force of each side-wing, N
g	horizontal projected distance between the centroid of the ploughshare and the side-wing, m
H	normal interfacial force of the ploughshare, N
h	horizontal projected distance between the junction point of the handle and the beam, and the ploughshare centroid, m
$\mathbf{i}$	horizontal unit vector
K	normal interfacial force of the each side-wing, N
$\mathbf{k}$	vertical unit vector
l	the height of junction point 'Q' of the beam and the handle assembly from the ground level, m
M	total moment, N m
M_1	moment effect of force applied by the operator and transferred to the upper tip of the ploughshare, N m
M_W	moment about centroid of the left side-wing, N m
M_O	moment acting on the centroid of the ploughshare, N m
m	offset dimension of the centroid of the side-wing (where interfacial forces are assumed to be concentrated) from the axis of the handle and the ploughshare, m
n	distance between the point of intersection (of the beam and the handle) and the position of metal loops with leather strap attachment on the ploughshare, m
p	distance between the position of metal loops with leather strap attachment on the ploughshare and the assumed point where soil resistance is to be concentrated on the ploughshare, m
r	distance between the position of pin connection of the side-wing and the point where soil resistance is assumed to be concentrated on the side-wing surface, m
$\vec{r}_{JO}$	position vector from point 'J' (point of operator's force application) to the ploughshare centroid 'O', m
$\vec{r}_{BO}$	position vector from point 'B' (tip of the beam) to the ploughshare centroid 'O', m
$\vec{r}_{PW}$	position vector from point 'P' (point of application of pulling force on the side-wing) to the centroid of the left side-wing 'W', m
$\vec{r}_{QO}$	position vector from point 'Q' (junction point of the beam and the handle assembly) to the ploughshare centroid 'O', m
$\vec{r}_{T'O}$	position vector from point 'T′' (point of application of tension by the leather strap/rope on the ploughshare) to the ploughshare centroid 'O', m
$\vec{r}_{T'W}$	position vector from point 'T′' (point of application of tension by the leather strap/rope on the side-wing) to the centroid of left side wing 'W', m
$\vec{r}_{UO}$	position vector from point 'U' (point of force application by the left draught animal) to the ploughshare centroid 'O', m
$\vec{r}_{VO}$	position vector from point 'V' (point of force application by the right draught animal) to the ploughshare centroid 'O', m
$\vec{r}_{WO}$	position vector from point 'W' (centroid of the right side-wing where interfacial forces are assumed to be concentrated) to the ploughshare centroid 'O', m
$\vec{r}_{W'O}$	position vector from point 'W′' (centroid of the left side-wing where interfacial are forces assumed to be concentrated) to the ploughshare centroid 'O', m
s	distance between the position of leather strap attachment (including metal loops) on the side-wing and the point where soil resistance is assumed to be concentrated on the side-wing (W for the left side-wing, and W′ for the right side-wing), m
T	tension on the leather strap or rope, N
V	gravitational force of the implement (excluding weight of the yoke and about 1/3 of the beam), N
α_1, α_2	pulling angle by the right and left draught animals, respectively, degree
β_1, β_2	angle of the beam at the lower and upper position from the ground level, respectively, degree
γ	angle of the side-wing from horizontal, degree
θ_1	share-rake angle (angle of attack), degree
θ_2	inclination angle of the handle, degree
λ	angle of the applied force by the operator F_o from horizontal, degree
σ	tail angle, angle between the side-wing plane surface and the handle, degree

ϕ	angle between the handle (along with its ploughshare) and the leather strap, degree	Ψ	angle between side-wings, degree
φ	angle between the side-wing plane surface and the leather strip, degree	ω	angle of force F_P acting on the wooden pin from horizontal, degree

Around 75% of farmers in North and East Africa, South-East Europe, the Near and Far East and Latin America are still using *ard* ploughs of various types (Schmitz, 1991). Depending on a specific design, the ploughs are used for making a furrow and leaving a ridge on one or both sides by partially turning the soil and loosening the layer interface. Tractor-powered tillage implements are used to a limited extent mainly on larger private or commercial farms, but also sometimes for initial tillage of smallholder plots through rental agreements (Pingali *et al.*, 1987; World Bank, 1987). However, the relative simplicity and regenerative character of animal traction technologies, their strong indigenous nature and simple support systems have resulted in their integration into many small-farm systems. Thus, draught animals remain a major power source utilised by a significant number of smallholder farming.

The *ard* type of plough was first described in the poems of Hesiod, in approximately 700 BC (Frazer, 1984). It is the most commonly used implement by Ethiopian highland farmers. It is known locally as 'Maresha' in Amharic, as 'Gindii' in Afaan Oromo, and as 'Mahresha' in Tigrigna. It is a light implement ranging from 17 to 26 kg (Goe, 1987), which makes it possible to be transported to and from the field over different terrains by one person. However, most of the time, 10-year boys can carry and transport both the *ard* and yoke to the fields. The *ard* plough is suitable for use in both sandy soils and heavy crusty clays.

The improvement of the design and performance of the *ard* plough has been undertaken by various researchers and research centres. In 1960, the 'Jimma' plough provided better tillage than the traditional *ard* plough on sandier soils during on-farm trials (UNDP, 2000). In 1968, the Chilallo Agricultural Development Unit (CADU), later changed to the Arsi Rural Development Unit (ARDU), initiated a research programme to develop tillage implements (CADU, 1969, 1970, 1971). In 1970, the 'Vita' plough was introduced, and constructed from a metal mouldboard assembly instead of the metal tine and wings that had characterised previous designs (UNDP, 2000). In order to allow the adaptation of the angle of the handle for easier use, the 'Vita' plough design was modified to come up with the 'Ardu' plough (ARDU & MAS, 1980). In 1976, the Institute of Agricultural Research (IAR) of Ethiopia started developing and testing farm tools and equipment (mouldboard plough, spike tooth harrow, imported tool-bar and hand-operated planter) appropriate for the agricultural conditions in Ethiopia (Berhane, 1979). The International Livestock Centre for Africa (ILCA) conducted research on tillage implements including power requirements, cultivation and weeding times, and crop yields on different soil types (Astatke & Mathews, 1982, 1984). The traditional implement was also modified in view of the selective use of single oxen. This involved replacing the traditional long beam with a shorter beam and skid that connected to a swingle tree and traces (Gryseels *et al.*, 1984; Astatke & Mohammed-Saleem, 1992). During 1983, the International Livestock Centre for Africa (ILCA) developed a yoke and modified the traditional 'Maresha' enabling the use of a single ox (Astatke & Mohammed-Saleem, 1992). Pathak (1988) accounted for the performance of the components of the type plough and recommended that new ploughs be developed to meet the necessary soil operations with low draught requirements. A reversible animal-drawn plough and ridger have been developed (Gebresenbet, 1995; Gebresenbet *et al.*, 1997; Gebresenbet & Kaoumbtho, 1997) at the Swedish University of Agricultural Sciences, taking into consideration the basic design principle of conventional mouldboard ploughs and the Ethiopian *ard* type of plough. Asefa *et al.* (1997) developed a four-row seeder in order to solve the problem with the funnel type of hand-metered seed drill. Temesgen (1999) and Temesgen *et al.* (2001) incorporated the 'Maresha' plough designs into newly developed implements after avoiding the weak points. Accordingly, four implements were developed, namely the modified plough, the ripper/subsoiler, the winged plough, and the tie ridger.

Most developments in the Ethiopian *ard* plough were based on experience, culture, and trial and error methods. However, most of the prototypes were found to be expensive, heavy, complicated and did not fit on the traditional plough frames used in Ethiopia. Therefore, designing an implement must take into account the agricultural and industrial systems, within which the implements are manufactured and operated. Furthermore, efficiency of tillage is measured in terms of draught or input energy (Gill & Vanden Berg, 1968). Optimisation of tillage tool design necessitates minimisation of the input energy and subsequently the draught. The availability of data on the draught requirement of tillage implement is an important factor while selecting tillage implements for a particular farm situation (Sahu & Raheman, 2006). High tillage forces were found to be associated with smaller yield (Neményi *et al.*, 2006). Thus, the optimisation of the Ethiopian *ard* plough is to be directed towards better tillage efficiency.

The objective of the paper is to perform a static analysis on the *ard* plough of Ethiopia, aiming at optimising the structure for minimum draught requirement, structural stability and simplicity and lightweight implement. The results of the force analysis are validated with the finite element (FE) modelling technique.

2. Equipment

Most components of the implement (Fig. 1) are products of local timber except for the ploughshare (4) and the metal loops (5) and (6) or the sheath. Blacksmiths make the ploughshare sourcing metal from recycling the broken leaf springs of vehicles, whereas the two metal loops or sheath are made from steel by forging to the required shape and size.

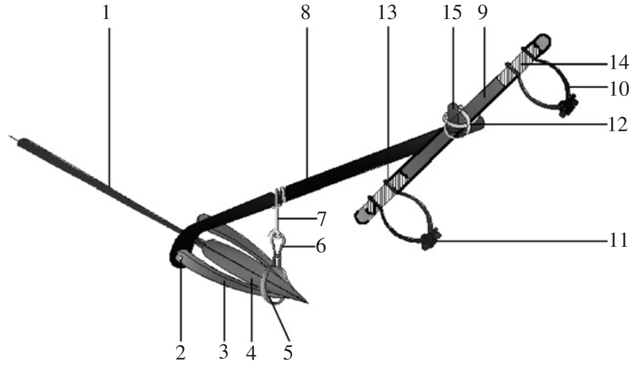


Fig. 1 – Three-dimensional sketch of the Ethiopian *ard* plough 'Maresha': (1) handle; (2) wooden pin; (3) side-wing; (4) ploughshare; (5) lower metal loop; (6) upper metal loop; (7) leather stripe (8) beam; (9) yoke; (10) neck holder sticks; (11, 12) leather strap or rope; (13) rubber as washer; (14) leather for safety; (15) centring pin.

The ploughshare (4) is attached to a handle (1) by means of a socket and held in place by friction. The friction in most cases is between the ratchet and the Teflon-like material wound around the bottom end of the handle. The larger diameter of the lower bottom of the beam (8) allows for the hole, through which the handle (1) passes. The lower bottom of the beam also helps as counter weight to keep the ploughshare in the soil. The clearance in this assembly helps to vary the rake angle by inserting any wooden spacer. The side-wings (3) are two pieces of wood with opposite orientation in order to be assembled at both sides of the ploughshare (4). The rear ends are pinned to the beam (8), located behind the joint position of the handle (1) and the beam (8), by means of a pin-like wooden material (2) forming a 'sledge' shape. The other ends of these side-wings are held together with the ploughshare (4) by means of a metal loop (5). Another metal loop (6) is interlinked with the first loop, and a piece of wood is inserted between the two metal loops to reduce metal-to-metal friction. In many cases, only one component is used instead of two loops. The metal loop (6) is then fastened to the beam (8) using a strap made from a combination of leather and rubber (7). However, in many cases farmers use a simple rope. The beam (8) is assembled to the yoke (9) by means of a centring pin (15) inserted to the hole at the centre of the yoke and the leather strap or rope (12). The yoke (9) has two holes at each end, into which the four-neck holder 'sticks' (10) with different orientations are inserted. These 'sticks' are used as a guide to keep the oxen at a relatively balanced position by introducing a constant gap between the two oxen.

3. Force analysis

The forces acting on the traditional *ard* plough of Ethiopia are the pulling force applied by the draught animal, the gravitational force (weight of implement), the force exerted by the operator, the gravitational force of the soil, the soil resistance, the interface forces between the soil and plough (share and side-wings at the front and back sides) and the inertia force.

The mathematical description of the *ard* plough is discussed based on the static analysis of the structure at equilibrium. The dynamic effect was considered negligible, since ploughing with animal traction occurs at a low speed compared to the ploughing speed with agricultural tractors. To develop mathematical equations, the forces acting on the plough and the dimensional relation of the structure were taken into account.

3.1. *Assumptions for the force analysis*

The following assumptions were taken into account for further approximation of detailed force analysis.

1. The implement is symmetric in shape.
2. The ploughshare performs soil penetration. The side-wings are used for crack propagation and furrow making. Thus, the major portion of soil resistance acts on the ploughshare, allowing the tangential F2 and normal K interfacial forces of each side-wing acting on the two side-wings to be ignored.
3. The lateral force applied by the operator is to reduce draught requirement and also to keep the width of ploughing. The operator usually vibrates the plough in the lateral direction to assist the loosening and breaking process. Though it is a continuous process, its effect can be minimised by introducing a lateral slot at the juncture of the beam and the handle assembly. Thus, its effect can be neglected.
4. The effect of inertial force is negligible because of the low speed of tillage process.
5. Soil type and soil properties were neglected, since no interaction analysis between the soil and ploughshare was considered.
6. The tangential interfacial force at the bottom side of the ploughshare and side-wings has a significant effect during initiation of the soil penetration process, because of initial full-surface contact with soil. Depending on the soil texture, the surface contact decreases and its magnitude reduces as the tillage process progresses. Thus, this force can be neglected during development of the mathematical equations.
7. The magnitude of the downward force exerted on the handle by the operator increases to enhance the penetration of high-resistance soils. In other cases, this force is very small.
8. The handle and ploughshare axes are collinear, for which share-rake angle θ_1 and inclination angle of the handle θ_2 are equal ($\theta_1 = \theta_2 = \theta$).
9. The two draught animals have same size and weight, and walk at the same pace. For this assumption, the pulling force by the right draught animal F_{t1} equals the pulling force by the left draught animal F_{t2} and pulling angle by right α_1 and left α_2 draught animals are also equal ($F_{t1} = F_{t2} = F_t$ and $\alpha_1 = \alpha_2 = \alpha$).
10. The two draught animals keep their position equidistant from the centring pin, for which the horizontal distance between the centre of the yoke and the position of the right c_1 and left c_2 draught animal are equal ($c_1 = c_2 = c$).

3.2. *Input forces*

The pulling forces applied by the two oxen F_{t1} and F_{t2} in N can be written as a function of angles α_1 and α_2 in degree, respectively as follows [see Fig. (2a)]:

$$\vec{F}_{t1} = \vec{F}_{t1x} + \vec{F}_{t1z} = F_{t1}\vec{i}\cos\alpha_1 + F_{t1}\vec{k}\sin\alpha_1, \tag{1}$$

$$\vec{F}_{t2} = \vec{F}_{t2x} + \vec{F}_{t2z} = F_{t2}\vec{i}\cos\alpha_1 + F_{t2}\vec{k}\sin\alpha_2, \tag{2}$$

where $\vec{i}$ is a unit vector of horizontal X axis; $\vec{k}$ is a unit vector of vertical Z axis; and α_1, α_2 are pulling angles by the right and left draught animals, respectively, in degree.

Vertical (Z axis), longitudinal (XZ plane) and lateral (YZ plane) forces applied by the operator, control depth and reduce draught requirement. Vibration of the plough in the lateral direction, perpendicular to the ploughing direction, assists in the loosening and breaking process of the soil. Here, the vertical and longitudinal forces are considered because of the relative importance for depth control that has significant impact on draught requirement and cultivation. The operator input force F_O in N is written as [Fig. (2a)]:

$$\vec{F}_O = \vec{F}_{Ox} + \vec{F}_{Oz} = F_O\vec{i}\cos\lambda - F_O\vec{k}\sin\lambda, \tag{3}$$

where λ is the angle in degree of the applied force by the operator F_O from horizontal.

3.3. *Output forces (capacities)*

The normal interfacial force of the ploughshare H in N, *i.e.* the implement structural force that withstands the normal force of soil resistance, is written as component forces as a function of inclination angle of the ploughshare θ_1 in degree as follows [see Figs 2(b) and (c)]:

$$\vec{H} = \vec{H}_x + \vec{H}_z = -H\vec{i}\sin\theta_1 - H\vec{k}\cos\theta_1. \tag{4}$$

Similarly, the tangential interfacial force on the ploughshare F_1 in N, shown in Fig. 2 is given as follows:

$$\vec{F}_1 = \vec{F}_{1x} + \vec{F}_{1z} = -F_1\vec{i}\cos\theta_1 + F_1\vec{k}\sin\theta_1. \tag{5}$$

For the normal and tangential forces of the side-wings, it was assumed that same weight of soil with similar soil properties pass over both side-wing surfaces. Moreover, both wings have geometrical similarity with opposite orientation, *i.e.* symmetrical to the ploughshare axis. The normal interfacial force of the side-wing K in N is written as component forces as a function of angle γ in degree the inclination of side-wing from horizontal; and is given as follows [see Figs. 2(b) and (c)]:

$$\vec{K} = \vec{K}_x + \vec{K}_z = -K\vec{i}\sin\gamma - K\vec{k}\cos\gamma. \tag{6}$$

Similarly, the tangential interfacial force of each side-wings F_2 in N is given as follows [see Figs 2(b) and (c)]:

$$\vec{F}_2 = \vec{F}_{2x} + \vec{F}_{2z} = -F_2\vec{i}\cos\gamma + F_2\vec{k}\sin\gamma. \tag{7}$$

The load of gravitational force of the implement (excluding the weight of the yoke and about a third of the beam, which is assumed to be carried by the draught animals) was assumed to be concentrated on the centroid of the ploughshare, and written as

$$\vec{V} = -V\vec{k} \tag{8}$$

where V is gravitational force in N of the implement (excluding weight of the yoke and a third of the beam)

3.4. *Force balance*

The implement structure is considered as a rigid body, and analysed at static equilibrium. A rigid body is considered to be in equilibrium when both the sums of the resultant forces and the resultant moments are zero $\left(\sum\vec{F} = 0; \sum M = 0\right)$.

From the free body diagrams shown in Fig. 2, the normal interfacial forces of the ploughshare H and each side-wing K are given by Eqs. (9) and (10), respectively.

$$+\rightarrow \sum\vec{F}_x = 0; \quad +\uparrow \sum\vec{F}_z = 0$$

$$H = \left\{ \frac{\begin{array}{c} F_{t1}(\tan\gamma\sin\alpha_1 - \cos\alpha_1) + F_{t2}(\tan\gamma\sin\alpha_2 - \cos\alpha_2) - F_O(\tan\gamma\sin\lambda + \cos\lambda) \\ +F_1(\tan\gamma\sin\theta_1 + \cos\theta_1) + 2F_2(\tan\gamma\sin\gamma + \cos\gamma) - V\tan\gamma \end{array}}{(\tan\gamma\cos\theta_1 - \sin\theta_1)} \right\} \tag{9}$$

$$K = \frac{1}{2}\left\{ \frac{\begin{array}{c} F_{t1}(\cos\alpha_1 - \tan\theta_1\sin\alpha_1) + F_{t2}(\cos\alpha_2 - \tan\theta_1\sin\alpha_2) + F_O(\tan\theta_1\sin\lambda + \cos\lambda) \\ -F_1(\cos\theta_1 - \tan\theta_1\sin\theta_1) - 2F_2(\tan\theta_1\sin\gamma + \cos\gamma) + V\tan\theta_1 \end{array}}{(\sin\gamma - \tan\theta_1\cos\gamma)} \right\} \tag{10}$$

3.5. *Moment balance*

For moment at point ‘O’, {(x,y,z) → (0,0,0)}, where all forces on the ploughshare were assumed to be concentrated, the coupling effects of H, F_1, and V vanish because of zero position vector (see Fig. 3). Since the weight of the yoke and about 1/3 of the beam is supported by the draught animals and directly transferred to the ground, it does not have coupling effect on the structure. Hence, point ‘O’ is considered as the centroidal point on the ploughshare of soil–metal interface. The centroid can be approximated by area centroid considering the small soil–tool interface area. Accordingly, the coupling effect M_O on the ploughshare centroid due to the pulling force by the draught animals and the operator input force can be deduced from total moment balance M in N m, given as follows:

$$\begin{aligned} \sum M = {} & (\vec{r}_{JO} \times \vec{F}_O) + (\vec{r}_{VO} \times \vec{F}_{t1}) + (\vec{r}_{UO} \times \vec{F}_{t2}) \\ & + (\vec{r}_{WO} \times \vec{K}) + (\vec{r}_{WO} \times \vec{F}_2) + (\vec{r}_{W'O} \times \vec{K}) \\ & + (\vec{r}_{W'O} \times \vec{F}_2) + M_O = 0, \end{aligned} \tag{11}$$

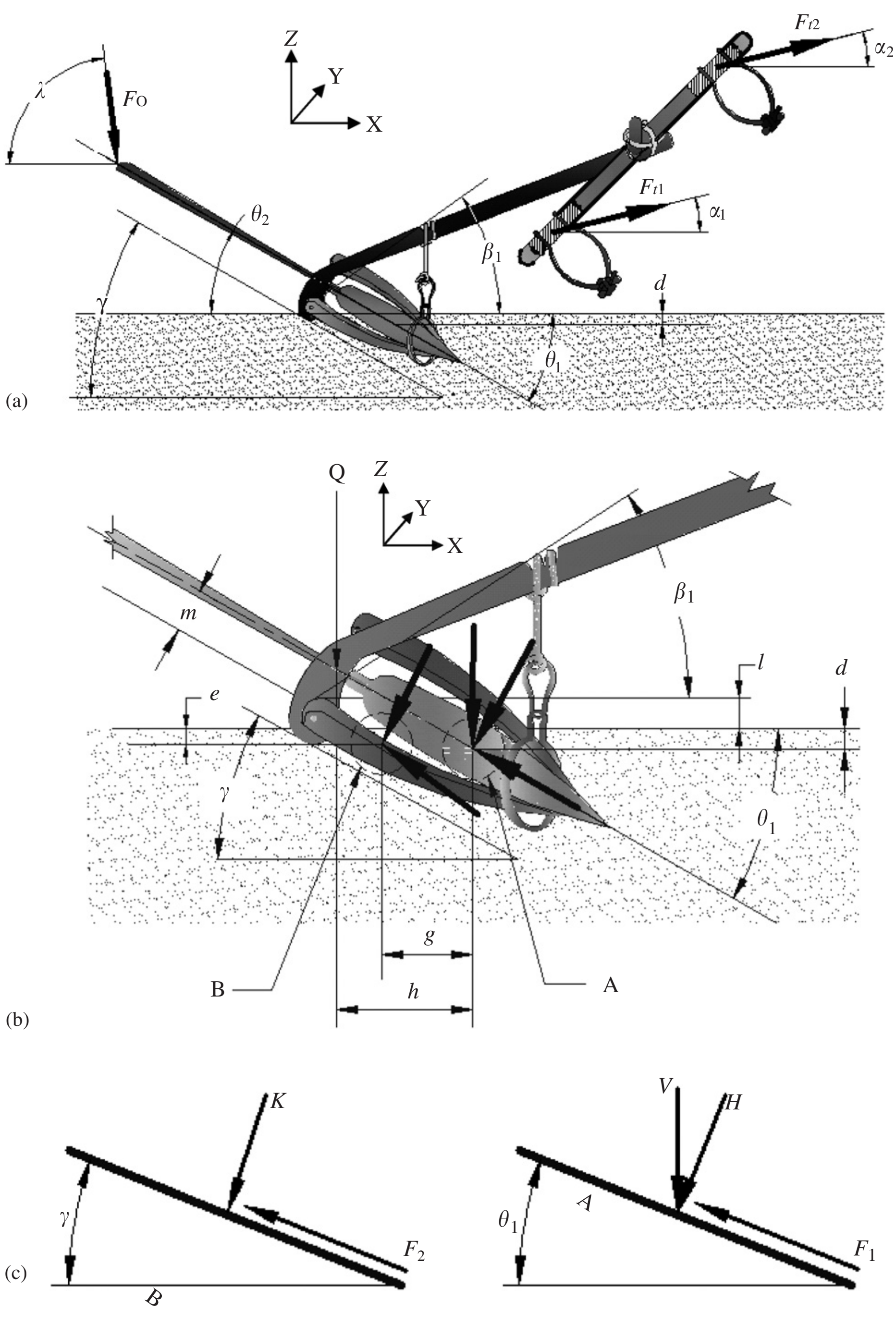


Fig. 2 – Forces acting on the Ethiopian *ard* plough 'Maresha': (a) input forces; (b) output forces at the share and two side-wings; (c) detailed force analysis output on ploughshare A and side-wing B: *d*, the depth where forces assumed to be concentrated on ploughshare; *e*, depth where forces assumed to be concentrated on side-wings; F_O, operator force; F_{t1}, F_{t2}, pulling forces by the two draught animals; F_1 and F_2, tangential interfacial force of ploughshare and each side-wing, respectively; *g*, horizontal projected distance between centroid of ploughshare and side-wing; H, normal interfacial force of ploughshare; *h*, horizontal projected distance between the junction point of the handle and the beam, and the ploughshare centroid; *l*, the height of junction point Q of the beam and the handle assembly from the ground level; m, offset dimension of centroid of side-wing (where interfacial forces are assumed to be concentrated) from the axis of the handle and the ploughshare; *V*, gravitational force of the implement (excluding weight of yoke and about 1/3 of the beam); α_1 and α_2, pulling angle by the draught animal 1 (right) and the draught animal 2 (left); β_1 and β_2, angle of beam, at lower position from ground level; γ, angle of side-wing from horizontal; θ_1, share-rake angle (angle of attack); θ_2, inclination angle of the handle; λ, angle of the applied force by the operator F_O from horizontal.

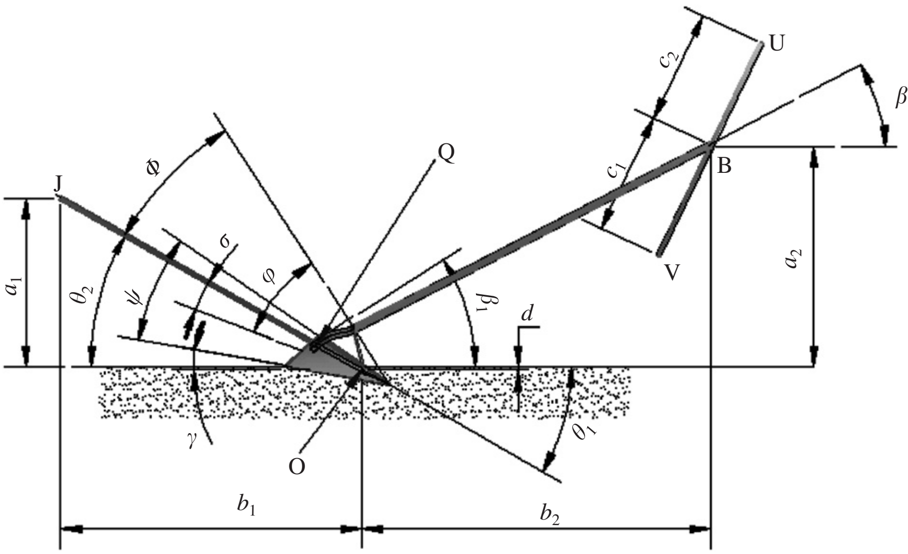


Fig. 3 – Line representation and respective dimensions of Ethiopian *ard* plough 'Maresha': a_1, height of the tip of handle (where the operator apply force) from horizontal; a_2, height of the yoke from horizontal; b_1, horizontal projected distance between the tip of handle J and the centroid of ploughshare O; b_2, horizontal projected distance between middle of the yoke B and the centroid of ploughshare O; c_1, the horizontal distance between the centre of the yoke and the position of the right draught animal; c_2, the horizontal distance between the centre of the yoke and the position of the left draught animal; d, the depth where forces assumed to be concentrated on ploughshare; e, depth where forces assumed to be concentrated on side-wings; F_O, operator force; Q, junction point of the beam and the handle assembly; β_1 and β_2, angle of the beam, at lower position from ground level; γ, angle of side-wing from horizontal; θ_1, rake angle (angle of attack); θ_2, inclination angle of the handle; λ, angle of the applied force by the operator F_O from horizontal; σ, tail angle, angle between the side-wing plane surface and the handle; ϕ, angle between handle (along with its ploughshare) and the leather strap; φ, angle between side-wing plane surface and the leather strip and Ψ, angle between the side-wings.

where M_O is moment acting on centroid of the ploughshare in N m; $\vec{r}_{JO}$ is position vector from point 'J', point of operator's force application, to the ploughshare centroid 'O' in m; $\vec{r}_{UO}$ is position vector from point 'U', point of force application by the left draught animal, to the ploughshare centroid 'O' in m; $\vec{r}_{VO}$ is position vector from point 'V', point of force application by the right draught animal, to the ploughshare centroid 'O' in m; $\vec{r}_{WO}$ is position vector from point 'W', centroid of the left side-wing where interfacial forces assumed to be concentrated, to the ploughshare centroid 'O' in m; $\vec{r}_{W'O}$ is position vector from point 'W′', centroid of the right side-wing where interfacial forces assumed to be concentrated, to the ploughshare centroid 'O' in m.

$$\begin{aligned}M_O = \{&-F_{t1}[b_2 \sin \alpha_1 - (a_2 + d) \cos \alpha_1]\\ &- F_{t2}[b_2 \sin \alpha_2 - (a_2 + d) \cos \alpha_2]\\ &+ F_O[(a_1 + d) \cos \lambda - b_1 \sin \lambda]\\ &- 2K[g \cos \gamma + (d - e) \sin \gamma]\\ &+2F_2[g \sin \gamma - (d - e) \cos \gamma]\},\end{aligned} \qquad (12)$$

where a_1 is height of the tip of handle, where the operator apply force 'J', from horizontal in m; a_2 is height of the yoke from horizontal in m; b_1 is horizontal projected distance between the tip of handle 'J' and centroid of ploughshare 'O' in m; b_2 is horizontal projected distance between middle of yoke 'B' and centroid of the ploughshare 'O' in m; d is the depth where forces assumed to be concentrated on the ploughshare 'O' in m; e is the depth where forces assumed to be concentrated on side-wings in m; g is horizontal projected distance between centroid of the ploughshare 'O' and of the side-wing in m.

3.5.1. *Pulling force between the yoke and the beam*

The pulling force F_b on the beam in N can be derived directly from the yoke input forces from force balance. At equilibrium, the sum of forces between the yoke and the beam in X and Z directions equals zero (Figs. 2 and 4). The transferred pulling force from the two draught animals to the beam F_b and its angle of action β_2 can be given by Eqs. (13) and (14), respectively, as follow:

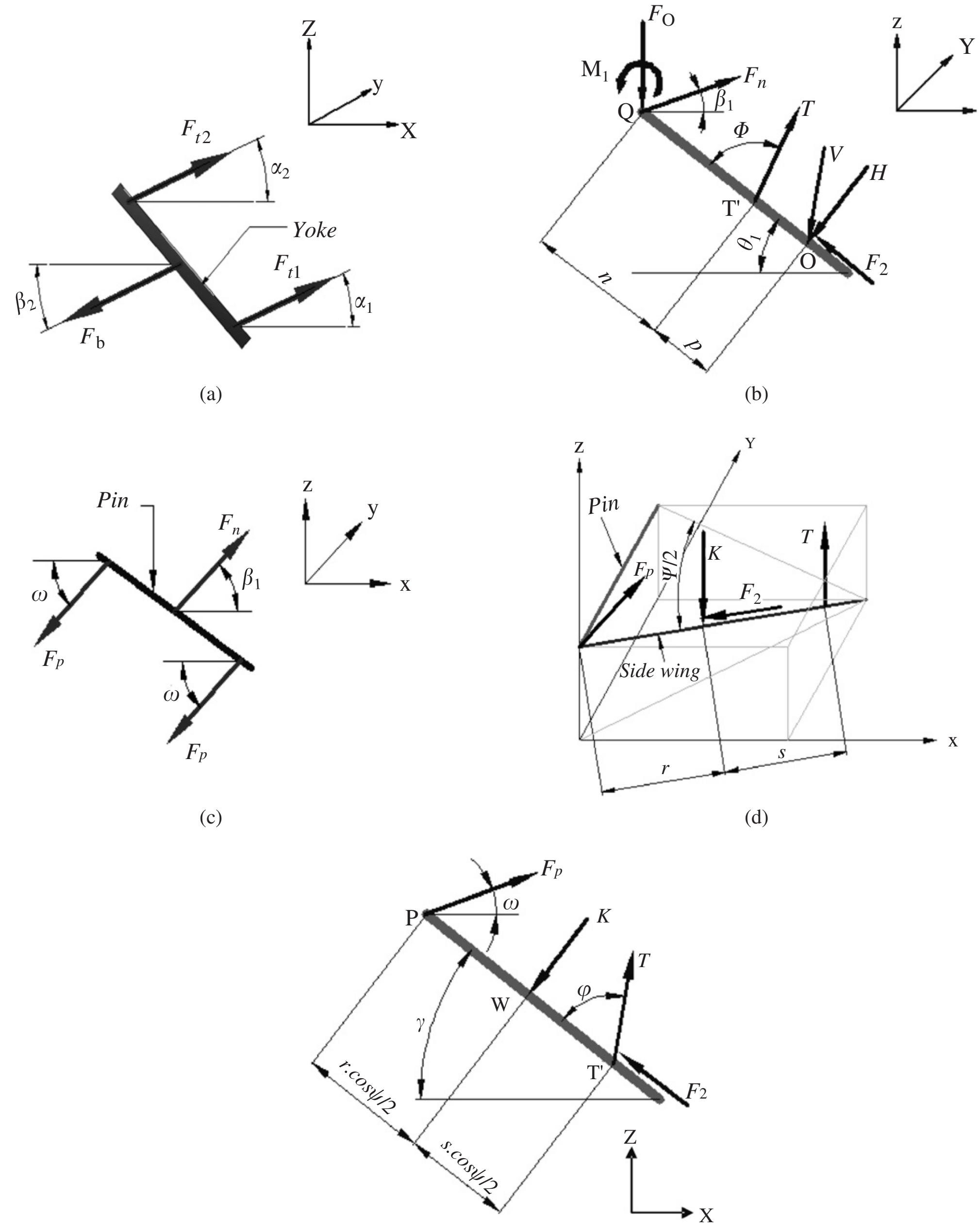
$$F_b = \frac{F_{t1} \cos \alpha_1 + F_{t2} \cos \alpha_2}{\cos \beta_2} = \frac{F_{t1} \sin \alpha_1 + F_{t2} \sin \alpha_2}{\sin \beta_2}, \qquad (13)$$

$$\beta_2 = \tan^{-1}\left\{\frac{F_{t1} \sin \alpha_1 + F_{t2} \sin \alpha_2}{F_{t1} \cos \alpha_1 + F_{t2} \cos \alpha_2}\right\}, \qquad (14)$$

where β_2 is angle of the beam at the upper position from ground level in degree.

3.5.2. *Pulling force between the beam and other components excluding the yoke*

From Figs. 2 and 4, at equilibrium condition, the normal forces acting on the ploughshare H in N and of each side-wing K in N are expressed by two equations similar to the



(a) (b) (c) (d) (e)

Fig. 4 – Pulling force acting on different parts of the Ethiopian *ard* plough 'maresha': (a) force transfer between the yoke and the beam; (b) forces acting on ploughshare; (c) force acting on wooden pin; (d) force acting on side-wing in two-dimensional view (X–Z plane); (e) force acting on side-wing in three-dimensional view F_b, pulling force acting on the beam, top position, N; F_n, pulling force acting at the junction of the beam and the handle; F_O, operator force; F_p, pulling force transferred from the wooden pin to the side-wing; F_1 and F_2, tangential interfacial force of ploughshare and each side-wing, respectively; H, normal interfacial force of ploughshare; K, normal interfacial force of each side-wing; M_1, moment effect of force applied by the operator and transferred to the upper tip of ploughshare; n, the distance between the point of intersection (of the beam and the handle) and the position of metal loops with leather strap attachment on the ploughshare; *p*, the distance between the position of metal loops with leather strap attachment on ploughshare and the assumed point where soil resistance is to be concentrated on the ploughshare; Q, junction point of the beam and the handle assembly; *r*, the distance between the position of pin connection of the side-wing and the point where soil resistance is assumed to be concentrated on the side-wing surface; s, the distance between the position of leather strap attachment (including metal loops) on the side-wing and the point where soil resistance is assumed to be concentrated on the side-wing (W for left-side wing, and W′ for right side-wing); T, tension on leather strap or rope; V, gravitational force of the implement (excluding weight of yoke and about 1/3 of the beam); α_1 and α_2, pulling angle by draught animal 1 (right) and draught animal 2 (left); β_1 and β_2, angle of the beam, at lower position from ground level; γ, angle of side-wing from horizontal; θ_1, rake angle (angle of attack); ϕ, angle between the handle (along with its ploughshare) and the leather strap; φ, angle between side wing plane surface and the leather strip; Ψ, angle between the side-wings; ω, angle of F_P acting on the wooden pin from horizontal.

Eqs. (9) and (10), respectively. However, the pulling force by the two draught oxen F_{t1} and F_{t2} is replaced by pulling force acting on beam, top position F_b. The angle of action β_2 becomes:

$$\beta_2 = \tan^{-1}\left\{\frac{H\cos\theta_1 + F_O\sin\lambda - F_1\sin\theta_1 - 2F_2\sin\gamma + 2K\cos\gamma + V}{H\sin\theta_1 - F_O\cos\lambda + F_1\cos\theta_1 + 2F_2\cos\gamma + 2K\sin\gamma}\right\}. \tag{15}$$

Moment balance

Moment equals zero at the point ‘O’ where the forces on the ploughshare are assumed to be concentrated, and thus the coupling effect of H and F_1 vanishs. Accordingly, the coupling effect M_O [Eq. (16)] on the ploughshare resulting from the pulling force F_b, the operator input force, and the normal and tangential interfacial forces of both side-wings can be deduced as follows:

$$\begin{aligned}\sum M = (\vec{r}_{BO}\times\vec{F}_b) + (\vec{r}_{JO}\times\vec{F}_O) + (\vec{r}_{WO}\times\vec{K})\\ + (\vec{r}_{WO}\times\vec{F}_2) + (\vec{r}_{W'O}\times\vec{K})\\ + (\vec{r}_{W'O}\times\vec{F}_2) + M_O = 0,\end{aligned} \tag{16}$$

$$\begin{aligned}M_O = \{&F_b[b_2\sin\beta_2 - (a_2+d)\cos\beta_2]\\ &+ F_O[b_1\sin\lambda + (a_1+d)\cos\lambda]\\ &-2K[g\cos\gamma + (d-e)\sin\gamma]\}\\ &+ 2F_2[g\sin\gamma - (d-e)\cos\gamma],\end{aligned} \tag{17}$$

where $\vec{r}_{BO}$ is position vector from point ‘B’ at the top tip of the beam to the ploughshare centroid ‘O’ in m.

Due to the basic design of the plough, the part of the beam the share is curved upwards. This makes the line of pull coincide with the line of the resultant pulling force, which reduces draught requirement.

3.5.3. *Pulling force on the ploughshare*

Force balance

From Fig. 4, the tension T on the leather strap at equilibrium, considering maximum operator input force acting vertical, can be given as follows:

$$T = \frac{H(\cos\theta_1 - \tan\beta_1\sin\theta_1) - F_1(\sin\theta_1 + \tan\beta_1\cos\theta_1) + V + F_O}{[\sin(180-\theta_1-\varphi) - \tan\beta_1\cos(180-\theta_1-\varphi)]}, \tag{18}$$

where T is tension on leather strap or rope in N; β_1 is angle of beam at lower position from ground level in degree; φ is angle between side-wing plane surface and the leather strip in degree.

Moment balance

The moment balance at point ‘O’ (Fig. 4), considering (x, y, z) at this point to be (0, 0, 0) is given by

$$\sum M_O = (\vec{r}_{QO}\times\vec{F}_n) + (\vec{r}_{T'O}\times\vec{T}) + M_1 = 0, \tag{19}$$

where F_n is pulling force acting at the junction of the beam and the handle in N; M_1 is moment effect of force applied by the operator and transferred to the upper tip of the ploughshare in N m; $\vec{r}_{T'O}$ is position vector from point ‘T′’, point of application of tension by the leather strap/rope on the ploughshare, to the ploughshare centroid ‘O’ in m; $\vec{r}_{QO}$ is position vector from point ‘Q’ (junction point of the beam and the handle assembly) to the ploughshare centroid ‘O’ in m.

After matrix formulation, the tension on the leather strap is given as follows:

$$T = \frac{1}{p}\left\{\frac{F_n(n+p)[\cos\theta_1\sin\beta_1 + \sin\theta_1\cos\beta_1] - M_1}{[(\cos\theta_1\sin(180-\theta_1-\phi) + \sin\theta_1\cos(180-\theta_1-\phi)]}\right\}, \tag{20}$$

where n is the distance between the point of intersection (of the beam and the handle) and the position of metal loops with leather strap attachment on the ploughshare in m; p is the distance between the position of metal loops with leather strap attachment on the ploughshare and the assumed point where soil resistance is to be concentrated on the ploughshare in m.

3.5.4. *Pulling force at wooden pin*

Based on the assumption that the side-wings are symmetrical in shape and face moving soil of the same weight, physical and mechanical properties, the draught force transferred from the beam to both wings has the same magnitude. Neglecting the effect of offset dimension between the force acting on pin and at the junction point of the beam and the handle, at equilibrium condition, the angle of pulling ω and the pulling force on the pin F_P (Fig. 4) is given as follows:

$$\omega = \beta_1 \text{ and } F_p = \tfrac{1}{2}F_n, \tag{21}$$

where ω is angle of force F_P acting on the wooden pin from horizontal in degree; F_P is pulling force transferred from the wooden pin to the side-wing in N.

3.5.5. *Pulling force at side wings*

Force balance

From the force balance, the angle of pulling (Fig. 4) on the side-wing ω is given by Eq. (22). This angle is equal and opposite of the angle of pulling on the pin.

$$\omega = \tan^{-1}\left\{\frac{K\cos\gamma - F_2\sin\gamma - T\sin(180-\gamma-\varphi)}{K\sin\gamma + F_2\cos\gamma - T\cos(180-\gamma-\varphi)}\right\}. \tag{22}$$

Moment equation

Taking the moment at point ‘W’ [Fig. 4(d)], and considering (x, y, z) at this point to be (0, 0, 0), the pulling force F_P acting on the each side wing is given by Eq. (24)

$$\sum M_W = (\vec{r}_{PW}\times\vec{F}_P) + (\vec{r}_{T'W}\times\vec{T}). \tag{23}$$

where M_W is moment about centroid of the left side-wing in N m; $\vec{r}_{PW}$ position vector from point ‘P’ (point of application of pulling force on the side-wing) to the centroid of the left side-wing ‘W’ in m; $\vec{r}_{T'W}$ is position vector from point ‘T′’ (point of application of tension by the leather strap on the side-wing) to the centroid of left side-wing ‘W’ in m.

$$F_P = \frac{sT}{r}\left\{\frac{\cos\gamma\cos\frac{\psi}{2}\sin(180-\gamma-\varphi) + \sin\gamma\cos(180-\gamma-\varphi)}{\cos\gamma\cos\frac{\psi}{2}\sin\omega + \sin\gamma\cos\omega}\right\}, \tag{24}$$

where r is the distance between the position of pin connection of the side-wing and the point where soil resistance is assumed to be concentrated on the side-wing surface in m; s is distance between the position of leather strap attachment (including metal loops) on the side-wing and the point where soil resistance is assumed to be concentrated on the side-wing in m; Ψ is angle between two side-wings in degree.

Considering the assumptions mentioned in 3.1, Eq. (9) can be re-written as follows:

$$H = \left\{\frac{2F_t \cos\alpha + F_O \cos\lambda - F_1 \cos\theta}{\sin\theta}\right\} = \left\{\frac{2F_t \sin\alpha - F_O \sin\lambda + F_1 \sin\theta - V}{\cos\theta}\right\}. \quad (25)$$

Accordingly, from Eqs. (1)–(5) and (8), the normal and tangential interfacial forces of the structure at the ploughshare can be written in terms of animals pulling force, operator input force, and implement weight by the following two equations, respectively:

$$F_1 = \frac{2F_t(\cos\alpha - \tan\theta \sin\alpha) + F_O(\cos\lambda + \tan\theta\sin\lambda) + V\tan\theta}{(\tan\theta\sin\theta + \cos\theta)}, \quad (26)$$

$$H = \frac{2F_t(\tan\theta\cos\alpha + \sin\alpha) + F_O(\tan\theta\cos\lambda - \sin\lambda) - V}{(\cos\theta + \tan\theta\sin\theta)}. \quad (27)$$

From Eqs. (26) and (27) the draught and vertical forces can be calculated. For instance, for the case, when the effects of gravitational weight of the implement and the operator's input force were not considered, these formulae are written as:

$$F_x = F_1 \cos\theta + H\sin\theta, \quad (28)$$

$$F_z = H\cos\theta - F_1\sin\theta, \quad (29)$$

where F_x is draught force in N; F_z is vertical force in N.

Similarly, the force acting on the beam F_b and its angle of action β_2 are given by the following two equations, respectively:

$$F_b = 2F_t = \frac{H\sin\theta - F_O\cos\lambda + F_1\cos\theta}{\cos\beta_2} = \frac{H\cos\theta + F_O\sin\lambda - F_1\sin\theta + V}{\sin\beta_2}, \quad (30)$$

$$\beta_2 = \tan^{-1}\frac{H\cos\theta + F_O\sin\lambda - F_1\sin\theta + V}{H\sin\theta - F_O\cos\lambda + F_1\cos\theta}. \quad (31)$$

From Eqs. (13) and (14)

$$\beta_2 = \alpha \text{ and } F_b = 2F_t. \quad (32)$$

The force F_b can be measured or derived directly from interfacial force, implement weight and operator input force.

Considering the above approach, for stable operation, the sum of vertical downward forces has to be greater or equal to the sum of vertical upward forces, i.e. $V + 2K_Z + H_Z + F_O \geqslant 2F_{tZ} + 2F_{1Z} + 2F_{2Z}$. For high-resistive soils, the operator should apply a force F_O on the handle to assist the plough to penetrate soil during tillage process. The alignment of the line of pull with the line of pulling of the resultant force acting on the plough body could benefit in minimising impact of bending moment. Such an arrangement decreases the bending moment on the beam so that the beam is subjected mainly to tension and hence a lighter beam can be used.

4. Results

4.1. *Sensitivity of draught and vertical capacities of the implement with pulling angle*

The sensitivity analysis is required to investigate and visualise the effect of the dimensional parameters and forces acting on the structure of the *ard* plough. Here, the word 'force' is substituted by 'capacity' to indicate structure output forces that can be provided at the ploughshare. The sensitivity analysis was conducted for the draught F_x, vertical F_z, normal interfacial F_1 and tangential H capacities provided on the ploughshare. This analysis was based on calculations made using Eqs. (26)–(29) and the following assumed parameters:

(1) rake angle $\theta = 19^\circ$;
(2) animal pulling force $F_t = 600\,\text{N}$ at $\beta_2 = \alpha = 10^\circ$–$60^\circ$;
(3) implement gravitational weight $V = 150\,\text{N}$; and
(4) operator force $F_O = 150\,\text{N}$ at $\lambda = 60^\circ$.

From the sensitivity analysis outputs given in Table 1, it can be concluded that the weight of the implement affected the vertical capacity, but not the horizontal capacity. The operator's input force affected both the vertical and horizontal capacities. However, both the weight of the implement and operator's input force affected the tangential and normal interfacial capacities. The tangential interfacial capacity of the implement was higher than the normal interfacial capacity at lower pulling angles. The horizontal capacity decreased (draught requirement increased) with the pulling angle, whereas the downwards vertical capacity increased (downwards vertical force requirement decreased), which will introduce the problem of keeping the ploughshare in the soil. This increases the draught requirement and decreases the downwards force of tillage process. Draught requirement is smaller at smaller pulling angle β. In fact, this angle is used in practice for depth regulation. For primary tillage, it is set small to reduce depth so that the animal can pull the plough. For secondary tillage, this angle is usually increased to increase depth of tillage. The operator input force decreased the upward vertical force to keep the ploughshare at the proper tillage depth. In general, the analysis indicates that the maximum draught capacity can be provided at small pulling angles. This conclusion is inline with what was reported by Gebresenbet *et al.* (1997) that the angle of pull for the Ethiopian traditional plough varies from 10° to 20°.

4.2. *Validation of sensitivity of draught and vertical capacities using the finite element method*

In order to validate the calculation [using Eqs. (26)–(29)] of draught F_x and vertical F_z capacities provided on the ploughshare, a 3-dimensional (D) FE analysis was performed with ABAQUS FE software.

The 'Maresha' frame model was developed using a 3D discrete rigid wire, planar model (Fig. 5). Each component (part) created was oriented in its own coordinate system and was independent of the other parts in the model. Using the

Table 1 – Draught, vertical, tangential interfacial and normal interfacial capacities of the plough structure at ploughshare versus pulling angle $\beta_2 = \alpha$

		Angle of pull α, degree										
		10	15	20	25	30	35	40	45	50	55	60
Weight of implement and operator's input force are considered	Draught, N	1256	1233	1201	1160	1111	1054	989	917	839	754	664
	Vertical, N	−69	33	134	232	325	414	498	575	646	709	765
	Tangential, N	1210	1155	1092	1022	945	862	773	680	583	482	379
	Normal, N	343	433	518	597	669	735	793	842	884	916	940
Excluding only the effect of implement weight	Draught, N	1256	1233	1201	1160	1111	1054	989	917	839	754	664
	Vertical, N	80	183	284	382	475	564	648	725	796	859	915
	Tangential, N	1161	1106	1043	973	896	813	724	631	534	433	330
	Normal, N	485	575	660	739	811	877	934	984	1026	1058	1082
Excluding only the effect of operator input force	Draught, N	1181	1158	1126	1085	1036	978	914	842	764	679	589
	Vertical, N	60	163	264	362	455	544	626	705	776	839	895
	Tangential, N	1097	1041	979	908	831	748	660	567	469	369	266
	Normal, N	442	532	617	695	768	833	891	941	982	1015	1038
Excluding the effect of operator input force and implement weight	Draught, N	1181	1158	1126	1085	1036	979	914	842	764	679	589
	Vertical, N	210	314	414	512	605	694	778	855	926	989	1045
	Tangential, N	1049	993	930	960	983	700	611	518	420	320	217
	Normal, N	584	674	758	837	910	975	1033	1083	1124	1157	1180

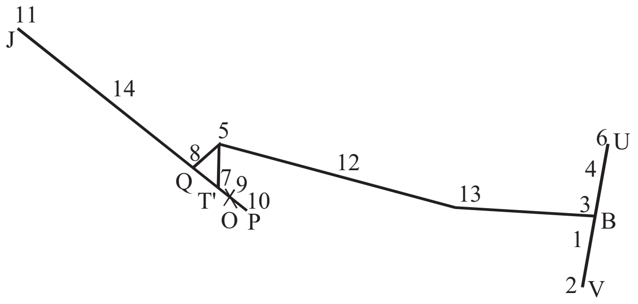


Fig. 5 – Finite element (FE) model of the structure of the Ethiopian *ard* plough 'maresha', showing the 14 nodal points on the yoke VU, beam BQ, handle JQ and ploughshare QP: O, centroid of ploughshare; T′, point of application of tension by the leather strap/rope on ploughshare.

assembly module available in ABAQUS software, the geometry of the entire plough was assembled by creating instances of parts, and then positioning the instances relative to each other in a global coordinate system. ABAQUS uses two stages meshing, *i.e.* seeding the edges of the part instance based on the desired element size or number of elements, and then meshing the part instance. In total, 14 nodes and 14 elements, with element type of linear 3D rigid beam were considered.

In the FEM model, the boundary conditions were applied only on the ploughshare centroid 'O', where the draught and vertical forces were assumed to concentrate. The centroid of the ploughshare 'O' was constrained to prevent displacements and rotations in all directions. Identical animal pulling force F_t of 600 N (at $\beta_2 = \alpha = 10°–60°$) and operator's force F_O of 150 N (at $\lambda = 60°$) to those forces considered during the traditional force analysis (sensitivity analysis) were applied for the FE analysis. Thus, concentrated forces were applied at three positions, accounting for forces exerted by the two draught animals and that of the operator. After running the FE analysis, the reaction capacities (draught and vertical capacities) were determined at the ploughshare centroid 'O'. These capacities could also be translated into normal and tangential interfacial capacities using traditional force balance calculation as a function of the rake angle θ.

The comparison of traditional force analysis calculation and FE model of draught F_x and vertical F_z capacities is given in (Table 2 and Fig. 6). This comparison showed small computational errors of less than 3% and 5% for draught and vertical capacities, respectively, at pulling angles $\beta_2 = \alpha$ smaller than 30°. Even for larger pulling angles, these errors were still small (Table 2), proving that the traditional force analysis discussed in this study provides accurate estimation of F_x and F_z. This encourages using the force analysis of different plough components to establish further conclusions to optimise the structure of the Ethiopian *ard* plough.

5. Conclusions

Mathematical descriptions based on traditional calculations were developed, considering the static analysis of the implement structure of the *ard* plough at equilibrium condition. The traditional calculations were then verified by means of finite element (FE) analysis and ABAQUS software, with error less than 3% (draught capacity) and 5% (vertical capacity) for working rake angles of ⩽30°. Based on the existing structure and the parametric relations developed, the

Table 2 – Comparison of finite element (FE) and traditional calculations of draught and vertical capacities of the plough structure at plough share for different pulling angle $\beta_2 = \alpha$ (effect of implement weight is excluded)

Pulling angle α, degree	Finite element calculation		Traditional calculation		Error of draught capacity, %	Error of vertical capacity, %
	Draught capacity F_x, N	Vertical capacity F_y, N	Draught capacity F_x, N	Vertical capacity F_z, N		
10	1257	78	1256	80	−1	2
15	1234	181	1233	183	−1	3
20	1203	281	1201	284	−2	4
25	1163	377	1160	382	−3	5
30	1114	470	1111	475	−3	5
35	1058	558	1054	564	−4	6
40	994	641	989	648	−5	6
45	924	719	917	725	−6	6
50	846	789	839	796	−8	6
55	763	853	754	859	−9	6
60	675	909	664	915	−11	6

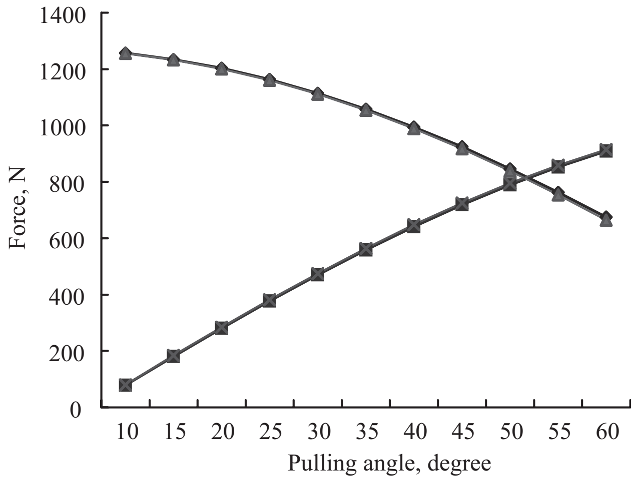


Fig. 6 – Matching between finite element (FE) model and traditional force analysis calculations of capacities provided at the centroid of the ploughshare: ▲, traditional draught capacity ×, traditional vertical capacity; ♦, FE draught capacity; ■, FE vertical capacity.

following general design considerations and guidelines are foreseen:

(1) For stable operation, the relation vertical forces should be in equilibrium. For high resistive soil, the operator needs to apply a force on the handle to assist the plough to penetrate soil during tillage process.
(2) The alignment of the line of pull with the line of pulling of the resultant force acting on the plough body could benefit in minimising impact of bending moment. Such an arrangement decreases the bending moment on the beam so that the beam is subjected mainly to tension and therefore a lighter beam can be used.
(3) To minimise contacts between the beam and the soil moving along the ploughshare, which increases the draught requirement, the part of the beam nearest to the ground is designed curved. This helps the straight part of the beam to coincide with the line of pulling, a case for which the line of pull coincides with the line of the resultant pulling force.
(4) The design considered lowering the beam angle to attain minimum draught force requirement so that to increase the draught capacity and thus the efficiency of draught animals.
(5) The design considered the effect of vibrating of the plough in lateral direction (perpendicular to the travel direction) by the operator to assist soil penetration and reduce the draught requirement. Introducing lateral slot at the juncture of the beam and the handle assembly could lead to comfort operation by the farmer.

The following recommendation can be taken into consideration for further research and improvements of the Ethiopian *ard* Plough:

(1) The design is to consider the performance in terms of field capacity. The available ploughshare forms a V shape furrow and un-ploughed land is left between parallel neighbouring furrows. Thus, several extra cross-ploughings are required depending on the type of seed to be sown in order to till the whole surface. However, area of interaction between the soil and plough (share and side-wing) should decrease to minimise the friction forces and draught requirement.
(2) The design is to consider the safety mechanism in case when there are strong roots or stones. This is because, the animals are forced to stop and move back and the farmer has to pull the plough out of the engagement with the object.

(3) The design takes into account the case of using different animal size/height. Here, the design should allow change of angle of pull to maintain good penetration and stability.

Acknowledgements

The authors acknowledge the financial support of the Flemish Interuniversity Council (VLIR) under the framework of the project entitled 'VLIR & Mekelle University Inter University Partnership Programme, 2003–2013; subproject Farm Technology'.

REFERENCES

ARDU & MAS (1980). Progress Report No. 5. Agricultural Engineering Section. ARDU Publication No. 14. Arsi Rural Development Unit and Ministry of Agriculture and Settlement, Addis Ababa, Ethiopia

Asefa T A A; Tanner D G; Melesse T; Girma K (1997). On-farm evaluation of an animal-drawn implement developed in Ethiopia for row placement of wheat seed and Basal fertilizer. African Crop Science Journal, **5**(4), 359–369

Astatke A; Matthews M D (1982). Progress report of the cultivation trials at Debrezeit and Debreberhan by International Livestock Centre for Africa. Addis Ababa, Ethiopia

Astatke A; Matthews M D (1984). Cultivation research in the Highlands Programme of International Livestock Centre for Africa. Addis Ababa, Ethiopia

Astatke A; Mohammed-Saleem M A (1992). Experience with the use of a single ox for cultivation in the Ethiopian Highlands. Animal Traction Network for Eastern and Southern Africa Workshop held 18–23 January 1992, Lusaka, Zambia

Berhane T (1979). Study on the of ox-drawn equipment for the production of cowpea, maize, cotton and groundnut under irrigation in the middle Awash valley- Melka Werer. Agricultural Engineering Bulletin No. 1. Institute of Agricultural Research, Addis Ababa, Ethiopia

CADU (1969). Progress Report No. 1. Implement Research Section. Publication No. 32. Chilalo Agricultural Development Unit, Addis Ababa, Ethiopia

CADU (1970). Progress Report No.2. Implement Research Section. Publication No. 52. Chilalo Agricultural Development Unit, Addis Ababa, Ethiopia

CADU (1971). Progress Report No. 3. Implement Research Section. Publication No. 79. Chilalo Agricultural Development Unit, Addis Ababa, Ethiopia

Frazer R M (1984). Works and days. In: The Poems of Hesiod, pp 91–142. University of Oklahoma Press, Norman, OK

Gebresenbet G (1995). Optimization of animal drawn tillage implements: part I, performances of a curved tillage implement. Journal of Agricultural Engineering Research, **62,** 173–184

Gebresenbet G; Kaumbutho P G (1997). Comparative analysis of the field performances of a reversible animal drawn prototype and conventional mouldboard ploughs pulled by a single donkey. Soil and Tillage Research, **40,** 169–183

Gebresebet G; Zerbini E; Astatke A; Kaumbutho P (1997). Optimization of animal drawn tillage implements: part 2, development of a reversible animal drawn plough and ridger. Soil and Tillage Research, **67,** 299–310

Gill W R; Vanden Berg G E (1968). Soil Dynamics in Tillage and Traction. United State Department of Agriculture, Handbook No. 316. US Govt. Printing Press, Washington, DC

Goe MR (1987). Animal traction on small holder farms in the Ethiopian Highlands. PhD Dissertation. Department of Animal Science, Cornell University, Ithaca, New York, USA

Gryseels G; Astatke A; Anderson F M; Asamenew G (1984). The use of single ox for crop cultivation in Ethiopia. International Livestock Center for Africa Bulletin, Vol. 18, pp 20–25. Addis Ababa, Ethiopia

Neményi M; Mesterházi P Á; Milics G (2006). An application of tillage force mapping as a Cropping Management Tool. Biosystems Engineering, **94**(3), 351–357

Pathak B S (1988). Survey of agricultural implements and crop production techniques. Research Report 1/1988, Institute of Agricultural Research, Addis Ababa, Ethiopia

Pingali P; Bigot Y; Binswanger H (1987). Agricultural Mechanization and the Evolution of Framing Systems in Sub-Saharan Africa. The John Hopkins University Press, Baltimore

Sahu R K; Raheman H (2006). Draught prediction of agricultural implements using reference tillage tools in sandy clay loam soil. Biosystems Engineering, **94**(2), 275–284

Schmitz H (1991). Animal Traction in Rainfed Agriculture in Africa and South America, German Technical Cooperation (GTZ), Community Development Library, Berlin, Germany, P. 311. (http://sleekfreak.ath.cx:81/3wdev/CD3WD/APPRTECH/G01ANE/B39_9.HTM)

Starkey P (1995). Animal traction in south Africa: Empowering rural communities. South African Network of Animal Traction (SANAT), South Africa. The Development Bank of Southern Africa and the South African Network of Animal Traction (DBSA-SANAT) publication. ISBN 1–874878-67–6, http://www.atnesa.org/sanat/animaltractionZAbook-Empowering.htm

Temesgen M (1999). Animal-drawn implements for improved cultivation in Ethiopia: participatory development and testing. In: Kaumbutho P G; Pearson R A; Simalenga T E (Eds). Proceedings of the Workshop of the Animal Traction Network for East and Southern Africa (ATNESA), 20–24 September, Mpumalanga, South Africa, 344p (ISBN 0507146104).

Temesgen M; Georgis K; Goda S; Abebe H (2001). Development and Evaluation of tillage implements for maize production in the dryland areas of Ethiopia. Seventh Eastern and Southern Africa Regional Maize Conference, 11–15 February, pp. 308–312

UNDP (2000). Plowing for progress: Ethiopia. Sharing Innovation Experience, Science and Technology, **1**, 209-217. ⟨http://tcdc.undp.org⟩

World Bank (1987). Agricultural Mechanization: Issues and Options. A World Bank Policy Study. World Bank, Washington, DC