Mechanics of a simple tillage tool

- Tillage tool in the shape of an inclined blade traveling through soil

Soehne (1956) concluded that soil-metal friction, shear failure, acceleration force for each block of soil, and cutting resistance act on the tillage tool as it moves through the soil. Figure 8.40a shows a free body diagram of a segment of soil as it reacts to the advancing tool. Forces CA_1 and μF_1 are due to soil shear and are those present at the instant incipient shear failure occurs. Forces due to soil-metal friction ($\mu' F_o$) and acceleration (B) are also present. The soil cutting resistance, defined as the cutting force per unit length of the cutting edge, is given by k. The forces acting on the tillage tool are shown in Figure 8.40b. These forces are soil cutting resistance (kb) obtained by multiplying the unit cutting resistance (k) by the cutting width (b); soil normal reaction (F_o); soil frictional reaction ($\mu' F_o$); and the tool support forces (V) and draft (D).

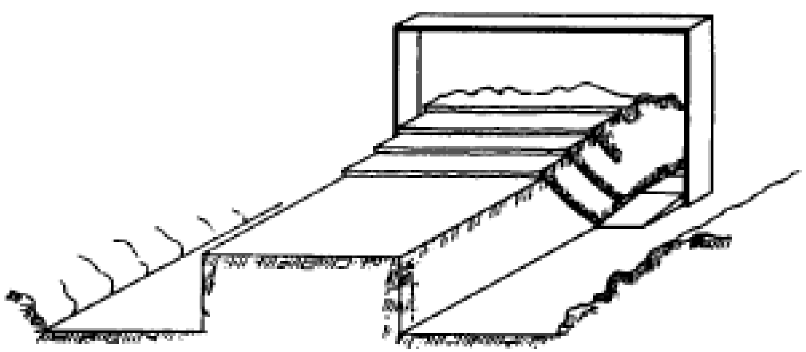


Figure 8.39 – An inclined plane tillage tool (Soehne, 1956, cited in Gill and Vandenberg, 1968).

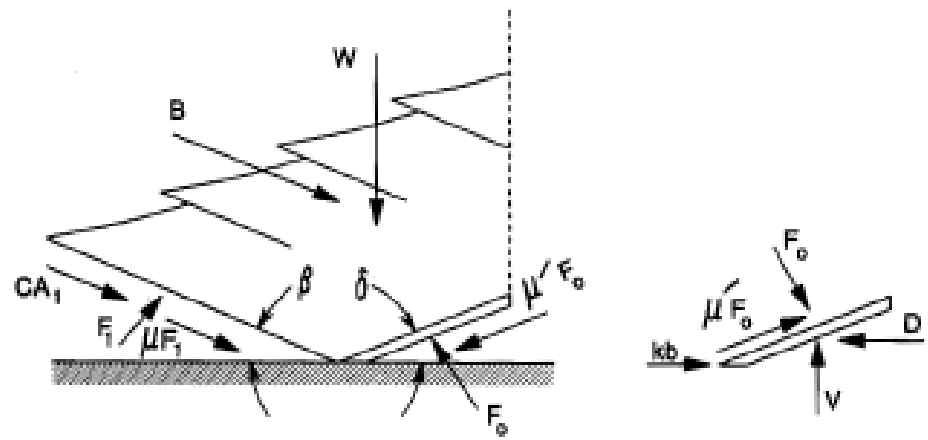
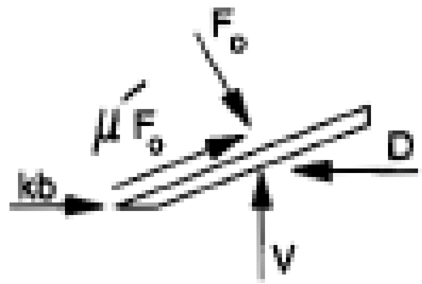


Figure 8.40 – Soil and tool reaction forces (Soehne, 1956, cited in Gill and Vandenberg, 1968).

Mechanics of a simple tillage tool



Summing forces in the horizontal direction and equating them to zero the following equation is obtained:

$$D = F_o \sin\delta + \mu' F_o \cos\delta + kb \qquad (8.23)$$

where D = horizontal draft force

F_o = normal load on the inclined plane

δ = tool lift angle

μ' = coefficient of soil-metal friction

k = soil cutting resistance

The specific draft force (D*) is defined as:

$$D^* = D - kb$$

or

$$D^* = F_o \sin\delta + F_o \mu' \cos\delta \qquad (8.24)$$

Summing all the vertical components of forces acting on the soil mass and equating them to zero for equilibrium results in the following equation:

$$W - F_o(\cos\delta - \mu' \sin\delta) - F_1(\cos\beta - \mu\sin\beta) + (CA_1 + B)\sin\beta = 0$$

where W = soil weight, N

μ = coefficient of internal soil friction, no units

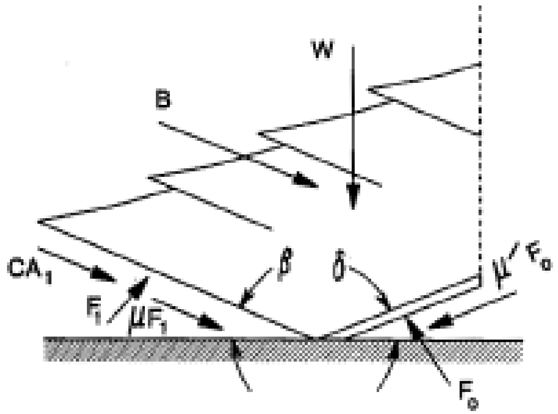
F_1 = normal force on the forward failure surface, N

β = angle of the forward failure surface, rad

C = soil cohesion, Pa

A_1 = area of forward shear failure surface, m^2

B = soil acceleration force, N



The horizontal forces on the soil segment can be summed and placed in equilibrium from the relations shown in Figure 8.40 to give:

$$F_o(\sin\delta + \mu' \cos\delta) - F_1(\sin\beta + \mu\cos\beta) - (CA_1 + B)\cos\beta = 0 \qquad (8.26)$$

Equation 8.25 can be used to solve for F_o. Substituting F_o in Equation 8.26 to solve for F_1 we get:

$$F_1 = \frac{D - (CA_1 + B)\cos\beta}{\sin\beta + \mu\cos\beta} \qquad (8.27)$$

$$D^* = F_o \sin\delta + F_o \mu' \cos\delta$$

$$F_1 = \frac{D - (CA_1 + B)\cos\beta}{\sin\beta + \mu\cos\beta}$$

$$W - F_o(\cos\delta - \mu'\sin\delta) - F_1(\cos\beta - \mu\sin\beta) + (CA_1 + B)\sin\beta = 0$$

$$W - \left(D^* \frac{\cos\delta - \mu'\sin\delta}{\sin\delta + \mu'\cos\delta}\right) - \left[D^* - (CA_1 - B)\cos\beta\right]\left(\frac{\cos\beta - \mu\sin\beta}{\sin\beta + \mu\cos\beta}\right) + (CA_1 + B)\sin\beta = 0$$

Expanding and rearranging terms gives:

$$D^*\left(\frac{\cos\delta - \mu'\sin\delta}{\sin\delta + \mu'\cos\delta} + \frac{\cos\beta - \mu\sin\beta}{s\sin\beta + \mu\cos\beta}\right) = W + \frac{CA_1 - B}{\sin\beta + \mu\cos\beta}$$

and by letting the geometric factor, z, be:

$$z = \left(\frac{\cos\delta - \mu'\sin\delta}{\sin\delta + \mu'\cos\delta} + \frac{\cos\beta - \mu\sin\beta}{\sin\beta + \mu\cos\beta}\right)$$

then

$$D^* = \frac{W}{z} + \frac{CA_1 + B}{z(\sin\beta + \mu\cos\beta)} \quad (8.28)$$

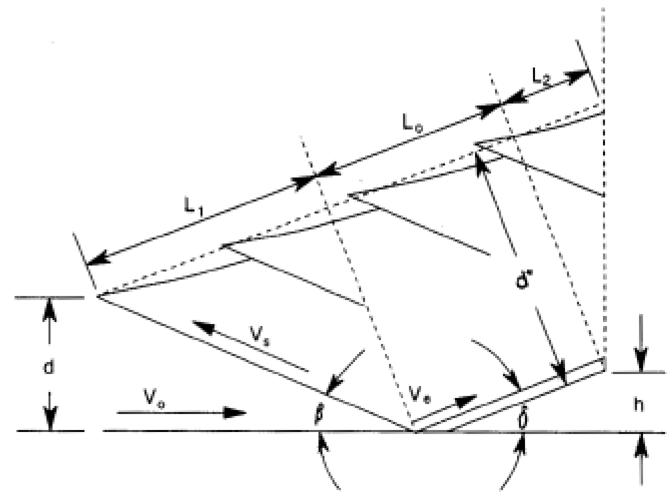


Figure 8.41 – Segment of soil on the inclined tillage plane tillage tool (Soehne, 1956, cited in Gill and Vandenberg, 1968).

$$\mu = \tan\phi$$

$$\beta = (90^\circ - \phi)/2$$

$$A_1 = \frac{bd}{\sin\beta}$$

$$B = m\frac{dv}{dt}$$

$$B = \frac{\gamma}{g} b d v_o^2 \frac{\sin\delta}{\sin(\delta + \beta)}$$

$$m = \frac{\gamma}{g} d b t_o v_o$$

where t_o = average time a particle of soil is engaged by the tool, s
v_o = tool velocity, m/s
g = acceleration due to gravity, m/s^2

$$W = \gamma b d^*\left(L_o + \frac{L_1 + L_2}{2}\right)$$

where γ = wet bulk density of soil, kg/m^3
b = tool width, m
$d^* = d\,\{[\sin(\delta+\beta)]/\sin\beta\}$, m
d = tool depth, m
$L_1 = d\,\{[\cos(\delta+\beta)]/\sin\beta\}$, m
$L_2 = d^*\tan\delta$, m

- Rowe and Barnes (1961)

$$D^{*} = \frac{W}{z} + \frac{CA_1 + B}{z(\sin\beta + \mu\cos\beta)} + \frac{C_a A_0}{z(\sin\beta + \mu\cos\beta)}$$

$$B = \frac{\gamma}{g} b d v_o^2 \frac{\sin\delta}{\sin(\delta + \beta)}$$

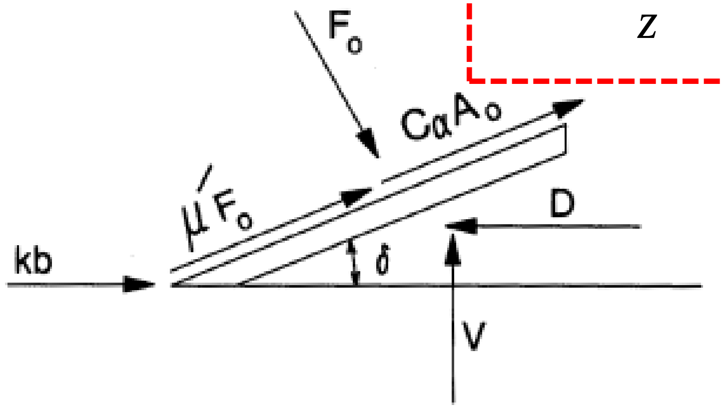
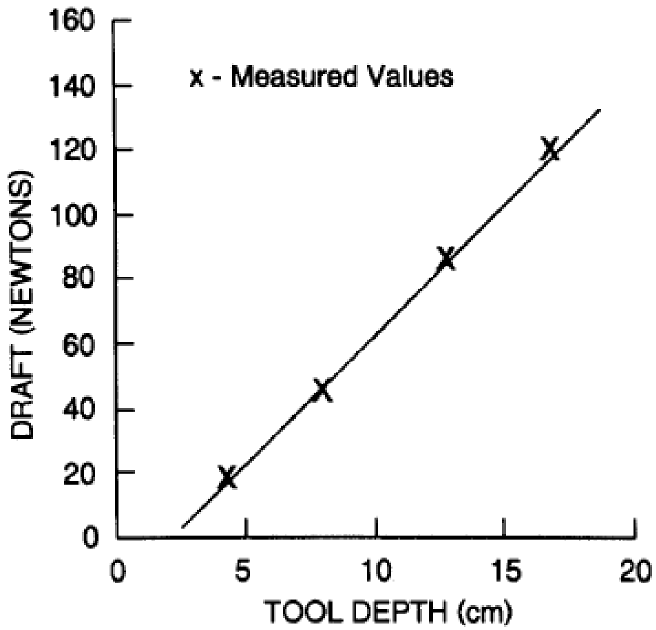
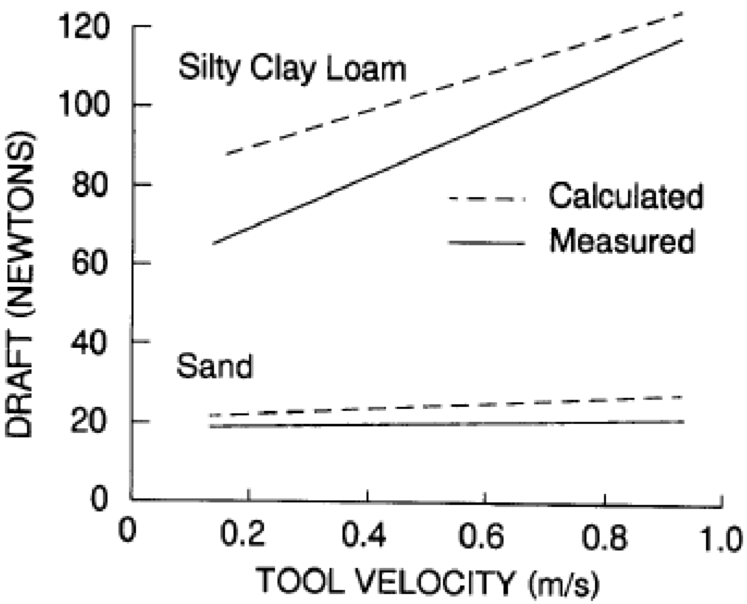


Figure 8.43 – A free body diagram of the tillage tool showing soil adhesion force (Rowe and Barnes, 1961, cited in Gill and Vandenberg, 1968).





Performance of tillage implements

- Performance is determined by draft, power requirement, and quality of the work
- Quality of work: for plow, degree of soil inversion an pulverization; for harrow, level of clod break-up

Moldboard plows

- Draft: component of tractor pull acting on the plow parallel to the line of travel
- Specific draft: draft divided by the cross-sectional area of the furrow
- Factors affecting specific draft: soil type and condition (e.g., soil moisture content, density), operating depth and speed

$$\frac{D_s}{D_r} = 0.83 + 0.00730S^2 \qquad (8.37)$$

where D_r = draft at the reference speed, 4.83 km/h

D_s = draft at speed S, in same units as D_r

S = speed, km/h

Hendrick (CRC, 1988) gave the following equations for the specific draft (in N/cm^2; S = speed in km/h) for different soil types:

Silty Clay (South Texas)	Specific draft $= 7 + 0.049\ S^2$
Decatur Clay Loam	Specific draft $= 6 + 0.053\ S^2$
Silt Clay (N. Illinois)	Specific draft $= 4.8 + 0.024\ S^2$
Davidson Loam	Specific draft $= 3 + 0.020\ S^2$
Sandy Silt	Specific draft $= 3 + 0.032\ S^2$
Sandy Loam	Specific draft $= 2.8 + 0.013\ S^2$
Sand	Specific draft $= 2 + 0.013\ S^2$

❑ Disk implements

- Draft, specific draft, power requirement, depth of penetration (determined by the implement weight and soil condition)

Disk plows

Disk plows. Hendrick (CRC, 1988) developed equations for the specific draft of a furrow slice for a 66 cm disk, 22° tilt and 45° disk angles. Specific draft (in N/cm^2; S = speed in km/h) is given by the following equations:

Decatur Clay	Specific draft $= 5.2 + 0.039\ S^2$
Davidson Loam	Specific draft $= 2.4 + 0.045\ S^2$

Disk harrows

Disk harrows. For disk harrows the draft (in N) is a function of mass M (in kg) for any speed as follows:

Clay	Draft = 14.7 M
Silt Loam	Draft = 11.7 M
Sandy Loam	Draft = 7.8 M

Disk tillers

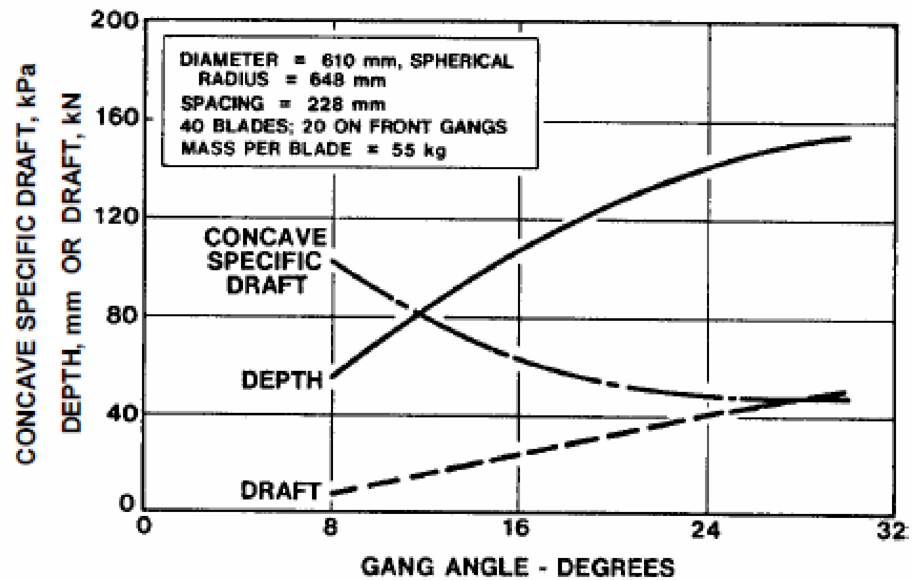


Figure 8.46 – Effect of gang angle on disk performance (Sommer et al., 1983).

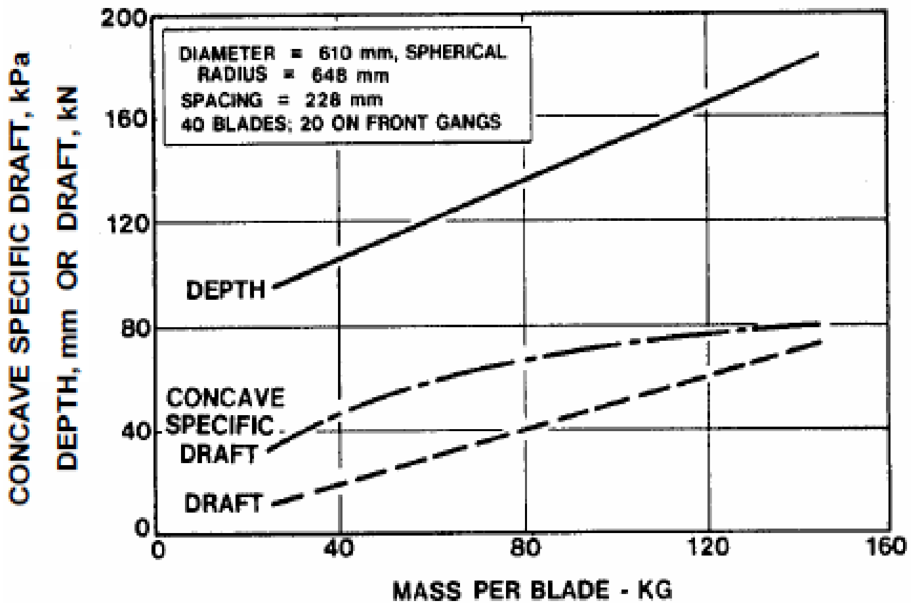


Figure 8.47 – Effect of mass per blade on disk performance (Sommer et al., 1983).

❑ Cultivators

- Sweep pitch: angle between bottom of the sweep and the horizontal

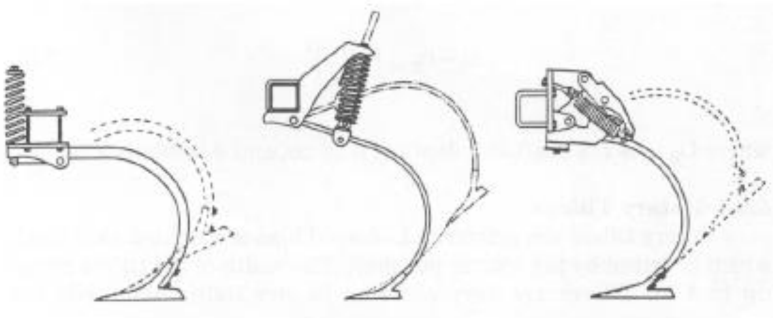


Figure 8.48 – Typical shank assemblies (Gullacher and Coates, 1980).

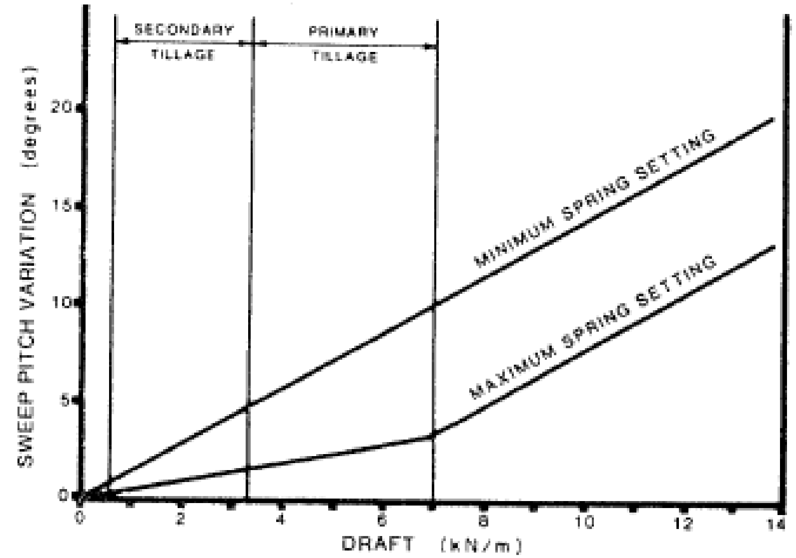
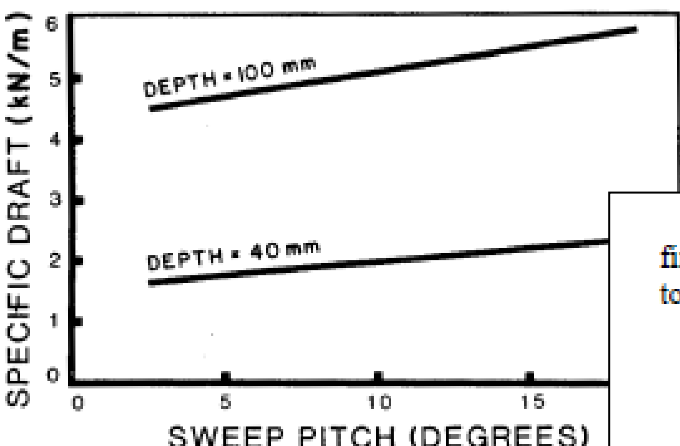


Figure 8.49 – Variation in sweep pitch over a range of normal tillage forces for one shank assembly (Gullacher and Coates, 1980).



Hendrick (CRC, 1988) reported the draft for chisel plows and field cultivators in firm soil spaced at 30 cm apart and operating at a depth of 8.26 cm and traveling at 5.5 to 10.5 km/h as follows:

Loam (Saskatchewan): Draft (N) = 520 + 49.2 S

Clay Loam (Saskatchewan): Draft (N) = 480 + 48.1 S

Clay (Saskatchewan): Draft (N) = 527 + 36.1 S (8.44)

Draft at other depths is given by:

$$D_d = D_{8.26}\left(\frac{d}{8.26}\right)^2 \qquad (8.45)$$

where $D_{8.26}$ is the draft at a depth of 8.26 cm and d is depth in cm.

❑ Rotary tillers

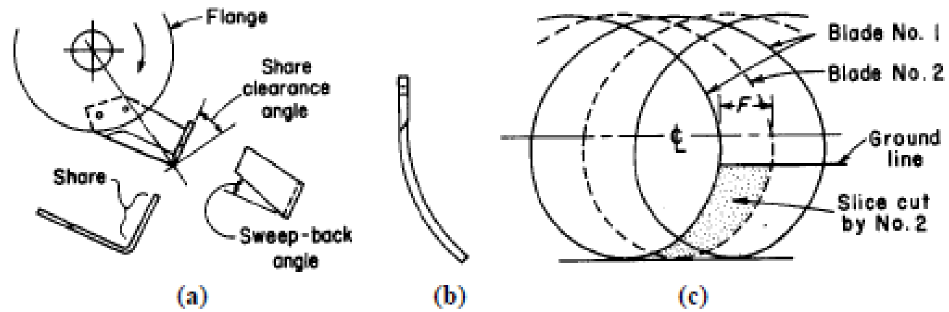


Figure 8.53 – (a) Three views of an L-shaped blade for a rotary tillage, (b) curved blade, (c) paths of cutting edges or tips for two blades 180° apart, in relation to forward speed (reprinted from Kepner et al., 1978).

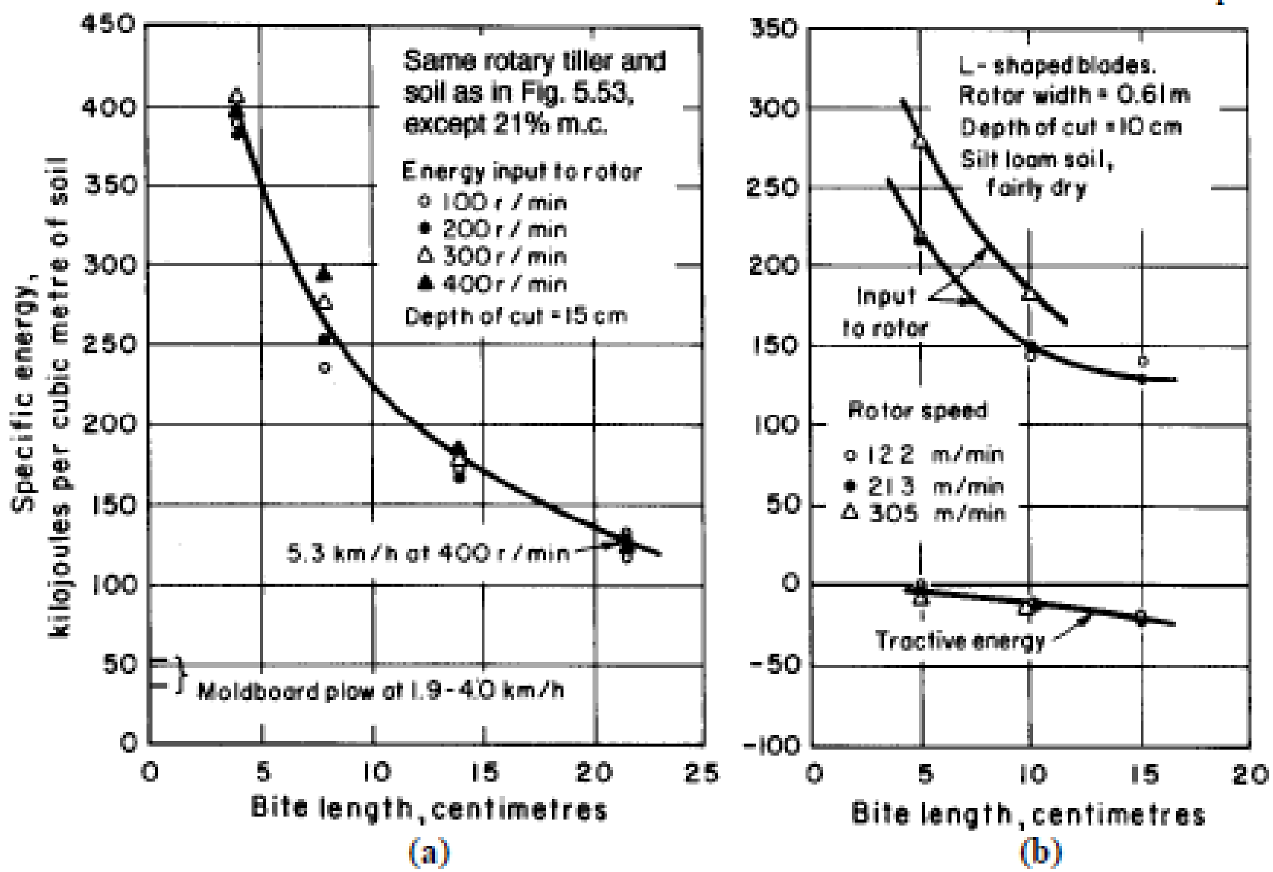
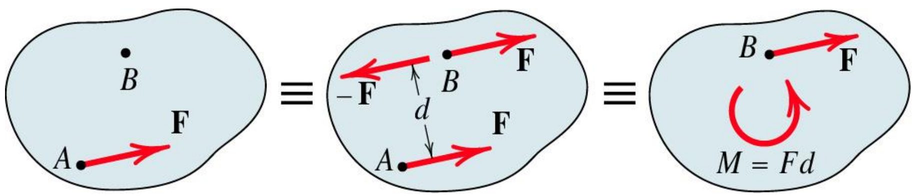


Figure 8.54 – Effect of bite length upon specific energy requirements for a conventional rotary tiller (reprinted from Kepner et al., 1978).

Hitching of Tillage Implements

- Forces on tillage tools: implement weight / soil reaction forces / forces exerted by the prime mover



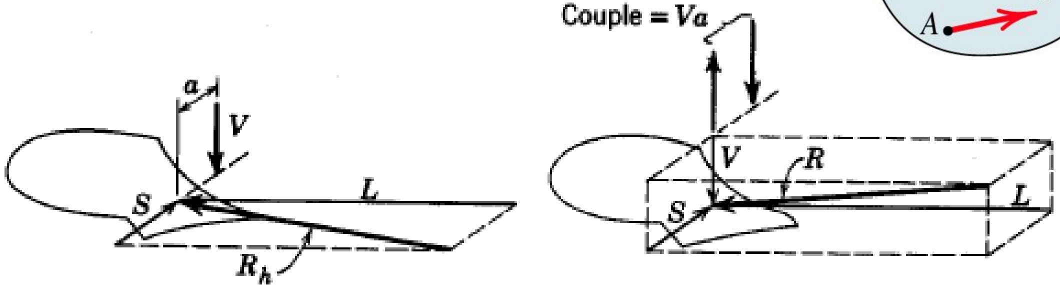


Figure 8.55 – Two ways of expressing the total soil reaction on a tillage tool when a rotational effect exists: (a) two non-intersecting forces, R_h and V, (b) one force R and a couple Va in a plane perpendicular to the line of motion (reprinted from Kepner et al., 1978).

The following notations will be used while analyzing hitching of tillage implements:

- R = resultant of all useful forces acting on the plow
- L = longitudinal component of R
- S = lateral component of R
- V = vertical component of R
- Q = resultant of all parasitic forces acting on the plow
- P = resultant pull exerted by the tractor
- W = implement weight

Subscripts:

- h = horizontal component of a force
- v = vertical component of a force

❑ Forces on a moldboard

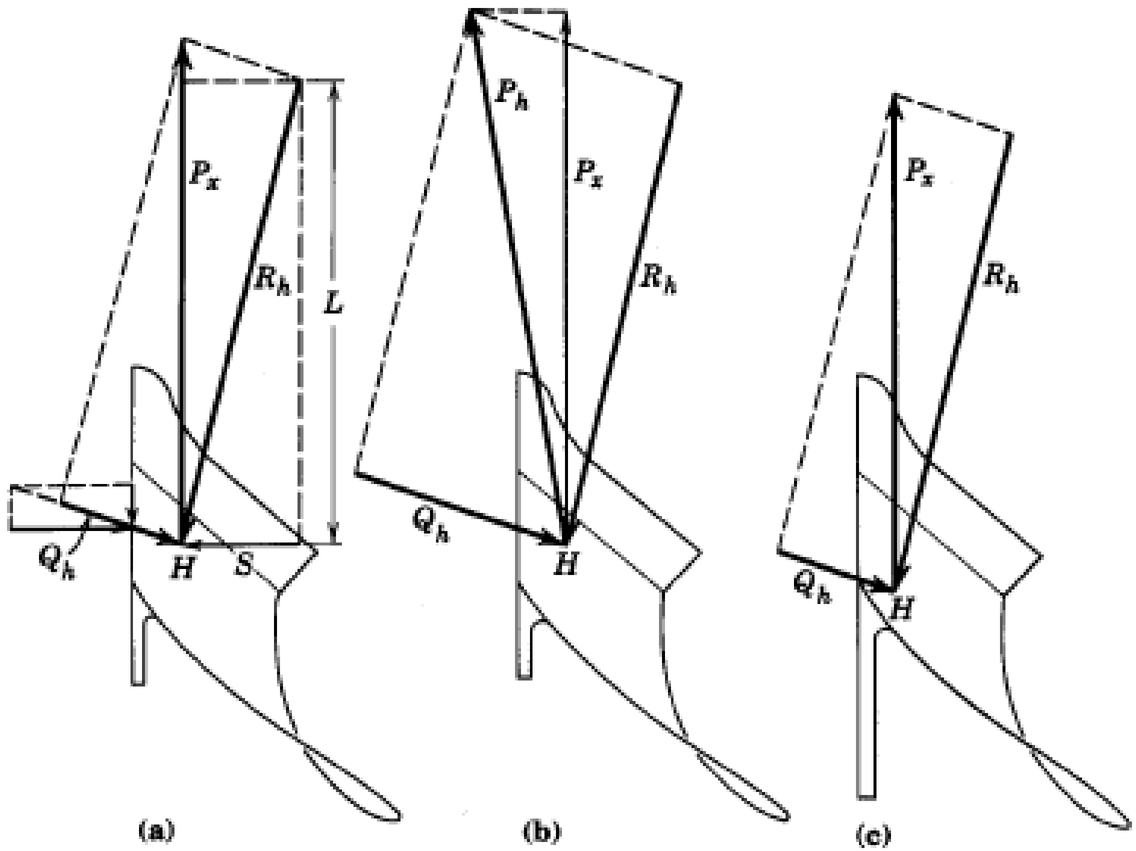
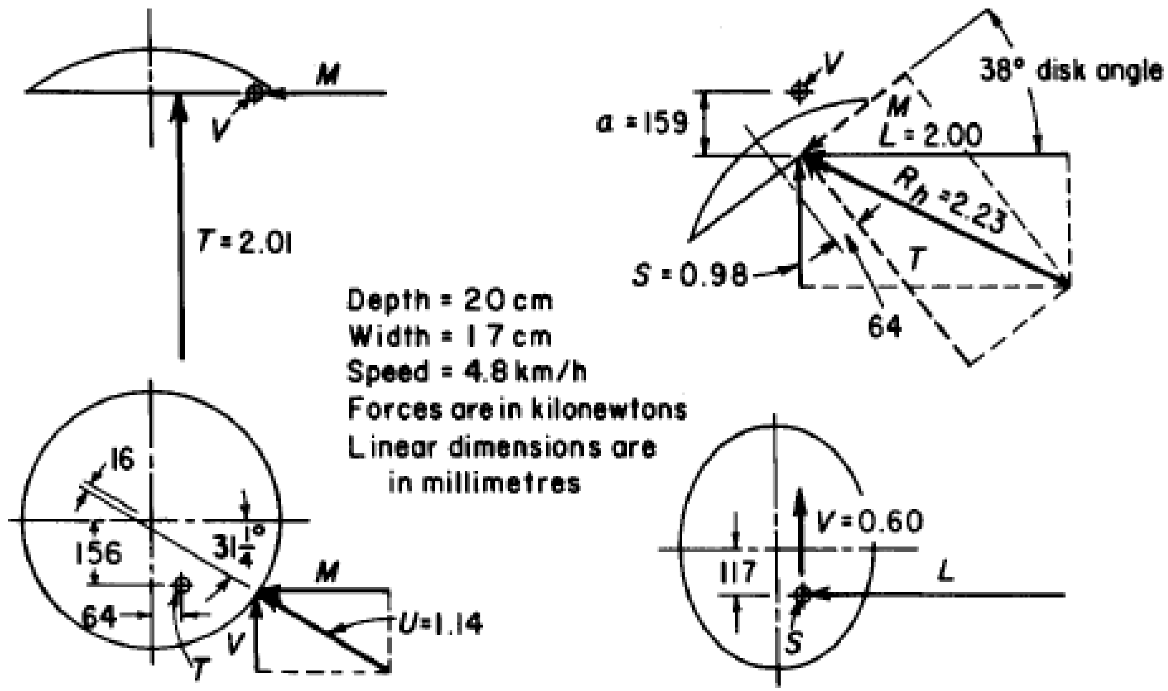


Figure 8.56 – Typical location of Rh and its relation to the landside force and pull: (a) straight pull, (b) angled pull, (c) long landside (reprinted from Kepner et al., 1978).

Forces on a disk blade



(a) (b)

Figure 8.57 – Example of resultant soil forces acting upon a vertical disk blade. The total effect is represented by two non-intersecting forces: (a) a thrust force T and a radial force U, (b) a horizontal force V (reprinted from Kepner et al., 1978).

- Forces on a disk harrow

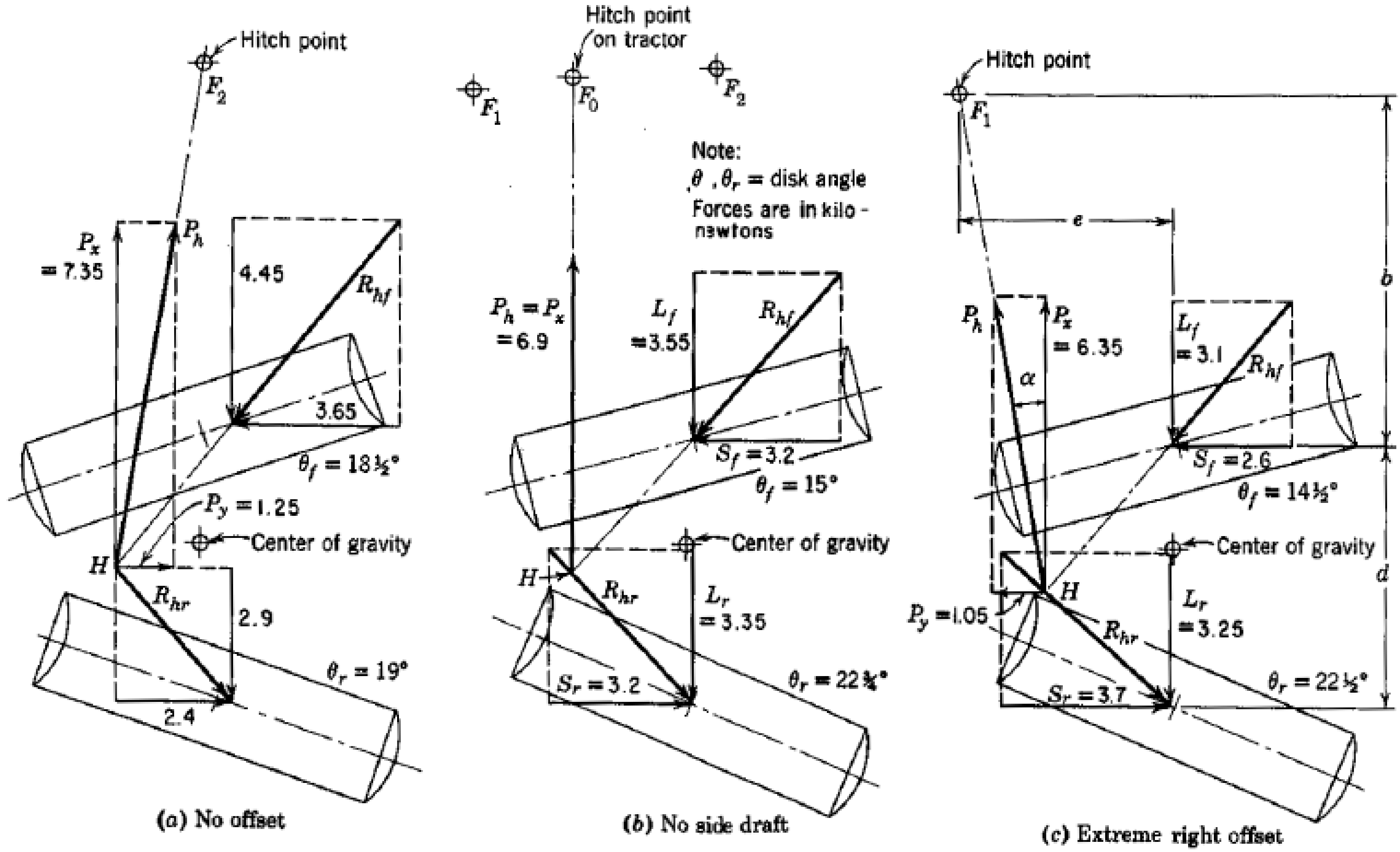


Figure 8.58 – Horizontal force relations for a pull-type, right-hand offset disk harrow without wheels (reprinted from Kepner et al., 1978).

Amount of offset available (Fig. 8.58c) for no side draft

$$eL_f + eL_r + b\,S_f - (b + d)\,S_r = 0$$

$$e = \frac{b(S_r - S_f) + dS_f}{L_f + L_r} = b\tan\alpha + \frac{dS_r}{L_f + L_r}$$

$$e_o = \frac{dS}{L_f + L_r}$$

❑ Pull-type implements

- Vertical hitching: implements having hinged pull members and support wheels or runners

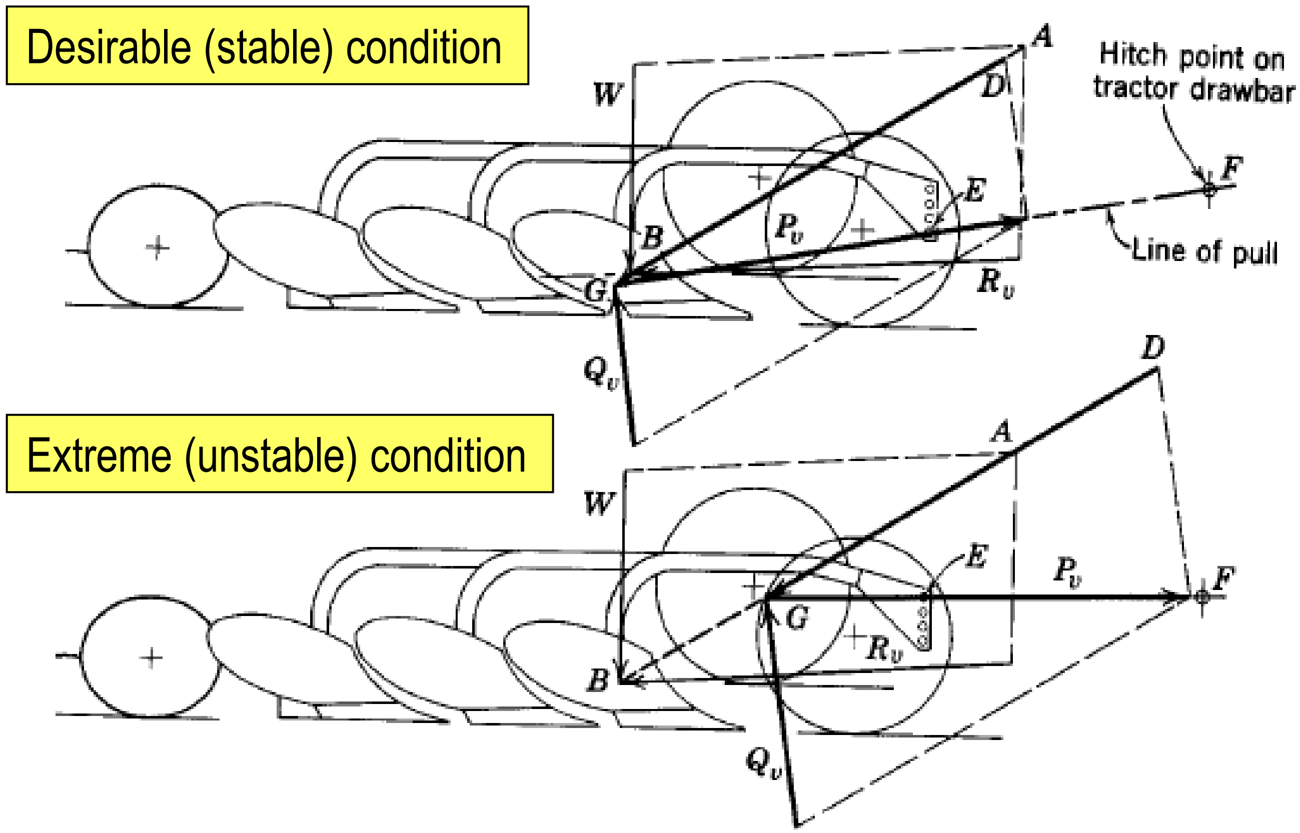


Figure 8.60 – Vertical force relation for a pull type implement having support wheels and a hinged pull member (reprinted from Kepner et al., 1978).

❑ Pull-type implements

- Vertical hitching: implements with hinged pull members but without support wheels or runners

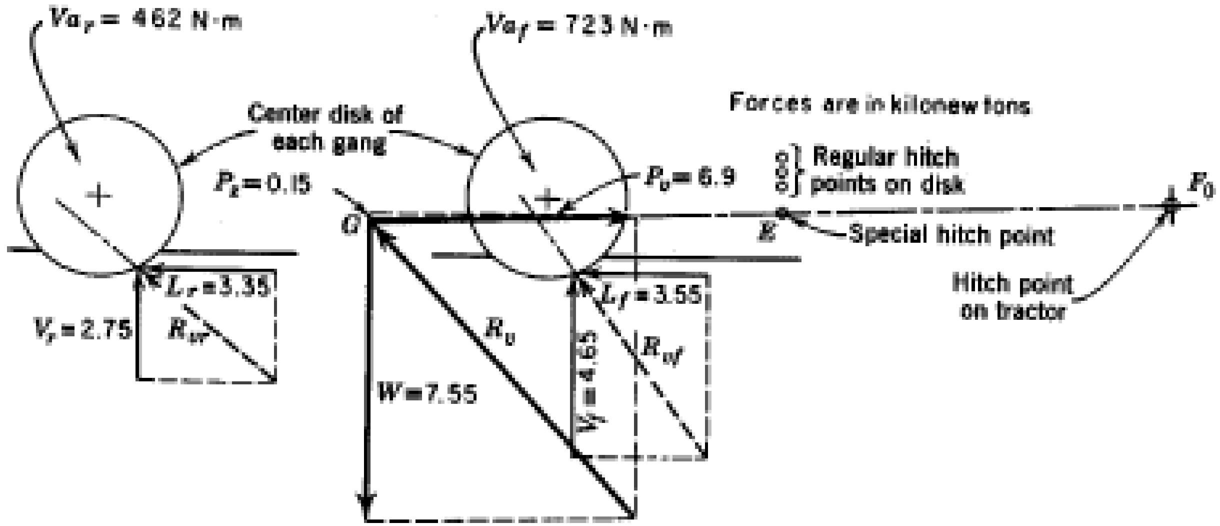


Figure 8.61 – Vertical force relation for a pull type offset or tandem disk harrow without wheels and no hinge axis between the front and the rear gangs (reprinted from Kepner et al., 1978).

❑ Pull-type implements

- Single-axle implements with rigid pull members

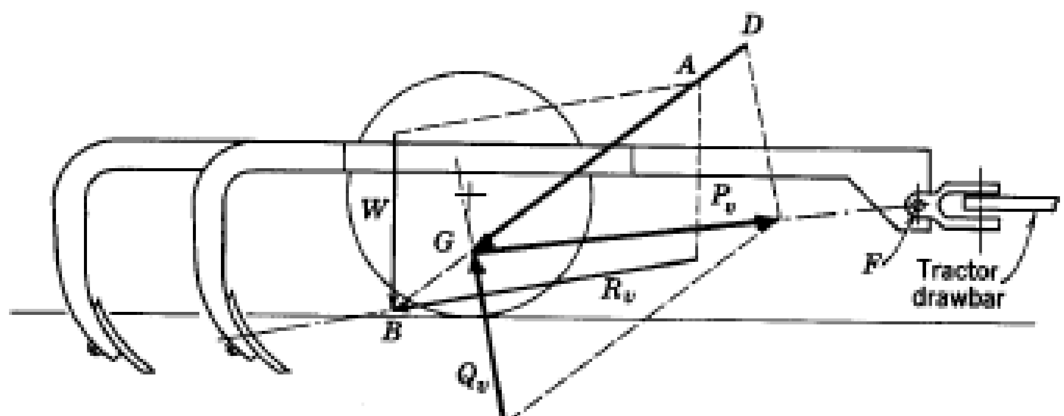


Figure 8.62 – Vertical force relations for a single-axle, pull-type implement receiving vertical support only through its wheels (reprinted from Kepner et al., 1978).

❑ Pull-type implements

- Most tillage implements are symmetrical about their longitudinal centerline. The side components of the soil forces are balanced, the horizontal center of resistance is at the center of the tilled width, and the horizontal line of pull is in the direction of travel
- Horizontal hitching of pull-type moldboard plows

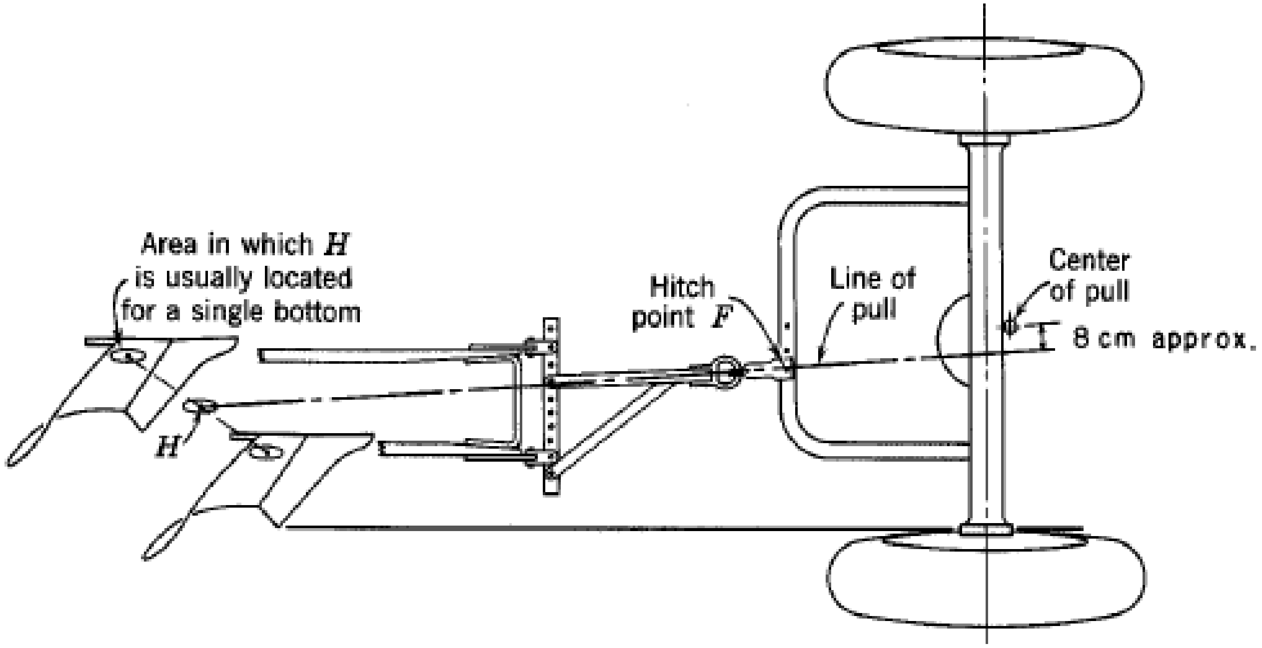


Figure 8.63 – Recommended horizontal hitching for a moldboard plow pulled by a wide tractor (reprinted from Kepner et al., 1978).

❑ Mounted implements

- Hitch linkages: free-link operation, restrained-link operation
- Free-link operation of three-point hitches: depth is controlled by gage wheels or other supporting surfaces on the implement

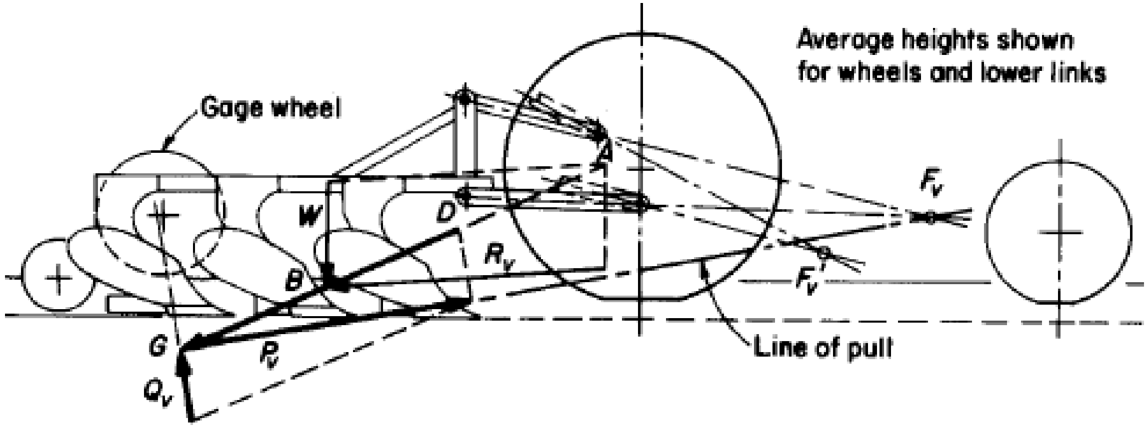


Figure 8.65 – Vertical force relations for a three-point hitch when operated as a free-link system (reprinted from Kepner et al., 1978).

- Restrained-link operation of three-point hitches

Greater vertical load on the tractor rear wheels, tractive ability than free-link

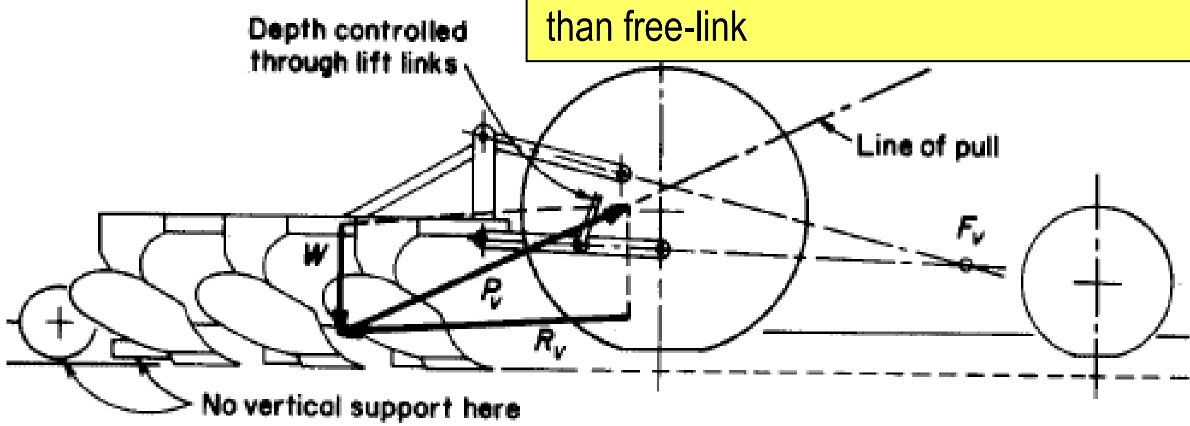


Figure 8.66 – Vertical force relations for a mounted implement when supported by restrained links (reprinted from Kepner et al., 1978).