DIMENSIONING AND DRAFT FORCE REQUIREMENT FOR SUBSOILERS

J. BALATON

Department of Agricultural Machines, Institute of Machine Design,
Technical University, H-1521, Budapest
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Presented by Prof. Dr. L. Varga

Abstract

Mathematical relationships have been developed for approximating the draft force requirement of the subsoiler and the vertical soil reaction, in knowledge of physical-mechanical characteristics of the soil. In selecting the width of the foot the critical cutting depth, size and shape of foot and shank holding the tiller wings are to be taken into consideration.

The tools of subsoilers consist of a shank and a foot (horizontal blade) symmetrically mounted onto the shank. Shanks may be straight or curved.

The tool passing at depth H compresses and deforms the soil. Due to this deformation, at ultimate stress, the soil cracks and loosens (Fig. 1).

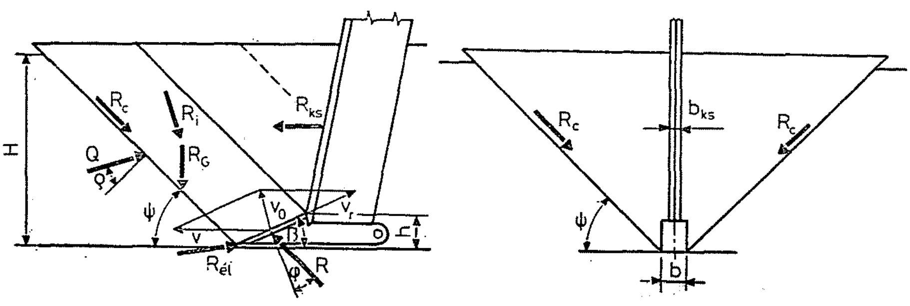

Fig. 1. Interaction between soil cut and subsoiler

The soil cut (furrow) may be separated and crushed by tension, shear or compression, depending on the type of deformation, determined by soil properties, stress state of the soil cut, and the tool parameters. To correctly select the tool parameters, let us consider the interaction of foot, shank and soil.

The draft force requirement of the subsoiler is composed of resistances of foot and shank:

$$F = R_{\acute{e}k} + R_{ks} \tag{1}$$

where: $R_{\acute{e}k}$ — resistance of the foot;
R_{ks} — resistance of the shank.

Resistance of the foot

In subsoiling, the tilling depth markedly exceeds the width of the foot. Lateral cracking of the soil prevails and is predominant in determining the energetic and work quality characteristics of the technological process. Forces acting on the foot and the soil cut are shown in Fig. 2. The width of cracked soil apparently exceeds that of the foot.

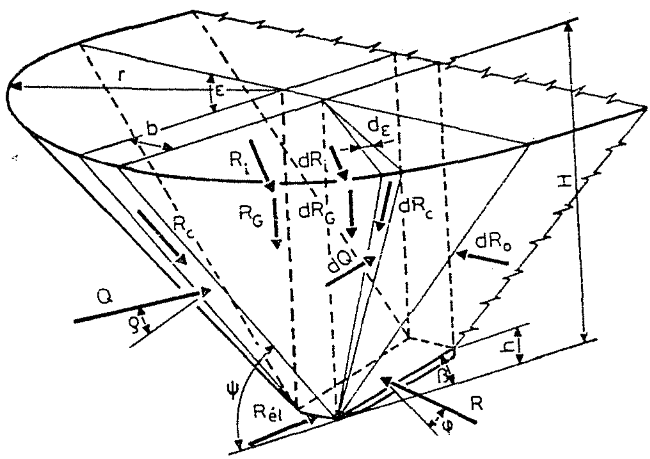

Fig. 2. Forces acting on tiller blade and soil cut

Foot resistance:

$$\bar{R}_{\acute{e}k} = \bar{R} + \overline{2R}_0 \tag{2}$$

where: $R_{\acute{e}k}$ — foot resistance in free cutting (without wings);
R_0 — soil resistance at the wings.

Forces acting on the soil cut and the foot are:

Q — reactive force of the soil before the foot, including angle ϱ with the normal to the crack direction;
R_c — cohesive force in the direction of the cracking plane;
R_G — soil furrow mass;
R_i — force of inertia in raising the soil cut;

$R_{él}$ — edge resistance;
R — resultant of elementary normal and friction forces acting on the foot surface containing the soil, including angle φ with the foot normal.

Wedge resistance in free cutting:

$$\bar{R} = \bar{R}_{él} + \bar{R}_c + \bar{R}_G + \bar{R}_i. \tag{3}$$

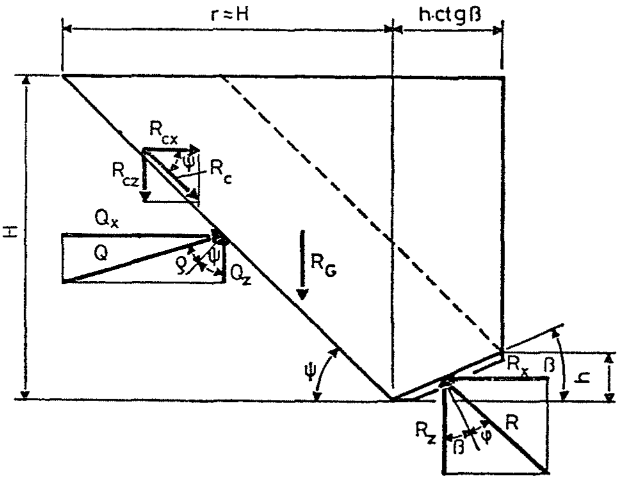

Fig. 3. Forces acting on tiller blade and on soil cut without lateral wings

Computations for a practical example showed that, because of foot resistance $R_{él}$ (in case of a sharp tool) and low working velocity, inertia R_i is insignificant (0.2 to 1.6%) hence negligible. In subsequent computations of foot resistance, only forces in Fig. 3 will be reckoned with. Equilibrium equations of components in the direction of advancement and vertically, resp.:

$$\left.\begin{aligned} \sum F_x &= R \cdot \sin(\beta+\varphi) - Q\sin(\Psi+\varrho) - cHb\operatorname{ctg}\Psi = 0 \\ \sum F_z &= R \cdot \cos(\beta+\varphi) + Q\cos(\Psi+\varrho) - \gamma g b A - cHb = 0 \end{aligned}\right\} \tag{4}$$

where: c — soil cohesion;
A —surface area of the lateral section of the soil cut above the foot:

$$A = \frac{H^2}{2}\operatorname{ctg}\Psi + \left(H - \frac{h}{2}\right) h \operatorname{ctg}\beta \tag{5}$$

where: h — lifting height of the foot.

Expressing R from (4), solution and simplification yields for the foot resistance:

$$R = \frac{\gamma g b A \sin(\Psi+\varrho) + cHb\sin(\Psi+\varrho) + cHb\operatorname{ctg}\Psi\cos(\Psi+\varrho)}{\sin(\beta+\varphi)\cos(\Psi+\varrho) + \cos(\beta+\varphi)\sin(\Psi+\varrho)}, \tag{6}$$

Hence:

$$R_x = R \sin(\beta + \varphi) = \frac{\gamma g b A + c H b[1 + \operatorname{ctg}\Psi \operatorname{ctg}(\Psi + \varrho)]}{\operatorname{ctg}(\beta + \varphi) + \operatorname{ctg}(\Psi + \varrho)} \tag{7}$$

$$R_z = R \cos(\beta + \varphi) = \frac{\gamma g b A + c H b[1 + \operatorname{ctg}\Psi \operatorname{ctg}(\Psi + \varrho)]}{1 + \operatorname{tg}(\beta + \varphi) \operatorname{ctg}(\Psi + \varrho)}. \tag{8}$$

Forces developing on lateral breaking surfaces near the foot are determined alike [2, 3]. The cracking surface of the soil cut is considered approximately as a cone shell. The axonometric view of soil cuts cracked off both sides of the foot is similar to a quarter of a cone each, of which the base radius is about equal to the operation depth H (Fig. 2). Summing up elementary forces acting on the surface:

$$\left.\begin{aligned} \sum F_{ox} &= dR_o \sin(\beta + \varphi) - dQ \sin(\Psi + \varrho) - \frac{cH^2}{2} \operatorname{ctg}\Psi \, d\varepsilon = 0 \\ \sum F_{oz} &= dR_o \cos(\beta + \varphi) + dQ \cos(\Psi + \varrho) - \\ -\gamma g \left[\frac{H^3 \operatorname{ctg}^2 \Psi}{6} d\varepsilon + \left(H - \frac{h}{2}\right) \frac{h}{2} \operatorname{ctg}\Psi \operatorname{ctg}\beta\right] &- \frac{cH^2}{2} \operatorname{tg}^2 \Psi \, d\varepsilon = 0 \end{aligned}\right\} \tag{9}$$

Hence:

$$dR_o = \frac{\gamma g \left[\frac{H^3 \operatorname{ctg}^2 \Psi}{6} d\varepsilon + H\left(H - \frac{h}{2}\right) \frac{h}{2} \operatorname{ctg}\Psi \operatorname{ctg}\beta\right]}{\sin(\beta + \varphi) \operatorname{ctg}(\Psi + \varrho) + \cos(\beta + \varphi)} + \\ + \frac{\frac{cH^2}{2}[\operatorname{tg}^2 \Psi + \operatorname{ctg}\Psi \operatorname{ctg}(\Psi + \varrho)] \, d\varepsilon}{\sin(\beta + \varphi) \operatorname{ctg}(\Psi + \varrho) + \cos(\beta + \varphi)}. \tag{10}$$

The component of force dR_o in the direction of advancement:

$$dR_{ox} = dR_o \sin(\beta + \varphi) \cos\varepsilon \tag{11}$$

and the vertical one:

$$dR_{oz} = dR_o \cos(\beta + \varphi) \cos\varepsilon. \tag{12}$$

Integration of (11) and (12) yields forces in the direction of advancement, and vertically:

$$R_{ox} = \int_0^\varepsilon dR_{ox} \, d\varepsilon = \frac{\gamma g \left[\frac{H^3 \pi \operatorname{ctg}^2 \Psi}{12} + H\left(H - \frac{h}{2}\right) \frac{h}{2} \operatorname{ctg}\Psi \operatorname{ctg}\beta\right]}{\operatorname{ctg}(\beta + \varphi) + \operatorname{ctg}(\Psi + \varrho)} + \\ + \frac{\left\{\frac{cH^2}{2}[\operatorname{tg}^2 \Psi + \operatorname{ctg}\Psi \operatorname{ctg}(\Psi + \varrho)]\right\} \sin\varepsilon}{\operatorname{ctg}(\beta + \varphi) + \operatorname{ctg}(\Psi + \varrho)} \tag{13}$$

$$R_{oz} = \int_0^\varepsilon dR_{oz} \, d\varepsilon = \frac{\left\{\frac{\gamma g H^3 \pi}{12} + \frac{cH^2}{2}[1 + \operatorname{ctg}\Psi \operatorname{ctg}(\Psi + \varrho)]\right\} \sin\varepsilon}{1 + \operatorname{tg}(\beta + \varphi) \operatorname{ctg}(\Psi + \varrho)}. \tag{14}$$

Inserting surface A from Eq. (5) into Eqs (7) and (8), and adding forces from Eqs (13) and (14), taking shank angle ε as 90°, after the needed operations and simplifications, the draft force requirement of the foot is:

$$R_{\text{ék}\,x} = R_x + 2R_{ox} = \frac{\gamma g\left\{(b + H\,\text{ctg}\,\Psi)\left[\frac{H^2}{2}\,\text{ctg}\,\Psi + \left(H - \frac{h}{2}\right)h\,\text{ctg}\,\beta\right]\right\}}{\text{ctg}\,(\beta+\varphi)+\text{ctg}\,(\Psi+\varrho)} + \frac{cH\{b[1+\text{ctg}\,\Psi\,\text{ctg}\,(\Psi+\varrho)]+H[\text{tg}^2\,\Psi+\text{ctg}\,\Psi\,\text{ctg}\,(\Psi+\varrho)]\}}{\text{ctg}\,(\beta+\varphi)+\text{ctg}\,(\Psi+\varrho)}. \tag{15}$$

Similarly, the vertical force acting on the foot:

$$R_{\text{ék}\,z} = \frac{\gamma g\left\{(b + H\,\text{ctg}\,\Psi)\left[\frac{H^2}{2}\,\text{ctg}\,\Psi + \left(H - \frac{h}{2}\right)h\,\text{ctg}\,\beta\right]\right\}}{1+\text{tg}\,(\beta+\varphi)\,\text{ctg}\,(\Psi+\varrho)} + \frac{cH\{b[1+\text{ctg}\,\Psi\,\text{ctg}\,(\Psi+\varrho)]+H[\text{tg}^2\,\Psi+\text{ctg}\,\Psi\,\text{ctg}\,(\Psi+\varrho)]\}}{1+\text{tg}\,(\beta+\varphi)\,\text{ctg}\,(\Psi+\varrho)}. \tag{16}$$

According to earlier experiments, the soil has a cracking angle Ψ of about 45° [6, 8]. (Angle Ψ may vary slightly as a function of soil cohesion.) Again, tests have shown that for an operation of the desired rate, the tiller foot has to lift the soil cut by about 10% of the tilling depth (9), as confirmed by the author's tests [1].

Inserting $\Psi=45°$ and $h=0.1\,H$ into Eqs (15) and (16), and after simplifications:

$$R_{\text{ék}\,x} = \frac{H(H+b)\left\{\frac{\gamma g H}{2}(1+0.2\,\text{ctg}\,\beta)+c[1+\text{ctg}\,(45°+\varrho)]\right\}}{\text{ctg}\,(\beta+\varphi)+\text{ctg}\,(45°+\varrho)}, \tag{17}$$

$$R_{\text{ék}\,z} = \frac{H(H+b)\left\{\frac{\gamma g H}{2}(1+0.2\,\text{ctg}\,\beta)+c[1+\text{ctg}\,(45°+\varrho)]\right\}}{1+\text{tg}\,(\beta+\varphi)\,\text{ctg}\,(45°+\varrho)}. \tag{18}$$

The draft force requirement for the tilling foot of the subsoiler is obtained from Eq. (17), in knowledge of foot width b, sweep angle β, tilling depth H, soil specific density γ, cohesion c, inner friction angle ϱ and soil to tool friction angle φ. Vertical load acting on the gauge disk is obtained from Eq. (18).

Critical cutting depth

A narrow shank and foot cutting and tilling the soil in depth cause lateral cracking and reducing of the soil cut only down to the critical cutting depth [10].

Beyond the critical cutting depth the tool resistance abruptly increases, at the lower part of the tool, soil parts do not crack off but get laterally compacted.

To have the soil cut cracked all along the tilling depth, the foot (wedge) width has to be increased. Down to the critical cutting depth, the soil slice is separated by tension. Here the draft force is: [4]

$$R_{xsz} = \frac{2\sigma_B(H-h)\left[b+\frac{(H-h)\pi}{2}+2h(1+\mathrm{ctg}\,\beta)\right]}{\nu+\mathrm{tg}\,\Psi}, \tag{19}$$

where: σ_B — soil tensile strength;
ν — Poisson's ratio.

Beyond the critical cutting depth, the foot resistance may be expressed in terms of compression:

$$R_{xny} = \sigma_{ny} \cdot b \cdot h \tag{20}$$

where: σ_{ny} — compressive strength of the soil.

At the critical cutting depth, resistances due to tensile and to compressive strength are equal. From (19) and (20):

$$\frac{2\sigma_B(H-h)\left[b+\frac{(H-h)\pi}{2}+2h(1+\mathrm{ctg}\,\beta)\right]}{\nu+\mathrm{tg}\,\Psi} = \sigma_{ny} \cdot b \cdot h \tag{21}$$

For soils, Poisson's ratios of $\nu=0.3$ to 0.35 have been published (computations below involve $\nu=0.33$). Inserting $h=0.1\,H_{kr}$ and $H-h=0.9\,H_{kr}$ into Eq. (21) yields for the critical cutting depth:

$$H_{kr} = \frac{b\left[0.09\frac{\sigma_{ny}}{\sigma_B}(1+3\,\mathrm{tg}\,\Psi)-5\right]}{8.05+\mathrm{ctg}\,\beta} \tag{22}$$

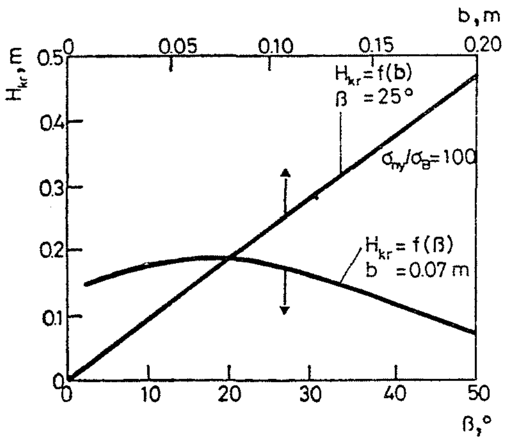

Fig. 4. Critical cutting depth

showing it to be proportional to the foot width. The higher the σ_{ny} to σ_B ratio, the greater is the critical cutting depth of the given tool. Computation results for sandy loam soils have been plotted in Fig. 4. For a tilling depth of $H=0.5$ m, a tilling foot at least $b=0.21$ m wide is shown to be needed. Such a wide, straight foot is inconvenient for soil cutting. A composite (skew) foot, that is, a wing-tiller is better. Tilling wings of the cultivator tool including an angle γ are symmetrically mounted on the shank. Analysis of forces acting on the foot show that to let soil crumbles slip along the foot, wings have to include a sweep angle $\gamma/2<90°-\varphi$ with the advancement direction [7].

The critical cutting depth of the foot of given width as a function of angle β is shown in Fig. 4. The most favourable values arise for $\beta=20$ to 25°.

Shank (vertical blade) resistance

The feet are mounted on the shank with its top end at the machine frame. In front of the shank an edge is needed to cut the soil in the vertical plane. This is often formed by edging the shank made of steel, but it may also be a separate part (a blade) mounted onto the shank (Fig. 5). Blade-and-shank resistance develops from the r acting force of soil deformation due to the blade, and the friction force due to soil pressure acting on shank sides [5].

With symbols in Fig. 5:

$$R_{ks} = (H-h)\left[k_1 b_{ks}\left(1+\operatorname{tg}\varphi\operatorname{ctg}\frac{\alpha}{2}\right)+2k_2\cdot s\cdot\operatorname{tg}\varphi\right], \tag{23}$$

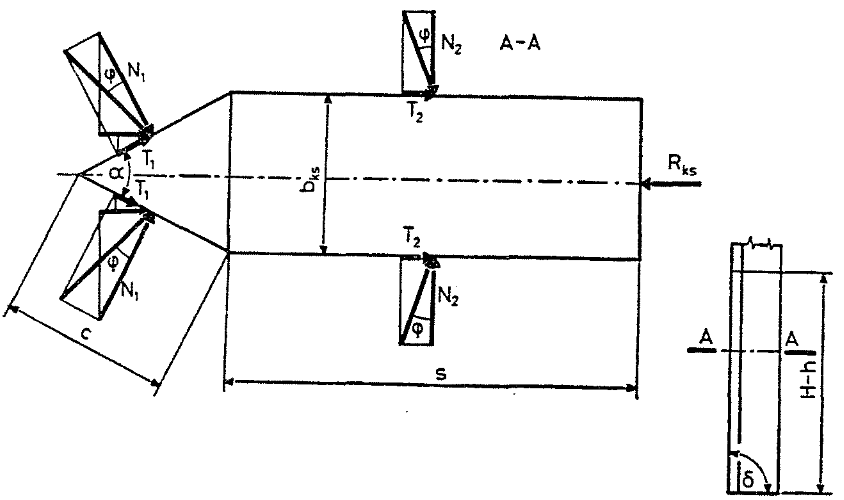

Fig. 5. Forces acting on blade and shank

where: k_1 — specific resistance due to soil deformation;
k_2 — specific soil pressure on side surfaces.

Variation of the resistance as a function of the ratio of blade and shank thickness to width b_{ks}/s according to Eq. (23) is seen in Fig. 6a. Accordingly, to meet strength requirements, thinner but wider blade and shank have to be applied. Actually, the optimum is $b_{ks}/s=0.1$ to 0.125. About 40% of shank resistance is shown in Fig. 6b to be due to the friction of lateral surfaces. To reduce the draft force, the shank is advisably made to have uniform strength (by reducing the width of the lower part).

The draft force is also affected by the shank angle δ. Angle δ has to be taken so that angle α^* of the force normal to the cutting edge exceeds friction angle φ (Fig. 7a). Experiments showed the resistance of a curved shank to be lower than

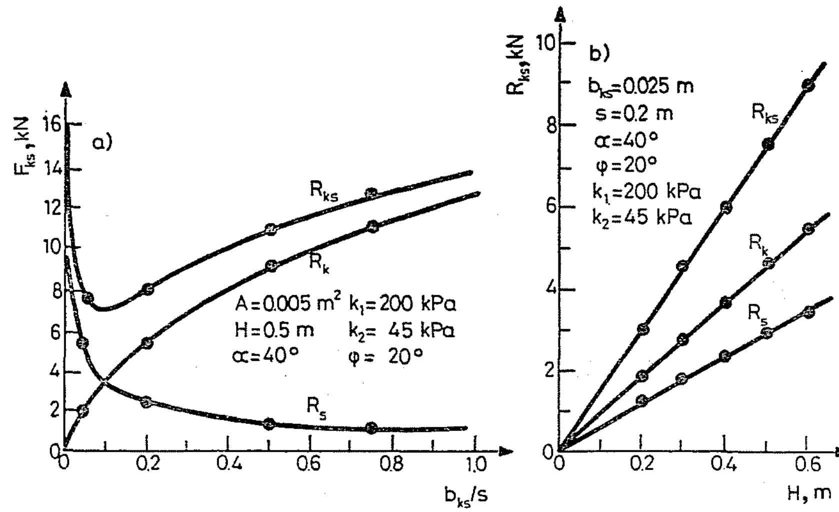

Fig. 6. Blade and shank resistance vs. b_{ks}/s and H

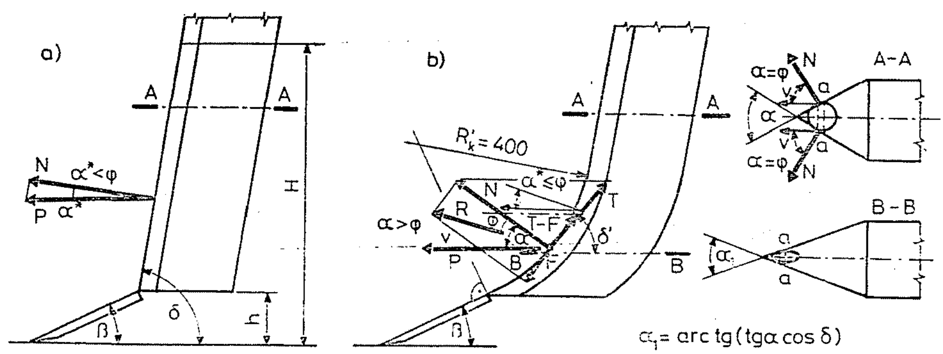

Fig. 7. Blade and shank forms

that of a straight shank. As seen in Fig. 7b, this is also due — in addition to a better stress pattern — to the gradual decrease of shank width in horizontal plane sections at greater depths due to the curvature (section B) and to the improvement of edging angle with wear. (Several attempts have been made to determine the theoretical curvature radii of blades cutting the soil but the multitude of affecting factors prevented us to obtain a result that can be generalized.) The foot edging angle will not be considered here, it being covered by recommendations in literature [5, 6].

Overall resistance of the subsoiler

Insertion of forces determined by Eqs (17) and (23) into (1) yields the draft force requirement for the subsoiler (for bilaterally hampered cutting):

$$F = H\left\{\frac{(H+b)\left\{\frac{\gamma g H}{2}(1+0.2\operatorname{ctg}\beta)+c[1+\operatorname{ctg}(45^\circ+\varrho)]\right\}}{\operatorname{ctg}(\beta+\varphi)+\operatorname{ctg}(45^\circ+\varrho)}+\right.$$

$$\left.+0.9\left[k_1 b_{ks}\left(1+\operatorname{tg}\varphi\operatorname{ctg}\frac{\alpha}{2}\right)+2k_2 s\operatorname{tg}\varphi\right]\right\}. \tag{24}$$

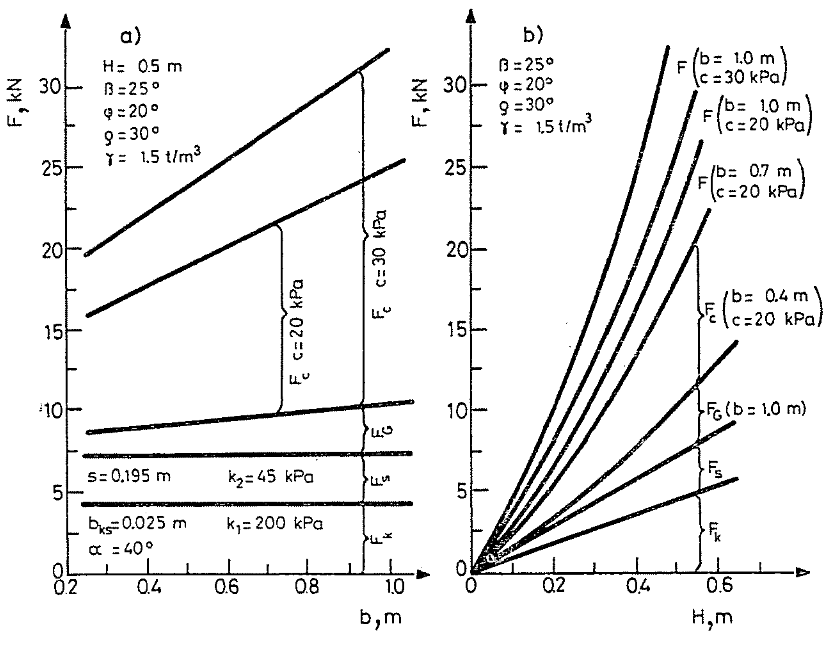

Fig. 8. Overall resistance of the subsoiler as a function of tiller wing width (a) and tilling depth (b)

Accordingly, the draft force is the most affected by the cohesion (50 to 70%), the foot resistance (20 to 25%), lateral friction of the shank (10 to 15%), and the least, by the soil cut mass (8 to 10%) (Fig. 8), showing the importance for the draft force of correctly selecting the foot and shank parameters.

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J. BALATON, H-1521, Budapest

* In Hungarian.