Chapter 2
Mechanics of Machine Demining

Abbreviations

a_t [m/s^2]	Tangential hammer acceleration
b [m]	Tool blade width, tooth
CI [Pa]	Soil cone index
D [m]	Diameter of wheel
f_k [-]	Rolling resistance coefficient
F_a [N]	Mine activation force
F_i [N]	Hammer force impulse
F_{in} [N]	*G*rasping hammers force impulse
F_{cf} [N]	Flail centrifugal force
F [N]	Hammer striking force
F_N [N]	Striking force normal component
F_H [N]	Striking force horizontal component
F_1 [N]	Impact force
F_2 [N]	Dragging force
h [m]	Soil cutting depth
h_r [m]	Rotor axis height
k_1 [N/m^2]	Specific cutting resistance
k [-]	Collision factor
k_o [-]	Relative soil resistance
L [m]	Cutting tool width
M [-]	Mathematical expectation
MMP	[Pa] Mean Maximum Pressure
MI [-]	Mobility Index
m_h [kg]	Hammer mass
m_c [kg]	Chain mass [kg]
M_u [Nm]	Total flail rotation resistance moment
M_e [Nm]	Moment of eccentric rotor weight
M_μ [Nm]	Friction moment in shaft bearing
M_d [Nm]	Moment of flail to soil friction

D. Mikulic, *Design of Demining Machines*,
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M_i [Nm]	Moment of shaft, hammer and chain inertia
NGP [Pa]	Nominal Ground Pressure
p_i [Pa]	Tyre inflation pressure
p_1 [%]	Probability that disk sections will hit the mine in minefield
p_2 [%]	Probability that mine will be activated
P_v [W]	Power required for machine movement
P_r [W]	Power required for machine operation (flail)
P_T [W]	Total power required for machine movement and operation
P_m [W]	Engine power of machine
r [m]	Hammer rotation radius
R [%]	Reliability of mine activation
R_1 [N]	Cutting resistance
$R_{\sigma i}$ [N]	Non-coherent soil resistance to crushing
R_{ki} [N]	Coherent soil resistance to digging
R_k [N]	Rolling resistance (wheels/tracks)
R_i [N]	Inertia resistance
R_α [N]	Slope resistance
ΣR [N]	Movement resistance
S_t [m]	Current cutting layer thickness
Δt [s]	Time interval of hammer soil grasping
t [s]	Acceleration time
u [m/s]	Circumferential hammer velocity after collision
v_o [m/s]	Circumferential hammer velocity before collision
VCI [Pa]	Vehicle Cone Index
w [%]	Moisture content
W [N]	Wheel load
Z [m]	Sinkage
ω [s^{-1}]	Angular hammer velocity
θ [°]	Hammer striking angle (angle of chain)
φ [°]	Flail angle
ε [s^{-2}]	Angular hammer acceleration
$_w$ [-]	Wedge efficiency of striking hammer
α [°]	Cutting angle
β [°]	Wedge angle
γ [°]	Back pin angle

2.1 Soil Categorization

Machine working conditions are very important for demining operations. It is necessary to be familiar with soil characteristics as well as mine features, because of their influence on machine design and demining technology. Soil characteristics, possible soil conditions and physical–mechanical characteristics are described by *Soil mechanics*.

Categorization of real demining conditions is extremely important, when demining equipment is concerned (probes, detectors, machines). Four soil categories where mines can be neutralized with demining equipment are presented in Table 2.1. Additionally, soil configuration is important for use of certain demining technique; flat soil with rocks may be on one location, hilly terrain with rocks may be on another location, and flat terrains on a third.

With regard to difficult treatment of soil with manual tool and demining machines, soil categorization and vegetation categorization [1] are provided, Tables 2.1, 2.2.

2.2 Soil Trafficability

Use of machines and vehicles in demining depends on state of soil. On soft and moist soil, machines and vehicles move with difficulty. There exists a problem of soil trafficability. This problem is more evident with wheeled vehicles than the tracked ones. Indicators of soil trafficability on basis of vehicle pressure on soft soil, are:

1. Nominal Ground Pressure (NGP)
2. Mean Maximum Pressure (MMP)
3. Soil load capacity, soil cone index (CI)
4. Rut depth (Z), sinkage
5. Vehicle Cone Index (VCI)

2.2.1 Mean Maximum Pressure

In a study of soil trafficability often times a nominal vehicle pressure is used on soil NGP (Nominal Ground Pressure), as an easiest approach to soil trafficability estimate. However, nominal pressure on soil is a marginal tangential pressure of wheel on soil, which doesn't provide a competent soil trafficability estimate because of neglecting the impact of laden wheel pneumatics deformation while moving, or because of track chain deformation.

Mean maximum pressure (MMP) is a referent pressure of the vehicle on soft soil through the wheels. It is defined as the mean value of peak pressure magnitudes acting on the soil under the wheels. A partial empiric model (*British Army Engineer Corps*) for evaluation of vehicle mobility on coherent (clay) soil has been developed. Lower value of MMP decreases wheels sinkage, which provides better soil trafficability and mean movement speed, which further provides better vehicle mobility. Linking MMP and CI soil load, correlation that defines vehicle mobility is being determined (go/no go). MMP Eq. (2.1) enables analysis of design factor

Table 2.1 Soil categorization

Soil category	Soil features	Method used
I	Medium and hard soil, covered with vegetation, humus, loam, compact sand	Manual tool, probes, shovel, use of machine.
II	Dirt mixed with rocks, dirt prevails with rare low and medium vegetation. Stone is limestone-schist, soft, easily crushed by machine working tool.	Probe used with difficulties. Use of machine.
III	Stony soil, stone sheets with dirt between them, low vegetation. Swampy soil.	Probe used on surface. Possible use of machine.
IV	Specific conditions, very hard soil, other categories not applicable.	Not possible to use probes. Machine is used with difficulties.

(*Source* Ref. [1])

Table 2.2 Vegetation categorization

Vegetation categorization	Vegetation features	Vegetation texture	Height and diameter
Low	Fresh or dry grass of low or higher density, weed, rare low bushes	80 % grass, and 20 % bushes	1 m
Medium	Grass, weed, single bushes, thick vegetation, single trees	50 % grass, 50 % bushes, 10–15 trees	1–2 m >ø10 cm
High	Bushes, weed, grass, high vegetation density, single trees	20 % grass, 40 % bushes, 40 % underbrush, over 15 trees	> 2 m >ø 10 cm
Forest	High forest and dense underbrush	High trees Tree diameter	>3 m >ø 20 cm

(*Source* Ref. no. [1])

influence on decreasing the pressure to the base and accordingly evaluation of mobility of different vehicles.

2.2.1.1 Wheeled Vehicle

$$MMP = \frac{kW_T}{nb^{0.85}d^{1.15}\sqrt{\frac{\delta}{d}}} \quad [\mathbf{kPa}] \tag{2.1}$$

W_T vehicle weight (kN)

k number of drive axis factor (2.05 for 4 drive axlex; 1.5 for 3 drive axlex; 1.83 for 2 drive axlex)

n number of vehicle wheels
b tyre width, non-loaded wheel (m)
d tyre diameter, non-loaded wheel (m)
δ tyre deflection due to the load (m)

Pneumatics deflection

$$\delta = \left(0.365 + \frac{170}{p_i}\right)\frac{W}{1000} \quad [\mathrm{m}] \tag{2.2}$$

p_i tyre inflation pressure (kPa)
W wheel load (kN)

2.2.1.2 Tracked Vehicle

Use of machines in demining depends on the state of soil. When weather conditions change (rain, mud), soil load capacity (soil strength) also changes. When soil is humid and the machine is too heavy, it won't move or perform demining. Machines with less pressure on soil offer greater soil trafficability.

$$MMP = \frac{1.26\,W_T}{2nb\sqrt{Dt}} \quad [\mathrm{kPa}] \tag{2.3}$$

W_T vehicle weight (kN)
n number of wheels of one track
b track width (m)
D diameter of wheel (m)
t track pitch (m)
L track length, in contact with level ground (m)

Nominal ground pressure

$$NGP = \frac{W_T}{2Lb} \quad [\mathrm{kPa}] \tag{2.4}$$

2.2.2 Soil Cone Index

CI soil cone index is a soil load capacity indicator, which is measured with penetrometer, Fig. 2.1. Resistance to penetration of penetrometer cone into the certain type of soil is measured. *Standardized value of cone penetration measurement on depth of 15 cm (ASAE EP542 1999) is called cone index (CI).* For

Fig. 2.1 Penetrometer for measuring the soil cone index

example, load of very soft soil has soil cone index of $CI < 300$ kPa, medium hard soil is 300–500 kPa, and very hard soil more than 500 kPa.

Coherent soil load capacity [3], cone index CI:

0–21,	load capacity has no practical value
40–62,	a man has difficulty walking on soil without sinking
103–165,	special light tracked vehicles can surmount approximately 50 driveways
186–228,	light tracked vehicles can pass about 50 times
276–352,	medium weight tracked vehicles can surmount approximately 50 passages
372–497,	vehicles of Jeep type, can pass around 50 times
517–662,	heavy vehicles
683–935,	passenger vehicles
1000,	without problems in soil trafficability

Limiting cone index

$$CI = CI_L = 0.827\,MMP \quad [\text{kPa}] \tag{2.5}$$

This expression can be used to determine the lowest soil load, where vehicle with certain MMP is mobile. In another words, soil load should be at least 83 % of given MMP for certain vehicle, in order to successfully cross the passage.

For multiple passes on the same coherent soil track and determination of adequate CI_L, multiplication index are used. They are gained experimentally [2] and given as RI coefficient of soil load alteration (*Remoulding Index RI*) which considers soil sensitivity regarding the soil strength loss due to road traffic. Evaluation of such cone index rate *(Rating Cone Index)* is $RCI = RI \times CI$.

Multipass multiplicator

Number of passes	1	2	5	10	25	50
RI	1	1.2	1.53	1.85	2.35	2.8

2.2.3 Wheel Rut Depth

Many factors effect vehicle moving, firstly its physical characteristics (structure, density, moisture, watertightness, and other) and mechanical characteristics (load capacity, shear resistance, cohesion characteristics, tackiness, and other). Coherent soil, while wheel rotation, plastically deforms. Under the wheel, soil is exposed to complex normal and tangential constraints. That leads to soil compaction and shear. Deformation degree depends on soil properties, i.e. its mechanical features. When the resistance for deforming is higher, soil provides more convenient conditions for vehicle movement, that is better soil trafficability.

Prevention of wheel vegetation destruction on certain depth becomes a new requirement of modern vehicles users, which has to be considered when procuring these vehicles. This means that negative influence of wheel tracks on vegetation should be blocked. This is very important for sensitive soil of forest areas with aim of avoiding the negative influence on ecological, economic and social function of vegetation. Soil deformation depth to 10 cm, protocol EcoWood suggests as environmentally acceptable. To evaluate environmental acceptability of different vehicles, as a relevant parameter general formula for wheel index (wheel numeric) is defined: $N_k = CI/p$.

Rut depth for one vehicle pass [3]:

$$z_1 = D\left(\frac{0.224}{N_k^{1.25}}\right) \tag{2.6}$$

Rut depth for multipass: $z_n = z_1 n^{1/a}$

D tyre diameter
z_1 first pass sinkage (m)
z_n sinkage after pass n (m)
n number of passes
p tyre inflation pressure
a coefficient of multipass (low soil load capacity $a = 2$–3; mean load capacity $a = 3$–4; high load capacity $a = 4$–5)

2.2.3.1 Vehicle Cone Index

Vehicle cone index (VCI) is accepted as referent NRMM model for unit mobility evaluation, developed by WES [2]. VCI is developed based on partially empiric term for ***MI*** *(Mobility Index).* Experiments are used to determine the expressions for calculation of VCI values for one and for fifty indexes (VCI_1 and VCI_{50}). *VCI—Vehicle Cone Index represents minimum soil load (psi—pounds per square inch) within critical layer which enables that vehicle successfully completes certain number of passes.* In the US Army, expression *Soils Trafficability* is used, which means the capacity of soil to support military vehicles. Regarding mobility of one or more vehicles on the same track on typical low load terrain, soil trafficability is modelled, because vehicle mobility is related to humid coherent soil (fine grain soil/clay-loam, mud).

2.2.4 Mobility Index

$$MI = \left(\frac{K_{KP}K_T}{K_G K_L} + K_{OK} - K_{CL}\right)K_M K_{MJ} \tag{2.7}$$

K_{KP}	contact pressure factor, $K_{KP} = w/0.00035\ n_1 d\ b;$
K_T	vehicle axis load factor, $K_T = 0.073(w/1000) + 1.050;$
K_G	tyre width factor, $K_G = (10 + b/25.4)/100$
K_L	grouser factor *(without chain 1.00; with chain 1.05)*
K_{OK}	wheel load factor, $K_{OK} = w/907.2$
K_{CL}	chassis to soil distance factor, *H/254, H* distance between the ground and axle
K_M	vehicle specific power factor *(>7.36 kW/t → 1.0; <7.36 kW/t → 1.05)*
K_{MJ}	gearbox factor *(automatic = 1.0; manual = 1.05)*
w	average axis load (kg)
n_1	number of wheels on the axis
b	tyre width, non loaded wheel (mm)
d	tyre diameter, non loaded wheel (mm).

Vehicle cone index

For one passage:

$$VCI_1 = 11.48 + 0.2MI - \left(\frac{39.2}{MI + 3.74}\right)6.89655 \ \ [\text{kPa}] \tag{2.8}$$

For fifty passages:

$$VCI_{50} = 28.23 + 0.43MI - \left(\frac{92.67}{MI + 3.67}\right)6.89655 \ \ [\text{kPa}] \tag{2.9}$$

Vehicle mobility and traction capability:

- for one vehicle pass: $CI > VCI$, "go"
- for multiple vehicle passes: $RCI = RI \times CI > VCI$, "go".

Table 2.3 MMP and VCI for escort vehicles

Vehicle		Mass (kg)	MMP (kPa)	VCI_1 (kPa)
1	Land Rover Defender 110 TDi 4 × 4	3,000	343	172
2	MB G270 CDI 4 × 4	3,000	310	158
3	TAM 110 T7 4 × 4	7,000	358	207
4	TAM 150 T11 6 × 6	11,000	319	207
5	IVECO ML 100 E21 W 4 × 4	10,000	354	221
6	MAN 10.225 LAEC 4 × 4	10,800	368	234

(*Source* Ref. [4])

Table 2.4 MMP and NGP values for demining machines

Demining machine	Mass (kg)	MMP (kPa)	NGP (kPa)	CI_L (kPa)
MV-4	5,500	125	46	108
MV-10	18,000	150	39	124

Soil trafficability evaluation for some types of escort vehicles is given in Table 2.3, while in Table 2.4, value of *MMP* pressure, *NGP* pressure and CI_L index of light and medium demining machine, is given. A big difference is evident between MMP indicators of wheeled and tracked vehicles. Tracked demining machines offer significantly greater soft soil trafficability.

The basic demining machine *MV-4* has a nominal soil pressure of 46 kPa ($\approx$0.46 bar) and mean maximum soil pressure 125 kPa ($\approx$1.3 bar). Based on NGP value, quality assessment of soil trafficability is not possible. Comparing *MMP* machine value with the practically measured *CI* index, the use of the demining machine on certain terrain can be considered. Also, the required Limiting Cone Index (CI_L) can be evaluated, which determines the use of the machine: $CI_L = 0.827\ MMP$.

2.3 Toolbox Demining System

Demining machines using only a single tool are less useful than multipurpose machine which use more types of tools. Hence the development of demining machines is based on one basic machine of certain category and a greater number of different specialist tools for demining. Thereby a greater demining effectiveness is achieved. Such a universal working tool system and quick working tool replacement is called a toolbox demining system. Development of a demining working tool has established the following kinds of working tools, Fig. 2.2:

- Flail
- Tiller
- Combination of a flail and tiller
- Demining roller

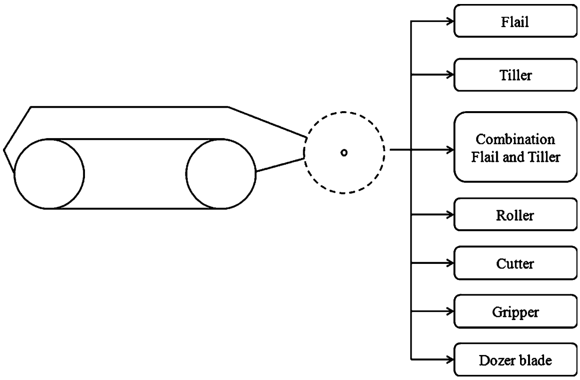


Fig. 2.2 Toolbox demining system

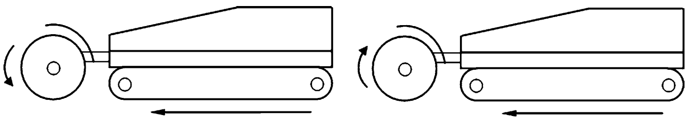


Fig. 2.3 Counter direction and same direction of rotor rotation to machine movement

- Vegetation cutter
- Gripper
- Dozer blade
- Other

Rotation of flail and tiller is in counter direction to machine movement, Fig. 2.3. Thereby during soil treatment a working tool impact is provided upon buried mines toward their neutralization. Rotation of working tool in the direction of the machine movement digs and throws out mines to the sides of the machine, offering a faster pass through the lane, to the expense of not actually destroying the mines. Such passage clearance through a minefield belongs to military demining rather than humanitarian demining.

A lower amount of engine power is needed for flail work than for the tiller. However, it is considered that tillers in certain categories of soil provide a greater quality in soil mine-clearance. Engine power has to be available to current machine movement resistances and operation of the working device. Hence, a demining machine of a specific category (light, medium, heavy) must have available power for usage of different tools in the toolbox system. Moreover, machines have to show a certain level of resistance to mine detonations. Light machines are to be resistant to AP mines, medium machines to AP mines and certain AT mines, whereas the heavy ones have to be resistant to all types of AP and AT mines.

The majority of demining machines use working tool switching, with flail or tiller, depending on the soil condition. A complex combination of working tools consisting of flail and tiller is used towards a greater reliability in the machine's neutralization of buried mines and its preservation from the impact of AT mine detonations.

A demining roller consists of several discs and they are used for opening up unsafe passages for vehicle convoys, and other. Other kinds of working tool are occasionally used for clearing of various obstacles in the demining process.

2.4 Soil Digging Resistance

Soil digging is based on sharp wedge, which has geometrical shape of digging blade. Basic parameters are: blade angle (20°–25°), back angle (5°–10°) and soil cutting angle (25°–35°). Lowest soil digging resistance provides semicircular shape and convex front part of blade. Soil digging process with working tools consists of two phases: soil cutting phase and soil disposition phase. In the soil cutting phase, soil layer is removed by the force of the tool blade. Cutting resistance is significant and depends on soil characteristics and tool blade condition. Soil disposition resistance on working tool depends on tool shape. Tool blade is a basic element of soil digging and mine destruction. With development of demining machines, different shapes of soil cutting/digging tools were also developed. For flails, hitting tool has a shape of a cutting and crushing hammer and for milling and tillers a shape of a wedge or a knife. During soil cutting phase, the soil is compacted first, than part of the layer shears in the plain of highest stress and after that soil is dispositioned.

2.4.1 Soil Cutting Resistance

When machine moves and digs the soil using working tools, (such as bulldozer, loader, and tractor), tool is subject to digging resistance. This resistance is much higher than resistance to machine movement so digging resistance requires deeper study. Digging resistance consists of cutting resistance (R_1) and displacement resistance of dug soil (R_2), different for each tool type. Cutting resistance is tangential component of overall digging resistance [4]. For supporting machine, bulldozers for example, cutting resistance can be formulated as:

$$R_1 = k_1 L h \ \ [\mathrm{N}] \tag{2.10}$$

k_1 specific cutting resistance (N/m^2)
L cutting tool width (m)
h soil cutting depth (m)

Cutting resistance depends on the type of working tool (flail, tiller) and working conditions. Soil cutting shapes with flail and tiller are presented in Fig. 2.4. According to soil categorization, specific soil resistance (k_1) can range from 25 kN/m^2 for the first soil category up to 320 kN/m^2 in fourth soil category.

Fig. 2.4 Soil cutting: on the *left* tiller; on the *right* flail

Average values of specific resistance:

I. $k_1 = 25$ kN/m^2 sandy clay, gravel
II. $k_1 = 95$ kN/m^2 compact sandy clay, medium clay, soft coal
III. $k_1 = 175$ kN/m^2 hard sandy clay with gravel, hard clay, conglomerate
IV. $k_1 = 320$ kN/m^2 medium slate, hard dry clay, chalk and soft plaster stone, marl

To operate in hard soil category, teeth are mounted on toll blade, which loosen the soil and decrease cutting resistance for 25 %. It is important to properly set up digging depth and adequate distance between teeth in order to achieve less resistance.

Cutting resistance is dominant in relation to machine movement resistance (cca. 90 % of machine power is used for digging resistance). Cutting resistance increases more due to increase of cutting depth (h), then with increase of cutting width (L). In order to achieve required efficiency on certain soil category, machine operator should adjust cutting depth "h" and regularly inspect tool blades.

Soil cutting resistance [5]:

$$R_1 = k_1 b S_t \quad [\mathrm{N}] \tag{2.11}$$

k_1 specific soil cutting resistance (N/m^2)
b tool blade width, tooth
S_t current cutting layer thickness

2.4.2 Flail Force Impulse

Demining working device has a large number of flails attached to the rotor, rotating at 400–1000 rpm. Each flail has a striking hammer at the end of a chain for soil digging and mine neutralization. Hammer strikes on the soil can be viewed as analysis of collision of two bodies.

Based on *Law on Momentum Conservation*:

$$m_h v_o - m_h u = F_i \Delta t \tag{2.12}$$

Hammer behaviour during impact with soil can be described with collision factor k:

$$k = u/v_o \tag{2.13}$$

v_o circumferential hammer velocity before collision
u circumferential hammer velocity after collision

Factor k is related to soil categories, i.e. soil hardness, in order to notice the differences in digging in these soil categories (coefficient of restitution). Relative soil resistance according to soil hardness:

$$k_o = (1/k)100\,\% \tag{2.14}$$

Relation between the velocity before and after collision is provided through factor k, which provides the formula for calculation of hammer force impulse:

$$F_i = m_h v_o(1 - k)/\Delta t \;\; [\mathrm{N}] \tag{2.15}$$

F_i single hammer force impulse (N)
m_h hammer mass (kg)
Δt force impulse time interval of hammer soil grasping (s)

Hammer force impulse has to be higher than resistances for soil cutting or soil crushing. Hammer friction resistance causes decrease of hammer rotation speed which provides resistance factor k_O. Hammer rotation speed decreases due to friction resistance or inadequate power supply. When friction between hammer and soil is lost, hammer rotation speed increases. Increase of digging resistance is related to increased relative soil resistance. In these conditions, flail rotor requires more power.

2.5 Demining Machines with Flails

2.5.1 Flail Mechanics

Physical parameters of flails

General flail parameter is centrifugal force of striking hammer and chain. This force is applicable when choosing flail chain and rotor balance.

(a) *Flail centrifugal force*

$$\begin{aligned} F_{cf} &= m_h r\,\omega^2 + m_c r_s \omega^2 \\ F_c f &= 2\sigma d^2 \pi/4 \end{aligned} \tag{2.16}$$

Chain diameter:

$$d^2 = 2\,\omega^2 (m_h r + m_c r_s)/\,\pi \tag{2.17}$$

m_h hammer mass (kg)
m_c chain mass (kg)
r hammer rotation radius (m)
ω angular hammer velocity (s^{-1})
d chain diameter
r_s chain mass radius (*r/2*)
σ strain of chain material

(b) *Hammer striking force*

$$\begin{aligned} F &= m_h a_t = m_h r \varepsilon \\ \varepsilon &= \Delta\omega/\Delta t \end{aligned} \tag{2.18}$$

$$F = m_h r \omega/\,t \tag{2.19}$$

a_t tangential hammer acceleration (s^{-2})
ε angular hammer acceleration (s^{-2})
ω angular hammer velocity (s^{-1})
r hammer rotation radius/flail radius (m)
t acceleration time (s)

Striking force F components, Fig. 2.5.
F_N normal component:

$$F_N = F\cos\theta \tag{2.20}$$

F_H horizontal component:

$$F_H = F\ \sin\theta \tag{2.21}$$

$\varphi + \theta = 90^0$
θ hammer striking angle (angle of chain)
Flail striking force acting on soil is tangential force F.

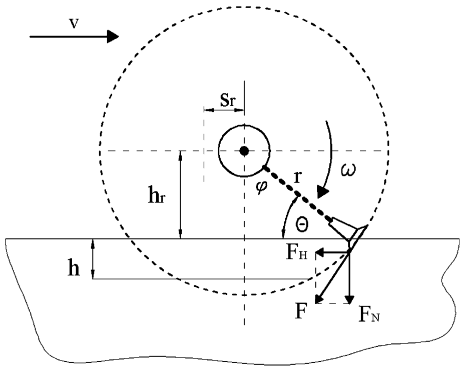


Fig. 2.5 Hammer striking force and parameters of flail

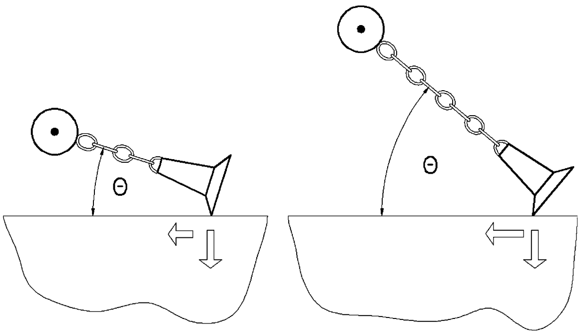


Fig. 2.6 Effect of hammer striking angle on the components of hammer striking force

Normal component of striking force $\boldsymbol{F_N} = F\,cos\theta$ depends on hammer striking angle θ. If striking angle θ decreases, vertical component of striking force increases. Accordingly, horizontal component of force $\boldsymbol{F_H} = F\ \sin\theta$ decreases, Fig. 2.6. The goal is to achieve required soil digging depth $\boldsymbol{h}$ with highest vertical striking force. That means that optimal height of rotor axis h_r can be determined as one of design parameters, based on normal component of striking force F_N.

Rotor axis height:

$$h_r = r \sin\theta \tag{2.22}$$

Relation between striking force and real conditions of soil treatment is practically expressed through hammer force impulse. Hammer force impulse has to be has to be higher than resistance at soil cutting or soil crushing.

Hammer impact to the soil can be analyzed through zone of soil stress below impact point. Shock waves are transmitted from impact point to under surface zone in expanding circles in all directions evenly, Fig. 2.7. Within this effect zone, mine can be detonated or crushed. On hard soil, shock waves are shallow, spreading more on the surface than into the deep ground. On medium hard and soft soil, the situation is opposite. Such a load distribution within the wave effect zone allows the possibility of mine destruction, using indirect contact of hammer—mine.

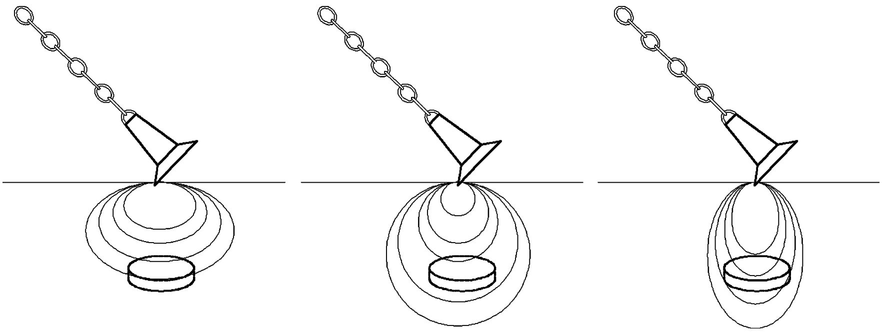
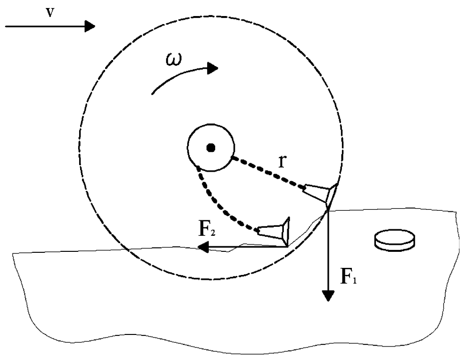


Fig. 2.7 Effects of soil on impact zones and soil stress distribution on a mine, hard soil, medium soft, soft soil

Fig. 2.8 Flail forces at soil digging



However, within interspaces of untreated area, where shock wave effect does not have influence, certain "pockets" can be found, so it is important to achieve necessary striking density in practice. Soft and medium hard soil require higher striking density. On hard soil, mines cannot be embedded deeper, and surface wave spreading may be adequate for mine destruction.

(c) *Empirical flail mechanics*

When analyzing flail impact on different soils, it can be found that such impacts are extremely complex and not thoroughly researched. Very important contribution in this area was provided by *Shankhla* research [6, 7].

Mechanics of flail is based on two main forces, Fig. 2.8:

F_1 —*Impact force,* hammer normal force when striking the soil. This hammer striking force provides penetration into the soil, which can neutralize embedded mines. Depending on tool type and tool blade geometry, force F_1 can cut certain soil or vegetation.

F_2 —*Drag force,* horizontal flail force which occurs after the force F_1; so called flail dragging force upon penetrated soil. This increases friction resistance between

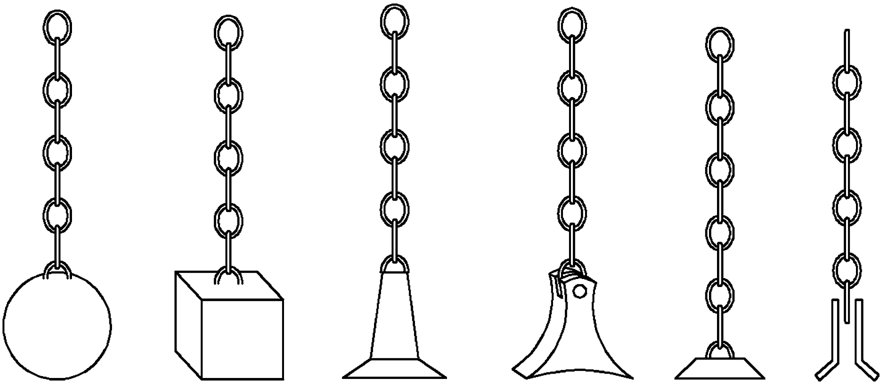


Fig. 2.9 Hammer shapes

flail and soil, which causes soil bulking and asymmetry in soil clearance. This force has negative influence on clearance performance; primarily, more power is needed for machine operation, and second, there is possibility of throwing the mines on already cleared area. Force F_2 causes problems to flail designers, because it cannot be exactly calculated. Magnitude of this force is based on assumptions, such as soil type, digging depth, shape and radius of working tool, rotation speed, etc. It is estimated that this force will double if soil is dug at depth of 20 cm instead of 10 cm. Additionally, extra weight is added approximately at chain mid length, in order to reduce the length of snake-shaped chain after the impact and reduce negative effect of dragging force. Smaller radius of flail provides lesser drag force, conversely a greater radius of flail increases the drag force, i.e. adds to the dragging force moment M_d. However, if there exists a zone of thick soil during treatment within a zone of soft soil, drag force will be greater than in treatment of homogenous soil.

2.5.2 Hammer Shapes

Geometry of striking hammer is highly important in the process of soil digging and mine neutralization. Common shapes of striking hammer are: *ball shape, block shape, mushroom shape, chisel shape and other shapes,* Fig. 2.9. Influence of hammer shape on demining process has not been thoroughly researched. Shape of striking hammer determines the position of striking force F_1 on soil and minimizing the force influence F_2, which causes drag resistance and soil shearing. Hammer shape is chosen according to soil category, digging depth, costs and experience. For example, ball shaped hammer may be ideal for areas where deeper penetration is not required and without vegetation. For deeper penetration, block shaped hammer could be very useful. However, when operating on medium soil category and for vegetation cutting, hammer shape is very important, for instance hammer shaped as a chisel. For soil cutting and mine neutralization, *mushroom shaped* hammer is favourable. There is no optimal hammer shape that could be used in all demining conditions. As mentioned earlier, mushroom shaped hammers are considered as universal. Optimal hammer shape is closely related to optimal soil digging depth, i.e. optimal penetration depth. Experience shows that there is no need to dig deeper than 10 cm, due to decreased efficiency in mine crushing, as well as negative effect of drag force. This also has significant influence on required power that has to be delivered to flail working tool, i.e. working costs.

(d) *Empirical flail mechanics*

Law on Momentum Conservation

$$m_h v_o - m_h u = F_i \Delta t \tag{2.23}$$

$$F_i = m_h v_o (1 - k) / \Delta t \tag{2.24}$$

F_i single hammer force impulse
F_{in} grasping hammers force impulse (refers to total impulse force the number of hammers that are engaged in the soil at any point in time)
m_h hammer mass
v_o circumferential hammer velocity $(r \pi n/30)$
k collision factor of soil category/ratio between hammer velocity before and after collision (factor of restitution)
Δt time interval of soil grasping hammers force impulse

Soil digging conditions

$$F_i > R_{\sigma i}, F_i > R_{ki} \tag{2.25}$$

Non-coherent soil resistance to crushing by hammer (approx.)

$$R_{\sigma i} = \sigma \cdot A \tag{2.26}$$

Coherent soil resistance to digging by hammer (approx.)

$$R_{ki} = z_n k_1 b \Sigma S_{ti} \tag{2.27}$$

z_n number of hammers in same digging position, two hammer helixes
k_1 specific resistance to soil digging, depending on soil category (N/m^2)
b hammer cutting width
ΣS_{ti} total thickness of soil digging layers ($S \sin\varphi$)
r flail hammer rotating radius
σ soil strength/normal stress (N/m^2)
$A = z_n b \Sigma S_{ti}$ surface of the hammer impact blade

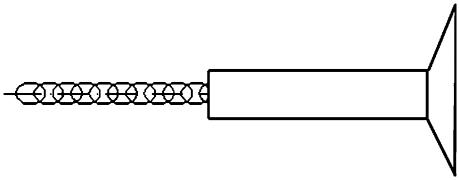


Fig. 2.10 Flail of demining machine (chain, hammer—”mushroom” shape)

2.5.2.1 Features of Hammer Force Impulse

Flail operation is based on impact force of the flail (flail strike) that strikes and digs the soil. Depending on soil humidity, soil is cut by hammer strikes and is moved towards machine shields. If the soil is dry and hard, soil is crushed and scattered. To simplify demining machine calculations, two theories of soil digging apply: theory of soil cutting and theory of soil hardness/crushing. Therefore, two tool types that are commonly used. For soft soil, cutting blade of lower weight is preferable, and for hard soil and cutting a rectangular shape of higher weight is advantage. Because of practicality, universal “mushroom” hammer shape is used. Soil that is coherent and soft can be cut using tool blade. Soil that is non-coherent, dry and hard can be crushed using different tool shapes. For the soft coherent soil, calculations from equation of soil cutting theory are applied, and for the hard non-coherent soil a criteria of soil hardness limit “σ“ is applied. Hammer working principle is based on force impulse overcoming the resistance at soil digging (force impulse = change in momentum). In order to perform cutting, hammer force impulse has to be higher than resistance $F_i > R_{ki}$, i.e. for soil crushing condition of $F_i > R_{\sigma i}$ has to be fulfilled. Phase shift between flails (attached to rotor’s helix/spiral (n $\times$ 180°) starting from the rotor centre towards the rotor edges) decreases digging resistance, removes the influence of axial forces and unbalance of the flail. These flails are used on demining machines.

Total resistance momentum to flail rotation includes static and dynamic momentum of flail’s parts rotation, until hammer strikes the soil, when kinetic energy is lost, angular velocity is changed and flail rpm is decreased. Since this change in energy is not well known in practice, each flail cyclical operation is assumed: hammer acceleration and stopping at cutting the soil layer.

The striking hammer is of “mushroom” shape with a cutting blade, Fig. 2.10.

Hammer Impact to the Soil

Hammer strikes to the soil can be viewed through two analyses of two body collision. It is necessary to determine the hammer force impulse. One method of determining this force assumes that force is acting in finite time interval, in which hammer is using part of its momentum it had before impact. It can be assumed that hammer behaviour during impact with soil can be described with collision factor:

$$k = \frac{u}{v_0} \tag{2.28}$$

v_o circumferential hammer velocity before impact
u circumferential hammer velocity after impact

Through the introduction of collision factor k problem of hammer striking the obstacle can be viewed as a problem from classical mechanics, not using the assumption of a firm obstacle. Factor "k" is within interval:

$$0 \leq k \leq 1 \tag{2.29}$$

$k = 0$ impact is ideally plastic
$k = 1$ impact is ideally elastic
$k_o = (1/k)$ 100 % relative soil resistance

Based on Eq. (2.23), ratio between velocity before and after collision is provided through factor k, leading to equation for force impulse in time interval, Δt (2.24): $F_i = m_h\, v_o\, (1\ k)/\Delta t.$

Hammer Force Impulse Analysis

Example: digging depth $h_1 = 100$ mm, hammer weight, $m = 1.2$ kg, $\varphi = 35°$, $n = 900$ rpm.

Assumption:

- factor k for 3 different collision conditions; $k = 0.3$; 0.5; 0.7; relative soil resistance; $k_o = 333$; 200; 143
- time interval of force impulse impact in interval up to $\Delta t = 10^{-4}$ s

Using factor k different situations for the working tool could be described, from striking the obstacle (i.e. how much energy is lost because of that), to the situations when hammer strikes the mine and the factor k sign changes. Accordingly, depending on the soil type, obstacle k, digging depth h and flail rotation n, calculations could be performed of force impulse influencing the hammer when striking the soil,.

Factor k can be brought into relation to the soil category, i.e. soil hardness, in order to determine the differences between them. Coefficient k can be simulated as well as digging depth h, under the assumption that $k = 0.7$ for III soil category, $k = 0.5$ for IV soil category and $k = 0.3$ for V soil category (special). Hammer force impulse of one hammer F_i for specific digging depth is multiplied with number of hammers that are grasping the soil. Increasing the hammer's rpm for the same factor k, force impulse $F_i = \mathrm{f}(n)$, $\Delta t = 1 \times 10^{-4}$ s, increase is linear, Fig. 2.11.

For hammer force impulse in the time interval $F_i = \mathrm{f}(\Delta t)$ it can be concluded that, when hammer strikes the soil, force impulse decreases. The force is highest when hammer is striking the soil, and is decreasing during removal of the dug soil layer. It can be assumed that with decrease of coefficient k on the flail's rotor shaft additional power will be required for acceleration of the lagged flail. Theoretically, hammer rotation speed can decrease to zero value. It is not possible to quickly reestablish hammer speed due to dragging force that appears at hammer's reacceleration. Practice shows that such hammer lagging causes rapid wear-out and chain

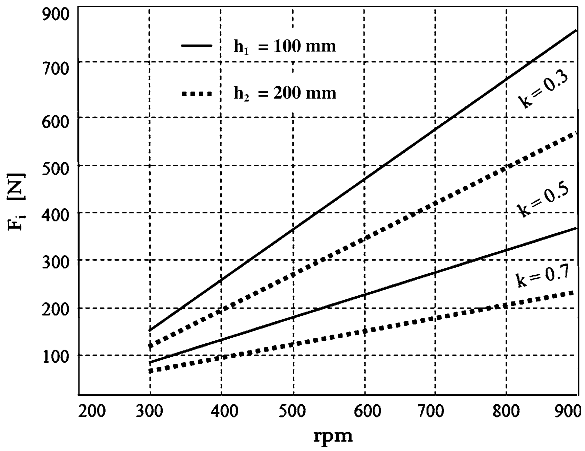


Fig. 2.11 Hammer force impulse in relation to *k*, as a function of rpm $F_i = f(n, t)$

Table 2.5 Grasping hammers force impulse at soil digging F_{in} [N]

Digging depth *h* [mm] *n* rpm	k	h_1 = 100 mm (z = 6) $\varphi_1 = 35°$	h_2 = 200 mm (z = 8) $\varphi_2 = 50°$
n = 200	0.3	1,009.75	1,003.50
	0.5	721.25	716.79
	0.7	432.75	430.07
n = 500	0.3	2,524.38	2,508.75
	0.5	1,803.13	1,791.96
	0.7	1,081.88	1,075.18
n = 900	0.3	4,543.88	4,515.75
	0.5	3,245.63	3,225.53
	0.7	1,947.38	1,935.32

elongation (in practice—when hammers are replaced because of wear-out, chain elongation is 10 %). Finally, with relative restitution coefficient k_0 increment, rotor's resistance increase, meaning that flail rotor requires more power. Grasping hammers force impulse is given in the Table 2.5. It refers to the total impulse force of the number of hammers that are engaged in the soil at any point in time.

2.5.3 Machine Power

Power required for flail rotor rotation

$$P_r = M_u \omega \text{ [W]} \tag{2.30}$$

M_u— total flail rotation resistance moment, includes:

$$M_u = M_{st} + M_{din} + M_d \text{ [Nm]} \tag{2.31}$$

$M_{st} = M_e + M_\mu + M_g;\ M_{din} = M_i$
M_e = *moment of eccentric rotor mass*
$M_e = \Sigma_{i\text{-}n}\ m_{ri}\ g\ r_{ri}$
M_μ = *friction moment in shaft bearing (insignificant)*
$M_\mu = F_\mu\ r_v = \Sigma_{i\text{-}n}\ F_{ci}\ \mu\ r_v$
M_i = *moment of shaft, hammer and chain inertia*
$M_i = J\omega/t + \Sigma_{i\text{-}n}\ m_i\ a\ r_i = \Sigma_{i\text{-}n}\ m_i\ a\ r_i + J\varepsilon$
M_d *moment of flail dragging force* (F_2)

$$M_u = \Sigma_{i-n} m_{ri} g\, r_{ri} + \Sigma_{i-n} F_{ci} f_t r_o + \Sigma_{i-n} m_i a\, r_{oi} + J\varepsilon + M_d \text{ [Nm]}$$

m_i	striking hammers and chains mass (kg)
r_i	flail hammer rotating radius (m)
J	shaft total inertia moment (rotor, hammers, chains) (kgm^2)
ω	angular rotor velocity (s^{-1})
ε	angular acceleration (s^{-2})
F_{ci}, f_t	centrifugal hammer force, resistance factor
r_i *(r)*	rotating flail radius

Power required for machine movement

$$P_v = \Sigma_{i-n} R_i v \text{ [W]} \tag{2.32}$$

$\Sigma_{i\text{-}n}\ R = R_k + R_i + R_\alpha$
$R_k = G\ cos\alpha\ f_k$, rolling resistance (wheels/tracks)
$R_i = m\ a$, inertia resistance
$R_\alpha = G$ sinα, slope resistance
v = machine speed

Total power required for machine movement and operation:

$$P_T = P_r + P_v \text{ [W]} \tag{2.33}$$

Most of the machine power is used for soil treatment using flail, and less power for machine movement. *Engine power* of machine is increased due to losses in power train and additional devices (η_p):

$$P_m = \frac{P_T}{\eta_p} \text{ [W]} \tag{2.34}$$

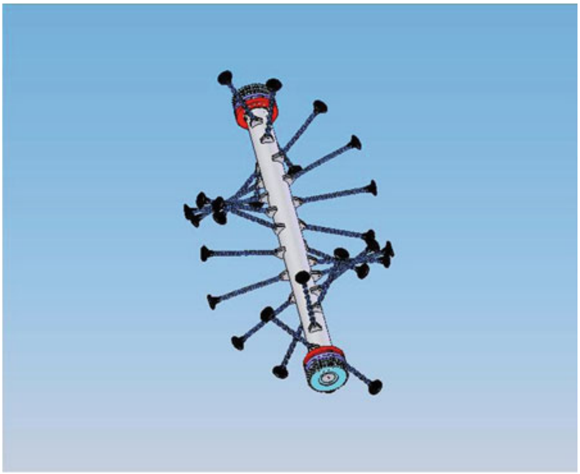


Fig. 2.12 Flail demining helix system

2.5.4 Flail Design

The best soil digging density is achieved by hammer shear of 16 mm, where machine movement speed is less than 1 km/h. Higher machine speed is achieved by hammer shear of 30 mm, which provides for better working efficiency. Machine should maintain required soil digging density (depth, 10, 15, 20 cm), with possibility to lower its movement speed if flail rotor rpm suddenly decreases.

On flail rotor of 2.5 m digging width, 50–70 flails could be attached on several helixes with calculated positioning of flails, which will provide required soil digging density, Fig. 2.12. Flail strikes overlaying for few millimetres ensure that each mine will be destroyed for the whole flail width, i.e. even smallest mine or explosive ordnance will not be missed.

Good machine speed is 0.7–0.8 km/h, and flail rpm is 600–800. In theory, resulting untreated area is extremely small in relation to the size of the smallest mine or its fuse, meaning that the risk of mines not destroyed is very low. Tool shear remains constant; increase in machine movement speed is resulting in increase of rotor rpm, and vice versa.

Most common are machines with flails for soil digging to a certain depth, during which buried mines can be neutralized. In practice, detailed knowledge and understanding of flail design and operation is still not sufficient. That is why evaluation of flail performance, i.e. digging depth, soil treatment quality and ability to destroy smallest AP mines, is done through testing. That provides an analytical model for flail calculations and design of basic flail parameters. Technological working speed and flail rpm are adjusted, interaction forces between flail hammers and soil based on force impulse of flail hammer, and shape of flail hammer and chain in relation to their durability are defined, and dimensions of working tool rotor and flails are determined. Calculation results need to be verified through testing of light and medium demining machines. The flail system has to destroy embedded AP and AT mines. Effects of AP mine explosion

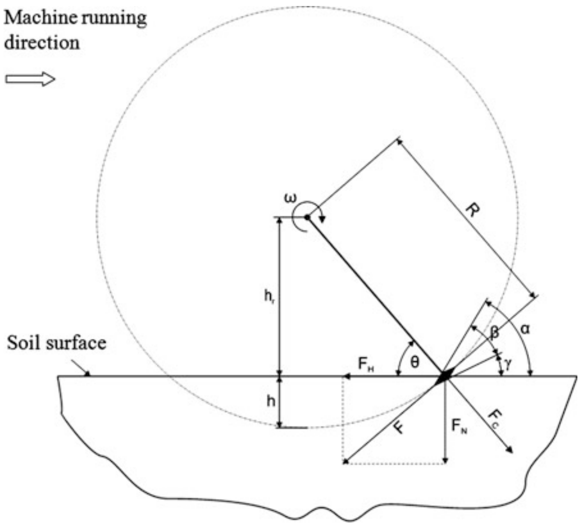


Fig. 2.13 Striking hammer force and geometric parameters of flail; θ hammer striking angle, α cutting angle, β wedge angle, γ back angle, h soil digging depth

shouldn't damage the flail. AT mine activation can cause damage to some chains of the flail. Rotor of the flail system has to remain undamaged and the machine is ready for further demining.

Flails on rotor are mounted along the helix path on the rotor shaft. Helix starts from the middle of the rotor towards the end on each side. Often, two helices with phase shift of 180° are set up. Basic flail dimensions are: flail diameter D, rotor width b, number of helix n_Z, and number of flails/hammers z. In order to reduce number of grasping hammers, number of helix can be increased. Good flail positioning reduces number of grasping hammers and soil treatment resistance.

2.5.4.1 Flail and Soil Interaction

Striking hammer force and geometric parameters of flail are presented in Fig. 2.13. Tangential force F causes hammer penetration and compressive soil disturbance. According to second Newton's Law, follows:

$$F = m_h a_t \text{ [N]} \tag{2.35}$$

m_h hammer mass,
a_t tangential hammer acceleration, $a_t = r\varepsilon$
r hammer CG rotation radius around rotor's axis,
ε hammer angular acceleration

Flail's task is to treat the soil with certain digging depth and neutralization of AP and AT mines. Normal component of force F_N should be as high as possible in

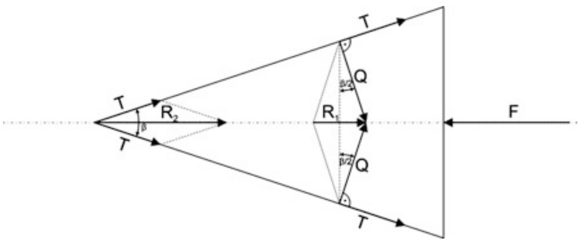


Fig. 2.14 Forces on the wedge when digging the soil

order to dig the soil and crush embedded mines. Force F_H is function of angle sinus θ, and can be decreased, but not too much, because without this force hammer penetration into the soil could not be achieved.

Hammer Force Impulse According to Law on Momentum Conservation

Relation between circumferential hammer velocity before and after collision can be established through soil resistance factor ($k = u/v_o$; v_o—circumferential hammer velocity before collision, u—circumferential hammer speed after collision). Collision factor may be perceived as soil resistance factor, because it can be brought into relation with soil hardness, in order to distinguish the differences for digging of certain soil categories.

Hammer impulse force:

$$F_i = m_h v_0 (1 - k)/\Delta t\,[N],\ \Delta t - \text{impulse duration time}$$

Hammer impulse force has to be higher than cutting resistance or soil cutting resistance, i.e. soil digging condition has to be fulfilled → $F_i > R_{ki}$, i.e. $F_i > R_{\sigma i}$. (R_{ki}—soil cutting resistance/coherent soil, $R_{\sigma i}$—soil crushing resistance/non-coherent soil).

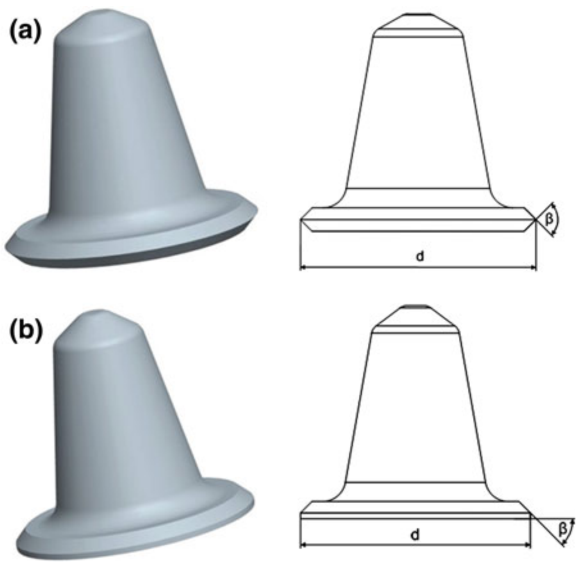
2.5.4.2 Flail Modelling

A part of hammer that strikes the soil can be modelled in a shape of wedge, Fig. 2.14. On the wedge surface, stress pressure force Q appears as reaction to hammer striking force—hammer impulse force. These forces cause digging resistance.

Resultant force R_1 is opposed to tangential hammer force F and represents a part of digging resistance. Stress forces Q acts vertically on wedge surface and cause friction forces T, which appear on the wedge surface. Their resultant is force R_2 which represents a part of digging resistance. The wedge efficiency is determined with ratio of wedge force without friction R_1 and required wedge force F [8]:

$$\eta_w = \frac{R_1}{F}$$

Fig. 2.15 Optimal shapes of striking hammer, hammer diameter d and wedge angle β



$$\eta_w = \frac{1}{1 + \mu \, ctg \, \frac{\beta}{2}} \tag{2.36}$$

The wedge efficiency is higher if friction coefficient μ is lower between the wedge and the soil, and if angle β is higher. For humid plastic soil, smallest digging resistance can be achieved at smaller angles, and for hard soil at higher cutting angles. This means that in this area the wedge efficiency can be observed. It can be assumed that optimal shape of striking hammer for soil treatment in all soil categories is shape of a bell or mushroom, Fig. 2.15. Bell blade vertical cross section has a shape of wedge, and horizontal has cross section shape of a circle. This causes the smallest soil cutting resistances. Hammer's centre of gravity (CG) is placed on hammer axis approximately at (*1/5*-*1/3*)*L* from the hammer base. Hammer head diameter (*d*) is 50–60 (90) mm. Favourable hammer shape for lighter soil categories is shown at Fig. 2.15b. Blade of such hammer has a shape of a wedge, designed so that lower part is vertical to strained chain. This wedge shape enables that necessary cutting angle α can be achieved with smaller flail radius r.

In practice, working tool shapes are simple, in order to manufacture them more easily and of less cost, Fig. 2.16. Material, from which hammers are made, is usually steel for cementing, EN 16MnCr5. With cementing, hard surface layer is achieved, resistant to wear out, and core retains its ferrite—perlite structure, which is tough and resistant to dynamic and strike loads. Striking hammer exploitation life cycle is 40,000–50,000 m^2 of treated soil, i.e. around 50 working hours, after which they should be replaced. Hammer mass is between 0.75–1.5 kg, depending on soil hardness. Flexible connection between shaft and hammer is a chain of 12–15 mm in diameter. Chain's exploitation life cycle is around 80,000 m^2 of treated

Fig. 2.16 Working shapes of striking hammers (*Source* CROMAC-CTDT)

soil, i.e. around 80 working hours, after which it should be replaced. At the contact surface of the chain links, chain extreme wearing out is present, which causes its elongation during operations. Chains that are used for flails are usually made of steel used for improvement EN C45, and is heat treated and tempered and in order to achieve high tensile and yield strength, while retaining toughness and dynamic durability.

2.5.5 Flail Geometry

When determining optimal rotor and flail dimension, the goal is to achieve required soil digging depth h with highest standard force F_H. From this fact, it can be concluded that based on standard striking force F_N component, an optimal rotor axis height h can be determined as a design parameter.

Rotor's height from the ground, Fig. 2.13, is:

$$\begin{aligned} h_r &= r \sin \theta [\mathrm{m}] \\ h_r &= (h + h_r) \sin \theta \end{aligned} \tag{2.37}$$

Hammer impact angle:

$$\sin\theta = \frac{h_r}{h + h_r}$$

$$\theta = arc \sin \frac{h_r}{h + h_r} [^\circ] \tag{2.38}$$

Soil digging depth h is usually known and is 10–20 cm. When calculating dependence of certain flail parameters, soil digging depth h = 10–20 cm and rotor radius r = 400–1000 mm were simulated. Diagram of flail parameters is shown on the Fig. 2.17.

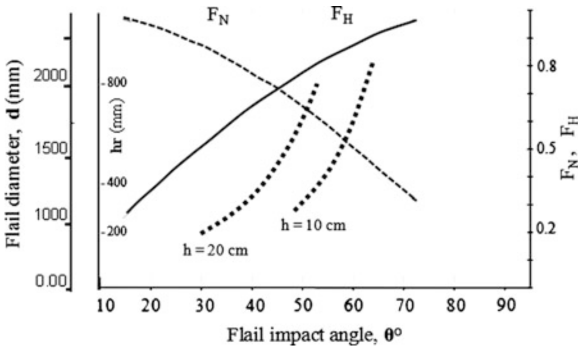


Fig. 2.17 Flail parameters in function of hammer impact angle θ

If rotor height h_r increases, flail angle at which hammer strikes the soil θ increases too. The wedge angle β is chosen according to soil hardness:

- angle of soil cutting: $\alpha = \beta + \gamma$, $\beta = \alpha - \gamma$
- back angle: $\gamma = 90° - \beta/2 - \theta$

When digging resistance increases, rotor height h_r should be increased too, which further increases striking force for the same hammer angular speed. Dependence between hammer striking angle θ and soil cutting angle α can be considered. This dependence determines if the soil is treated by cutting or crushing. For digging soil of lighter category a greater cutting angle α needs to be set, i.e. a lesser hammer impact angle θ, and conversely. For determined wedge angle (e.g. $\beta = 20$–$40°$) dependence between impact angle θ and cutting angle α is linear, e.g.:

- for wedge angle $\beta = 20°$, hammer impact angle is $\theta = 70°$, and cutting angle is $\alpha = 35°$
- for wedge angle $\beta = 30°$, hammer impact angle is $\theta = 60°$, and cutting angle is $\alpha = 45°$

2.5.5.1 Rotor Width and Quantity of Helixes and Flails

Rotor should be designed in a way that number of hammers in grasping operation is the minimum number of hammers, because digging resistance is the lowest, and required engine power is lower, which results in lower fuel consumption and higher efficiency. Number of grasping hammers depends on rotor radius r, and digging depth h. Axial hammer distance is determined by soil treatment density requirements and is usually $l_u = 0$–15 mm. If hammer distance is equal to zero, than there is no difference between the strikes in transverse direction, and if distance is e.g. 15 mm, than distance between strikes in transversal direction is 15 mm. This is acceptable, because the length of mine fuse that is to be crushed is 16 mm, and radius of the smallest AP mine (PMA-2) is 68 mm. Increase of axial

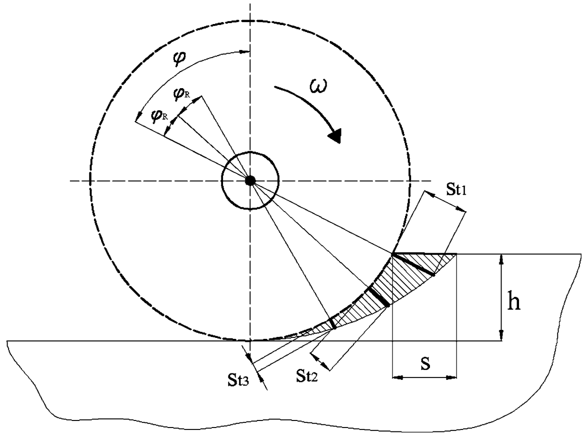


Fig. 2.18 Hammer digging of coherent soil/hammer's phase shift

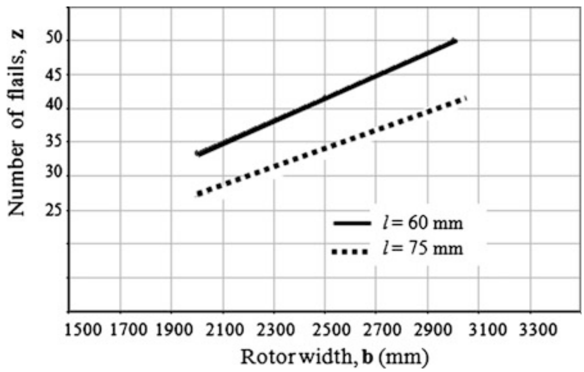


Fig. 2.19 Number of flails/hammers z in function of rotor width b and axial flail distance l on the rotor

hammer distance causes decrease of number of grasping hammers, as well as digging resistance.

Calculated values of hammer blades in grasp φ, hammer phase shifts φ_R, number of grasping hammers z_m and required quantity of flails/hammers z on one helix for different rotor width $b = 2000\ldots3000$ mm, number of helixes on rotor $n_z = 1\ldots3$, axial flail distance $l = 60\ldots75$, axial striking hammer distance $l_u = 0\ldots15$ mm, hammer diameter $d = 60$ mm and digging depth h $= 100\ldots200$ mm, were simulated too (Figs. 2.18, 2.19).

Angle of hammer chain

$$cos\varphi = (r - h)/r \tag{2.39}$$

Hammer's phase shift/angle between two hammers

$$\begin{aligned} \varphi_R &= 360l/Z \\ Z &- helix\ step \end{aligned} \tag{2.40}$$

Number of helixes on rotor

$$n_z = 1 \ldots n_n \tag{2.41}$$

Number of flails on one helix

$$z = 360/\varphi_R \tag{2.42}$$

Number of hammers in grasp

$$z_m = \varphi/\varphi_R \tag{2.43}$$

Axial flail distance between hammers

$$l = (2d + l_u)/2 \tag{2.44}$$

d hammer diameter,
l_u distance between hammer grasps

Machine working speed and rotor rpm

$$v = Sn, n = v/S \tag{2.45}$$

S hammer shear,
v machine speed, n rotor rpm

Current thickness of dug soil layers

$$\begin{aligned} S_{t1} &= S \sin \varphi \\ S_{t2} &= S \sin(\varphi - \varphi_R) \\ S_{t3} &= S \sin(\varphi - 2\varphi_R) \end{aligned} \tag{2.46}$$

If rotor width increases, total number of rotor flails increases too. If axial flail distance on rotor is higher, number of flails decreases. Rotor width is important parameter from the machine efficiency point of view, because machine with wider rotor can treat the soil faster. Rotor width is constant, and digging depth depends on users' requirements, flail optimization is done by selecting the number of helixes and rotor radius. At the end of analysis and flail dimensions calculation, *optimal flail parameters* can be estimated.

For soil digging depth of 20 cm and flail width up to 2 m, flail radius is between 0.75–2.0 m. According to this parameter, necessary flail striking force or impulse force, which enables soil cutting, can be determined. Number of striking hammers is 25–40 for the rotor width of up to 2 m, and they can be placed on two or more helices. Striking hammer mass, regarding its volume, is 0.6–1.5 kg. Based on analytical calculation and machine design, it can be concluded that considered flail calculation model is adequate. Relevant values of flail parameters regarding soil digging criteria and AT mine detonations are provided in Table 2.6.

Table 2.6 Relevant values for flail design parameters

Rotor width, b	2.0 m	2.5 m	3.0 m
Rotor radius, r	400–1000 mm	400–1000 mm	400–1000 mm
Digging depth, h	to 200 mm	to 200 mm	to 200 mm
Number of hammers, z	33 (27)	42 (33)	50 (40)
Hammer weight, m_h	0.6–1.5 kg	0.6–1.5 kg	0.6–1.5 kg
Hammer diameter, d	60 mm	60 mm	60 mm
Number of helix, n_z	1–3	1–3	1–3
Distance between strikes, l_u	0 mm (15 mm)	0 mm (15 mm)	0 mm (15 mm)
Rotor rpm, n	300–1000 min^{-1}	300–1000 min^{-1}	300–1000 min^{-1}
Working speed, v	0.5–1.7 km/h	0.5–1.7 km/h	0.5–1.7 km/h

Table 2.7 Parameters of the MV-4 flail system

Light machine	MV-4
Rotor width, b	1800 mm (2015)
Rotor radius, r	450 mm
Digging depth, h	200 mm
Number of hammers, z	27 (34)
Hammer shape and weight, m_h	Bell-shaped hammer, 0.8 kg
Hammer diameter, d	95 mm (60 mm)
Number of helixes, n_z	3 (2)
Distance between hammer strikes, l_u	48 mm (34.5 mm)
Rotor rpm, n	0–900 min^{-1}
Working speed, v	0.5–2 km/h

2.5.5.2 Mine Neutralization and Flail Durability

Calculation results were verified on development and testing of the MV-4 demining machine. Parameters for soil treatment of the working unit MV-4 are provided in Table 2.7. Neutralization of AP mines after soil treatment is shown on Fig. 2.20.

Effects from AP mine explosion are not significant and do not damage the flail. However, AT mine activation, e.g. of 6 kg TNT can cause major damage to the flail system. For low rotor position above the ground (small r) damage to the working device is major, requiring replacement of whole device. Evaluation of "cone of destruction" of AT mine effects has been done, according to NATO II level protection (6 kg TNT). Evaluation is based on *MV-4* demining machine testing results.

To verify flail durability, reflective blast pressure p_{ur} which appears under the flail, is applicable [9]. To verify striking hammer durability, pressure of detonation products p_d is applicable, and to verify flail sides, a pressure of a blast wave p_{us}, is applicable, Fig. 2.21. At the distance of rotor shaft from the ground of 50 cm, reflective blast pressure p_{ur} of AT mine with 6 kg TNT-a, is up to 60 MPa (600 bar). Regarding tests performed, this pressure does not have important influence on the rotor's shaft of 150 mm in diameter, except for the few damaged flails which were in direct contact with the mine. However, if explosion happens at

Fig. 2.20 Neutralized mines, crushed mines (Reproduced with permission from CROMAC-CTDT)

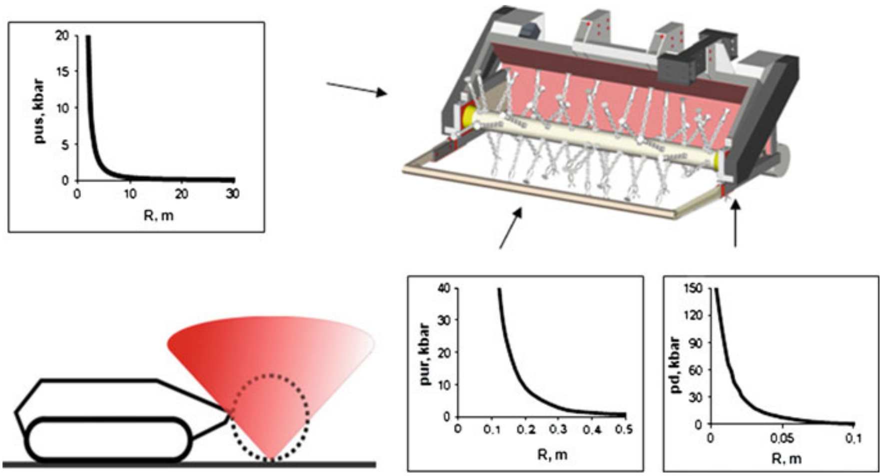


Fig. 2.21 Blast test—AT mine striking wave effect on flail, under the rotor, on the end of the rotor, and aside the rotor

the end of the shaft, there is possible damage to the shaft bearing. When testing MV-e flail durability against a more destructive mine (8 kg of TNT) under the rotor, 4–5 flails were damaged. Rotor itself had been undamaged and the machine was ready for further operations [10].

2.5.5.3 Conclusion

1. Design of flail system is done based on soil category that will be treated using machines and requirements for digging depth h and resistance to detonation of AT mines. If treated soil is of lighter category, than rotor radius can be smaller. If treated soil is of heavier category, than rotor radius has to be bigger in order to provide adequate striking force F to overcome digging resistance.
2. Wedge angle β is selected according to soil category that has to be treated, and for lighter soils that are treated by cutting, a smaller angle β is selected, while for harder soils that are treated by crushing, a higher wedge angle β is selected. Additionally, for treatment of lighter soils, hammer of light weight are used, and for soils of harder categories hammers of heavier weight are used.
3. Rotor width depends on user's requirements for machine working efficiency. If rotor is wider, working efficiency U is higher. Number of flails with hammers for soil digging is $z = 25$–30 for digging width of $b = 2$ m. Soil treatment density depends on machine movement speed v and rotor rpm n, i.e. on longitudinal distance of striking hammers l_u and distance between the hammer strikes. Optimal flail diameter is within $D = 1$–2 m for digging of all soil categories at depth down to $h = 30$ cm.
4. "Cone of destruction" of AT mine with 6 kg of TNT destroy several flails on the rotor, but does not damage the rotor. Explosion at the end of the flail can cause damage that could require rotor replacement.

2.6 Demining Machine with Tillers

Tillers design is based on principle of digging the soil and mine neutralizing. Soil digging mode shows rotor relative rotation in relation to machine movement, i.e. shows direction in which the soil under the rotor is thrown out, Fig. 2.22. Counter-direction mode of soil digging is used for neutralizing mines under the rotor, and the same direction mode is used for neutralizing the mines in front of the rotor, Fig. 2.23. When digging the soil in the same direction mode cutting force is trying to lift the object off the ground, and mine can be crushed, detonated or ejected. In counter-direction soil digging mode, tiller tries to press the object into the ground, and mine can be crushed, detonated or embedded deeper. Regarding tool durability, digging in the same direction is better for the soil with hard surface layer, because tool blades are first digging through the softer soil under the hard surface layer. In counter-direction mode, tool blades are striking the hard surface layer first.

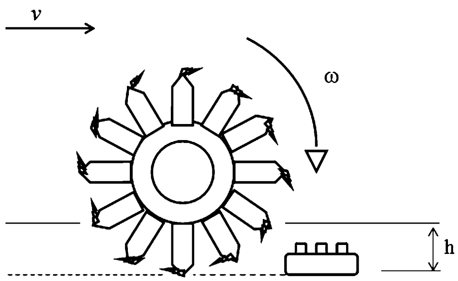


Fig. 2.22 Principle of mechanical demining with tiller

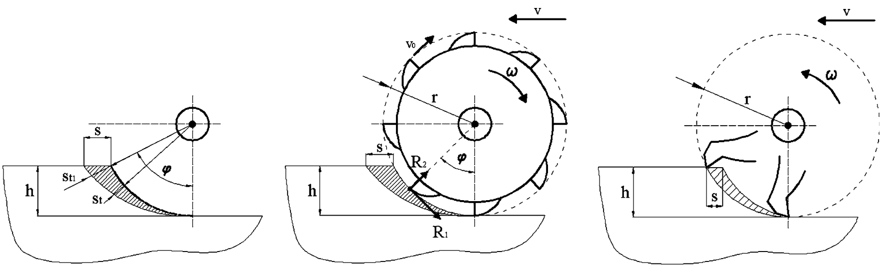


Fig. 2.23 Soil digging—in the same direction and counter direction, shape of cut layer

2.6.1 Helix System

Positioning model of tiller tool has a shape of helix bolted along the rotor (to the left and to the right from the rotor centre) with sharp teeth for soil digging and mine neutralizing. Helix acclivity angle is $\alpha = h/2\ r\ \pi$, where h—helix pitch, and r—radius of tiller rotor. Along this helix, teeth are attached to the rotor. Density of mounted teeth and tiller cutting resistance depends on helix acclivity. Besides milling, one part of unmilled soil has uniform movement along the rotor, due the helix, acting as tape-loop. For each rotor revolution, material is moved forward for the distance equal to helix pitch.

Teeth blades should be positioned tangentially in relation to tiller rotor. Positioning of teeth blades on rotor depends on object that should be destroyed. For AP mines, critical size or tool shear of 16–30 mm is assumed. Size of 16 mm is strictly set up, for destruction of smallest mine fuses. Distance between teeth blades on circumference rotor lines has to be less then critical value. From the mine-clearance diagram technological machine movement speed and rotor rotation speed are determined.

2.6.2 Cutting Resistance

When digging, most of the teeth blades are grasping the soil. Number of grasping teeth blades depend on digging depth. Uneven number of tools that are grasping the soil, and change in depth of soil cutting, is causing asymmetric digging resistance and asymmetry in required rotor torque. Soil digging consists of two phases, *cutting phase* and soil layer *displacement phase*. Total digging resistance of the first phase consists of tangential component in direction of tangent on blade trajectory, and perpendicular vertical resistance component directed towards rotor axis, i.e. radial components. Displacement resistance between material and teeth along the rotor helix is not negligible, because part of excavated material is moved along the tool.

Cutting resistance is tangential component of digging resistance

$$R_1 = k_1 b\, S_t \text{ [N]} \tag{2.47}$$

k_1 specific cutting resistance
b tool blade width, teeth
S_t cutting layer thickness

Total cutting resistance m—blade in grasp

$$R_{1u} = \sum\nolimits_{1-m} k_1 b\, S_{ti} \text{ [N]} \tag{2.48}$$

Normal force is radial component

$$R_2 = (0.2 - 0.6)R_1 \text{ [N]} \tag{2.49}$$

Specific cutting resistance depends on tool shape and condition of its blade. More significant for resistance is increase of cutting depth in relation to width, i.e. resistance decreases if lower cutting depth and higher width apply. Resistance is slightly changed with change of blade angle (β), increase of cutting angle above $\alpha = 45°$ is followed by high increase of resistance. Blade can be in shape of cone, semicircular, rectangular, etc. The best results provides arched circular blade with convexed frontal part under the angle of 12–15°. Tool blade enters the soil quickly, pressure spreads to the tool sides, and soil prism is formed in front of the rotor. Used and blunt blades could increase digging resistance up to 30 %. At digging velocities (0.5–2.0 m/s) resistance change is negligible, but with the double amount of velocity increases resistance significantly. Soil layer cutting depth is only value that could be counted on, when decrease of all resistances is concerned, but this decreases working efficiency.

For hard and rocky soils, blade is strengthened using additional teeth, which are taking over the initial load and are scattering the soil. Teeth are decreasing cutting resistance for 10–30 % and are protecting tool blade from wearing out too quickly. At soft soils of categories I and II, teeth influence is insignificant, because it increases friction resistance and digging resistance. Soil sticks to teeth and tool,

Fig. 2.24 Tiller working tool shape, wedge blade with "ears" (MV-4)

Fig. 2.25 Verification of a demining machine with tiller (Reproduced with permission from CROMAC-CTDT)

obstructing soil powdering and dumping. Teeth are mounted at the end of the discs for soil scattering and destruction of mines. Teeth can be made of abrasive resistant steel. Teeth or bits are mounted onto the holder of the demining roller. Bit material must be abrasive resistant to withstand the impact loading while cutting in the category of hard soil. Use of tungsten carbide has partially solved the problem and improved bit life.

Working tool should use adequate rotation speed and should be provide with adequate power for soil digging, in order to overcome digging resistance, Fig. 2.24. Usually, shape of cutting tool is adjusted according to soil category. Required working power should be adjustable and verified, due to uneven increase in digging resistance on the tiller, Fig. 2.25.

Power Required for Machine Work

$$P_r = R_{1u} v_o \ [\mathrm{W}] \tag{2.50}$$

v_o circumferential rotor velocity
Power Required for Machine Movement
Machine movement resistance

$$R_u = R_k + R_i + R_\alpha \ [\mathrm{N}] \tag{2.51}$$

$R_k = G f_k \cos\alpha$, rolling resistance (wheels/tracks)
$R_i = m\ a$, inertia resistance ($G\ v/g\ t_s$)
$R_\alpha = G \sin\alpha$, acclivity resistance
v machine speed
G machine mass
f_k rolling resistance coefficient
a machine acceleration (t_s machine acceleration time)
Power required for machine movement

$$P_v = R_u v \ [\mathrm{W}] \tag{2.52}$$

Total power required for demining machine

$$P_T = P_r + P_v \ [\mathrm{W}] \tag{2.53}$$

Engine power should be increased for the losses in transmission (η_p), engine cooling system, hydraulic oil cooling system, air filtration, power for auxiliary devices, etc.

$$P_m = \frac{P_T}{\eta_p} \ [\mathrm{W}] \tag{2.54}$$

2.7 Demining Machine with Rollers

Demining rollers were first used by armed forces. AP and AT mines are destroyed by direct pressure of the roller onto mine fuse. Device with discs, for AT mine activation, mounted in front on the tank is well known. By the use of discs, higher speed in opening of the passages through the minefields can be achieved. After that, machines of miller and tiller type can be used for complete soil treatment to a certain digging depth. In humanitarian demining, demining machines with rollers are used, designed and adapted for real demining conditions. For example, on very dry terrains, use of tiller is causing sand clouds, which prevents machine demining. In these conditions, devices with demining rollers can be used.

Through the analysis of efficiency of one disc device, relevant parameters for design of humanitarian demining devices can be determined. Criteria of disc durability in minefield and significant factors of reliability of buried mines destruction are identified. The most important factors are quantity of explosive, machine movement speed, soil type, and soil profile and condition.

2.7.1 Heavy Mine Rollers

Mine explosion is caused by disc pressure on mine fuse. Explosion pressure of AT mine ejects the section of discs to the height of 1.0–1.5 m [11]. When ejected, discs could be damaged. Total weight of demining device is 7000 kg. Weight of one disc is 500 kg, because AT mine are activated by pressure of 300 kg. Due to better mine detection and their activation, disc hole is larger than axis diameter for 250 mm, so they can moved in vertical plane and adjust to ragged terrain profile. *Discs rims are ribbed in order to cut through the masking soil layer and to activate mine fuse, and to ensure discs rolling—to prevent sliding that will push the mine without destroying it.* Working speed during demining is 10–15 km/h. Slope and side slope can be up to 20°. Mechanical durability of disc sections to mine explosion impacts should be around 10 explosions of AT mines (5.0–7.0 kg of TNT). Disc shortcomings are inability for quick change of direction, i.e. poor maneuverability of machine equipped with disc, difficult use on slopes, poor performance on soft soils.

Reliability of Mine Activation

When opening the passage in minefield, it is expected that under one demining disc section several mines will be activated (up to three mines). Number of destroyed AP mines in a minefield can be calculated using probability theory. Detection of AT mines and their activation using demining disc device determines reliability of mine-clearing machine operation, evaluated through two scenarios, Fig. 2.26:

$\boldsymbol{p_1}$ —probability that disc sections will hit the mine in minefield,
$\boldsymbol{p_2}$ —probability that mine will be activated by, for example, device equipped with two disc sections.

As both scenarios have to occur simultaneously, reliability of mine activation, when two disc sections ($\eta = 2$) cross over one mine lane in minefield, is $\boldsymbol{R = p_1 p_2}$. Probability $\boldsymbol{p_1}$ that mineclearing machine will hit the mine in one minefield lane, depends on distance between two neighbouring mines, diameter of pressure sensitive mine cover, disc section width, required overlap of the mine cover and disc section. Randomly set minefields are excluded.

Demining device has to protect the vehicle it is mounted on, and probability for sections hitting the mines has to be higher than the probability of vehicle hitting the mine in one lane. It is obvious that this is achieved by width of disc sections being higher than width of wheels or tracks. Probability $\boldsymbol{p_2}$ depends on disc profile,

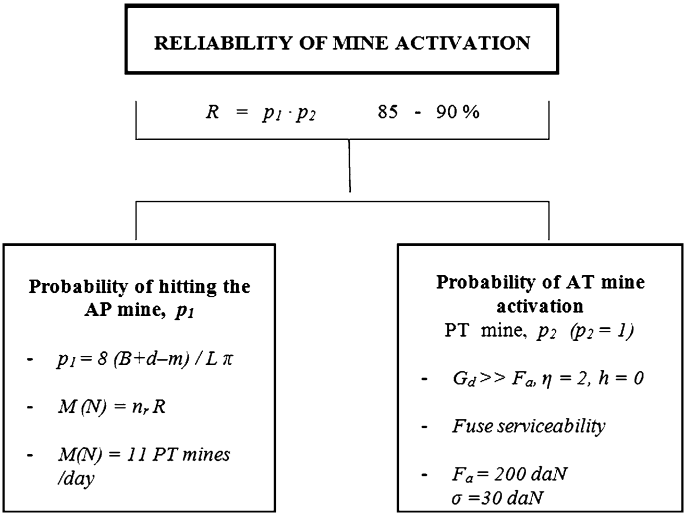


Fig. 2.26 Reliability calculation for AT mine activation

so that disc intersects the protective soil layer above masked mine and ensures direct contact for activation, $h = 0$, where h is depth of masking layer. It is assumed that the force of disc weight on the mine is always higher than force needed for mine activation, which is assured by disc weight safety factor.

Mathematical expectation for number of activated mines, when mine-clearing machine crosses minefield with "n" lanes, is:

$$M\,(n) = n_r R \tag{2.55}$$

Reliability of mine activation in one lane of a minefield is usually around 61 %. Expected number of activated mines M = 11 PT mines daily, with assumption that mines are laid at the common military distance of 4.5 m [11].

$$p_1 = (8/\pi)\,(B + d - m)\,/\,L \tag{2.56}$$

B	width of one disc section, 0.89 m.
d	diameter of AT pressure sensitive mine cover, PT mine, 0.2 m.
m	required overlap of the mine cover and disc section, in order to activate the mine, 0.05 m.
L	distance between two neighbour mines (from axis to axis), 4.5 m.
p_2	probability of mine activation, 1.0.
n_r	number of cleared lanes per day, 18.
R	reliability of mine activation for one minefield lane, $R = p_1 = 61$ %.
$M\,(n)$	mathematical expectation for number of activated mines per day, 11 mines/day.

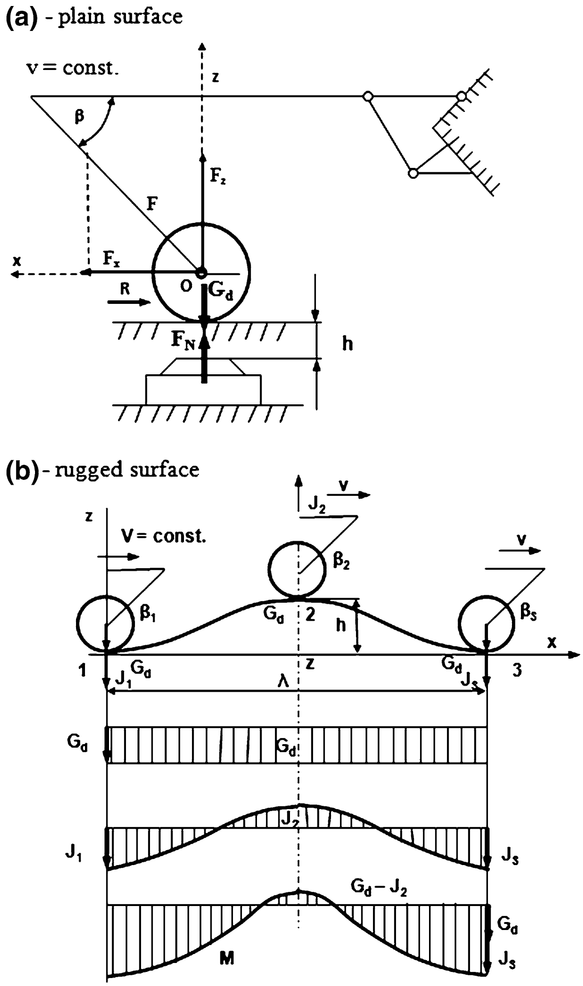


Fig. 2.27 Load at disc movement on plain (**a**) and rugged surface (**b**)

Identification of Factors for Mine Activation

According to force scheme for disc movement on ***plain surface*** and *uniform movement*, soil reaction *(F_N)* depends on soil type and disc shape, Fig. 2.27a. When disc is shaped cut through masking layer *($h = 0$)*, and when soil load bearing capability is sufficient to prevent mine from sinking under the load, soil reaction force is equal to mine activation force *(F_a)*. Discs weight has to be equal or higher than activation force, i.e. condition for mine activation is $G_d \geq F_a$.

Due to equilibrium condition, disc weight equals:

$$G_d = F_a(1 + f_r tg\beta) \quad (2.57)$$

This means that force by which disc acts on mines depends on disc rolling resistance coefficient *(f_r)* and section inclination *(β)*, not only on disc weight.

Disc movement on ***rugged surface*** can be set up along ***cos*** curve with constant movement speed, Fig. 2.27b:

$$z = h/2[1 - cos(2\pi x/\lambda)] \tag{2.58}$$

X—travelled distance, λ—period (bump length), *h*—bump height.

At disc movement on rugged surface, inertia force J_i appears, which depending on direction, decreases or increases reaction force of the surface:

$$\begin{aligned} F_N &= (G_d \pm J_i)/(1 + f_r tg\beta) \\ J_i &= M_d Z'' \end{aligned} \tag{2.59}$$

Acceleration:

$$\begin{aligned} z'' &= h/2(2\pi v/\lambda)^2 cos(2\pi t/\lambda) \\ x &= vt \end{aligned} \tag{2.60}$$

$$G_d = F_a(1 + f_r tg\beta) / 1 \pm 2h/g\,(\pi v/\lambda)2 \tag{2.61}$$

Force, by which disc affects the mine in movement on rugged foundation, depends on rolling resistance coefficient (f_r), on angle (β), on movement speed (v), on bump length (λ) and on bump height (h). Based on Eq. (2.61), disc design parameters can be calculated, as well as diameter (D) and disc width (e), Fig. 2.28. Influence of particular factors on buried AT mine activation using disc demining device is presented in Fig. 2.29 [11].

Analysis

It may be assumed that mine activation force is random value, distributed according to standard law: $F_a = F_a^{sr} \pm 3\sigma$. Mine activation force F_a is practically within limits of 1200–3000 N ($\approx$120–300 daN), mine activation diagram shows:

1. With increase in movement speed, force required for mine activation is decreasing. With speed higher than 14 km/h, mine will not be activated according to $F_N = 451–1.56\ v^2$ (daN). If tank moves at high speed, solders have to be satisfied with mine destruction reliability of 80–90 %.
2. With increase of disc rolling coefficient, $f_r = 0.12–0.45$, expressed force values F_N are adequately high for safe mine activation.
3. With increase of bump height *h* over 300 mm, mines are left inactivated. In order to follow the terrain profile, a gap between discs bore and axis of 160–250 mm is introduced. To decrease the influence of rough surface even more, discs rims are ribbed. Soil is cut by ribs and influence of rough surface is decreased, $F_N = 451–11.2\ h$ (daN).
4. With increase of bump length $\boldsymbol{\lambda}$ over 2 m, activation of all mines may be expected, but not below distance of $\boldsymbol{F_N} = 451–2016/\boldsymbol{\lambda}^2$ (daN). For value $\boldsymbol{\lambda} = \infty$, movement on smooth surface is established.

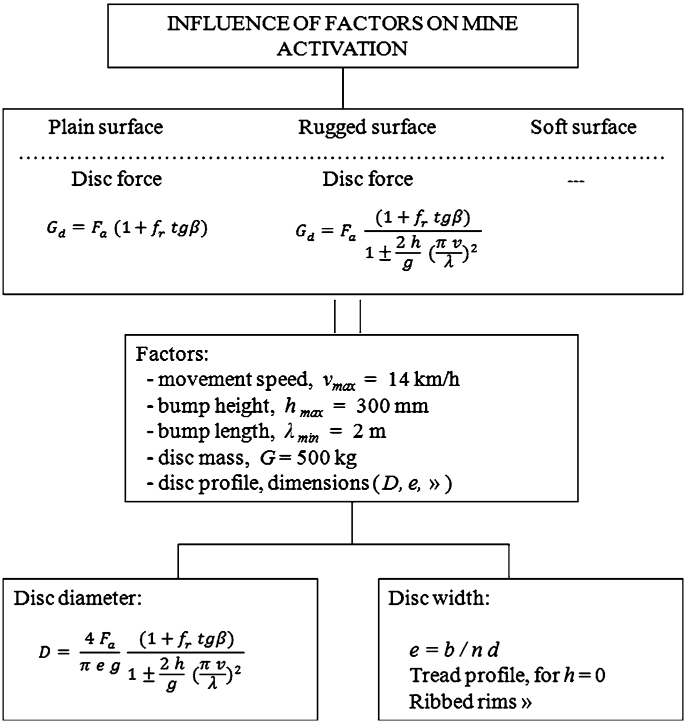


Fig. 2.28 Influence of factors on AT mine activation and disc design parameters

Therefore, *significant factors for mine activation using discs are* movement speed, surface profile, disc shape, soil conditions and inclination of disc sections.

Basic user requirements for demining machine development, i.e. demining device with discs are as follows:

Durability of device against AT mine explosions, (6 kg TNT—at least 11 mine),

Reliability of mine activation and mine destruction, $p = 80–90\ \%$,

Movement speed for mine removal of 10 km/h,

Crew protection against AT mine impulse noise, peak value of 150 dB,

Quick replacement of damaged discs.

2.7.2 Medium Mine Rollers

Demining machines can neutralize laid AP mines using weight of discs, which are placed in one or more roller sections. Behind machine, rakes for soil preparation can be attached in order to collect metal fragments from soil surface using magnets, before inspection with metal detectors.

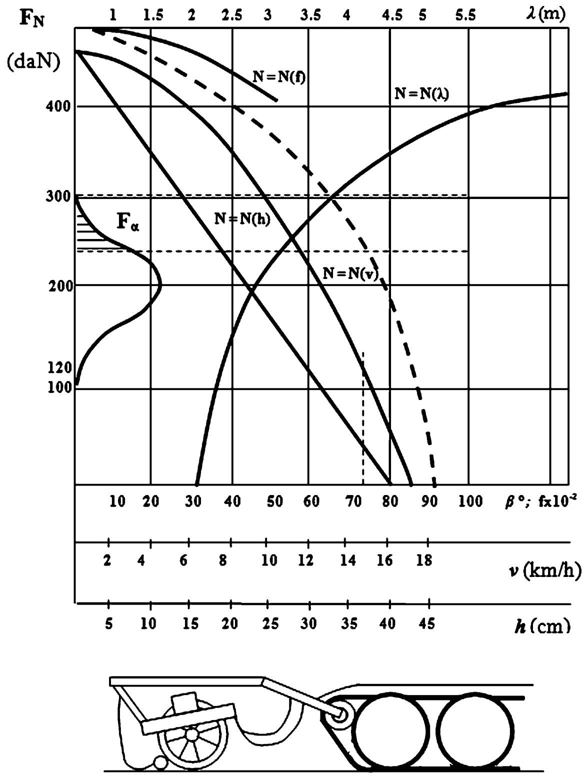


Fig. 2.29 Mine activation diagram of buried AT mine with pressure-activated fuse, using disc demining device

Machines with medium and mini rollers may serve as additional machines in machine demining, for the following purposes:

- to prepare surface for demining, to detect mine polluted areas and to reduce mine polluted areas,
- for demining the areas that are polluted only with AP mines, as part of overall demining mechanization based on mine neutralization (crushing, activation),
- for the control of mine pollution of roads for road maintenance in mine suspicious areas.

Advantages of medium and mini rollers in demining

- for determining the level of mine pollution in mine suspicious areas, larger number of rollers can be used at the same time in demining operations,
- possibility to replace rollers with other demining tools,
- collecting the metals after the use of other demining machines,
- low serial roller production costs.

Disadvantages

Due to soil intersection, especially spongy and muddy soil and massive vegetation, demining of mine polluted area by pushing the rollers in front of the

Fig. 2.30 Light demining machine with roller, 2t, 10 segments. (Reproduced with permission from Ref. [8])

machine, is aggravated or almost impossible. That's why rollers are in some cases towed behind the mine resistant machine.

Accidental AT mine activation can damage the rollers, although well designed discs provide possibility of blast ventilation.

It can be concluded as follows:

demining machines with medium and mini rollers can be used in humanitarian demining as a part of entire mechanization for machine demining as well as for road maintenance in mine suspicious areas (Fig. 2.30).

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