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Foreword

The book *Construction Machines* shows the *theory and design* of these machines. This is a professional book that provides knowledge on how to model, calculate, and design the machinery for construction operations. The key technical solutions of mobile construction machines are presented.

Carrying out the construction works is unthinkable without construction machines. Therefore, knowing the role and properties of construction machines is very important for their construction, production, application, and maintenance. The fundamental properties of the basic construction machines, bulldozers, loaders, excavators, vibratory rollers, cranes, telehandlers, and construction trucks are defined.

The authors of the book used an expert methodical approach that connects theory, construction and practice of using machines, in a gradual, expert and illustrative way, with the help of pictures, schemes and examples.

The content of the book covers the requirements of professional literature that enables an efficient approach to the application of technical knowledge in the field of mechanical engineering. The book can also be used in vocational educational institutions and businesses.

We hereby thank the authors for creating this publication. This should help the development of construction machines in the world and their use in construction operations.

Zagreb, Croatia

Vladimir Koroman
Andrija Šaban
Reviewers

Preface

The book *Construction Machines* describes the properties of modern construction machines and their design. There are three important factors that influenced its writing; the lack of professional literature for the education of engineers for the development, application and maintenance of these machines.

The technical solutions of the machines are processed step by step in an expert and illustrative manner, with the help of pictures, diagrams, tables, and examples. The properties of representative machines for earthworks, bulldozers, loaders, excavators, vibratory rollers, as well as other machinery, truck cranes, telehandlers, construction trucks, and their maintenance systems are explained.

The knowledge about the construction machines is very important for their efficient use and maintenance. With partial or complete automation of work, the construction works are carried out precisely, quickly, and safely. For work operatives and entrepreneurs, the machines are, along with manpower, a decisive factor in the execution of contracted jobs.

The book is primarily intended for students of professional studies, and it can be used in other educational institutions and businesses. For some of the images used, we sincerely thank their authors, all for the purpose of educating experts. We would like to thank the reviewers of the book who willingly accepted the review and offered useful advice.

Special thanks to cooperating institutions: *University of Applied Sciences Velika Gorica, DOK-ING Company, Teknoxgroup Hrvatska Croatia.* Also, we thank the collaborators for their support in writing the book, Andrija Šaban, Josip Rauker, Goran Košir, and Emil Hnatko.

We believe that the book will help in the education of engineers and technicians in solving the problems of construction machinery.

Zagreb, Croatia — Dinko Mikulić
February 2024 — Draško Mück

Contents

Abbreviations

CG	Center of Gravity
CI	Soil Cone Index
E	Electric transmission
EBS	Electronic Braking System
FOPS	Falling-Object Protective Structure
GP	Global Positioning System
H	Hybrid transmission
HD	Hydrodynamic transmission
HS	Hydrostatic transmission
M	Medium active time of preventive and corrective maintenance
MDT	Mean downtime time due to maintenance
MMP	Mean maximum ground pressure
MTBF	Mean time between failures
MTBM	Mean time between maintenance
MTTR	Mean active repair time
PTO	Power Take-Off
ROPS	Roll-Over Protective Structure

Chapter 1
Introduction

1.1 Role and Importance of Construction Machines

Construction works are carried out on various buildings, civil engineering and high-rise construction, and other facilities. Civil engineering works are construction works on the objects of transport and water management projects. The main feature of these works is the extent of earthworks over a larger area. Construction works are works on residential, commercial and social facilities. The main feature of these works is that they are performed in relatively small spaces. Other construction works on objects are communal works, works on bridges, viaducts, tunnels, and the like.

The wide scope of construction works increases the use of construction machinery. Advanced construction technology requires the construction of new construction machines. Only by using construction machines can demanding work be done in a short time. Therefore, the role of construction machines in the construction of buildings is very important.

The construction operative is equipped with a variety of machines. The efficiency of the construction machines is their basic indicator. The efficiency of the machine is the amount of material that can be processed in a unit of time, expressed by volume, mass, per piece (m^3/h, t/h, pc/h, etc.). On the example of efficiency of several construction machines for earthworks, their importance for the execution of construction works is recognizable. The efficiency of a medium-class crawler bulldozer, for digging and pushing the earth, in a radius of 15–30 m, is up to 100 m^3/h. The efficiency of a wheel loader when excavating the earth is approximately 100 m^3/h, and when loading loose material by truck it is 150 m^3/h. The efficiency of a rotary backhoe on the construction of canals in waterworks with a depth of up to 1.5 m is 200–300 m/h, etc.

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Therefore, in construction development and the humanization of human work, it is not possible to achieve social progress without construction machines. That is why the development and production of construction machinery is developing intensively. New machines are appearing adapted to new construction technologies, with high performance and quality of work performed. By partial or complete automation of the work process, the construction works are performed precisely, quickly, and safely. For construction work organizations and entrepreneurs, the machines are often a decisive factor in the performance of contracted work. Therefore, it is almost unthinkable to talk about construction and not think of the construction machinery at the same time.

1.2 Division of Construction Machines

Considering the required variety of construction works, construction companies use a large number of dedicated machines. The division of construction machines according to purpose, classifies the machines into four main groups:

- Earthmoving machines;
- Machines for working in stone and concrete;
- Machines for lifting and moving cargo;
- Transport machines / cargo vehicles.

Machines can be divided into self-propelled, attached, light, medium, and heavy machines, as well as machines with cyclical and continuous work.

Earthmoving machines

Bulldozers
Graders
Scrapers
Loaders
Excavators
Vibrating rollers and plates

Machines for working in stone and concrete

Compressor machines
Drilling rigs
Crushers
Milling machines

Machines for lifting and moving cargo

Mobile cranes
Telehandlers
Tower cranes

Transport machines/freight vehicles

Conveyor belts and the like
Construction trucks and trailers.

1.3 Construction Machines Structure

A construction machine consists of the basic machine (undercarriage) and one or several working devices for performing works, Fig. 1.1. The necessary power for the working devices is provided by the drive engine, which can be located in the undercarriage or on the superstructure, or sometimes the power is provided by the engine of the attached means.

The chassis of the machine is tracked or wheeled. Tracked machines are more mobile off-road than wheeled machines. However, wheeled machines intended for off-road movement also provide good mobility on soft ground, because the surface pressure on the ground approaches that of tracked machines. Considering the trafficability of the soil, modern 6×6 and 8×8 wheeled vehicles can be compared to

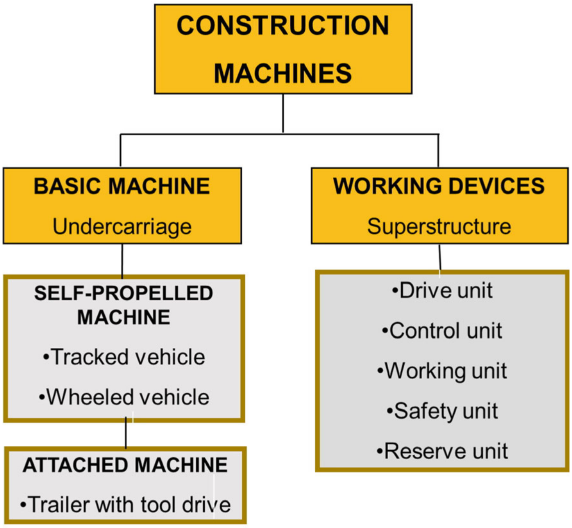

Fig. 1.1 Construction machine structure

tracked vehicles. Therefore, tracked and wheeled machines represent the basis of the development of construction machines.

The working device is directly related to the purpose of the construction machine. The executive body of the working device directly performs the technological process. The working body is controlled by hydraulic and electronic system components. The required working pressure is created by a hydraulic pump driven by a drive motor. The safety of the machine operation depends directly on the installed measuring equipment, which prevents the consequences of disturbances due to poor handling of the machine.

Basic machine drive (undercarriage)

- Diesel engine and mechanical transmission
- Diesel engine and hydraulic transmission
- Diesel engine and hydro-mechanical transmission
- Diesel engine and electric transmission
- Hybrid transmission.

Working device drive (superstructure)

- Diesel engine and hydrostatic transmission

1.4 Lifetime of Construction Machines

An important property of construction machinery is its working life or durability. The working life of a construction machine is based on the resistance of key assemblies and parts of its construction. In accordance with the purpose of the machine, the computer calculation of the structure is carried out for static and dynamic load, wear resistance, and in the case of special machines, for resistance to mine destruction.

When the machine is overloaded, parts can fracture in the mechanical construction, which can be plastic, rigid, and fatigue. Rigid fracture occurs at places of stress concentration, and fatigue fracture occurs due to highly variable stresses. Fatigue fracture is of particular importance for the durability of parts. The working life of key parts of the machine is defined as 10,000 working hours, which determines the lifetime of the machine. These are usually complex and expensive parts, which cannot be repaired or replaced. The calculations are made according to the load spectrum during the working life of the machine. By simulating the load according to the load spectrum and the fatigue curve, the durability of the parts can be determined. The reliability of parts can be determined based on the probability of working and critical loads.

For the key parts of the working device mechanism, the materials with increased tensile strength, increased strength, high toughness at low temperatures, and resistance to cracking are used.

The cause of a higher load on the machine may be due to the blunting of the blade of the working tool. That is why it is important to evaluate the durability of parts according to the rate of wear. The durability indicator is the number of machine hours at which wear reaches the limit value. This increases the efficiency of the machine, i.e. the ability to perform tasks at minimal costs.

1.5 Development of Construction Machines

Based on the requirements of construction technology, various machine designs have been developed. From the point of view of development or procurement of the machine and its economy, three directions of development can be distinguished:

A—development of a special machine
The development of a special machine is economical for large construction organizations, when contracting large jobs, where the machine can be used (large and complex jobs—they can accept an expensive machine).

B—development of a standard machine
The development of a standard machine is economical when performing medium- and large-scale intensive works (e.g. bulldozers, excavators, etc.), where the degree of machine utilization is high.

C—development of a multipurpose machine
The development of a multi-purpose machine is economical for performing communal work, for smaller work organizations, and entrepreneurs (various jobs, small-scale works, combiners).

The development of the machines is closely related to the automation of the work process. Computer systems are installed in the machines to increase quality and work performance. Information reception systems, management programs, remote execution of works, control of work safety and efficiency, and others, are installed. A higher level of automation increases the price of the machine and requires higher level of training for operators and mechanics.

Technical requirements

Basic technical requirements that can be set before the development or purchase of a construction machine include:

- machine weight;
- machine dimensions;
- level of automation;
- machine efficiency/performance;
- working life of the machine / durability;
- universality of use;
- soil trafficability;
- fuel consumption and working fluids;

- environmental acceptability of the machine;
- machine performance/mobility;
- typification and unification of the machinery park;
- reliability of the machine (low intensity of failure);
- availability of the machine (short repair time);
- transportation of the machine;
- maintenance equipment;
- spare parts;
- qualification of machine operators.

The operation of construction mechanization requires, first of all, the reliability of the machines in various conditions (terrain, temperature, moisture, energy, etc.), the safety and durability of the main assemblies and parts during the depreciation of the machine, and a high degree of utilization of the machine in a group of several different machines.

Artificial Intelligence

Environmental directives and incentives for the use of clean vehicles and machines accelerate the process of automation. It is believed that smart machines will contribute to higher quality, efficiency, work safety, and environmental cleanliness. Therefore, construction technology is looking for a new vision of using machines that will provide greater utilization. The basis for this is provided by artificial intelligence applied to construction machines.

The Global Positioning System (GPS) uses multiple satellites in the Earth orbit. A technique such as kinematic positioning in real time (*real-time kinematics*/RTK) provides precise coordinates of the object on the ground. The coordinates are determined based on the distance between the satellite and the receiver on the object.

Well-known platforms on which machine operation management is performed are *AccuGrade* and *Trimble*, which use GPS technology for simpler and more complex surface shaping works. Automatic knife management reduces the burden on the machine operator and ensures precision and higher productivity. Artificial intelligence makes it possible to perceive the environment. Based on the correction signal, the hydraulic control system raises or lowers the knife to maintain the elevation of the cutting edge of the tool.

Driving systems

Battery machines are primarily recognized for the fact that they do not pollute the environment by emitting harmful exhaust gases. The electric drive provides favorable performance in the most difficult working conditions. The direct current from the batteries (*lithium-ion batteries*) is converted into alternating current to run the three-phase electric motors that drive the wheels or the tracks, Fig. 1.2.

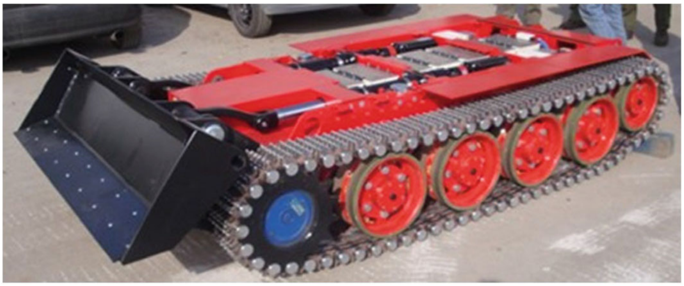

Fig. 1.2 Battery mini bulldozer (*DOK-ING, Zagreb*)

Hybrid electric machines use a combination of electricity and fossil fuel. The combination of batteries and internal combustion engines contributes to lower consumption of fossil fuels and, therefore, lower harmful emissions of exhaust gases.

Chapter 2
Soil Properties

2.1 Division of Soil

Soil is the surface layer of the Earth crust. It is formed by the decay and erosion of rocks under the influence of atmospheric phenomena, water and the work of organisms. The action of organisms creates loose layers on the surface of which the organic world develops. Soils differ in appearance and properties.

Complex physical, chemical, and biochemical processes are continuously taking place in the soil, causing constant changes, and altering soil quality and forms. Soil science, or pedology, has determined that the dependence is based on the interaction of the parent substrate, climate, plant and animal life, the duration of soil formation, and relief.

Soil consists of solid and liquid substances. Solid components are: mineral substances (45%) and organic substances (5%), and liquid substances are: water (20–30%) and air (20–30%). Their constant mixing and changes alter the appearance, composition and structure of the soil. Soil can be divided into several layers: biologically active soil layers (in which organisms live), followed by biologically inactive layers.

The structure of the soil, its potential states, and its physical and mechanical properties are determined by soil mechanics. One of the fundamental laws of soil mechanics is the law of soil shear strength, as proposed by *Charles-Augustin de Coulomb*. The choice and dimensions of construction facilities depend on the load that the soil can bear.

The old builders solved the tasks very successfully, as evidenced from many historical legacies. There have been failures, such as the *Leaning Tower of Pisa* (fourteenth century), which were the result of incorrect assessment of the properties of the soil.

Classical soil mechanics (nineteenth century) is based on two idealizations of actual soil. The first assumes that the soil is a rigid plastic body when considering the limit load problem, and the second assumes that the soil is an elastic body when

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Table 2.1 General division of soil [1]

Soil	Type of soil	Grain size (mm)
Monolithic (Rock)	Crumbs, rocks	70–300
Incoherent	Gravel	2.0–70
(Loose)	Sands	0.06–2.0
	Dust	0.002–0.06
Coherent	Organic soils	0.002–0.05
(Bonded)	Clay	0.0002–0.002

considering the problem of deformations. The actual soil does not correspond to any of the models, but under certain typical conditions, an idealization of the actual soil is appropriate. By applying modern methods of soil mechanics, the solution of soil loading tasks is more comprehensive.

The properties of natural soil differ from those of a homogeneous substance. The force that loads one contour of the granular soil mass is transmitted within that space by individual forces in contact between adjacent particles which crush and move the particles. The number of contacts per grain depends on the grain size, compactness, and granulation of the sample. The stress in the granular mass is not distributed homogeneously over the cross-sectional area, but it is the resultant of individual forces. The increase in stress causes deformations, not only from forces in contact with the grains, but also from the sliding and rotation of the neighboring grains, as well as crushing and changing the arrangement of the grains, thus reducing the volume of pores between the particles.

By reducing the load on the soil, the volume is only partially restored, ~~because~~ since the sliding, rotation and crushing of the grains cause the process to be irreversible. The behavior of such materials when the stress changes determines the type of medium in the pores: air or water, i.e. air and water. Soil saturated with water is less compressible than a granular structure with air in its pores. Volume changes are possible if part of the water is removed from the pores. The process of transferring stress from pore water to the soil skeleton is referred to as consolidation. For coarse-grained soil, the duration of consolidation is shorter than that of fine-grained soil.

The general division of soil is shown in Table 2.1. All types of rocks whose particles are firmly connected by a cementing substance form a special type of hard monolithic soil. When the soil is destroyed under load or blasting, it cannot be restored to its original state. Smaller forms are formed by crushed stone ranging from 70 to 300 mm. Incoherent soil is loose, permeable, and changes shape under load. Gravel and sand can be classified into several subtypes individually.

Coherent soil has solid, interconnected particles, so it is usually impermeable. Fine-grained cohesive soil can be classified into several groups. Organic soils contain large quantities of organic and plant matter, which is why they bind large amounts of water and are highly unstable (silt, humus).

By sieving the mixture through a sieve, the grain diameter is determined and displayed with a granulometric curve, which gives a picture of soil properties such as permeability and capillarity of sandy and dusty materials.

Atterberg limits determine more precisely the properties of fine-grained soil, which can be found in four stable states according to water content; the soil is solid when dry, semi-solid when mixed with water, and can change into a plastic or liquid state. According to the water content, the soil is divided into dry (up to 5% water), moist (10–25% water), and wet (25% water and more).

According to the difficulty of carrying out construction works and the density of the soil, the soil can be divided into a number of categories. The first four categories of soil can be processed mechanically using machines, Table 2.2.

Table 2.2 Soil categories [1]

Soil category	Soil type and characteristics	Density (kg/m^3)
Loose soil I.	– Hummus without roots	1200
	– Sand of natural humidity with an additive gravel or crushed stone up to 20%, sandy and clayey light soils	1600
	– Loose slag	750
II. Ordinary soil	– Hummus with roots	1200
	– Clay of natural humidity soil with addition of gravel	1800
	– Clay soil, loam	1750
	– Greasy, soft or loose clay,	1700
	– Settled with addition of gravel, pebbles	1800
III. Solid soil	– Hard settled clay	1800
	– Heavy and slate clay with addition gravel, pebbles up to 10%	1950
	– Construction mortar	1850
IV. Hard soil	– Hard clay, heavy	2000
	– Soft chalk	1550
	– Soft marl	1900

2.2 Physical and Mechanical Properties of Soil

In the field of application of construction machines in the changing climatic conditions, the physical and mechanical properties of soil are important, since they affect the design and performance of the machines. The basic physical and mechanical properties of the soil [2] are:

- Soil density;
- Clay content;
- Looseness of soil;
- Soil humidity;
- Soil strength and bearing capacity;
- Shear strength of soil;
- Soil cohesion;
- Plasticity and abrasiveness of the soil;
- Stickiness of the soil;
- Natural ground angle.

Soil density

Soil density in its natural state:

$$\rho = m/V[\text{kg/m}^3]$$

γ	Volume weight of soil, natural state: $\gamma = G/V$ [N/m^3],
γ_{pr}	Volume weight of soil, loose state: $\gamma_{pr} = G/V_{pr}$ [N/m^3].
m	Mass of soil,
G	Weight of soil,
V	Volume of soil in natural state,
Vpr	Volume of soil in temporary loose state.

Content of clay particles

The granulometric composition determines the ratio of clay particles to the mass of the sample:

Up to 3%	Sands
3–12%	Clayey sand
12–25%	Sandy clay
> 25%	Clay
50%	Loam.

Looseness of the soil

Looseness of the soil is determined by the factor of temporary (k_{pr}) and permanent volume increase (k_{tr}) factors. The average values of temporary and permanent looseness factors according to soil category are:

$$I.cat: \quad k_{pr}/k_{tr} = 1.15/1.02$$
$$II.cat: \quad k_{pr}/k_{tr} = 1.20/1.04$$
$$III.cat: \quad k_{pr}/k_{tr} = 1.25/1.05$$
$$IV.cat: \quad k_{pr}/k_{tr} = 1.30/1.08$$

Soil moisture

Soil moisture w is determined by the ratio of the mass of water in the soil to the mass of dried soil, i.e. its solid components. Relative humidity w_r is the ratio of the mass of water to the mass of wet soil. Normal soil moisture is 10–25%. The soil humidity corresponding to the highest density of the soil during compaction is called the optimum moisture content w_o.

$$w = m_v/m_0; \; w_r = m_v/m$$

m_v Mass of water in the sample, $m_v = m - m_0$.
m Mass of wet soil sample.
m_0 Sample mass after drying during 24 h at temperature 105–110 °C.

Soil strength and soil bearing capacity

Soil strength is its resistance to external forces that want to break it due to pressure, tension, bending, and shearing. Hardness is the resistance that the soil offers to the penetration of another body, during which plastic or short-term destruction of the surface layer occurs.

The strength of the soil determines its bearing capacity, i.e. the amount of load it can support. The highest soil load that causes its deformation is called the ultimate bearing capacity or compressive strength of the soil. The bearing capacity of the soil depends on the ~~soil~~ humidity content, the amount of clay, and the compaction of the soil. By compacting the soil, its carrying capacity increases, which is essential for the construction of buildings and the mobility of machines.

The bearing capacity of the soil decreases with increasing soil humidity. The ultimate bearing capacity depends on the humidity, the amount of clay, and the compaction of the soil. Soil with a clay content of about 10% has low strength. Compacting the soil increases its strength. When determining the permeability of the soil, the compressive strength of the soil is important, as it deforms and crushes at a certain depth. The force on the surface of 1 cm^2 at which deformation of the soil at 1 cm depth occurs is called the unit crushing resistance σ_0. Under the wheels of construction machines, the permissible soil crushing depth of 6–12 cm corresponds to the permissible soil load, i.e. the limit bearing capacity of the soil (σ).

Shear strength of soil

The shear resistance of the soil depends on the cohesion force of the particles and the force of internal friction between the particles [2]. The soil shear stress τ has a linear dependence (*Ch. A. Coulomb*):

$$\tau = c + \sigma_n tg\varphi [\text{Pa}]$$
$$t = c + \sigma_n \mu [\text{Pa}]$$

c Cohesion force (20–30 kPa), loose incoherent soil $c = 0$,
σ_n Normal stress on the shear surface, normal pressure ($p = G/A$),
μ Coefficient of internal friction.

Soil cohesion

Soil cohesion is the degree of internal connection between particles. The forces of cohesion oppose external forces that tend to disrupt their bond. The cutting resistance of the soil depends on the cohesion force. Coherent soils with higher cohesion are clayey soils. By increasing the surface pressure in non-coherent soils, for example sand, its ability to bond increases.

Soil plasticity and soil abrasiveness

Plasticity of the soil is its ability to change shape under the load of external forces and to retain it after the cessation of the action of those forces. Plasticity depends on soil humidity, which reduces strength and shear resistance. Such is the case with clay soils. With a small amount of sand, wet plastic soils become sticky and difficult to shake out of the shovel of the earthmoving machine.

The abrasiveness of soil is a property that causes rapid wear of tools (drill bits, excavator shovel teeth). There are weakly abrasive soils, significantly abrasive soils, and extremely abrasive soils. For example, significantly abrasive soils include quartz sandstones and granites.

The stickiness of the soil

The stickiness of the soil is its property of adhering to another material. Shear resistance of such soil on an adhesive metal surface:

$$F = \tau_1 A \, [\text{N}]$$

A Surface to which the soil adheres.
τ_1 Shear stress of bonded soil on metal /sandy clay $\tau = 0.5–0.7$ N/cm^2; fat clay, $\tau = 0.7–1.0$ N/cm^2

Natural ground angle

When pouring from a certain height, the loose material is arranged in an approximately conical pile. The natural angle of the ground refers to the internal friction angle of the material during its motion, which is the shear angle of the loaded soil. This angle corresponds approximately to the pouring angle, $tg\varphi \approx \mu$, where μ is the material-specific friction coefficient. For example, the natural angle of sandy clay is: φ_p ~ wet, moist, dry/30°, 35°, 45°.

2.3 Soil Trafficability

The mobility of the machines depends on the soil trafficability. Soft soils can create a problem for the mobility of machines, as they can impede their movement. Machines typically move on wheels or tracks. Construction machinery and construction trucks require off-road mobility. The assessment of the machine ability to work is based on the load capacity of the soil and the maximum pressure exerted on the soil. The greater the bearing capacity of the soil and the lower the pressure of the machine on the soil, the greater the soil trafficability. The trafficability of the soil for machines and vehicles can be assessed based on the measurement of the bearing capacity with a penetrometer (*Cone Index,* CI) and using a model for estimating the maximum pressure of the vehicle on the ground (MMP) [3].

Evaluation of soil trafficability using *CI* index

CI—soil cone index, an indicator of the bearing capacity of the soil, is measured using a penetrometer. The penetration resistance of the penetrometer cone into a specific soil is measured, as shown in Fig. 2.1. *The standardized value of measuring resistance to cone penetration at a depth of 15* cm *(ASAE EP542) is known as the soil cone index (CI).* The bearing capacity of the soil and asset mobility is shown in Table 2.3.

Fig. 2.1 Penetrometer—measurement of the bearing capacity of soil (*Cone Penetrometer*, kPa/psi; *Soil trafficability*)

Table 2.3 Scale of soil bearing capacity and vehicle mobility [4]

CI (kPa)	Description
0–21	No practical movement value
40–62	A man has difficulty walking on soil without sinking
103–165	A special tracked vehicle can make about 50 passes
186–228	A light tracked vehicle can make about 50 passes
276–352	A medium tracked vehicle can make about 50 passes
372–497	A Jeep-type vehicle can make about 50 passes
517–662	Heavy vehicles
683–935	Passenger vehicles
1000	All vehicles pass

Soil cone index:

- For very soft soils: $CI < 300$ kPa (3 bar).
- For medium hard soils: $CI = 300$–500 kPa (3–5 bar).
- For solid soils: $CI > 500$ kPa (5 bar).

Evaluation of soil trafficability based on soil pressure

With wheeled construction machines, there is a problem of high wheel pressure on soft ground, which causes decreased ground trafficability. With tracked construction machines, this problem of pressure on the ground is generally much less severe.

An estimate of the maximum ground pressure of a wheeled or tracked machine can be shown using the MMP model, which stands for *Mean Maximum Pressure*—the mean maximum pressure of the driving force on the ground.

Wheeled machine

The MMP model of the maximum pressure of a wheeled machine [3], depends on the following parameters:

$$MMP = k\, W_T / n\, b^{0.85} d^{1.15} (\delta / d)^{0.5} [\text{Pa}]$$

W_T Machine weight (kN),
k Factor of the number of drive axles,
n Number of vehicle wheels,
b Tire width, unloaded tire (m),
d Tire diameter, unloaded tire (m),
δ Tire deflection due to load (m).

The MMP model allows for comparison of the mobility of machines with different construction solutions. The lower the MMP, the greater the trafficability, thus making the machine more mobile. A greater number of passes on the same track significantly affects the trafficability of the ground because the depth of the ruts increases, which reduces the height of the undercarriage from the ground.

Tracked machine

Normal pressure of the tracked machine on the ground:

$$NGP = W_T / 2L\,b(\text{Pa})$$

W_T Machine weight (kN),
L Track length (m),
b Track width (m).

Mean maximum ground pressure [3]:

$$MMP = 1.26 W_T / 2Ln\,b\sqrt{Dt}[\text{kPa}]$$

W_T Machine weight (kN),
L Track length (m),
b track width (m),
n Number of support wheels of one track.
D Wheel diameter (m),
t Track pitch (m).

Limiting Cone Index, CI_L

$$CI_L = 0.827\,MMP[\text{kPa}]$$

The limiting cone index determines the minimum bearing capacity of the soil at which a machine with a certain MMP index can be mobile. In other words, the bearing capacity of the soil should be at least approximately 83% of the calculated MMP for a particular machine in order for it to successfully complete the pass.

Wheel machine rut depth

To estimate the depth of soil deformation (z), the wheel index is defined:

$$N_k = CI / p$$

p Tire inflation pressure

Wheel rut depth for one pass of the machine:

$$z_1 = d\,(0.224 / N_K^{1.25})$$

Wheel rut depth for multiple passes:

$$z_n = z_1 n^{1/a}$$

d wheel diameter,
a coefficient of multiple passes (2–3 for low soil load capacity; 3–4 for medium soil load capacity; 4–5 for high load capacity).

Some examples of soil trafficability [5]: *MMP*/z_1

$$\begin{aligned} \text{Off - road vehicle } 4 \times 4(3\text{ t}): &\quad 340\,\text{kPa}/5.3\,\text{cm} \\ \text{Construction truck } 6 \times 6(11\text{ t}): &\quad 320\,\text{kPa}/8.0\,\text{cm} \\ \text{Construction truck } 8 \times 8(22\text{ t}): &\quad 300\,\text{kPa}/8.8\,\text{cm} \end{aligned}$$

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Chapter 3
Soil Digging Resistances

3.1 Introduction to Soil Digging Theory

Digging the soil is based on a sharp wedge. The wedge is the basic element for achieving the thrust force of the machine for the purpose of digging the soil. The starting dimensions of the wedge are: the angle of the blade β, and the width of the wedge b, Fig. 3.1. The position of the wedge in space is determined by the angles: the back angle, i.e. the angle of inclination towards the ground γ, the engagement angle towards the direction of cutting φ, and the angle of cutting α in relation to the horizontal position.

The development of the digging blade resulted in its various forms. The high-quality wedge blade was achieved by adding a special cutting knife, which can be replaced in case of wear or damage. The knife is a direct part of the working tool of the construction machine for digging the soil. The knife can be designed in different ways: straight, curved, disk-shaped, or as a plow knife with or without teeth. Sometimes the entire working mechanism for digging the soil is referred to as a knife. By adding additional teeth on the knife, the cutting through hard layers of soil is made easier.

The basic forms of working tool of earth-moving machines are shown in Fig. 3.2, as well as the ideal shapes of blades in Fig. 3.3.

Phases of soil digging

The process of excavation consists of cutting the layer of soil (***cutting phase***) and displacement of soil along the executive body (***displacement phase***). The soil cutting phase is the first and most important phase in the excavation process. The separation of the soil layer is performed with a knife blade under the action of force, and depends on the physical properties of the soil and the shape of the knife and the state of its blade, Fig. 3.4. In the phase of cutting the soil, compaction of the soil pushed in the direction of movement occurs, followed by shearing of a part of the soil layer in the

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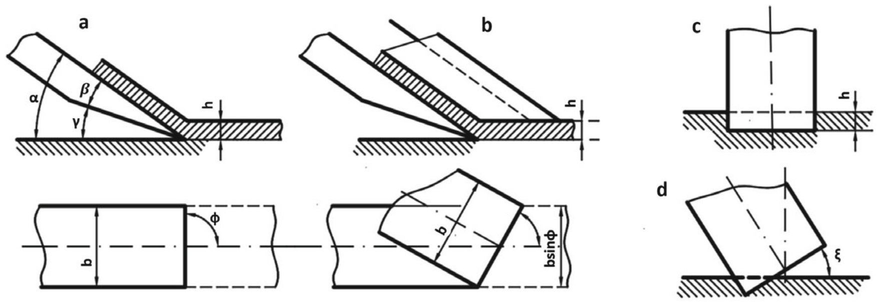

Fig. 3.1 Wedge parameters. α—cutting angle, β—wedge blade angle, γ—back angle, φ—angle of engagement according to the direction of soil cutting, ξ—tilting angle

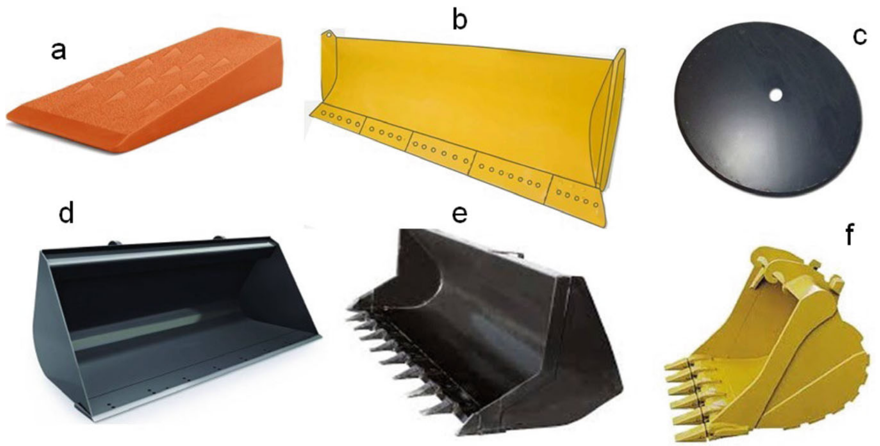

Fig. 3.2 Shapes of working tools. **a**—wedge, **b**—flat dozer knife, **c**—disc-shaped knife, **d**—shovel with knife without teeth, **e**—shovel with teeth, **f**—excavator shovel with teeth

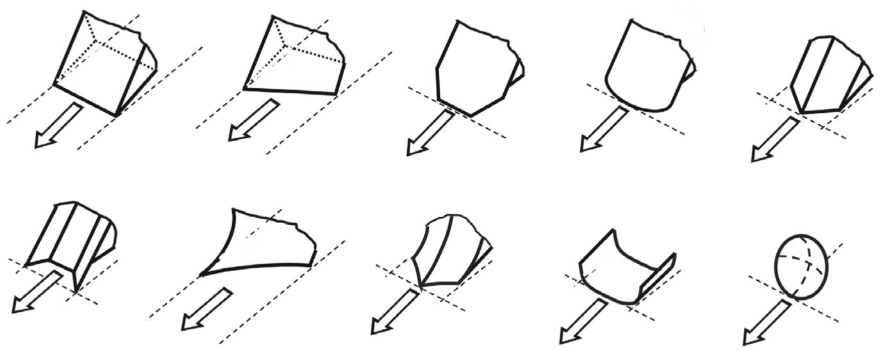

Fig. 3.3 Ideal knife shapes for cutting soil [1]