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MECHANICAL TUNNELING IN SOLID ROCK

by

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16. Abstract

This report is a complete translation of the German book "Mechanischer Tunnelvortrieb im Festgestein". It is an introduction to the principles of mechanized tunneling and provides detailed guidelines for practical application. The subject is introduced with a detailed review of technical aspects and terms relating to mechanized tunneling. This is followed by a discussion of the mechanics of rock cutting and implications on machine performance. Two related issues, the stability of underground openings and rock mass classification for tunneling are then presented; this serves the purpose of familiarizing the reader with aspects other than rock cutting that affect machine tunneling. All this forms the basis for a comprehensive description of the entire mechanized tunneling system and its operation. Finally, recommendations for bid preparation and project execution are given, followed by a discussion of application limits.

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AUTHOR'S FOREWORD

Machine tunneling, which according to reliable sources was done for the first time in the U.S.A. in 1856, and which was used successfully from 1881 to 1883 for the boring of two experimental tunnels for the English channel tunnel project, is a tunneling process which has gained increasing importance ever since the 1950's. Originating in the U.S.A. where it was used with spectacular success, mechanical tunnel cutting (or boring) has since been used on other continents and in other countries. Today, the greatest density of tunnel boring machines by any standard can be found in Europe. Although initially it was only used in low-strength sediments, mechanical tunnel boring machines today also cut high-strength and abrasive organic rock with technical as well as with economical success.

Apart from a great number of successful tunneling projects which total several hundred kilometers, failures have also been recorded. Only in a few cases these could be attributed to the boring machines that were used. More often, the drive system was insufficient, or the condition of the rock required the withdrawal of a tunnel boring machine which was only designed for solid rock, or the management of the tunneling project did not acknowledge the special requirements of tunnel boring.

These failures, which for the most part could have been avoided, as well as the fact that in journals and on occasion of tunneling symposiums only partial aspects of mechanical tunnel boring were dealt with, and that a complete presentation has been unavailable so far, have motivated the author to try to describe the process from all its aspects. According to developmental trends, the emphasis of the presentation lies on mechanical tunnel boring in medium and high-strength as well as in abrasive rock, and thus on full face excavation of radially symmetric cross sections.

This document is intended for construction managers, design and project engineers, as well as for students. The reader will find that mechanical tunnel boring is not the magic answer for tunnel building. However, he should also arrive at the conclusion that with critical planning and a project-oriented design of boring machines and systems as well as with a highly qualified work team and supervisory personnel, tunnels can be constructed within a wide range of geological conditions. These projects can be technically and economically more successful and can be constructed with more safety and speed than ever before.

The author wants to express appreciation for:

- the permission to visit the construction sites of numerous construction companies in Europe, North America and Africa.

- the good contacts - in part existing for fourteen years: the manufacturers and representatives of the tunneling machine companies Atlas Copco (previously Habegger), Calweld, Demag, Dresser, Jarva, Lawrence, Robbins, and Wirth.

- the permission to publish research material of the Gotthard basis tunnel project: Dipl.-Ing. M. Portmann, director of the construction service of the Swiss Federal Railways.

- the proofreading of the manuscript or parts thereof by Dipl.-Ing. W. Diethelm, Dipl.-Ing. A. Hurter, Dipl.-Ing. M.A. Borel and Dr.-Ing. M.A. Gaillard.

Adliswil/Zurich, May 1974

Werner Rutschmann
Author

TRANSLATOR'S FOREWORD

The widespread use of mechanized tunnel excavation has brought with it publication of many case histories and a variety of research reports and papers. Still missing so far was a textbook or similar publication that introduces principles and basic practical issues and that provides the tunnel designer and project manager with a guideline on how to consider mechanized tunneling. This gap has, to a large extent, been closed by the book "Mechanischer Tunnelvortrieb in Festgestein", which has been completely translated and is presented as this Report No. UMTA-MA-06-0100-79-12. The author, Werner Rutschmann,* a tunnel designer and project manager with over 30 years of experience, has been involved in modern mechanized tunneling since its beginning. During the course of his work he not only became a leading expert in the area, reflected by his many consulting jobs involving tunnel boring machine application, but he also became convinced that the tunnel engineer needs to tailor his design to the excavation methods shown herein and thus should be familiar with machined tunnels.

As indicated in Rutschmann's foreword, the book attempts to satisfy this objective and to serve also as an educational tool for civil and mining engineering students. The book was originally written in German and published by VDI Publishing House, Dusseldorf, in 1974 (VDI, Verein Deutscher Ingenieure, the German Engineering Society). Richard Robbins who was aware of the book's existence and who saw the necessity of providing the tunnel design profession and newcomers to mechanized tunneling with a solid background, suggested its translation to the U.S. Department of Transportation. Russel MacFarland favorably responded to this idea and initiated negotiations with the author and publisher. Both generously agreed to have the book translated for the benefit of the tunneling profession to have a limited issue of 200 copies published and sold through NTIS, and to forego any compensation. The translation was performed by Dr. Keith H. Morehouse of Raytheon Service Co., Cambridge, Massachusetts; Richard Robbins and this writer checked the translation for accuracy and technical terminology.

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PREFACE

Statistical surveys and prospective studies conducted by international organizations have revealed an extraordinary demand for underground construction in the near future, and have also produced relevant figures. These projects which are planned primarily for developed countries will serve a wide variety of purposes. The greatest number concerns elongated cavities with a constant cross section of function and type; constructed either as traffic tunnels or pipe conduits, horizontally or inclined, with large or small diameters.

Aside from demand, the art of tunneling itself is going through a change at present. Technical progress, the desired better working conditions, and economical factors have - at least in some countries, for the time being - given in a relatively short time a great impetus to the application and the development of mechanical boring of tunnels and galleries. There is no doubt of the increased use of this method in the future considering the number of successful projects and the great growth potential that must surely exist.

By scientific exploration of the many involved phenomena, by successive technical solutions of the problems that are still to be solved, and also in view of the technological progress which can be expected, mechanical tunneling will become applicable in other fields even though it will never be a standard method under all conditions. Unlike most other construction projects, mechanical tunneling is a multi-disciplinary activity. A great number of different areas of knowledge are tapped: from petrography and engineering geology via rock mechanics to the art of engineering, and from machine and electrical engineering to problems of metallurgy, ventilation, and management, and general problems of construction site installations.

Dipl.-Ing. W. Rutschmann deserves great merit for tackling this difficult task. With great care and much work he has managed to collect and evaluate the experience and insights which have been gained worldwide. He has been successful in dealing with the subject matter in a clear and intelligible way and also - considering the amount of material - in giving a concise and nevertheless comprehensive survey of the whole field, thus closing a gap in tunneling literature. Although obviously inspired with a justified enthusiasm for this new method, which is undergoing rapid development, the author nevertheless does not neglect to point out system-related limitations in order to prevent failures and rashly conceived expectations.

The fact that not only unsolved problems are mentioned but also that ideas are formulated concerning their possible solution, should be an incentive for continued research.

Hopefully, this first comprehensive work on mechanical tunneling will serve as a contribution to the progress of this highly interesting and future-oriented field of engineering.

Locarno, May 1974

Dr.-Ing. G. Lombardi

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D)

TABLE OF CONTENTS (CONT'D)

TABLE OF CONTENTS (CONT'D)

TABLE OF CONTENTS (CONT'D)

TABLE OF CONTENTS (CONT'D)

TABLE OF CONTENTS (CONT'D)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF TABLES

ABBREVIATIONS AND SYMBOLS

WD	Work days
a	Number of tools on cutting head
α	Wear coefficient
b	Cutter spacing
β_D	Uniaxial cylinder pressure strength
β_Z	Cleavage tensile strength
c	Sliding plane shear strength
γ	Volumetric weight of rock
D	Cutting diameter
δ	Deformations
δ_i	Penetration index of the Lawrence test
δ_m	Average radial deformation of the tunnel soffit
d	Diameter of a rock test sample
d_K	Average grain diameter of the main components
E	Elasticity modulus
E_{t50}	Elasticity modulus tangent at 50% fracture strength
e	Construction strength
F_e	Average penetration force
F_f	Free-cutting force
F_r	Rolling force
F_v	Feeding force
G	Weight of air
H	Height of cover, superimposed rock mass
h	Height of a rock test sample
L	Boring performance
λ	Side pressure coefficient
N	Installed performance
n	Revolutions of cutting head
p	Pressure
p_m	Average support force resp. stabilization pressure resp. excavation resistance
Q	Quantity of liquid
ϕ	Sliding plane friction angle
r	Half of cutting diameter resp. tunnel radius
r_i	Cutting track radius of inner bit closest to the center
SH	Saw-cutting hardness
σ_h	Horizontal stress component
σ_v	Vertical stress component
σ_t	Tectonic stress component
T_L	Temperature of air in tunnel
T_{FU}	Original temperature of the rock mass
t	Penetration
t_K	Cutting head penetration
t_W	Boring tool penetration
t_{spec}	Specific penetration
V	Tunneling speed
Δ_V	Volume increase in fracture zone
TD	Tunneling days
v_n	Net boring speed
v_s	Cutting resp. rolling speed of a bit

ABBREVIATIONS AND SYMBOLS (CONTINUED)

W_G	Heat amount from rock mass
W_V	Total heat production of tunneling machine
W_{BK}	Heat production on cuttings from heat production at cutting head
W_{SL}	Heat transfer to dusty air from heat produced at cutting head
W_{VR}	Heat production of tunneling machine outside the cutting head area
W_{spec}	Specific energy
Z	Number of cutting tools per row resp. cutting track

1. DEFINITIONS OF TECHNICAL TERMS

1.1 CONVENTIONAL AND MECHANICAL TUNNELING

Conventional tunneling or tunneling by means of explosives in solid rock is divided into four main operations: drilling, blasting, mucking, and supporting of the blasted cavity. The three operations mentioned first, and often all four, follow each other consecutively. They require the use of various machinery at the face: the carriage with the hammer drills, in large profiles devices for tamping the bore holes, loading machines and, if temporary support is necessary, also support installation machinery. Mechanical tunnel cutting or tunnel boring is done by means of a tunnel boring machine. It simultaneously disaggregates the rock, collects the muck, and removes them from the boring zone. Unless the tunneling cross sections are small, the machinery for the installation of temporary support is part of the tunneling machine, and the securing of the bored cavity can take place in many cases without interruption of the boring process.

1.2 TUNNELING SYSTEMS

A tunneling system consists of the totality of the installations in the tunnel which are necessary for the tunneling, and for the processes directly connected with it, among others: boring machine, transportation installations, supply lines, installations for dust elimination and ventilation, and if applicable, also the air condition units for the work places or the operation center or the machine area, Figure 1-1.

1.3 BORING MACHINE (TUNNELING MACHINE, CUTTING MACHINE)

A suggestion for the systematic classification under various aspects is given in Figure 1-2.

A full face cutting machine usually consists of a basic machine with one or more auxiliary trailers.

The most important functional elements of a basic machine are: cutting head, cutting head carrier, machine frame, the hydraulically operated bracing-and support-devices, as well as the cutting head drive motors. In Figures 1-3 to 1-5, the design and relative position of these elements is given for boring machines manufacutred by Lawrence, Robbins and Wirth. Electrical installation and hydraulic supply machinery is usually arranged on a trailer.

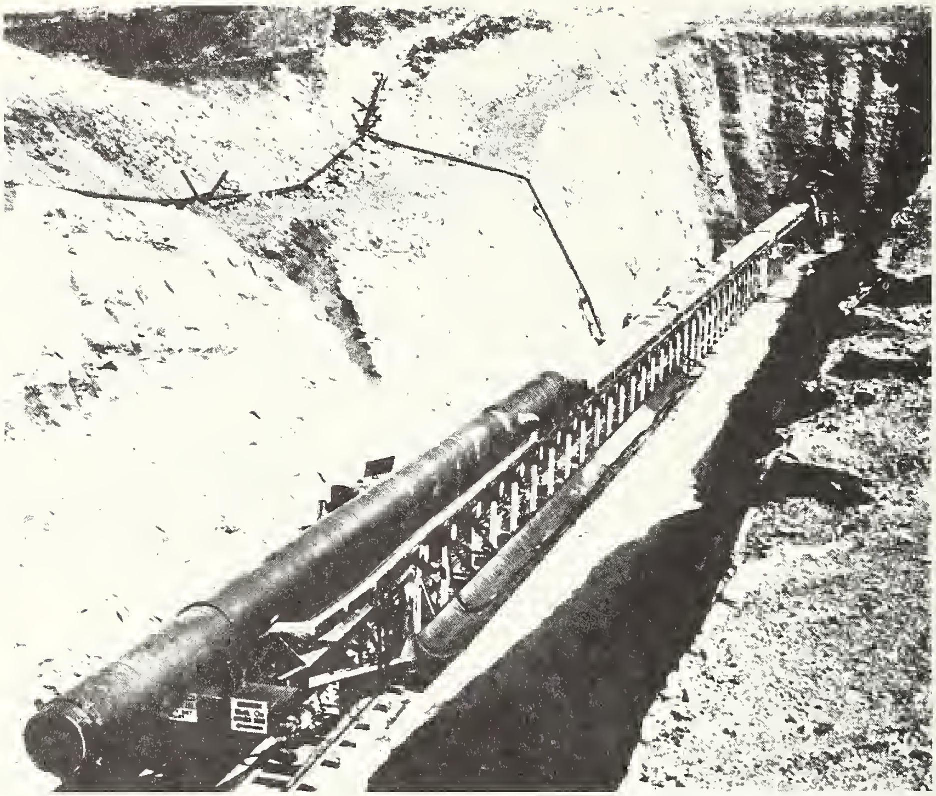


Figure 1-1. Tunneling System with Tunneling Machine, Transfer and Loading Belt, and Air Duct Telescope

1.4 TECHNICAL TERMS RELATED TO BORING

1.4.1 Boring System (Cutting System)

This term refers to the cutting head or the boring tool carrier of a tunneling machine. It defines its geometric form as well as type, number and arrangement on the head of the boring tool.

The boring tools of a full face tunneling machine work on the whole cross section of the tunnel face simultaneously. They cut a circular cross section, Figure 1-6. Those of a partial face machine only cut partial sections, and the boring of the whole cross section is achieved by successive cutting of partial sections. Usually, partial face boring machines permit the boring of non-circular cross sections, Figure 1-7. The shape of the tunnel cross section is dependent on the boring system. Exceptions confirm the rule. Figure 1-8 shows the tunnel face cut by a machine with the undercutting head arrangement presented in Figure 1-9.

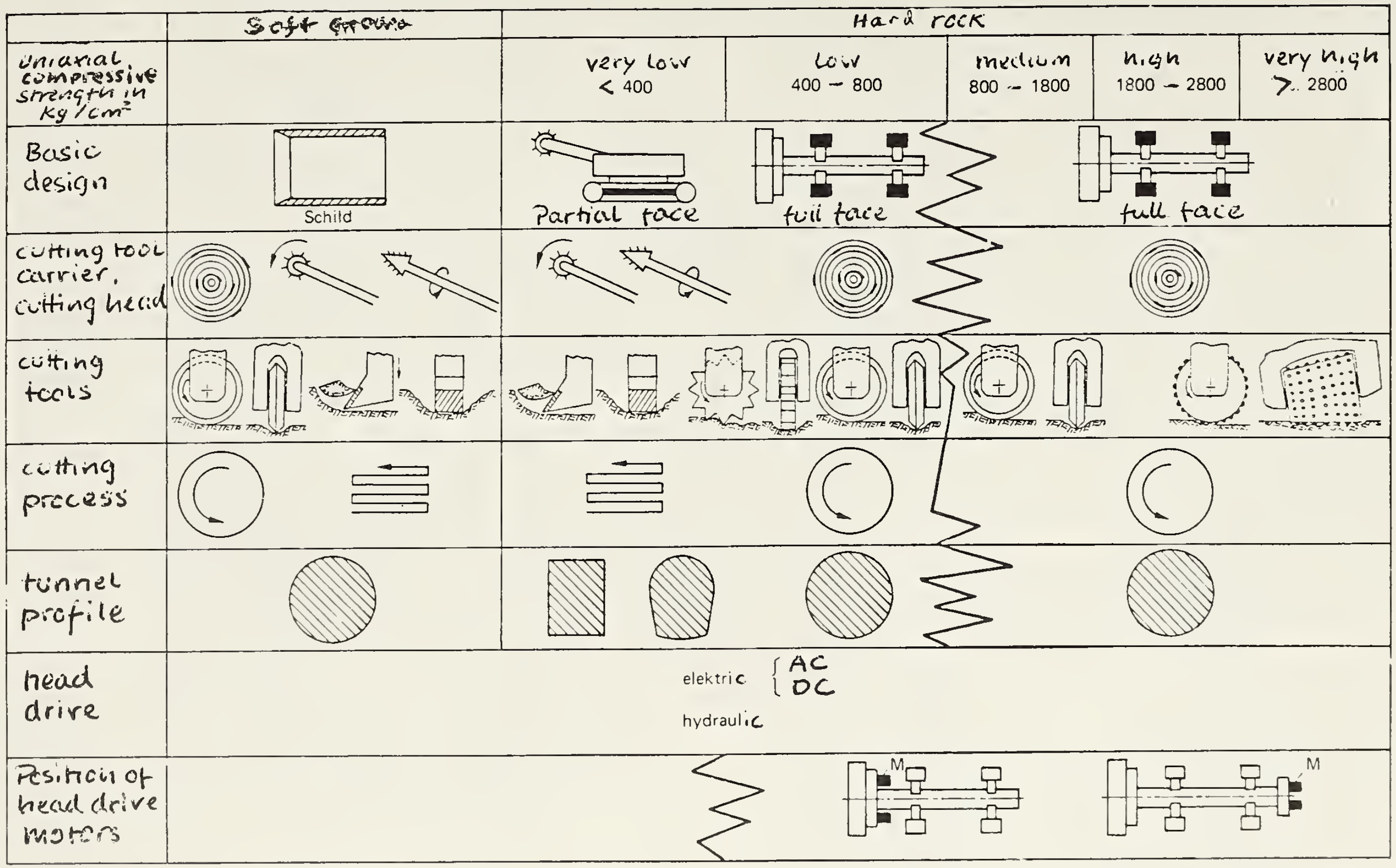
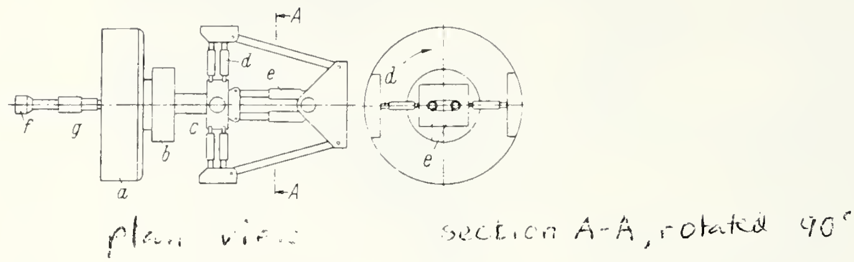


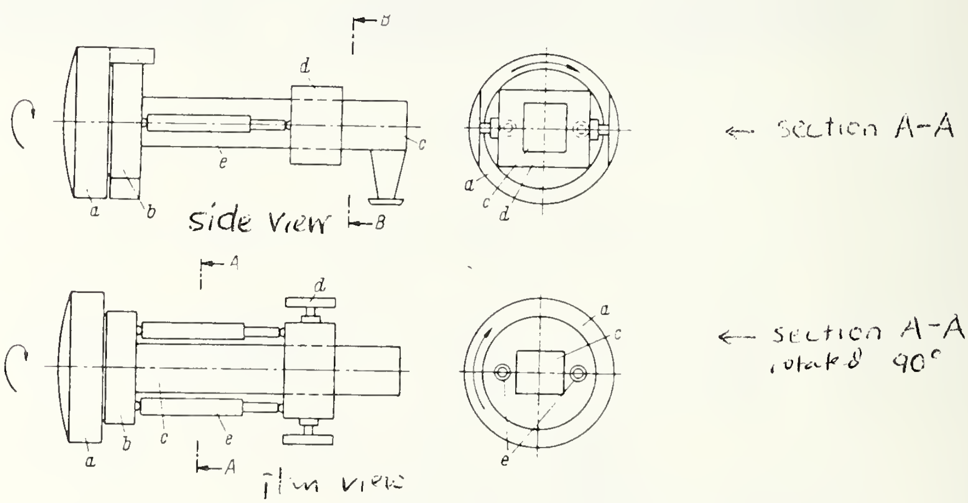
Figure 1-2. Suggestion For A Systematic Classification of Tunneling Machines Under Various Aspects



a cutting head
b cutting head carrier
c machine frame
d gripper pad
e (advancing device), thrust jacks
f pilot drill
g anchor

Cutting head drive motors located on head carrier.

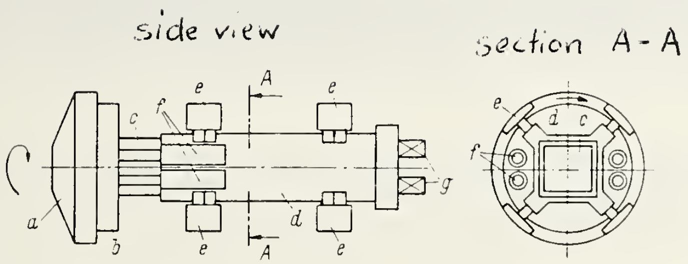
Figure 1-3. Manufacturer Lawrence



a cutting head
b cutting head carrier with skid, lateral guides and top shield
c machine frame
d gripper pads
e (advancing device), thrust jacks

Cutting head motors located on cutting head carrier.

Figure 1-4. Manufacturer Robbins



a cutting head
b cutting head carrier
c inner machine frame
d outer machine frame
e gripper pad
f (advancing device), thrust jacks
g cutting head drive motors

Figure 1-5. Manufacturer Wirth

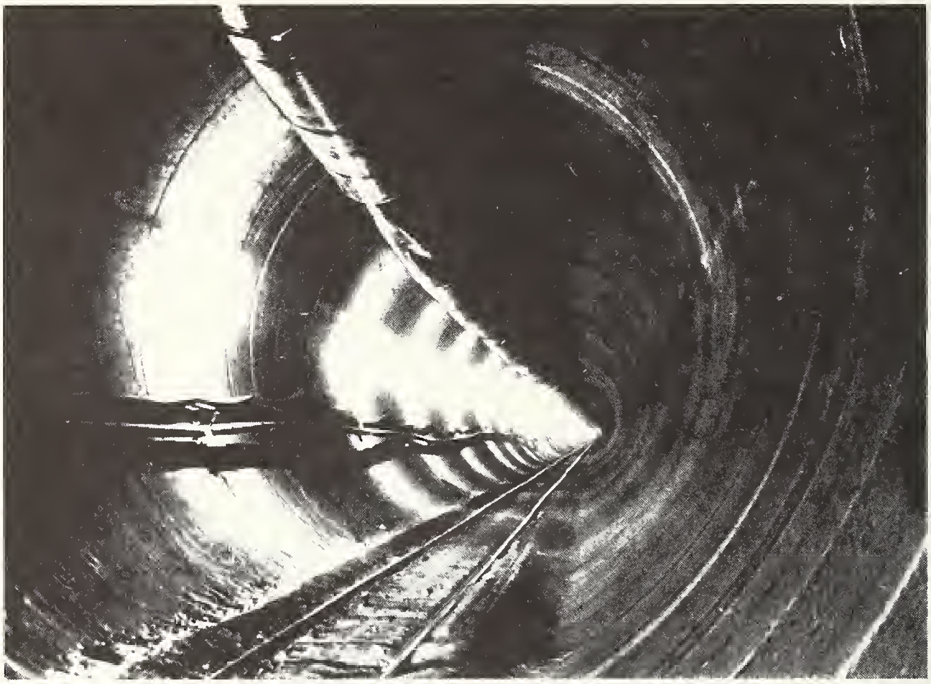
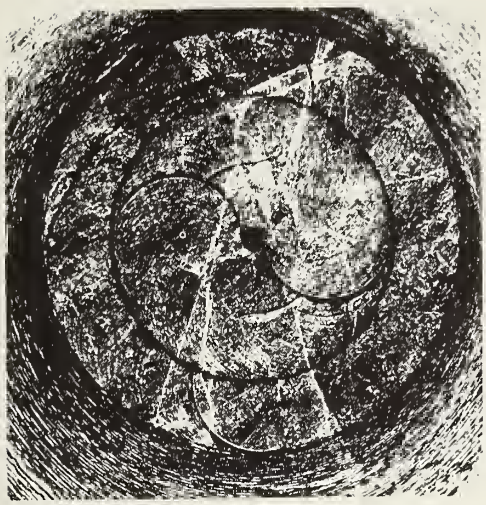


Figure 1-6. Tunnel Bored with a Tunneling Machine Equipped with Roller Bits (Hughes Tool Co.)

Figure 1-7. Tunnel Bored with a Partial Face Cutting Machine (Anderson Mavor Ltd.)



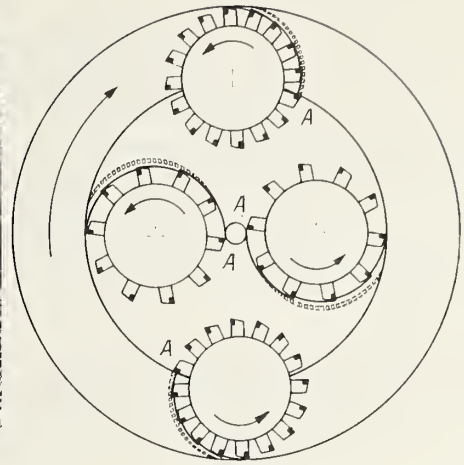


Figure 1-8. Tunnel Face Cut By Machine Shown in Figure 1-9

Figure 1-9. Arrangement of Undercutting Heads on Hubegger-Atlas Copco Machine

1.4.2 Boreability

This is the property of a geological formation to suffer, when subjected to certain boring tools, the expansion of existing cracks and weak points of the material components or of the material formation until fracture occurs.

The boreability of the material formation rock may be called basic boreability. Usually, it is smaller than the boreability of the rock mass formed by this rock because in the large material formation - rock mass - weak spots which are an important pre-condition of the disaggregation of rock, occur more frequently. The boreability is dependent on:

- the formation to be bored and
- the tunneling machine, in particular it is dependent on the boring system.

1.4.3 Index Values of Basic Boreability

Mechanical rock characteristics can be defined as influential factors for boreability. The following index values apply:

- uniaxial cylinder compression strength β_D,
- cleavage tensile strength β_Z
- elasticity modulus tangent at 50% compression strength E_{t50},
- a hardness definition, such as sawing hardness SH.

1.4.4 Penetration t and specific penetration t_{spec}

The penetration is a measure for the boreability of a certain formation by means of full face tunneling machines.

Boring head penetration t_K (in mm) means the average penetration of the boring head into the formation with a single rotation of the head and the boring tool carrier.

Boring tool penetration t_W(in mm) means the average penetration of the cutting edges of an individual tool with a single pass over the boring face.

The boring tool penetration corresponds to the boring head penetration if all tools on a head have different geometric arrangements, i.e., if in one row only a single tool is installed.

The penetration is influenced by
- the formation to be bored,
- the tunneling machine, (the boring system in particular) and on
- the actual drive force F_V of the machine being effective on the boring head, and the average penetration force F_e of a boring tool:

$$F_e = \frac{F_V}{a},$$ with "a" as the number of boring tools on the head.

Specific penetration t_{spec} is the relation of the boring head penetration to the penetration force:

$$t_{spec} = \frac{t_K}{F_e} = \frac{t_K}{\frac{F_V}{a}} .$$

1.4.5 Net Boring Speed (Rate of Penetration) v_N and Boring Performance L

Net boring speed v_N means the actual tunneling speed of full face tunneling machines excluding all down times for technical reasons.

$$v_N = t_K n,$$

with "n" as the revolutions of the cutting head.

Here, it is practical to give v_N in cm/min or m/h, t_K in cm or m and n in 1/min or 1/h.

When tunneling machines with variable cutting head revolutions are concerned, it is practical to avoid the term of cutting head revolution "n" and to use the actual boring time for the calculation:

$$v_N = \frac{\text{boring length}}{\text{actual boring time}}.$$

The boring performance L is a term which can be used for full as well as for partial tunneling machines. It consists of a net performance in relation to natural rock:

L = net boring speed x tunnel cross section

performance in m^3/h, speed in m/h, tunnel cross section in m^2.

1.4.6 Tunneling Speed V

It consists of the tunneling work per time unit without consideration of the actual boring time:

$$V = \frac{\text{advance}}{\text{time}}$$

Here, the advance can be given in meters (m), the tunneling time in work days (WD), tunneling days (TD), weeks (W), or months (M).

1.4.7 Specific Energy W_{spec}

This term which is used occassionally means the relation of the energy used for boring to the solid volume of the cut rock:

$W_{spec} = \frac{\text{electric energy}}{\text{cut rock}}$, with W_{spec} in kWh/m^3, electric energy in kWh, and cut rock in m^3.

1.5 BORING TOOL WEAR

1.5.1 Boring Tool Costs

The wear is expressed collectively by the term of boring tool costs. This is defined as the sum of the actual material costs for complete tools without tool holders at the manufacturing plant (black costs) for m^3 cut rock, without transportation costs, customs duties, and labor costs for exchange and regular maintenance.

1.5.2 Index Values of Boring Tool Wear

This concerns:
- a strength standard combined with
- the nature, the portion, and the average grain diameter of the main components of the rock.

1.6 TERMS RELATING TO OPERATION

1.6.1 Boring, System-Related and Non-System-Related Interruptions

The effective working time in the tunnel is divided into:
- boring, (or tunneling),
- system-related down-times and
- non-system-related down-times.

System-related down-times are caused by lack of technical operation readiness at the point of operation of the components in the tunnel system used. Non-system-related interruptions are waiting times for the tunneling system which, technically speaking, is functional.

1.6.2 Utilization Factor of the Tunneling System

The utilization factor, or coefficient of utilization, means the relation of boring time (i.e., of effective revolution time of the cutting head) to the total effective working time on or behind the system, expressed in percent.

1.7 TERMS RELATING TO ROCK MECHANICS

1.7.1 Instant Rock

Instant rock is a compound of minerals with isotropic and anisotropic structures or directed textures whose cohesion is not influenced by water, unless it is in the form of ice. We distinguish between:
- igneous rock
- sedimentary rock and
- metamorphous rock.

1.7.2 Rock Strength

The uniaxial compressive strength is the most commonly used standard for the determination of rock strength. A universally standardized classification of compressive strength, ranging for a corresponding classification of rock does not exist. On occasion,. the following classification is used as shown in Table 1-1.

TABLE 1-1. CLASSIFICATION OF ROCK ON THE BASIS OF ITS UNIAXIAL COMPRESSIVE STRENGTH

Compressive strength kg/cm^2	Classification
over 2800	very high
1800 to 2800	high
800 to 1800	medium
400 to 800	low
below 400	very low

$1\ kg/cm^2 = 1$ bar

1.7.3 Rock Hardness

Rock hardness generally means the resistance against mechanical influences. The terms "soft" or "hard" which are often used for rock are not defined in a standard way. In any case, hardness does not mean strength. High strength and a large portion of minerals that are harder than steel (among others quartz, garnet, fieldspar, hornblende) characterize the term "hard rock".

1.7.4 Rock and Rock Mass

Rock mass is the large spatial formation of rock. This mass contains discontinuities; for example, bedding planes, joints, and faults which separate faces with sediments and chavage planes.

1.7.5 Characteristic Line of the Deformation Behavior of the Tunnel Invert

This characteristic curve is the graphic representation of the average radial deformation δ_m of the tunnel invert as dependent on the average support force P_m, and on the stabilization pressure, and the lining resistance of this pressure.

1.7.6 Cases of Rock-Mechanical Stability

Four cases of stability can be distinguished in relation to the behavior of the tunnel invert and the work face during tunneling as shown in Table 1-2.

TABLE 1-2. CASES OF STABILITY OF ROCK MASS BEHAVIOR

CASE	INVERT	WORK FACE
1	stable	stable
2	stable	unstable
3	unstable	stable
4	unstable	unstable

These cases of stability define the behavior of the rock mass before installation of the lining.

1.8 ROCK MASS CLASSIFICATION

Together with the geological documentaiton and the rock-mechanical prognosis, classification serves for the evaluation of the rock mass with regard to its behavior during tunneling. Classification can also be used for proposal requests and for the calculation of the costs of tunneling.

The rock formation classification for applications of mechanical tunneling should include:

- The boreability of the formations which will be tunneled, given by the index values for the basic boreability,
- the boring tool wear, given by the index values for boring tool wear, and
- the measures to be taken for securing and stabilizing the rock mass during tunneling.

This classification with regard to the securing and stabilization requirements should take into consideration primarily the following conditions:

- the tunneling machine is gripped, and remains gripped during the boring process,
- the tunneling machine is gripped, or remains gripped during boring with impairments, or
- tunneling through fault zones that cannot be bored.

These three main caterogies are divided into subcategories with respect to manner, extent, place and time of the installation of the first securing and stabilizing support during the tunneling.

2. BORING OF SOLID ROCK WITH TUNNELING MACHINES

2.1 MATERIAL TO BE DRILLED, CONSIDERATIONS IN BREAKING OF ROCK

The material which will be subjected to the tools of a tunnel boring machine is a formation of minerals. In general, it is only in limited areas that this formation - the rock - shows structural uniformity - genetic structure, characterized by size, shape, and interrelation of the components of the matrix (1) - and a uniform texture - spatial structure, characterized by the spatial arrangement of the components of the matrix, and their space filling (2). This structural and textural inhomogeneity, again as a general rule, is responsible for the anisotropy - dissimilar behavior in different directions - of the mechanical properties. The mechanical properties which are decisive in disaggregation are the hardness of the minerals and the mineral matrix, as well as the properties of strength and deformation.

In principle, the matrix is attacked primarily by applying a pressure load of continuous or intermittent nature. The mineral components and the mineral matrix are crushed within the immediate effective radius of a tool which is applied with high pressure, and for this reason penetrates the rock. Within a wider radius from the point at which the tool is applied, however, the matrix is not destroyed directly by the pressure load. Compressive strength is the predominant strength property of rock. Shear strength and tensile strength are distinctly lower in comparison.

Except for the zones at the beginning of a load and before the breaking, the compression increase follows a curve which is practically linear to the increasing load on a test rock sample. Also, solid rock between these two zones shows a practically elastic behavior; i.e., when the load is removed, the deformations are reversed. For most hard rocks, the zone of elastic deformation is much greater than the starting zone which is usually characterized by permanent deformation, and the zone with plastic behavior before the actual fracture. The destruction of the formation can be explained as follows: the compression load applied to the interior of the rock creates stresses which affect its weakest strength properties (i.e., the shear strength and tensile strength) until fracture occurs. The formation of fracture planes is facilitated by the presence of weak spots in the formation or within its components. Weak spots already present in the microstructure (i.e., in basic rock bodies) may be of genetic origin, such as faults in the mineral crystallization, in the grain cohesion of igneous rocks, or in the cementation of sediments. However, they can also be caused by a metamorphosis of the rock, for example by lamination of minerals, and also by mechanical stresses such as Mylonitization of hard minerals.

Mechanical stress is, with few exceptions, also responsible for cracks forming weak spots in the large spatial formations of rock, the rock mass. Rock discontinuities are another weak spot in the large formation rock mass.

These weak spots are especially helpful for disaggregation if they are positioned as planes within the field of the interior shear and tensile load caused by exterior pressure loads in such a way that the shear loads occur plane-parallel; the tensile loads occur perpendicular to the plane of weakness.

2.2 BORING TOOLS

With regard to the direction of pressure on the cutting face of a tunnel and the work taking place there, basically two groups of boring tools can be distinguished [2]:

- tools with an effect primarily perpendicular to the tunneling direction, and

- tools whith an effect primarily in the direction of the tunneling.

2.2.1 Tools with an Effect Primarily Perpendicular to the Direction of Tunneling

These are:

- drag bits or teeth, and

- cutting heads with undercutting plates.

These drag bits, Figure 2-1, armored by hard metals, are mounted on the spokes. The blade arms of the cutting head form a small angle to the plane of the tool carrier. During rotation of the cutting head, under pressure, the blades dig into the work face, and cut concentric grooves into the uneven edges of the rock. The rock to be peeled, which is relatively brittle, breaks during the peeling process. Use of these tools is successful only in practically non-abrasive rocks; i.e., in low-strength rocks which cause little wear to the boring tools. However, these tools are suited for the boring of material with ductile behavior.

Like cutting blades, drag bits can also be mounted at the circumference of cutters (i.e., cutting heads), Figure 2-2. For the boring of circular profiles, two or four cutters are arranged on a drum. During the slow revolution of the cutting heads around the machine axis, they also rotate relatively fast around their axes in the direction opposite to the drum because the cutters are arranged on the drum in such a way that their axes form small angles with the axis of the machine. During simultaneous rotation of the drum and of the cutter heads, as well as during simultaneous

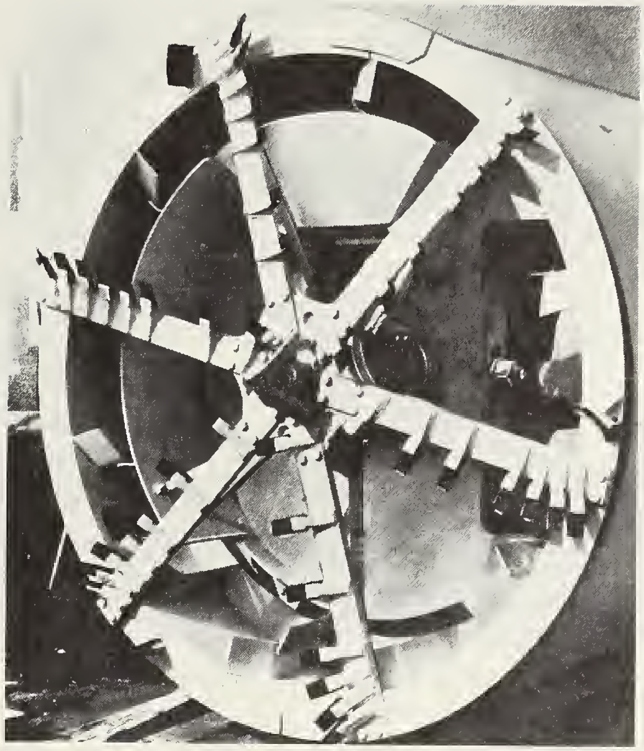


Photo: Calweld

Figure 2-1. Drag Bits

advance of the machine frame, the individual undercutting plates move in the form of cycloids on the work face. The cutting heads equipped with the undercutting plates have the tendency, due to the divergence of their axes with the axis of the drum, to cut into the work face (Figures 1-8 and 1-9).

Tunneling machines equipped with this type of cutting edge have also been developed for the cutting of rectangular profiles. The fullfacer of Atlas Copco is equipped with four cutting heads arranged in two pairs at the face of the machine frame. During the boring each can be rotated in pairs around a vertical axis (Figure 2-3).

The mini-fullfacer by the same manufacturer for the boring of minimal, upright rectangular profiles has only one cutting head with a horizontal swivel axis. During the boring, the rotating

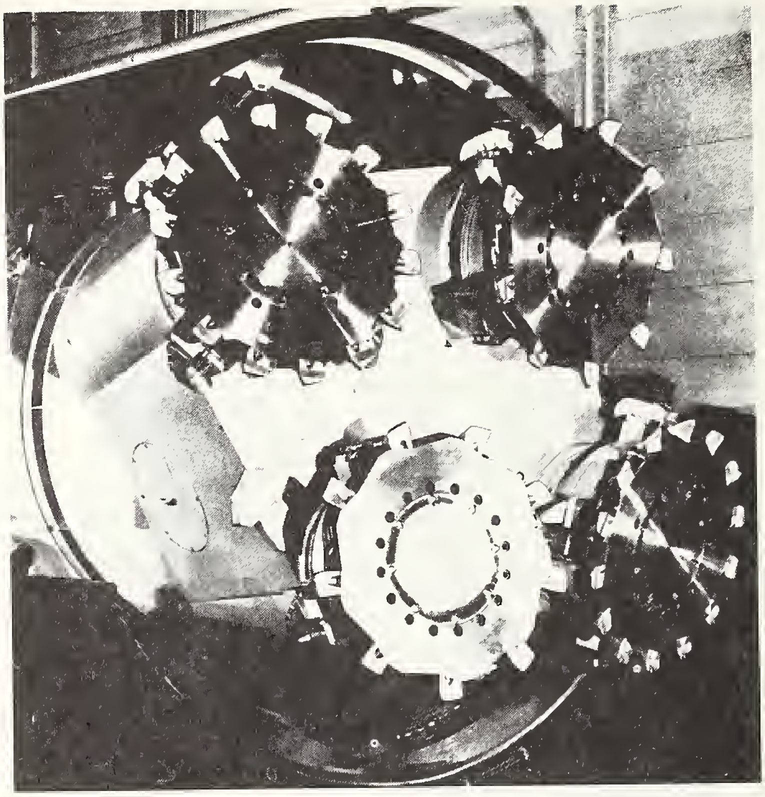


Photo: Atlas Copco

Figure 2-2. Drum with Cutting Heads and Undercutting Plates For the Cutting of Circular Sections

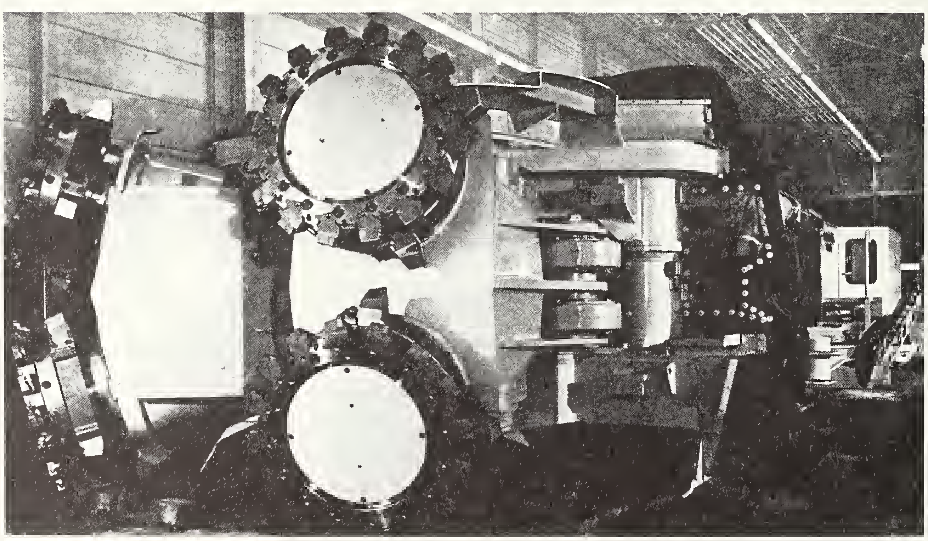


Photo: Atlas Copco

Figure 2-3. Fullfacer with Four Cutting Heads for Cutting of Rectangular Sections 4.8 x 2.6 m cutting head swivels upward, (Figure 2-4). The form of rock disaggregation developed by Wohlmeyer, and further developed by Habegger and Atlas Copco, is called the undercutting process, or "milling". When the cutting heads penetrate the work face, brittle rock in the path of the hard metal undercutting plates is sheared off in the form of chips. Non-brittle material is ground up as the cutting heads undercut the work face. The undercut rock does not form shavings due to its mechanical properties, but breaks into relatively large chips, (Figures 2-5 to 2-7). The advantage of the relatively small feeding force required is counter-balanced by problems related to the material of the undercutting plates which consist of hard metals: i.e., a sintered alloy with tungsten carbide as the wear-resistant main component, and cobalt as binder. During the cutting, several of the hard metal undercutting plates of a cutting head are always in sliding contact with the rock. Here, wear of the cutting edges occurs as the tungsten carbide grains break out of the sinter structure. Occurrence of high friction temperatures also lead to oxidation of the tungsten carbide grains. Impact stresses during the cutting cause mechanical fatigue of the sinter structure [3]. The content of abrasive minerals and their grain size; the strength properties of the rock; as well as the cutting speed influence even the wear of tools which are properly cooled with water or a water-compressed air mixture. Tunnel boring, by means of the undercutting process in high-strength and simultaneously abrasive rock, is more closely limited by technical and economical factors than by methods employing roller bits.

2.2.2 Tools With An Effect Primarily in the Direction of Tunneling

These are:

- cutting teeth as well as styli, and

- roller bits, i.e. tooth, button and disk roller bits.

These tools mounted on spokes or plates of the cutting head describe concentric circles on the work face with rotating tool carrier, and form either grooves or furrows, depending on the nature of the rock and on the tool.

Cutting teeth, Figure 2-8, and styli, Figure 2-9, produce furrows in a rock of low strength. The ridges remaining between the furrows are removed either by the wedge effect of the teeth and styli further penetrating into the rock, or are cut radially against the neighboring furrows by roller bits rolling between these tools. Successful use of teeth and styli is limited to rocks of low strength and low abrasiveness.

The roller bits rotate around axes that are approximately parallel to the work face, but they are not driven. Their blades, the teeth, the buttons, and disk rings roll on the work face when the cutting head is rotating. Instead of the sliding friction

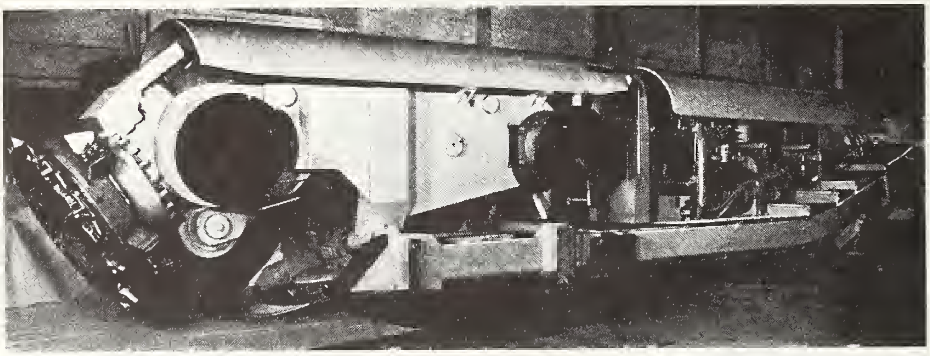


Photo: Atlas Copco

Figure 2-4. Mini Fullfacer with Cutting Head for the Cutting of Small Upright Rectangular Sections 1.5 x 2.4 m

Figure 2-5. Undercutting of the Face in Sandstone

Figure 2-6. Muck (Sandstone) from Undercutting Shown in Figure 2-5

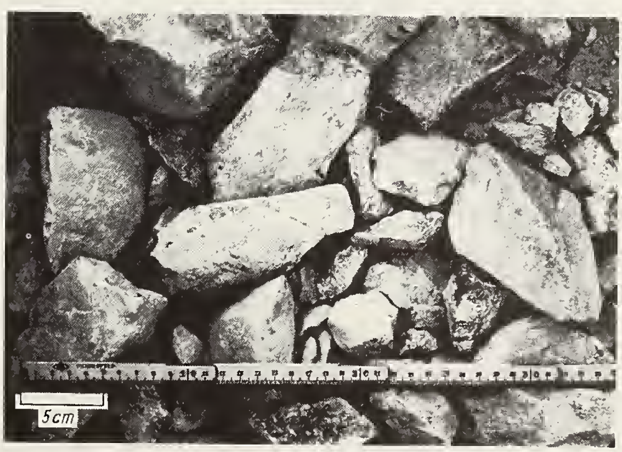


Figure 2-7. Muck from Figure 2-6 After Flushing Out of Fine Material

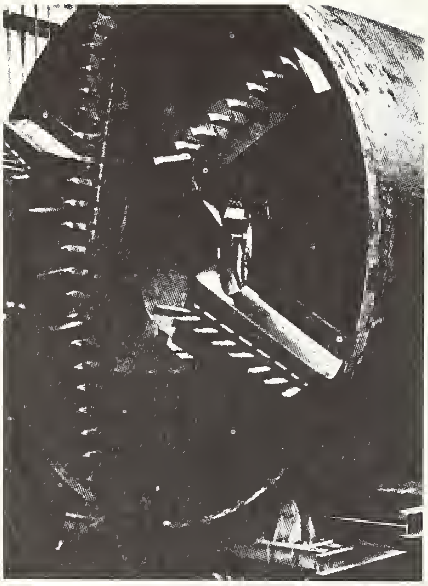


Photo: Kinnear Moodie Tunneling Machines Ltd.

Figure 2-8. Cutting Teeth

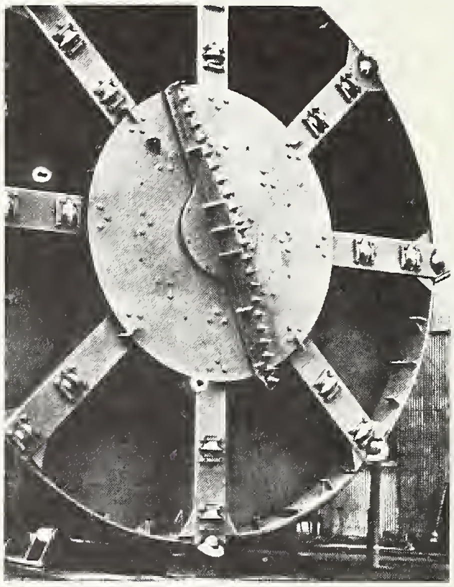


Photo: Calweld

Figure 2-9. Styli in Cutting Head Center

effect characterizing the functional principles of the tools mounted in a fixed position on the cutting head described so far, the effect of these tools is based on a rolling friction between cutting edge and work face. Due to the process of the drilling of the work face, the contact between cutting edge and rock is not permanent, and not all roller bits mounted on a cutting head are in contact with the rock simultaneously. Sliding friction is reduced to a very high degree but is not eliminated completely.

Under the static effect of the pressure, and the dynamic effect of the rotation, the cutting edges penetrate the rock in varying degrees. The mineral matrix and its components are crushed in the immediate radius of effect of any kind of penetrating cutting edge carrying a pressure load. The tips of the teeth of the tooth bits, and the tips of the hard metal button of the button bits form craters in the work face whose volume is larger than that of the metal pushed into them. In addition, they disaggregate the rock in a direction tangential to the rolling tool as well as perpendicular to it.

The edges of the tooth and button roller bits are identical to those of the tricone rock bits as used for drilling of holes, e.g., for oil wells. The body of the bit, however, has the shape of a truncated cone. The tooth and button roller bits are mounted on the cutting head in such a way that, during rotation of the cutting head, the whole area of the work face is covered by the tooth tips; i.e., the hard metal lugs, Figure 2-10.

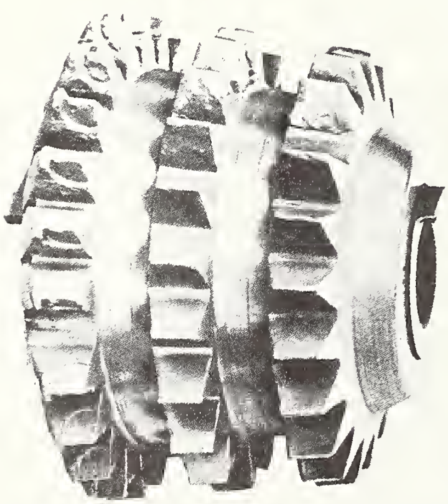
The body of the bit, and the teeth of the tooth bits machined from it (Figures 2-11 and 2-12) consist of heat-treated alloyed steel [4]. According to the strength behavior of the rock to be bored, bit types, i.e., the geometric form and the number of teeth are selected. Types with few, long, and relatively sharp-angled teeth per row are used for a rock of lesser strength. When the bit rolls over the rock, the teeth penetrate the work face in varying extents, forming craters and shearing off chips in a tangential direction. The bit types for solid and hard rock have many rows of short and relatively obtuse-angled teeth. The nature of the rock allows only small penetration, and the disaggregation of the work face is achieved predominantly by removal of small rock chips.

In hard and also abrasive formations, the use even of surface-armored tooth bits becomes uneconomical. In their place, button bits (Figures 2-13 and 2-14) are used. Hard metal pins with a diameter of 5 millimeters are inserted at distances of approximately 4 cm into the steel body of this type of roller bit. If they are pressed into the rock, under high pressure and during rotation, the above-mentioned craters form underneath the buttons, as well as cracks in their vicinity, and shallow fractures whose planes are approximately parallel to the work face. The chipped-off rock particles can have the dimensions of a coin (Figures 2-15 and 2-16). The button bit is a technically suitable and expensive tool for the boring of high-strength and abrasive formations which do not provide a spectacular penetration.

The disk roller bit (which due to its basic design consisting of bearing bit body, bearing seals, and cutting edge also belongs among the roller bits) has been developed especially for machine tunneling. It has not been in use long for large diameter boring, but it has replaced the traditional types of roller bits. The cutting edge of a disk bit represents an endless wedge. The wedge angles in use range from 60° to 105°, Figure 2-17. No cutting edge has the sharpness of a knife. However, relatively durable blades are produced today that may justly be called sharp-edged, and whose cross section between the flanks no longer shows a rounding with a radius in the magnitude of millimeters. Under pressure, a sharp-edged wedge has excellent penetration properties. These are still further improved by the rolling motion. Even a work face consisting of high-strength rock is penetrated at least superficially. A groove with varying depth, with flat slopes which do not at all correspond to the wedge angle, and is filled with rock powder at the bottom, marks the course of a sharp disk bit on the work face. The work face is directly affected only in the immediate zone of the disk course. The distance between the courses is called cutter spacing b, Figure 2-18. The fracture

Photo: Wirth & Co.

Figure 2-10. Face Cut with Button Roller Bits



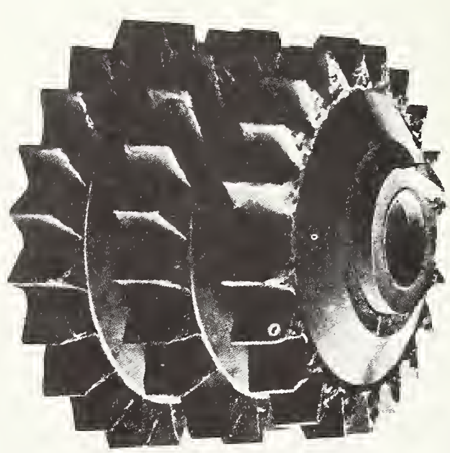


Photo: Smith Tool Co.

Figure 2-11. Caliber (Gauge) Bit

Figure 2-12. Inner Bit

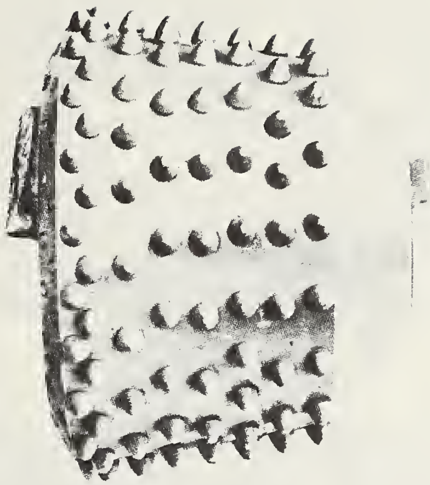


Figure 2-13. Caliber (Gauge) Bit

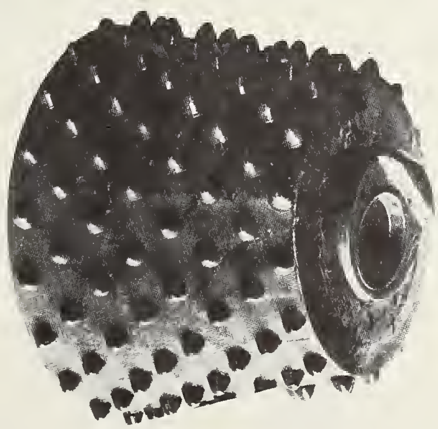


Photo: Smith Tool Co.

Figure 2-14. Inner Bit

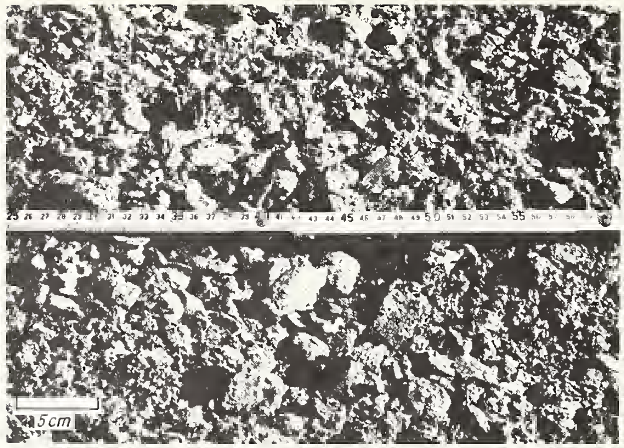


Figure 2-15. Muck, Granite Bored with Button Roller Bits

Figure 2-16. Muck of Figure 2-15 After Flushing Out Of Fine Material

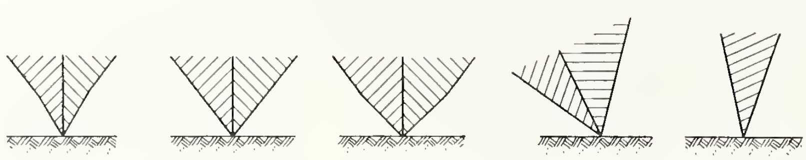


Figure 2-17. Geometric Shapes Of Sharp-edged Disk Cutters

planes extending from both sides of the groove usually form only after the disk has rolled over the work face several times under pressure, and are directed either against the work face or against the neighboring grooves. In rock which deforms in a double manner (Figure 2-19), or with too large a cutter spacing, the effect of a disk blade may be restricted to the formation of grooves. In extreme cases, the disks dig in until the body of the bit rests on the rock. In brittle rock, and with appropriate cutter spacing, chips the size of a hand are splintered off above the fracture planes. The cross section of these chips corresponds to that of an airplane wing, Figure 2-20. The chips have a predominantly oblong shape. A generally applicable statement on the granulometry of the cuttings cannot be made. It is influenced by a great number of factors such as wedge angle and condition of the blade, cutter spacing, rock properties, separation planes of the rock, etc.

Depending on the manufacturer, the ring blade of the disk is part of the disk body, or it is shrunk into the disk body as ring with wedge-shaped cross section. This last-mentioned type construction is found more often. It is based on the experience that usually the blade of a disk roller bit has a shorter life than the disk body and the bearing.

Manufacturing of replaceable ring blades of construction steel or of tool steel is basically very simple and inexpensive. A large problem arises from the requirement that the sharpness of the blade should be retained as long as possible, even in hard and abrasive rock. For this purpose the following measures are used:

- hardening of the wedge planes of the steel ring blades,

- armoring of the wedge planes by means of welded-on hard metal which, however, leads to a certain loss of the blade sharpness, and thus a loss of penetration capacity under equal pressure,

- attaching hard metal inserts to the circumference of the ring blade that show the cross section of sharp wedges,

- disk bit whose blunt disk is manufactured as part of the disk body, and where hard metal buttons inserted into the periphery serve as blades,

- ring blades made from hard metal.

Besides the blade characteristics with regard to satisfactory abrasion resistance, the different versions of disk roller bits also differ in the number of the blades or ring blades mounted on the bit body:

- monodisk bit, Figures 2-21 to 2-26,

- double or multiple disk roller bits with two or more neighboring blades rolling over the work face, Figures 2-27 to 2-29, double or multiple disk roller bits with two or more ring blades which roll on the work face on both sides of a track belonging to a neighboring bit, Figures 2-30 and 2-31.

The single disk with surface-hardened steel ring blade is the effective, relatively inexpensive, and commonly used tool for tunneling. Its use is limited less by the forces applied to the ring blade through large penetration pressure than by a large portion of wear-intensive minerals in the rock to be bored. For such cases, the button disk roller bit may, for the time being, be used as a less effective and also more expensive replacement of the sharp-edged single-disk bit. It will be used until attempts have been successful to develop an economical material and an economical production process for sharp-edged disk ring blades with high strength properties and high resistance against the abrasive effect of minerals.

Figure 2-18. Face in Limestone Cut with Sharp-edged Disk Cutters (Tunnel Circumference Top Left)

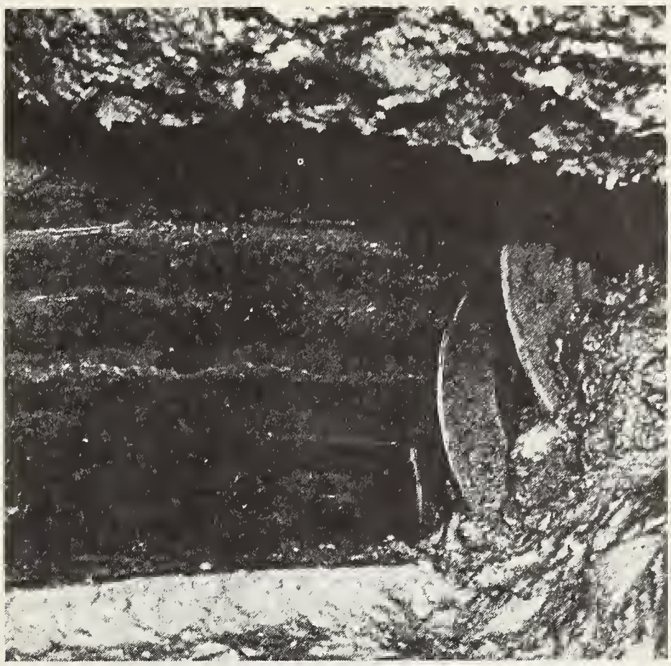


Figure 2-19. Grooves Cut By Disk Cutters In Ductile Rock

Figure 2-20. Cuttings Cut With Disk Bits. From Left To Right: Medium-Hard Sandstone, Soft Sandstone, High-strength Limestone, Soft Sandstone, Medium-hard Granite (All Cut With Robbins Machine), Medium-hard Granite (Wirth), Hard Limeston (Jarva), Hard Granite (Demag)

Photo: The Robbins Company

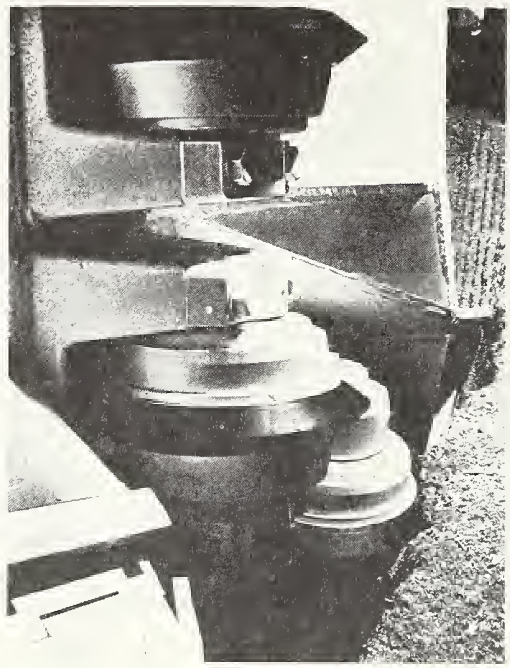


Figure 2-21. Disk Cutter Design

Figure 2-22. Muck, High-strength Limestone Bored with Disk Cutters Shown in Figure 2-21

Figure 2-23. Muck of Figure 2-22 After Flushing Out of Fine Material

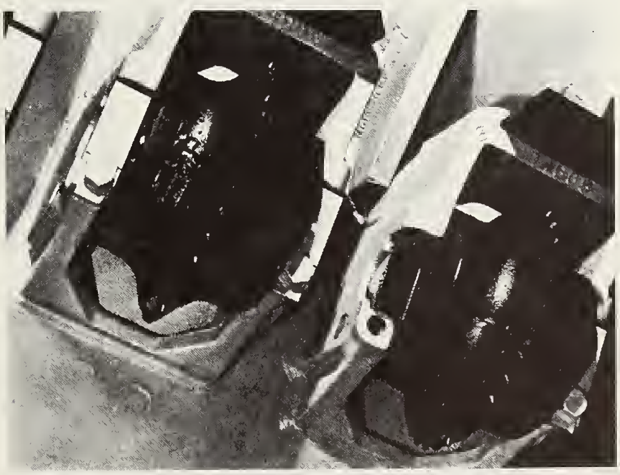


Figure 2-24. Bit Design (Lawrence) Button Disk Roller Bits

Figure 2-25. Muck,High-strength Limestone Bored with Button Disk Rollers Shown in Figure 2-26

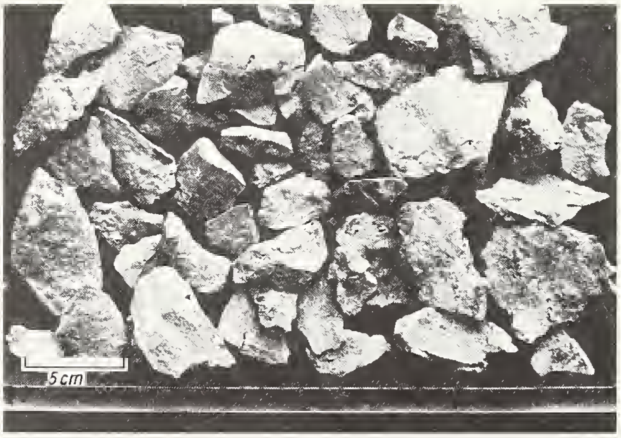


Figure 2-26. Muck of Figure 2-25 After Flushing Out of Fine Material

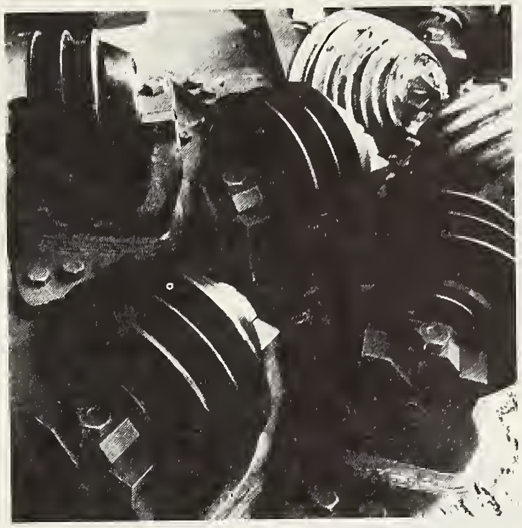


Figure 2-27. Triple-Disk Bit Design

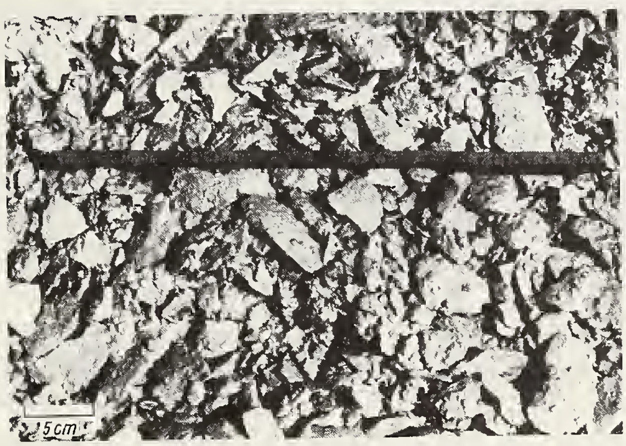


Figure 2-28. Muck From High-strength Limestone (Bored With Triple-Disk Bits Shown in Figure 2-27)

Figure 2-29. Muck of Figure 2-28 After Flushing Out of Fine Material

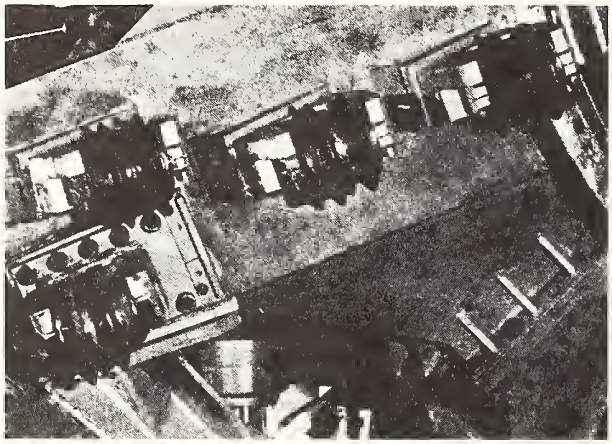


Figure 2-30. Double-Disk Bit Design

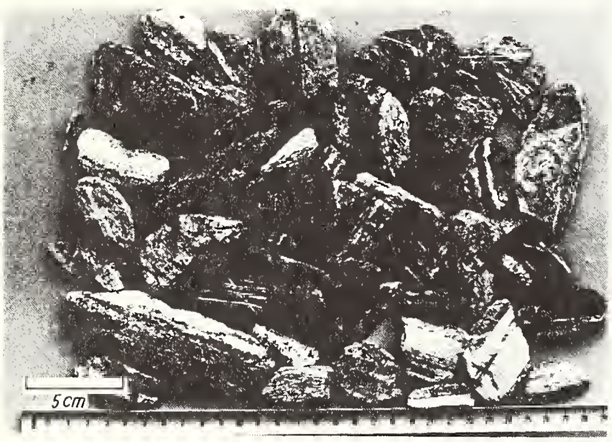


Figure 2-31. Muck Consisting of Mica- and Hornblende-Gneiss, Bored with Double-Disk Bits Shown in Figure 2-30

2.3 BOREABILITY OF ROCK AND ROCK MASS

Until now, no formula has been published yet for reliable calculations of the boreability - with reference to a given boring system, of course

- in terms of their dependence on mechanical properties and mineralogical-petrographical characteristics of the rock of rock mass to be bored.

However, results are known of:

- laboratory analysis; these usually examine the effectiveness of one to three cutting tools, for example [5 to 9].
- laboratory analysis whose results are checked during use of tunneling machines equipped with identical cutting tools, for example [10 to 12] and
- boreability analysis with tunneling machine [13]; compare section 2.3.1.4.

For the evaluation of the boreability of a geological formation the tunneling system to be used must be defined first, in any case, and, in addition, it must be distinguished between:

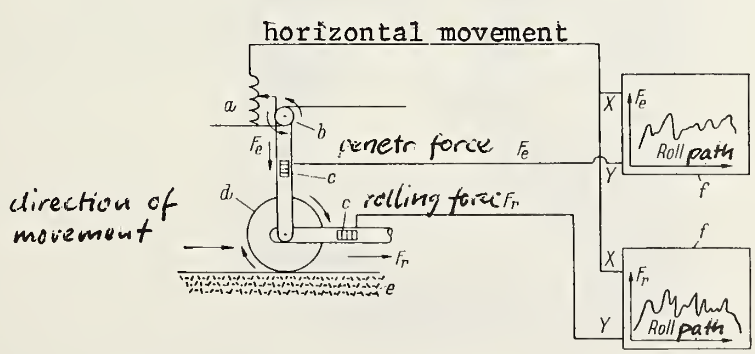
- rock-related boreability, i.e., basic boreability, and the
- influence of the rock mass structure on the basic boreability.

2.3.1 Rock-related boreability on basic boreability

In the following, the preconditions and the most important results of analyses on the basic boreability are described, in particular:

- a laboratory analysis with a linear apparatus, section 2.3.1.1,
- a laboratory analysis with a rotary table, section 2.3.1.2.,
- laboratory analysis, verified on location by means of a tunneling machines, section 2.3.1.3.,
- experiments on location with tunneling systems respectively tunneling machines, section 2.3.1.4.

2.3.1.1 Analysis with a linear apparatus at the Twin Cities Mining Research Center (TCMRC) of the Bureau of Mines - At the TCMRC [6], experiments were conducted on the influence of cutting tools on four different kinds of rock, and on the forces necessary for penetration. A linear apparatus was used, Figure 2-32.



a	linear potentiometer	c	wire strain gauge	e	test specimen
b	pulley	d	disk bit	f	recorder

Figure 2-32. Linear Testing Apparatus of the Twin Cities Mining Research Center (TCMRC) [6]

By means of this test installation, one disk roller bit, each with a wedge angle of 60° or 90°, was pulled over the cut surface of the test rock. The vertical penetration force F_e, maximally approximately 5 Mp(50kN), and the horizontal rolling force F_r necessary to overcome the rolling friction were measured and recorded continuously. In addition, the depth, i.e., the penetration t of the disk blade, and the volume of the groove were determined. The most important results of these tests conducted under limited conditions are:

a) relation between penetration force F_e and penetration t:

- between penetration force and penetration a linear relation exists.
- with equal penetration forces, the penetration achieved with a 60° disk blade is larger than the one caused by a 90° disk blade, for all rock samples used in the test.
- under the condition of equal penetration force and equal angles of the disk blade, the penetration in a rock of lesser strength and surface hardness as well as with a smaller elasticity modulus E is larger than in a rock with higher strength, hardness, and stiffness.

b) relation between penetration force F_e and rolling force F_r:

- with increasing penetration force, the necessary rolling force increases slightly more than proportionally.
- with equal penetration force, the rolling force necessary for advancing a disk bit with a 60° disk blade is larger than the rolling force necessary for the rolling of a disk with a 90° disk blade.
- the rolling force necessary for bit movement over rock of high strength, hardness, and stiffness is smaller than that necessary for rolling a bit over rock whose relevant properties are inferior.

The special value of the TCMRC analysis consists of the recognition of qualitative relationships between the parameters cutting tool, penetration force, rolling force, and rock. The narrow limitation of the test conditions - among others, the model similarity is questionable, and only the production of the groove track and not the actual disaggregation of the rock by separation of chips were simulated - limits the application of the quantitative data obtained here for the evaluation or construction of tunneling machines.

2.3.1.2 <u>Investigation with disk roller bits rolling in concentric circles, conducted at the Technical University of Clausthal-</u>

These analyses [7] had the goal of determining the forces to be supplied by the tunneling machine, torques and drive power for a certain penetration and net tunneling speed. The tests were conducted in particular with bit configurations for appropriate exploitation of the relatively inferior strength properties of the rock. The modified rotary table of an oil drilling rig as carrier of the test samples was used as test device. Three cutting tool holders with one disk roller bit each were mounted on a support installed in the rotational axis of the table. This support could be moved axially. The construction of the holders permitted variations of the cutter spacing between the bits as well as variable indication of the bits for boring of a conical work face, Figures 2-33 and 2-34.

Figure 2-33. Tool Holder With Disk Bit

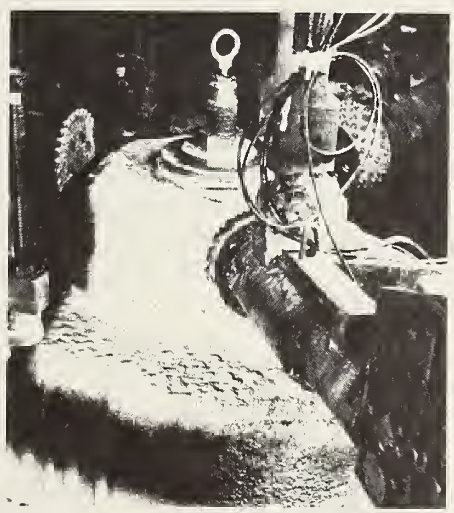
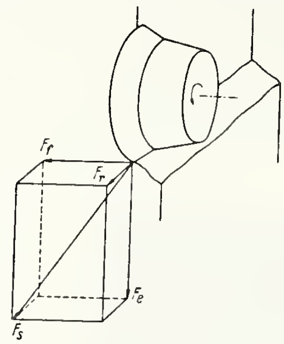


Figure 2-34. Tool Holder With Button Bit

The construction of the tool holders also permitted the separation of the so-called action forces influencing the bits during boring into axial, tangential, and radial components in relation to the rotating rock samples; i.e., into the penetration force F_e, the rolling force F_r, and, with conical work face along with disks rolling non-perpendicular to the work face, into the free cutting force F_f as shown in Figure 2-35. These three cutting force components and, among others, the penetration t as well as the boring distance were measured and recorded.



F_e penetration force
F_r rolling force
F_f free cutting force (= force separating chip from rock mass)
F_s resulting cutting force.

Figure 2-35. Forces Acting On A Disk Roller Bit

Three abrasive sedimetary rocks with different strength properties, and, to a lesser extent, also one granite were used as test rock samples. The mill-stone-shaped test bodies were free of cracks, and of relatively homogenous structure. The dimensions and the installed power of the system, as well as the dimensions of the rock test samples with a finished diameter of one meter, permitted - notwithstanding the constructively less realistic model disk roller bits - the conducting of tests on a 1:1 scale for a continuous, real disaggregation of the rock, and the gathering of data which are also quantitatively relevant to a high degree for practical tunneling. The most important results of these tests are:

- peak values of the action forces

  The penetration forces F_e and the free cutting force F_f, with conical tunnel face, reached peak values that were three times as high as the average values. The peak of the rolling force reached the ten-fold value of the average.

- relation between the action forces and the penetration

  The penetration force F_e and, less distinctive, the free cutting force F_f with conical tunnel face showed a parabolic dependence on the penetration t, i.e., with increasing penetration force, the penetration increased more than proportionally. This rule which had occurred during cutting in all solid rock increased with increasing cone angle of a cone-shaped work face. The rolling force F_r showed linear dependence on the penetrations t.

- the influence of the cutting speed on the action forces

  The penetration force F_e necessary to achieve the penetration t, as well as the other action forces resulting from that were independent of the rolling cutting speed of the disk roller bits.

- influence of the curvature of a disk track on the action forces

  The necessary penetration force F_e as well as the resulting other action forces for the penetration t were independent of the disk track curvature. This is explained by the observation that always only a small section of the straight disk blade is in contact with the rock.

- influence of the shape of the work face on the action forces

  The penetration force F_e necessary for a certain penetration t as well as the resulting other action forces was smallest when boring free surfaces. They increased with decreasing cone angle of a cone-shaped tunnel face, and were largest during the boring of a cavity, Figures 2-36 to 2-39. The net cutting speed, and the specific energy consumption during cutting, changed accordingly.

- Relation of the quantitative results

- Figure 2-40 shows the relation between the penetration t and the action forces on a disk roller bit for various cone angles of the work face respectively for various angles between the blade plane and the tunnel face (cutter spacing b=50 mm), and for a representative solid and abrasive sedimentary rock, such as a typical Ruhr valley sandstone with uniaxial pressure strength of approximately 1,600 kg/cm^2 (equals 1,600 bar) with test sample dimensions d:h = 1:1.

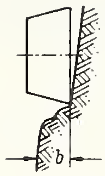


Figure 2-36. Arrangement on a free surface

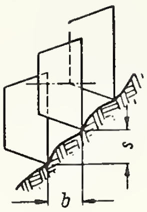


Figure 2-37. Arrangement in steps

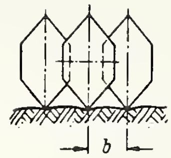


Figure 2-38. Arrangement perpendicular to the work face

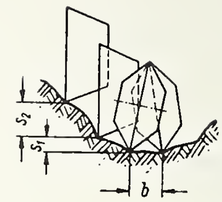


Figure 2-39. Arrangement for the boring of a cut

Figures 2-36 to 2-39. Arrangement of the disk bits in relation to the work face [7]. b is cutter spacing and s, s_1, s_2 are height of steps.

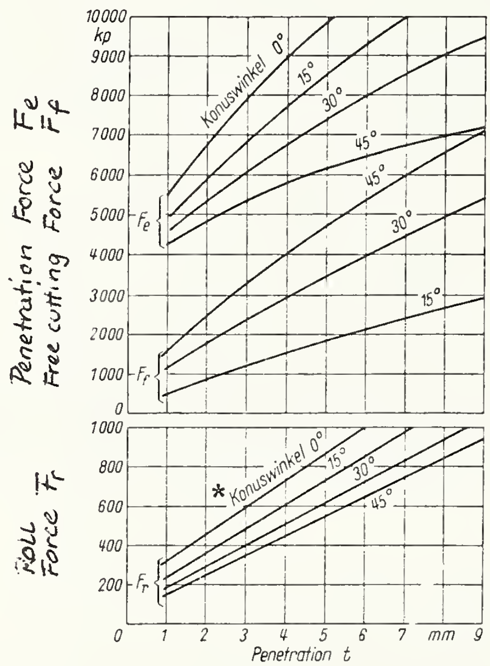


Figure 2-40.
Relation between the penetration t and the forces F_e, F_f, and F_r with cutter spacing b = 50 mm, and various cone inclination angles (0° corresponds to a disk position perpendicular to the work face as in Figure 2-38 [7])

2.3.1.3 Boreability Analyses by the Lawrence Company - This tunneling machine manufacturer has developed a process for direct predetermination of the rock boreability [5, 10] for use with their own tunneling system equipped with button disk bits.

The rock sample which is to be tested is cast together with a special mortar with defined strength and expansion properties in a steel cylinder with 11.2 cm diameter in such a way that a cut rock surface is obtained on one cylinder frontal face. This rock surface should be oriented towards the cylinder axis in correspondence to the orientation of the rock in nature to the tunnel axis. A hard metal pin is pressed in the direction of the cylinder axis into the surface of the test rock inserted into the cylinder to simulate natural conditions. This pin corresponds to the buttons as they are used for insertion into a disk ring blade. For purposes of testing the rock, the permanent deformation δ resulting from four to six increasing values of the penetration force F_e is measured, Figures 2-41 to 2-43. Based on this, the so-called penetration index δi is calculated as follows:

$$\delta i = \frac{\frac{F_{e_1}}{\delta_1} + \frac{F_{e_2}}{\delta_2} + \ldots + \frac{F_{e_6}}{\delta_6}}{6} .$$

Under the condition of a penetration force F_e, for example 12 Mp (120kN), the penetration t which is to be expected during the actual drilling operation (for the Lawrence tunneling system, the cutting tool penetration t_w and the cutting head penetration t_k are equal) will be:

$$t = \frac{F_e}{\delta i}$$

and the net cutting speed v_N of the tunneling machine with a cutting head revolution:

$$v_N = tn.$$

A comparison of basic boreability, or net cutting speeds (those predicted by means of laboratory experiments, and those measured during the operation of tunneling machines) showed good consistency. Under the condition of sufficient cutter spacing, the errors of the prediction were claimed not to have exceeded approximately $\pm$ 15%.

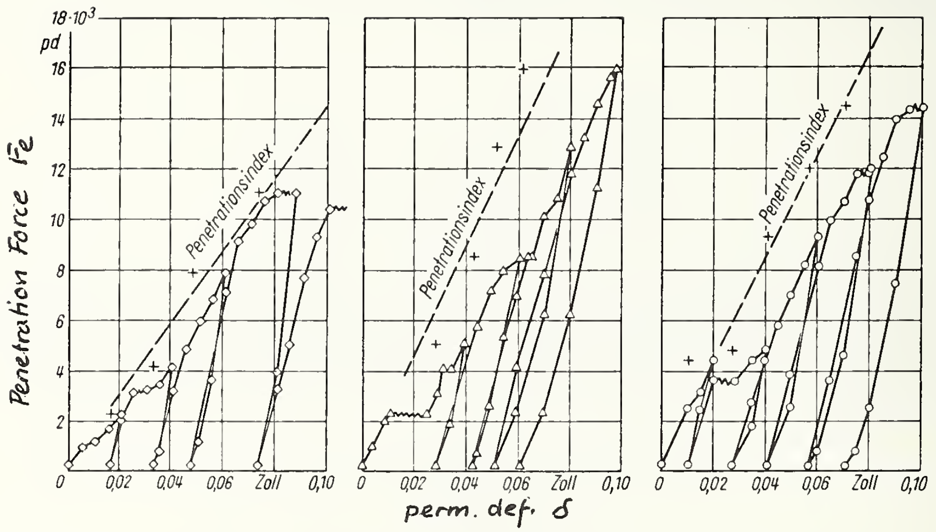


Figure 2-41. Basalt

Figure 2-42. Barre Granite

Figure 2-43. Dolomitic Limestone

Figures 2-41 to 2-43. Boreability Test by Lawrence. Graphic Representation of the Relation Between Permanent Deformation δ and Penetration Force F_e [5]

2.3.1.4 Investigation with Tunneling Machines on Relations Between Rock Properties and Rock Boreability - Ever since 1970, the author has made observations, taken readings on location, and had the cut rock tested with a goal to recognize relations between the penetration of cutting systems equipped with roller bits on the one hand, and mechanical properties, and maybe also mineralogical-petrographical characteristics of the rock, on the other hand. The express limitation of the analysis on the boreability of the rock implies that observation and measurements on tunneling sites can only then be used if the work face consists predominantly of the rock of the same kind or at least of basically identical rock, and if tunneling takes place in undisturbed rock formations. At any one location meeting these requirements the following data samples were taken:

a) Concerning the tunneling machine

- cutting diameter D,
- feeding force during cutting F_V,
- net cutting speed v_N,
- cutting head revolutions during cutting n,
- cutting system;

b) Concerning the geological conditions

- rock-characteristics formation relative to the tunnel axis,
- geological specimen or drill cores for mechanical and mineralogical-petrographical analyses,
- cuttings.

In reference to the anlyses and observations mentioned in section 2.3.1.1 to 2.3.1.3, it is assumed that with a given boring system, the boreability of the rock is influenced decisively by some of its mechanical properties; i.e., by its strength and deformation behavior as well as by its hardness in a wider sense. In general, none of these properties by itself characterizes the behavior of the rock under the influence of cutting tools. The occassionally mentioned connection between strength and boreability only applies to individual kinds of rock. The boreability must be assumed as a result of the interaction of mechanical properties. The following index values for boreability were defined:

- uniaxial compressive strength of cylinders β_D,
- tensile cleavage strength of disks β_Z,

- tangent modulus of elasticity at 50% compressive strength on cylinders E_t 50,

- saw-cutting hardness SH during sawing of disks.

- Of these index values, two characterize the strength behavior, and one each, the deformation behavior as well as a special hardness. The concentration on these properties in particular is also based on the possibility to determine the saw-cutting hardness already during the production of certain test specimens, and to determine the uniaxial compressive strengths simultaneously with the deformation behavior.

a) test specimen dimensions

Only rock pieces or drilled cores that are macroscopically free of cracks are used for the production of test bodies.

- cylinder-test body, diameter d = 24.7 mm, height h = 50.0 ± 0.5 mm; i.e., d:h = approximately 1:2 is used for the determination of:

  stress/strain relation and cylinder pressure strength.

Selection of the cylinder form made a comparison possible with data in American publications without questionable conversions [14]. The relation d:h = approximately 1:2 largely, if not completely, excludes an influence on the results by the geometric form of the test samples [15]. The absolute values of the dimensions take into account the difficulty to take rock samples from undisturbed rock formations out of bored tunnels without special equipment. Smaller dimensions which would be desirable in this respect are problematic with coarse-grained rock, for example porphyritic rocks or matrices. In most cases, the chosen absolute dimensions are sufficient with regard to practice. If coarse-grained components are present, they should be increased with the ratio of d:h = approximately 1:2 kept the same:

- disk test samples, diameter d=24.7 mm height h=9.05 ± 0.05 mm are used to determine the cleavage tensile strength and, during their production, they serve to determine the saw-cutting hardness.

The ratio d:h = approximately 2.7:1 is sufficient to practically prohibit an influence on the results by the dimensions of the test sample [16, 17]. In many cases, the chosen dimensions of diameters and height make it possible to produce disk test samples out of chips that can easily be recovered at the tunneling site.

b) The production of the test samples, i.e., the boring of the cylinders by means of a diamond cutting bit, cutting length of the cylinders and disks by means of a diamond saw, and the production of strictly parallel end faces by means of grinding is achieved with conventional methods.

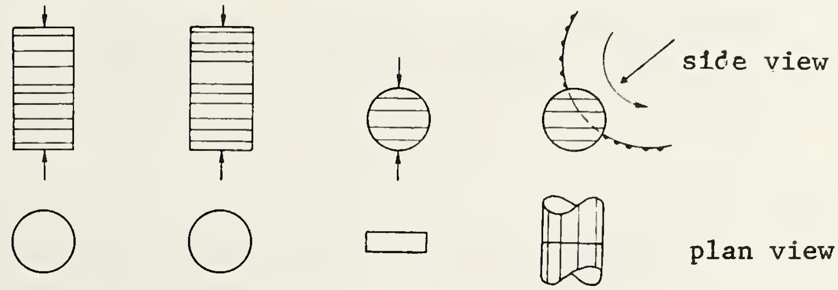


Figure 2-44. Stress-strain relation

Figure 2-45. Uniaxial (cylinder) compressive strength

Figure 2-46. Brazilian test

Figure 2-47. Saw-cutting (abrasion) hardness

Figures 2-44 to 2-47: Intact Rock Testing

c) Conducting of tests, Figures 2-44 to 2-47

- stress/strain relation: determined with three test samples, load perpendicular to the layering of lamination characteristic for the basic sample;

- load applied in stages with rate of load application of 25 kg/s;

Measurement of the strain after reaching each stage on two diametral surface lines by means of Tensomat, accuracy 0.05%, determination of average;

Calculation of the strain for each average;

Measurement of the first cylinder without load relief until breakage;

Measurement of the second and third cylinders each with a practically complete load relief after reaching of approximately 1/3 and 2/3 of the breaking load;

Calculation of the tangent modulus of elasticity for the central, practically linear, range between approximately 1/3 and approximately 2/3 of the breaking load; i.e., in the range of 50% of the breaking strength;

- uniaxial cylinder pressure strength: determined simultaneously with three test samples by means of the stress/strain behavior, taking into consideration that the pressure strength depends on the possibility of a lateral expansion of the test samples;

- cleavage tensile strength: determined, as a rule, on five test samples with a load applied perpendicular to the layering or lamination characteristic for the basic sample, continuous application of loads until fracture, with a rate of load application of 25 kg/s;

Saw-cutting hardness: This term is based on the fact that a measure for the resistance against deformation - even of a surface - is expressed during boring or sawing of a test sample. Under defined steady conditions for the tool, the tool drive, the penetration force, and the rinsing, it has been attempted to use as the practical means of comparing the time necessary for the sawing of a rock cylinder perpendicular to the axis and perpendicular to a layering or lamination characteristic for the basic body. This sawing time under defined preconditions is called saw-cutting hardness. It is determined on two test samples with two to three saw-cuts each.

d) Relation between index values and penetration

In Figures 2-48 to 2-51, the correlations are given graphically of the index values of the bored rocks determined in the laboratory to the specific penetration t_{spec} determined in location on the respective tunneling machines or tunneling systems.

$$t_{spec} = \frac{t_K}{F_e} = \frac{t_K}{\frac{F_v}{a}} .$$

Meaning of the symbols;

F_v is the actual feeding force effective at the cutting head. The portion of the force which is necessary for pulling of the auxiliary carriages has been subtracted. Not subtracted was the friction in the feeding system of the basic machine.

a is the number of cutting tools on the cutting head, including the center bit,

F_e is the average penetration force of a cutting tool.

From Figures 2-48 to 2-51 (showing relation between the index values of the basic boreability and the specific penetration t_K F_e) it can be seen that there is a tendency for a dependence between all defined index values and the specific penetration t_K:F_e. The specific penetration decreases with increasing index values.

For the evaluation of the results, the following must be taken into consideration:

- the curves are drawn for three to five observations. The portions of the work face that were cut by the caliber (gauge), inner, and center bits were of different size in each observation.

- the penetration force was calculated as an average under the precondition that all bits, i.e., caliber (gauge), inner, as well as center bits, take the same portion of the feeding force effective at the cutting head.

Despite the simplified assumptions, the empirical method of the boreability determination has proved for four different boring systems the present tendency of an interrelationship between the given index values and the specific penetration. The relations described here were determined during the boring of undisturbed rock formations consisting of the same rock. This boreability, expressed by the specific penetration dependent on defined mechanical properties of the rock, can be called rock boreability or basic boreability.

e) Mineralogical-petrographical characteristics of rock

Besides mechanical properties, mineralogical-petrographical characteristics of rock were analyzed also. On the basis of thin sections which were evaluated microscopically and also by means of crossed Nicols, and also by means of hand specimen, the following were determined:

- rock-forming minerals, qualitatively and quantitatively,

- structure, qualitatively,

- texture, qualitatively, and

- diaclase, qualitatively.

Figure 2-52 shows as example the results of mineralogical-petrographical analyses.

The results of the determination of the main components of a rock formation serve, together with the cleavage tensile strength, to calculate the so-called wear coefficient a [18].

Figures 2-48 to 2-51. Relation between index values for basic boreability and the specific penetration t_K/F_e. Systems A, B, C, D, Table 2-1.

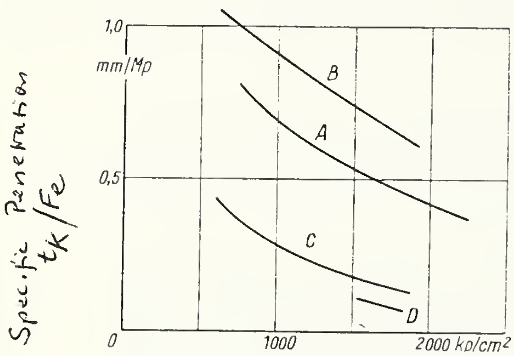


Figure 2-48.
Uniaxial (cyl) compressive strength β_D

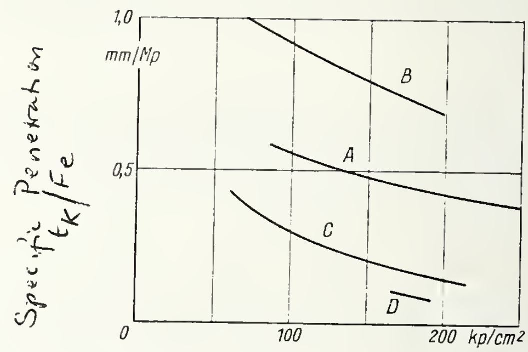


Figure 2-49.
Cleavage tensile strength β_z from Brazilian test

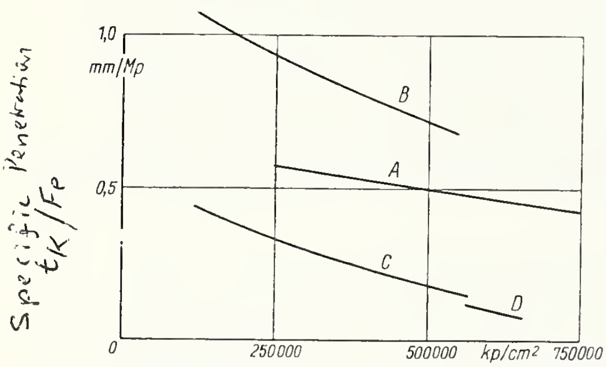


Figure 2-50.
Tangent Modulus of Elasticity (E_{t50})

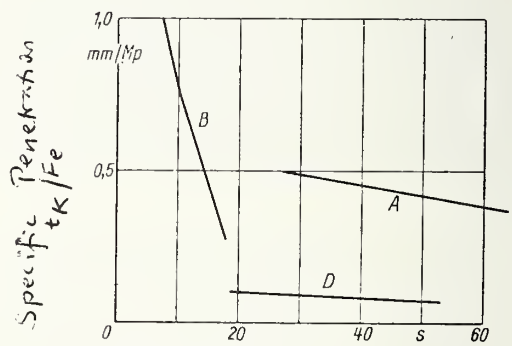


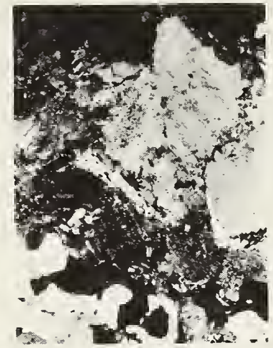
Figure 2-51.
Saw-cutting hardness SH

Figures 2-48 to 2-51 include the boring systems given in Table 2-1.

TABLE 2-1. BORING SYSTEMS USED FOR BOREABILITY EXPERIMENTS WITH TUNNELING MACHINES

System	boring diameter m	bit	cutting width b = cutter spacing cm	penetration force F_e Mp
A	4.2 to 5.6	button disk	6.5 to 7	8 to 11
B	4.2 to 5.5	monodisk	8 to 8.5	8 to 12
C	2.2 to 10.5	double disk	5.0	7 to 8
D	3.8	triple disk	4.0	13 to 14

1 Mp ≈ 10,000 N

Name	fine-grain muscovite	fine-grain sandstone	heterogenous grain grainte	compact marly limestone
Origin	Gotthard Pass, Switz.	Rorschach, Switz.	[illegible]henen, Switz.	Vierwaldstättersee, Switz.
Thin-section				
Minerals resp. components = M/K	M/K	M/K	M/K	M/K
1 hard, not cleavable	1 quartz - 40%	1	1	1
1	1	1 quartz - 25%	1 quartz 25%	1
1	1	1	1	1
2 hard, cleavable	2 plagioclase feldspar 5-10%	2 microcline } 20%	2 microcline 35%	2
2	2	2 plagioclase (feldspar types)	2 plagioclase 35%	2
2	2	2	2	2
3 medium hard	3	3	3	3
3	3	3	3 epidote 3%	3
3	3	3	3	3
4 soft	4 muscovite (white mica) 50 - 58%	4 calcite (calc spar) 50%	4	4 calcite } 100%
4	4	4 mica <5%	4 biotite (black mica) 2%	4 clay
4	4	4	4	4
grain size mm (K)	K	K	K	K
5 all minerals	5 0.2 - 0.7	5 0.1 - 0.2	5 0.5 - 3.0	5 0.02
6 quartz, average	6 0.5	6 0.15	6 aggregate 1.5 - 3.0	6 ----
Structure (S)	S grano-lepido blastic	S psammitic, in discontinuous calcite matrix	S granular, deteriorating, idiomorphic (lightly interlocked	heterogenous, very fine grained calcite granules dispersed grain by grain (i.c., in reduced matrix)
Texture (T)	T layered 0.5 - 0.7mm, generally slightly schistose, though strongly so in some strata	T massive	T massive	T massive
*Diaklase (D)	D ---	D ---	D recrystallized quartz aggregate	D ---

*(altered term on original unclear)

Figure 2-52. Example For Results From Mineralogical-Petrographical Analysis

$$a = \frac{\%}{100} d_K \beta_z$$

The symbols in this equation mean:

% percentage portion of the main components with hardness relating to quartz [19],

d_K average weight of the grain diameters in cm of the main components with the hardness in relation to quartz as weight,

β_z cleavage tensile strength in kg/cm^2 (bar).

f) Comparison of the index values and mineralogical-petrographical characteristics of different rock.

In Table 2-2, the defined index values and mineralogical-petrographical characteristics of some kinds of rock are given, subdivided into the groups:

granites,
basalts,
sandstones
limestones and
metamorphous rock.

Figures 2-53 to 2-55 show relations between the index values of the basic boreability.

Figure 2-53, $\beta_z:\beta_D$: the uniaxial cylinder pressure strength increases with increasing cleavage tensile strength. There is the tendency of the linear relation

for the granites and the gneisses #9, 28, 53, 55, 56, 57, 58, 62, 63, 65, 66: $\beta_z:\beta_D$ 1:14

as well as for limestones and sandstones: $\beta_z:\beta_D$ 1:10.

There appears to be no mathematical interrelationships for the metamorphous rock, with the exception of the gneisses that are similar to granite.

Figure 2-54, $\beta_z:E_t\sqrt{50}$ becomes larger with increasing cleavage tensile strength. The tendency of the linear connection can be be seen

for granite and gneisses similar to granite $\beta_z:E_t\sqrt{50}$ 1:4000
as well as for limestones and sandstones $\beta_z:E_t\sqrt{50}$ 1:2450.

Except for rock similar to granites, a mathematical interrelationship is not evident for metamorphous rock.

Figure 2-55, β_z:SH: the saw-cutting hardness increases with increasing cleavage tensile strength.

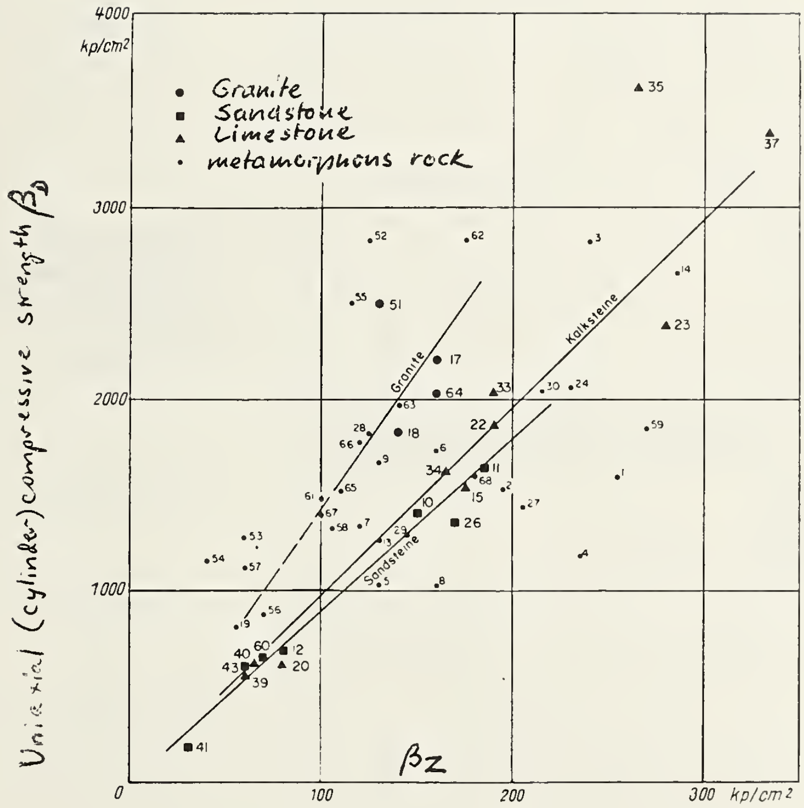


Figure 2-53. (Cleavage) Tensile Strength β_Z

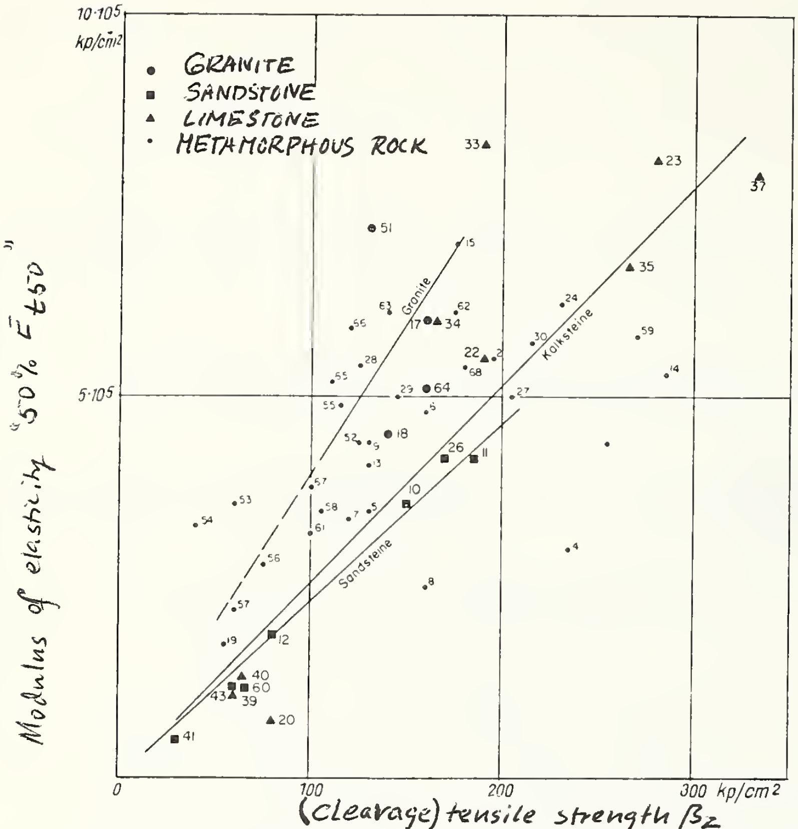


Figure 2-54. Relation: Cleavage tensile strength β_z to modulus of elasticity 50% E_{t50}

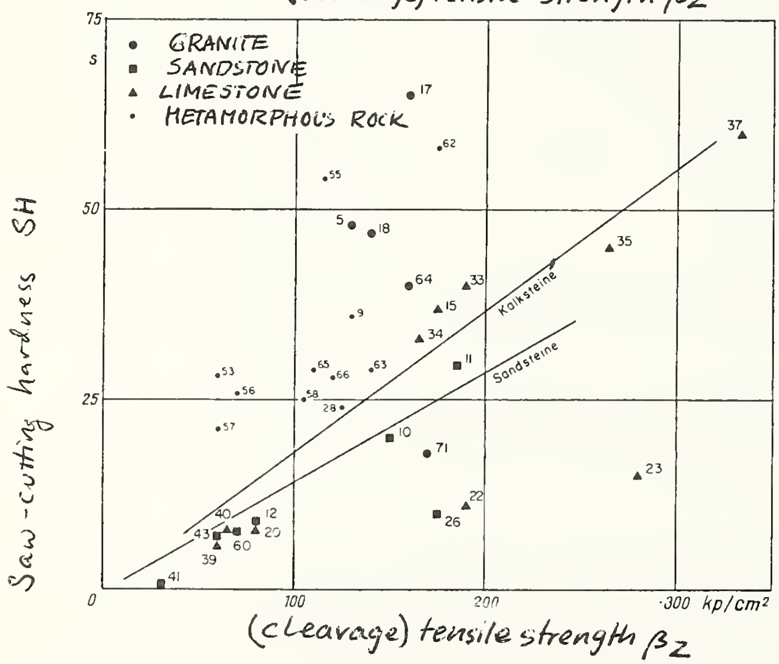


Figure 2-55. Relation: Cleavage tensile strength β_z to saw-cutting hardness SH

Figures 2-53 to 2-55. Relations Between The Index Values for Basic Boreability

TABLE 2-2. INDEX VALUES AND MINERALOGICAL-PETROGRAPHICAL CHARACTERISTICS OF SOME ROCK TYPES[4]

no.	name	origin[2]	index values[1] E_{t50} kp/cm²	β_D kp/cm²	β_z kp/cm²	SH s	main components (5) Quarz	Feldspa	Hornblende		calcite	av. grain[3] Ø mm	wear coefficient
	granite												
17.	Biotite granite	Gurtnellen, Switz.	6,0 · 10⁵	2210	160	65	35	60	—	5	—	4	33,92
18.	Granite	Goschenen, Switz	4,5	1830	140	47	25	70	—	—	—	1,5	9,66
51.	Granite	Grimselpaß, Switz.	7,2	2500	130	48							
64.	Biotite granite	Goschenen, Switz.	5,1	2030	160	40	25	70	—	5	—	2,5	18,40
71.	Granite	Nehanga, Zambia	—	—	170	18*)	15	80	—	—	—	5	33,15
	basalt												
31.	Basalt	Sudan	8,5	2610	450	59	--	30	65	—	—	1,5	8,27
72.	Basalt	Sudan	—	—	510	51	30 (glas, Erz)[5]	55	15 (Augit)[5]			0,6	14,99
	sandstones												
10.	Sandstone	Rorschach, Switz.	3,6	1400	150	20	45	10	—	—	40	0,2	1,48
11.	Sandstone, slightly breccia-like	Rorschach, Switz.	4,2	1640	185	29	15	5	—	—	80	0,3	1.05
12.	Sandstone	Rorschach, Switz.	1,8	690	80	9	25	20	—	—	50	0,15	0,39
26.	Sandstone	White Pine, USA	4,2	1350	170	10	70	30	—	—	—	0,1	1,55
41.	Sandstone	Zurich, Switz.	0,5	180	30	1	15	5	—	—	80	0,15	0,09
43.	Sandstone, marlaceous	Zurich, Switz.	1,2	600	60	7	5	5	—	—	90	0,03	0,03
60.	Sandstone	Sihltal, Switz.	1,2	660	70	8							
74.	Sandstone	Sudan	—	—	360	—	40	40	—	20	—	0.2	3,80
	limestones												
15.	Biomicrit limestone	Simmental, Switz.	7,0	1540	175	37	—	—	—	—	100	heterogen	
20.	Biomicrit limestone	Herbern, Bundesrep, W. Germany	0,75	620	80	8	2	—	—	—	98	heterogen	
22.	Limestone	Chicago, USA	5,5	1870	190	11	— —	—	—	—	100	0,05	0 03
23.	Limestone	Chicago, USA	8,1	2380	280	15	—	—	—	—	100	0,05	0,04
33.	Limestone	Vierwaldstattersee, Switz.	8,3	2030	190	40	—	—	—	—	100	0,01	0,05
34.	Limestone	Vierwaldstattersee, Switz.	6,0	1620	165	33	—	—	—	—	100	0,01	0,01
35.	Limestone	Vierwaldstattersee, Switz.	6,7	3620	265	45	(Kalzitkorn, in z. T. kieseliger Matrix)						
37.	Limestone	Vierwaldstattersee, Switz.	7,9	3390	335	60	—	—	—	—	100	0,02	0,02
39.	Lime-arenite, marlaceous	Zurich, Switz.	1,1	560	60	6	5	—	—	—	95	0,45	0 02
40.	Limestone, marlaceous	Zurich, Switz.	1,3	610	65	8	5	—	—	5	90	0,05	0,02
	metamorphic rock												
1.	Muscovite gneiss	Gotthardpaß, Switz.	4,3	1590	255	30	40	10	—	50	—	0,5	5,74
2.	Hornblend schist	Gotthardpaß, Switz.	5,5	1530	195	14	25	25	45	5	—	0.2	1.36
3.	Hornblend schist	Gotthardpaß, Switz.	11,0	2820	240	41	5 (Granat)	5	90	—	—	0,2 bis 0,5	0,53
4.	Two-mica gneiss[6]	Airolo, Switz.	3.0	1180	235	18	50 (inkl. Granat)	10	—	40	—	0.3	3,85
5.	Two-mica gneiss, straited	Lukmanierpaß, Switz.	3,5	1030	130	36	40	55	—	5	—	0,5	3,67
6.	Two-mica gneiss[6]	Biasca, Switz.	4,8	1730	160	45	35	60	—	5	—	1.0	8,46
7.	Two-mica gneiss[6]	Chiggiogna, Switz.	3.4	1340	120	34	40	50	—	10	—	1,0	66,0
8.	Two-mica gneiss[6]	Airolo, Switz.	2,5	1030	160	20	35 (inkl. Granat)	20	—	45	—	0,8	5,51
9.	Granite porphyry, gneissic	Lukmanierpaß, Switz.	4,4	1670	130	36	30	65	—	5	—	heterogen	
13.	Calcite marble	Oberhalbstein, Switz.	4.1	1270	130	22	15	—	—	- -	85	0,1	0,23
14.	Limestone, slightly marbleized	Oberhalbstein, Switz.	5.3	2660	285	30	10	—	—	—	90	0,08	0,29
19.	Chlorite gneiss	Andermatt, Switz.	1,75	810	55	7	40	15	—	- -	—	0,05	0,12
24.	Siltstone, argillaceous	Boston, USA	6,2	2060	230	14	50	—	—	50	—	0,05	8,88
27.	Biotite gneiss	Rveras, Switz.	5,0	1440	205	28	35	60	—	5	—	0,5/1,5	7,43
28.	Granite porphyry, gneissic	Gotthardpaß, Switz.	5,4	1820	125	24	30	65	—	5	—	0,5 bis 1.0	3,00
29.	Monzonite (syenite-diorite)	Chateland, Switz.	5,0	1290	145	30	—	95	—	—	—	heterogen	
30.	Granodiorite	Chateland, Switz.	5,7	2040	215	26	35	60	—	5	—	3,0	54,18
52.	Microcline-plagioclase gneiss	Grimselpaß, Switz.	4,4	2830	125	58							
53.	Grandiorite	Grimselpaß, Switz.	3,6	1280	60	28							
54.	Sericite-chlorite gneiss	Gletsch, Switz.	3,3	1160	40	42							
55.	Mica gneiss	Gletsch, Switz.	4,9	2500	115	54							
56.	Quartz diorite (tonalite)	Gletsch, Switz.	2,8	880	70	26							
57.	Ortho gneiss	Ulrichen, Switz.	2,2	1120	60	21							
58.	Paragneiss	Ulrichen, Switz.	3,5	1330	105	25							
59.	Garnet schist	Nufenenpaß, Switz.	5,8	1850	270	39							
61.	Chlorite gneiss[7]	Amstag, Switz.	3,2	1480	100	15	35	35	—	—	—	0,2	0,91
62.	Biotite granite[7]	Gurtnellen, Switz.	6,1	2530	175	58	20	75	—	5	—	2,5	18,59
63.	Biotite granite gneiss	Goschenen, Switz.	6,1	1970	140	29	20	75	—	5	—	2,5	14,86
65.	Biotite gneiss, sericitized	Goschenen, Switz.	5,2	1540	110	29	20	70	—	10	—	0,2	0,90
66.	Gneissic granite porphyry	Lukmanierpaß, Switz.	5,9	1770	120	28	50	40	—	10	—	heterogen	
67.	Hornblend gneiss	Airolo, Switz.	3,8	1400	100	19	20	30	35	5	10	1,0	3,08
68.	Two-mica gneiss[6]	Chiggiona, Switz.	5,4	1600	180	36	35	55	—	10	—	1.5	13,90

[1] kp/cm² ≈ 1 bar

[2] Under: Origin, terminal word -paß in compound names = Pass, e.g. Gotthard Pass

[3] Nos. 15,20,9,29 and 66 annotated under "av. grain Ø mm" as - heterogenous

[4] All commas in numerical values to be read as decimal points

[5] No. 72, basalt annotated under "main components": quartz (glass, mineral); hornblend (augite)

[6] Annotation under: main components - 4,5 include garnet.

[7] Slightly foliated (schistoid)

The tendency of a linear relation is evident for sandstones and for limestones, with the exception of numbers 22 and 23, both from Chicago.

There is evidence for an exponential relation for granites and abrasive rock in general. However, no mathematical interrelationship can be seen for non-abrasive metamorphous rock.

The saw-cutting hardness increases with increasing wear coefficient. There is no evidence for a mathematical growth with any kind of rock.

The tendency for mathematical interrelationships between the index values of the basic boreability of the analyzed rock is

- evident for sandstones,

- somewhat less evident for limestone, with the exception of deposits from the Molasse and the alpine Mesozoic periods, and is only evident with restrictions for granites and geneisses that are similar to granite.

No mathematical interrelationship is proven for the wear coefficient and the index values of the analyzed rock. The wear coefficient is the only numerical value which is determined directly from the also quantitatively determined mineralogical-petrographical characteristics. Until now, the attempt was unsuccessful to derive index values for boreability from the mineralogical-petrographical characteristics of a rock. Of course, the characteristics are expressed indirectly by the interaction, for example by the cleavage tensile strength characterizing the quality of the mineral matrix [15].

g) Application of the results of the analysis

The basic boreability, expressed by the specific penetration $t_K:F_e$, and related to a certain boring system, can easily be estimated for sandstone and - with restrictions - also for limestones. The estimation requires as a precondition the knowledge of one of the four defined index values β_D, β_Z, E_t 50, or SH, as well as their relationship for example Figures 2-48 to 2-51, for the respective boring system.

For all other rock without mathematical interrelationships between the index values, the specific penetration for each individual index value is to be determined by means of the respective relationship and the basic boreability as arithmetic average of the four individual values is to be calculated in consideration of the interaction.

Index value with relationship t_{spec}

$$t_K = t_{spec}\ F_e.$$

2.3.2 Influence of the Rock Main Structure on the Boreability

The boreability of geological formation in relation to a certain boring system depends on the properties of the rock and on those of the rock mass.

It is influenced by:

a) the boreability of the rock, i.e., the basic boreability,

b) the number, the nature, and the quality of the discontinuities on a large scale, as well as their position relative to the primary working direction of the boring tools, i.e.:

  - separating rock for numbers and bedding planes sediments Figure 2-56, and also inclusions.

  - planes of chavage that are not part of the fundamental rock sbustance, and cracks, as well as by, under certain circumstances,

c) the tectonic tensions characteristics for the rock mass, i.e., by the primary tension conditions.

Separation planes and tectonic tensions in the rock formation can increase the boreability, but they can also create conditions which exclude the application of mechanical tunneling for obvious reasons. In any case, separation planes are weak points in the rock formation.

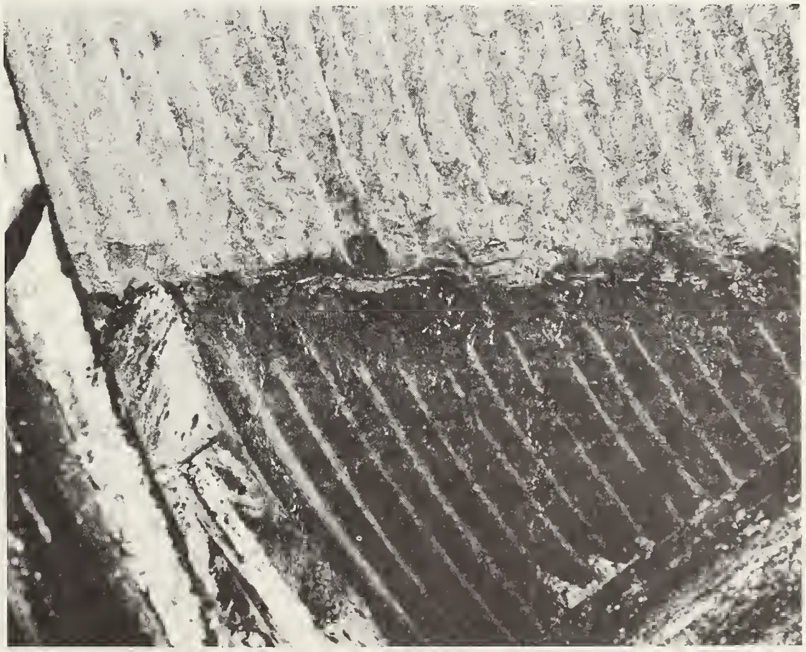


Figure 2-56.
Open boundary (zone) between layers in a tunnel face in limestone

2.3.2.1 Favorable Influence of Separation Planes on Boreability - The boreability is increased by closed, i.e., dense, or not clearly recognizeable separation planes. The increase can become especially significant with intensive layering and chavage, with heavy cracking, and with a position of the separation planes approximately perpendicular to the tunnel axis. In this position, the separation planes are situated approximately parallel to the work face, and therefore - if roller bits are used - parallel to the preferred fracture planes. These separation planes, as weak spots, have approximately the same directions as the interior shearing stresses, and follow a direction which is approximately perpendicular to the interior tensile stresses to which the disaggregation of the rock formation can be attributed due to the relatively small respective strengths. The presence of rock with different quality of the mechanical properties in the work face generally increases the boreability of a formation. This increase is the more noticeable the more intensive the change of rock. Figure 2-57 shows the result of a relevant analysis proving this tendency. If tunneling machines are used whose cutting head or cutting tool carrier is equipped with hard metal buttons or if ripper machines are used which are equipped with a ripping arm, this phenomenon is exploited for the start of the cutting of a new work cycle. A favorable formation of hard, and less hard rock can make such a machine technically and economically successful, whereas the presence of compact hard rock exclusively would reduce the success, or even prohibit any success. Thus, one of these tunneling machines is offered expressly as suitable for rock with a uniaxial pressure strength up to approximately 1,100 kg/cm^2, but under the condition of "sliding planes and fractures."

2.3.2.2 Impairment of Boreability by Separation Planes - The boreability by means of tunneling machines is reduced by noticeably open separation planes, and by an alternation of layers greatly differing in strength. In both cases, the effective rolling of the cutting tools on the work face is impaired. They are exposed to especially strong blows, and thus to increased wear. Separation planes parallel to the tunnel axis have an especially unfavorable influence since large pieces of rock can be knocked loose above them. These can get stuck in the cutting tool holders, in the scraper which picks up the cuttings, in the transportation buckets or in the loading channel for the conveyor belts, and may thus at least stop the tunneling machine. Such break-outs may occur singularly. However, they may also occur systematically with increasing superpositioned heights as well as with large cutting diameters and low strength and deformation properties of the rock formation.

The effectiveness of a tunneling machine, however, can also be reduced or rendered ineffective by phenomena which do not occur on the work face but are also caused by the separation planes of the rock formation. The rock mass is subjected to heavy stresses

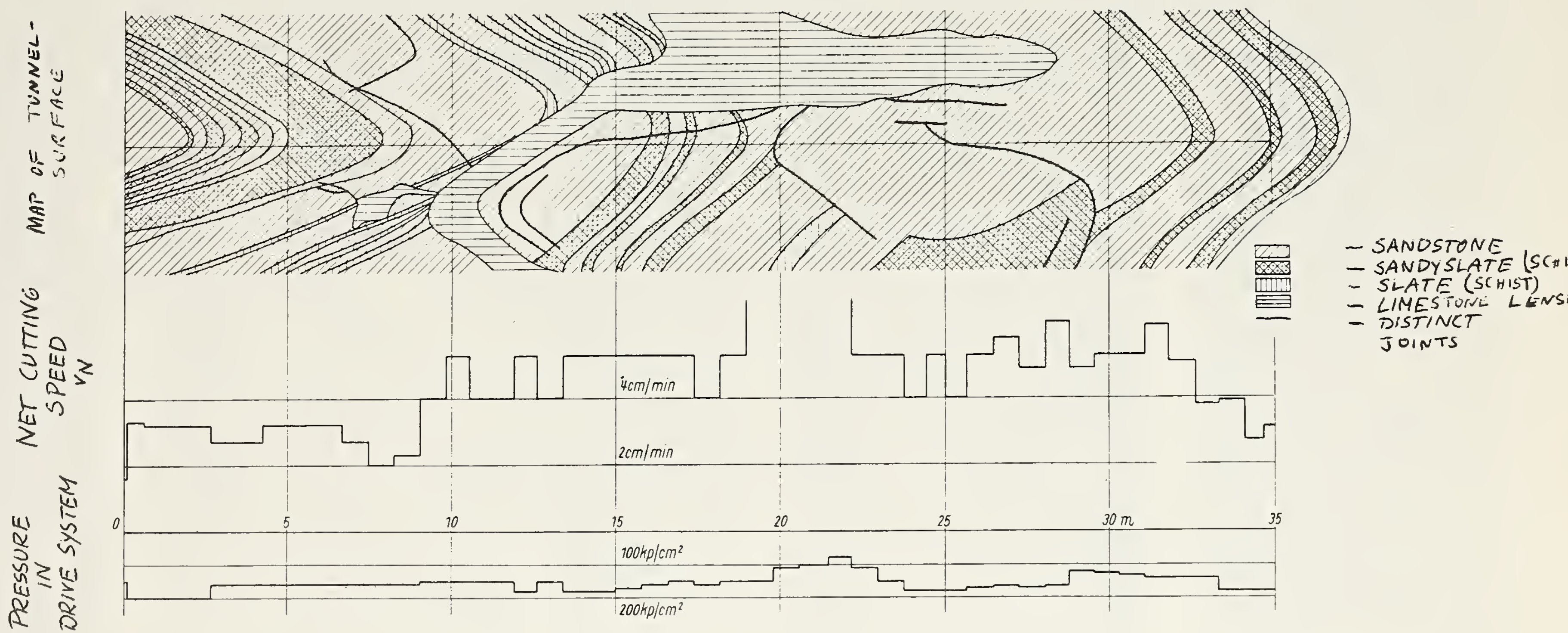


Figure 2-57.
Map of rock types in the tunnel surface (above), net boring speed v_N and pressure p in the feeding system (below)

through the weights of a tunneling machine gliding or supported on the tunnel floor, or by the pressure of its gripper shoes [20]. Existing separation planes can become sliding planes if their angle of friction or their shearing strength are insufficient for the load. The gripper shoes, or the sliding shoe and the support column can squeeze the sliding material out of the tunnel walls and out of the tunnel floor. The tunneling machine may lose its braceability, or may even sag down under its own weight. A tunneling machine which cannot be gripped properly should not be, and in many cases, cannot be used for cutting. Before the tunneling work can be resumed, the rock mass must be stabilized.

2.3.2.3 Influence of the Overburden Depth on the Boreability - The strength behavior of a material depends on the state of its stress. In natural rock formations, the stress condition changes with the depth. The weight of the superimposed rock mass causes a stress in the lower-placed rock or rock mass. In particular, the compressive strength is increased [21]. On the basis of this fact which is known from the drilling of deep wells and from laboratory tests the question must be asked concerning the influence of the height of the superimposed rock mass on the boreability.

At present, we have little practical experience concering mechanical tunneling under high superimposed rock mass. By means of rock-mechanical considerations, however, a general estimation can be given.

During the tunneling, no matter whether conventional or mechanical, the forces which are originally present in the rock mass are shifted, and the work face and the tunnel invert, can shift in the direction of the cavity. These displacements are limited, and come to a stop fairly quickly provided the strength and deformation property of the rock mass in the zone of work face and tunnel invert are sufficient to accept the increased load caused by the redistribution of the forces. The work face, which is higher stressed, but still shows elastic behavior and is not deformed to the point of fracture, will be harder to cut than under lower stress, i.e. with smaller superimposed heights. If, however, the rock formation cannot absorb the increased stress, the deformations will not stop. After an initial elastic deformation, the rock mass will begin sliding towards the cavity on the existing separation planes. If the movements necessary to reach a new state of balance cannot use the existing separation planes as preferred sliding planes, additional sliding planes will be formed in the rock mass by fracture of the rock. The area around the cavity will become a fracture zone showing plastic behavior. The boreability of the work face deformed and fractured beyond its elasticity limit is larger than prior to the beginning of sliding.

2.3.2.4 Prognosis of the Influence of the Rock Mass Structure on the Boreability - The types of rock can be easily determined, and the separation planes can be determined by means of a tectonic survey based on a surface analysis as well as on evidence from existing mines and also on drill cores. The reliability of the construction of a geological longitudinal profile on the basis of extrapolations of the cores of determined rock separation and chavaging planes is reduced with increasing depth, and is problematic with a complex rock mass structure. It is more difficult for a rock mass consisting of horizontal layers than for a structure consisting of vertical tectonic units. The projection of fissures or cracks to the route of a tunnel, which is lower or off to the side, must assume identical types of rock, identical deposits, and identical forming of the rock mass. Even under these conditions, this projection cannot give more than a rough guideline for the structural configuration.

For certain types of rock with observed discontinuity plane configurations the boreability has been measured, Figure 2-56 and [22;23]. The results of such measurements have been shown to be very sensitive to changes of the parameters, i.e., the type, the nature and the position of the separation planes relative to the tunnel axis. The transposition of such results to a prognosed separation plane configuration which has only the character of a guideline is very problematic.

Therefore, it can only be stated with certainty, that the boreability of a rock mass is influenced by the separation planes of the rock mass, that the influence depends heavily on the configuration of the separation planes, and that for locally occurring, evidently optimal configurations, the boreability determined by rock and rock mass can be - locally - a multiple of the basic boreability which is exclusively determined by the type of rock.

2.4 THE NET BORING SPEED (RATE OF PENETRATION)

The net cutting speed is the product of cutting head penetration and cutting head revolutions:

$$v_N = t_K n.$$

2.4.1 Cutting Head Penetration

For boring systems with, apart from the center and from the caliber (gauge), only one boring tool per row, the following applies theoretically:

cutting head penetration = boring tool penetration.

Cutting systems equipped with Z tools per cutting track show a greater theoretical effectiveness:

cutting head penetration = Z x boring tool penetration.

With regard to the type and the arrangement on the cutting head, three different types of boring tools must be distinguished:

- center bit,
- inner bit and
- caliber (gauge) bit.

The boring tool penetration determined in laboratory tests is representative for the inner bits. However, this is based on the assumption that the effective zones of the boring tools originating from neighboring cutting tracks overlap to such an extent that no ribs remain between the tracks during the cutting process. The disaggregation of the rock must be more or less level within the entire rolling area of the inner bits.

The proportionality of cutting head and boring tool penetration is also tied to the condition that the rock disaggregation in the zone of effect of the center and the caliber (gauge) bits is the same as in the rolling zone of the inner bits. The caliber (gauge) bits cut the periphery of the work face as well as the corner formed by work face and tunnel invert. As far as forces are concerned, they are stressed differently and more heavily than the inner bits, and roll on the longer track as well as with a higher rolling speed. In this zone, cutting performance can be achieved without difficulty by equipping the rows with several cutters, and by very small cutter spacing between the rows. For this reason, there are always several tools installed in the caliber zone of a cutting head, frequently even on the same track.

In the center zone of the cutting head the available space is insufficient for the installation of boring tools that show the same variety as inner and caliber (gauge) bits. Apart from having the same effectiveness as the inner and caliber bits, the center bits must also have an appropriate lifespan. The familiar variants for center installation which also depend on the rock are numerous, Figures 2-58 to 2-61 and 5-3. They give evidence for the attempt of the designers of boring (cutting) systems to achieve an effectiveness of the center tool which is equal to that of the other tools.

In case of a cutting head with Z tools per row the assumed head penetration as the Z-fold tool penetration can only be achieved, if all cutting tracks of the inner bits have the same number of tools, and if the center and caliber (gauges) bits are equally as effective as the inner bits.

In addition, the precision of production and installation of the cutting head and of the boring tool holders of one row, and also the condition of the installed tools must be such that they have an equal effect on the work face. The cutting edges of the boring tools must have the same exterior dimensions and the same degree of wear. In order to fulfill this requirement, all tools in one row must be replaced if the replacement of one boring tool becomes necessary.

Figures 2-62 to 2-65 show the relation between average penetration force F_e and cutting head penetration t_k for four boring

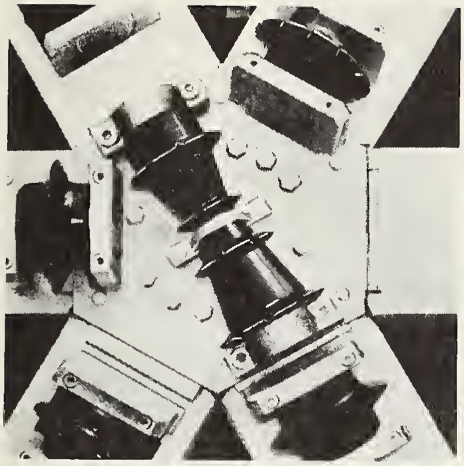


Photo: Calweld

Figure 2-58. Disk Bits

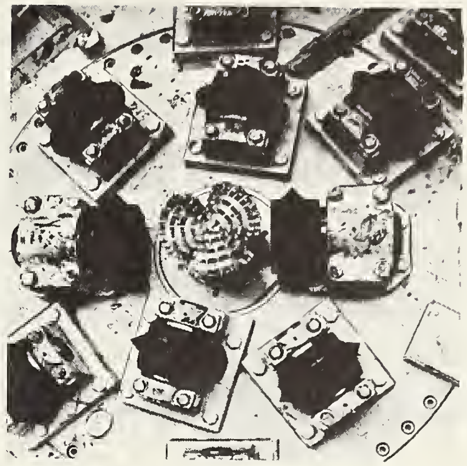


Figure 2-59. Tricone tooth bits

Photo: Jarva Inc

Figure 2-60.

Monocone multiple button disk bits

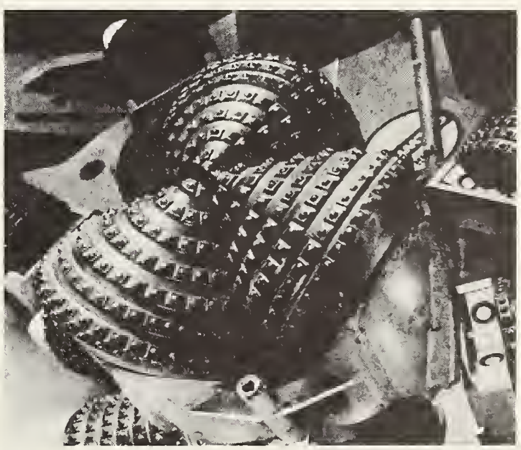


Photo: Calweld

Figure 2-61.

Tricone button bits

FIGURES 2-58 to 2-61. Alternate Arrangements of Center Bits

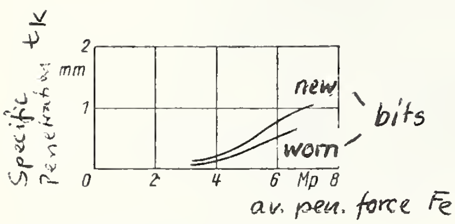


Figure 2-62.

Boring system with button bits in center and on gauge caliber and inner disk bits, hard limestone

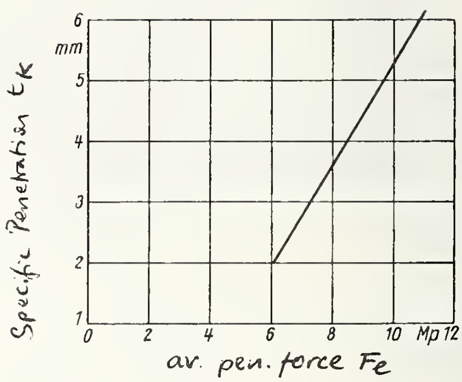


Figure 2-63.

Boring system with disk bits: Limestone-schist with distinct discontinuities

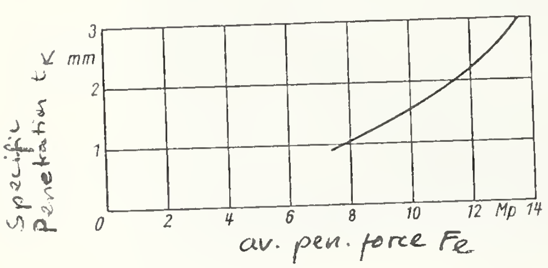


Figure 2-64.

Boring system with multiple disk bits, limestone-schist compact

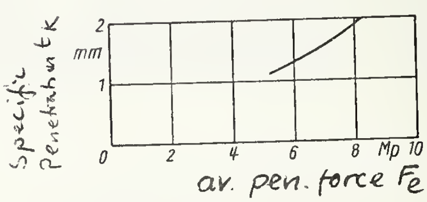


Figure 2-65.

Boring system with button bits; mylonitized granite

Figures 2-62 to 2-65.

Relation between average penetration force F_e and specific penetration t_K

systems, measured in location. The measurements were conducted in different geological formations. This representation therefor cannot serve for comparison of the effectiveness of the boring systems but characterizes the relation between these two parameters.

2.4.2 The Cutting Head Revolution

The rotation of the cutting head is produced by its drive motors, i.e. by electric motors or hydro-motors. Usually, the tunneling machines equipped with synchronous motors have constant revolutions. The synchronous motors can also be equipped with mechanical gears, or are pole-reversible. The revolutions can then be controlled in two or three, at the most four stages. Collector motors connected via controllable rectifiers provide variable revolution control. Hydrostatic cutting head drives also permit variable revolution control.

The maximum revolutions of a cutting head depend ususally on the highest permissible rolling speed cutting speed v_s of the caliber (gauge) bits installed at the periphery of the cutting head. With increasing rolling speed, the temperature of the bearings and of the cutting edges of the boring tools increases, leading to increased wear of the boring tools. In individual cases the cutting head revolution may be determined by the performance of the buckets removing the cuttings. The following relation exists between the cutting speed and the cutting head revolution.

$$v_s = \pi Dn \text{ respectively } n = \frac{v_s}{\pi D};$$

The symbols mean:

v_s cutting respectively rolling speed in m/min.

D cutting diameter in m.

n cutting head revolution per min.

The maximum cutting speed varies depending on the manufacturer of the tunneling machine and roller bits, Table 2-3.

2.5 BORING TOOL WEAR

The wear of the boring tools is one of the main problems of mechanical tunneling. The unavoidable, periodically recurring necessity of tool replacement creates costs for

- the replacement, or the repair
- the installation, and for
- the closing down of tunneling during the removal of the worn and the installation of the new boring tools.

Under certain circumstances, these costs can greatly increase the expenses of mechanical tunneling, and may render this process economically unfeasible. Generally, the relation applies:

$$\text{boring tool costs} \sim \frac{\text{rock strength and rock abrasiveness}}{\text{penetration}}.$$

The boring tool costs, however, are also influenced by:

- the construction and quality of the material used as well as those of the tool production,
- the precision of the installation of the boring tool holders on the cutting head
- the effectiveness of the scrapers at the cutting head periphery, and the buckets for removal of the cuttings from the tunnel floor; incomplete removal of the cuttings has the effect that the caliber (gauge) tools must cut through these, and are therefore exposed to additional wear,
- the way the tunneling machine is operated; tunneling with too high a feeding force, abrupt steering during cutting, or alignment of the machine while cutting head and work face are still in contact cause extraordinary stresses on the tools; neglecting checks and maintenance as well as timely replacement of damaged tools also increases the cost.

TABLE 2-3. CUTTING SPEED FOR VARIOUS MANUFACTURERS OF TUNNELING MACHINES

manufacturer	cutting head drive	cutting head diameter m	cutting head rpm/min.	max. cutting speed m/min.
Demag	el. el.	3.9 a. 4.3 4.4 a. 4.8	7.5 7	92 and 101 +) 97 and 106
Jarva	el.	4.2	8	105
Lawrence	hydr. hydr.	5.05 5.6	0 to 8.4 0 to 9	133 141
Robbins	el. el. el.	4.8 a. 5.1 6.4 a. 6.65 10.65	4.95 3.75 2	75 and 79 76 and 79 67
Wirth	hydr. el. hydr.	3.0 a. 3.3 5.3 a. 5.6 5.9	0 to 10 3.075 a. 6.15 0 to 6.15	94 and 104 102 and 108 114

+) These values correspond to the respective cutting diameters.

The cutting tool costs are defined as the sum of the pure material costs for complete tools at the manufacture plant (black costs) per m^3 of cut rock. According to this definition, transportation costs and customs duties are not included. These costs also do not consider labor costs incurred during closed-down periods, the costs for removal and installation and the operation of a boring tool shop. They also do not include the holders of the tools on the cutting head.

The following refers to roller bits whose basic construction consists of bearing, bit body, bearing seals, and cutting edge. With regard to the roller bit design most commonly used for mechanical tunneling, we differentiate between the bearing wear on the one hand, and the wear of the cutting edges on the other hand.

2.5.1 Wear of the Roller Bit Bearings

With prescribed lubrication, a given stress, and a given revolution per time unit, a bearing has a certain life span which is expressed in hours of operation. Peak loads, as well as shock loads and increased revolutions reduced its life span.

In the practice of cutting, the wear of roller bit bearings, i.e., of cups, balls, cylinders, and seals if frequently expressed by the average number of hours of operation of the tunneling machine, or by the tunnel length produced between two bearing changes. These are general data. They do not consider whether a bit was rolling slowly in one of the inner rows, and was practically stressed only radially, or whether it was rolling relatively fast in the caliber row, and was also stressed axially. Not infrequently, the cost of the bearing wear for an advance is not at all determined directly. This procedure is understandable if at least in the course, and after the termination of the advance, the total costs of the boring tool wear as well as those of the wear of the cutting edges and bearing bodies are determined, and the costs of the bearing wear are calculated as the difference. It is not possible to give the generally applicable statement on the portion of the costs of the bearing wear relative to the total boring tool costs, or on the relation between the costs of bearings and cutting edges. The data collected on numerous construction sites, and also partially for comparable conditions, vary over a wide range; for example, cutting edge costs, costs of the bearing and the bit bodies equal 1:1.25 to 1:3.

2.5.2 Wear of the Roller Bit Cutting Edges

The forces effective at the cutting edge of a roller bit are reactions of the radial penetration force F_e, the tangential rolling force F_r, and during the cutting of a free surface or of a conical work face, also the free cutting force F_f.

During the production of craters by teeth and buttons, and of grooves by disk cutters, the components of the rock and powderized.

In part, this mineral powder remains in the grooves. The flanks of the cutting edges of the rolling bits rub in this powder, and partially also along the slopes of the craters, or grooves. Depending on the content of abrasive minerals - mainly quartz, but also feldspars - of this abrasive compound, the tip and the flanks of the cutting edge are worn off. The teeth of the tooth bits, and the hard metal pins of the button bits can also break off during cutting, and the buttons can be pulled out of the bit body.

Of special interest is the wear of sharp-edged disk roller bits. These edges do not become worn when they are rolling penetratingly. The abrasive mineral powder, and the groove slopes grind off the hardened flanks of the steel cutting ring, but the sharpness of the edge is preserved, Figures 2-66 and 2-67. The self-grinding of the sharp-edged disk blades during penetrating rolling may lead to interesting forms of the cutting edges, Figures 2-68 to 2-70. On the basis of these cutting ring cross sections, conclusions can be drawn, among others, concerning the suitability of the selection of a certain wedge angle or concerning the stability of the cutting head during the cutting process.

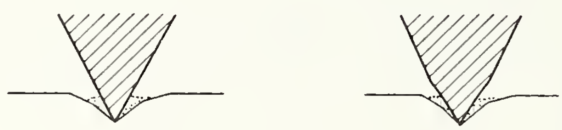


Figure 2-66. Theoretically Figure 2-67. Practically
Figures 2-66 and 2-67. Self grinding of sharp-edged disks.

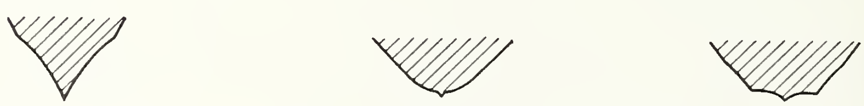


Figure 2-68 — Rock abrasive easy to penetrate

Figure 2-69. — Rock abrasive, hard to penetrate, "flutter" of cutting head possible

Figure 2-70. — Diskring to such an extent that the cutting edge is already in its non-hardened "soft" core.

Figure 2-68 to 2-70. Wear of Sharp Edged Disks.

The useful life of roller bit cutting edges is, like that of bearings, sometimes given as the average number of cutting hours or as the length of the tunnel cut between two changes of edges. These data, too, are little informative, and are only useful for a certain object, a certain type of tunneling machine.

It is much more appropriate to give wear of roller bit cutting edges in terms of the so-called rolling distance. The rolling distance is the length of a path along which the cutting edge rolls during the cutting process on the work face. In Figures 2-71 and 2-72, the work face of a tunnel with diameter of 2.25 m is shown as an example, (Figure 2-71) cut with double disk roller bits, (Figure 2-72) cut with button bits. In this case, the average tunnel length cut between two cutting ring changes which amounts to 75 m (also 75 cutting hours) corresponds to an average rolling distance of approximately 295,000 m. The average tunnel length cuts between two changes of a button body amounted to 315 m, corresponding to 370 cutting hours, and the rolling distance amounted to approximately 1.4 x 10^6m.

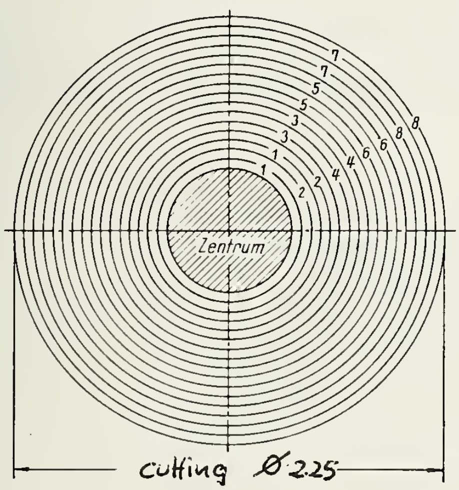


Figure 2-71.

Position of concentric traces of the double disk cutting edges on tunnel.

Inner roller bits No. 1 to 6 (6 bits)
Caliber (gauge) roller bits No. 7 (2 bits), No. 8 (3 bits), (total 5 bits)
Cutting head revolutions 12.51/min.
total rolled distance/h 86,400 m
tunnel advance 75 m
average rolled distance per disk ring 295,000 m
rock mass, schistose mylonitized gneiss
quartz content 0-30%
feldspar content 60-90%

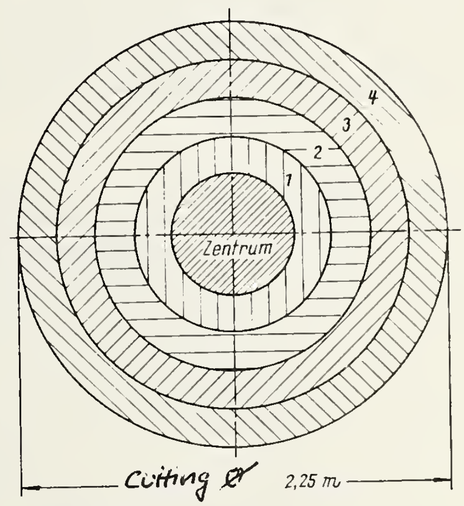


Figure 2-72.

Position of button bits trace on the tunnel face.

Inner roller bits No. 1 to 3(2 bits; total 6 bits) Caliber (gauge) roller bits No. 4 (5 bits: total 5 bits)
Cutting head revolutions 12.51/min.
total distance rolled by all bits per h 41,800 m
tunnel advance 315 m
cutting time 370 m
average rolled distance per button 1.4 x 10^6 m
rock mass, more or less porphyric granite partially jointed zones

Figures 2-71 and 2-72. Determination of the average rolled distance during the tunneling of a tunnel with a diameter of 2.25 m.

The rolling distance as expression of the cutting edge wear is not the same for all bits arranged in different rows, or cutting tracks, on a cutting head. The caliber bit cutting edges which are exposed to higher forces and roll with a higher cutting speed are exposed to a higher wear that those of the inner bits. The Figures 2-73 to 2-76 show as an example the result of an observation concerning the wear of sharp-edged single disk cutting rings. The position of the concentric paths of the cutting edges can be seen in Figures 2-73. Figure 2-74 shows the tendency that, with the exception of the rows close to the center, the number of worn disk roller bits increases to the outside. Figure 2-75 and 2-76 show that the rolled distances of caliber (gauge) bits are smaller than those of inner bits. They also show - in this case for practically uniform abrasiveness of the rock and uniform penetration force - that in a rock which is harder to cut, Figure 2-75, the rolling distances are smaller than in a rock which is easier to cut; Figure 2-76 shows the use of the same tunneling system in other tunnels. Average rolling distances of approximately 900,000 m in solid limestone, and of 2-3 x 10^6 m in marly sandstone have been determined.

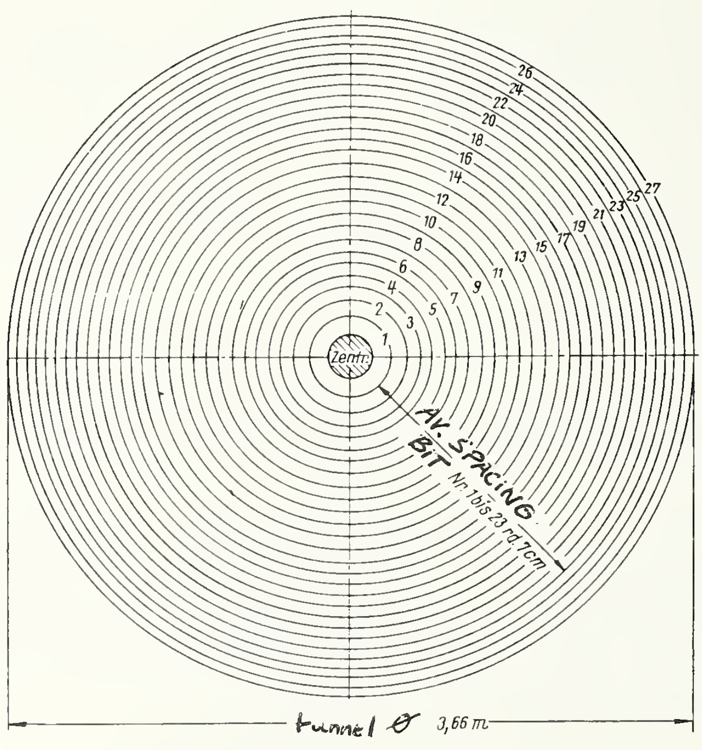
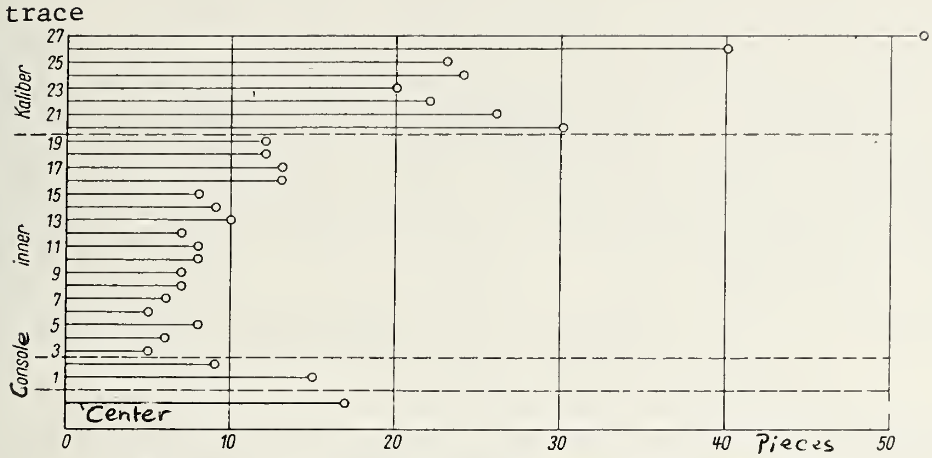


Figure 2-73. Position of the concentric mono-disk traces on the tunnel face

console bits close to center	No.1 and No.2 (2 bits)
Inner bits	No.3 to No.19 (17 bits)
Caliber (gauge) bits	No. 20 to No. 27 (8 bits)

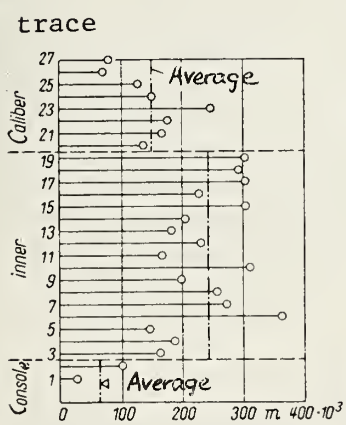


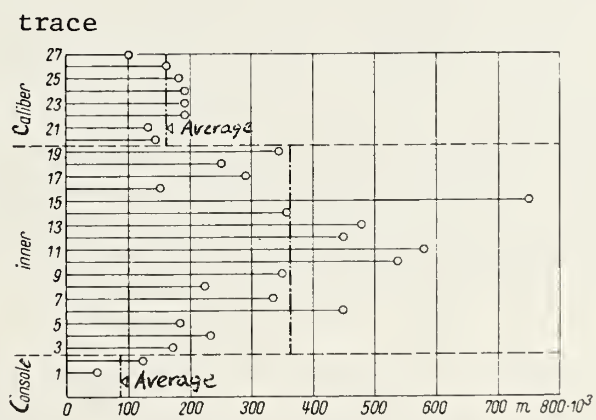
Number of worn-out disk rings and center bits.

Figure 2-74. Consumption of monodisk cutting edges in end trace rows, and of center bits

tunnel diameter	3.66 m	tunnel advance	825 m
cutting head rpm's	6.25 min.	cutting hours	822 h

rock was granite of changing strength, partially fractured, quartz content appr. 20%, feldspar appr. 75%.





rolled distance

Figure 2-75

tunnel advance 209 m
cutting hours 242 h
average net boring speed 0.86 m/h
rock: granite, fractured

Figure 2-76

tunnel advance 314 m
cutting hours 299 h
average net boring speed 1.14 m/h
rock: granite, in part heavily fractured

Figure 2-75 and 2-76. Rolled distances of monodisk rings for each trace

The abrasive behavior of a rock towards the cutting edges and also towards the bit bodies is influenced significantly by its content of abrasive minerals, in particular, of quartz. The wear coefficient a [18] has proved to be a suitable term for the determination and prognosis of wear of hard metal cutting edges mounted in a boring tool carrier. The possibility of a useful application of such tools is said to be limited by a = 0.5 [18]. On the basis of other experiences, such tools were used at another construction site with technical and economical justification up to a value of a ~ 1. It may also be useful to use the coefficient for the evaluation of the cutting edge wear of roller bits. Rock with a wear coefficient of a ≈ 30 has been cut with sharp-edged disk roller bits with technically justifiable but economically problematic success.

Every tunneling machine manufacturer uses a more or less reliable method for the prediction of the penetration and of the cutting tool wear, respectively of the boring tool costs. With one exception, these methods are well kept secrets of the manufacturers. Practical tunneling offers the possibility to collect experience concerning the penetration and the boring tool wear. This possibility, however, can only be exploited by systematically operating observers of the contractor, or of the construction supervision, or even of the machine maufacturer. The observation must be evaluated systematically, and must be recorded with reference to the process. Among such boreability and wear analyses belongs in any case the determination whether the cut work face consists predominantly of the same rock or of different types of rock, and whether the rock mass has seperating planes. If only one type of rock is present or, at least, predominates, and if no separating planes are existent in the rock mass, the basic boreability and a normal cutting tool wear may be derived from these observations for the boring system used. If this condition of uniformity of the rock does not apply, and if the rock mass has fault zones, only results can be obtained that are locally applicable, and whose value for a generalization is restricted.

2.6 PRETREATMENT OF FORMATIONS WHICH ARE TO BE CUT

The hardness of the minerals and of the mineral formation, as well as the stress/strain properties of a rock are assumed to be decisive for the disaggregation by means of cutting tools. The mechanical disaggregation increases with increasing primarily effective pressure force. Today, roller cutting tools are available for an average operational bearing load up to approximately 15 Mp (150 kN) and with disk cutting edges which can accept a penetration force of well above 10 Mp (100 kN) under conditions of permanent operation. High penetration forces are necessary for the cutting of high-strength rock in order to achieve performances that are comparable to those of conventional methods. The design and construction of tunneling machines with appropriate drive and gripping installations are relatively easy. These machines, however, will be even heavier than the present ones. The possibilities for a transition to distinctly higher penetration forces, however, are limited for the time being by the effectiveness of the boring tools. The cutting with tools manufactured from the materials which were used until now, and of the same design which is in use now, would cause extraordinarily high tool costs, especially in abrasive rock. Mechanical tunneling would lose its attractivity even in cases where not its economy but other advantages count. This fact which at present cannot be disregarded has also led to a consideration of other processes that also provide a disaggregation of the rock. These are:

a) Reduction of the rock strength by
   - reduction of the surface energy, and by
   - enlargement of existing, or production of new cracks, as weak spots in the formation will facilitate disaggregation, as well as

b) Influencing of crack formations, and the grain erosion.

2.6.1 Reduction of the Rock Strength by Reduction of its Surface Energy

The specific surface energy of a rock may be reduced by means of chemicals [24;25]. Thirty different surface-active substances were used in laboratory tests; among others, a fluid on the basis of fluoride, and a 0.1% aluminum chloride solution. This process was also tested in practice, i.e., during tunneling in hard limestone and sandstone. The strength reduction depends above all on the type of rock, on the fluid sprayed onto the work face, and on the duration of the soaking. During the limited tests on location, an increase of the net boring speed of 10 to 20% was determined. This process, which does not produce spectacular increases of performance, is little developed for practical application, and also involves the problem of corrosion protection of the tunneling system if certain chemicals are used.

2.6.2 Reduction of the Rock Strength by Enlarging Existing, or Producing New Cracks

The heating, and the production of temperature differences, lead to temperature stresses in the rock which surpass its strengh This may lead to spalling on the rock surface, and to the enlargement of existing, or the production of new cracks in the surface zones of the rock. Laboratory tests have been conducted on the heat treatment of rock by means of laser and electron beams with regard to their application in mechanical tunneling. In both cases, the highly concentrated heat energy produced by the transformation of electric energy is said to merely cause a reduction of the rock strength through crack enlargement and multiplication, but in no case the melting of the rock. It appears reasonable to consider strength reduction by heat treatment initially for the hard-to-cut center of the work face, and for the effective zone of the caliber (gauge) bits that are exposed to a specially high wear. The heat treatment may cause a weakened ring, or even a furrow within the area of a roller bit track. The effect of the heat treatment depends mainly on the type of rock, on the applied energy, and on the duration of the heat radiation. On the basis of laboratory tests with a 600-Watt laser, and a linear device with a penetration force of the roller bit of approximately 2 Mp (20 kN), an increase of the cutting performance of approximately 50% was estimated for practical cutting operations [26]. This process requires very high amounts of energy, and the devices for the energy transformation and for the beam generation require much space. The efficiency of a laser is small [24], and the energy not used for the heat treatment of the rock must be eliminated in the form of heat. It cannot be used yet for the practice of tunnel cutting.

2.6.3 Influencing the Formation of Cracks in the Rock, and Grain Erosion by Means of a Water Jet

The use of hydraulic energy for mechanical rock disaggregation has been used for a long time in mining for the production of coal, ore, and precious stones, as well as for the elimination of loose rock in excavation. The application of this process for solid rock has become known in connection with a so-called water cannon. A relatively small volume of water is shot at the rock cyclincally, as well as with high pressure and high speed by means of a water cannon. For mechanical tunneling, the use of a continuous high pressure water jet has been considered [27]. The water jet shot at the rock surface under high pressure and with high speed produces a crater, under the condition, such that the jet pressure is approximately 50% higher than the rock strength. The formation of the crater is caused by the erosion of rock grains or particles. This type of stress also enlarges the existing cracks, and produces new ones. With extremely high jet pressure and unchanging position of the jet, rock chips may be separated from the crater or from the vincinity of the hole. With a jet moved continuously over the work face, a slot can be produced, and the mechanical disaggregation of the rock can be continued by means of bits rolling in this slot or between slots. The periphery and the center of the work face are preferred areas for the application of this process. On the basis of laboratory tests, it is assumed that the efficiency of this process during the boring of crystalline rock is two to three times higher than that of a process that only employs disk roller bits. The most important components of the necessary hydraulic system are the water supply, the high pressure pump, and the jets of a very small caliber. The special constructive problems which must be solved if this process is to be applied in practice are the water tightness of the high pressure components of the system, The life span of the jets, as well as the installations for the production of concentric slots on the work face with the speed of a rotating cutting head. This process is also characterized by extraordinarily high requirements of specific energy, by its high noise, and by the problems involved with the supply and the elimination of the large amounts of water through the tunnel. This process, too, has not reached the stage where it can be used in practice.

All processes mentioned above concerning the reduction of the rock strength, and also that concerning grain erosion, are subjects of continuing research. Their practical application in combination with roller bits appears feasible for the future.

3. STABILITY OF TUNNELS

3.1 BASIC ROCK-MECHANICAL BEHAVIOR OF THE ROCK MASS

Before the excavation of a tunnel, a stress equilibrium exists in the rock mass, and so-called primary stress conditions. The stresses are caused by the interaction overburden depth of strength and deformation properties of the rock and the rock mass, tectonic stresses, water saturation of the rock, and of separation planes. In the absence of better information it is assumed in approximation that the vertical component of the stress corresponds to the weight of the overburden depth rock mass. The horizontal stress component varies between half to twice the superimposed load.

Primary stresses:

vertical component $\sigma_v = \gamma h + \sigma_t$

horizontal component $\sigma h = \lambda \sigma_v$.

These are:

γ volumetric weight of the rock,

H overburden depth,

σ_t tectonic stress component,

λ lateral stress coefficient.

During the tunneling, parts of the rock mass which had previously been under stress, and had participated in the transfer of forces, are eliminated. A force transfer takes place onto rock mass areas in the zone around the cavity that are not directly involved by the tunnel excavation. At the same time, it now becomes possible for the work face and the invert which are no longer exposed to all-around pressure to shift in the direction of the tunnel. In consequence, the force and stress redistribution continue, and the deformation increases until, after a certain time, a new stress equilibrium has been reached, the secondary stress condition. The deformations are relatively small and come to a stand-still relatively quickly if, after the stress redistribution, the concerned parts of the rock mass are able to accept the increased stresses. The deformations continue if the strength as well as the deformation capacity of the work face and the tunnel invert are exceeded by the new distribution of the forces. After initially elastic deformations, the rock mass starts sliding in direction of the cavity on the existing separating planes. Also, additional sliding planes can be formed in the rock mass through fracture of the rock if the displacements necessary to reach a new equilibrium cannot take place on the existing separating planes that act as preferred sliding planes. The area around the cavity becomes a so-called fracture zone or plastic zone whose behavior follows the laws of plasticity. Depending on the structure of the rock, and on the configuration of the separating planes, ravelling and rock falls may occur with continuing deformation as well as in certain cases, a cavity which is left unsupported may close up.

By securing the excavated surfaces the falling of rock due to loosening can be prevented.

By stabilizing the tunneled rock mass, a state of equilibrium can be creased, and the deformations can be arrested in a certain phase or after a certain period. The stabilization is achieved by applying a pressure from the inside to the tunnel invert, if necessary also to the work face. This stabilization pressure tunneling resistance of support force can be applied by means of the lining or supporting method such as concrete, rock golts, or steel, sets, and, in part, also through the tunneling machine. The interior pressure which can be produced only reaches a fraction of the original value present in the primary stress condition, especially with tunnels with a high superimposed rock mass. However, experience and calculations show that the deformations and the increase of the fracture zone can be arrested with a relatively small supporting force.

3.2 CHARACTERISTICS OF THE DEFORMATION BEHAVIOR

The problems involved in rock-mechanical calculations have changes. Previously, it was attempted to determine the forces in effect during the temporary or final stage of the tunneling. This was based on assumptions concerning the position of the tunnel cavity and the weights of loosened rock mass portions resting on the lining that were only subject to the laws of gravity. A connection between this loosened mass and the still solid rock mass was not assumed. That period of rock-mechanical calculations has been called "loosening-pressure period" [28]. The new tendencies of exploration are directed towards the quantitative relation between supporting force and deformation [29;30]. They take into consideration the fact that during the tunneling process, deformations of its circumference, and in a majority of the cases also a more or less extensive fracture zone must be expected, whose generation is even desirable and necessary within certain limits. Today's state of the knowledge of elastoplastic theories, the possibility and also the desire to include the observations during actual construction as boundary conditions in mathematical formulations of the equilibrium conditions, as well as the availability of computers for purposes of calculation are preconditions for a relevant and fast solution of these problems. This interaction is taken into consideration between:

- the stress/strain properties of the rock mass before the tunneling as well as during and after, the tunneling, and also in differing degrees for the fracture zone with plastic behavior, and for the outer rock mass which is subject to the laws of elasticity,

- the construction method and

- the stress/strain properties of the lining.

It is not one natural condition by itself, but all these factors that cannot be combined in one closed equation which are involved in the phenomenon called pressure of the rock mass.

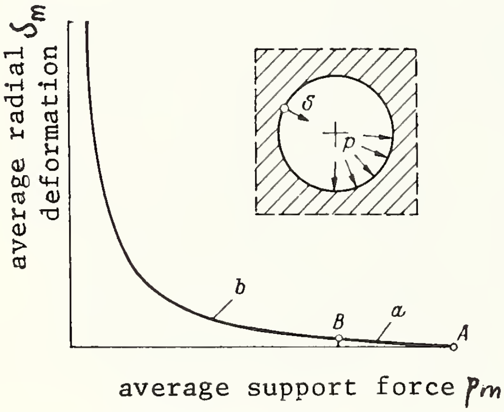


Figure 3-1. Characteristic Curve for Displacement Behavior of the Tunnel Circumference at a Distance from the Tunnel Face Perforated Disk

a elastic behavior
b elasto-plastic behavior

This rock-mechanical calculation method which is being used increasingly may be called characteristic-curve-method [29;31;32; 33]. The graphic representation of the average radial displacement δ_m of the soffit in dependence on the average support force p_m on it is defined as the characteristic curve of the deformation behavior of the tunnel invert, Figure 3-1. A certain supporting force is assumed for the calculation of one point of the characteristic curve. In the following, the stresses that are produced are calculated under consideration of the zones with plastic and with elastic behavior, and the displacements resulting from the change of stress are then determined. The average displacement resulting for the tunnel invert is related to is the graphic representation of the assumed supporting force. If the supporting force corresponds to the primary stress condition, point A, no radical displacement occurs. With decreasing supporting force, i.e., with continuing advancement of the tunnel, a change of shape occurs. Up to a certain reduced value of a supporting force, point B, the deformation increases in a linear way. Following that, the increase may be more than proportional since, beside the elastic deformation of the rock mass, the deformation and the volume increase of the plastic zone generated by the sliding and the fracture of the rock mass around the cavity begins. If the supporting force is further reduced, the radial displacement may reach a point, depending on the strength and the defomation behavior of the rock mass, which leads to a collapse of the cavity, or it is squeezed together.

For the calculation of the characteristic curve of the tunnel invert outside the work face zone, the rock mass is assumed as a plane, perforated disk of a certain thickness, and the primary stress condition as well as the strength of the deformation behavior of the rock mass is assumed to be uniform over a defined length of the tunnel, the so-called homogeneous area. The rock-mechanical calculation requires the knowledge of the following conditions:

a) primary stress condition of the rock mass

If no measurements are available, it is assumed that:

- the vertical and the horizontal stress are principal stresses,
- the vertical stress corresponds to the weight of the superimposed rock mass, and that
- the horizontal stress is equal to the product of vertical stress and lateral stress coefficient.

b) strength properties of the rock mass

The separating planes existing in the rock mass, i.e., the rock joint faces, the chavage planes, and the cracks, are weak zones. The strength of the rock mass can be expressed by the friction angle ϕ (friction angle) of the separating plane or sliding plane and by the sliding plane steering strength c (cohesion) characterized by the waviness and roughness on a macroscale [34].

We distinguish:

- the area with static friction subject to the laws of elasticity, and
- the fracture zone with sliding friction.

c) deformation properties of the rock mass

It must be distinguished between the elasticity modulus E:

- in the outer zone with elastic behavior, and
- in the zone bordering on the cavity with plastic behavior.

In addition, hypothetical values must be assumed for:

- the transverse expansion according to Poisson, and
- the volume increase in the fracture zone.

None of these conditions, however, offers a possibility for the prognosis by calculation of a rock burst. The calculation of the characteristic of the tunnel invert in the area of the work face requires as a model no longer a perforated disk, but takes into consideration the spatial conditions. Also, a characteristic curve of the deformation behavior of the work face can be determined, Figure 3-2. For this calculation, the work face is assumed to be a core disk whose thickness is smaller than that of the perforated disk representing the tunnel. This assumption takes into consideration the reduced stiffness of the work face which is no longer supported by horizontal forces. The radial forces occurring at the circumference of the work face, caused by the rock mass which has lost its radial supports, cause corresponding deformation. Depending on the tunnel diameter and on the overburden depth mass, the unsupported work face is subjected to a stress which corresponds no longer to its strength and deformation properties. Sliding occurs in the rock mass forming the work face, and under certain circumstances, also fracturing of the rock. The values of the numerous calculation parameters must be based for the time being on estimations as well as on results of rock tests which were then applied to the natural separating planes, because, until now, only a few systematic measurements have been conducted on location. The calculations

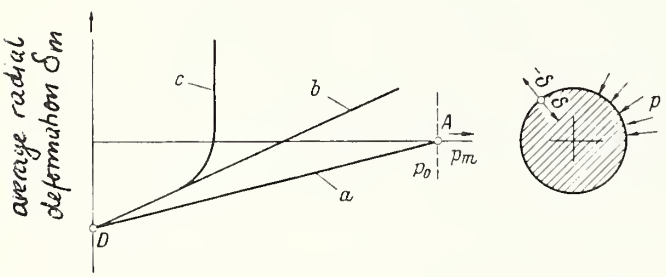


Figure 3-2. Characteristic Curve for Displacement Behavior of Tunnel Face Core Disk

- a unstressed core disk with elastic behavior.
- b re-stressed weakened core disk with elastic behavior
- c re-stressed weakened core disk, no longer elastic after yielding

3.3 ROCK-MECHANICAL CASES OF STABILITY

3.3.1 Definitions

In Figures 3-3 to 3-5 [35], characteristic curves of the deformation behavior of the invert and of the work face of a tunnel with eleven m boring diameter, and 1,000 m height of covering rock mass are represented. The three representations are based on different sliding planes friction angles ϕ and sliding plane sheering strengths c, and they are also based on two assumptions concerning the volume increase ΔV in the fracture zone. All characteristic curves of the invert show that the rock mass surrounding the tunnel does not show any longer elastic behavior, and that a fracture zone exists all around the cavity. The characteristic curves of the work face and of a core disk with half the thickness of the perforated disk also indicate the beginning of sliding. The failed tunnel invert is stable due to

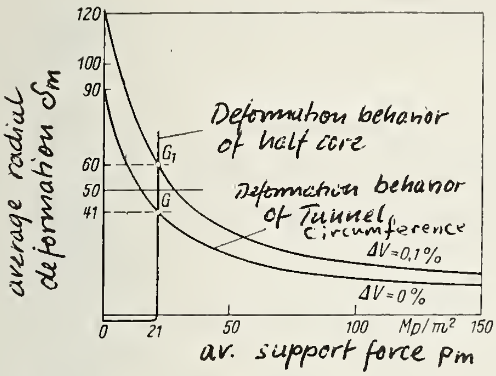


Figure 3-3.
Elast. Zone φ = 45°
Friction Angle Fractured Zone φ = 40°

Sliding Plane Elast. Zone = 2 kg/cm^2
Shear Strength Fractured Zone =
1 kg/cm^2

G, G_1 Points of Equilibrium
ΔV Volume Increase

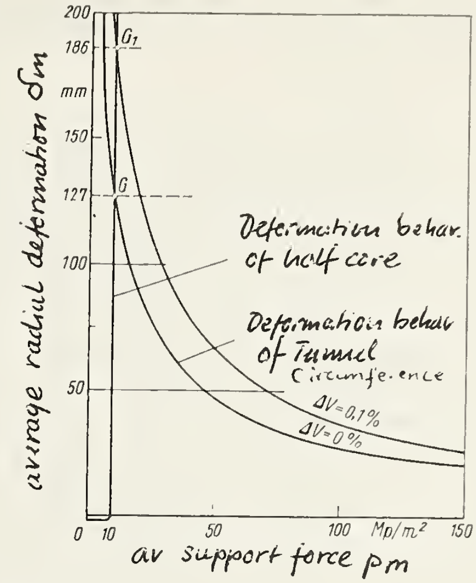


Figure 3-4.
Sliding Plane Friction Angle
Elast. Zone φ = 40°
Fractured Zone φ = 35°
Sliding Plane Shear Strength
Elast. Zone C = 1.5 kg/cm^2
Fracture Zone C = 0.5 kg/cm^2

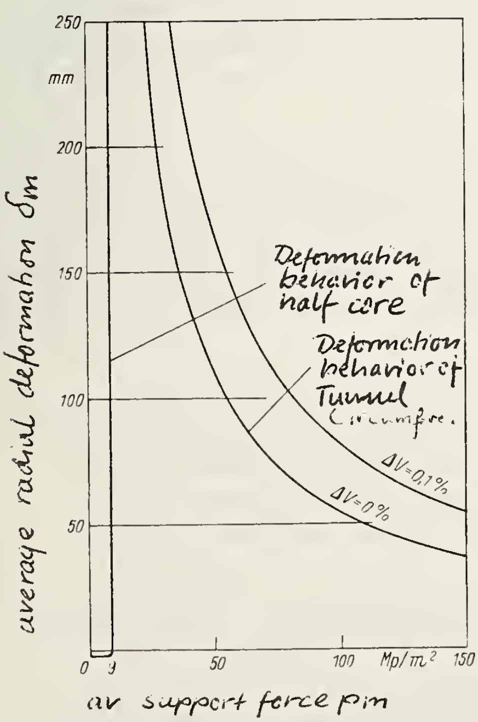


Figure 3-5.
Sliding Plane Friction Angle
Elast. Zone φ = 35°
Fractured Zone φ = 30°
Sliding Plane Shear Strength
Elast. Zone C = 1.5 kg/cm^2
Fracture Zone C = 0.5 kg/cm^2

Figures 3-3 to 3-5. Rock-Mechanical Cases of Stability [35]

Tunnel φ	D = 11.0 m
Overburden	H = 1,000 m
Elasticity Moduli	
Elastic Zone	E = 4 x 10^5 kg/cm^2
Fracture Zone	E = 2 x 10^5 kg/cm^2
Coefficient of Lateral Stress	λ = 0.7

the existing sliding plane friction angle and the sliding plane shearing strength as long as the equilibrium condition given by its characteristic curve is met. The failed work face, too, is kept together due to the present strength properties, as long as the radial compression is not larger than the calculated critical value for failure.

In Figures 3-3 and 3-4, the curves of the invert and that of the work face intersect. The intersections G and G_1 express a state of equilibrium for the invert and for the work face. The work face is stressed by a radial compression of the invert, and reacts by creating a supporting force for the invert. Work face and invert are deformed to the same extent at this point. The sections of the characteristic curves of the invert expending to the right from the equilibrium point G and G_1 characterize the stress-deformation behavior in front of the work face necessary for the equilibrium. The distribution of stress produced by the tunneling is effective in front of the work face already, i.e., on the other side of the work face. No tunneling is done in untouched rock, i.e., a rock mass that is not influenced by preparatory work. The deformations occurring in that zone, however, can only be determined with special measuring methods, and are not evident for an observer stationed in the tunnel. The characteristic curve sections extending to the left from the equilibrium points G and G_1 represent the stress-deformation equilibrium conditions on the excavated side of the work face.

In Figure 3-3, the characteristic surves of the invert intersect the ordinate, i.e., in spite of the absence of a supporting force, the invert still shows only a relatively limited deformation, and is theoretically stable. In case the relation between the deformation and the tunnel diameter exceeds a certain measure, individual occurrences of falling rock must be expected even in a "stable tunnel."

In Figure 3-4, the characteristic curves of the invert do not intersect the ordinate; i.e., due to the decrease of the supporting force on this side of the work face, very large deformations of the invert occur. The invert is no longer stable. During the excavation, a supporting force stabilizing the rock mass must be created by the installation of a support.

In Figure 3-5, the characteristic curves do not intersect. The cavity is no longer stable. Without special technical measures that would lead to a displacement of the invert characteristic to the left, or to a displacement of the work face characteristic to the right, the tunnel could not be advanced.

Finally, the case not represented graphically of a stable invert and of an unstable work face must be mentioned, the characteristic curve of which would practically coincide with the ordinate. Such a case can occur, for example, if there are cracks, or a distinct joint approximately perpendicular to the tunnel axis, and if the work face has low strength properties.

On the basis of the characteristic curves of the tunnel invert and of the work face, four rock-mechanical cases of stability must be distinguished, Table 3-1.

TABLE 3-1. ROCK-MECHANICAL CASES OF STABILITY

Case	Circumference	Face
1	stable	stable
2	stable	unstable
3	unstable	stable
4	unstable	unstable

These cases of stability define the behavior of the rock mass before installation of the support.

3.3.2 Parameters of the Stability Behavior

3.3.2.1 Parameters of the Rock Mass - The parameters influencing the stability behavior of the rock mass are:

- the sliding plane friction angle,
- the sliding plane shearing strength,
- the elasticity modulus,
- the volume increase of the fracture zone, and
- the lateral stress coefficient.

In Figures 3-6 to 3-8 [35], the characteristic curves of the invert and of the work face are given for different sliding plane friction angle (Figure 2-6), sliding plane shearing strengths (Figure 3-7), and side pressure coefficients (Figure 3-8) for a tunnel with 4 m boring diameter, a height of cover of 1,000 m, and a volume increase in the fracture zone of 0.1 percent.

The other parameters remaining the same, the stability conditions become worse with:

- decreasing sliding plane friction angles,
- decreasing sliding plane shearing strength,
- increasing lateral stress coefficient

and, as can be seen from Figures 3-3 to 3-5, with increasing volume of the fracture zone.

3.3.2.2 Parameters of the Tunnel Project - Increasing overburden depth H, and increasing boring diameter D influence the stability of the tunnel in an unfaborable way, if the parameters of the rock mass remain the same, Figure 3-9 [35].

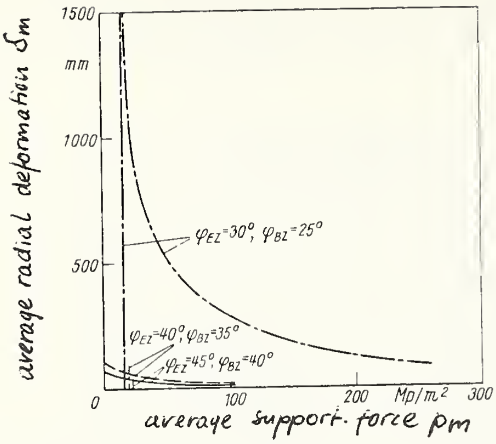


Figure 3-6. Dependence on (Sliding) Plane) Friction Angle
SL. Plane Shear Strength
Elast. Zone C = 2.0 kg/cm^2
Fractured Zone C = 1.0 kg/cm^2
Lateral Stress Coefficient
$\lambda = 0.7$

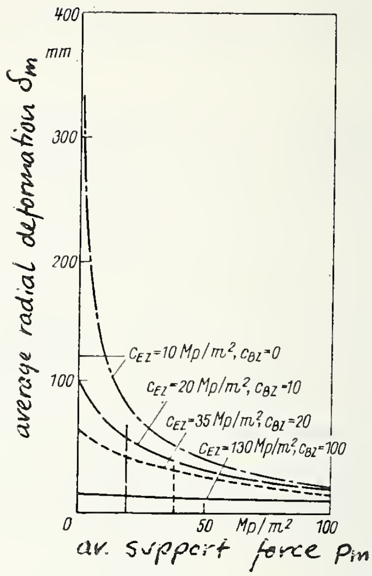


Figure 3-7. Dependence on (Sliding Plane) Shear Shear Strength
SL. Plane Friction Angle
Elast. Zone φ = 40°
Fractured Zone φ = 35°
Lateral Stress Coefficient
λ

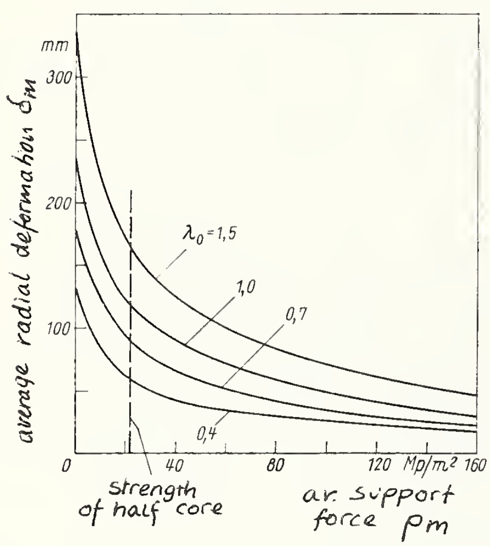


Figure 3-8. Dependence on Lateral Stress Coefficient λ Assuming σ_v is Constant
Sliding Plane Friction Angle
Elast. Zone φ = 45°
Fractures Zone φ = 40°
SL. Plane Shear Strength
Elast. Zone C = 2.0 kg/cm^2
Fractures Zone C = 1.0 kg/cm^2

Figures 3-6 to 3-8. Influence of Rock Mass Parameters on Stability Behavior [35]

Tunnel Diameter	D = 4.0 m
Overburden Height	H = 1000 m
Volume Increase ot Fractured Zone	
	$\Delta V = 0.1\%$.

3.3.2.3 Tunneling Processes - Figure 3-10 [35] shows the characteristic curve of the invert of a bored, and of a conventionally advanced, tunnel with with a diameter of 4 m for the same primary stress condition and the same parameters of the rock mass.

During conventional excavations, an initial fracture zone is created abruptly by the blasting. Beside the original sliding planes which have now become activated, it also creates cracks that are caused by the blasting. The supporting capacity of this rock mass zone is reduced immediately, and accordingly, an immediate redistribution of forces begins. Usually, however, the corresponding deformation only begins slowly, and with a delay. If the rock mass bordering on the initial fracture zone, and not affected by the blasting, is capable of supporting the subsequent increased stress, no further fracture zone is formed. Except for the loosening caused by the blasting, the rock mass shows a stable behavior. If the neighboring rock mass cannot support the new stresses, the relocation of stress forms a second fracture zone; compare Figure 3-10.

During mechanical tunneling the relocation of forces is a slow process corresponding to the net boring speed. Usually, the corresponding deformation starts slowly and with a delay, as with the tunneling by blasting. If the rock mass surrounding the tunnel cavity cannot accept the increased stresses, a fracture zone is formed. This applies to the example shown in Figure 3-10. The expansion of the finally existing fracture zone is smaller with a bored tunnel than with a blasted tunnel, all other conditions being the same. The tunneling process can thus change the stability, as in the example shown.

3.4 POSSIBILITIES OF SECURING AND STABILIZING THE ROCK MASS DURING THE TUNNELING

3.4.1 Characteristics of the lining

The lining has the following tasks:

- preventing of individual rock falls,
- creating a supporting force for the tunnel invert to reduce (but in no case prohibit the deformation to a tolerable measure of activating the co-supporting capacities of the rock mass, also of the possibly existing fracture zone, i.e., stabilization, and, under certain circumstances,
- preventing of the contact between air and rock mass is case of moisture-sensitive rock by means of a direct surface-covering lining.

The necessity for the installation of lining is given (apart from protection against weathering) if:

- bodies of rock are not connected coherently any longer with the surrounding rock mass due to open separating planes, and, at the same time, have lost their supports through the elimination of rock mass portions by the tunneling process, so-called singular rock fall, and

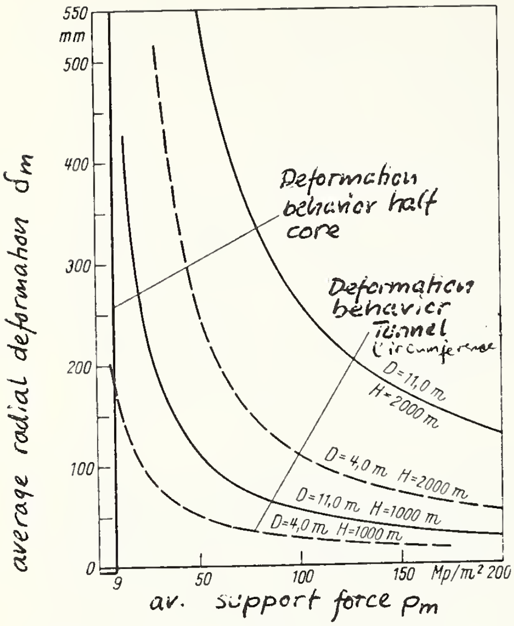


Figure 3-9. Influence of Project Parameters on Stability Behavior [35]

Sliding Plane Friction Angle
Elast. Zone φ = 35°
Fractured Zone φ = 30°

Sliding Plane Shear Strength
Elast. Zone c = 1.5 kg/cm^2
Fractured Zone c = 0.5 kg/cm^2

Elasticity Moduli
Elast. Zone E = 4.10^5 kg/cm^2
Fractured Zone E = 2.10^5 kg/cm^2

Coefficient of Lateral Stress λ = 0.7

Volume Increase Fractured Zone
ΔV = 0%

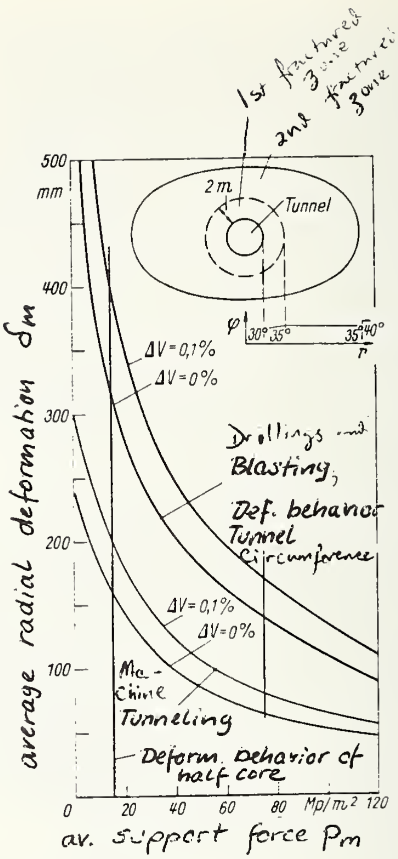


Figure 3-10. Influence of Tunneling Process on Stability Behavior [35]

Tunnel Diameter D = 4.0 m
Overburden Height H = 2000 m

SL. Plane Friction Angle
Elast. Zone φ = 40°
2nd Fractured Zone φ = 35°
1st Fractured Zone φ = 30–35°

Sliding Plane Shear Strength
Elast. Zone c = 2.0 kg/cm^2
2nd Fractured Zone c = 1.0 kg/cm^2
1st Fractured Zone c = 1.0 kg/cm^2
Elast. Zone E = 4.10^5 kg/cm^2
Fractured Zones E = 2.10^5 kg/cm^2
Coefficient of Lateral Stress
λ = 0.7

- the invert on this side of the work face shows large deformations due to the reduced and finally even missing supporting force that are inadmissible for the project or may be the cause of large rock falls.

A characteristic curve can be calculated for any kind of temporary or permanent lining. Its characteristic curves depend on the lining material, whose strength and deformation properties are well known, and on the construction of the lining, such as rock bolt density, distance of lining rings. The curve of these characteristics is determined by the tunnel diameter, Figures 3-11 to 3-13 [35].

The stiffer the lining, the greater its capacity to accept the load. Increased loads, however, also mean increased stress. On the other hand, the load acceptance capacity of a flexible lining is relatively small. The lining shows the tendency to evade the load, i.e., it is deformed, and cannot accept any further load after reaching a certain deformation. Especially with the presence of large primary stresses (cover height), no lining can exert a supporting force on the invert that would be equal to that before the tunneling. However, this is also not necessary. It must rather be assured that the lining produces a supporting force which guarantees the equilibrium of the invert as long as the unavoidable deformations are admissible for the project, and have not caused rock falls. We must admit, however, that at the present time reliable and generally applicable knowledge concerning the time dependent behavior of deformations is not available.

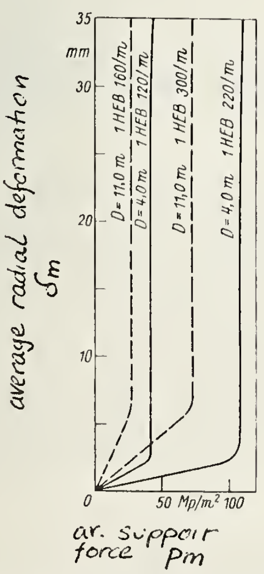


Figure 3-11. Characteristic Curves for Steel Rings, HEB Steel 37

Figures 3-11 to 3-13. Characteristic Curves for the Deformation Behavior of Supports [35]

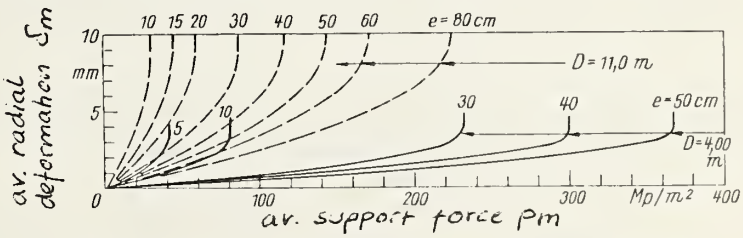


Figure 3-12. Characteristic Curves For Concrete, Shotcrete
e=Concrete Thickness

$E_b = 2\times 10^6 \cdot Mp/m^2$, $\beta_{BR} = 1650\ Mp/m^2$

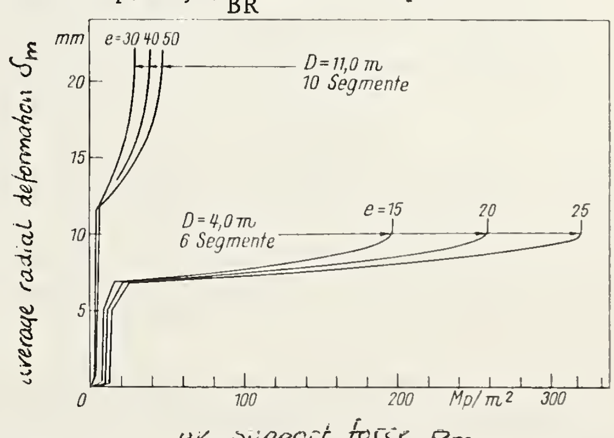


Figure 3-13. Characteristic for Concrete Precast Elements with Polyurethane Joint Inserts
e Concrete Thickness

$E_b = 3.3 \times 10^6\ Mp/m^2$, $\beta_{BR} = 2720\ Mp/m^2$

The number of observations conducted systematically is still very small, and is limited to certain kinds of rock masses and tunneling processes.

3.4.2 Combination of Characteristics

The characteristic of a rock mass can be combined with those of a lining, Figures 3-14 and 3-15 [35]. If a lining could be installed directly at the work face, Figure 3-14, the deformation of work face and invert that would be invisible from the tunnel would already amount to δ_1. Until the equilibrium is reached, the lining would have a radial deformation in the extent of $\Delta\delta$, and the rock mass would have a total deformation of δ_2, respectively $\delta_1 + \Delta\delta$.

If a lining can be installed only at a certain distance from the work face, Figure 3-15, the deformation of the invert will already have reached the measure $\delta_1 + \delta_2$. The equilibrium is reached after the lining is deformed by $\Delta\delta$, and after the invert is deformed by a total of δ_3, i.e., $\delta_1 + \delta_2 + \Delta\delta$. Both cases are based on a steel support that is in full contact with the tunnel circumference. A lining as protection against singular rock fall, or against weathering, should be installed as soon as possible.

In order to determine the type of lining against the pressure of the rock mass, two aspects are decisive, apart from the costs and the available possibilities:

- in order to avoid large-scale loosening of the rock mass around the tunnel, the lining should be installed as soon as possible after the advancement of the tunnel. If the lining is installed as early as possible, however, the rock mass is only relatively little deformed, and its stabilization requires a large supporting force.
- in order to avoid the necessity of a massive lining, a certain tolerable deformation, i.e., loosening of the rock must be accepted, and the lining should be installed only sometime after the advancing of the tunnel.

The justly increased safety requirements in the interest of the tunnel workers usually demand an immediate support lining. A concrete vaulting of the tunnel, sometimes of great thickness and stiffness, is impossible at this time, if only due to constructional reasons. Generally, however, a quickly effective and flexible lining should be installed.

The most common types of lining show, in the sequence of their listing, increasing supporting force, and decreasing deformability, Table 3-2.

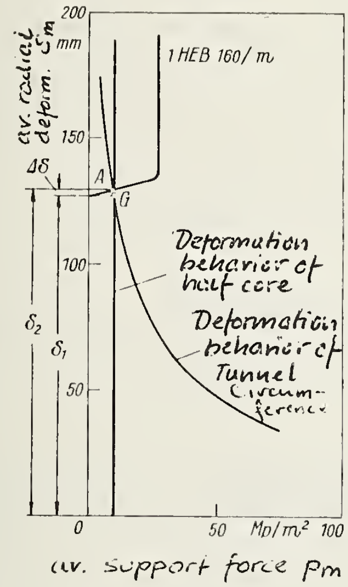


Figure 3-14. Theoretical Case of Support Installation Directly At Face

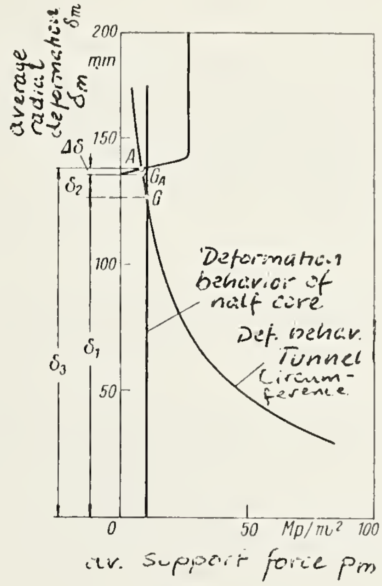


Figure 3-15. Practical Case of Support Installation (Steel) At a Certain Distance From the Face

Figures 3-14 and 3-15. Combination of Rock Mass Characteristics With Support Characteristics [35]

Tunnel Diameter D = 11.0 m, Overburden Height		H = 1,000 m
Sliding Plane Friction Angle	Elastic Zone	φ = 40°
	Fractured Zone	φ = 35°
Sliding Plane Shear Strength	Elastic Zone	c = 1.0 kg/cm^2
	Fractured Zone	c = 0.5 kg/cm^2
	Elastic Zone	E = 4.10 kg/cm^2
	Fractured Zone	E = 2.10^5 kg/cm^2
Lateral Stress Coefficient ℓ	= 0-7	
Volume Increased in Fractured Zone ΔV	= 0%	

TABLE 3-2. MOST COMMON TYPES OF SUPPORTS

Types	Remarks
bolting	usually only temporary support
thin shotcrete yielding steel rings rigid steel rings	later used for permanent support
precast rings with articulated joints precast rings with rigid joints	usually permanent support

3.4.3 Installation of the Support and Lining During the Tunneling

3.4.3.1 Preconditions and Possibilities - During tunneling, singular rock fall, and also frequently significant deformations of the tunnel cross section with the above-mentioned consequences must be reckoned with. These facts make it difficult to understand the pamphlets and offers of manufacturers concerning tunneling machines for "stable rock." The protection cage (Figure 5-23) that sometimes surrounds the tunneling machine and the protective roofs against rock falls have no stabilizing influence on the rock mass.

Mechanical tunneling has available the same instruments for securing the rock mass as the conventional processes. Their application, hoever, is tied to the precondition, that sufficient work room is available, and that the relevant additional devices are installed on the tunneling machine, such as bolt drills, steel ring segments, transportation and installation devices for steel, shotcrete equipment, or prefabricated segment installation devices.

A temporary lining support can be installed in the area of a tunneling machine regardless of its type:

- between basic machine and first trailer,
- between the trailers, and
- behind the tunneling machine.

These lining zones are approximately 10, 15 to 30 m this side of the work face. Cages (Figure 5-23), and protective roofs over the tunneling machine are useless whenever the time for excavating the stretch between work face and the point of lining installation is longer than the time span of stability of the rock mass above the same stretch. They only offer protection against singular rock falls. If large deformations must be expected, a lining should be installed as close as possible to the work face, i.e., immediately behind the cutting head.

This possibility is easier to realize with conventional tunneling, and with tunneling by means of partial tunneling machines, than when full-face tunneling machines are used. The minimal distance between work face and foremost lining point amounts to 1.5 to 3 m for such machines. In addition to that, the possible point of time for the installation of the lining, the distance from the work face as well as the nature and the extent of possible measures for stabilization of the rock mass depend on the boring diameter, and - at present still to a quite decisive degree - on the construction, i.e., on the manufacturer of the tunneling machine. Generally, the possibilities are: the less limited, the larger the boring diameter.

Table 3-3 (compare page 86) shows the presently most widely used technical possibilities for rock mass stabilization during tunneling with full-face tunneling machines. In the following, some of these processes are explained.

3.4.3.2 Rock Bolt Support Lining - The drilling of anchor bolt holes can be done systematically and with great precision from the tunneling machine, Figure 3-16. Under conditions that resemble those of a workshop, the bolts can be installed, and even methods can be applied that require special care, such as the use of short synthetic resin cartridges with fast hardening adhesive for the bottom of the bolt holes, and the use of longer cartridges with adhesives that react relatively slowly for the remaining length of the hole. This process makes it possible to pre-stress the bolts after the hardening of the fast-reacting adhesives, and to mortar them to the rock mass subsequently over their whole length. By means of this technique, a stabilizing segment can be installed in the crown of the tunnel, Figure 3-17, and possibly a systematically constructed stabilizing and flexible ring all around the tunnel segment element.

3.4.3.3 Gunite and Shotcrete Lining - The gunite and shotcrete lining, for example as local cover, or as the "New Austrian Tunneling Method" is a possibility of securing a rock mass which is very well adapted to the rock mass behavior. Two restrictions, however, cannot be overlooked:

- the moist and dusty, also muggy, climate caused by the shotcrete application makes it difficult to hire and retain workers for this rather unpleasant type of work.
- dust and rebound are deposited on the tunneling machine. Through a special design of sensitive parts of the tunneling machine, for example through casing of joints, casing of motors, damage can be avoided. Also, a special design of the shotcrete equipment may be able to localize the dust and rebound.

In order to reduce the technical disadvantages of the shotcrete lining during mechanical tunneling, an alternating process is sometimes used, if the rock mass behavior permits it, with tunneling and simultaneous bolt lining as well as installation of invert prefabricated (segmented) elements in two work shifts, and subsequent shotcrete lining in one daily work shift.

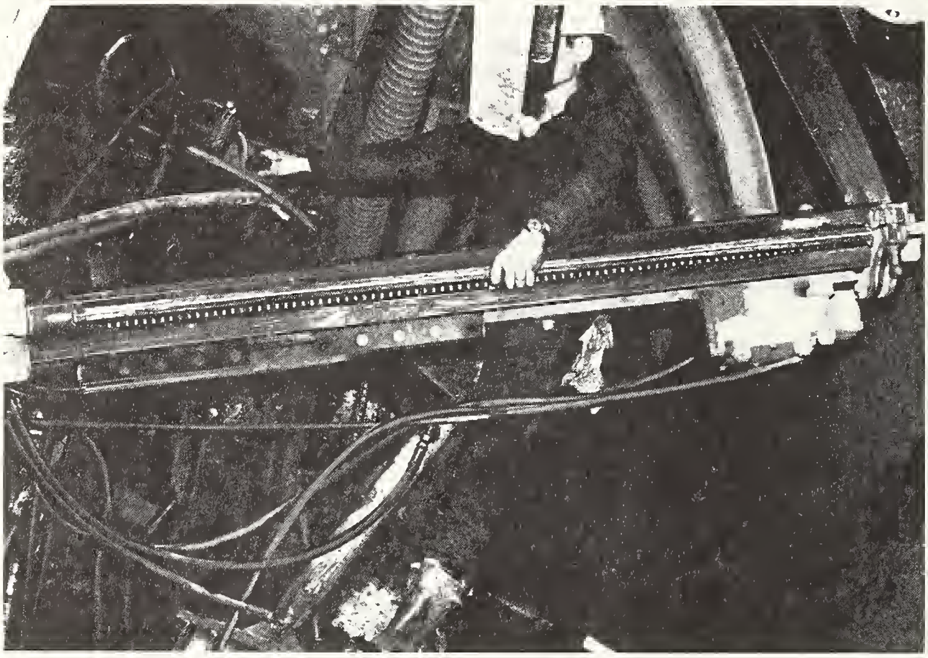


Figure 3-16. Drilling of Bolt Holes From The Tunneling Machine During Tunneling

Figure 3-17. Overhead Protection Consisting of Systematically Placed Bolts, Sheet Metal Segments, and Wire Mesh

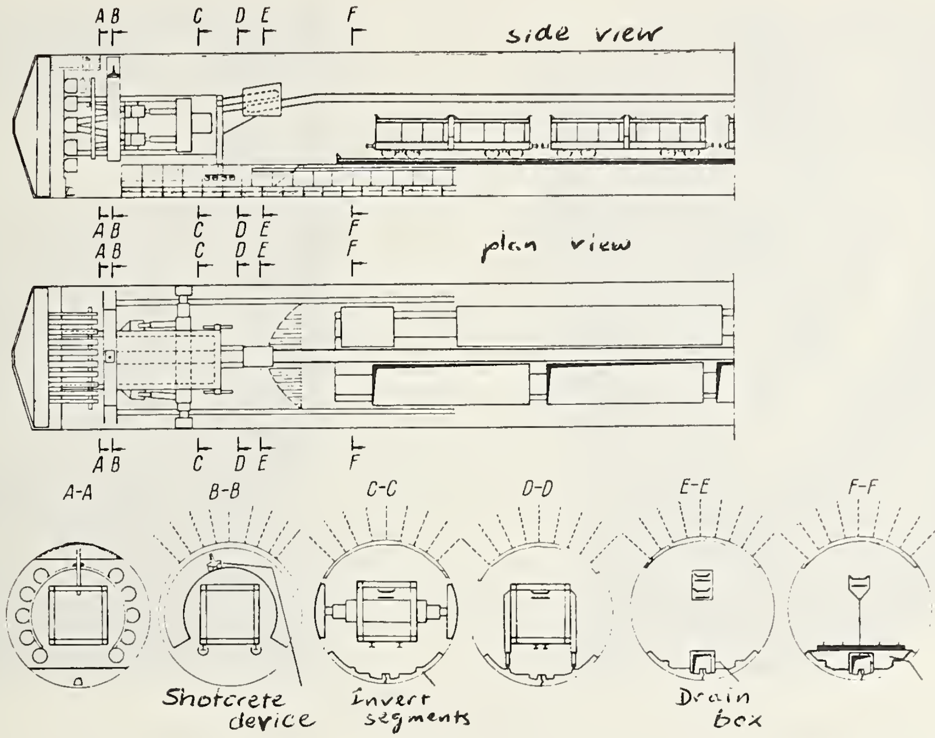


Figure 3-18. Tunneling Machine Equipped With Bolt Drilling and Shotcrete Equipment for Systematic Stabilizing of The Rock Mass and Extension of The Tunnel Invert During Tunneling Advance

3.4.3.4 Steel Set Support - Flexible or relatively rigid steel rings consisting of individual segments can be installed from the tunneling machine by means of installation devices, or at least with installation aids, Figure 3-19. By means of a simply hydraulic press, the ring can be pressed against the tunnel invert before the last segment connection is tightened. This ring which is in close contact with the circular invert, and is bolted to it, produces a large supporting force. The steel can accept considerably plastic deformations without the ring losing its supporting capacity immediately. The disadvantages of steel lining during conventional tunneling, such as its sensitivity to localized loads or the requirement to fill up the space remaining between ring and an irregular rock face, do not apply.

3.4.3.5 Lining with Segmented (Prefabricated) Elements - Lining with segmented (prefabricated) elements is a type of lining which is well adapted to mechanical tunneling. By means of erectors, the segments and flexible element rings can be installed from the tunneling machine. However, the segments can only be installed behind the basic machine unless special designs provide open spaces for the gripper shoes of the tunneling machine. Leaving temporary openings in the flexible element rings, however, is an emergency solution, and usually the segmented elements are installed only behind the gripper shoes. If the startup time of the invert is shorter than the excavation time necessary to complete a tunnel stretch corresponding to the distance between work face and installation point, a temporary support of the invert between cutting head and element installation point is unavoidable. A combined steel ring elements lining could be used, Figure 3-20. Sometimes, the use of a shield tunneling machine is recommended for such rock mass behavior. Such a machine may be of advantage in loose ground under certain conditions. Its use in hard rock, especially, as assumed, in a rock mass showing especially large deformations, is extremely problematic. The deposit of fracture zone material on the shield mantel can impair, or eliminate the possibility of controlling and adjusting the tunneling machine because even very small movements of the mantel against the rock mass encounter vary large passive rock pressure. A so-called segmented shield surrounding the basic machine (compare section 3.4.4), may offer the opportunity to support the rock mass and guarantee the free movement of the tunneling machine. A carefully installed segmented lining where the ring space is filled after the deformations have subsided may become a permanent support.

3.4.4 Special Support of the Tunneling Machine

The cutting head of every tunneling machine has a supporting effect on the work face as long as the boring tools are in contact with the rock mass under pressure. When the tunneling machine is removed, during inspection, maintenance, etc., in front of the cutting head, this support is eliminated.

By means of special types of the tunneling machine, the stability behavior of the rock mass can be influenced within limits, even during the readjustment of the tunneling machine, and partially also during work in front of the cutting head. By means of a short cutting head shield consisting of several parts whose segments can be shifted radially, a supporting force can be applied to the rock mass all around the cutting head. This supporting force stabilizes the tunnel invert locally, and reduces the pressure of the invert on the work face, Figure 3-21.

In the rear section of the short cutting head shield segments, rock bolts, liner plates, or steel rings can be installed. In cases where an exclusive lining with segmented elements is planned for a rock mass with a short time of stability, the cutting head shield of the tunneling machine can be supplemented by two support systems in form of a supporting in stages, Figure 3-22. These support systems have radially adjustable support beams and are arranged all around the basic machine behind the cutting head shield. The cutting head shield and the support beams must overlap for a little more than one length of travel before the state

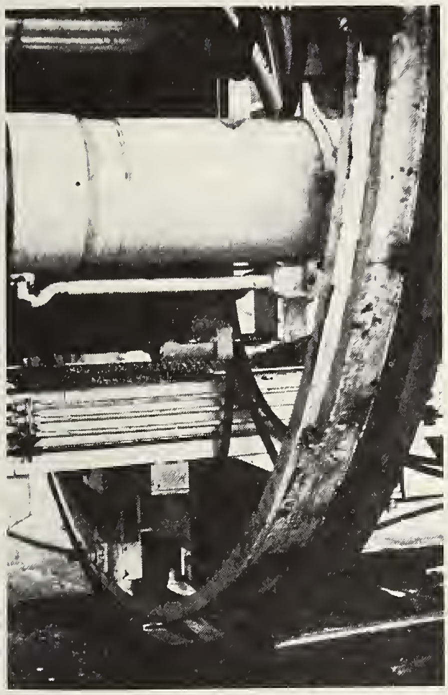


Figure 3-19. Ring Sliding In Direction of Machine Axis and Pivoting Around It, For Assembly and Installation of Steel Support Segments

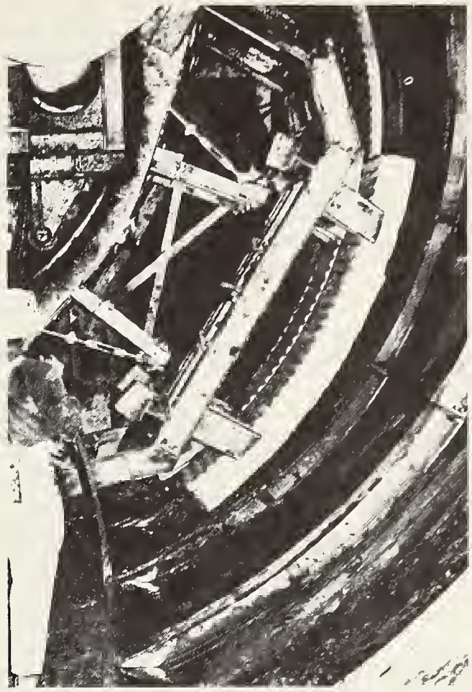


Figure 3-20. Installation of Prefabricated Segments with Erector Behind Basic Machine. Steel Rings Have Been Previously Installed Directly Behind Cutting Head Carrier

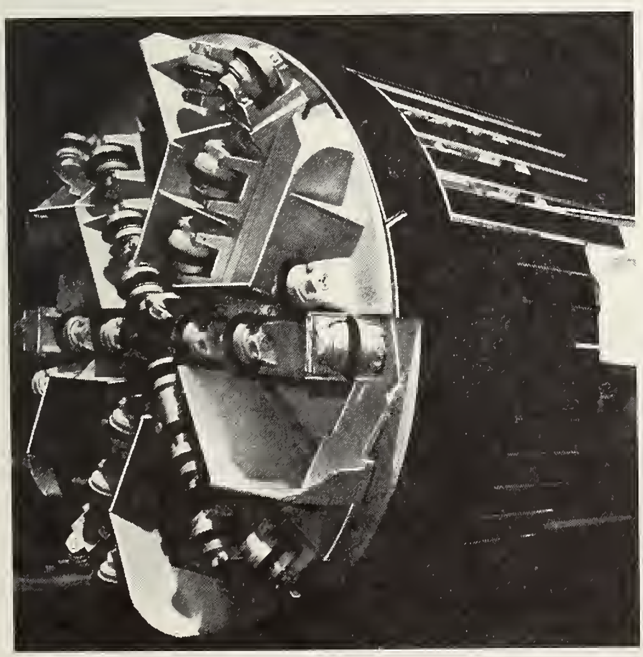


Figure 3-21. Segmented Cutting Head Shield, with Gripper Plate, and Radially Sliding Segments
Photo: The Robbins Company

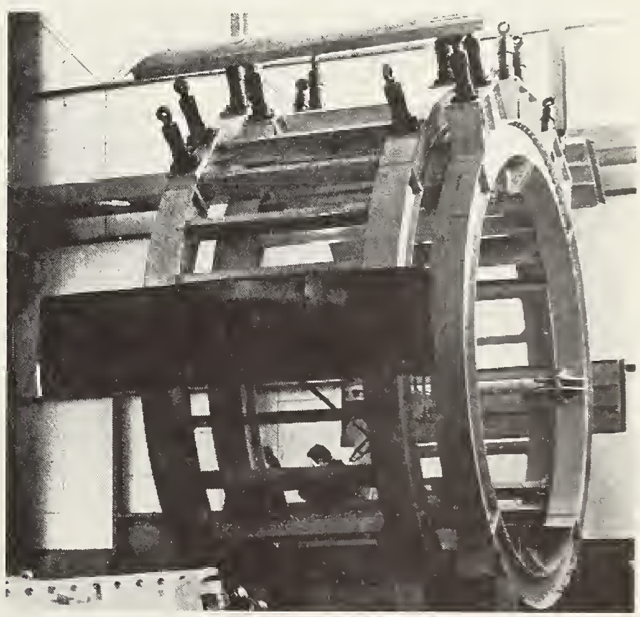


Figure 3-22. Segmented Shield Consisting of Two Suppport Systems

of the excavation. Such a special construction may be called a segmented shield. The stiffness of the construction can be selected. According to that, the influence on the deformation of the rock mass can be controlled. During the excavation process, the short head shield which is in close contact with the rock mass slides forward with the cutting head, and the beams of both support systems remain pressed to the invert. These systems are moved forward one after the other after one stroke.

3.4.5 Tunneling Through Fault Zones that Cannot be Excavated by TMB

The previous presentation of proven technical possibilities for stabilizing rock masses should not lead to the opinion that a tunneling machine equipped with all kinds of support features, and with large boring diameters, can be used for cutting through every fault zone. The full use of the tunneling machine in solid rock can be limited technically, if:

- the machine cannot be braced sufficiently for boring by any method, such as shotcrete lining of broken-out holes, or cushioning the bracing plates with timber,
- the tunneling machine cannot even be supported via the rear faces of its gripping by a heavily bolted support which would make boring with shoes reduced force possible.
- the tunneling machine settles in the rock mass under its own weight,
- the rock mass is extremely inhomogeneous, and consists, for example, of blocks of solid rock imbedded in clay, or if
- the standing time of the rock mass is shorter than the time necessary for boring the section corresponding to the distance between the work face and the cutting head carrier as the first point for the installation of a temporary support.

Whenever such conditions arise, the tunneling should be stopped temporarily. The tunneling machine should be pulled back a few meters, and the problematic zone should be defined with horizontal test drill holes, and should be tunneled conventionally. The tunnel profile, usually in pickable rock, should be cut large enough that its diameter permits the advancing of the tunneling machine after completed stabilization by means of a temporary support, i.e., after the deformations of the invert have subsided. The access to the work place at the work face, and its supply with lining material must be guaranteed for the entire zone of the machine. The dismantling of the dust shield of the tunneling machine, or an open cutting head (Figure 3-28) facilitate these movements. The material resulting from manual tunneling or from blasting may be pushed by means of a scraper into the range of the scraper and buckets of the tunneling machine. There, it is picked up by the totating cutting head of the immobile tunneling machine, and is transported through the machine area by means of the cuttings transportation system to the loading belt, and from this it is loaded into the transportation vehicles.

Alertness and adaptiveness of construction management and construction supervision, in particular a timely organization of the change of operation, are decision for the success of this method.

4. ROCK MASS CLASSIFICATION FOR TUNNELING

The evaluation of the rock mass with regard to its behavior during tunneling as well as with regard to measures for the stabilizing of the rock mass which might become necessary is of great importance for the project design, the determination of the construction program and the construction costs, as well as the bidding process of the contractor. This evaluation is usually expressed by:

- a geological documentation, and
- a rock-mechanical forecast.

However, it should also be expressed by:

- a prognosis of the classification of identical areas of the tunnel track, the so-called rock mass classes, or of types

4.1 GEOLOGICAL DOCUMENTATION

The requirement of a geological survey for a tunnel project, and for the bidding process is undisputed. Usually, this survey must give information on the type of the rock that will be tunneled through, as well as on its nature, on its position relative to the tunnel axis, on the amount of water that can be expected, and on gas which might be encountered, assumed temperature of the rock mass in cases with large overburden height. A diagram showing the discontinuity configuration would be desirable. The engineer in charge of the project should formulate the questions which are to be answered with regard to the project by the geologist. These questions should facilitate this survey. The engineer expects from the geologist that he will answer those questions by applying the theories of geology, by using his experience, and by employing all relevant methods of geological exploration. This is the more difficult the more complex the rock mass is structured, and the deeper the tunnel track is located below the surface. By asking for absolutely correct prognostics, the engineer would ask the impossible from the geologist, and he would also ignore the difficulties of the task. However, with regard to the reliability of the project design, he may ask the geologist to classify all his statements according to whether they are based on factual knowledge, or, if that does not apply, according to probability and possibility of unfavorable conditions for the project.

A long text preference should be given to a geological documentation with emphasis on diagrams - for example, a longitudinal section, a horizontal section at the tunnel level, and, if possible, one of each with regard to probability and to possibility - with a listing of geological data for the regions that are representative for the project with regard to rock mass structure and rock, and with a survey of the petrographic characteristics and the most important geotechnical properties of the rock types.

4.2 ROCK-MECHANICAL PROGNOSIS

The geological documentation (in particular the information on the type, the nature, and the position of the rock, and if available beyond doubt, the diagram of the discontinuity configuration of the rock mass which is to be tunneled through) is an important basis for the subsequent rock-mechanical prognosis conducted by a trained engineering geologist, or by an engineer who is familiar with the field of rock mechanics.

The actual rock-mechanical calculations are preceded by the determination of the computation parameters and of the so-called homogeneous areas. The rock type longitudinal profile of the tunnel, Figure 4-1, shows the homogeneous areas. A homogeneous area is characterized by identical assumed numerical values of the sliding plane friction angle and of the sliding plane shearing strength as well as by approximately identical elasticity moduli and height of cover layer. It would be justified to relate the height of cover to the relief line instead of to the topographical longitudinal profile. The heights of the relief line at one point of the track correspond to the average heights of the topographical cross profile perpendicular to the tunnel axis, whose width on both sides of the axis is as large as the cover layer height of the tunnel that relates to the topographical profile, Figure 4-2.

In the first phase of the rock-mechanical calculation, the stability behavior for each homogeneous area is determined by means of, for example, the characteristic-curve-method. The results can be represented in a longitudinal section of the assumed local distribution of the cases of stability, Figure 4-3, line a.

In the second phase of the rock-mechanical calculations only those areas of tunnel track are considered for which a nonstable behavior of the tunnel invert on the work face can be expected. These require support in any case. On the basis of a catalogue for the technical possibilities of securing support the rock mass during the tunneling, for example Table 4-1 and for the characteristic stabilizing of the rock

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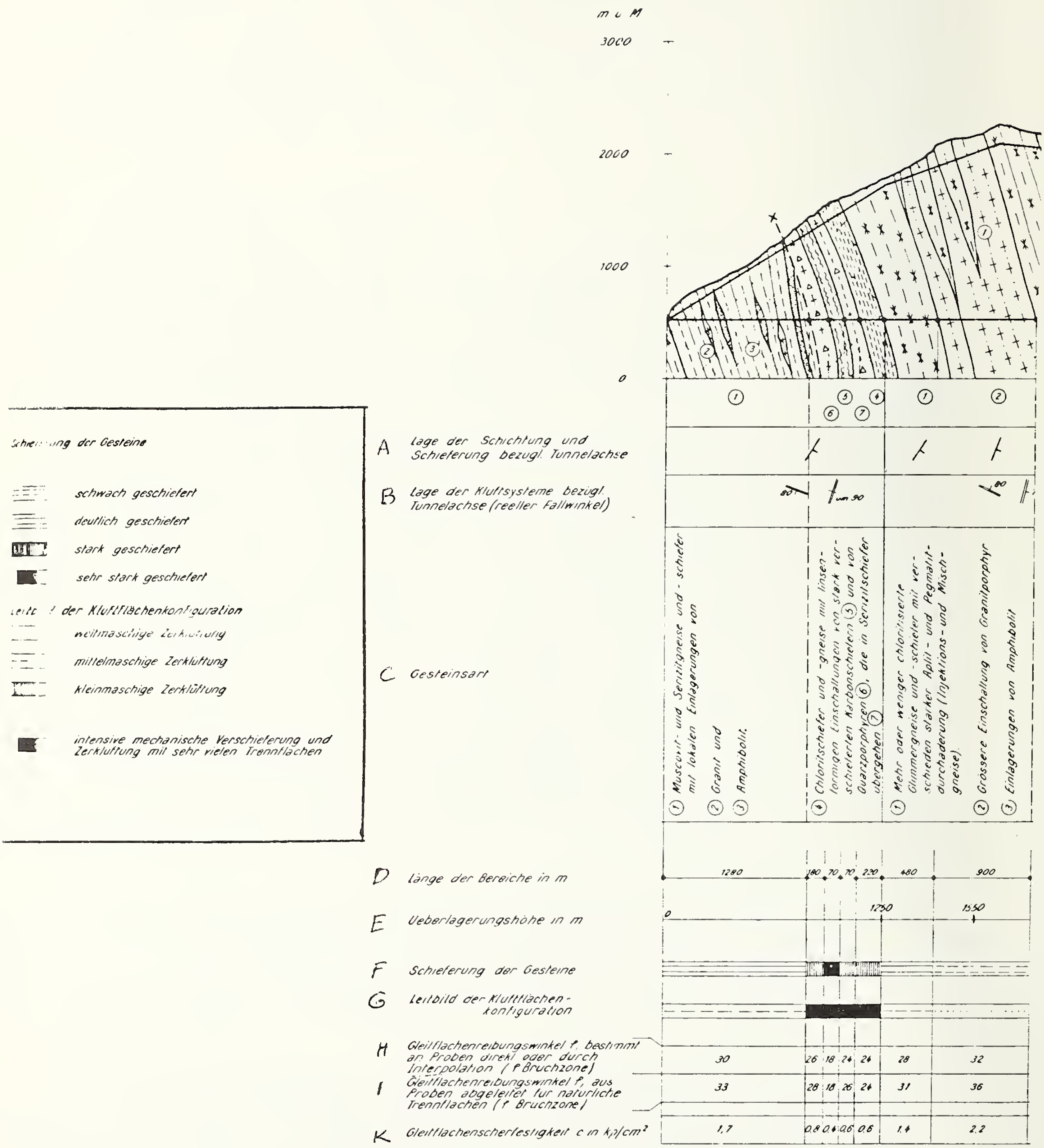

m ü M
3000
2000
1000
0
Schie[…]ung der Gesteine
schwach geschiefert
deutlich geschiefert
stark geschiefert
sehr stark geschiefert
Leitb[…] der Kluftflächenkonfiguration
weitmaschige Zerklüftung
mittelmaschige Zerklüftung
kleinmaschige Zerklüftung
intensive mechanische Verschieferung und Zerkluftung mit sehr vielen Trennflächen
A Lage der Schichtung und Schieferung bezügl. Tunnelachse
B Lage der Kluftsysteme bezügl. Tunnelachse (reeller Fallwinkel)
80
um 90
80
C Gesteinsart
(1) Muscovit- und Serizitgneise und -schiefer mit lokalen Einlagerungen von
(2) Granit und
(3) Amphibolit.
(4) Chloritschiefer und -gneise mit linsenförmigen Einschaltungen von stark verschieferten Karbonschiefern (5) und von Quarzporphyren (6), die in Serizitschiefer übergehen (7)
(1) Mehr oder weniger chloritisierte Glimmergneise und -schiefer mit verschieden starker Aplit- und Pegmatitdurchaderung (Injektions- und Mischgneise).
(2) Grössere Einschaltung von Granitporphyr
(3) Einlagerungen von Amphibolit
D Länge der Bereiche in m
1280
180
70
70
220
480
900
E Ueberlagerungshöhe in m
0
1750
1550
F Schieferung der Gesteine
G Leitbild der Kluftflächenkonfiguration
H Gleitflächenreibungswinkel f, bestimmt an Proben direkt oder durch Interpolation (f Bruchzone)
30
26
18
24
24
28
32
I Gleitflächenreibungswinkel f, aus Proben abgeleitet für natürliche Trennflächen (f Bruchzone)
33
28
18
26
24
31
36
K Gleitflächenscherfestigkeit c in kp/cm²
1,7
0,8
0,4
0,6
0,6
1,4
2,2

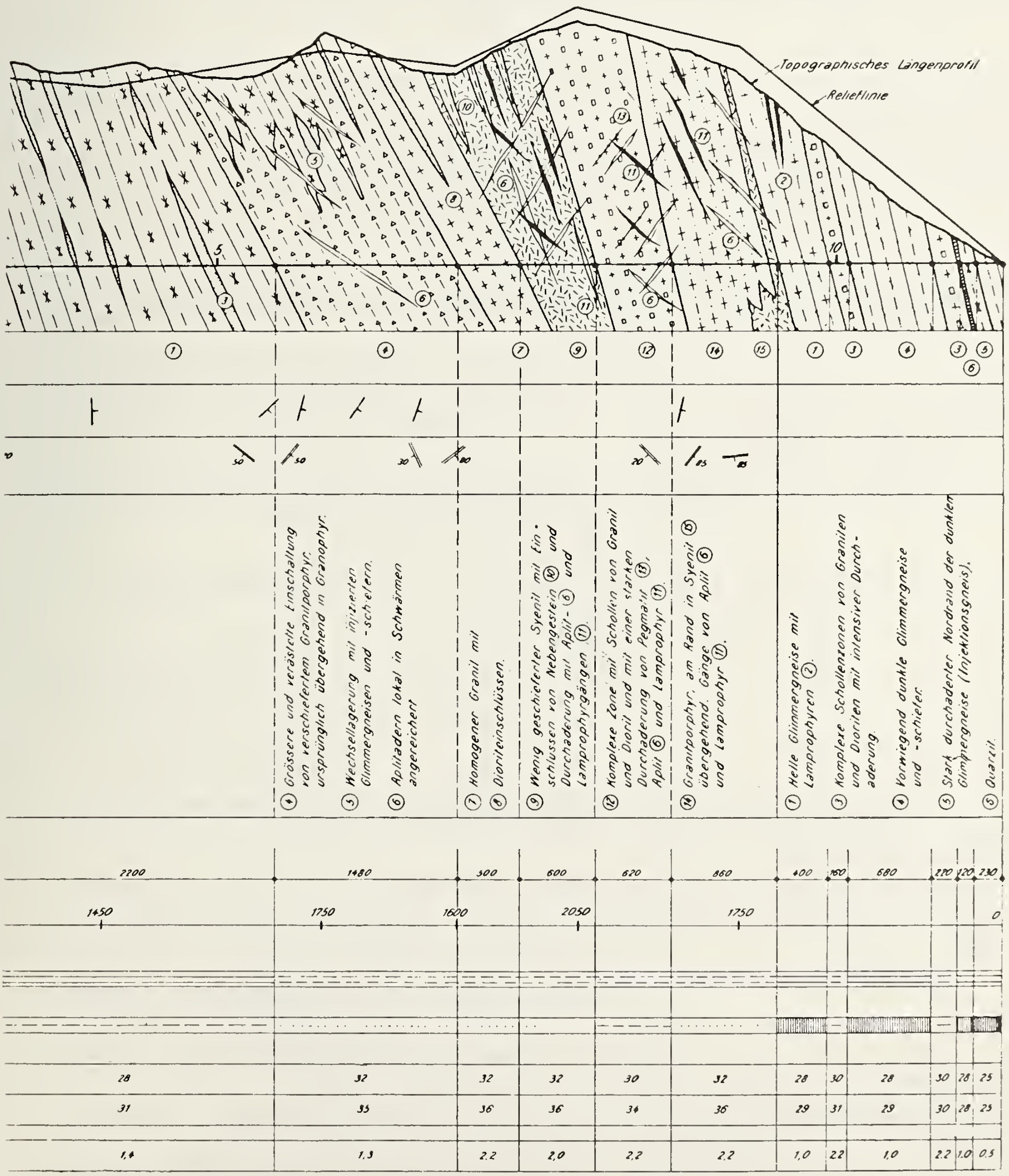


Figure 4-1. Probable Geologic Profile
Along a Tunnel Alignment

Text for Figures 4-1 and 4-3.

Table 4-1A.

Foliation of the rock
slightly foliated distinctly foliated heavily foliated very heavily foliated
Discontinuity configuration
wide-spacing medium-spacing narrow-spacing
intensive foliation and jointing with very many discon- tinuity planes

A Attitude of layers and joint sets relative to tunnel axis

B Attitude of discontinuities relative to tunnel axis (real dip angle)

C Type of rock

D Length of zones in m

E Overburden in m

F Foliation

G Discontinuity configuration

H Sliding plane friction angle obtained directly with samples, or by interpolation

I Sliding plane friction angle from samples derived for natural sliding planes

K Sliding plane shear strength c in kg/cm^2

Table 4-3A.

Supports	
Rock bolts installed behind cutting head.	
Steel rings installed after each round	
Shotcrete.	
Prefab segments installed behind machine.	
Concrete cast in place	
$\beta_D \beta_Z$	1500, 100 mean 1700, 120 maximum

A Attitude of layers and foliation chavage relative to tunnel axis

B Attitude of discontinuities relative to tunnel axis (real dip angle)

C Type of rock

D Length of areas in m

E a) stabilitv category

F b) support temporary / permanent

G c) basic boreability

H d) cutting tool wear

I e) rock burst

Text for Figure 4-1 and 4-3 (Continued)

Column "Types of Rock" (identical in both Figures).

1. muscovite and sericite gneiss and schist with local inclusions of

2. granite and

3. amphibolite

4. chlorite schist and gneiss with lense-shaped inclusions of heavily foliated carboniferous schist 5. and of quartz porphyry 6. changing to sericte schist 7.

1. more or less chloritized mica gneiss and schist with differing streaks of aplite and pegmatite (injection gneiss and mixed gneiss).

2. large inclusions of granite porphyry.

3. inclusions of amphibolite.

4. large and branched-out inclusion of foliated granite porphyry, originally changing to granoporphyry.

5. alternatingly deposited with injected mica gneiss and schists.

6. veins of aplite with local concentrations.

7. homogeneous granite with

8. diorite inclusions.

9. slightly foliated syenite with inclusions of country rock 10. and streaked with aplite 6. and lamprophyr 11.

12. complex zone with pieces of granite and diorite, strongly streaked with pegmatite 13. and aplite 6. and lamprophyr 11.

14. granite porphyry changing to syenite at the boundaries. dikes of aplite 6 and lamprophyr 11.

1. light mica gneiss with lamprophyr 2.

3. complex zones of granite and diorites with extensive veins

4. predominantly dark mica gneiss and schists.

5. northern boundary of mica gneiss with many veins (injection gneiss).

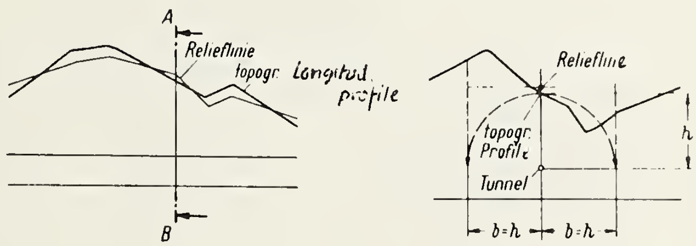
6. quartzite.

TABLE 4-1. TECHNICAL POSSIBILITIES FOR STABILIZING THE ROCK MASS DURING TUNNELING WITH FULLFACER TUNNELING MACHINES

measure	lining/ support	extent	installation directly behind cutting head	installation without interruption of tunneling
rock bolts	temporary	crown 120°	yes	yes
	temporary	whole sect.	no	yes
liner plates	temporary	whole sect.	yes	yes
shotcrete, gunite	temporary	crown 120°	yes	no *)
	temporary or permanent	whole sect.	no	no *)
steel rings with bolts				
- light profile				
distance larger than gripper pad width)	temporary	whole sect.	yes	yes
distance smaller than gripper pad width	temporary	whole sect.	only every 2nd or 3rd ring (every 2nd or 3rd ring is placed at distance greater than gripper pad width)	only every 2nd or 3rd ring
- heavy profile				
distance larger than gripper pad width	temporary	whole sect.	yes	no
distance smaller than bracing gripper pad width	temporary	whole sect.	only every 2nd or 3rd ring	no
segmented elements	permanent,			
poss.	temporary	whole sect.	no	yes
	temporary	crown	yes	no
grouting	temporary	crown	yes	no
		whole sect.		

*) yes with large diameters.

mass as well as of the supports, the extent, the place, and the time of the installation of the support is determined subsequently for each area. During this determination, the safety and the economy of possible solutions are also considered. These results can be represented in a longitudinal section of the assumed local distribution of the support lining, respectively of the rock mass classes with regard to the linings, Figure 4-3, line b.



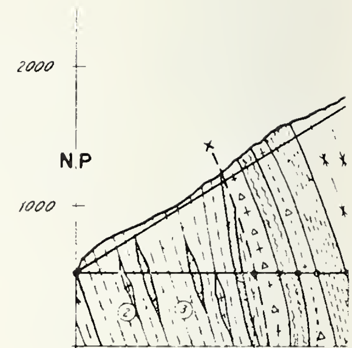
Cross Section A-B

Figure 4-2. Topographical Longitudinal Section and Relief Line

4.3 DEFINITION OF ROCK MASS CLASSES

4.3.1 Basic Principles of Classification

The classification of a rock mass that is to be tunneled through with regard to measures that are unequivocally defined qualitatively as well as quantitatively, and which are necessary for the tunneling in order to prohibit singular rock fall, and in order to retain the stability of the tunnel until the permanent lining can be installed, has proved its general validity for conventional tunneling. It does not depend on geological terms whose interpretation depends on the planner. Measureable values, i.e., the nature, the extent, the place, and the time of the application of those measures during the construction are its basis. This type of classification indeed largely characterizes a conventional tunnel project of given excavation shape and surface. The estimation of the support requirement also implies a determination of the requirements with regard to workers, to equipment, and to the tunneling performance. On this basis, and after



Ausbau	
▭	Felsanker hinter dem Bohrkopf versetzt
▥	Stahlringe nach jedem Abschlag versetzt
▭	Spritzbeton
▭	Tübbinge hinter der Grundmaschine versetzt
■	Ortsbeton
	β_D & β_Z
$\overline{1500}$, $\overline{100}$	Mittel
1700, 120	Maximum

				①	⑤ ④ ⑥ ⑦
A	Lage der Schichtung und Schieferung bezügl. Tunnelachse				
B	Lage der Kluftsysteme bezügl. Tunnelachse (reeller Fallwinkel)			80	um 90
C	Gesteinsart			① Muscovit- und Serizitgneise und -schiefer mit lokalen Einlagerungen von ② Granit und ③ Amphibolit.	④ Chloritschiefer und -gneise mit linsenförmigen Einschaltungen von stark verschieferten Karbonschiefern ⑤ und von Quarzporphyren ⑥, die in Serizitschiefer übergehen ⑦
D	Länge der Bereiche in m			1280	180, 70, 70, 220
E	a) Stabilitätsfall			1a	4
F	b) Ausbau	vorläufig			▥
					konventionell
		endgültig		▭	■
G	c) Basisbohrbarkeit	Gesteinsart		① ③	④
		$E_{t\,50}$	10^5 kp/cm²	3,2 11,0	-
		β_D	kp/cm²	$\overline{1500}$-1700 2800-3200	$\overline{800}$-850
		β_Z	kp/cm²	$\overline{100}$-120 $\overline{240}$-290	$\overline{55}$-65
		SH	s	15 41	-
H	d) Bohrwerkzeugverschleiss	Gesteinsart		① ③	④
		Quarz	%	35 5	40
		Feldspate	%	35 5	15
		Hornblende	%	- 90	-
		Tonminerai	%	- -	-
		Mittl. Korn ø	mm	0,2 0,2	0,05
I	e) Ev. Abschalen oder Bergschlag				

Klassifikation hinsichtlich

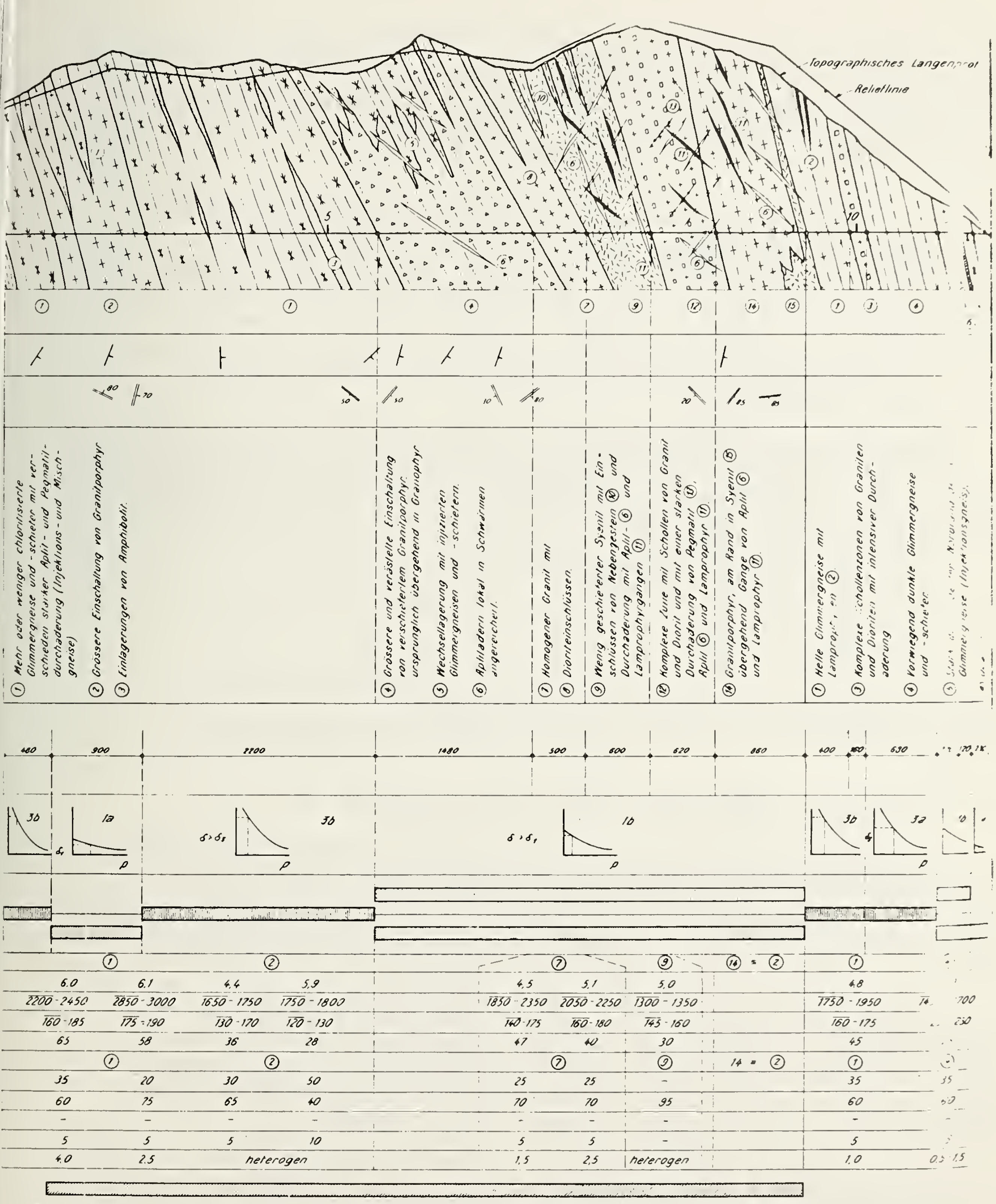


Figure 4-3. Probable Geologic Profile
Along a Tunnel Alignment

an estimation of the drilling steel consumption, the drilling time, and the explosive requirement, a cost calculation can be conducted for conventional tunneling. An error in the estimation of the drilling steel or even of the explosive consumption per cubic meter of rock, influences the price of its excavation only by a few percentage points.

The advantages of this classification system also suggest its evaluation with regard to mechanical tunneling. The system may be applied but not all aspects of mechanical tunneling are covered by it. The classification with regard to the nature, the extent, the place and the time of the installation of temporary support lining does not relate to the boreability of the rock mass - and with that to a boring system - or to the cutting tool wear. It is insufficient for a cost calculation.

Mechanical tunneling cannot be described by a single term including all significant characteristics of the process as is largely possible for conventional tunneling. Mechanical tunneling must be classified with regard to three aspects:

- boreability of the formation to be tunneled,
- boring tool wear, and
- braceability of the tunneling machine, as well as temporary lining.

All three classifications should be formulated with general applicability, and not with regard to only one certain boring system, or a given tunneling machine manufacturer.

4.3.2 Classification According to Boreability

On the basis of a proven and apparently existing tendency of an interrelationship between strength, deformation, and hardness properties of a rock on the one hand, and the penetration of a boring system on the other hand. The above-mentioned properties may be used as index values for basic boreability.

The difficulty in prognosing a reliable diagram for the discontinuity configuration, and the problem to reliably determine the discontinuity planes influence on the boreability in a quantitative way, make it impossible at the present time, to also define index values for the discontinuity plane configuration influencing a given basic boreability.

4.3.3 Classification According to Cutting Tool Wear

The content and the grain size of abrasive minerals as well as the strength of the rock largely determine the wear of cutting edges and bit bodies. Strength properties were already mentioned for the classification with regard to basic boreability. The nature, the portion, and the average grain size of the main components of the rock may also be used as index values for the cutting tool wear.

The quantitative consideration of the influence of separating planes of the rock mass on the cutting tool wear is problematic and it should refrain from defining corresponding index values at the present time.

4.3.4 Classification According to Supporting Requirements

This classification relates to the measures to be taken during the tunneling concerning the braceability of the tunneling machine, and also concerning the stabilization of the rock mass, and, in certain cases, concerning the profile types of the lining that will be used, and which differ basically as far as their strength is concerned. A relevant determination of rock mass classes considering the special conditions of mechanical tunneling is given in Table 4-2. Three main classes are distinguished:

a) The tunneling machine retains its grip unimpaired during the cutting.

b) The tunneling machine retains its grip during the cutting not without impairment,

c) Tunneling through fault zones that cannot be bored.

These three main classes are divided into subclasses. Those are defined by the nature, the extent, the place and the point of time of the installation of the first support lining during the advancement of the tunnel. This subdivision is based on the most commonly used technical possibilities for the rock mass during tunneling with the tunneling machine (given in Table 4-1). The processes contained in one subclass do not lead, or do lead to approximately equally long non-system-related interruption during tunneling - on the condition of a suitably designed tunneling machine equipped with lining installation equipment.

The continuous development in the design of tunneling machines, and the imagination of trailor owners may well lead to a modification of the presented classification, or to a new definition of the sub-classes. Such requirements can be recognized during the bidding process, and can be considered during the bidding negotiations.

TABLE 4-2. ROCK MASS CLASSIFICATION WITH REGARD TO SUPPORTING REQUIREMENTS

Class	Subclass	Measures to be taken during tunneling
1		Tunneling machine retains its grip during tunneling without impairment.
	1.1	Rock mass stabilization unnecessary, or the extent of work is less than would be necessary for categorizing in classes 1.2 to 1.7;
	1.2	Directly behind cutting head, for a distance of at least 5 m, installation of: - rock bolts in crown area, possibly simultaneously with sheet metal ring segments and wire mesh, possibly simultaneously also with rock bolts on remaining part of circumference, behind basic machine, or - liner plates, type ..... completely bolted, or - steel rings, profile .... (light), with bolts and wire mesh in crown area or entire circumference, ring spacing ... (larger than gripper pad width.)
	1.3	Directly following rear gripper pads of basic machine, always for longer distances, installation of - segmented elements, type .... according to plan .....;
	1.4	Directly behind cutting head, for a distance of at least 5 m, systematic installation of - steel rings, profile ... (heavy), with bolts and wire mesh in crown area or entire circumference, ring spacing ... (larger than gripper pad width).
	1.5	Either directly behind cutting head, for a distance of at least 5 m, systematic application of - shotcrete or gunite in crown area, possibly simultaneously with shotcrete or gunite on remaining circumference, behind basic machine or behind the tunneling machine, for a distance of at least 5 m, systematic application of: - shotcrete or gunite over the entire circumference;

TABLE 4-2. (CONTINUED)

Class	Subclass	Measures to be taken during tunneling
	1.6	Directly behind cutting head, at distance larger than gripper pads width, as well as directly following the rear gripper pads of the basic machine, between the already mounted ones, for a distance of at least 5m, systematic installation of: - steel rings, profile ... (light), with bolts of wire mesh in crown or entire circumference;
	1.7	Like 1.6, but steel rings, profile: ... heavy
2		Tunneling machine is, or does not retain its grip unimpaired during tunneling. Special measures in addition to stabilizing of the rock mass must be undertaken at the start of, or during, the tunneling to produce the grip and support of the tunneling machine in the rock mass in order to generate thrust, such as: - shotcrete application to fractured surfaces, backpacking threat the gripper shoes with timber to secure the machine grip, or, in exceptional cases, - reinforcing the longitudinal bracing of the steel supports to achieve at least a limited support of the tunneling machine by means of the rear face of the gripper pads:
	2.1	no stabilizing of rock mass is necessary, or the extent of the measures is smaller than necessary for a classification in 2.2 to 2.7:
	2.2	same as 1.2
	2.3	same as 1.3
	2.4	same as 1.4
	2.5	same as 1.5
	2.6	same as 1.6
	2.7	same as 1.7

TABLE 4-2. (CONTINUED)

Class	Subclass	Measures to be taken during tunneling
3		Tunneling through fault zones that cannot be bored Stop mechanical tunneling, local pull-back of tunneling machine, change and reorganization of the operation. Conventional tunneling with limited use of the TBM, and installation of temporary support during tunneling and directly in the face area, excavation diameter selected with respect to subsequent advance of the tunneling machine;
	3.1	systematic placement of rock bolts, possibly simultaneous with sheet metal segments and wire mesh, also application of shotcrete or gunite;
	3.2	like 3.1, but also lining of face with same methods;
	3.3	installation of steel rings, profile:.., with rock anchors and wire mesh;
	3.4	like 3.3, but additionally support of face with rock bolts, as well as, possibly, shotcrete or gunite.

4.4 PRACTICAL APPLICATION OF THE TRIPLE CLASSIFICATION

The longitudinal classification section of a tunnel track, Figure 4-3, represents the assumed local distribution of the cases of stability, line a, as well as the rock mass classes with regard to support - the first and the second main classes are combined - line b, with regard to basic boreability, line c, and with regard to cutting tool wear, line d. Line e gives an indication of possible cave-ins or rock bursts that are phenomena which cannot be covered by a rock-mechanical stability calculation.

The classification of the rock mass with regard to support requirements is effected by means of direct data on the nature, the extent, the place and the point of time of the installation of the support. If the classified geological prognosis of a longitudinal section is based on "factual knowledge", and if the rock type longitudinal profile also is not questionable, a single representation of the support requirements is sufficient. However, if the geological evaluation is reflected by a "probable" and a "possible" prognosed longitudinal profile, and if also the data of the rock type longitudinal profile are not substantiated, two representations are necessary for the support requirements. The classification of the rock mass with regard to boreability and cutting tool wear is based on index values, and not on direct data, as, for example, the boring system-related penetration or the maximum rolling distance of a bit edge. These data also consider the deviations found with rock tests and analyses. The knowledge of these deviations is of special importance if the longitudinal classification profile is to be used as the document for the bidding process representing the extent of work and the working conditions. During the construction, the class boundaries may shift. This possibility must be considered by accordingly formulating the bidding documents; the actual cost calculation must follow the actual distribution and length.

If, for any reasons, the production of a reliable geological documentation, or a reliable classification of the rock mass is not possible, the tunnel project can be planned only to a limited extent. However, the unavailability of these documents would also influence decisively the bidding process, the award of the bid, the tunneling process, and the accounting of the tunneling.

5. TUNNELING SYSTEM

5.1 TUNNELING MACHINE

The acquisition of a tunneling machine through purchase, leasing, or renting is in most cases a significant project for a contractor. Usually, a machine will be used for several tunneling projects. This fact must be considered in the decision in favor of a certain manufacturer or a certain model. A polyvalent tunneling machine suitable without compromise for loose rock as well as for solid rock will not be on the market in the foreseeable future. The requirements for a machine suitable for soft ground are much too different from those concerning the cutting of solid rock, thus making it almost impossible to combine the strictly different characteristics in the same design. However, the band width of a possible use has become wider in recent years. Deposits in the form of blocks can also be tunneled through with individual special loose-rock machines designed for tunneling with a work face which fully rests on the cutting head. Individual solid rock machines are suitable for the cutting of marl and of granite, and are equipped with special installations for measures concerning the securing and the stabiliiation of the rock mass in the machine area. From an objective point of view, no one manufacturer of the presently available solid rock machines could be called best, but some manufacturers are better suited for certain construction purposes than others.

When soliciting offers of a tunneling machine, a project description, the geological documentation, and samples of the rock types representative for the tunnel track should be submitted to the manufacturers whose products are being considered. With regard to directly comparable offers it is also recommended, to submit to the manufacturing firms the desired specifications or requirements concerning the design of the tunneling machine. For each point of this catalogue, the offer should contain a detailed suggestion of the manufacturer. In general, the questionnaires prepared by individual manufacturing firms for their clients are much too general, and the offers relating to these do not enable a potential customer to conduct a comparison of the offers, and do not supply all data necessary for his decision.

In the following, the technical specifications and the non-technical criteria to be considered for the evaluation of an offer concerning a full-face tunneling machine for solid rock are dealt with.

5.1.1 Maximum Dimension and Weights of Parts or Components

These should be determined by the contractor with regard to transportation:

- by rail,
- via roads and bridges to the construction site,
- if applicable, through a previously conventionally excavated tunnel, which may contain supply lines,
- if applicable, through a shaft inside an elevator, or as a load attached to same,
- if applicable, after terminated or suspended tunneling through the tunnel and temporarily or permanently lined tunnel which may already contain a road surface.

5.1.2 Requirements Concerning Assembly Dismantling

It must be possible to assemble or dismantle the construction parts and component groups without extraordinary efforts concerning personnel and equipment on the surface as well as in an assembly chamber underground.

The basic construction of a machine must provide a sufficient accessibility to all components that need inspection, maintenance, and frequently scheduled repairs. General repairs and replacement of all components must be possible inside the tunnel. It must be possible to exchange all parts without largely dismantling other elements in the interest of accessibility. Only in case of extraordinary repair work underground a local enlarging of the tunnel profile should be necessary.

5.1.3 Cutting Head

5.1.3.1 Minimum cutting diameter, and possibility for diameter variation - For the determination of the cutting diameter of a tunnel, the planning engineer and the contractor must consider that

- the cutting diameter may be reduced by up to approximately 3 cm. due to the wear of the guage bits, and that
- it is not easy to follow, during the tunneling, the precise direction and inclination of the tunnel.

Whereas deviations from the planned course are of no great importance for some objects, this condition must be considered for pipe conduits and traffic tunnels. The prefabricated meet liner, the lane dividers in road tunnels and, without any restrictions, the tracks in railroad tunnels must be installed according to plan, and the filling around the segmented elements and the lining of the tunnel must be installed with the prescribed thickness.

This requires an enlarging of the cutting diameter relative to the theoretical profile. A total technical leeway of 20 cm. relative to the planned radius is reasonable for a two-track railroad tunnel. The possibilities are limited to cuts with various cutting diameters by means of a tunneling machine without requiring different cutting heads.

With some models, the diameter can be increased in two or three stages by extending or relocating the buckets and the scrapers. With other models new buckets and scrapers must be installed. Enlarging the diameter also requires the installation of adapters on gripper shoes, also sometimes on the support, and on the top or on the cutting head shield. It requires the consideration of dimensioning the cutting head bearing and of the drive system.

5.1.3.2 Basic construction. - A closed cutting head, Figure 5-1 whose static construction is covered by plates carrying the inner bit holders, does not at all offer the ease in cutting a jointed work face as is often assumed.

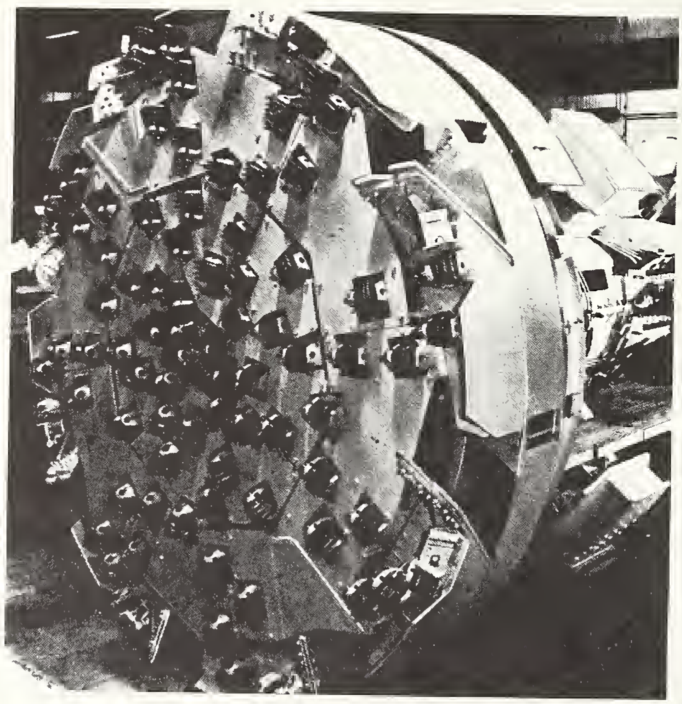


Figure 5-1. Closed cutting head

Photo: Jarva Inc.

Pieces of rock may lodge between the cutting tools or between the tools and the work face and the soffit. Covering the peripheral spaces between the gauge bits with steel bars or bent plates, Figure 5-1, and, above all, the installation of the cutting tool holders on the rear side of the head plates, Figure 5-2, reduce damage and interruptions of operation. However, a closed cutting head cannot take over the function of a face shield for

Figure 5-2. Cutting tool holder attached to the back side of a cutting head

Photo: Calweld.

mechanical tunneling where the work face is resting fully on the cutting head.

With an open cutting head, Figure 5-3, with scrapers and buckets mounted on the inside, pieces of rock of a limited size that were pulled out of the work face can fall through the spokes carrying the cutting tools into the removal system of the tunneling machine. The same openings may serve for replacing individual cutting tools from the side without forcing the personnel to step directly in front of the work face. They also offer a relatively free access to the work face, for example for the disaggregation of larger pieces of rock, or for purposes of conventional tunneling on the other side of the tunneling machine in fault zones that cannot be cut.

5.1.3.3 Cutting head shape. - This is an important characteristic of the boring systems of the individual machine manufacturers, Figures 5-4 to 5-7. A buyer will have hardly an influence on the shape.

When a new tunneling machine is delivered, the responsibility for the boring system, and therefore also for the cutting tools, and the other components of the machine must rest fully with the manufacturer. He may consider suggestions of the buyer, for example concerning certain types and makes of cutting tools. At a later point, the manufacturer may assist with the change to the cutting tools of another manufacturer, if it turns out that the delivered boring system does not meet the expectations. Such an enterprise,

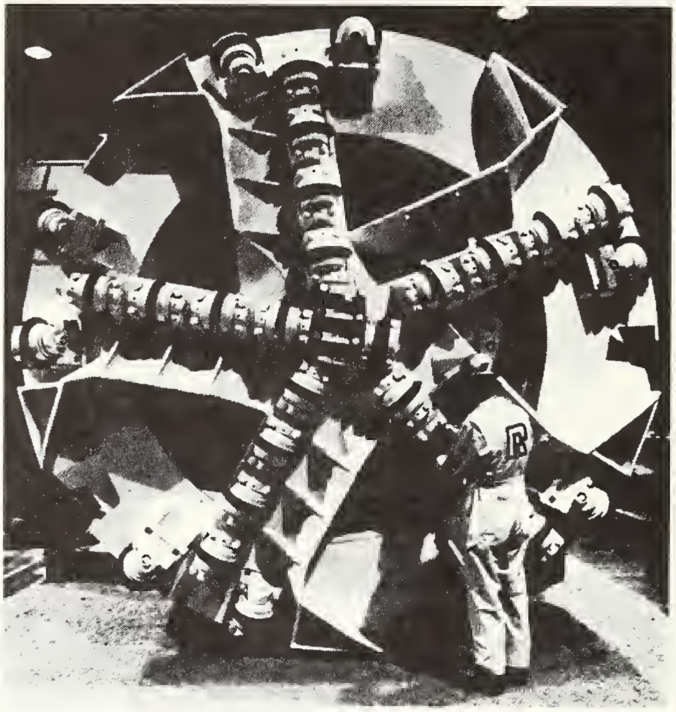
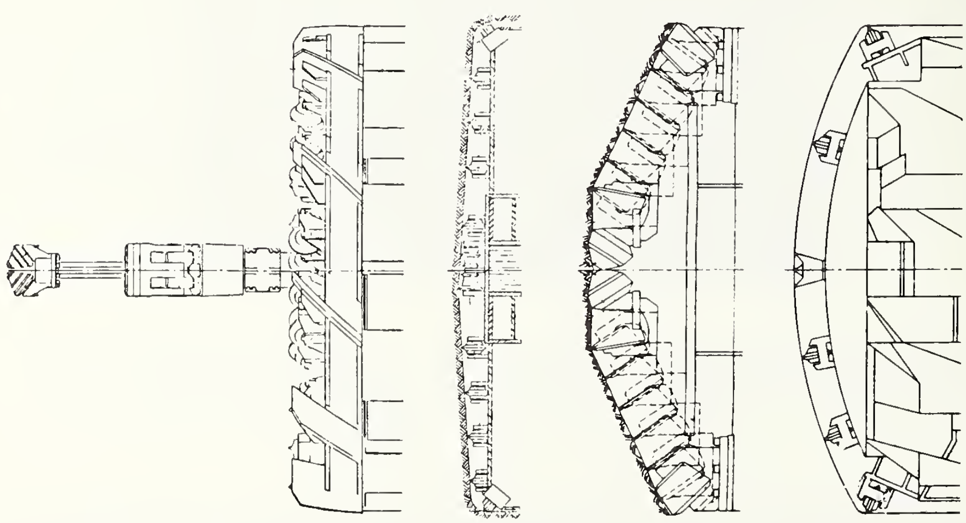


Figure 5-3. Open cutting head.

Photo: The Robbins Company.



Figures 5-4 to 5-7. Shapes of cutting heads.

Figure 5-4. Flat (Lawrence)
Figure 5-5. Slightly conical (Calweld)
Figure 5-6. Conical (Wirth)
Figure 5-7. Hemispherical (Robbins)

however, involves significant changes on the available cutting head. Usually, it requires the delivery of a new head with tuned geometry of cutting tool arrangement, cutting head shape, and of scrapers and buckets.

5.1.3.4 Cutting tools - Type and manufacturer, as well as number of the center, inner, and gauge bits, holders, cutter spacing of the inner bits, average operational bearing load (penetration force), necessity of a cutting tool cooling.

With a few exceptions, the manufacturers of tunneling machines produce the cutting tools of their machines themselves, and most of them are in a position to offer several varieties of bits. This possibility is of advantage when the tunneling machine is used in formations with differing index values of boreability and cutting tool wear. It permits the equipment of the cutting head with the most suitable type of bit provided the formations in one tunnel project are long enough, or for subsequent tunnel projects.

The installation of the cutting tool in saddle-shaped holders is preferable to that in console-type holders. These holding devices should accept all tool varieties of one manufacturer. The attachment of the holding devices on the cutting head must be appropriate for the exceptionally large stress. Pinning, in addition to bolting or welding, is of advantage. Specially useful are holding devices for gauge bits that permit a replacement of these tools without having to cut a cavity into the tunnel soffit.

When double and triple disk bits are used, the cutter spacing is determined once and for all. If single disk bits are employed, the cutter spacing may be changed. This, however requires the expensive relocation of the holding devices.

Material, construction, and production today permit the availability of cutting tools with weights that are acceptable for the tunneling practice for an average operational bearing load up to approximately 15 Mp (150 kN). Since sharp-edge disk cutting blades can be manufactured that will economically withstand a penetration force of distinctly more than 10 Mp (100 kN) during permanent operation it is not easy to understand why triple and multiple disks are still being offered, if one considers that the penetration increases at least proportionally to the penetration force. With limited space on the cutting head, the installation of single disk bits with small cutter spacing may be problematic. The use of double disk bits whose cutting rings roll on the work face on both sides of the track of a cutting edge belonging to a neighboring bit, is an acceptable compromise in this case.

The cooling of the cutting tools with water may be acceptable within limits if the rock does not swell too much. The water used for this should be sprayed in order to simultaneously bind part of the dust generated in the cutting head area. However, it must be settled completely by the cuttings. Cutting tool cooling which leads to free water and to cutting sludge which cannot be completely absorbed by the cuttings must be reduced.

5.1.3.5 Scrapers - Their arrangement and construction is of special importance for a thorough removal of the cuttings from the tunnel floor. Also, the gauge bits which are subject to increased wear anyway, would be worn additionally if they were to roll through remaining excavations. For the purpose of controlling adjusting movements of the tunneling machine, the diameter of the scraper area must always be 4 to 6 centimeters smaller than the cutting diameter, and a minimum layer of excavation on the tunnel floor is unavoidable. Their detrimental influence can be reduced by the installation of small spring loaded scrapers in front of the guage bits.

5.1.4 Cutting head carrier, cutting head bearing, bearing lubrication and sealing, dust shield, sludge pusher

The cutting head bearing is arranged between the cutting head and the support shaft of the machine frame. Depending on the manufacturer, the axial and the radial forces are carried by the same bearing, or the machine has an axial as well as a radial bearing.

The lubrication and the sealing are decisive for the useful life of the cutting head bearing.

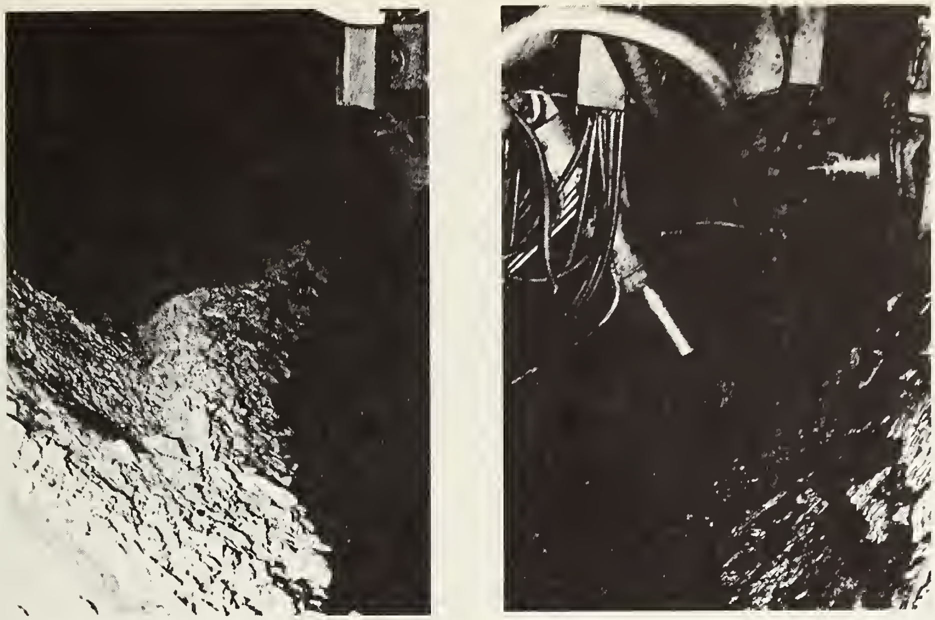
The dust shield which is equipped with rubber skirts at its periphery, must have manholes offering access to the cutting head that are easy to open. With regard to the sometimes necessary conventional tunneling in fault zones that cannot be bored, it must be easy to remove and easy to reinstall.

With tunneling machines whose cutting head carried rests on the tunnel floor on a sliding shoe, the cuttings not removed from the scrapers are continuously pushed into the range of the scrapers by the sliding shoe in the course of forward movement. On this side of the sliding shoe, the tunnel floor is practically completely clean of cuttings. Tunneling machines without sliding shoe require a so-called sludge pusher. The designs that are being offered are usually insufficient, Figures 5-8 and 5-9.

Without effective sludge pusher scraped, a special worker must frequently be for a preliminary cleaning of the tunnel floor during the tunneling.

5.1.5 Cutting head drive

5.1.5.1 Cutting head drive motors, revolution control - Electric or hydromotors, constant or variable cutting head revolutions.



Figures 5-8 and 5-9. Insufficiency of sludge (muck) scrapers

TABLE 5-1. CUTTING HEAD DRIVE MOTORS

Cutting head revolutions	Electric motor	Hydromotor
constant	3-phase ac synchronous motor	
Stepwise control	3-phase ac with mechanical gears synchronous motor 3- phase ac pole-switch synchronous motor	
variable control	dc collector motor	rotary piston radial piston axial piston gear motor

The cutting head drive employs primarily electric energy. Electric or hydraulic motors may be used as the actual cutting head drive motors. A decision for one or the other types of motor as well as for a certain type of electric motor involves also a decision regarding the control of the cutting head revolutions. The basic possibilities are given in Table 5-1.

Variable revolution control offers the following possiblities:

- starting up the cutting head with full power and low revolution and corresponding high torque,
- reduction of the cutting head revolution for slow cutting, for example in a blocky formation,
- optimum combination of revolution and feeding force with regard to a small cutting tool wear,
- adaptation of the revolutions when the tunneling machine is used for the transportation of material from rock falls, or from conventional tunneling in front of the cutting head,
- avoiding vibrations which may occur in the basic machine at a certain revolution.

The synchronous motor and the hydromotor are the types most commonly used for driving cutting heads. The following short description of some charateristics of the individual drives is not to be considered as a critical evaluation.

The electric direct drive with synchronous motors, Figure 5-10, is characterized by the relation : N ~nM, with N as power, n as motor revolution, and M as torque.

Figure 5-10. Synchronous motors mounted on the cutting head carrier

With the exception of a hardly noticeable slip between the rotary field in the stator and the rotor, the revolution "n" is constant during normal operational load. The pole-switch synchronous motors used for cutting head drive are usually designed for three revolutions: 1/2, 3/4, and full revolutions. With a large feeding force on the cutting head, or with a cutting head blocked due to geological circumstances, the motor can be overloaded with regard to its torque. The rotor can follow the rotary field of the stator only irregularly, or, under certain circumstances, not at all. At first, however, the motor current increases, and thus the torque. The motor may be overloaded within certain limits of its nominal power. The measure of this overload is not the same for all products of one manufacturer. A motor that cannot be overloaded over longer periods of time is hardly controlling itself. If, with increasing load, the rotor cannot follow the rotary field any longer, the motor would tip if an overload protection does not switch if off first. With the exception of a stuck cutting head, the motors should be started without the cutting tools and the work face in contact. It should be first switched to a star connection, and then to a triangle connection, in order to avoid current peaks. Starting under load leads to an extraordinary stress on the mechanical parts of the drive in the absence of a clutch, and may lead to a thermal overload and to switch-off.

The synchronous motor is built simply and solidly, and requires practically no maintenance. It is a high-speed motor. This drive requires a multiple reduction gear between motor and drive sprocket in the cutting head.

The hydrostatic drive requires the syncrhonous motor as pump drive, requires pumps for the hydraulic fluid, hydromotors, Figure 5-11, as well as pipes and hoses for the fluid circulation. A hydrostatic cutting head drive has a closed circulation. The following relation applies again $N \sim nM$.

The rpm "n" of a hydromotor is directly proportional to the pumped quantity of fluid Q, and has variable control. The torque M increases linearly with increasing pressure "p", i.e.:

$$N \sim pQ.$$

Under normal conditions, constant, maximally admissible, or optimal rpm's are used for cutting. Correspondingly, a constant amount of liquid circulates in the circulation system of the hydraulic system. With increasing feeding force, or with blocked cutting head, the pressure in the drive circulation increases, and the torque increases also. As long as the quantity of the circulating fluid is not changed, the cutting head rpm's remain constant. As soon as the maximally admissible pressure in the drive circulation is reached, a safety valve is activated, and a part of the circulating hydraulic fluid flows through a bypass back to the fluid container, not reaching the hydromotors. During excessive pressure increases with corresponding excess increase of the nominal torque of the tunneling machine, the circulation is short-circuited completely. In a system which is properly adjusted, the hydraulic circuit adjusts itself, and the synchronous motor driving the pump is not exposed to a thermal overload.

Under normal conditions, the drive should be started up with the cutting head slightly removed from the work face. After the electric pump drive motors are switched on, the amount of the circulating fluid is selected according to the admissible operational cutting head revolutions, and the feeding device is activated. As a consequence of that, the pressure in the circulating system increases. If the cutting head is blocked, an attempt should be made to start with revolutions that are as low as possible. If the circulating fluid quantity in the circulation system is small, a high pressure results. When the nominal torque is reached, the circulation is short-circuited.

The hydrostatic drive includes more components than the direct drive by means of synchronous motors. However, it is also very reliable. The tightness of the circultion system is no longer problematic; cases of hydromotors are known that have operated for several thousand hours without interruption. Hydromotors have relatively low rpm's. The power transfer to the cutting head can be achieved by means of a single-step gear. Hydromotor and built-in gears have small dimensions.

A cutting head drive using DC voltage is little tested in practical operation. It consists of the components collector motor and controlled rectifier. Thyristors are modern and of simple construction and do not have rotating parts for the rectification of current and voltage. They permit any desired intersection of the phases and thus also the control of current and voltage. For the DC drive, too, the relation $N \sim nM$ applies.

The DC motor is a collector motor. Current is supplied to the stator as well as - via the collector - to the rotor. The current flowing through the rotor in the stationary field of the stator in turn produces an electromagnetic force, and a torque. The detail construction of DC motors is different mainly by the mode of the current supply to the stator and to the rotor. The so-called compound motor is an intermediate design between a series-wound motor and a shunt-wound motor. By changing the supplied voltage, the motor rpm's can be changed as desired. With decreasing rpm's, the torque increases. In addition, a given torque can be produced within a certain range of rpm's again by changing the voltage.

In addition to the cooling related to the rpm's, the collector motors require an auxiliary cooling system; both requiring maintenance. The high-speed motor is sensitive to dust. A multiple reduction gear is necessary for driving the cutting head. A driving unit consisting of motor and gears requires much room.

5.1.5.2 <u>Torque, drive power</u> - The torque to be provided by the cutting head determines to a high degree the installed performance of the tunneling machine. If a constant cutter spacing $b = \frac{r}{a}$ is assumed between the center and the gauge, as well as an average rolling force F_r per disk, the torque is calculated with only one bit per cutting path as

$$M = \frac{F_r}{2} \left(\frac{r^2}{b} + r,\right)$$

and sufficiently accurate

$$M = \frac{F_{r-} \; r^2}{2_b},$$

if each cutting path is equipped with Z bits, the torque is calculated sufficiently accurate as

$$M = \frac{Z \; F_r \; r^2}{2b} .$$

For a cutting head with a separately driven center, or a cutting head with a ring-shape design, such as with an enlarging machine, the torque is - if equipped with Z x a cutting tools, and the cutting path radius r_i of the bit rolling closest to the machine axis - :

$$M = F_r \; Z \; a \left[r_i + \frac{b}{2} (a-1)\right]$$

for the installed power N in kW of the cutting head drive the following applies:

$$N = \frac{Mn}{974 \; 7T},$$

with M in kpm, "n" in 1/min, and 7T as total effectiveness of all elements of the drive; here,

$$974 = \frac{1,000 \times 60}{2 \pi \times 9.81} .$$

Table 5-2 shows the magnitude of the effect of the individual elements.

5.1.5.3 Power transmission - Cutting head drive motors installed on the cutting head carrier or on the machine frame, gears, maximum cutting head revolutions, clutches.

The arrangement of the cutting head drive motors should not take up much space in the area of the basic machine, and should not restrict at all the possibilities for the installation of the support lining immediately behind the cutting head carrier. All motors must be easily accessible, and easy to replace. The motors may be installed on the cutting head carrier, or on the machine frame which is rigidly connected with it. The installation on the side of the machine frame requires several shafts running along the frame in order to transmit the power to the cutting head or to a transmission. If the motors and the gear box are attached at the rear end of the frame, the power transmission is done by means of a shaft leading through the machine frame. Such a machine is called a shaft machine. The operations should not be interruped for long through breakdowns of one motor or of the power train, and the machine should be capable of tunneling, within limits even with a reduced number of motors.

TABLE 5-2. EFFECTIVENESS OF THE ELEMENTS OF THE CUTTING HEAD DRIVE IN PERCENT

Element	Electric ac* voltage	hydrostatic	Electric dc voltage
synchronous motor	92	92	-
rectifier	-	-	95
pump	-	90	-
hydromotor	-	90	-
collector motor	-	-	90
gear and cutting head bearing	88	90	88
Total effect	81	67	75

*if an hydraulic clutch is used, its effectiveness of approximately 97% must be considered.

With the mechanical gears which usually cannot be shifted, the rpm's of the cutting head drive motors are reduced to those of the cutting head. The maximally admissible cutting head revolutions are almost always determined by the highest admissible rolling speed of the gauge bits.

Clutches installed between the synchronous motors and the cutting head, at least in case of tunneling machines with high driving power, are useful for the starting of the cutting head motors, and hydraulic clutches are also effective for the tunneling.

Mechanical clutches are operated by means of compressed air. The motors are started with the clutches disengaged. Thus, the starting voltage can be limited. It increases first during the clutch release, and then of course, when the driving force is applied to the cutting head. In case of a stuck cutting head, the clutch release leads to a sudden transfer of the kinetic energy released by the rotating rotors to the head. The sticking may thus be overcome, under certain circumstances, however, this may also produce a breaking effect on the rotating masses. With the clutch release, the current consumption of the motors increases immediately; if the cutting head cannot be freed, the motors are protected from overload by switching-off. This method requires extremely strong gears.

Hydraulic clutches connect the drive motors elastically with the cutting head. They are an overload protection during the starting of the motors, and during cutting. A hydraulic clutch receives increasing flow-through during the start of its motor. The maximum torque is only reached with the full flow through the clutch. Momentary forces and acceleration affecting the head during the tunneling process are compensated by the clutch. The drive motors cannot be overloaded as fast, and occurring shocks are dampened. During the start-up of the motors with blocked cutting head, a hydraulic clutch may be disadvantageous due to its compensating effect.

5.1.6 Gripping, Propulsion, Rolling Compensation, Travel Length, Supports

System and arrangement of the machine gripping and of the advance system, possibilities for the compensation of the rolling, travel length, support of the machine during relocation of the gripping system are discussed.

The advance joints which are also connected through articulated joints with the cutting head carrier are supported by the gripping system which remains stationary during the tunneling. These joints transmit the hydraulically produced advancing force onto the cutting head carrier and the cutting head. After one travel length has been tunneled, and the machine frame supported, the reversibly activated advancing joints also advance the gripping system. They also serve for pulling back the tunneling machine from the work face.

The unimpaired gripping of the tunneling machine which continues during the tunneling process is a fundamental condition for the tunneling of hard rock, and necessary to prohibit rolling of the machine. Insufficient gripping leads to a flutter of the cutting head, and thus to a reduction of the penetration, and an increase of the cutting tool wear. In Figures 1-3 to 1-5, three of the most commonly used systems of machine gripping are represented.

-Figure 1-3: gripping is done by means of plates behind the cutting head against the tunnel walls, and by means of an expanding anchor which leads the shaft of the pilot drill, in front of the cutting head in the pilot's drill hole. This system is characteristic for the Lawrence tunneling machine.

-Figure 1-4: two bracing plates behind the cutting head pressed against the tunnel walls serve for the bracing. The head is not gripped but supported on the tunnel floor by means of a sliding shoe, and is guided during the tunneling process through plates arranged at the sides, as well as through a top shield, all of which can be moved radially, and are pressed slightly against the tunnel walls during the cutting process. This system is used for the tunneling machines of the manufacturers Dresser and Robbins.

-Figure 1-5: the machine frame consists of two parts. The interior frame is connected rigidly to the cutting head carrier, and moves forward axially during the cutting process. The outer frame encloses and guides the inner one. In front and in the rear it carries two or four bracing plates each of which is pressed against the tunnel soffit during the tunneling process. This system is used by the firms Calweld, Demag, Jarva, and Wirth.

With tunneling machines intended for use in less solid formations, gripping is sometimes achieved by means of a push ring that can be pressed against the tunnel wall, or by gripping against the already installed lining.

The bracing plates must be attached to the hydraulic cylinders via articulated joints so they are also in full contact with the rock mass in zones with irregular surface. The pressure which must be transferred from the plates to the rock mass, and with it the quality of the bracing depends, with a given plate surface, on the sliding plane friction angle and on the sliding plane shearing strength of the rock mass forming the tunnel soffit. Depending on the size of the plate surface which is variable only within certain limits with respect to the power-flow in the joints, and on the strength and deformation properties of the rock mass, a fracture zone may form under the plates. Also, the unstressed rock all around the plate may become plastically deformed and may be sheared out of the tunnel soffit [20].

The gripping cylinders are arranged either horizontally, with one pair of plates (Figures 1-3 and 1-4), or diagonally, with two pairs of plates (Figure 1-5). With a basic machine without supporting sliding shoe that is very top heavy, diagonal bracing plates reduce the possibility of the cutting head sagging. in relatively deformable rock.

Bracing which is even slightly impaired may also lead to rolling of the machine, i.e. the basic machine turns around its axis under the influence of the reaction forces in the opposite direction of the cutting head. For this reason, the machine should be equipped with a device for straightening it up again. Theoretically, the possibility exists to let the cutting head turn in the opposite direction periodically. This possibility could be used with electric as well as with hydraulic drive systems as long as the cutting head is equipped with a system of scrapers and buckets that is adapted to this mode of operation.

After one travel length has been cut, the advance of the tunneling must be interrupted, and the bracing system must be relocated. The time of the interruption necessary for this relocation is different for the individual manufacturers of machines, but remains within the magnitude of minutes in any case. With regard to a satisfactory exploitation of the tunneling machine, a long travel length would be desirable. However, this is opposed for structural reasons, by the requirement of a complete and uniform gripping of the machine during the tunneling, and by considerations relating to the installation of a steel lining behind the cutting head. The practical travel length limited by a limiter switch should correspond to the distance of the lining rings, Figures 5-12 and 5-13. The maximum stroke should be larger by about 5 cm.

The basic machine must be supported on the tunnel floor when it is not braced. This requires a support in front and in the rear. With machines equipped with a sliding shoe the front support is provided by this. If, beside the rear one, a machine is also equipped with hydraulically operated supports in front, their arrangement between cutting head carrier and gripping system should not impair the installation of an anchor and steel ring support lining, or of liner plates, even immediately at the beginning of a cutting phase.

For top heavy basic machines without sliding shoe, the contact surface of the front supports must have large enough dimensions.

A front support by means of columns may help with the freeing of blocked cutting heads.

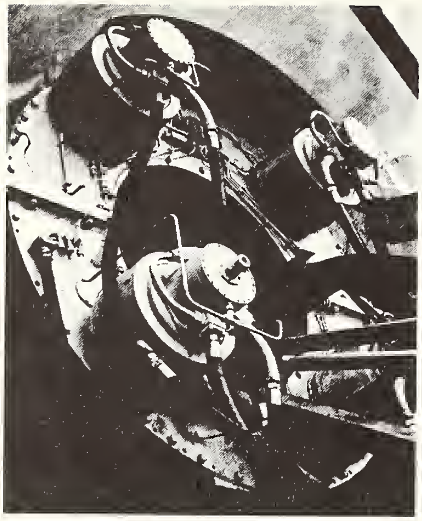


Figure 5-11. Hydromotors mounted on the cutting head carrier of an enlargement machine

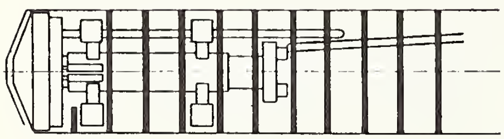


Figure 5-12. Position at the beginning of one stroke

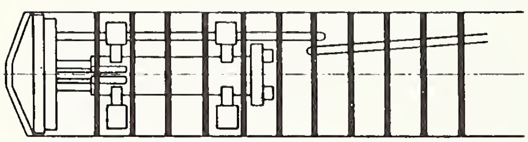


Figure 5-13. Position at the end of one stroke

Figures 5-12 and 5-13. Interrelation between stroke length, between spacing of front and rear gripper plates, and support ring spacing

5.1.7 Aligning, Steering

There is the possibility to align the basic machine only when not in operation, or the possibility to steer during the tunneling, system, pivoting point.

At the beginning of each tunneling phase, the basic machine must be aligned according to the planned course. The requirement that it should also be steerable during the tunneling might be based on the necessity for the cutting of curves, or for the correction of a deviation from the planned course that has occurred during one tunneling phase. A course deviation may indeed occur in distinctly inhomogeneous rock due to differing stress distribution on the cutting head, or through impaired braceability of the machine. The advantages of the steerability of the machine must be compared to its effect on the machine.

The tunneling machine can be aligned on a new tunneling course by means of horizontal and vertical adjustments relative to the axis of the cut tunnel of the machine frame that is rigidly connected with the cutting head carrier, or only of the cutting head carrier as with the Dresser tunneling machine. These movements are carried out by means of hydraulic joints, by means of the support columns for adjustment in non-braced condition, in braced condition by uneven pressuring of the gripping cylinders, for steering during the cutting by means of steering cylinders. These movements cause a small tilting of the cutting head, as a consequence of this, squeezing may occur in the gauge zone, and, if the head is in contact with the work face, over the whole cutting head depending on the geometric shape of the head, and on the position of the pivot point in relation to the head. The cutting edges and the bearings of the cutting tools, in particular those of the gauge bits, and also the cutting head bearing are thus exposed to increase wear, which may be extraordinary under certain circumstances. Alignment of the tunneling machine should therefore only be conducted when the cutting head is not in contact with the work face. In order to limit the tilting of the cutting head during alignment or steering, a pressure limiter should be installed in the respective hydraulic circuit.

The curves of a tunnel should be planned with a radius that is as large as possible, and they may be cut in form of polygons with sides that correspond to one travel length.

The actual position of the basic machine in relation to the planned position can be determined by means of a photo-electric measuring device, and the result may be fed into the control center of the machine operator. Necessary corrective movements are usually executed manually. Automatic steering is possible. However, its reliability is still problematic, and there is no great necessity for it.

5.1.8 Electrical Equipment

The electrical equipment of a tunneling machine must comply with the local regulations, and must also meet the requirements and standards determined by the project.

The buyer makes a decision concerning:

a) voltage of the tunnel supply, and

b) connected power of special consumers, as for example,

- sludge pump behind the cutting head carrier,
- ventilators in the machine area,
- air condition,
- dust collection system,
- bridging and trail conveyor belt,
- traveling winches,
- lighting,
- laser equipment, and
- reserves.

The manufacturer determines the power to be installed for

a) cutting head drive, inclusive of its nominal voltage,
b) electric motors of the hydraulic pumps for all circuits,
c) basic machine and trailer conveyor belts,
d) lining, and transportation installation.

The following is determined in cooperation by buyer and manufacturer

a) installed power of the main transformer on the machine, as well as transformer type and number (secondary nominal voltage corresponds to that of the electric motors of the cutting head drive). The main transformer must have a circuit in case a large voltage loss occurs in the cables of the primary supply in longer tunnels;

b) transformation for the control circuits, if necessary a separate one for the lighting;

c) controls for the high voltage supply and for the low voltage networks;

d) protective installations in addition to the official regulations;

e) lock settings, for example with regard to the starting of the motors: bracing, cutting head lubrication, starting of the cutting head drive, water supply for the cutting head;

f) the secondary distributions based on the main distribution (with their consumers).

Usually, water-protected electrical equipment is used. Explosion protection must meet the regulations connected with the project.

5.1.9 Hydraulic System

Users of hydraulic energy, main circuit, secondary circuits, hydraulic fluid, and power are discussed.

Hydraulic energy is needed for the following functions of a tunneling machine:

- gripping of the base machine,
- advancing of the cutting head, and pulling of the trailers, if necessary, also of the bridging and loading belt, simultaneously with, or after a travel length, and also holding of all not directly braced machine parts during the cutting of inclined tunnels,
- alignment, if necessary, steering,
- supporting,
- depending on the manufacturer of the tunneling machine, also for the driving of the complete cutting head, the center bit, or the pilot bit, the lubrication of elements of the power transmission, the operation of lateral guide plates and of the top shield of the cutting head, if necessary, also for supporting or lining equipment, for the cutting head shield, and for a segmented telescopic shield.

Gripping and advancing require relatively high pressures, approximately 150 to 250 kg/cm^2 (approximately 150 to 250 bar), and small amounts of hydraulic fluid. During normal cutting operation, the hydromotors of a hydraulic cutting head drive swallow large flow-through quantities at pressures between 100 and 150 kg/cm^2 (approximately 100 to 150 bar). With increasing torque, the pressure rises by approximately 50%, and the flow-through volume decreases. Other users, sometimes supplied with pressures below 100 kg/cm^2 (100 bar). Some models have separate main circuits with respective pumps for high pressure and for low pressure operation. The circuits are connected with these main circuits, or with a single pump circuit. They consist of, for example:

- operating valve, pressure reduction valve, tubing, push cylinders for the advance,

- operating valve, pressure control, tubing, gripping cylinders for the gripping,

- pump, check valve, distributor to hydromotors and/or hydraulic fluid container, pressure relief valve, tubing, hydromotors.

In most cases, mineral oil is used as hydraulic fluid. For special application, for example in coal mining, the use of a non-flammable hydraulic fluid such as Pydraul is required. The use of Pydraul requires a specially designed hydraulic system.

This fluid
- is corrosive, especially for gaskets,
- has less lubrication capacity than mineral oil,
- heats up more than mineral oil,
- is malodorous, and also environmentally detrimental in other aspects.

Pyrogard has fewer disadvantages, but still does not have the properties of mineral oil.

The tubing, in particular the hoses, must be protected against rock fall through their installation under the protective cover of less sensitive machine parts, or by means of sheet metal shields.

5.1.10 Water Distribution

The machine manufacturer determines the water supply for

a) cutting tool cooling,
b) cooling of the cutting head drive motors,
c) cooling of the hydraulic fluid, and
d) removal of the cuttings from the pilot drill hole.

The buyer determines the water requirements for

a) spraying the cutting zone in order to bind part of the dust generated by the cutting process,
b) dust collecting system,
c) cleaning purposes, and
d) if necessary, anchor drilling machines.

In the interest of a reduced need for water, and of a limitation of the amount of water which would have to be pumped or otherwise removed from the tunnel floor, this water should be used several times if possible. Thus, the water used for the cooling of the hydraulic fluid may be used, under the condition that it is not too hot, subsequently for the cooling of the cutting tools and for the spraying of the cutting area. In any case, an electric locking device must be included for the cutting head drive, the water supply for the cutting head, and also for the sludge removal of the dust collection system. Supply and overflow will be put in operation only with the starting of the cutting head drive, and will be switched off together with it.

5.1.11 Compressed Air Distribution

The buyer determines the compressed air need for:

a) cleaning purposes,
b) anchor hole drills, and
c) if necessary, compressed air motors for various devices.

The operation of the Lawrence tunneling machine requires a mixture of water and compressed air for the removal of the cuttings from the pilot drill holes. The operation of a compressed air clutch in the cutting head drive, if present, also requires compressed air.

5.1.12 Excavations Removal

Position in relation to the machine, type and nature of the drive of the basic machine and of the trailer conveyor belt, conveyor belt transfer point.

The cuttings that are picked up by scrapers and shovels, or by falling into the collecting pockets of an open cutting head through a feeding hopper in the cutting head carrier, or by falling directly onto the basic machine conveyor belt.

Depending on the manufacturer of the tunneling machine, this may be located

-above the basic machine, for example Jarva, Wirth,
-inside the machine frame, for example Dresser, Robbins, or
-below the basic machine, for example Demag.

If the conveyor belt is located above the machine frame, the machine can be protected by means of a sheet metal shield against dirt. With smaller cutting diameters, this location of the conveyor belt impedes the access to the cutting head. The cleaning of the machine frame interior, and certain maintenance and repair work require the time-consuming dismantling of a conveyor belt which goes through the machine frame. In the case of the occurrence of water pockets in the rock mass, the cuttings may be flushed off the conveyor belt if this is located below the machine. This arrangement also requires a greater length on the machine because the low machine belt must be led up to the bridging and loading belts which are located high up. A mixture of cuttings and water cannot be elevated at all, even if a scraper-conveyor is employed. Rubber belts, if necessary cleated on both sides, or chain conveyors are used. With abrasive cuttings, the chain conveyors are subject to increased wear.

The drive rollers may be driven by means of electric or hydraulic motors. The surface of those for rubber conveyor belts should be specially treated in order to avoid slipping with wet cuttings. Width and speed of the conveyor belts must be dimensioned so that the cuttings produced during maximum net boring speed can be removed without overflowing of the belts.

Self-adjusting scrapers should clean the belts on both sides.

The belt transfer point should have a small height. In case of significant dust development, it should be encased.

5.1.13 Support-Install and Transportation Equipment

Only a tunneling machine equipped with supporting aids, if necessary with a cutting head shield and a segmented shield, meets the requirement for tunnel cutting which is infrequently interrupted by the rock mass behavior.

Anchor drills mounted on machine parts stationary during the tunnel process as well as installations for the insertion of steel rings are elementary aids for the installation of temporary support lining between the cutting head carrier and the foremost gripper plates.

Usually a steel ring can be installed faster with simple installation gear that eliminates more heavy work but not all manual work than with a fully mechanized but sensitive lining installation device.

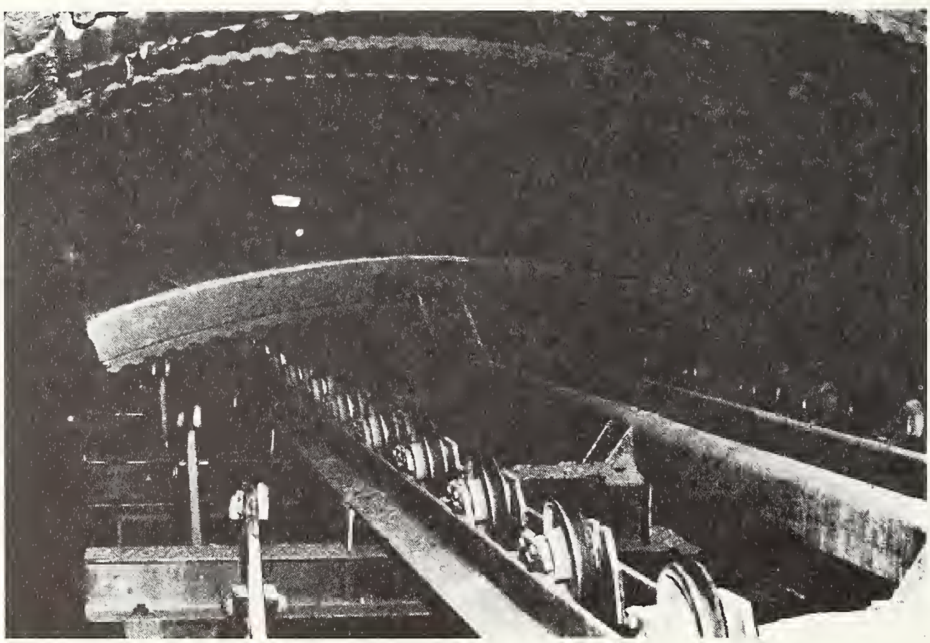


Figure 5-14. Transport System for Segmented (Prefabricated) Liner Elements

The installation devices as well as the transportation equipment for the lining material through the whole machine area (Figure 5-14) should be designed cooperatively by manufacturer and user.

5.1.14 Test Drilling Equipment

A jackhammer drill for the drilling of even relatively long test holes should be mountable on the basic machine. These test holes should not be drilled into the work face but should be started in the transition zone between the work face and the tunnel walls and should follow a course diverging from the tunnel axis. This arrangement prevents the impediment of subsequent tunneling through broken off and stuck drills.

5.1.15 Protection of Structural Parts Against Abrasive Cuttings

Those parts of the structure coming in direct contact with abrasive cuttings, or sliding on the tunnel soffit, such as cutting tool holders, scrapers, shovels, the feeding hopper for the basic machine conveyor belt, and even the sliding shoe, the lateral guide plates and the top shield of the cutting head, or a cutting head shield, must be armored with hard metal, or must be made of special wear-resistant material. Bolted connections are unsuitable in the cutting head area. The bolt heads may not only be torn off, they might also be eroded.

5.1.16 Trailers

Number, movement on sliding or rolling carriage, movement during the tunneling or during the advancing process.

If the space on the basic machine is insufficient, parts of the electrical equipment, such as machine cables, transformers, distribution boxes, parts of the hydraulic systems such as electric motors, pumps, fluid containers, and possibly even the driver stand and the dust collecting system are arranged on trailers. Usually, they are distributed over several trailers, especially with smaller cutting diameters. This facilitates the transportation, the assembly, and the dismantling as well as the curve negotiating characteristic of the machine, but also necessitates considerable length of the structure.

These trailers may be equipped either with skids and may be pulled over the tunnel floor, or they may be equipped with wheels so that they can roll directly on the floor, or on tracks. Rolling on tracks is usually preferable to direct rolling on the floor because of the great weight of the trailers. However, it requires the installation of tracks between the basic machine and the first trailer, and also the installation of a bridging belt between these as well as an extension of the tunneling machine, Figure 5-15. On the other hand, this system is more reliable than a carriage rolling directly on the tunnel floor, Figure 5-16. In spite of steerable bogies, the stabilization of the trailer is not easy, and the negotiation of the floor segments of a steel support requires the installation of some kind of rolling surface, such as boards or U-rails.

No matter how the trailers are moved, it must be considered that the pulling of the trailers during the tunneling consumes a considerable portion of the driving force of the machine. With the exception of movement on rails, the necessary pulling force does not simply correspond to the product of trailer weight and friction coefficient. Rather, it is influenced by other forces that are generated during the movement of the trailers due to a lack of steering. Generally, the trailers and the loading belt which is hitched to them should remain stationary during the tunneling, and should only be pulled up during the relocation of the gripping system of the basic machine. This makes it necessary that the connection between that part of the basic machine which remains in place during the tunneling and the first trailer is established by means of hydraulic cylinders.

5.1.17 Non-technical Criteria for the Evaluation of an Offer

5.1.17.1 Delivery Date - The term of delivery for a new tunneling machine amounts to 8 to 12 months. If the delivery requires new designs, if components other than those offered by the manufacturer are to be used, or if the buyer wants numerous special options, the term of delivery will be longer.

5.1.17.2 Factory Costs - In order to determine the factory cost of a tunneling machine, the following must be considered: price at the production plant, possible changes of this price through fluctuations of labor and material costs, or changes of the foreign exchange rates,financing costs largely depending on the purchase terms, costs of letters of credit and delivery guarantees, transportation and transportation insurance, custom duties and other expenses.

5.1.17.3 Guarantees - In his offer, the machine manufacturer must describe expressly the characteristic of his delivery which he is prepared to guarantee. The interest of the buyer does not concentrate primarily on the electric power installed in the tunneling machine, the available torque, or the generated driving force. Rather, he should ask the manufacturer for binding guarantees concerning:

- performance, i.e. guaranteed net boring speed for rock corresponding to the submitted samples, length of the test stretch, or the testing time for the proof of the guaranteed net boring speed, consequences for the machine manufacturer in case the guaranteed net boring speeds are not reached,

- technical availability within twenty-four hours, checking process, consequences in case the guaranteed values are not reached,

- cutting tool costs, guaranteed costs or splitting of the risk, possibly a suggestion for a so-called cutting tool contract which requires the manufacturer to provide the maintenance and the replacement of the cutting tools during the whole tunneling project, or parts thereof, and requires the buyer to pay a fixed price per meter or cubic meter of cut tunnel,

- material and production quality, boring length or number of operating hours of operation during which the manufacturer replaces defective parts at his cost, consequences for the manufacturer from the occurrence of secondary damage resulting from damage of the machine.

5.1.17.4 Spare Parts - The offer should contain a list of those parts, with prices, which, according to experience, must be replaced relatively frequently, and which should therefore be stored in sufficient numbers at the construction site.

Also, agreement should be suggested concerning the supply of parts whose replacement usually is necessary only infrequently, such as the cutting head bearing, but which should be available from the parts department of the manufacturer or his representative at short notice in order to avoid prolonged down-time of the tunneling.

5.1.17.5 Service - Reliable service, provided by the manufacturer directly, or by a representative who is not only a sales representative but also familiar with the problems of mechanical tunneling, is not only desireable but necessary.

5.1.18 Summary of Offer Evaluation

A comparative calculation relating to the specific tunneling project under consideration offers good technical and economical information necessary for a decision by a contractor who is faced with a choice of a tunneling machine. It should include at least:

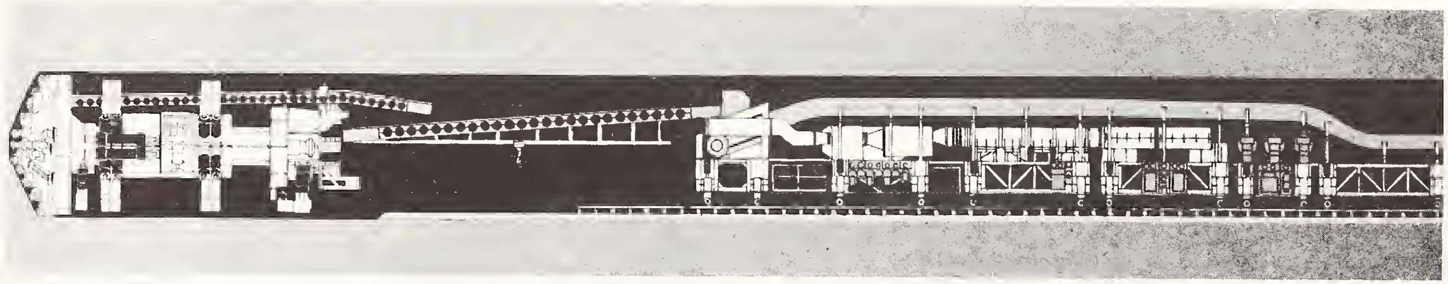


Figure 5-15. Trailers on Tracks Installed Behind the Basic Machine (Wirth)

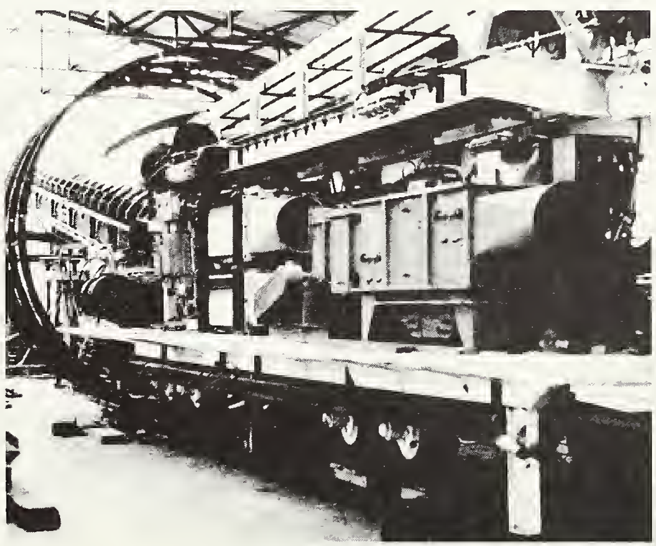


Figure 5-16. Trailers Rolling on Tires

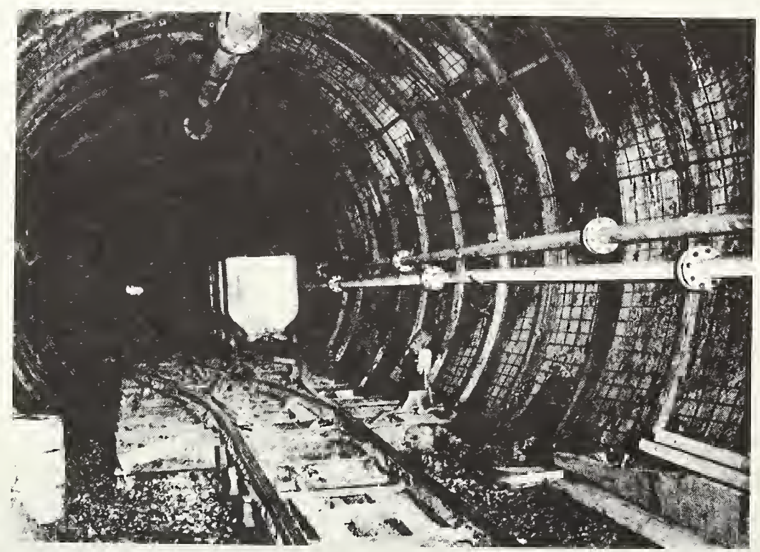


Figure 5-17. Mobile Train Switching System

- the actual cost of the tunneling machine, as a function of the factory cost, the net boring speed, and the extent of its use,

- the labor cost for the personnel employed for the tunneling, dependent on the necessary number of personnel, the net boring speed, and the extent of its use,

- the costs for the cutting tools and the frequently required spare parts, and

- the estimated costs of the overhaul after the termination of the project.

Such a comparative calculation which, in any case, should be conducted for a machine prototype with rational alternatives concerning net boring speed, cutting tool costs, utilization factor, and possibility for the installation of the lining, may possibly lead to the discovery that the purchase of a significantly more expensive machine may permit the submission of a lower bid than would be possible with the use of a less expensive machine.

5.2 AUXILIARY INSTALLATIONS

The system, the construction, the aquisition, and the operation of the installations following the tunneling machine must be given as much attention as the machine itself. Here, the contractor also usually makes the decisions. In certain cases, as for example in mining, his project owner may supply already existing transportation systems, supply lines, or ventilation installations.

5.2.1 Removal of the Borings

Table 5-3 gives an impression of the magnitude of the weight and of the volume of the cuttings produced by mechanical tunneling (assuming a swell factor of 1.8). It is well possible, that these weights and volumes will be produced uninterruptedly for hours, except for short interruptions during the relocation of the gripping system device of the tunneling machine.

The remark "waiting for removal" can be found in numerous shift reports from construction sites. Its frequent repetition gives evidence of the fact that the removal system is inadequate for the requirements of mechanical tunneling. Usually, the continuous production of cuttings meets with a removal system which operates continuously only with restrictions (Table 5-4).

TABLE 5-3. MUCK-MASS IN t/h, AND VOLUME IN m^3/h WITH DIFFERENT CUTTING DIAMETERS AND NET BORING SPEEDS

Tunnel diameter	Net boring speed					
	1.0 m/h		2.0 m/h		4.0 m/h	
	mass	volume	mass	volume	mass	volume
3.0 m	19	13	38	26	76	52
5.0 m	52	35	104	70	208	140
10.0 m	210	140	420	280	-	-

TABLE 5-4. FUNCTION OF THE MOST COMMONLY USED MUCK REMOVAL SYSTEMS

Continuous -	Partially continuous	Not continuous
conveyor belt pneumatic transportation hydraulic transportation -	vehicles with bunkering transfer within machine area	vehicles with transfer distinctly behind the machine -

Removal by truck can only be considered during the tunneling of large profiles. The removal by vehicle usually involves the use of rails.

5.2.1.1 Conveyor Belt Operation - This is the removal system best suited for mechanical tunneling. It requires the following installations:

- transfer between trailer belt and conveyor belt that can be extended,

- a conveyor belt that can be extended during the tunneling, immediately behind the tunneling machine and pulled by it, and

- stationary conveyor belt that can be extended in stages.

The conveyor belt can be installed alongside the soffit or in the crown of the tunnel. This method has been proven, provided suitable belts are used, and there are no problems with the transfer points which will possibly have to be encased. It is especially well suited for the cutting of large profiles. The requirement of an additional transportation system for supply, and the limited available space with smaller cutting profiles restrict its application.

5.2.1.2 Pneumatic Removal - The removal is done by means of a spray, and requires:

- an air generator, usually producing large volumes at low pressure,

- possibly a crusher if the cuttings are too large, as, for example when disk bits are used,

- feeding installation between conveyor belt and removal pipe,

- removal pipe,

- installation of output with dust collecting system, and

- also an air supply line in case the air generators cannot be installed next to the feeding installation.

The air supply and the removal pipe may be installed alongside the soffit of the tunnel. The supply requires an additional transportation system. This process has been little used during tunneling, and further development is necessary. Its special problems are [36]:

-large installed power of the air generators, for example around 400kW for maximum operational pressure

	1.0 kp/cm^2 (appr. 1 bar)
air quantity	160 m^3/min,
cuttings quantity	1.5 t/min,
transportation distance horizontal	300 m,
transportation distance vertical	75 m,
removal pipe diameter	254 mm;

-resistance of the removal pipe, in particular its bent parts, against abrasive cuttings;

-noise generation in the zone of the air generators, transfer and output installations;

-dust development at the transfer and output installation points;

-accidents in case of breakage of the removal line.

5.2.1.3 <u>Hydraulic Removal</u> -A suspension consisting of cuttings and water is removed. This process requires:

-solid removal pumps,

-possibly crushers,

-feeding installation between conveyor belt and removal pipe,

-removal pipe,

-water supply pipe,

-output installation with sift system and sedimentation basin.

The water supply and removal pipes can be installed alongside the soffit of the tunnel. This process also requires an additional transportation system for the supply. It has been used occasionally during tunneling, primarily for the removal of loose rock. It needs further development. From the description of one application for the removal of solid rock [37] the following can be seen:

installed power of removal pumps	1260 kW,
quantity water	6 m^3/min,
quantity solid rock	5 t/min,
transportation distance horizontally	20 m,
transportation distance vertically	130 m,
removal line diameter	224 mm.

5.2.1.4 Operation by Rail - As a rule, it is desirable to remove the cuttings of one stroke with one train, and to exchange the full train for an empty one during the relocation of the gripping system of the tunneling machine. Even so, interruptions of the tunneling can only be avoided if:

- the empty train is either positioned in a waiting zone possibly close behind the tunneling machine, provided the two trains can pass each other; a mobile train passing installation consisting of two symmetrical switches with two parallel track systems in between are usually used for this purpose, Figure 5-17; this system is usually advanced periodically during the maintenance shift for the tunneling machine,

- or if, after the relocation, tunneling can be resumed without the necessity to wait for the empty train; this requires a bunker, frequently bunker vehicles with chain conveyors built into the bottoms are used as actual bunkers as in a shuttle car train composition.

The loading of trains consisting of dump cars requires, apart from the vertical car change, a loading conveyor belt, Figures 5-18 to 5-20, of the approximate length of a train. A loading belt in form of a cleated rubber belt or scraper can be designed with curve negotiation characteristics. By means of deflecting flaps at the transfer point, or by special design of the facing walls of the cars, the dumping of cuttings between the car bodies can be avoided.

A short loading belt, Figure 5-20, is sufficient for the loading of a bunker car or bunker train. The filling capacity of cars with conveyor bottoms depends on the granulometry and on the water content of the cuttings. Fine-grain plastic cuttings can form a bridge between the walls of the cars through the opening of which only little material can be transported.

Between the trailer conveyor belt and the loading conveyor belt a bridging conveyor belt is installed unless the trailers also move on rails. The rails are installed underneath these belts, possibly also floor segments, Figures 5-22 and 5-23.

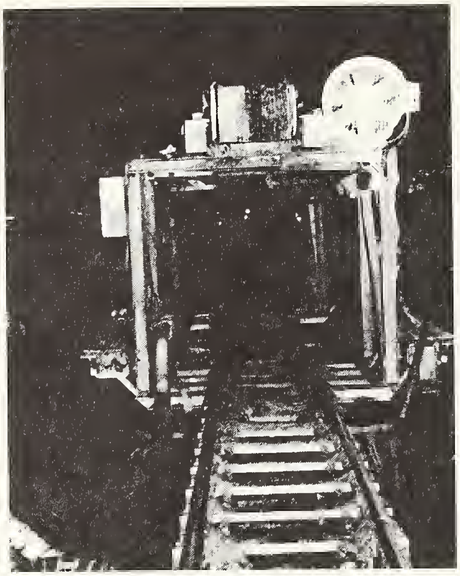


Figure 5-18. Loading (Conveyor) Belt
Track Mounted

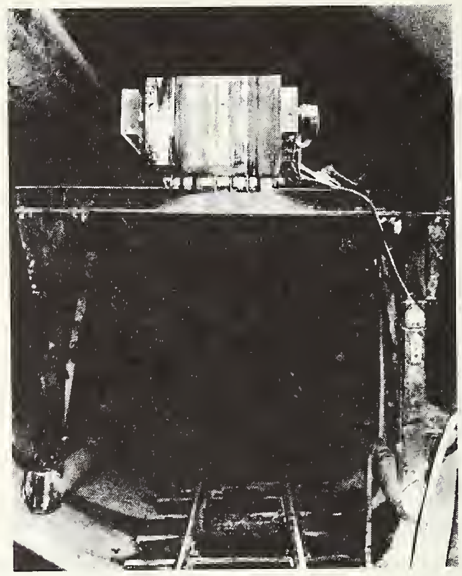


Figure 5-19. Loading (Conveyor) Belt
Skids Mounted

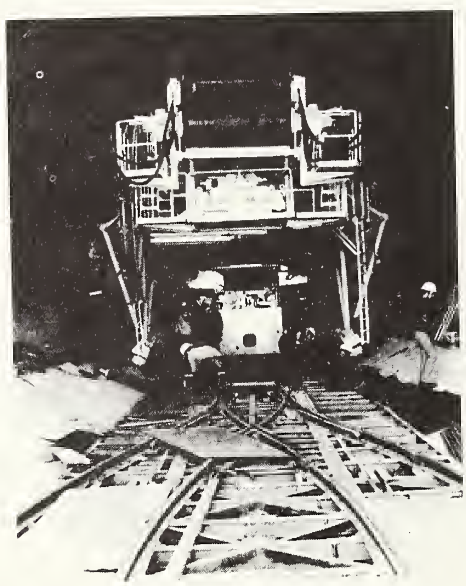


Figure 5-20. Loading Conveyor Belt
Tires Mounted

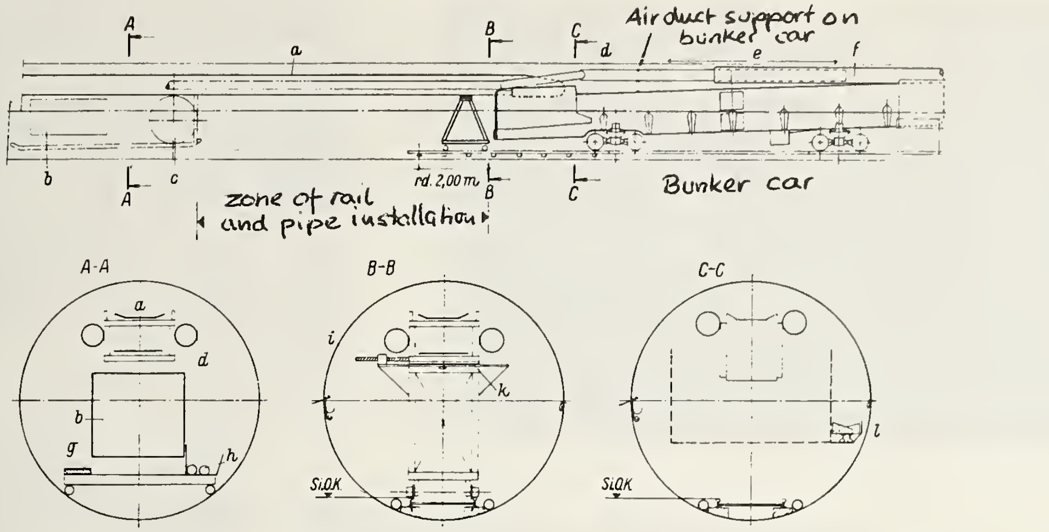


Figure 5-21. Transfer and Loading Belt with Use of Bunker Car

a conveyor belt
b converter
c spool for high voltage cable
d machine air duct
e air duct telescope
f tunnel air duct
g catwalks
h storage for pipes and rails
i spindle for negotiating curves
j sliding plate with slot
k trough for rail transport

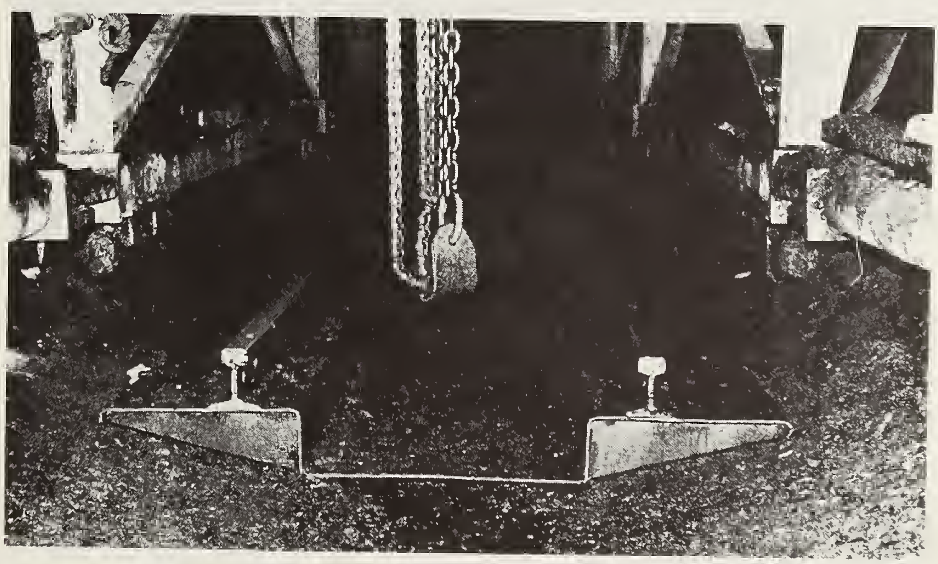


Figure 5-22. Tracks Consisting of a Steel Box Serving as Tunnel Drainage Trench with Welded-On Rails

under the condition that those are not part of a temporary lining, and are installed already in the machine area. The loading belt is not pulled along during the tunneling like the trailers of the tunneling machine but it is pulled up during the relocation of the bracing system. A pulling rod connection between the rear-most trailer and the loading belt is better than the use of steel wires or chains causing jerky movements.

5.2.2 Supply of the Machine Area

5.2.2.1 Transportation of Personnel and Material - This is usually done by rail.

5.2.2.2 Supply Lines and Installations - The machine area is supplied:

- with electric energy via a high voltage cable, in form of a permanently installed cable up to a maximal distance of approximately 300 meters to the machine, and from there by means of a special cable which rolls off a cable roll installed on a trailer during the tunneling process, Figure 5-24, or is pulled off a loop storage, Figure 5-25. The permanently installed cable is advanced in intervals of 300 meters, and the special cable is rolled up again.

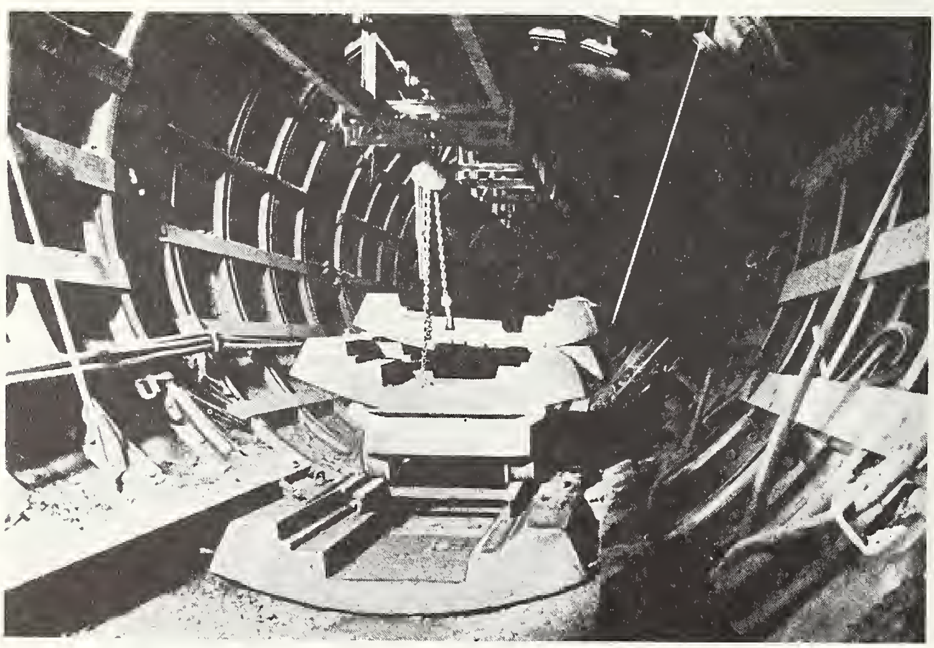


Figure 5-23. Prefabricated Concrete Tunnel Invert Segments; Rear End of Machine with Protective Cage

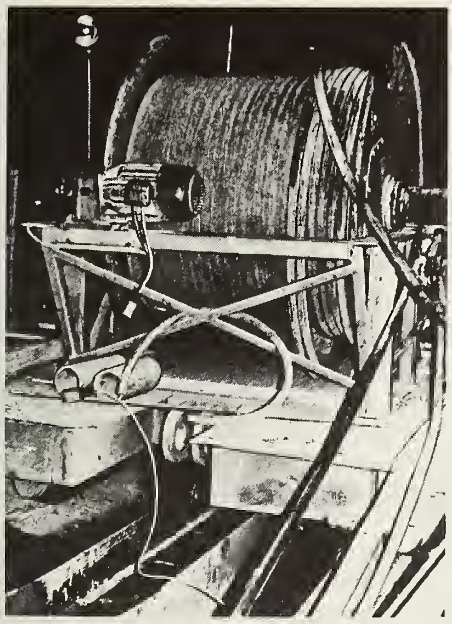


Figure 5-25. Loop Storage of Machine Cable

Figure 5-24. Spool with Machine Cable

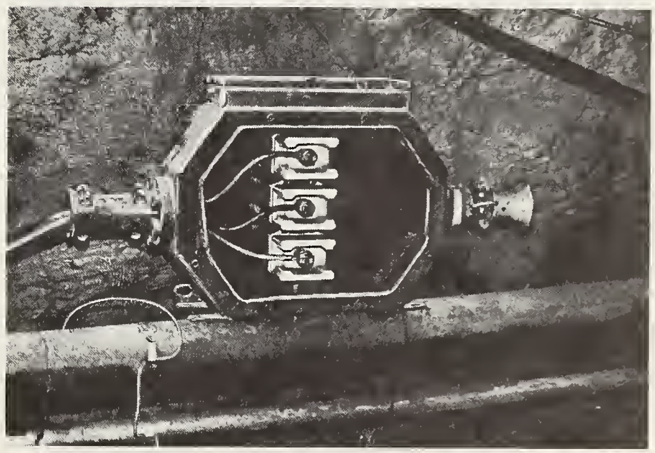


Figure 5-26. High-Voltage Junction Box

The cables are connected with each other in a high voltage junction box, Figure 5-26. High voltage transformers are connected to the permanently installed cable in intervals of one to two kilometers. The ventilators and lighting equipment, possibly also locally employed laser devices, are supplied by the low voltage currents taken out at these points. The machine area is supplied further

- with water, for the distribution of operating water, and in special cases also for the cooling water recirculation of heat exchangers, through one pipeline each with hose connection,

- with compressed air also through a pipeline with hose connection,

-with fresh air either through the cut tunnel, i.e. suction ventilation with regard to the machine area, or through an air duct, i.e. blow ventilation; likewise, the used air returns to the tunnel entrance either through an air duct, or through the bored tunnel.

The connecting hoses are the mobile connections between the permanently installed water, compressed air line, and the corresponding distributions on the tunneling machine. In general, they are at least twice as long as the individual pipes. After several strokes have been cut, with a total length of at least one pipe, the pipelines are advanced, too. At the same time, the rails and the air duct can also be installed, provided they are of the same length, Figure 5-27. Air duct telescopes, Figure 5-28, are installations for the flexible connection of the air ducts and of those parts of the ventilation system located in the machine area.

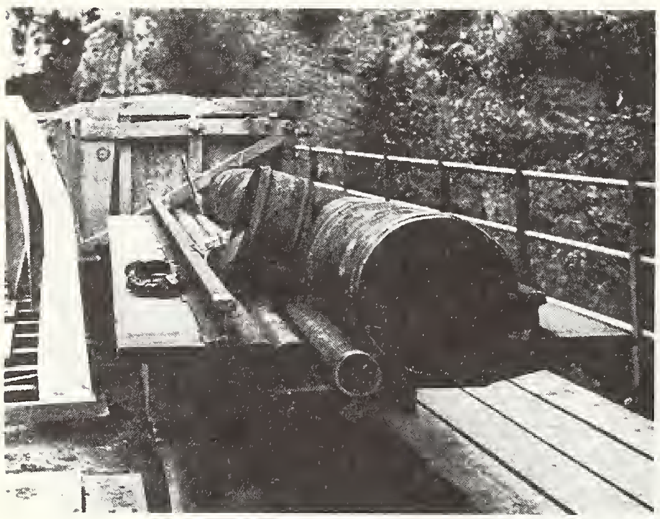


Figure 5-27. Supply Car Loaded with Rails, Air Duct, Water and Compressed Air Pipes, and Connectors for Systematic Installation

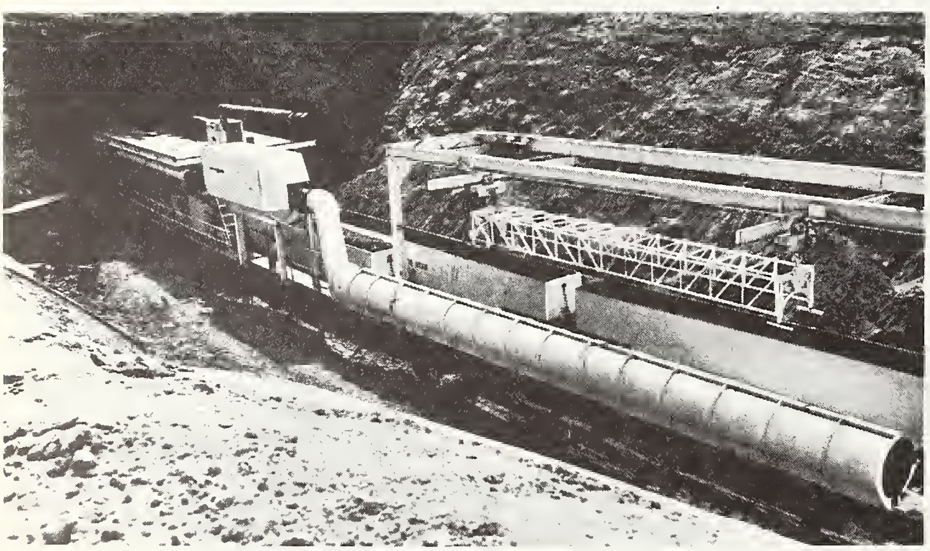


Figure 5-28. Air duct Telescope Connected to a Dust Collector, and Installed at the Side of a Loading Belt Frame

Photo: Dresser.

A pump line consisting of permanently installed pipes and of a connecting hose to the pump on the tunneling machine is also installed in stages.

Usually, the machine area is connected by telephone with the installation area at the tunnel entrance, and with the transfer area in case of tunneling projects originating from the bottom of a shaft. This telephone connection consists of a permanently installed cable and of an intermediate cable leading to the telephone on the tunneling machine that rolls off during the tunneling process. The installation of this connection is done in the same fashion as the installation of the high voltage cable.

5.2.3 Ventilation, dust removal, cooling

The machine area as well as the rear area of the tunnel where people are working must be ventilated, the concentration of possible noxious material must be diluted, and this stretch of the tunnel must be cooled. The measures necessary for the ventilation, dust removal, and, if necessary, for cooling, will not be given individually, but within the framework of a summarizing evaluation. The requirements to be met are not the same for all countries. Besides generally valid guidelines, project-related regulations and standards must be observed for special work, such as mining.

5.2.3.1 Ventilation - The ventilation during the tunneling serves:

- the air renewal for the personnel,
- thinning of the dust concentration,
- the dilution of the irritant concentration during the use of diesel engines, for example for the traction during the cutting removal and the supply of points of operation,
- the dilution of the concentration, and the increase of the air speed in the presence of natural gas, as well as
- heat dispersion.

Two different ventilation systems can be used, either

- suction ventilation, Figure 5-29; the fresh air flows through the excavated tunnel up to the cutting head, the used air is led to the entrance of the tunnel by means of an air duct, or
- blow ventilation, Figure 5-30; the fresh air is led into the machine area by means of an air duct, and the used air flows back through the excavated tunnel to its entrance.

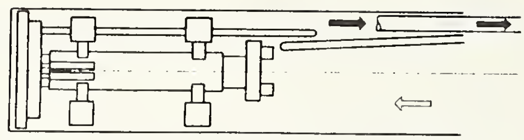


Figure 5-29.
Suction ventilation

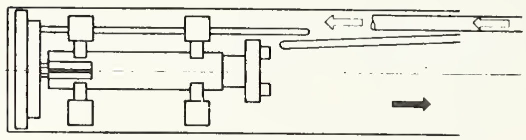


Figure 5-30.
Blow ventilation

Figures 5-29 and 5-30. Ventilation Systems

Apart from possible project-related regulations, ventilation, dust removal, and, if necessary, also the cooling must be considered during the selection of a system. The length of the tunnel and its diameter, as well as work places possibly located between tunnel entrance and tunneling machine are influential factors. Whereas usually tunneling projects with predominantly small cutting diameters are ventilated by means of suction, blow ventilation is preferred for long tunnels, and for the cutting of galleries in mining operations.

With regard to the well-being of the personnel, and with electric traction, a fresh air quantity can be assumed for the air renewal on the basis of the precondition that smaller tunnel diameters, up to approximately 25 m^2, cutting diameters approximately 5.5 m, should have air speed of at least 0.1 m/s, and larger tunnels, from approximately 25 m^2, should have an air speed of at least 0.05 m/s. The air quantities derived from this refer to the machine area. Considering the unavoidable air losses in air ducts, a correspondingly larger amount of air should be sucked in at the tunnel entrance, and the fans should be operated with low pressures. For this reason, several fans distributed along the air duct are preferable to one high pressure blower.

5.2.3.2 - <u>Dust collection</u> - During mechanical tunneling, dust is formed,

- in the cutting zone, during the penetration of the cutting tools into the rock, during the falling of the cuttings as well as by its movements caused by scrapers and shovels,
- in the feeding hopper between the shovels of the cutting head and the basic machine conveyor belt, as well as
- at the transfer points of the conveyor belt.

The quantity and the grain size distribution of the dust depends on

- the type and the portion of the main components, as well as on the strength of the rock,
- on the boring system, in particular on the bit type and on the condition of the cutting edges, as well as on
- the moisture of the rock.

The amount of dust generated in the cutting zone amounts to some 100 g/m^3 of cut rock even with spraying of water [38]. The trapping of dust is an absolute necessity with dust containing quartz. Grain sizes smaller than 5 μm can pass into the lungs, and are major health hazards for this reason. The bearable concentration of hazardous materials is expressed by the so-called MAK values, maximum work place concentration for a daily work period of 8 hours. The MAK value for very fine-grain dust containing quartz, determined by the Swiss accident insurance company SUVA can be seen in Table 5-5 [39].

Dust trapping is done by:

- spraying of water,
- supply of fresh air for dilution of the concentration,

TABLE 5-5. MAK VALUES FOR VERY-FINE-GRAINED DUST CONTAINING QUARTZ

Quartz content of the dust %	MAK values for grain sizes <5 μm mg/m^3 air
10 to 20	10
20 to 30	5
30 to 50	3
50 to 70	2
over 70	1

- dust collectors.

The spraying of water for the purpose of trapping suspended dust is a traditional method of dust trapping. However, its effectiveness is insufficient even with large amounts of water - undesirable for other reasons - and is unable to meet the requirements set by the MAK values [40]. Only relatively large dust grain fractions adhere to the water droplets under atmospheric conditions, whereas the smaller particles that are capable of passing into the lungs remain largely free. The reduction of the dust concentration through dilution requires the supply of a very large quantity of fresh air.

Even the removal of the dust-containing air, and the binding of the dust grains in dust collectors, does not completely fulfill the requirements. The effectiveness of the dust trapping system which also depends on the dust content of the raw air is smaller than 100%, and the residual dust contained in the released air, the so-called pure air, consists predominantly of the fractions that are capable of passing into the lungs. During machine tunneling, a combination of these three dust trapping methods is usually used.

No matter whether the machine area is ventilated by suction or by blowing, the cutting zone must be separated from the remaining machine area by means of a shield due to the very heavy dust generation occurring there. By producing a water fog in the cutting zone - possibly the water necessary for the boring tool cooling may be used - primarily the surfaces of the cuttings will be moistened more or less. In addition, part of the generated dust will be bound to the water droplets, and will be deposited. The dust concentration in the air sucked from the cutting zone, the so-called raw air, decreases with increasing amount of sprayed water. According to that, large amounts of water would seem to be most effective. However, this is contradicted by the experience that cuttings and cutting sludge that are dripping wet wear out machine parts; in addition, the requirement must be considered that the cuttings should completely absorb the sprayed water, which is difficult with a large quantity of water. Also, the use of water should not be considered for rock masses that have a tendency to swell.

Despite the spraying of water, the air circulating inside the cutting zone is saturated with dust. It must be sucked off continuously. Otherwise, it would pass through the openings of the dust shield, and would cause, together with the cuttings, an intolerable visible and smellable dusting of the rear machine area. The amount of air to be sucked up must stay within certain limits. The speed of the air entering the cutting zone through the openings in the cutting head carrier must be large enough so that the air turbulence in the cutting zone dones not permit at any point a counter-flow of the dust-containing air to the outside. On the other hand, it must not be so large that fine cuttings are stirred up, and are removed with the raw air. In general, it can be assumed that the raw air quantity G that is to be sucked off is proportional to the cutting performance L, and correspondingly to the cutting head penetration t_K and to the cutting diameter D.

$$G \sim L = v_N \ F = ntF \sim \frac{1}{D} \ t \ D^2 = tD.$$

For tunneling projects with blow ventilation, and with cutting diameters around 5 m, and with cutting performances with 0.5 to 1 m^3/min solid rock, it was shown to be sufficient to suck off 90 to 100 m^3/min dusty air from the cutting zone, to process it in the dust collector, and to subsequently mix it with the remaining fresh air in order to reduce the following dilution ratio results:

$$\frac{\text{Total amount of fresh air at the point of operation}}{\text{amount sucked out of the cutting head.}} \approx 2.3:1 \text{ to } 5:1 \ [38]$$

For ventilation by suction less thorough dust catching is necessary because the clean air leaving the dust collector directly enters, and flows in, the air ducts. According to experiences gained so far, 1 to 1.5 m^3/s raw air should be sucked out of the sprayed cutting zone for a cutting diameter of approximately 3 to 5 m.

The low pressure necessary for the suction of the air out of the cutting zone is produced by means of an air duct fan, or, if a dust collector unit follows, by means of a fan integrated in the dust collector, the raw air is transported by means of two flexible air ducts made of medium-hard plastic material connected to the upper part of the dust shield. In order to avoid dust deposits in the air duct, the air speed feed should be at least 20m/s.

Whenever a point of operation is ventilated by blow-ventilation, a dust collector must be installed. This would not be necessary for ventilation through suction if the speed of the raw air in the extracting air duct amounts to approximately 20 m/s, and if the sand blasting effect of the raw air on the air duct and on the ventilators is considered acceptable. In general, this method is only used for short tunnels, and with small amounts of air, with ventilation through suction.

For mechanical tunneling, wet dust collectors must be employed, in particular, so-called high-performance wet dust collectors with ventilation by blowing. With all manufacturers, the basic design of a high-performance dust collector consists of the actual dust collector with a following fan of a water circulation with pumps, conduits, and sludge catchers, of the solids removal unit, and of the electrical installations. The dust-containing raw air from the cutting zone flows through the dust collector with very high speed. Here, the air comes in contact with finely sprayed water. After different processes characterizing the individual dust collector manufacturers, the dust particles are first absorbed by water droplets, and are then separated from the air while clinging to the water. The sludge, consisting of water and deposited dust particles, is collected in a catcher, and may be added to the cuttings by means of a sludge pump.

With ventilation by suction, the use of a system slightly less effective than a high-performance dust collector is justifiable because the small quantities of finely fractioned residual dust remaining in the pure air will not come in contact anymore with the tunnel air. A future reduction of the emission limits to approximately 100 mg solids per m^3 pure air entering the atmosphere, however, may preclude the use of coarse dust collectors.

If an appropriate amount of water is sprayed in the cutting zone, additional dust-collective measures are usually not necessary at the conveyor belt transfer points. If necessary, water may be sprayed again at these points, or they may be encased with suction ventilation of the dust and an air quantity of approximately 0.5 m^3/s may be arranged.

5.2.3.3 Cooling - Heat is generated by the mechanical tunneling. The heat sources are:

- the tunneling system, in particular the tunneling machine, and
- possibly also the rock mass.

The generated heat is called heat output, and the heat transferred to the air in the machine area, or in the working zone, is called heat amount.

TABLE 5-6. MOST IMPORTANT HEAT SOURCES OF TUNNELING MACHINE, AND THEIR ZONES OF OCCURRENCE

	Trailer	Basic machine rear	 cutting head carrier	 work face
- Conversion at Head drive	- Main converter			
- hydraulic	E - motors H - pumps		H - motors gears, head bearing	crushing
		- H - lines -		
- electric DC voltage motors on head carrier	Rectifier		E - motors gears, head bearing	crushing
- electric AC voltage shaft machine		E - motors gears H - clutches	head bearing	crushing
		- drive shaft -		
- electric AC voltage motors on head carrier			E - motors gears head bearing	crushing
advance		- cylinders -		
gripping steering dust collection ventilation reserve	E - motors H - pumps dust collector additional ventilation Miscellaneous possibly cooling possibly air conditioning compressor			

For practical purposes, it can be assumed with sufficient accuracy that the electric energy transmitted to the tunneling machine is transformed completely into heat. The largest heat outputs are found in the areas summarized in Table 5-6.

The following basic distribution of its total heat output Wv applies for the tunneling machine:

$$W_V = W_{BK} + W_{SL} + W_{VR}$$

The predominant part of the electric energy supplied to the tunneling machine is transformed into heat output at the work face. Of this, the major portion W_{BK} is produced on the surfaces of the cuttings. The estimate of approximately 90% is justified because it considers that the heat is generated in the direct effective area of the boring tools, and in the disaggregation planes in the rock. If the average temperature of the cuttings removed from the cutting zone is larger than the temperature of the air in the tunnel, the cuttings release part of their heat content into the tunnel air. The calculation of this heat amount is difficult, and depends on numerous parameters, among others, on how the cuttings are loaded onto the conveyor belt. Cuttings that are distinctly colder than the air in the tunnel absorb heat from the tunnel air.

The remaining portion of the heat output produced at the work face - approximately 10% - is the heat amount W_{SL}. It is removed together with the dusty air sucked out of the cutting zone.

The heat output W_{VR} generated in the remaining area of the basic machine and on the trailers, with the exception of the heat removed by cooling water, is absorbed by the tunnel air.

The heat amount from the rock mass W_G is dependent on the original temperature of the rock mass T_{FU}, on the air temperature in the tunnel T_L, on the time which has passed since the beginning of the tunneling, and on material constants. For the calculation of the original temperature in the tunnel track it must be distinguished between an extensively flat, approximately horizontal, and an actually mountainous earth surface. In the first case, it can be assumed that, starting from the average yearly temperature of the area, the temperature increase in the ground amounts to approximately 3°C/100m of depth. This assumption is insufficient for tunnels in mountains. The geothermal gradient below mountain ranges is larger, and accordingly the heat gradient is smaller than under plains. The conditions are reversed underneath valleys. The calculation can be conducted following the method suggested by Thoma and Koenigsberger [42;43].

A calculation method for the temporal curve of the heat flow from the rock mass with a given original temperature T_{FU} and a tunnel air temperature T_L has been described by Carslaw and Jaeger [44]. It requires the knowledge of a temperature conductivity and of the heat transfer number of the rock mass, as well as of the heat transfer number for the tunnel invert. The heat amount per meter of the tunnel, kcal/h, decreases quickly immediately after the start of the tunneling. With a constant difference $T_{FU}-T_L$ it amounts to approximately 20% after a week, and to approximately 10% after a month, of the heat amount present at the beginning of the tunneling. The heat amount from the rock mass, in kcal/h, in the machine area of the length L, is calculated by the integration of the amount per meter over the area. The influence of time is considered by the introduction of the theoretical average hourly tunneling speed derived from the monthly tunneling distance. Figure 5-31 shows the results of calculations made for a given example [45]. Under the given conditions, this diagram is valid for the determination of the heat amount from the rock mass (i.e., $T_{FU}-T_L$ is positive), as well as for the determination of the heat transfer from the tunnel air to the rock mass with negative values of $T_{FU}-T_L$.

Difference between original rock temperature T_{FU} and ambient air temperature T_L

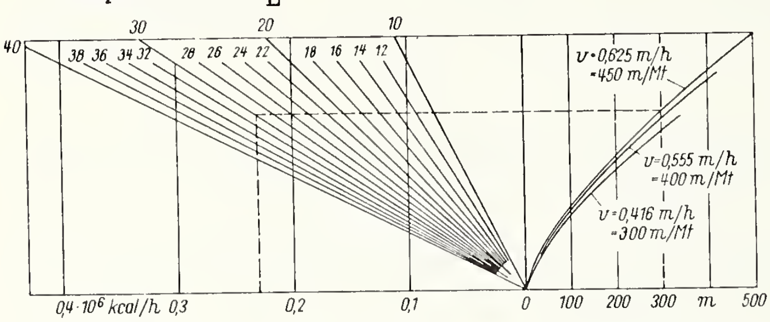


Figure 5-31. Heat release from rock mass; heat absorption of rock mass in the machine area [45]

Heat release from rock mass if: $T_{FU}-T_L$ (+)

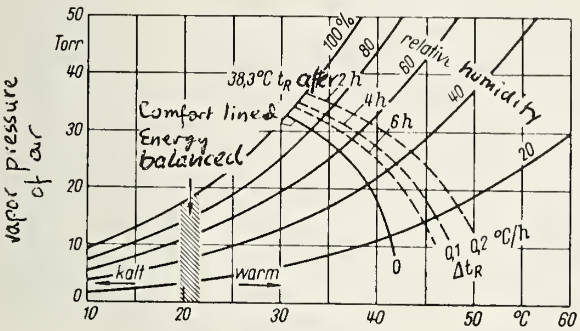
Heat absorption of rock mass if: $T_{FU}-T_L$ (-)

Length of machine area

Calculated for the tunnel ∅ D = 4.2 m
Temperature Index a = 0.0045 m^2/h
Nusselt number Nu_D = 21

If the temperature of the tunnel air which may be controlled by cooling is higher than the temperature of the tunneled rock mass, the latter will absorb heat. If the rock mass temperature is higher than the temperature of the tunnel air, with tunneling under a great cover height, for example, the heat amount of the rock mass W_G, and the amount generated by the tunneling system in the work area, accumulate. Without cooling measures, this would lead to a great impairment of the climate in the work area whose parameters are the temperature, the moisture, and the speed of the tunnel air. Adherence to appropriate climate values is decisive for the well-being and the effectiveness of the personnel.

Figure 5-32 shows the critical climate values determined by the Swiss accident insurance company for medium-heavy work underground.



room temp.

Figure 5-32.
Comfort limits for average underground work based on an energy of 242 kcal/h and an air speed of 0.3 m/s [41]

t_R = rectal temperature

Δt_R = increase of rectal temperature

During the tunneling, normal heat removal takes place:

- during the replacement of the air needed for ventilation and dust removal
- possibly with the cuttings, and
- with water, if a water cooling system is installed at all, as for example, for the hydraulic fluid or for the electric cutting head drive motors.

If this heat removal is insufficient to meet the requirements of the climate limits, special cooling is necessary. This may be done by:

a) increasing the original amount of air; however, because the heat removal by means of air is limited due to the relatively small practically producible enthalpy difference and the relatively small amount of air which can be moved in practice, by
b) cooling of the air by means of water

  - by spraying to achieve cooling through evaporation, or
  - by using heat exchangers with a cooling water circulation.

5.2.3.4 <u>Examples of calculations with simplified assumptions</u> - The exact calculation of the amount and the removal of heat during the tunneling process is complex since numerous processes influence each other. They must be considered as estimates of a magnitude. The following examples are based on simplified assumptions:

Given tunneling machine and its heat output

Tunnel diameter		4.2 m
Maximum cutting rpm		7.6 1/min
Nominal torque at the cutting head		55,000 kpm
Electric nominal performance of the cutting head drive		
Version A AC voltage	$\frac{55{,}000 \cdot 7.6}{0.8{,}974}$	= appr. 540 kW
Version B hydrostatic	$\frac{55{,}000 \cdot 7.6}{0.65 \cdot 974}$	= appr. 660 kW

Assumed average drive performance 75% of the nominal performance

Total average power for:	Alternative A	Alternative B
cutting head drive	440 kW	500 kW
rest of hydraulic system	30 kW	39 kW
dust collector system	15 kW	40 kW
ventilators	5 kW	30 kW
various consumers	10 kW	20 kW
	460 kW	620 kW
Of these, at the work face	80% of 400 kW = 320 kW	65% of 500 kW = 320 kW
	140 kW	300 kW

The transformers are neglected.

Total average heat output W_V	395,000	530,000 kcal/h
of this, at the work face	275,000	275,000 kcal/h
Removal with cuttings, 90%: W_{BK}	250,000	250,000 kcal/h
Removal in dusty air, 10%: W_{SL}	25,000	25,000 kcal/h
of this, in the remaining machine area, W_{VR}	120,000	255,000 kcal/h
Net boring speed	2.7 m/h	
theoretical average tunneling speed at 375 m/MT	0.52 m/h	
cuttings		
solid volume	37.5 m^3/h	
weight	98,500 kg/h	
specific heat	0.19 kcal/kg °C	
heat content per h and °C	18,700 kcal/h °C	

Average temperature increase of cuttings
250,000:18,700 = rd. 13.5 °C

Length of the work section respectively of the machine area 150 m

Example 1: Tunneling machine version A, suction ventilation

Original temperature of the rock mass T_{FU} (assumption)		8°C
Fresh air when entering the machine area in the tunnel cross section		
Volume (assumption)		2.5 m^3/s = 9,000 m^3/h
Weight G		10,000 kg/h
Temperature		8°C
Moisture, absolute/relative		4.5 g/kg/60%
The following steps of the calculation may be done by using a Mollier diagram, Figure 5-33.		
Input Enthalpy		4.5 kcal/kg
Fresh air in front of the cutting head carrier		
Temperature		34°C
Moisture, absolute/relative		4.5 g/kg/10%
Output enthalpy		10.8 kcal/kg
Enthalpy difference		6.3 kcal/kg
Heat removal by air	6.3·10,000	63,000 kcal/h
Average temperature of the tunnel air T_L = 1/2.(8 + 34) = $T_{FU} - T_L$		21°C -13°C
i.e. the rock mass absorbs heat heat absorption by the rock mass - W_G compare Figure 5-31		57,000 kcal/h
Total heat removal		120,000 kcal/h (W_{VR} = 120,000 kcal/h)
Average temperature of cuttings		13.5 + 8 = 21.5°C

i.e., between the cuttings and the practically equally warm tunnel air, a significant heat transfer does not take place. Therefore, only W_{VR} must be removed from the machine area.

No special cooling is necessary.

Air removed by suction at the cutting head for dust trapping		
Volume (assumption)		1.25 m^3/s = 4,500 m^3/h
Weight G		5,000 kg/h
Temperature		34°C
Moisture, absolute		4.5 g/kg
Input enthalpy		10.8 kcal/kg
Enthalpy difference, necessary for the removal of W_{SL}	25,000:5,000	5 kcal/kg

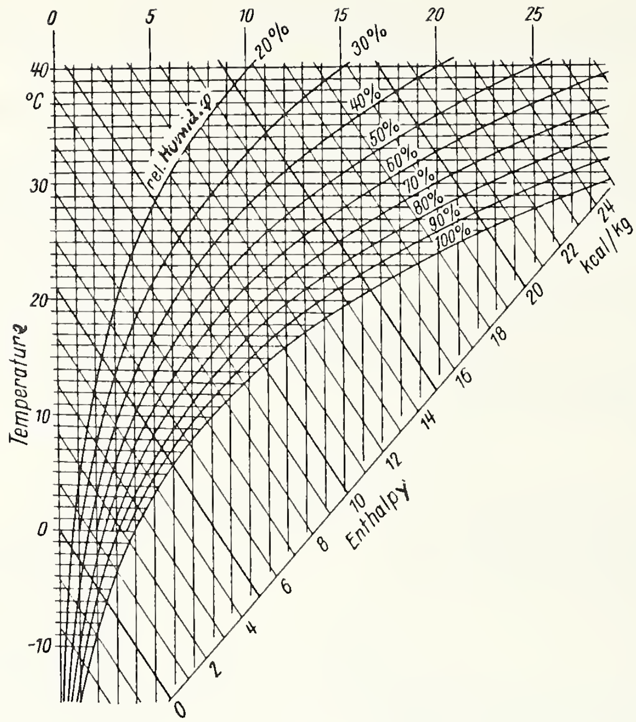


Figure 5-33. Mollier-Diagram (Absolute Humidity g Water/kg Air)

Air for dust removal, after the cutting head carrier

Output enthalpy	15.8 kcal/kg
Additional moistening in cutting zone	5 g/kg
Total moisture, absolute	9.5 g/kg
Temperature	42°C

Exhaust air during exit from the machine area in the

Air duct 1.25 m^3/s from the machine area to the front of the cutting head, and dust-free from the cutting head.

Volume (assumption)	2.5 m^3/s
Moisture	7 g/kg
Temperature	38°C

Example 2: Tunneling machine version B, blow-ventilation

Tunneling machine with hydraulic fluid cooling (assumption)

Heat removal 20% of 500 kW approximately 85,000 kcal/h

Original temperature of the rock mass T_{FU} (assumption) 40°C

Fresh air when entering the machine area in the air duct

Volume (assumption)	5.0 m^3/s = 18,000 m^3/h
Weight G	20,000 kg/h
Temperature	40°C
Moisture, relative	20%
Input enthalpy	15.8 kcal/kg

Exhaust air at the exit from the machine area in the tunnel cross section

Volume (assumption) 3.75 m^3/s + 1.25 m^3/s 5.0 m^3/s =	18,000 m^3/h
Weight G	20,000 kg/h
Temperature	25°C
Moisture, relative (the same absolute moisture is assumed as in fresh air)	49%
Output enthalpy	12.2 kcal/kg

Enthalpy difference between fresh air and exhaust air 3,6 kcal/kg

Additional heat to be removed due to a temperature difference between
fresh air and exhaust air 3.6·20,000 = appr. 70,000 kcal/h

Heat amount

From the cuttings produced at the work face, from the conveyor belts in the machine area, estimate: 50% of the heat excess of the cuttings (13.4 + 40-25)°C·18,700 kcal/h °C	appr. 265,000 kcal/h
from other sources in the machine area W_{VR}	255,000 kcal/h
from the rock mass W_G, T_{FU}-T_L = 15°C, compare Figure 5-31	70,000 kcal/h
due to temperature difference between fresh air and exhaust air	70,000 kcal/h
direct removal by hydraulic fluid cooling	./. 85,000 kcal/h
to be transferred primarily to tunnel air	575,000 kcal/h

No special cooling is necessary

Basic design of the heat exchanger

1. Heat exchangers on loading belt in front of air duct exit 5 m^3/s, Inputs 40°C/20%, output 16°C/85% humidity	120,000 kcal/h
2. and 3. Heat exchanger for tunnel air recirculation	2x230,000 kcal/h
distribution according to the heat amounts flow-through of fresh air and of recirculated air	
Suction at the cutting head for dust-trapping purposes (assumption)	1.25 m^3/s
Dusty air: fresh air	1:4

Cooling water

useable temperature difference (assumption) 10°C

specific heat 1.0 kcal/kg, °C

necessary volume

$$\frac{575000+85000}{1 \cdot 10} = 66{,}000 \text{ kg/h} - 18{,}3 \text{ l/s.}$$

5.2.4 Devices for Directional Control

During the tunneling process, it must be guaranteed under all circumstances by means of continuous control that the tunneling machine follows the design direction and the design inclination. The machine must be connected with a pilot control, and all tunneling must be stopped when this pilot control becomes defective. These requirements cannot be repeated often enough, and must be strictly enforced, since deviations from the course can be very expensive.

This pilot control, a line-of-sight device, or a narrow beam of light, is installed parallel to the design axis alongside the tunnel soffit, or under the tunnel crown with straight tunneling. During the tunneling of curves, it represents a tangent or a secant on a circular curve which is concentric to the axis of the design curve. The horizontal and the vertical distance of the pilot control from the tunnel axis must be determined before the start of tunneling, and remains the same during the tunneling process. One target each is installed on the cutting head carrier and possibly also at the rear end of the machine frame with the same distance to the axis of the basic machine.

The use of the line-of-sight method as pilot control is an obvious choice. It was commonly used when the mechanical tunneling was first introduced. The line-of-sight may be given by means of targets, or by the telescope axis of a theodolite. An observer checks the course and gives directions for a correction to the machine driver, if necessary. In order to avoid the disadvantages of periodic control, the observer may be replaced by a commercial television camera. The theodolite telescope must be connected with the television camera by means of a very precise adapter. The picture of the camera is transmitted via videocables to a viewing screen in the control center of the tunneling machine.

Much more often, however, a laser beam with a gas laser light source is used as pilot control. In principal, the laser is an energy converter. The systems used on construction sites accept energy in form of electric current, and emit radiation in the red light range. At the exit of the laser tube, the beam is very tightly focused, and has only a very small divergence. With modern systems, it is so small that a relocation is only necessary after a tunneling advance of several hundred meters. By means of a theodolite, targets are installed, and the laser tube is then aligned with these targets so that the axis of the tube is coaxial to the pilot control.

In order to simplify this process, the theodolite whose axis coincides with that of the pilot control may be left as is, and a laser tube may be attached to the theodolite in such a way that the axis of the tube is parallel to the axis of the theodolite. However, this involves a parallax between the two axes.

This parallax can be avoided with a laser theolite. Only a regular theodolite is used for this. The accompanying laser with its supply can be installed at its suspension or in a corner of the tunnel. The produced beam is led into the telescope of the theodolite by way of light transmission cable, and leaves the telescope in its axis. The practical range of a laser beam fed through a theodolite telescope is at present still shorter than that of a laser beam exiting directly from a laser tube.

Whenever a laser beam is used as pilot control, it must be controlled with 2 shutters or laser beam control in front of the device. When the device is displaced, through collision, or through a deformation of the tunnel soffit, the beam through the shutters is interrupted. This beam deflection is signaled by the laser beam control.

Photo-electric grids may be used as targets. They permit the registration of the impact points of the laser beam on the target. The measurements can be transferred to a target representing this grid plate located in the control center of the machine.

Laser beams have an extraordinary beam intensity. A beam hitting the human eye directly is very damaging. The personnel must be informed of this. Some countries have issued regulations for the protection of the personnel in the tunneling machine area.

5.2.5 Gas detection

Tunneling in formations containing natural gas requires, (as do conventional methods),

- continuous analyses of the composition of the tunnel air, and
- the preparation of organizational and technical measures to be taken when the gas content of the air reaches the highest admissible value.

Methane (CH_4) is the most commonly occurring natural gas. It can occur either by itself, or together with other gases. It is colorless and odorless, and can only be detected with gas detectors. A mixture of air and 4.5 to 15% CH_4 is explosive. In the presence of other gases, this range may be extended on both sides. The explosion can be caused by a spark. Below its explosion point, the air-gas mixture is flammable.

Individual countries have - differing - regulations concerning the protection of a tunneling project during gas occurrence. In any case, early detection of gas is of utmost importance. For this purpose, detectors are installed in the suction air ducts leading from the dust shield of the tunneling machine to the dust collector, and in the tunnel apex. In special cases, the pilot drill of the tunneling machine may be used. The air samples taken out of these pilot drill holes may be analyzed by means of the detectors; the accuracy of these instruments amounts to approximately 0.1%. As soon as a gas content of the air above the tolerance limit is determined, security measures must be put into effect by all means, such as a preliminary warning with a content of 1.5%, and switching off of all electrical systems, with the exception of the lighting and the ventilator motors which are explosion-safe, with a content of larger than 2% [46]. Usually, the amount of fresh air injected into the machine area is increased with regard to a better air turbulence, thus avoiding layering of air, or formation of air stagnation in the tunnel. Equipping the tunneling machine with an electric installation which is explosion-safe in all its parts is very expensive.

6. THE BIDDING PROCESS, AND THE EXECUTION OF THE TUNNELING PROJECT

6.1 BID DOCUMENTS

6.1.1 Possibilities for Contract Design

The common basic forms of a contract for the construction industry are:

- unit price contract,
- lump sum contract,
- cost-plus contract,
- cost-plus with incentive, and sometimes a
- combination contract.

Most commonly used are the request for bids, awarding, execution, and accounting for a tunneling project on the basis of unit price, i.e. with lump sum prices for the construction installations and for equipment rental, and with standard prices for the actual construction work. Underground construction with its specific uncertainties is little suited for the use of flat-rate prices for the total construction. The contractor cannot be expected to be responsible for, and to bear the consequences of, deficiencies of the earth crust which he does not know, or does not know sufficiently well. Construction based on cost-plus, or on cost-plus with incentive, is justified, or even necessary, if an extraordinary capital investment is required from the contractor, if a long construction time is projected, and if the extent of the work, or the work conditions are not known well enough to warrant a pre-calculation with fixed prices. This may be the case with risks that cannot be calculated or controlled, such as especially unfavorable geological-constructional conditions, or with the cooperation of third parties that is necessary but whose availability is uncertain, if interference with other operations must be avoided, if there is influence by third parties, or if the protection of the environment is involved. Combination contracts may also be suitable, such, as for example, the application of flat-rate prices to the construction installations and equipment on the one hand, and the compensation according to cost for all or parts of the tunneling and lining construction on the other hand.

6.1.2 Presentation of the Extent of Work and of the Work Conditions on the Basis of Standard Prices

The complete and determinative presentation of the extent of the work and of the work condition for the bidding requests for a construction project on the basis of standard prices is an important and possibly consequential duty of the owner, and of the engineer designing and supervising the project on his behalf.

This presentation can be done, for example, by:

- the wording of the construction contract as such,

- the schedule,

- the object-related conditions,

- the plans including the geological documentation and the longitudinal section of the assumed local distribution of the rock mass classes with regard to basic boreability, cutting tool wear, and support lining requirements,

- the performance regulations, and

- the safety regulations.

The engineer must communicate his knowledge concerning the projects, often based on years of preparation, and the technical conditions for its realization to the contractor. Of special importance is the geological documentation and the rock mass classification commissioned by the owner or by his engineer. The classification of the geological information according to substantiated knowledge, or, if that is unavailable, according to "probable" and to "possible" status must also be submitted to the bidding contractor. This information determines a geological and construction-technical area of the activity of the contractor. On the basis of the index values for the boreability and for the cutting tool wear, as well as by the prognosed supporting requirements the contractor can determine the basic requirements for the tunneling machine which he is to provide. The geological documentation and the classification of the rock mass are fundamental information for the development of the bid submitted by the contractor. For this reason, they must also be recognized as parts of the construction contract for the project.

In order to keep the bid simple and easy to understand, set dimensions for the longitudinal extension of the rock mass classes and for the profile type distribution must be included in the price list. Allowances for the deviations from the assumptions on which the bid is based can be made in final accounting which considers the actual extent of the work. Also, the flat-rate price for the installation based on an advance quantity given in the bid documents may be adjusted to a change in the construction time under consideration of the actual longitudinal extension of the rock mass class or also profile type areas.

The condition that the owner and his engineer must present the extent of the work and the working conditions, and that the submitting contractors must choose their equipment as well as the construction methods and also must conduct a pre-calculation on this basis, defines unequivocally the responsibilities, and determines the risk of the contractor. In preparing and documenting the project for the bidding process, the engineer must proceed with great care. The processing of the bidding documents, in particular the wording and formulation of the texts, is the domain of engineers with great experience in construction work, and not of recent graduates of engineering schools. The project and its special problems must be the center of the presentation. Copying and re-copying of standard texts used at many construction sites does not serve the purpose. A project engineer with construction site experience will also have a better understanding for the often-times significant problems of the contractors. His formulations should be of sufficient clarity, but their tone should also express the intention of a fair partnership between the owner and the contractor. The contractor can and should cooperate during the preparation, and later during the execution of the project. He does not have the right to revise his bid and to question the construction contract based on his bid as long as the actual conditions which he meets with during the execution coincide with the presentation of the extent of work and of the working conditions given in the bid documents. The owner is not responsible for the decisions which the contractor makes on the basis of his evaluations of the working conditions and of the extent of work that were presented correctly by the engineer. However, he must bear the consequences, and he must respond to the demands of the contractor, if the actual conditions are different and require performances of the contractor which are not covered by the description given in the bid documents.

6.1.3 Examples for Contract Combination

6.1.3.1 Provision of the Tunneling Machine - The tunneling machine to be used for a certain project is usually selected and provided by the contractor. The owner who best knows the extent of the work and the working conditions may determine special conditons to be met by the tunneling machine in form of specifications. He may pre-select types and brands of tunneling machines available on the market, and may submit a list of machines that are suitable, in his opinion, to the contractor. However, he will hardly prescribe a certain brand of tunneling machine, or details of the machine construction. Such extensive specification would have to be coupled with the acceptance of certain responsibilities. The selection and the provision of the machine on the part of the builder is the exception, although such cases are known. A builder may buy or lease his own machine if he also provides further performances for the tunnel project such as personnel or material supply, and if his tunnel construction program makes it possible to depreciate the purchased machine within a foreseeable period.

A bid-submitting contractor who would be required to assume responsibilities for a tunneling machine provided by the builder should retract his offer if he is not convinced of the suitability of the machine.

Whenever the extent of the work and the working conditions are known, the builder may ask for the provision of the tunneling machine bought or leased by the contractor at a fixed price, either as:

- lump sum price, guaranteed for the length of the tunnel project as described in the contract, or for the tunneling time described in the contract, or

- as lump sum price calculated as a per-meter price, and contained in the per-meter price.

Deviations of the actual longitudinal expansions of the classes, possibly also of the profile types area which may influence the tunneling time are provided for by the second possibility.

However, these deviations can also be considered, if a lump sum price has been agreed on the basis of the prognosed tunneling time mentioned in the contract, Table 6-1. Instead of this lump sum price, a modified lump sum price may be used. In this case, the tunneling time determining this modification must first be determined. It is calculated for each area of the longitudinal profile of the tunnel track as the quotient of actual length to contractual tunneling performance. The relation between the modified lump sum price and the lump sum price of the accepted bid is the same as that between the modified tunneling time and the contractual tunneling time. This means a transfer to the owner of the risk caused by the uncertainty of the longitudinal extension of the rock mass classes with regard to supporting requirements and boreability. However, the contractor still has the responsibility for providing the contractual tunneling performances.

The amount of the lump sum price for the provision of a tunneling machine may preclude the use of the mechanical tunneling process, especially if a tunneling machine must be first bought, or if the tunnel to be bored is short. However, the owner has several possibilities which permit the contractor to submit a lower lump sum:

- the combination of several tunnels with approximately equal boring diameters within the framework of a common construction program in which several builders may participate [2],

- the condition that the builder receives a certain portion of the lump sum price as a refund from the contractor if the contractor receives a new contract, possibly by another builder, within a certain period after the termination of the tunneling process.

TABLE 6-1. MODIFICATION FOR THE LUMP SUM PRICE FOR THE PROVISION OF THE TUNNELING MACHINE

Bidding, contract						
Tectonic unit						
general designation	A	A	B	B	B	B
Type of rock						
general designation	1	4	1	2	1	4
zone lengths in m	1280	540	480	900	2200	.....
support during tunneling	-	C^+	T^+	-	RB^+	.....
boreability	A1	conv.	B1	B2	B1	.....
tunneling speed in m/TD^+	23.0	3.0	16.0	21.0	18.5	.....
advance rate in TD+	56	180	30	43	119	
tunneling machine						
lump sum price	G1	G2	G3	G4	G5	.....

Total price of contract: G1 + G2 + G3 + ...

Execution of work						
zone lengths in m	1280	540	560	600/250	1950/200	.....
support during tunneling	-	C	T	- /RB	RB	
boreability	A1	conv.	B1	B2	B1/B2	.....
tunneling speed in m/TD						
effective	23.0	2.8	16.0	21.0/21.0	17.5/22.0	.....
contractual	23.0	3.0	16.0	21.0/21.0	18.5/21.0	.....
advance rate in TD						
effective	56	193	35	27/12	111/9	.....
relevant for mod.	56	180	35	29/12	105/10	.....
Modified lump sum price						
for tunneling machine	G1	G2	$\frac{35 \times G3}{30}$ =G3'	$\frac{41 \times G4}{43}$ =G4'	$\frac{115 \times G5}{119}$ =G5'	.....

Total modified lump sum price: G1 + G2 + G3' + ...

+) RB rock bolt T precast (segmented) liner elements C concrete TD tunneling day

6.1.3.2 Price Per Tunneled Cubic Meter or Meter - A builder submitting a reliable geological documentation, a reliable rock mass classification with respect to boreability, boring tool wear, as well as lining requirements, and a construction program to the contractor, may generally ask for the execution of the tunneling project on the basis of a firm price per cubic meter or meter. Estimating the net boring speed, the boring tool wear, and the utilization factor of the tunneling system, i.e. the numerical values of these terms that have an influence on each other, is then the task of the contractor.

Unfortunately it is not possible for every tunnel project to provide a reliable geological documentation or rock mass classification, and for some applications, areas of mechanical tunneling, little practical experience is available. This last statement applies especially to the tunneling of crystalline rock, and to tunneling with high cover heights. Only a few contractors and manufacturers of tunneling machines were involved in such projects.

During the bid requests and the execution of such construction projects the objective uncertainties must be considered without reducing the requirements of the contractor in areas in which he has a controlling influence. In such a case, the builder could accept the risk for the net boring speed and the cutting tool costs and could leave the risk for the technical readiness of the tunneling machine and of the utilization factor of the tunneling system to the contractor, under consideration, however, of the influence of net boring speed and cutting tool wear. Such a distribution of risk can be included in a contract, and the determination can easily be realized during the tunneling process:

a) the contractor offers gradated fixed cubic meter of meter prices supporting each rock mass class. There is a gradation for each class. The net boring speed as well as the down-time of the tunneling process caused exclusively by the maintenance and the exchange of the boring tools are the parameters of this gradation. These unit prices contain all costs of the tunneling, including those for the periodic inspection of the boring tools but excluding all others that are directly connected to the boring tool wear.

b) for the boring tool wear, the builder pays the contractor:

   - a lump sum price per time unit for the down-time of the tunneling caused exclusively by the maintenance and exchange of the boring tools, exclusive of the provision of the construction installations and equipment,

   - according to cost, the personnel for maintenance, replacement and repair if the boring, and (if the builder does not buy them himself) for new boring tools and their spare parts.

c) the billing and accounting, exclusive of the purchase of new boring tools and spare parts, is done for each work day. The supervising engineer and the construction site manager determine together the tunneling speed in meters per work day (m/WD), the average net boring speed (m/h), the down-time caused exclusively by the boring tool wear, as well as the hours of work performed in connection with the wear.

The costs of new cutting tools and their spare parts are paid upon billing. The principle of this arrangement can be seen from Table 6-2 and Figure 6-1.

TABLE 6-2. BASIS FOR THE PRICE DETERMINATION OF THE METER WITHOUT BORING TOOL COSTS, DEPENDING ON NET BORING SPEED AND BORING-TOOL-RELATED TUNNELING INTERRUPTION

Precondition: Three-shift operation with shift change in machine area, cycle length of tunneling machine 1.0 m, muck removal by train with change after two travel lengths.

		boring speed								
net boring speed		1.0 m/h			2.0 m/h			3.0 m/h		
cutting-tool-related interruption	h/TD	2	4	6	2	4	6	2	4	6
	min/TD	120	240	360	120	240	360	120	240	360
remaining working time	min/TD	1320	1200	1080	1320	1200	1080	1300	1200	1080
estimate of contractor										
boring time	min/TD	880	800	720	660	600	540	530	480	430
remaining interr. (relocation TM[2], train change, inspections, repairs etc.)	min/TD	440	400	360	660	600	540	790	720	650
resulting from estimate										
utilization factor	%	60	55	50	46	41.5	37	37	33.5	30
advance rate	m/TD	14.6	13.3	12.0	22.0	20.0	18.0	26.5	24	21.5

[1]TD tunneling day [2]TM tunneling machine

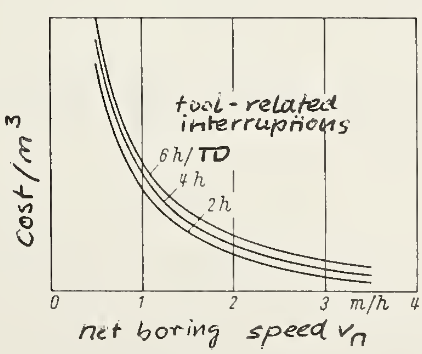


Figure 6-1. Price Per Tunneled Meter, Without Cutting Tool Costs, Depending On Net Boring Speed and Cutting Tool-Related Interruptions (TD)

6.2 PROJECT EXECUTION

6.2.1 Work Time and Shifts

Mechanical tunneling is done in two or three (in mining also in four) shifts. The employment of personnel at the work site around the clock permits the largest possible exploitation of the tunneling system. For this reason, it is used frequently, but requires at least a three-shift operation with a shift change at the point of operation, and also an uninterrupted presence of the personnel in the tunnel for at least eight hours. The meal breaks at the work site are staggered. Since the members of a work team do not all take their meal break at the same time, the tunneling can go on without interruption.

Legal and trade-union regulations which are different for individual nations, the contractual construction program, the work morale of the personnel, and possibly also the rock mass behavior are decisive for the number of the weekly work days and shifts.

6.2.1.1 Shift Types - The shift types, and the sequence of their use depends on the construction project. In any case, it must be differentiated between:

- tunneling shifts and

- maintenance shifts.

If the permanent lining is installed simultaneously with the tunneling, and if this lining consists of concrete, and if the tunnel diameter is too small to permit removal of the cuttings and the supply of the tunneling process through the section to be lined, the lining shifts must also be provided. Only the tunneling and maintenance shifts, typical for mechanical tunneling, are mentioned in the following.

6.2.1.2 Responsibilities of the Shifts - A tunneling shift has the responsibility for:

- the tunneling operation and, if necessary, the installation of the temporary lining, of pre-fabricated invert elements or of a precast lining, inclusive of all necessary transportation,

- the relocation, possibly without interruption of the tunneling and, possibly, only temporarily, of the tracks or the rails of an overhead conveyor, for the removal of the cuttings and the supply of the tunneling, the supply lines for water and compressed air, of the air ducts, and possibly of a pump line.

- inspection, maintenance and small repairs of the tunneling system either with or without interruption of the tunneling process.

A maintenance shift is responsible for:

- cleaning of the tunneling machine,

- maintenance of the total tunneling system through inspection, maintenance, and prophylactic as well as necessary repairs,

- improvement of the auxiliary installations installed by the tunneling shifts,

- cooperation during the periodical relocation of the alignment devices such as the laser system.

After 250 to 300 meters of tunneling a special work assignment of advancing the high voltage cables is necessary beside the tunneling or the maintenance shifts.

6.2.1.3 Sequence of the Shifts - It is distinctly shown by experience that successful mechanical tunneling depends on special maintenance shifts during which the tunneling operation is stopped.

The use of a special maintenance shift may be necessary after three to five tunneling shifts under conditions of fast tunneling in well boreable and largely identical rock masses, with relatively small wear and short down-times for the replacement of the boring tools. Slow tunneling in differing rock masses, and especially with a relatively large wear and frequent and also prolonged down-times for the exchange of the boring tools offers sufficient time for the personnel of the tunneling shifts to carefully conduct inspection, maintenance, and also smaller repair work according to their check list. One or two special maintenance shifts per week can be sufficient.

In any case, the relation of tunneling shifts to special maintenance shifts depends significantly on the tunneling system, not infrequently on the tunneling machine in particular, and, of course, on the time requirement for repairs necessary due to defects.

6.2.1.4 Distribution of the work time - The effective work time in the tunnel is divided in:

- tunneling and boring,

- system-related down-times, and

- non-system-related down-times.

The attempt must be made - but in no case at the expense of inspection, maintenance, and prophylactic repairs - to continue the tunneling as long as possible during each shift.

System-related down-times are caused by missing technical operational readiness of the components of the tunneling system employed at the operation point, among others during:

- advancement of the tunneling machine,

- inspections, maintenance, and all kinds of repairs, inclusive of cutting tools,

- installation works in the machine area.

System-related down-times are unavoidable. Non-system-related down-times are waiting times for the technically functional tunneling system at the point of operation. Such down-times occur while waiting for:

- removal and supply,

- electric energy, water, compressed air, ventilation, unless occurring in connection with the installation works in the machine area,

- installation works, maintenance, and repair outside of the machine area,

- survey and under certain circumstances, for the

- execution of measures for stabilizing the rock mass, or for the removal of excess water.

A large part of the non-system-related down-times occurring at construction sites could be avoided by the tunneling management. System-related down-times occur, in part, with a certain rhythm depending on time or tunneled distance. Inspections, maintenance, and scheduled repairs, for example, are time-related. After a certain tunneled distance interruptions occur, for example caused by the relocation of the tunneling machine, or by a train change. The necessity for repairs caused by defects is independent of tunneling time or tunneled meters.

Whenever an interruption occurs, no matter whether scheduled or unexpected, it must be attempted on the basis of the present work status, to use the interruption of the tunneling also for the execution of other work which might have necessitated an interruption within a foreseeable period.

Examples:

- during a checking of the cutting tools which is done on a scheduled basis depending on the type of rock and on the tectonics, the necessity for the replacement of three bits is determined. The interruption necessary for this exceeds one hour. This time is used to advance rails and supply pipelines, which otherwise would only have been necessary after three more meters of tunneling.

- checking of the reduced performance of a hydraulic valve of the tunneling machine shows the necessity for its replacement. A spare valve is not in stock, and must be furnished by the manufacturer. An interruption of approximately 12 hours must be expected. This interruption is used to execute the maintenance work which otherwise would not have been necessary for another two days.

Non-machine and non-system-related down-times may be avoided by appropriate installations and by an appropriate organization of the operation.

Example:

- during the tunneling with a relatively small cutting diameter, the use of a bunker car necessitates waiting for the cuttings removal at least up to a certain tunnel length. length.

- on the trailers of the tunneling machine, or beside the bunker car any kind of constantly needed material should be stored, if possible: hydraulic fluid, grease, lubrication oil, pipes, most frequently used sealing rings, some cutting bits, all tools for inspections and maintenance according to check list.

The consumption of material, in this case exclusive of rails and air ducts, should be organized in such way that the material stored in the machine area is used, and that the supply based on a general plan serves for the replenishment of this storage.

- The material storage of the construction site should contain the most frequently needed spare parts of the system, as well as those whose unavailability in case of need would interrupt the tunneling for longer periods of time.

6.2.1.5 <u>System Utilization Factor</u> - Frequently, the system utilization factor serves for the evaluation of a tunneling process.

$$\text{System utilization factor} = \frac{\text{boring time and revolution time of the cutting head} \times 100}{\text{working time in or behind the TBM system}} \text{ in \%.}$$

This definition only contains the effective work at the point of operation and in or behind the machine area. This value does not consider the transportation time to the site of operation which is different for each construction site. They do not apply to a three-shift operation with shift changes at the operation site. However, during the tunneling of an inclined gallery with shift changes at the face of the tunnel, they may amount to 15 minutes at the beginning, and 45 minutes at the end of the operations.

Net boring speed, cutting tool wear, and system utilization factor influence each other, compare Table 6-2. Here, it must be noted:

- the utilization factor drops with increasing net boring speed.

- if the net boring speed decreases, whereas the propelling force remains the same, an increased cutting tool wear frequency occurs.

- increased boring tool wear requires longer cutting-tool-related down-times, and thus leads to a lower utilization factor. During the execution of a tunneling project, the system utilization factor is determined for each work day. After termination of the tunneling, it is calculated for the total tunneling time. The boreability and the behavior of the rock mass must be considered for the evaluation of the system utilization factor. A utilization factor of 30% is not spectacular for tunneling in solid granite. A utilization factor of 55% is remarkable for tunneling in solid marly sandstone. Table 6-3 shows utilization factors determined at some construction sites.

The system utilization factor of a tunneling system must be distinguished from the other terms mentioned in the following:

$$\text{technical operating condition of tunneling machine availability} = \frac{\text{time of the full technical availability of the TM} \times 100}{\text{working time on or behind the TB system}} \text{ in } \%,$$

$$\text{technical operating availability of the tunneling system} = \frac{\text{time of the full technical availability of the system} \times 100}{\text{work time on or behind the system}} \text{ in } \%.$$

With none of these tunneling projects did significant interruptions caused by the rock mass occur. The utilization factor of a tunneling system is always smaller than its technical operation availability.

TABLE 6-3. UTILIZATION FACTORS FOR SOME TUNNELING SITES DETERMINED BEFORE THE END OF THE TUNNELING PROCESS

tunnel diameter m	type of rock	tunneled length m	tunneling time h	effective work time h	utilization factor %
5.61	shale	3,860	985	3,360	29
6.40	sandstone	3,450	2,000	6,250	32
5.03	hard sand and clay stones	3,320	2,182	7,440	29
4.16	hard limestone	920	493	1,790	28
4.20	hard limestone	4,380	2,438	4,650	52
5.13	hard limestone	3,410	1,868	4,760	39
3.30	limestone, also cherty limestone	1,675	2,069	2,800	75
2.25	granite and gneiss partially jointed	975	1,242	3,400	36
3.66	granite, part. jointed	1,260	1,339	5,280	25

In none of these tunneling projects did significant interruptions caused by the rock mass occur. The utilization factor of a tunneling system is always smaller than its technical operational availability.

6.2.2 Personnel and Specification Sheets

6.2.2.1 Personnel - The selection of the personnel and the selection of personnel for the individual shifts is even more important with mechanical tunneling than with the conventional process. Mechanical tunneling requires more specialists, but less personnel for large diameters.

The following jobs should be given to specialists:

- chief mechanic-electrician,
- foreman, and shift supervisor,
- machine operator,
- electrician,
- mechanic for general work, and
- mechanic for boring tool repair.

Substitutes must be trained and kept available with regard to vacations, sickness, accidents, and job changes. The chief mechanic-electrician, the machine operators, the electricians, and the mechanics for general work must know all components of the tunneling system thoroughly. They should be trained by experienced personnel of the machine manufacturer for the operation, inspection, maintenance, and repair of the tunneling machine. The chief mechanic-electrician should have a specially intensive training.

The number of the personnel of a tunneling shift is decisively influenced by the type and the extent of necessary measures for securing and stabilizing the rock mass. The following are normally used for tunneling in stable rock masses:

a) in the machine area: one foreman as shift supervisor, one machine operator, possibly one mechanic for general work, possibly one electrician, one handiman at the discharge point of the cuttings into the conveyor belt, up to three laborers for supply installations;

b) between machine area and dump: train driver, possibly handimen for supervision of the operation with conveyor removal, one handiman at the dump;

c) at the plant at the tunnel entrance, present only during the day shift, but otherwise available at short notice, at least: chief mechanic-electrician, one electrician, also as store manager of small construction sites, one mechanic for general work, one to three mechanics for cutting tool repairs, one handiman. A shift containing at least one mechanic and one electrician is used as maintenance shift.

6.2.2.2 Specification Sheets for Personnel - It is recommended to issue specification sheets defining their work at least for the specialists in a tunnel construction project. This specification sheet is fundamental. It goes without saying that each member of a shift will help out with work assigned to another member if he is not busy with his own work himself. Table 6-4 shows an excerpt from a specification sheet.

6.2.3 Checking of the Tunneling System

Inspections and maintenance of the components of the system must be carried out to increase the technical operation conditions. It must be distinguished between:

- continuous inspection and control of, for instance, temperatures, tightness, degree of the filling of containers,

- inspections, possibly connected with maintenance, by each tunneling shift,

- inspections and maintenance by a maintenance shift.

- long-term maintenance (for example, electric motors and wheel bearings).

TABLE 6-4. EXCERPT FROM A SPECIFICATION SHEET FOR THE PERSONNEL, EXAMPLE

a) Chief mechanic-electrician

He is responsible for the functional availability of the tunneling system,

- supervises the operation of the tunneling system and of its components,
- supervises inspections and maintenance as well as the repair of small defects by the personnel of the tunneling and maintenance shifts,
- localizes and repairs larger defects with the help of the mechanic/electrician and of the machine operator,
- supervises the bit shop, the general shop, and the store,
- orders material and spare parts on the basis of orders submitted by the store manager,
- supervises and improves the training of the machine operators, the training of drivers, electricians, and mechanics,
- continually checks the relevance and completeness of the check lists and of the directions of operation, changes or adds to them, if necessary after consultation with the manufacturers of system components.

b) Foreman

He is in charge of his tunneling shift,

- coordinates and directs the tunneling operation
- gives first directions during interruption of the operation, in particular during unscheduled ones,
- continuously supervises the storage of material in the machine area and, in the case of interrupted supply or interrupted muck removal of the cuttings, immediately contacts the personnel at the plant site at the tunnel portal,
- determines by means of spot checks whether the inspections and the maintenance of the components of the system are carried out in accordance with the tunneling shift check list, and whether the operation follows the direction,
- writes the shift report.

TABLE 6-4. EXCERPT FROM A SPECIFICATION SHEET FOR THE PERSONNEL, EXAMPLE (CONTINUED)

c) Machine operator

Organizationally, he answers to the foreman and, technically, to the chief mechanic-electrician,

- operates the tunneling machine according to operating instructions,
- carries out inspections and maintenance work according to the tunneling shift checklist, with the exception of the checking of the boring tools,
- supervises, by means of spot checks, the boring tool check carried out by the workman for the loading process,
- localizes and repairs defects of the tunneling machine if he is qualified for this. In special cases, he notifies the electrician or the mechanic for this purpose, and assists them,
- he furnishes information concerning the tunneling machine to the foreman for purposes of the shift report.

d) Electrician, stationed at the plant.

He supervises and repairs, if necessary, all electric machinery, apparatus, and installations of the construction site,

- is a member of the maintenance shift,
- manages the material and spare parts store of the construction site,
- supervises the consumption,
- submits orders to the chief mechanic-electrician.

e) Mechanic for general work, stationed at the plant.

He operates the machine shop of the construction site, with the exception of the cutting tool shop,

- is a member of the maintenance shift, and conducts checks and the maintenance according to the maintenance shift checklist,
- localizes and repairs defects of the tunneling system if the machine operator is not qualified for this; notifies the chief mechanic-electrician and assists him if his own boring qualification is insufficient.

TABLE 6-4. EXCERPT FROM A SPECIFICATION SHEET FOR THE PERSONNEL, EXAMPLE (CONTINUED)

f) Mechanic for boring tools

He operates the cutting tool workshop,

- repairs, if possible, the dismantled bits,
- manages spare cutting tools and boring tool spare parts,
- has the administrative control over the boring tools.

The objects and the timing of inspections and maintenance can be seen from the operating instructions of the component manufacturers. Their combination and representation leads to a checklist, compare Table 6-5, to a tunneling shift checklist, and Table 6-6, maintenance checklist. Both lists given here are examples.

TABLE 6-5. SAMPLE OF A TUNNELING SHIFT CHECKLIST

Date:............	Shift:.........	Foreman:...........

Tunneling machine	checked	serviced
cutting tools:		
cutters, bearings, holders	....	....
water jets	....	....
reduction gear oil	....	....
lubrication oil	....	....
lube oil filter	....	....
main bearing seal	....	....
hydraulic fluid container	....	....
hydraulic hoses, pipes	....	....
hydraulic oil filter	....	....
....	....	....
....	....	....
....	....	....
electric cable connections	....	....
conveyor belts		
basic machine	....	....
trailers	....	....
ventilation		
....	....	....
dust collector		
....	....	....
Transfer belt		
....	....	....
Loading belt		
....	....	....
Train switching system		
....	....	....
Muck cars		
....	....	....

TABLE 6-6. SAMPLE CHECKLIST FOR MAINTENANCE SHIFT

Date:............ Foreman:..................

	checked	serviced
Tunneling machine		
Cleaning		....
all inspections and maintenance according to tunneling shift checklist executed	....	....
buckets - scrapers	....	....
water filter	....	....
hydraulic fluid, sampling	....	....
spikes on gripper pads	....	....
guide plates and scrapers		
....	....	....
....	....	....
Lubrication		
....	....	....
....	....	....
Installations		
Tracks		
....	....	....
compressed air, water, pump line		
....	....	....
air duct		
....	....	....

6.2.4 Checking of the Tunneling Operations

6.2.4.1 Work Progress - The organization of the work, and the technical operation condition of the system should be checked continuously. This checking permits the recognition of defects, especially of systematic ones, it is the basis for each improvement, always with a goal to use the tunneling system effectively, and with a high system utilization factor. In order to avoid an unnecessary increase of administrative activity at the construction site, all data for the checking and for the accounting as well as for the work, should be supplied by a single report. Table 6-7 shows, as example, the form of such a shift report.

The graphic representation of the course of work, Figure 6-2, which is based on the shift reports provides comprehensive information on the course of the work and on the causes of defects and interruptions.

TABLE 6-7. SHIFT REPORT SAMPLE

date of shift report ...... Sheet No. ....

Tunnel TM

foreman:..........
shift: tunneling/maintenance
time:..........
time:..........manhours

Position start of shift: m ..... h........
Tunneled : ......m .... h .
Position end of shift : m...... h........

TIME at site	Tunneling						system-related down-times, cause, with bit changes position and number of bit, tunnel meter		non-system related down-times, causes	
h to h	min	stroke travel length m	propelling feeding thrust Mp kg/cm^2	current A	hydraul. motor kg/cm^2	min		min		min
Total										

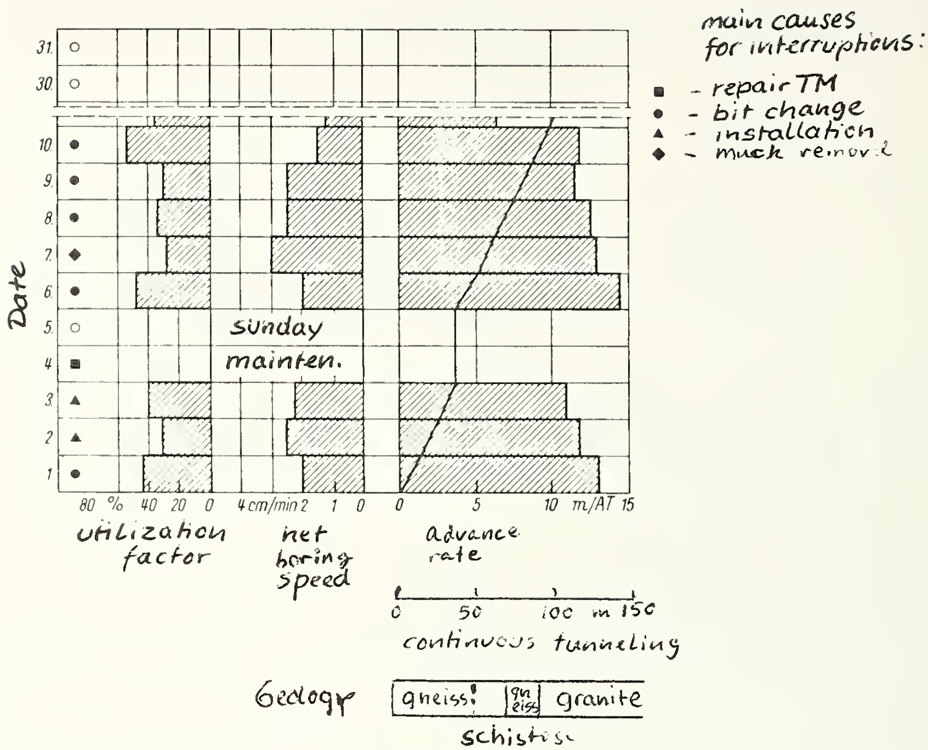


Figure 6-2. Graph of Work Progress

6.2.4.2 Boring Tool Wear - The boring tools must be inspected and serviced according to the checklist. At the start of the tunneling, with rock changes and with strongly jointed rock masses, the inspections must be conducted more frequently. Under such conditions, inspection intervals of two to three hours are not unusual. Defective cutting tools must be replaced immediately.

Each exchange of bits is recorded in the shift report. The graphic representation of the cutting tool replacement for the individual rows of the cutting head, Figure 6-3, shows not only the wear of bearings and boring edges, but possibly also a defective installation of boring tool mountings or an irregularity in the geometric shape of the head.

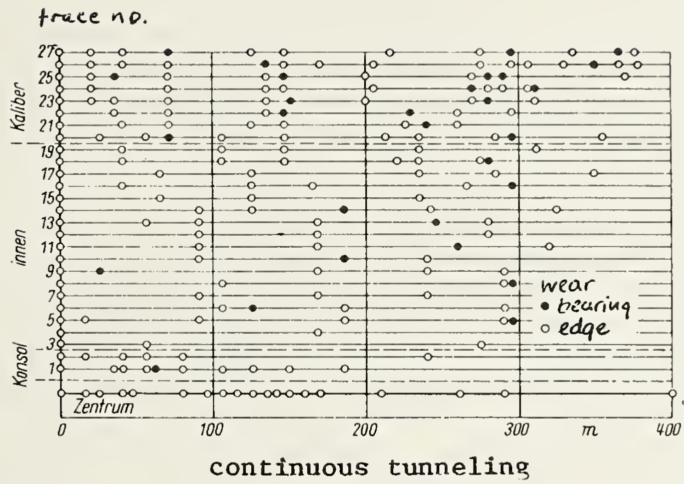


Figure 6-3. Graphic Representation of Cutting Tool Change

7. USE OF MECHANICAL TUNNELING

7.1 ADVANTAGES AND DISADVANTAGES

Mechanical tunneling should be used when it has advantages in comparison with the conventional methods. Usually, economical advantages are the basis of such considerations. However, time savings, savings with regard to personnel, or avoidance of emissions may also count.

Mechanical tunneling has advantages because:

- it causes little noise and is free of vibration, does therefore not impair the living conditions in residential and business areas, and does generally not cause damage by vibration;
- the stability of a mechanical tunnel-bored profile is larger than that of a blasted one, and because the fracture zone which possibly may form around the tunnel is smaller, with favorable consequences with regard to the supporting requirements, the labor market, and the construction costs;
- at least for the tunneling with larger cutting diameters fewer personnel are necessary, with favorable consequences for the labor market and the construction costs;
- the hiring and keeping of workers is less problematic due to the increased attractiveness of the physically safer work places, the almost eliminated heavy work, and the highly sophisticated tunneling operation.

Advantages may be there, not in every case, but for individual projects, if:

- greater tunneling performance can be achieved and thus an earlier termination of the tunnel project, resulting in reduced interest payments and an early start of operations or production;
- apart from a reduced requirement for tunnel support and for smaller numbers of personnel, construction costs may be saved because in a tunnel that must be lined no overbreak concrete must be installed, or, at least, less concrete than with a blasted profile; because a shorter construction time requires a shorter supply time for the conventional auxiliary installations; or because a smaller number of workers is affected by a possible inflation die to a shorter construction time.

The process also has disadvantages:

- the purchasing costs of a tunneling system, in particular those of a tunneling machine, are great. These, as well as the usual capital interest and amortization, require high charges for its operation;
- the boring tool costs in really hard and abrasive rock are high;

- between the signing of the order and a terminated assembly of a tunneling machine which is ready for operation, a time period of eight to twelve months must be anticipated. This would delay the start of the tunneling unless an already existing machine is available;
- the number of the personnel for a mechanical tunneling process is smaller, at least with large diameters, than with conventional tunneling, but the portion of specialists, however, such as electricians, mechanics, and hydraulic mechanics, is larger;
- the excavation section of a tunnel bored with a full-face boring machine is circular. Generally, this shape is favorable as far as static considerations are concerned. However, it is not suitable for all projects. The necessity for the installation of a tunneling floor increases the construction costs;
- the resulting cuttings are little or not suitable as fillers for concrete.

7.2 LIMITATIONS

The use of a tunneling machine may be limited technically or economically. The technical limit is reached, if:

- a fault zone exists which cannot be bored, or
- there is a requirement for the installation of supporting immediately behind the cutting head carrier, and the machine cannot be equipped with the necessary installation devices, either because the boring diameter is too small, or because the design of the machine is unsuitable even with a larger cutting diameter.

The economy may be limited due to the nature of the project, or by fault of the contractor. A limitation on the part of the project exists if:

- the tunnel is not long enough for the necessary installation work,
- the boreability is small due to the type of rock or type of rock mass,
- the boring tool costs are high,
- the non-system-related down-times necessary for measures concerning stabilization of the rock mass, or concerning removal of large amounts of water occur frequently and for longer periods of time, and if
- besides the actual tunneling other work must be carried out which impairs the use of the system.

The still permissible extent of these phenomena and characteristics which increase the construction costs cannot be given by a general formula. It depends on the project and on the time. Thus, the use of a tunneling machine may be unavoidable even for a short tunnel because constructions above it prohibit any kind of emission; or a tunnel must be bored in spite of small net boring speed and high boring tools because no workers can be found for the more dangerous and more heavy work involved in conventional tunneling.

Steps taken, or, more often, not taken by the contractor do not infrequently cause the exceeding of economical limits with regard to mechanical tunneling. The most important reasons are:

- wrong selection of tunneling machine,
- unsuitable cutting tools,
- insufficient cuttings removal;
- neglect of the special personnel-related and organizational requirements of a mechanical tunneling site.

7.3 SPECIAL TUNNELING PROJECTS

7.3.1 Large Sections

Most of the mechanical tunneling projects executed so far have a diameter between 3 and 5 m. This is the common diameter range for tunnels for water supply, sewers, cables, pipelines, or for high-pressure hydropower systems. Road, rail, and canal tunnels, as well as tunnels of low pressure hydropower systems require a significantly larger boring diameter if the whole section is to be cut. However, the possibility of employing one or several mechanical tunneling machines with small diameters, Figure 7-1, within the section area of such a tunnel should also be mentioned. The expectations in this method with regard to a very distinct reduction of the emission during the subsequent conventional expansion should not be over-optimistic. In the following, the use of full-face tunneling machines and of expansion machines with large diameters is dealt with. Available experience is shown in Table 7-1.

The cutting of a tunnel with a large diameter poses three special problems:

- the construction of the tunneling machine,
- the net boring speed, and
- the stability behavior of the rock mass.

The construction of a tunneling machine, Figures 7-2 to 7-6, with approximately 10 m diameter for the boring of really hard solid rock must be designed for a propelling force of a magnitude of 1000 Mp. The installed performance of the boring head drive will be around 1500 kW. These conditions pose extraordinary requirements for the stiffness of the cutting head bearing.

Depending on the manufacturer, the maximum rolling speed of the caliber bits of a cutting head is between 70 and 120 m/min. On the condition of 100 m/min, a head with a cutting diameter of 11.1 m would have a rpm of 2.87/min, and with only one boring tool on each row and from a boring head penetration of 3 mm, a net boring speed of only 0.52 m/h would result. With a utilization factor of 33%, the tunneling speed would amount to approximately 4.2 m/TD. This is, except for geological fault zones, not enough

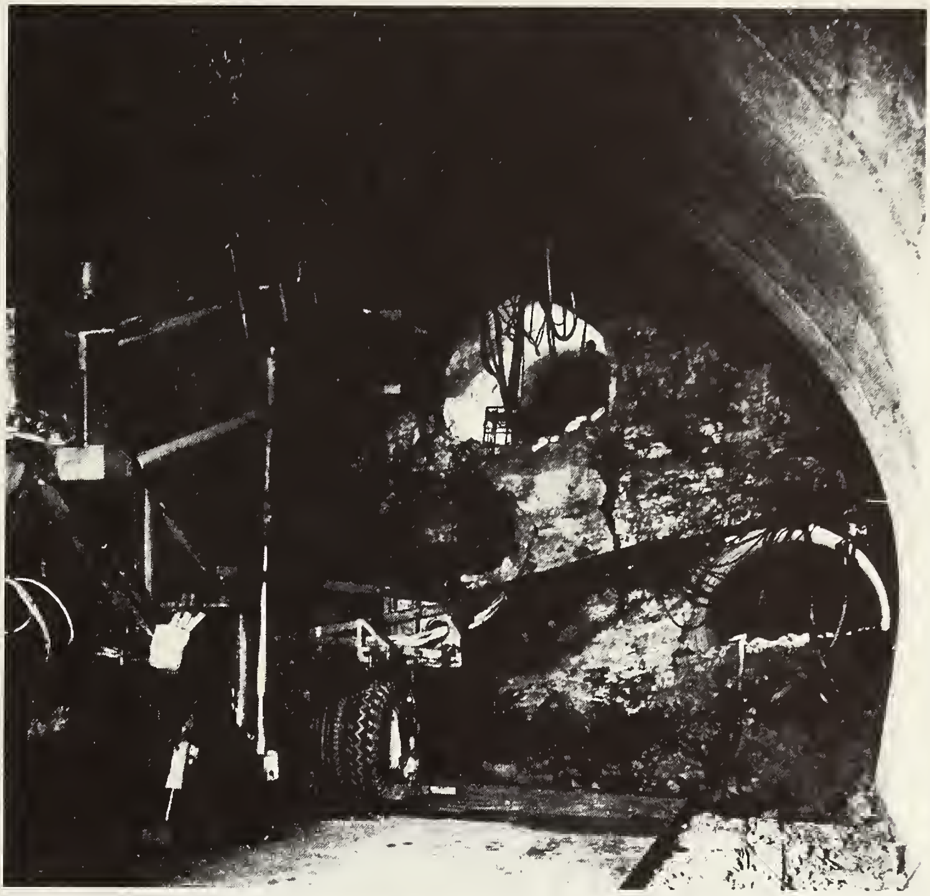


Figure 7-1. Excavation of a Road Tunnel After Previous Mechanical Excavation; One Drift Each in the Crown and the (Abutments) of the Tunnel

TABLE 7-1. MECHANICALLY EXCAVATED TUNNELS WITH LARGE DIAMETERS

cutting diameter m	project	type of rock	Year	illustration and literature
11.20	Feed tunnel, Mangla dam, irrigation and hydropower system	soft sand= stone, clay	1963/4	148[47]
10.25	Subway tunnel, Paris	limestone, marl sand	1965/68	149[47]
10.40	2nd Mersey tunnel, Liverpool	soft sand= stone	1967-70	150[47]
10.67	Heitersberg railway tunnel, Zurich	sandstone, clay, marl	1970-72	151[48]
10.46	Sonnenberg road tunnel, Lucerne	sandstone, marl	1970-73	152[47]

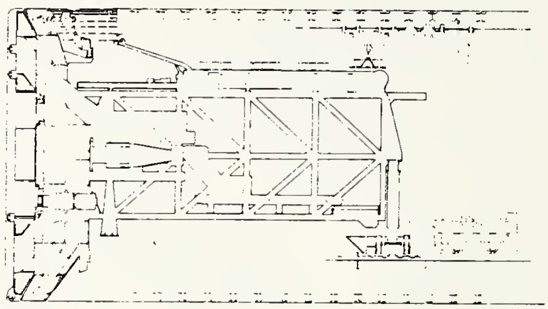


Figure 7-2. Robbins Tunneling Machine Model 371-110

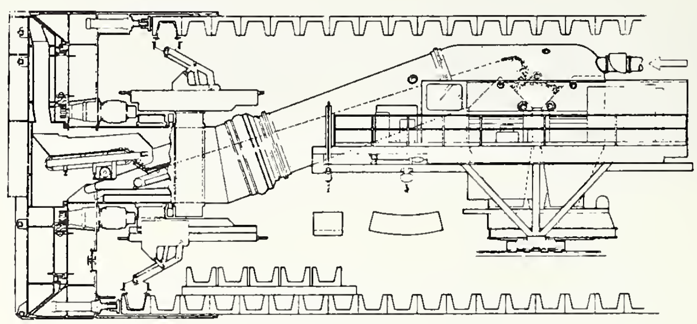


Figure 7-3. Robbins Tunneling Machine Model 341-111

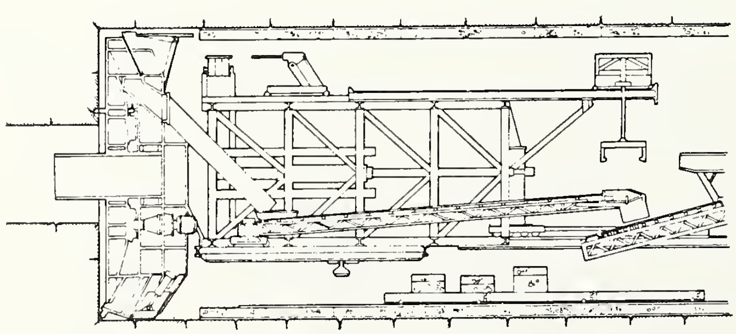


Figure 7-4. Robbins Tunneling Machine Model 371-110, modified

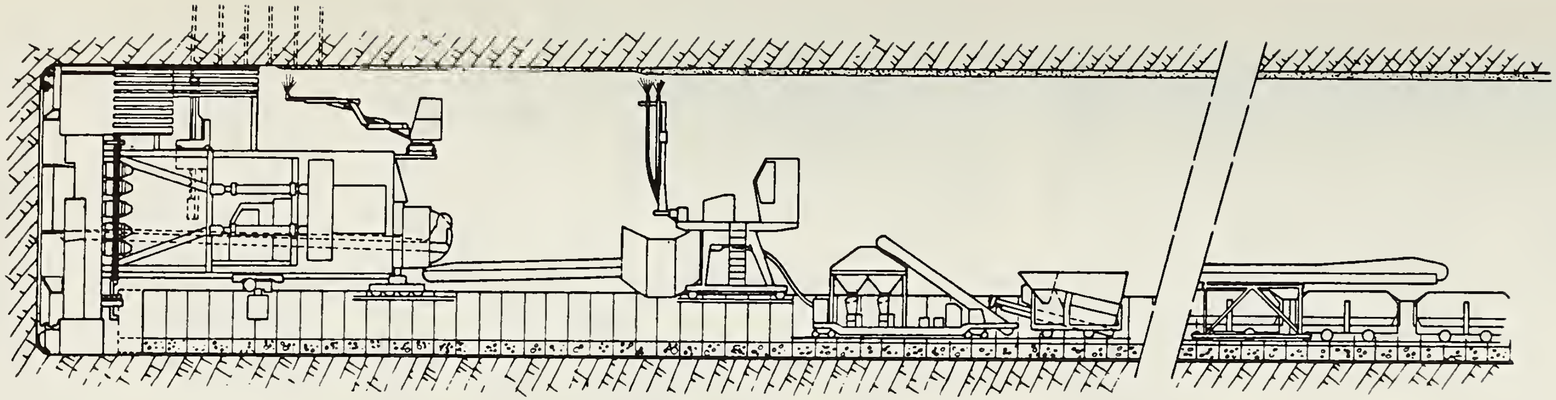


Figure 7-5. Robbins Tunneling Machine Model 352-128

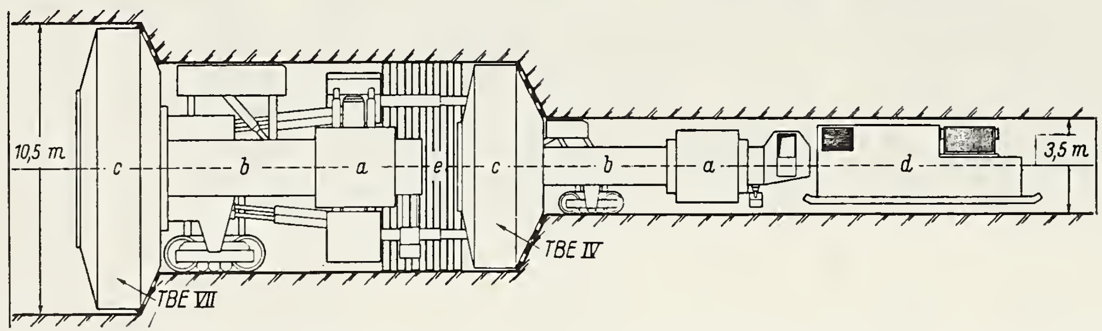


Figure 7-6. Wirth Tunneling Machine TBE 350/770 H and TBE 770/1046 for Two-Stage-Enlargement of a Tunnel.

a gripper device
b guide device
c cutting head
d drive unit with pump motors and hydraulic pumps for alternate use of enlargement machines
e stepwise support installation in a limited area between machines

Figures 7-2 to 7-6. Machines Build So Far for Large Cutting Diameters for a 3-shift operation. The question is, if and how it can be increased without increasing the utilization factor or the boring head revolutions or the average penetration force of a roller bit. This possibility is available. It can be realized by dividing the boring head into an inner circular disk and into an outer circular ring; The circular disk can rotate faster than the circular ring, for reasons of space, however, it can be equipped only with one bit per row. The circular ring must rotate slower than the circular disk, but it offers the possibllity to install Z bits on one cutting track. Since it is assumed that the net boring speed v_M of the inner cutting head disk with a radius r_{disc} is identical with that of the outer ring with the outside radius "r", and that the average boring tool penetration t_W is the same for all tools with identical penetration force F_e, the following applies

$$Z = \frac{r}{r_{disc}} \quad \text{and } r = Zr_{disc}$$

and, for the relation of the revolutions "n" of the two parts of the boring head:

$$\frac{n_{disc}}{n_{ring}} = \frac{r}{r_{disc}} .$$

The two-piece boring head has been used in practice already. However, it has proved unsuitable in hard solid rock, among other reasons, because rock pieces lodging between the two parts of the boring head have damaged or torn off boring tool holders. Also, this head design requires the use of a relatively large number of roller bits with console holders, Figures 7-7 and 7-8.

With the so-called reaming method, the tunnel section is divided into an inner circular section and into an outer circular ring, and each one of these sections is bored with a special cutting head or a special tunneling machine. The pilot machine with the cutting radius r_{disc} drives a gallery in the axis of the tunnel. Subsequently, the expansion machine with a ring-shaped cutting head with the radius r expands the pilot gallery centrically to the tunnel Figure 7-6. Whenever this method was used so far [50], the pilot gallery and the expansion were never cut simultaneously. Either, the pilot gallery was first bored in its full length, and subsequently expanded to a tunnel in one or two steps, or the pilot and expansion machines were boring alternately by using the same drive unit.

The expansion method is of advantage, if:
- a previously cut pilot gallery exists,
- a pilot machine is available at short notice when the contract is awarded, and if the delivery time for a machine with boring diameter of the tunnel is longer than the tunneling time of the pilot gallery, and if
- both machines can cut simultaneously.

Figures 7-7 and 7-8.
Two-part cutting head (Robbins)

Figure 7-7.
Overall view

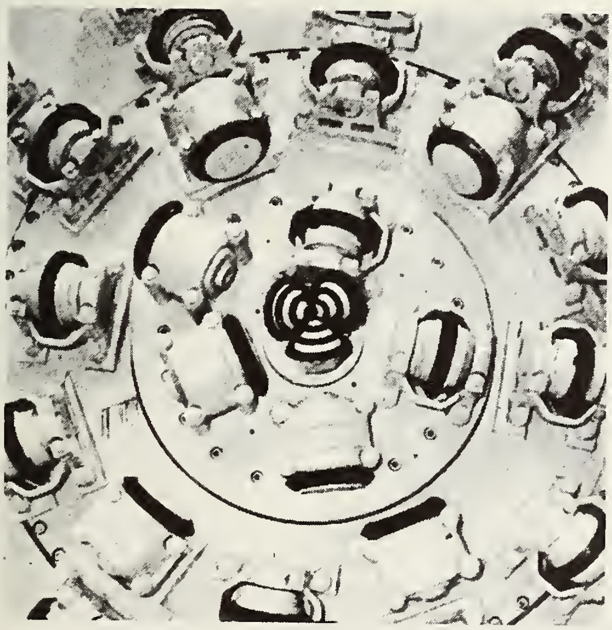


Figure 7-8.
Detail of inner part with three console bits, and part of the outer ring with four console bits

In any case, this method involves the problem of the rock mass stability between the pilot and the expansion of machines which should not be underestimated. If the expansion is not to be seriously delayed by the prior installation of a temporary support, only limited possibilities for the securing and the stabilization of the rock mass are available, i.e., simple steel ring supporting that can be easily dismantled, or shotcrete lining, but no combination of these methods, and also no anchor support. If two cutting steps follow each other directly, i.e., if a transportation distance does not have to be stabilized the use of a progressive supporting between the stages is suitable.

Whenever a temporary lining is not necessary in the area of the pilot machine, and if no lining is necessary between the pilot machine and the expansion machine, or if the progressive supporting is sufficient, an expansion system is more effective than a full-face cutting machine, even if the pilot and the expansion machine can only be operated alternately. The net cutting speeds that can be achieved with the pilot and with the expansion machine are greater. The utilization factors of each machine of the system is smaller, but the utilization factor of the system is usually larger since scheduled inspections, service, and repairs can be carried out on one machine of the system while the other machine is operating. Table 7-2 shows a relevant comparison.

A suitable tunneling machine for large diameters is a combination of the design of a full-face cutting machine with a two-piece boring head with the design of a system of a pilot and an expansion machine cutting at different times and at different locations. It consists of two units, a center machine and an expansion machine. The center machine can be aligned and braced within the frame box of the expansion machine. Its circular-disk-shape cutting head protrudes normally by approximately 2.5 meters from that of the expansion machine. The expansion machine can also be aligned, and is braced against the tunnel invert. Its circular-ring-shaped head counter-rotates relative to that of the center machine. Both machines cut simultaneously and independently of each other. However, their operational independence is limited in so far as during normal protrusion of the center machine of approximately 2.5 meters, the distance between the work faces of the two machines cannot fall below 2.0 meters, and may not exceed 3.0 meters. Over this length, the invert of the pilot gallery is covered, and if necessary, supported by the segmented boring head shield of the center machine. This design does not have the disadvantages of a tunneling machine with a two-piece boring head and of a system for traditional expansion; however, it combines their advantages. For example, a machine combination as in Table 7-3 could be used for a tunneling project with a cutting diameter of, for example, 11.1 m.

The stability behavior of the rock mass is more unfavorable with large cutting diameters, all other conditions being equal, than with a small boring diameter. The possibilities for the installation of a temporary support immediately behind the cutting head carrier are the less limited the larger the boring diameter. Also, special constructions for stabilization of the rock mass, such as installation aids, or a segmented shield, are easier to attach to a tunneling machine with a large boring diameter.

7.3.2 Inclined Galleries

Inclined galleries [51] are used in underground construction and in mining. In underground construction they serve as pipe conduits or pressure galleries of hydropower systems, ventilation galleries of conventional thermic power stations, ventilation galleries of road tunnels, or access, cable car, ventilation, and pipe galleries of underground installations with various purposes. In mining they are used for conveyor belts or ventilation.

TABLE 7-2. PERFORMANCE OF A FULLFACER AND OF AN EXPANSION SYSTEM WITH ALTERNATELY DRIVEN PILOT AND EXPANSION MACHINE WITH A BORING DIAMETER OF 11.1 m AND 24-h OPERATION

		Full-facer	Expansion System pilot machine	expansion machine
number bits/trace	number	1	1	3
boring diameter	m	11.1	3.7	11.1
max. rolling speed of caliber bits	m/min	100	100	100
boring head rpm	1/min	2.87	8.6	2.87
boring tool penetration	e.g. mm	3	3	3
boring head penetration	mm	appr. 3	appr. 3	appr. 9*)
net boring speed	m/h	appr. 0.52	appr. 1.55	appr. 1.55
utilization factor				
alternative 1	% h	33 8	16.5 4	16.5 4
alternative 2	% h	-	25	25 6
advance rate				
alternative 1	m/TD**)	appr. 4.2	appr. 6.2	appr. 6.2
alternative 2	m/TD**)	-	appr. 9.3	appr. 9.3

*Perfect geometry of boring head and uniform condition of all boring tools in one trace are a precondition.
**TD = Tunneling day

TABLE 7-3. SUITABLE TUNNELING MACHINE FOR A CUTTING DIAMETER OF 11.1 m

machine data		center machine	expansion machine
number bits/trace	number	1	3
boring diameter	m	3.7	11.1
max. rolling speed of caliber bits	m/min	100	100
boring head rpm	1/min	8.6	2.87
boring tool penetration	mm	3	3
boring head penetration	mm	3	9*)
net boring speed	m/h	appr. 1.55	appr. 1.55
utilization factor	% h	33 8	33 8
advance rate	m/VT**)	12.4	12.4

*Perfect geometry of boring head and uniform condition of all boring tools in one trace are a precondition.
**TD = Tunneling day

No matter by which method an inclined gallery is built conventionally, its execution always involves considerable danger for personnel and equipment. The excavated material will never all slide down to the bottom of the gallery. In a floor cover layer of varying thickness consisting of sand and small pieces, even larger pieces of rock lodge. The balance of this mass is unstable. It is very sensitive to even small vibrations, but especially to inflow of water. Parts of this deposit may start sliding in form of an avalanche. Pieces of rock falling out of the tunnel invert do not simply drop to the tunnel floor but will continue bouncing through the gallery.

These conditions which cannot be avoided make conventional tunneling of inclined galleries a dangerous enterprise. For this reason, it is not surprising that of the number of tunnel workers, that is decreasing anyhow, fewer and fewer are prepared to expose themselves to the danger and to the hard work involved in inclined galleries. This fact has opened the way for mechanical tunneling in the year 1968, under conditions, that were not ideal with regard to the boreability of the formations and the economy of the process.

Machines of the same design are used for the boring of inclined galleries as for horizontal mechanical tunneling. However, some parts are changed, and the machines must be equipped with a safety device to prevent sliding in galleries with steep inclinations. Two principles were observed during the boring of inclined galleries by conventional methods:

- tunneling should be done from below, with an excavation section that is as small as possible.
- if the excavation section prescribed by the project design is distinctly larger than the minimum excavation profile that is technically possible, the excavation should be done in two stages, one excavation process with the minimum work section from below, and subsequently an expansion to the designed excavation profile from above. With the exception of two mining projects in the United States, this method has been used until now also for the mechanical tunneling of inclined galleries.

With boring of tunnels from below whose inclination exceeds approximately 30°, and with rock masses which do not swell, the removal of boring can be made very simple. The chips can be flushed out from the steep floor. The buckets of the boring heads as well as the basic machine and the trailer conveyor belt are dismantled before the machine is put into operation. A bridging and a loading belt are not necessary.

With a tunnel inclination exceeding 20°, the tunneling machine must be equipped with a safety device against sliding. This will secure the tunneling machine against sliding back when the bracing devices are relocated. Three different systems are used, singly or in combination:

- steel cams attached excentrically to the boring head

carrier or the machine frame which move forward and wedge the machine when it is sliding back,
- an auxiliary gripping system which becomes immediately effective when the effect of the main bracing is reduced for any reason, and
- segments installed in the tunnel floor against which the tunneling machine can be braced during the relocation of the machine.

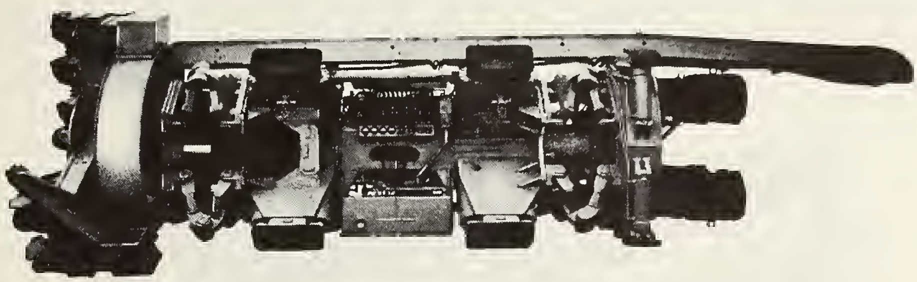


Figure 7-9. Tunneling machine with slip safety attached to box of combination gear

The auxiliary gripping system is the most frequently used design for a safety device against sliding. It can either be attached to the inner machine frame that is rigidly connected with a boring head, Figure 7-9, or can be arranged behind the basic machine separated from it by design, Figures 7-10 and 7-11. The main components of an auxiliary gripping system built into the frame are the gripper shoes, the springs pressing them against the tunnel invert, as well as hydraulic rams which, when activated, cancel the force of the springs. While the machine is braced, i.e. during the boring process, these presses are also activated, i.e. the auxiliary gripping is not effective, and is moved forward being attached to the basic machine. After the boring of one system, and whenever the pressure in the gripping system circuit of the hydraulic system drops, the presses of the auxiliary gripping released, and the hydraulic fluid leaves those cylinders, and the gripper shoes are pressed against the invert by the force of the strong springs. The auxiliary gripping unit is connected with the boring head carrier through push and pull rods.

The excentric cams and the auxiliary gripping have the disadvantage that they become ineffective as soon as the tunneling machine cannot be braced anymore, as, for example, in very loose rock masses, or rock masses with plastic behavior, or in fault zones that cannot be bored. If the effectiveness of the basic machine gripping and of the auxiliary gripping cannot be restored by means of a shotcrete, or by cushioning the gripper shoes with hardwood, a special safety device against sliding is necessary. Two solutions are known, i.e. the support of the tunneling machine by two-piece floor segments, or by a supporting tube.

With the first-mentioned process, Figure 7-12, a two-piece floor segment is installed behind the tunneling machine, and is anchored to the floor. During the cutting process, the machine is braced against the floor segments by means of two hydraulic presses that serve for support as well as for forward thrust. After one stroke is bored, first one, and then the other half of a new segment is installed which is as long as the length of one stroke. During the installation of one half of a segment, the machine supports itself by means of a press braced against the other half. If this process is applied over the whole length of the gallery, the floor segments can be made in form of a box with a channel for flushing out the chips, and possibly with an opening that can serve as a ventilation duct.

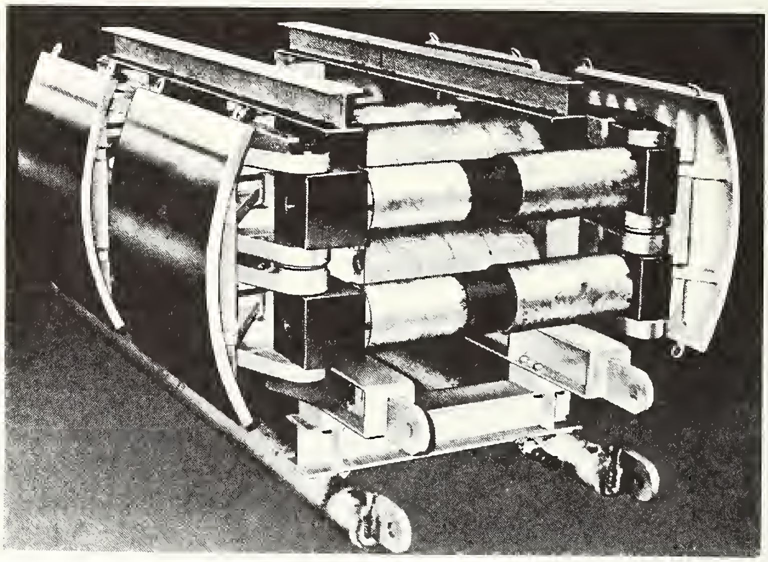


Photo:
Wirth & Co.

Figure 7-10. Auxiliary gripping system for installation between basic machine and trailer

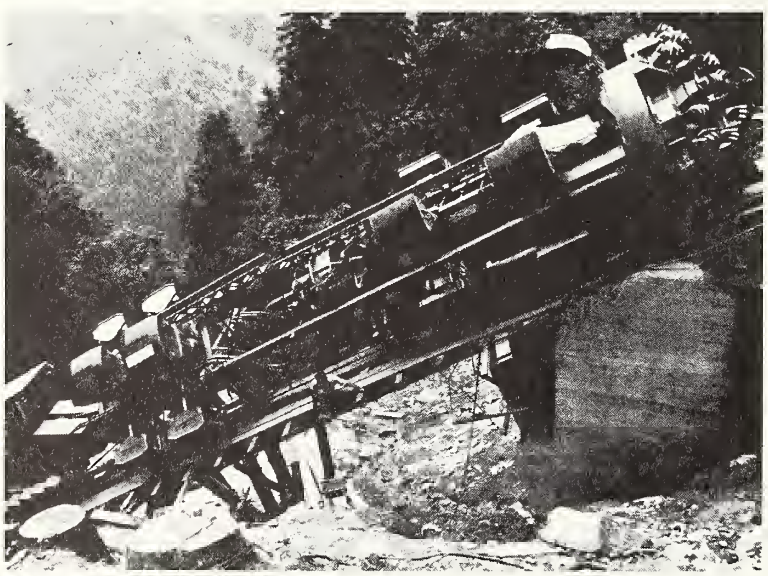


Photo:
Wirth & Co.

Figure 7-11. Basic machine with auxiliary gripping system, assembled

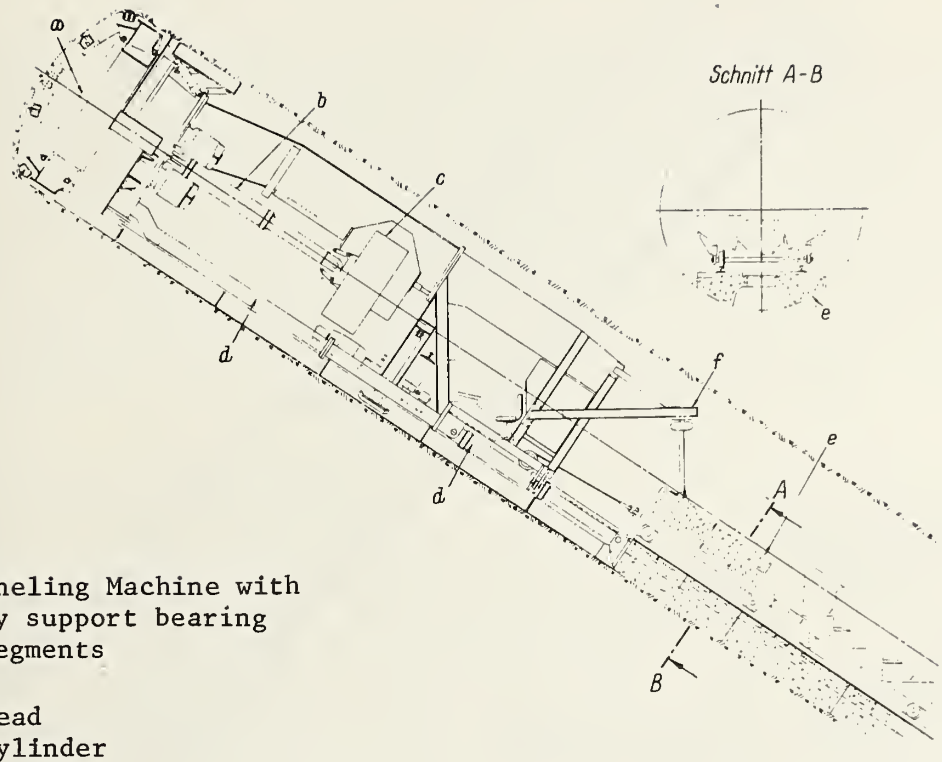


Figure 7-12
Robbins Tunneling Machine with an auxiliary support bearing on invert segments

a boring head
b propel cylinder
c gripper pads
d auxiliary support
e invert segment halves
f monorail crane for installation of invert segments

With the second process, Figure 7-13, a support tube is installed between the basic machine and the first trailer which is longer than the rock mass zone that cannot be braced. A two-piece auxiliary gripping system axially adjustable is installed on this support pipe. This auxiliary support system remains in the stable rock during the boring process. During the tunneling, the rear part of this system is braced. The front part is clamped on the support pipe, and is thus connected with the tunneling machine. The propel cylinders between the two parts of the auxiliary gripping push forward the support tube with the tunneling machine. After one travel length of these cylinder jacks is cut, the support tube is clamped to the rear part of the auxiliary gripping system, and the front part is loosened and pulled back. The system again is ready for boring after the front part of the auxiliary gripping system is clamped onto the support tube, and after the connection between the rear part and the support tube is loosened. The rear part of the auxliary gripping system remains braced also during the relocation. The equipment of both parts with gripper shoes permits the climbing-up of the auxiliary gripping unit on the support tube while the tunneling machine is held by itself.

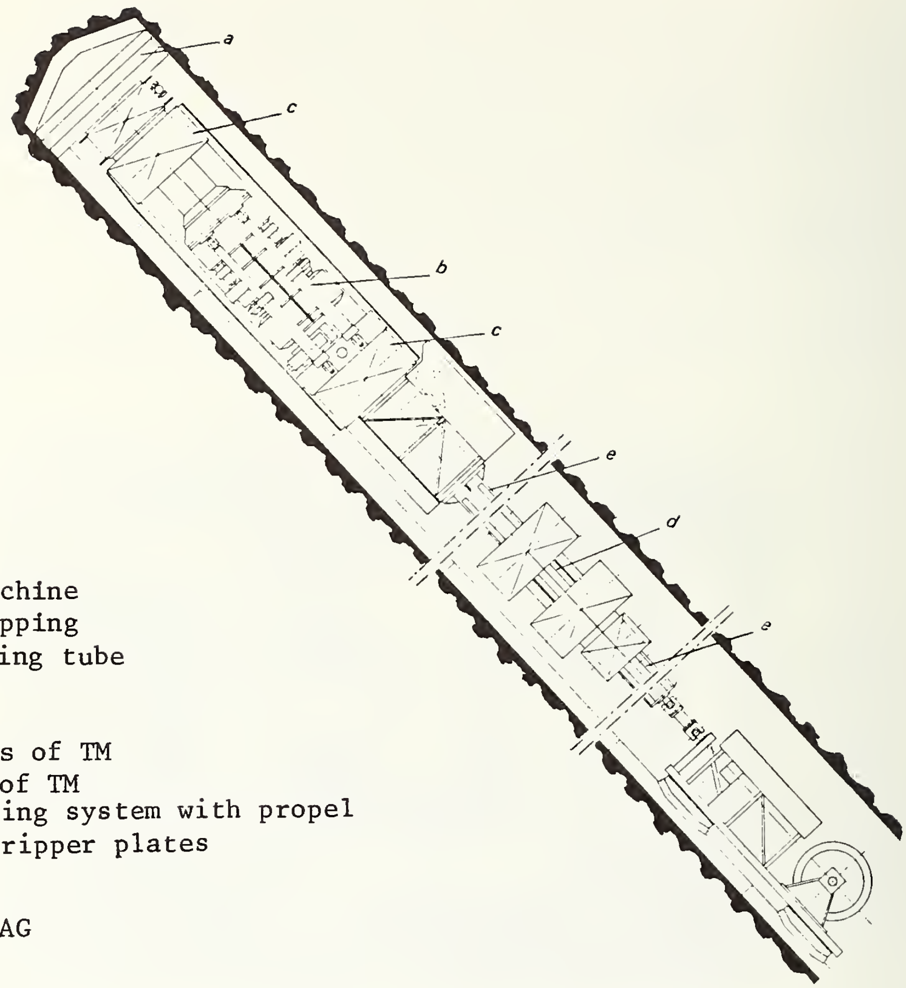


Figure 7-13
Demag Tunneling Machine
with auxiliary gripping
system and supporting tube

a boring head
b propel cylinders of TM
c gripper plates of TM
d auxiliary gripping system with propel cylinders and gripper plates
e suppport tube

Design: Demag AG

There are three possibilities to employ tunneling machines for the construction of shafts with large diameters. The first two possibilities correspond to the principles of conventional tunnel boring:

- boring of a pilot gallery from below, with subsequent conventional expansion, preferably from above.
- boring of a pilot gallery from below, with subsequent mechanical expansions from below or, under certain circumstances, from above.

The last possibility is less recommended:

- full-facing of the section from below, unless the project makes it necessary.

The advantages of the pilot gallery are generally recongnized. The decision in favor of a conventional, or of a mechanical expansion depends on various condition, such as the intended use of the gallery and its required quality, economy, finish date, as well as availability of working personnel and of an expansion machine.

In case of mechanical expansion, a decision must be made whether the tunneling machine will be employed from below or from above. In both cases, the chips are flushed out towards the lower end. With expansion from above, the problem must be solved of removing the chips from the corner formed by work face and floor into the pilot gallery in the center of the tunnel axis. If chips and water remain in this corner, heavy boring tool wear would be unavoidable. In addition, the boring head penetration would be reduced. The attachment of special scrapers in front of the boring tools for purposes of cleaning the effective range of the bits is mandatory, Figure 7-14. Expansion from below requires a tunneling machine with a safety device against sliding.

With mechanical tunneling of an inclined gallery from below, and with mechanical expansion of a pilot gallery from below or from above, the resulting chips are flushed out via the gallery floor if the inclination is large enough. The quantity of water must be controlled in such a way that a continuous flushing is guaranteed, and avalanches are avoided. In order to avoid uncontrolled movements of larger rock, the floor section necessary for the flushing can either be covered with wire mesh, or a steel box closed on top is installed on the floor. In special cases, as for example, in galleries with a small inclination, a conveyor chute is necessary. This chute is subject to heavy wear during the removal of chips [52]. At the lower end of the gallery the chips and the flushing water are caught in special cars, Figure 7-15. Before entering public water ways, the overflowing flushing water must at least be pre-treated in several sedimentation basins.

For the transportation of personnel and supplies, a transportation system is necessary in the gallery, either as a cable car, or as a monorail conveyor. For this purpose, either tracks must be installed on the floor of the gallery, or a rail in the crown of the gallery. The drive winch for the transport system is installed at the foot of the gallery, and a guide pulley for the cable is attached to the rear-most trailer of the tunneling machine.

The floor covering, the tracks and the rail, and the supply lines, among them the pump lines for the flushing water as well as the air duct, are installed continuously behind the tunneling machine as with a horizontal tunneling process.

7.3.3 Tunneling in Mines

Long after the first mechanical production in mining, and after the first mechanical wall mining, a rock tunnel was excavated by means of a tunneling machine for the first time in 1971 in West German coal mining.

Figure 7-14. Scrapers attached to the boring head of an enlargement machine in front of the boring tools

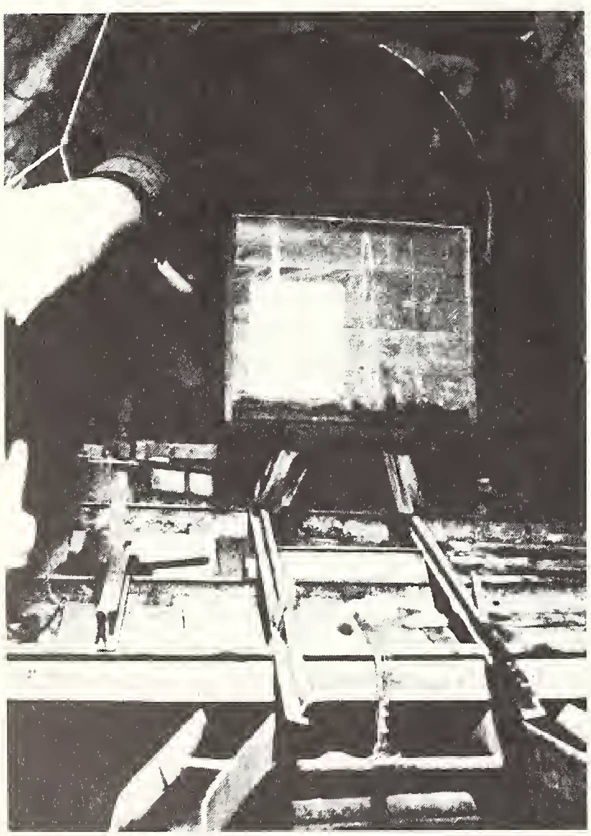


Figure 7-15
Bottom chamber of a bored inclined shaft with cable car and flushing water chutes

The delayed introduction of mechanical tunneling for horizontal or inclined transportation and ventilation of tunnels and shafts can be explained by the fact that its advantages in comparison to conventional methods are not as obvious for coal mining as they are for underground construction. In addition, a certain reverence for tradition in coal mining may have favored the blasting method.

The advantages of mechanical tunneling for rock tunnels in mining operations are not directly evident because the process is more expensive than conventional methods:

- the bored section is circular, its use as transportation tunnel with tracks requires filling of the floor with chips.
- the tunneled sections must always be supported. Steel-lining is the rule, and even in stable sandstone anchor supporting for purposes of head-protection is hardly permitted; the advantages converning the relatively small disturbing effect of mechanical tunneling can only be used up to a certain limit because the support must frequently be dimensioned with regard to the subsequent effect of the mining operation, and not only with regard to the one-time redistribution of forces and stresses occuring during tunneling, and to the secondary stress distribution.

- the tunneling of rock tunnels in a mine is not an individual project but marginal within the framework of an operation directed towards production, the scarcity of empty cars will effect the tunneling before the mining, and coal will have transportation priority above the chips and the tunneling supply; under these conditions, the non-system-related down-times will become longer.
- the existing regulations of the mining authority geared to the excavation and blasting operations limit the freedom of the contractor during the planning and execution of a tunneling project in comparison with underground construction. Special permits are not easy to obtain.
- the personnel requirements of a tunneling shift amounting to 10 to 11 miners, and to 2 to 3 supervisors are high, and although the labor cost amounts to only about 2/3 of that for conventional tunneling, it is however high calculated absolutely, and in comparison with heavy construction.

However, there are also advantages:

- the excavation speed is distinctly higher with mechanical tunneling than with the blasting process. Depending on the portion of sandstone, sandy shale, and shale, an average tunneling performance of 15 to 25 m/WD can be assumed for boring diameters of approximately 5 m, as opposed to 5 to 6 m/WD during conventional excavation of a section of 16 to 20m^2. The exploration of a new field or of a new gallery can be done faster, and capital costs can be saved with the later start of an excavation process.
- mechanical tunneling reduces the danger of accidents, the greater physical safety of the work place may slow down

the change of miners to other jobs, and may facilitate the hiring of new personnel.

- a systematically installed support with bolted steel rings flush against the invert usually without backfill, reduces the maintenance costs, Figure 7-16.
- The planning and the execution of a mechanical tunneling process in mining operations is an extraordinarily interesting and demanding job for an engineer. The planners of the coal mines must design a course for the horizontal or inclined galleries to be cut that is geared to the machine and avoids small curve radii. A planning team composed of engineers of both sides (the coal mine and the contractor), will be confronted with all problems of mechanical tunneling, and will have to make special decisions, for example on:
  - the tunneling machine with segmented cutting head shield, efficient supporting aids, explosion-protective electrical system, and a hydraulic system operated with a non-flammable fluid,
  - a fresh-air supply designed for degassing,
  - a dust trapping system which will meet the strict requirements of the MAK for mining, or on
  - the air conditioning at the point of operation under consideration of the heat generated by the tunneling system and the rock mass.

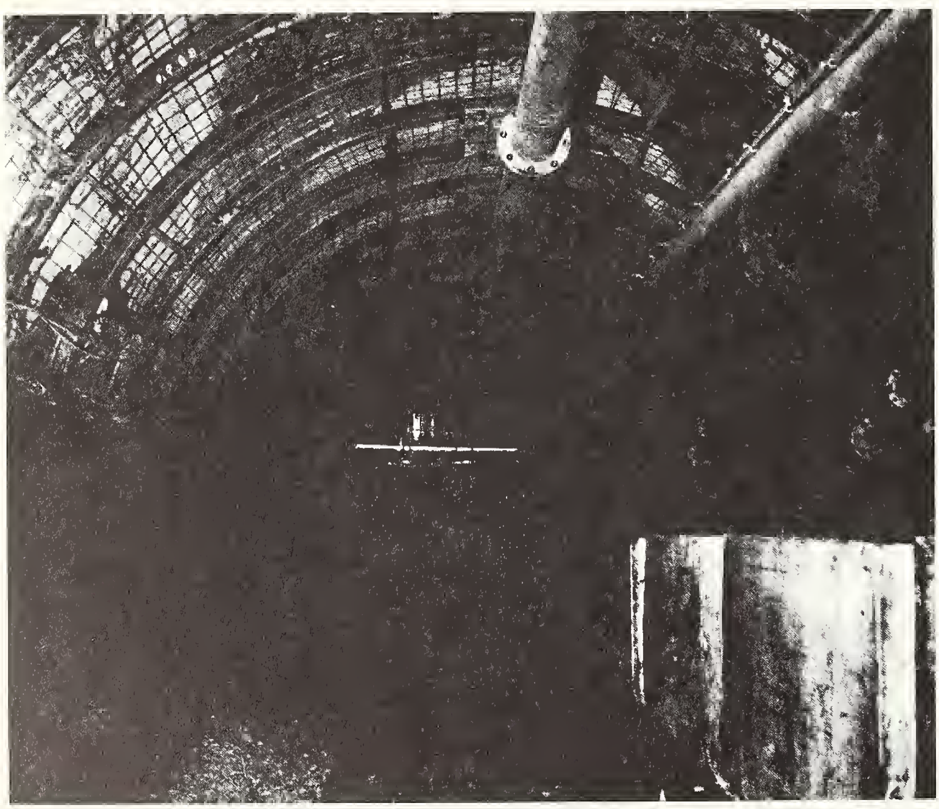


Figure 7-16
Bored and systematically supported heading in a coal mine

Also, during the tunneling, constant contact, and close cooperation between the representative for the tunneling project and the coal mine management is unavoidable in order to meet the requirements of mechanical tunneling - an auxiliary process in a coal mine operation - concerning the removal of chips and the supply with as few restrictions as possible.

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APPENDIX

REPORT OF NEW TECHNOLOGY

This report is a complete translation of the book written by Werner Rutshmann entitled "Mechanischer Tunnelvortrieb im Festgestein." The work performed under this contract, while leading to no new inventions, will be beneficial to engineers, managers and students associated with the tunneling profession on the principles, practical issues and operation of mechanized tunneling. The information contained in this report fills in the gap created by the lack of knowledge of tunnel designers and project managers of guidelines on how to consider the area of mechanized tunnel excavation in their everyday work.

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