

2nd Edition



Mechanised Shield Tunnelling

Bernhard Maidl
Martin Herrenknecht
Ulrich Maidl
Gerhard Wehrmeyer

 WILEY-BLACKWELL

 **Ernst & Sohn**
A Wiley Company

B. Maidl, M. Herrenknecht, U. Maidl, G. Wehrmeyer
Mechanised Shield Tunnelling

2nd Edition

Mechanised Shield Tunnelling

Bernhard Maidl
Martin Herrenknecht
Ulrich Maidl
Gerhard Wehrmeyer

Prof. Dr.-Ing. Bernhard Maidl
mtc – Maidl Tunnelconsultants GmbH & Co. KG
Fuldastr. 11
47051 Duisburg

Dr.-Ing. E.h. Martin Herrenknecht
Herrenknecht AG
Schlehenweg 2
77963 Schwanau

Dr.-Ing. Ulrich Maidl
mtc – Maidl Tunnelconsultants GmbH & Co. KG
Fuldastr. 11
47051 Duisburg

Dr.-Ing. Gerhard Wehrmeyer
Herrenknecht AG
Schlehenweg 2
77963 Schwanau

Translated by David Sturge, Kirchbach, Germany

Cover: Herrenknecht-EPB-Shield S-300 Madrid M-30
By-Pass Sue Túnel Norte, Madrid, Spain
Photo: Herrenknecht AG

Library of Congress Card No.:
applied for

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Bibliographic information published by
the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on
the Internet at <<http://dnb.d-nb.de>>.

© 2012 Wilhelm Ernst & Sohn, Verlag für Architektur und technische Wissenschaften GmbH & Co. KG, Rotherstr. 21, 10245 Berlin,
Germany

All rights reserved (including those of translation into other languages). No part of this book may be reproduced in any form – by
photoprinting, microfilm, or any other means – nor transmitted or translated into a machine language without written permission from
the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered
unprotected by law.

Coverdesign: Sonja Frank, Berlin, Germany
Produktion management: pp030 – Produktionsbüro Heike Praetor, Berlin
Typesetting: Reemers Publishing Services GmbH, Krefeld
Printing and Binding: Strauss GmbH, Mörlenbach

Printed in the Federal Republic of Germany.
Printed on acid-free paper.

2nd Edition
Print ISBN: 978-3-433-02995-4
ePDF ISBN: 978-3-433-60150-1
ePub ISBN: 978-3-433-60149-5
mobi ISBN: 978-3-433-60148-8
o-Book ISBN: 978-3-433-60105-1

***„A plan whatever it may be
must be made for the bad ground,
it must be calculated to meet all exigencies, all disasters
and to overcome them after they have occurred.“***

*Marc Isambard Brunel
on suggested improvements
after the flooding of the Thames Tunnel in 1831.*

The authors

1	Introduction	B. Maidl
2	Support of the cavity and settlement	U. Maidl
3	Construction and design methods	G. Wehrmeyer
4	Excavation tool and excavation process	M. Herrenknecht G. Wehrmeyer
5	Muck removal	M. Herrenknecht G. Wehrmeyer
6	The tunnel lining	B. Maidl
7	Shield tail sealing, grouting works	G. Wehrmeyer
8	Open shields	B. Maidl
9	Compressed air shields	B. Maidl
10	Slurry shields	U. Maidl
11	Earth pressure shields	U. Maidl
12	Convertible shields	B. Maidl
13	Special shields and special processes	B. Maidl
14	Guided microtunnelling processes	B. Maidl
15	Surveying and steering	M. Herrenknecht G. Wehrmeyer
16	Workplace safety	B. Maidl
17	Partnering contract models and construction	U. Maidl
18	Process controlling and management	U. Maidl
19	DAUB recommendations for the selection of tunnelling machines	U. Maidl

Foreword to the 2nd Edition

The rapid progress of mechanised tunnelling to market leadership has continued – even exceeded predictions; the general worldwide trend in construction towards mechanisation and automation clearly demanded a similar development in tunnelling. It is significant that even in Austria, the traditional home of the New Austrian Tunnelling Method (NATM), mechanised tunnelling has also established its position in the last decade. Occupational health and safety, faster advance rates, improved cost security and labour-saving opened opportunities for mechanised tunnelling on a few major projects – normally in competition with conventional construction methods.

So it is appropriate that this book should now be revised, 20 years after its first publication. The extent of innovations and practical experience led to a complete reworking. Incidentally, the book “Hardrock Tunnel Boring Machines“, which appeared in 2008, already offered access to the newest technology in the area of tunnel support. The team of authors has adapted the content to the latest technology and has been supplemented to provide the necessary specialist knowledge.

The original authors B. Maidl and M. Herrenknecht also worked on this edition. We have gained my son Dr.-Ing. U. Maidl and my former doctoral candidate Dr.-Ing. G. Wehrmeyer, who have particularly devoted themselves to new developments.

I am very thankful that I could still rely on the help of my former employees Herr H. Schmidt and Herr G. Kaufhold for the new revision. I would like to thank Herr Dipl.-Ing. M. Griese from MTC, who helped a great deal with the detailed work and overall coordination. I would also like to thank my grandson Max Maidl for his assistance. A thank-you to all, especially the author colleagues and the publisher.

Bochum, January 2011

Bernhard Maidl

Table of Contents

The authors	VII
Foreword to the 2nd Edition	IX
1 Introduction	1
1.1 Basic principles and terms	3
1.2 Types of tunnel boring machine according to DAUB	5
1.2.1 Categories of tunnelling machines German association for underground construction (TVM)	5
1.2.2 Tunnel boring machines (TBM)	6
1.2.2.1 Tunnel boring machines without shield (gripper TBM)	6
1.2.2.2 Reamer tunnel boring machines (ETBM)	7
1.2.2.3 Tunnel boring machines with single shield (TBM-S)	7
1.2.3 Double shield machines (DSM)	7
1.2.4 Shield machines (SM)	8
1.2.4.1 Shield machines with full-face excavation (SM-V)	8
1.2.4.2 Shield machines with partial face excavation (SM-T)	11
1.2.5 Adaptable shield machines with combined process technology (KSM)	11
1.2.6 Special types	12
1.2.6.1 Blade shields	12
1.2.6.2 Shields with multiple circular cross-sections	12
1.2.6.3 Articulated shields	12
1.2.7 Remarks about the individual types of tunnelling machines with diagrams	12
1.2.7.1 Tunnel boring machines (TBM)	12
1.2.7.2 Double shield machines (DSM)	13
1.2.7.3 Face without support (SM-V1)	13
1.2.7.4 Face with mechanical support (SM-V2)	14
1.2.7.5 Face with compressed air (SM-V3)	14
1.2.7.6 Face with slurry support (SM-V4)	14
1.2.7.7 Face with earth pressure support (SM-V5)	14
1.2.7.8 Face without support (SM-T1)	15
1.2.7.9 Face with partial support (SM-T2)	15
1.2.7.10 Face with compressed air support (SM-T3)	15
1.2.7.11 Face with slurry support (SM-T4)	16
1.2.7.12 Adaptable machines (KSM)	16
1.3 Origins and historical developments	16
2 Support of the cavity and settlement	25
2.1 Support of the face	25
2.1.1 Natural support	25
2.1.2 Mechanical support	26

2.1.3	Compressed air support	26
2.1.4	Slurry support	28
2.1.5	Earth support	32
2.1.6	Calculation models	32
2.2	Support of the cavity at the shield	37
2.3	Support of the cavity behind the shield	37
2.4	Settlement and damage classifications	39
2.4.1	Empirical determination of the settlement	41
2.4.2	Numerical models for the calculation of settlement	43
2.5	Heave and compaction	46
3	Design and calculation methods	47
3.1	Constructional parts of the shield	47
3.2	Loading on the shield	50
3.2.1	Loading on the shield skin	51
3.2.2	Loading on the pressure bulkhead	53
3.2.3	Loading from the thrust cylinders	54
3.3	Calculation of the necessary thrust force	54
3.3.1	Resistance to advance through friction on the shield skin	55
3.3.2	Resistance to advance at the front shield	56
3.3.3	Resistance to advance at the face through platforms and excavation tools	57
3.3.4	Resistance to advance with slurry support, earth support and compressed air support	58
3.3.5	Resistance to advance from steering the shield	58
3.3.6	Summary	59
3.4	Empirical values for the dimensioning of the shield and the thrust cylinders	60
3.5	Calculation and dimensioning basics	61
3.6	Regulations and recommendations for the design of shields	62
4	Excavation tools and excavation process	63
4.1	Excavation tools	64
4.1.1	Hand-held tools	64
4.1.2	Cutting edges	64
4.1.3	Scrapers	65
4.1.4	Drag picks, flat chisels, round chisels, rippers	66
4.1.5	Disc cutters, discs	68
4.1.6	Buckets	70
4.2	Excavation process	71
4.2.1	Tunnelling without cutting wheel	72
4.2.2	Manual digging	73
4.2.3	Partial-face mechanical excavation	73
4.2.4	Mechanical full-face excavation	78
4.2.5	Hydraulic excavation	91
4.2.6	Alternative excavation processes	91

5	Muck removal	93
5.1	Preparation for transport	93
5.2	Removal from the face	93
	5.2.1 Open shield machines	95
	5.2.2 Shield machines with pressure chamber	95
5.3	Transport along the tunnel and up shafts	101
	5.3.1 Open transport	101
	5.3.2 Piped transport	102
5.4	Quantity determination and measuring equipment	105
5.5	Separation	106
	5.5.1 Separating process	108
	5.5.2 Separating devices	108
5.6	Suitability of the muck for landfill	115
6	The tunnel lining	117
6.1	General	117
6.2	Construction principles for the tunnel lining	118
	6.2.1 Single-layer and Double-layer construction	118
	6.2.2 Watertight and water draining construction	119
6.3	Segmental lining	121
	6.3.1 General	121
	6.3.2 Constructional variants	122
	6.3.2.1 Block segments with rectangular plan	122
	6.3.2.2 Hexagonal segments	126
	6.3.2.3 Rhomboidal and trapezoidal segment systems	126
	6.3.2.4 Expanding segments	127
	6.3.2.5 Yielding lining systems	128
	6.3.3 Joint details	132
	6.3.3.1 Longitudinal joints	132
	6.3.3.2 Ring joints	135
	6.3.4 Steel fibre concrete segments	139
	6.3.5 Filling of the annular gap	139
	6.3.5.1 Filling with gravel	139
	6.3.5.2 Mortar grouting	139
	6.3.6 Measures to waterproof tunnels with segment linings	141
	6.3.6.1 Gaskets	141
	6.3.6.2 Grouting	143
	6.3.7 Production	143
	6.3.8 Damage	144
	6.3.8.1 Damage during ring building	145
	6.3.8.2 Damage while advancing the machine	145
	6.3.8.3 Damage in the shield tail seal	146
	6.3.8.4 Damage after leaving the shield	146
	6.3.8.5 Repair of damage	147

6.4	In-situ concrete lining	147
6.4.1	General.	147
6.4.2	Construction.	148
6.4.3	Concreting	148
6.5	Injected concrete, Extruded concrete	149
6.6	Shotcrete layers as the final lining	155
6.7	Structural calculations	156
7	Shield tail sealing, grouting works	157
7.1	Shield tail seals	157
7.1.1	Plastic seals	158
7.1.2	Steel brush seals.	160
7.1.3	Outer shield tail seals.	161
7.1.4	Elastically supported face formwork for the extrusion process	161
7.2	Grouting process.	162
7.2.1	Requirements.	162
7.2.2	Conception.	163
7.2.3	Grouting systems.	164
7.2.4	Grout	168
7.3	Grouting for ground improvement	169
7.3.1	Machinery and equipment	169
7.3.2	Grout	171
7.3.3	Grouting work at the Channel Tunnel	173
8	Open shields.	177
8.1	Shield construction	177
8.1.1	Hand shields	177
8.1.2	Part-face excavation	179
8.1.3	Full-face excavation	181
8.2	Projects	181
8.2.1	Example: Eurotunnel – under the English Channel, 1988 to 1991	181
8.2.2	Arrowhead Tunnel	191
8.3	Double shields [203].	195
8.3.1	Development	195
8.3.2	Functional principle.	195
8.3.3	Special features	196
8.3.3.1	Shield skin and bentonite lubrication	196
8.3.3.2	Telescopic shield	196
8.3.3.3	Examples	198
9	Compressed air shields	201
9.1	Functional principle	202
9.2	Compressed air facilities	203
9.2.1	Air locks	204
9.2.2	Compressed air supply.	206
9.2.3	Compressed air regulations	207

9.3	Air requirement	209
9.3.1	Determination of air requirement	209
9.3.2	Verification of safety (blowout safety)	212
9.3.3	Special processes	213
9.4	Further developments	214
9.4.1	Compressed air shield with unpressurised working space and full-face excavation	214
9.4.2	Compressed air shield with unpressurised working spaces and part face excavation	214
9.4.3	Membrane shield	216
9.5	The use of compressed air with other types of shield	216
9.6	Examples	217
9.6.1	Old Elbe Tunnel next to the St. Pauli landing stage, 1907 to 1911	217
9.6.2	Energy supply tunnel under the Kiel Fjord, 1989/90	219
10	Slurry shields	223
10.1	Development history	223
10.2	Functional principle	225
10.3	Scope of application	227
10.4	Machine types	228
10.4.1	Full-face machines with fluid support	228
10.4.2	Part face machines with slurry support	233
10.5	Machine and process technology	234
10.5.1	Soil excavation	234
10.5.2	Muck transport	235
10.6	Examples	237
10.6.1	Westerschelde	237
10.6.2	Lower Inn Valley railway, Münster/Wiesing Tunnel, main contract H3-4; Jenbach/Wiesing Tunnel, main contract H8, 2007 to 2009	243
10.6.3	Fourth bore of the Elbe Tunnel	247
10.6.4	Chongming	250
11	Earth pressure balance shields	255
11.1	Development history	255
11.2	Functional principle	256
11.2.1	Support pressure measurement and control	256
11.2.2	Soil conditioning	259
11.2.3	Mass-volume control	259
11.3	Areas of application	262
11.4	Operating modes and muck transport	264
11.4.1	Open mode (screw conveyor – conveyor belt)	264
11.4.2	Semi open mode (screw conveyor – conveyor belt)	265
11.4.3	Closed mode (hydraulic mucking circuit)	266
11.4.4	EPB mode (screw conveyor – conveyor belt or screw conveyor – piston pump)	266
11.4.5	Open mode (conveyor belt)	266

11.5	Components	267
11.5.1	Cutting wheel.	267
11.5.2	Bearing and drive construction	269
11.5.3	Excavation chamber	271
11.5.4	Screw conveyor.	271
11.5.5	Foam conditioning	273
11.6	Examples	276
11.6.1	Katzenberg Tunnel on the new railway line Karlsruhe – Basel, 2005 to 2007	276
11.6.2	Madrid M-30 (Bypass Sur Tunnel Nord)	280
11.6.3	Heathrow	284
11.6.4	DTSS Singapore	286
12	Convertible shields or multi mode machines.	291
12.1	Development strategies.	293
12.1.1	Convertible shield with integrated components for multiple operating modes	293
12.1.2	Building block systems	295
12.2	Machine concepts	295
12.2.1	Mixshield.	296
12.2.2	Polyshield	297
12.3	Examples	297
12.3.1	Grauholz Tunnel, 1990 to 1993.	297
12.3.2	Zürich Thalwil contract 2.01	301
12.3.3	Socatop	305
13	Special shields and special processes.	309
13.1	Blade shields.	309
13.1.1	Face support with blade shields.	311
13.1.2	Support types with blade shields	312
13.2	Multi-face shields	315
13.2.1	Arrangement of the cutting wheels in multi-face shields	316
13.2.2	Tunnel support with multi-face shields	317
13.3	Enlargement of shield tunnels	319
13.4	Pipe jacking	322
13.4.1	Pipe jacking	324
13.4.2	Box jacking	325
13.5	New concepts in mechanised shield tunnelling	328
13.5.1	Shield machines for flexible cross-sections.	328
13.5.2	Ultra-flexible shield	330
13.5.3	Horizontal and vertical shield machines	330
13.5.4	Enlargement shields.	331
13.5.5	Rotation shields	331
13.5.6	Shield docking method	332

14	Guided microtunnelling processes	337
14.1	Pilot tube process	338
14.2	Auger microtunnelling	339
14.3	Shield microtunnelling	340
14.4	English Mini Tunnel system	342
14.5	New developments	344
15	Surveying and steering	349
15.1	Surveying	350
15.1.1	Navigation with tunnel laser and automatic target unit.	351
15.1.2	Navigation with gyroscope system and hose water level	351
15.1.3	Navigation with total station and automatic target unit.	352
15.1.4	Navigation with total station and prisms	353
15.2	Ring design and calculation of the ring installation sequence	354
15.3	Ring convergence measurement	354
15.4	Steering	355
15.5	Further surveying and data logging tasks	357
16	Workplace safety	359
16.1	General safety requirements	360
16.2	Control stations	363
16.3	Electrical cut-out and safety devices	364
16.4	Control devices and control systems	364
16.5	Towing connections	366
16.6	Laser guidance	367
16.7	Ventilation and the control of dust and gas	367
16.8	Fire protection	368
16.9	Storage of safety equipment for the personnel	369
16.10	Maintenance	369
16.11	Content of handbook	369
16.12	Evaluation of risk in mechanised tunnelling [26].	370
17	Partnering contract models and construction	383
17.1	Introduction	383
17.2	Requirements for the contract model	384
17.3	Contract model according to VOB	385
17.4	Time and cost drivers	386
17.5	Under-pricing as a performance killer	387
17.6	Chances and risks of partnering	388
17.7	Partnering – contractual implementation	389
17.8	Partnering – mutual process optimisation	390
18	Process controlling and data management	393
18.1	Introduction	393
18.2	Procedure	393
18.3	Data management	394

18.4	Target-actual comparison	395
18.5	Target process structure	397
18.6	Analysis of the actual process	399
19	DAUB recommendations for the selection of tunnelling machines	401
19.1	Preliminary notes	401
19.2	Regulatory works	402
19.2.1	National regulations	402
19.2.2	International standards	403
19.2.3	Standards and other regulatory works	403
19.3	Definitions and abbreviations	404
19.3.1	Definitions	404
19.3.2	Abbreviations	406
19.4	Application and structure of the recommendations	406
19.5	Categorisation of tunnelling machines	408
19.5.1	Types of tunnelling machine (TVM)	408
19.5.2	Tunnel boring machines (TBM)	408
19.5.2.1	Tunnel boring machines without shield (Gripper TBM)	408
19.5.2.2	Enlargement tunnel boring machines (ETBM)	409
19.5.2.3	Tunnel boring machine with shield (TBM-S)	410
19.5.3	Double shield machines (DSM)	410
19.5.4	Shield machines (SM)	410
19.5.4.1	Shield machines for full-face excavation (SM-V)	410
19.5.4.2	Shield machines with partial face excavation (SM-T)	413
19.5.5	Adaptable shield machines with convertible process technology (KSM)	414
19.5.6	Special types	414
19.5.6.1	Blade shields	414
19.5.6.2	Shields with multiple circular cross-sections	414
19.5.6.3	Articulated shields	414
19.5.7	Support and lining	415
19.5.7.1	Tunnel boring machines (TBM)	415
19.5.7.2	Tunnel boring machines with shield (TBM-S), Shield machines (SM, DSM, KSM)	416
19.5.7.3	Advance support	417
19.5.7.4	Support next to the tunnelling machine	418
19.6	Ground and system behaviour	418
19.6.1	Preliminary remarks	418
19.6.2	Ground stability and face support	418
19.6.3	Excavation	419
19.6.3.1	Sticking	419
19.6.3.2	Wear	420
19.6.3.3	Soil conditioning	420
19.6.3.4	Soil separation	421
19.6.3.5	Soil transport and tipping	421
19.7	Environmental aspects	422

19.8	Other project conditions	424
19.9	Scope of application and selection criteria	425
19.9.1	General notes about the use of the tables	425
19.9.1.1	Core area of application.	425
19.9.1.2	Possible areas of application	425
19.9.1.3	Critical areas of application	426
19.9.1.4	Classification in soft ground	426
19.9.1.5	Classification in rock	426
19.9.2	Notes about each type of tunnelling machine	426
19.9.2.1	TBM (Tunnel boring machine)	426
19.9.2.2	DSM (Double shield machines)	426
19.9.2.3	SM-V1 (full-face excavation, face without support)	427
19.9.2.4	SM-V2 (full-face excavation, face with mechanical support).	427
19.9.2.5	SM-V3 (Full-face excavation, face with compressed air application)	427
19.9.2.6	SM-V4 (full-face excavation, face with slurry support)	427
19.9.2.7	SM-V5 (full-face excavation, face with earth pressure balance support).	428
19.9.2.8	SM-T1 (partial excavation, face without support).	428
19.9.2.9	SM-T2 (partial excavation, face with mechanical support)	428
19.9.2.10	SM-T3 (partial excavation, face with compressed air application).	428
19.9.2.11	SM-T4 (Partial excavation, face with slurry support).	428
19.9.2.12	KSM (Convertible shield machines)	428
19.10	Appendices	429
	Bibliography	449
	Index	463

1 Introduction

The mined construction of underground infrastructure has made steady progress over recent years. It is now possible to construct underground works with very little impairment of buildings or traffic flow at ground level. Particularly in inner-city areas, with sensitive infrastructure and high population density, there is an enormous demand for underground structures.

The cavities created in this way have until now mostly been for underground transport routes, although there are also other possible uses such as energy extraction, storage and refuge spaces, utility tunnels and, not least, underground urban development. This has led to extensive schemes and projects, particularly in Japan due to the very restricted space availability (Figure 1-1).

Particularly in the field of shield tunnelling, the prominent role of Japan has been unmistakable. But the development of this construction method is also at a high and internationally respected level in Germany and other parts of Europe. The shield construction process enables the production of elongated underground structures, even at shallow depths, in soil with poor load-bearing capacity or under the groundwater table, without causing any disturbance or significant settlement on the ground surface. Ground conditions with loose spherical material can be mastered, as can soft plastic or flowing soils. But the use of these machines is also practicable in temporarily stable ground, where the shield only acts as head protection. All in all, shield machines have a wide scope of application.

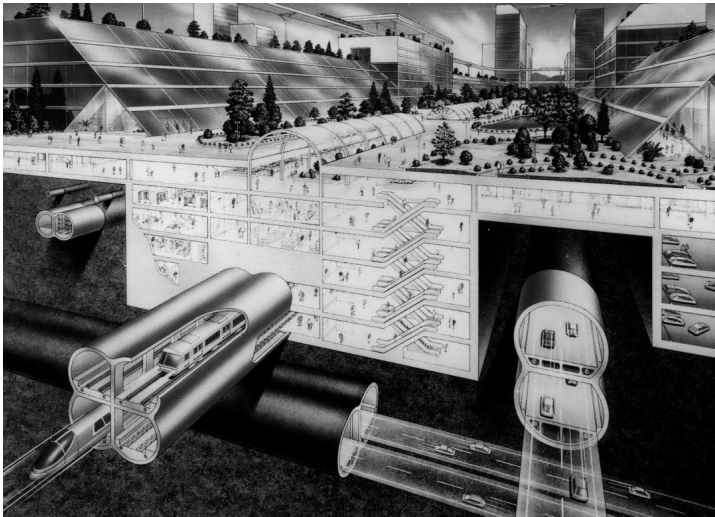


Figure 1-1 Japanese scheme for the exploitation of underground space in an inner-city area [155]

The shield construction process could but should not generally replace other methods of tunnelling. It can, however, offer a technically feasible and also economic alternative to other methods of tunnelling in unfavourable geological conditions, for long contract sections, high advance rate requirement or where stringent surface settlement limits apply. The essential advantages and disadvantages are summarised below.

Advantages:

- the possibility of mechanisation and high advance rate,
- precision of profile,
- minimisation of the effect on buildings on the surface,
- improved safety for the miners,
- environmentally friendly construction method,
- raising of the groundwater table,
- little noise,
- enables a high-quality and economic lining.

Disadvantages:

- long lead time for the design, production and assembly of the shield machine,
- long familiarisation time,
- elaborate and expensive site facilities (a separating plant may be required); tenders may only be competitive for longer tunnels,
- performance risk in changeable ground,
- the cross-section normally has to be round with little possibility of variation,
- high cost of altering the excavated geometry, e.g. for wider sections,
- the lining normally has to be specially designed to resist the thrust forces.

Application is therefore practicable where the advantages can be sensibly exploited and the disadvantages are taken into account as far as possible in the design and construction planning. Experience shows that a shield in the smaller diameter range can generally compete with other tunnelling methods for tunnel drives up to 2,000 m. For longer tunnels, economic applications of shield machines are possible and even cheaper than using open machines or conventional methods.

The successful use of a shield always requires meticulous design and planning of the machine, the lining and the logistics. Experience and know-how are essential for a practicable and economic scheme. According to [235], too many clients have chosen the wrong machine or construction concept for the ground conditions and have later been faced with unacceptable settlement on the surface, unexpectedly slow advance rates, spalling or failure of the lining, water ingress or other defects. For the client, only a tunnel constructed on schedule, of good quality and at reasonable cost, and with as little impact on the environment as possible is of interest. The designers of shield equipment need to take these natural concerns into consideration. Mechanical engineering issues have to be effectively linked to those of the tunnel itself. Constant exchange of experience between mechanical and civil engineers is essential, with the appropriate evaluation of experience from completed projects.

1.1 Basic principles and terms

The basic principle of a shield is that a generally cylindrical steel construction is driven along the tunnel axis while the ground is excavated. The steel construction supports the excavated cavity until temporary support or the final lining has been installed. The shield therefore has to resist the pressure of the surrounding ground and hold back any groundwater.

While the cavity along the sides of the tunnel is supported by the shield skin itself, additional support measures will be required to support the face, depending on the ground and groundwater conditions encountered. Figure 1-2 shows five different methods of stabilising the face, which are described in detail in Chapter 2. These are:

- natural support,
- mechanical support,
- compressed air support,
- slurry support,
- earth pressure balance support.

These methods of supporting the face represent the great advantage of the shield tunnelling process. In contrast to other methods of tunnelling, it is possible to provide immediate support of the ground as soon as it is disturbed.

In addition to the type of face support, the method of excavation is an important characteristic of shields. The most simple process is manual digging in hand shields, and this is still used today in exceptional cases, for example for short sections and under certain geological conditions. Mechanical excavation is, however, more usual. This can be differentiated into mechanical partial- and full-face excavation. In partial-face excavation, the face is worked in sections using machinery such as hydraulic excavators or roadheaders, which are operated and controlled either by operators or automatically. The full face can be excavated, according to the ground conditions encountered, by open-mode wheels, rim wheels (in some cases with shutters) or closed cutter heads. Further methods are hydraulic excavation using pressurised jets of fluid and extrusion excavation, where the action of the thrust cylinders on highly plastic soil forces it through closable openings in the front wall of the shield. Excavation processes are described in more detail in Chapter 4.

The removal of the excavated material requires special transport systems to move the muck from the face, through the shield and to the surface. The most suitable system depends directly on the nature of the ground encountered and the associated type of face support and excavation, since these factors have a great influence on the consistency and transport properties of the muck. Figure 1-3 gives an initial overview of the possible transport systems through the shield, which will be explained in more detail in Chapter 5. There are numerous transport methods available today, which can be categorised into the three basic groups

- dry transport,
- fluid/slurry transport,
- high-density solid pumping.

Transport along the tunnel can use pumped pipes, conveyor belts, dumpers or rail-based systems (muck trains). The transfer area to the tunnel transport system is integrated into the backup.

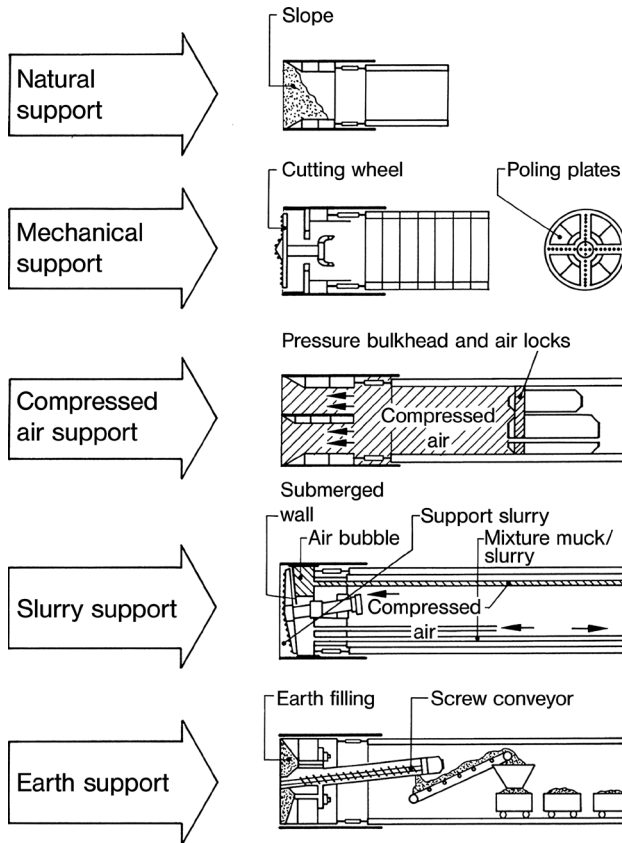


Figure 1-2 Methods of supporting the ground and holding water at the face [266]

The shield is pushed forward in the direction of the tunnel axis with the progress of excavation in order to support the resulting cavity. The required thrust forces are produced by hydraulic cylinders, normally pushing against the already installed lining. This means that the tunnel lining and boring machinery have to be finely matched. The correct function of the shield and the quality of the final tunnel lining both depend on this compatibility, which is dealt with in more detail in Chapter 6.

The cavity produced by excavation is mostly supported with precast elements called segments. There are numerous different forms, materials, possible layouts, sealing systems and installation methods, which require detailed description (Chapter 6). Other lining systems are also possible and are already in use today (Figure 1-4). The pumping of concrete under pressure into formwork (called the extrusion process) is an interesting possibility, but has not been further developed. Even shotcrete can be used in connection with shield tunnelling.

As the support is normally installed inside the protection of the shield skin, a gap remains as the shield progresses further. The gap has to be filled in order to minimise loosening and settlement. This has to be suitably backfilled or grouted and the shield must be provided with the appropriate equipment.

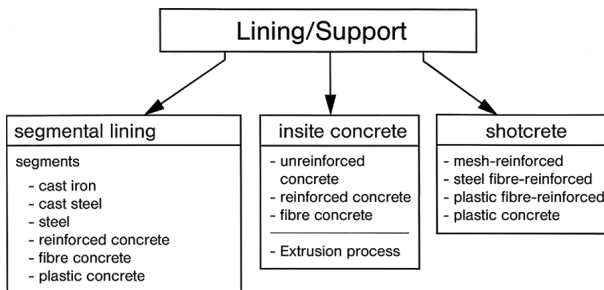
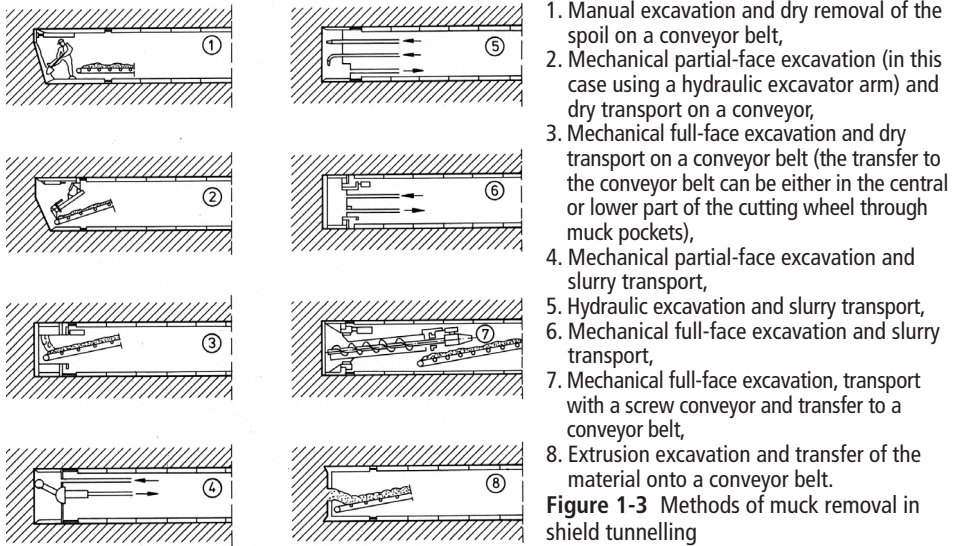


Figure 1-4 Possible types of lining in shield tunnelling

1.2 Types of tunnel boring machine according to DAUB

The recommendations of DAUB (the German Tunnelling Committee) are reproduced in their entirety in Chapter 19 [54].

1.2.1 Categories of tunnelling machines German association for underground construction (TVM)

Tunnelling machines either excavate the full face with a cutter head or cutting wheel or part of the face with suitable excavation equipment.

These can be tunnel boring machines (TBM), double shield machines (DSM), shield machines (SM) or combination machines (KSM). While the acronym “TBM” in English will be used for all types of tunnelling machines, the German DAUB reserves the abbreviation for the hard rock machines.

As the ground is excavated, the machine is pushed forward, either continuously or intermittently.

A systematic categorisation of tunnelling machines is shown in Figure 1-5 (see also Appendix 1 “Overview of tunnelling machines” in Chapter 19).

1.2.2 Tunnel boring machines (TBM)

Tunnel boring machines are used for driving tunnels through stable hard rock. Active support of the face is not required and, in any case, is technically impossible. These machines can normally only drive a circular cross-section.

Tunnel boring machines can be differentiated into those without shields (open gripper TBM), reamer or enlargement tunnel boring machines (ETBM) and shielded tunnel boring machines (TBM-S).

These machines are described in detail in [203].

1.2.2.1 Tunnel boring machines without shield (gripper TBM)

Open tunnel boring machines without shield are used in hard rock that has medium to long stand-up time. They have no complete shield skin. Economic application can be greatly influenced and limited by the high cost of wear of the excavation tools.

In order to be able to apply thrust force to the cutter head, the machine is braced radially by hydraulically driven grippers acting against the sides of the tunnel.

Excavation is carried out with little damage to the surrounding rock mass and to an exact profile by disc cutters mounted on the rotating cutter head. The machine fills a large part of the cross-section. Systematic support of the tunnel walls is normally installed behind the machine (10 to 15 m or more behind the face). In rock with a shorter stand-up time or

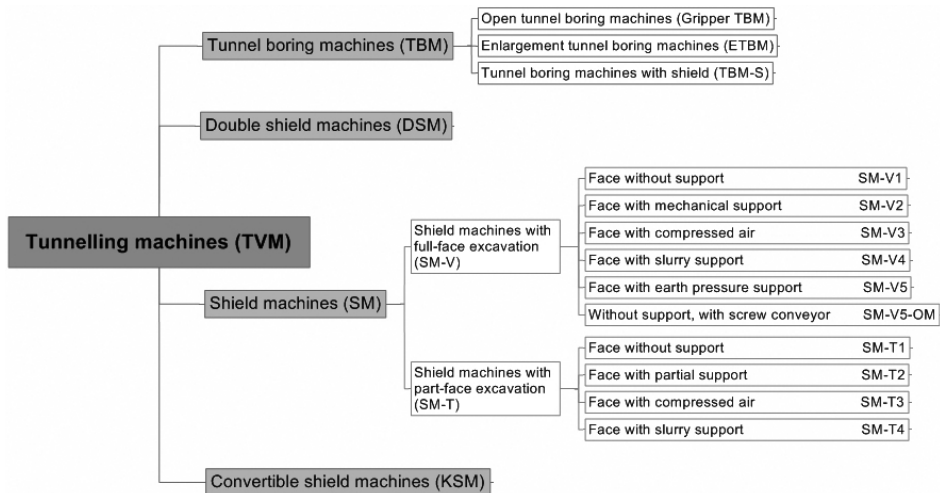


Figure 1-5 Types of tunnel boring machines

liable to rock falls, support measures such as steel arches, poling plates or rock bolts are installed at the closest possible distance behind the cutter head.

Where shotcrete lining of the tunnel is necessary, this should only be applied in the rearward part of the backup area in order to keep the mess off the machinery and control gear in the forward machine area as far as possible. In exceptional cases, however, shotcrete may have to be applied as close behind the face as possible.

If the geological forecast describes poor rock or a heterogeneous condition of the rock mass (high degree of jointing and fault zones), it is recommended to equip the machine to enable advance investigation drilling or advance rock consolidation.

The excavation of the face produces material in small pieces with the associated dust development. Machines therefore require equipment for the reduction of dust development and dedusting. This can be:

- spraying with water at the cutter head,
- a dust shield behind the cutter head,
- dust extraction with dedusting on the backup.

Material handling and disposal from the machine nowadays requires very long backup facilities.

1.2.2.2 Reamer tunnel boring machines (ETBM)

Reamer tunnel boring machines (enlargement machines) are used in hard rock to enlarge a previously bored pilot tunnel to the intended final diameter. The enlargement to the final diameter is performed in one or two working steps using an appropriately constructed cutter head.

The main elements of these machines are the cutter head, the bracing and the drive mechanism. The bracing of the specialised machines is situated in front of the cutter head with grippers in the pilot tunnel, and the cutter head of the machine is drawn towards the grippers as it bores. In faulted rock formations, measures to improve the fault zone can be carried out from the previously bored pilot tunnel in order to minimise the risks during the boring of the main tunnel.

1.2.2.3 Tunnel boring machines with single shield (TBM-S)

In hard rock with a short stand-up time or liable to rock falls, shielded tunnel boring machines are used. For this case, the installation of the lining within the shield is appropriate (segments, pipes etc.). While advancing, the machine can be supported from the lining, so bracing is not normally required. The remaining statements made about tunnel boring machines apply accordingly.

1.2.3 Double shield machines (DSM)

Double shield machines (DSM) consist of two parts arranged one behind the other. The front part is equipped with the cutter head and the main thrust cylinders, and the back part houses the auxiliary thrust cylinders and the grippers. The front part of the machine can be advanced by a complete ring length ahead of the back part using a telescopic section.

In stable hard rock, the gripper shoes resist the drive torque and the thrust forces. The secure fixing of the back part of the machine using the grippers enables the assembly of the segmental lining in the shield tail while boring is in progress. In a stable rock mass, it may also be possible to omit the installation of the lining.

In unstable ground, where the gripper shoes cannot find sufficient resistance, the thrust can be resisted from the last segment ring. The front and back parts of the machine are retracted together and the thrust forces are pushed from the segment ring by the auxiliary thrust cylinders.

It is not normally possible to actively support the face or the sides of the excavation.

Due to the rapid advance of the back part of the machine after a boring stroke has been completed and the grippers are being regripped, the rock mass has to be able to stand up independently until the annular gap has been completely filled with grout or stowed with pea gravel.

1.2.4 Shield machines (SM)

These can be shield machines with full-face excavation (with a cutter head: SM-V) and shield machines with partial-face excavation (using a roadheader boom, excavator: SM-T). Shield machines are used in loose ground above and below the groundwater table. This normally means that the ground around the cavity and at the face has to be supported. Shield machines can be further divided according to the type of face support (Figure 1-5).

1.2.4.1 Shield machines with full-face excavation (SM-V)

1) Face without support (SM-V1)

If the face will stand up, e.g. in clay soil with stiff consistency and sufficient cohesion or in solid rock, open shields can be used. The cutting wheel fitted with tools excavates the soil and the muck is removed on a conveyor belt.

In solid rock liable to rock falls, shield machines with a mostly closed cutter head fitted with disc cutters and fully protected from the unstable ground by a shield skin are normally used. The thrust forces and the cutter head drive torque are transferred through the thrust cylinders to the last ring of segments installed.

2) Face with mechanical support (SM-V2)

With tunnelling machines with mechanical support, the support of the face during excavation is provided by elastically fixed support plates arranged in the openings of the cutting wheel. In practice, however, experience shows that that no appreciable mechanical support of the face can be provided by the rotating cutting wheel. For this reason, this type of cutting wheel did not prove successful in unstable ground and is no longer in use today. The mechanical face support by the cutting wheel or the support plates should only be considered a supplementary safety measure and the supporting effect should not be taken into account in calculations to verify the stability of the face.