Bernhard Maidl/ Markus Thewes/ Ulrich Maidl

Handbook of Tunnel Engineering I

Structures and Methods

- **Valuable assistance in the planning and execution of tunnels**
- **internationally known authors**
- **complements Vol. 2complements Vol. 2**

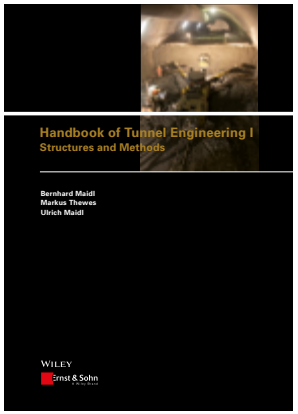
The book deals with almost all aspects of annular gap lubrication in pipe jacking - from ground conditions, through the properties of bentonite to the technical aspects. There is also a collection of calculations and suggested values for bentonite consumption quantities.

ORDER
+49 (0)30 470 31–236
marketing@ernst-und-sohn.de
www.ernst-und-sohn.de/en/3048

* All book prices inclusive VAT.

WILEY

Ernst & Sohn
A Wiley Brand



2013 · 482 pages · 473 figures · 58 tables

Hardcover
ISBN 978-3-433-03048-6 € 93.90*

WILEY Ernst & Sohn
A Wiley Brand

ABOUT THE BOOK

Pipe jacking is a construction process for the no-dig laying of pipes. Successful pipe jacking demands low skin friction between the ground and the jacked pipe. This is achieved with bentonite lubrication. The bentonite slurry fed into the annular gap fulfils several purposes. It stabilises the annular gap by supporting the surrounding ground and reduces friction contact between ground and jacked pipe. The Bentonite Handbook deals comprehensibly with the relevant aspects of annular gap lubrication: starting with the ground conditions, which are of decisive importance for lubrication, through the rheological properties of the bentonite slurry to the technical components of lubrication technology and lubrication strategy. The use of standardised measuring apparatus is described as well as mixing equipment and the automatic lubrication system. Overview tables with calculations and suggested values for bentonite consumption quantities depending on the prevailing ground conditions and the pipe jacking parameters complete the recommendations.

ORDER

Quantity	ISBN / Order-No.	Title	Price €
	978-3-433-03048-6	Handbook of Tunnel Engineering I [...]	€ 93.90*

Private ● Business

Please send your order to:
marketing@ernst-und-sohn.de

108208 Free Shipping

Company, Abteilung | VAT-ID

Name | Phone

Street, No.

Zip code / City / Country | E-Mail

Date, Signature

www.ernst-und-sohn.de/3048

. As of 7/2021

Table of Contents

Volume I: Structures and Methods

The authors VII

Foreword to the English edition IX

Foreword to the 3rd German edition X

Foreword to the 2nd German edition XI

Foreword to the 1st German edition XII

1 Introduction 1
1.1 General 1
1.2 Historical development 1
1.3 Terms and descriptions 4

2 Support methods and materials 9
2.1 General 9
2.2 Action of the support materials 9
2.2.1 Stiffness and deformability 10
2.2.2 Bond 11
2.2.3 Time of installation 11
2.3 Timbering 12
2.3.1 General 12
2.3.2 Frame set timbering 13
2.3.3 Trussed timbering 14
2.3.4 Shoring and lagging 14
2.4 Steel ribs 14
2.4.1 General 14
2.4.2 Profile forms 15
2.4.3 Examples of typical arch forms for large and small tunnels 15
2.4.4 Installation 16
2.5 Lattice beam elements 19
2.6 Advance support measures 21
2.6.1 Steel lagging sheets and plates 21
2.6.2 Spiles 23
2.6.3 Injection tubes 25
2.6.4 Pipe screens, grout screens, jet grout screens 25
2.6.5 Ground freezing 28
2.7 Rock bolts 29
2.7.1 General 29
2.7.2 Mode of action 29
2.7.3 Anchor length and spacing 32

2.7.4 Load-bearing behaviour . . . 33
2.7.5 Anchor types . . . 36
2.8 Concrete in tunnelling . . . 45
2.8.1 General . . . 45
2.8.2 Construction variants . . . 45
2.8.2.1 Two-layer construction . . . 46
2.8.2.2 Single-layer construction . . . 46
2.8.3 Shotcrete . . . 48
2.8.3.1 General . . . 48
2.8.3.2 Process technology, equipment and handling . . . 49
2.8.3.3 Mixing and recipes . . . 60
2.8.3.4 Influence of materials technology and process technology . . . 72
2.8.3.5 Quality criteria, material behaviour and calculation methods, quality control . . . 87
2.8.3.6 Mechanisation of shotcrete technology . . . 91
2.8.3.7 Steel fibre concrete . . . 100
2.8.3.8 Working safety . . . 106
2.8.4 Cast concrete . . . 111
2.8.4.1 Formwork . . . 111
2.8.4.2 Concreting . . . 114
2.8.4.3 Reinforced or unreinforced concrete lining . . . 115
2.8.4.4 Factors affecting crack formation . . . 118
2.8.4.5 Disadvantages of nominal reinforcement . . . 118
2.8.4.6 Stripping times . . . 119
2.8.4.7 Filling of the crown gap . . . 119
2.8.4.8 Joint details . . . 120
2.8.4.9 Single-pass process, extruded concrete . . . 120
2.8.4.10 After-treatment . . . 123
2.8.5 Precast elements, cast segments . . . 124
2.8.5.1 Steel segments . . . 124
2.8.5.2 Cast steel segments . . . 125
2.8.5.3 Cast iron segments . . . 126
2.8.5.4 Reinforced concrete segments . . . 127
2.8.5.5 Geometrical shapes and arrangement . . . 130
2.8.5.6 Details of radial joints . . . 131
2.8.5.7 Circumferential joint details . . . 131
2.8.5.8 Fixing and sealing systems . . . 132
2.8.5.9 Segment gaskets . . . 133
2.8.5.10 Production of reinforced concrete segments . . . 134
2.8.5.11 Installation of segment lining . . . 135
2.8.6 Linings for sewer tunnels . . . 136
2.8.7 Yielding elements . . . 142

3 The classic methods and their further developments . . . 145
3.1 General . . . 145
3.2 Full-face excavation . . . 147

3.3 Partial-face excavation . . . 148
3.3.1 Bench excavation . . . 148
3.3.2 The Belgian or underpinning tunnelling method . . . 148
3.3.3 The German or remaining core tunnelling method . . . 151
3.3.4 The Austrian or upraise tunnelling method . . . 154
3.3.5 The New Austrian Tunnelling Method . . . 155
3.3.6 The English tunnelling method . . . 161
3.3.7 The Italian or packing tunnelling method . . . 161
3.4 Classic shield drives . . . 163
3.5 The classic tunnelling machines . . . 164

4 Shotcrete tunnelling . . . 167
4.1 General . . . 167
4.2 Top heading process . . . 168
4.2.1 Shotcrete tunnelling method . . . 168
4.2.2 Underpinning method . . . 168
4.2.3 Crown pilot heading with crown beam . . . 170
4.2.4 Shotcrete tunnelling with longitudinal slots . . . 173
4.3 Core tunnelling method with side headings . . . 175
4.4 Special processes using shotcrete . . . 176
4.4.1 Compressed air . . . 176
4.4.2 Ground freezing, grouting . . . 176
4.5 Shotcrete in mining . . . 178
4.5.1 Tunnel support . . . 178
4.5.2 Shaft insets . . . 179
4.6 Outlook for further development . . . 182
4.7 The new Italian tunnelling method (ADECCO-RS) . . . 182
4.7.1 Theoretical model . . . 183
4.7.2 Procedure through the example of the new line from Bologna – Florence . . . 184

5 Drill and blast tunnelling . . . 189
5.1 Historical development . . . 189
5.2 Drilling . . . 191
5.2.1 General . . . 191
5.2.2 Drills . . . 192
5.2.3 Drill bits . . . 200
5.2.4 Wear . . . 206
5.2.5 Performance . . . 207
5.2.6 Costs . . . 210
5.3 Blasting . . . 211
5.3.1 General . . . 211
5.3.2 Explosives in tunnelling . . . 213
5.3.3 Detonators and detonation systems in tunnelling . . . 215
5.3.4 Transport, storage and handling of explosives . . . 221
5.3.5 Charge determination . . . 228

5.3.6 The drilling and firing pattern . . . 232
5.3.7 Charge loading . . . 235
5.3.8 Time calculation . . . 239
5.3.9 Blasting technology aspects . . . 241
5.4 Mucking . . . 243
5.4.1 General . . . 243
5.4.2 Loading machines . . . 244
5.4.3 Muck conveyance . . . 251
5.4.4 Output of transport vehicles . . . 260
5.4.5 Examples of transport chains . . . 260
5.4.6 Further developments . . . 265
5.5 Combination of drill and blast with mechanised tunnelling processes . . . 265
5.5.1 Combinations with roadheaders . . . 265
5.5.2 Combination with full-face machines . . . 266
5.6 Effects of blasting on the surroundings . . . 267
5.6.1 Vibration . . . 267
5.6.2 Composition and effects of the blasting gas emissions . . . 275
5.7 Mechanisation and Automation . . . 278
5.7.1 General . . . 278
5.7.2 Emphasis of mechanisation . . . 279
5.7.3 Computer-assisted drill jumbos . . . 280
5.7.4 Mucking and tunnel logistics . . . 282

6 Mechanised tunnelling . . . 285
6.1 General . . . 285
6.2 Categories of tunnelling machines . . . 285
6.3 Shield machines . . . 286
6.3.1 Categories of shield machines . . . 286
6.3.2 Basic principle, definition . . . 287
6.3.3 Face without support . . . 292
6.3.4 Face with mechanical support . . . 292
6.3.5 Face under compressed air . . . 293
6.3.6 Face with slurry support . . . 294
6.3.6.1 Functional principle . . . 295
6.3.6.2 Slurry shield . . . 295
6.3.6.3 Thixshield . . . 297
6.3.6.4 Hydroshield . . . 297
6.3.6.5 Mixshield as a Hydroshield version . . . 299
6.3.6.6 Hydrojetshield . . . 300
6.3.6.7 Hydraulic soil transport . . . 300
6.3.6.8 Soil separation in shield operation with hydraulic transport . . . 302
6.3.7 Face with earth pressure support . . . 306
6.3.7.1 Functional principle . . . 306
6.3.7.2 Scope of application and soil conditioning process . . . 307
6.3.7.3 Use of foam with earth pressure shields . . . 310

6.3.8 Blade tunnelling and blade shields . . . 311
6.3.9 The most important verification calculations . . . 313
6.3.9.1 Calculation of face stability with slurry and earth pressure support 313
6.3.9.2 Calculation of safety against breakup and blowout . . . 315
6.3.9.3 Calculation of thrust force . . . 316
6.3.9.4 Determination of the air demand for compressed air support . . . 320
6.4 Tunnel boring machines in hard rock . . . 322
6.4.1 Categorisation of machines for use in hard rock . . . 322
6.4.2 Basic principles . . . 322
6.4.3 Boring system . . . 327
6.4.4 Thrust and bracing system . . . 328
6.4.5 Support system . . . 332
6.4.6 Ventilation . . . 335
6.4.7 The use of slurry and earth pressure shields in hard rock formations . . . 336
6.5 Special processes: combinations of TBM drives with shotcrete tunnelling . . . 338
6.5.1 Areas of application . . . 338
6.5.2 Construction possibilities . . . 339
6.5.3 Example . . . 344
6.6 Roadheaders (TSM) and tunnel excavators . . . 353
6.6.1 Basic principle of a roadheader . . . 353
6.6.2 Rock excavation by a roadheader . . . 355
6.6.3 Ventilation and dust control with a roadheader . . . 359
6.6.4 Profile and directional control of roadheaders . . . 359
6.6.5 Construction sequence using a roadheader . . . 360
6.6.6 Additional equipment and variations of roadheaders . . . 361
6.6.7 Criteria for the selection of a roadheader . . . 362
6.6.8 Comparison of partial face and full face machines . . . 362
6.6.9 Combination of full face and partial face machines . . . 364
6.6.10 Contour cutting process . . . 364
6.6.11 Tunnel excavators . . . 364
6.7 Checking the tunnelling machine for suitability and acceptance based on a risk analysis . . . 366
6.7.1 Strategy to contain risk . . . 367
6.7.2 Basic design . . . 367
6.7.3 Analysis of obstructions . . . 368
6.7.4 Machine specification . . . 369
6.7.5 Acceptance of the TBM . . . 370
6.7.6 Shield handbook . . . 371
6.7.7 Data checks, functional tests . . . 372
6.7.8 Implementation of the strategy through the example of the Elbe Tunnel and the Lefortovo Tunnel . . . 372
6.7.9 Recommendations for the future . . . 378

7 The driving of small cross-sections . . . 379
7.1 General . . . 379
7.2 Manned processes . . . 380
7.2.1 General . . . 380
7.2.2 Pipe jacking . . . 380
7.3 Unmanned processes . . . 385
7.3.1 General . . . 385
7.3.2 Non-steerable processes, or with limited control of direction . . . 386
7.3.3 Guided processes . . . 395
7.4 Shafts and jacking stations . . . 400
7.4.1 Thrust shaft . . . 400
7.4.2 Reception shaft . . . 401
7.4.3 Main jacking station . . . 401
7.4.4 Intermediate jacking stations . . . 401
7.5 Support, product pipe . . . 402
7.5.1 Loading during pipe jacking . . . 402
7.5.2 Loading in operation . . . 403
7.5.3 Insertion of the product pipe . . . 407

8 Ventilation during the construction phase . . . 409
8.1 General . . . 409
8.2 Ventilation systems . . . 411
8.2.1 Natural ventilation . . . 411
8.2.2 Positive pressure ventilation . . . 411
8.2.3 Extraction ventilation . . . 412
8.2.4 Reversible ventilation . . . 412
8.2.5 Combined ventilation . . . 413
8.2.6 Recirculation systems . . . 413
8.3 Materials . . . 414
8.3.1 Fans . . . 414
8.3.2 Air ducts . . . 415
8.3.3 Dedusters . . . 416
8.4 Design and cost . . . 417
8.5 Special ventilation systems . . . 423
8.5.1 Ventilation for TBM drives . . . 423
8.5.2 Ventilation of roadheader drives . . . 425
8.5.3 Automatic ventilation . . . 425

Bibliography . . . 427

Index . . . 443

Foreword to the English edition

The "black book of tunnelling" has become a standard work in German-speaking countries since its first edition in 1984. It can be found on every tunnel site and in every design office – whether contractor or consultant. Students at universities and technical colleges use it as a textbook.

For many years, colleagues from abroad have been asking me for an English edition. Now the time has come to publish the two-volume book in English. An important step was that the publisher of the first German edition, VGE, gave their permission for the publishing of the English edition by Ernst & Sohn, Berlin. Special thanks are due to Dr. *Richter* from publisher Ernst & Sohn for his successful negotiations. However, preparation of the text for the translation showed that the 3rd German edition required updating and extending. In particular, the standards and recommendations have been revised. This will all be included in a 4th German edition, which will be published soon. Changes to the standards and recommendations are given in this edition, with the references stating the latest version.

As with all books, the first English edition has also required the collaboration of colleagues. Professor Dr.-Ing. *Markus Thewes*, who has succeeded me as the holder of my former university chair, and my son, Dr.-Ing. *Ulrich Maidl*, managing director of MTC, have joined me in the team of authors. Dipl.-Ing. *Michael Griese* from MTC is the overall coordinator, assisted by Dr.-Ing. *Götz Vollmann* and Dipl.-Ing. *Anna-Lena Hammer* from the chair of Prof. *Thewes*. I thank all those involved, also the translator *David Sturge* and the employees of the publisher Ernst & Sohn in Berlin.

Bochum, in March 2013 *Bernhard Maidl*

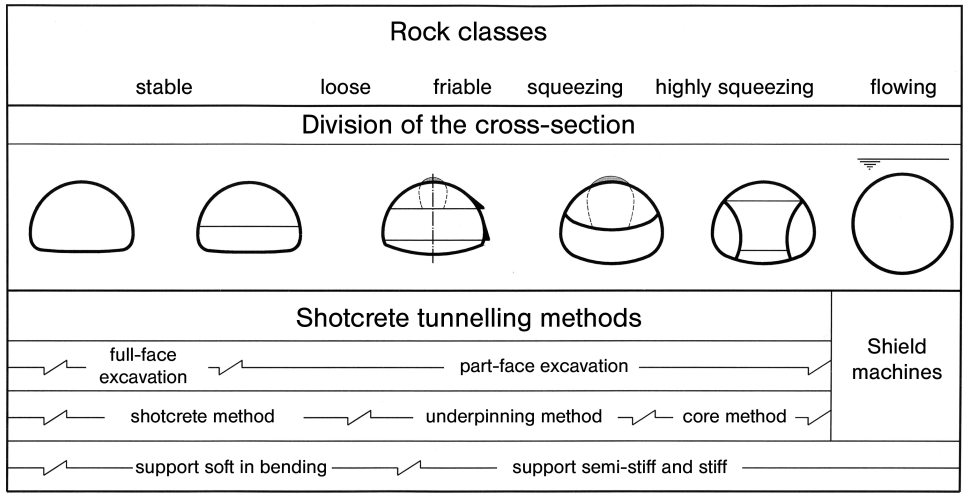


Figure 2-1 Categorisation of shotcrete processes according to rock mass classes [243]

2.2.1 Stiffness and deformability

Support systems are regarded as highly stiff in bending (rigid) when they can stand up freely without affecting the rock mass and only show negligibly small deformation under load (Table 2-1). As deformations are small when highly stiff support systems are used, restoring forces in the rock mass to reduce the bending moments in the lining can not be assumed. For the loading on the lining, the prevailing vertical and horizontal ground pressures, and particularly their relationship, are of great significance. As this is however generally not known, many limit cases of loading have to be investigated. After a highly stiff support system has been installed, subsequent stress redistribution in the rock mass is prevented. Because the loading that occurs is larger than with a deformable lining, highly stiff support systems should if possible only be installed after stress redistribution has largely taken place, in order to be cost-effective. Linings that are highly stiff in bending are today mostly made of reinforced concrete and relatively thick. Considering the cost, they should only be used for the final lining.

Table 2-1 Correlation of terms

Stiffness of the support	Deformability	Resistance to section forces	
		Bending moments	Normal forces
highly stiff in bending	rigid	high	low
stiff in bending	semi-rigid	high	low
weak in bending	highly deformable	low	high (plus shear forces)

Support systems that are stiff in bending (semi-rigid) are stable without the surrounding rock mass, but also deformable so that they can evoke structural response from the rock mass by stress redistribution. They can be used as temporary or final support, although mainly for the final support. Good bonding with the rock mass is important.

Some examples of the application of support systems that are highly stiff or stiff in bending are:

- Tunnels, which are constructed in an open excavation and subsequently backfilled (except for special linings like Armco Thyssen).
- Tunnels in heavily faulted zones.
- Tunnels with very shallow cover.
- Tunnels with weak bonding or no bonding between support and rock mass.
- All examples, where no structurally active ring can form in the surrounding rock mass.
- Low deformations and settlements.

Support systems that are weak in bending (highly deformable) are not stable under load on their own, but require the interaction with the surrounding rock mass. The support should be considered at the limit state as a reinforcement of the edge; it resists normal forces and shear forces, but no bending or only very slight bending. The normal application should be as yielding temporary support. It mostly consists today of unreinforced or reinforced concrete or shotcrete, also steel fibre shotcrete. Deformations are only permissible to such a magnitude that the assumption of restoring forces is justified. The bond with the rock mass is particularly important. The structural design should check the shear forces. The deformation capability of the lining can also be improved by deformation gaps and yielding elements (see Chap. 2.8.7) in special cases where deformation could otherwise not be controlled.

2.2.2 Bond

The bond between the support and the rock mass should ensure the transfer of radial forces over the whole area and the continuous transfer of tangential forces. Except for rare cases, the transfer of radial forces remains the most important requirement, as the shear transfer between the support measures and the rock mass is not normally assumed in calculations. If tangential forces are assumed, then the magnitude of the shear strength of rock mass and concrete has to be estimated or determined in tests. If a waterproofing membrane is installed between rock mass and support, or between temporary and final support, then no tangential forces can be transferred.

Support measures consisting of timber, steel, precast concrete elements or other assembled parts only support the rock mass at points, so there is no bonding effect. If shotcrete or pumped concrete is used with subsequent grouting (crown filling), then it can normally be assumed that there is a bond at the edge of the excavation between support and rock mass, which greatly influences the transfer of forces between rock mass and support.

2.2.3 Time of installation

If the rock mass is unstable, temporary support should be provided during or even before excavation. If the rock mass will stand up temporarily, the support is installed after excavation. In a stable rock mass, support is not generally necessary, although head protection may have to be considered. If the elastic condition of the rock mass can be largely preserved, then the support is installed early. If, however, the creation of large areas with plastic deformation in the rock mass is unavoidable, then installation after a controlled delay can lead to limited deformation of the rock mass and thus to reduced and bearable ground pressure.

Deformation of the rock mass leads to a reduction of the cavity cross-section, and this has to be taken into account in the design of the cross-section. If it is assumed that a deformable edge reinforcement increases the load-bearing behaviour of the structurally active ring in the surrounding rock mass, then it should be installed as early as possible as shotcrete or steel fibre shotcrete with high early strength. The jointed body bonding of the structurally active ring is also preserved; rock falls that could disturb the geometry of the load-bearing vault are avoided and the rock mass is protected against weathering. Immediate sealing of the exposed surface is especially important in ground susceptible to swelling.

For the time of installation, not only the support of the crown and sides is important but also the closure of the ring. This can be achieved through support measures like concrete, shotcrete, steel fibre shotcrete, precast reinforced concrete elements, steel ribs or rock bolts; or in the appropriate ground conditions by the rock mass itself. The ring closure time and the ring closure distance should be differentiated. The ring closure time is the time from the opening of the face to the installation of support measures to produce a load-bearing ring. The ring closure distance is generally the distance between the face and the location of the load-bearing ring closure. The ring closure distance is determined by operational considerations and mainly ensues from the construction method and the support materials used. For example, steel fibre shotcrete can favourably reduce the ring closure time and distance due to the reduced number of working steps and its high early strength behaviour.

2.3 Timbering

2.3.1 General

Timber is only used for temporary support and should always be removed. The original forms of longitudinal and transverse timbering are hardly ever used today. This is a result of the development of newer, more suitable support materials like steel, shotcrete, steel fibre shotcrete and rock bolts. Special cases for the application of timbering could still be: partial collapses, transition profiles and particularly as emergency support after collapses (Fig. 2-2). Timber is also suitable as a reserve material for immediate measures due to its adaptability and should be available on all tunnel sites.

Advantages and disadvantages of timbering are:

Advantages:

- Any critical increase of ground pressure is visibly and audibly indicated.
- Easy to transport.
- Easily worked and adaptable.

Disadvantages:

- No bonding with the rock mass.
- Large deformations under load.
- Seldom reusable.
- The support has to be removed, making re-bracing and underpinning necessary.
- Qualified craftsmen required.

Figure 2-2 Timbering as emergency support after a collapse in the Euerwang Nord Tunnel [136]

2.3.2 Frame set timbering

As the tunnel is advanced, poling boards are pushed over the cap pieces (Fig. 2-3) or driven into the ground. The space between boards and ground is wedged or stowed with stones. If high ground pressure is expected, then a sill piece is also installed. The normal spacing of frame sets is 1.0 to 1.5 m. In squeezing ground, the spacing can be so small that the sets are directly next to each other. This method is suitable for headings with partial face excavation and trapezoidal full-face excavations up to 9 m^2.

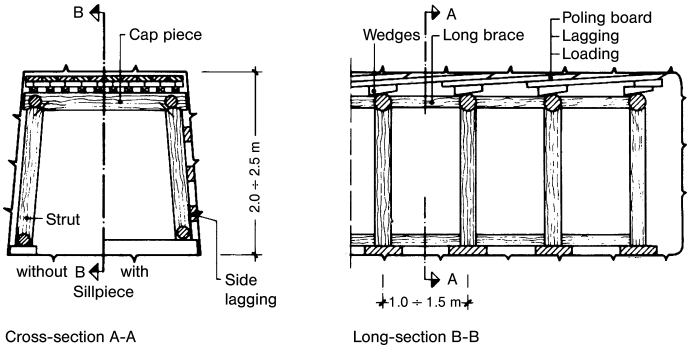


Figure 2-3 Frame set timbering. Lagging with timber poling boards

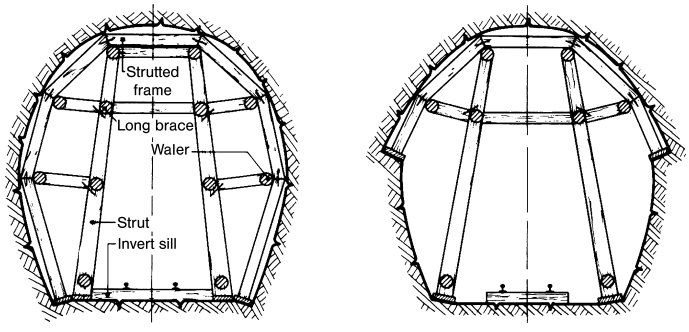


Figure 2-4 Trussed timbering. Fully braced cross-section (left) and strutted frame supported at the sides

2.3.3 Trussed timbering

Trussed timbering is a multi-part truss supported from the sills, a support construction or from the tunnel sides. As truss timbering is laterally unstable, bracing is important (Fig. 2-4).

2.3.4 Shoring and lagging

If the ground is friable, then the space between the sets or ribs has to be supported. This is done with lagging or forepoling boards, which rest on timber frames or a steel construction and are pushed forward, driven forward, pressed or simply installed in contact with the ground (Fig. 2-5). When the lagging can be pushed over an already installed frame, this is described as forepoling.

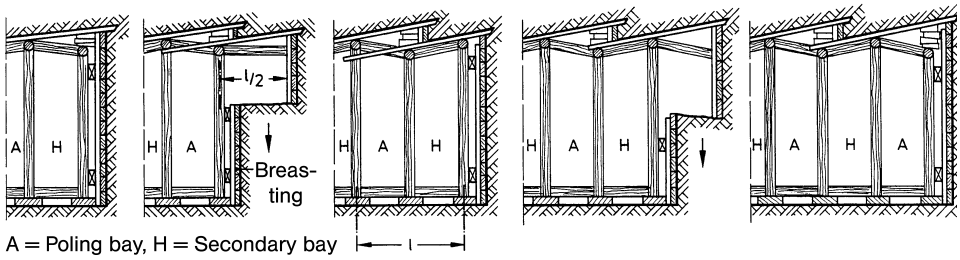


Figure 2-5 Driven lagging of forepoling boards

Timbering provides the support with driven lagging. The basic method is still in use today although with other materials as timber.

2.4 Steel ribs

2.4.1 General

Steel has been increasingly used instead of timber since the middle of the 20th century, since steel enables standardisation of support elements and prefabrication of the support. Steel support ribs are made of rolled profiles, U profiles, special mining profiles or composite sections, as closed arches or open at the bottom [240].

Advantages:

- Prefabrication is possible.
- Immediate load-bearing if in contact with the rock mass.
- Can be installed vertically or inclined according to the form of the face.

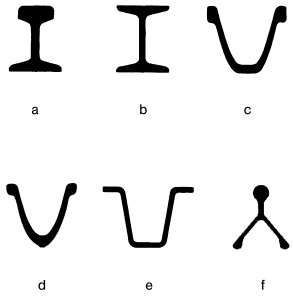
Disadvantages:

- Heavy profiles are difficult to handle.
- Poor flexibility.
- Long ordering times.

2.4.2 Profile forms

In contrast to the profiles that are commonly used in steelwork, special profiles have been developed for mining, which were than used for engineered tunnelling. Fig. 2-6 shows some types from various manufacturers; the criteria for their development were: large moment of inertia with small cross-sectional areas and weights, high strength and easy handling.

The steel quality can be DIN 21530-3 [71] type 31 Mn 4 and S235JR and S355JO according to DIN EN 10027 [76].



a Rail
b GI profile (Bochumer Eisenhütte Heintzmann GmbH & Co KG; Thyssen Industrie AG)
c TH channel profile (Bochumer Eisenhütte Heintzmann GmbH & Co KG)
d Bell profile (Bergbaustahl GmbH)
e Channel profile (Bergbaustahl GmbH)
f Star profile (Bochumer Eisenhütte Heintzmann GmbH & Co KG)

Figure 2-6 Steel profile shapes commonly used in German tunnelling and mining

2.4.3 Examples of typical arch forms for large and small tunnels.

The geometrical form of steel arches is determined by the intended cross-section of the excavation. The ribs are normally made to size (Fig. 2-7), although there are standardisations for mining.

For better or simpler handling, ribs are made in two or three parts. A variety of butt connections have been developed to meet different requirements. Fig. 2-8 shows, for example, rigid and yielding butt connections. The manufacturers will have to be contacted for special requirements like defined yielding or friction forces. Such problems occur in mining for the overcoming of large convergences or also in tunnelling with large-scale plastic deformation of the rock mass.

Steel ribs are anchored with special anchor clamps, or the anchors can pass directly through the steel profiles. Some examples are shown in Fig. 2-9.

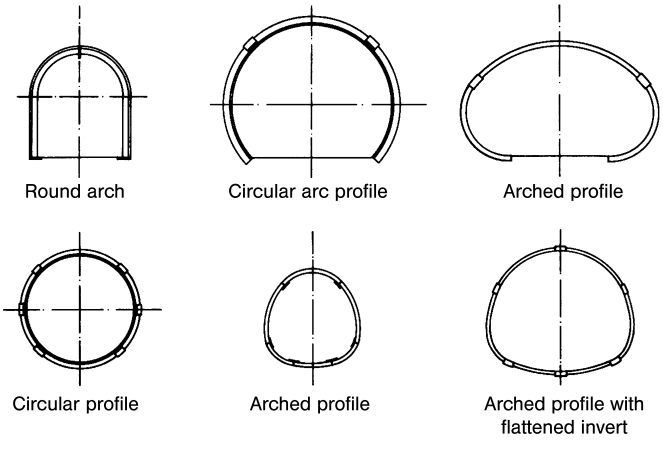


Figure 2-7 Typical arch forms with open invert (top) and with closed invert (bottom)

4 Shotcrete tunnelling

4.1 General

Tunnelling is characterised by dramatic leaps of development, but each age makes use of the experience of previous ages. We can still recognise the principles of classic tunnelling methods today in modern methods, which use the same excavation sequence. Only the support materials used, shotcrete, rock bolts, steel support elements, steel liner plates and prefabricated elements have superseded the former timber and masonry. There are numerous tunnelling methods today that are still based on the principles of classic methods.

Definitions, classifications etc. therefore have to consider historical developments (Fig. 4-1).

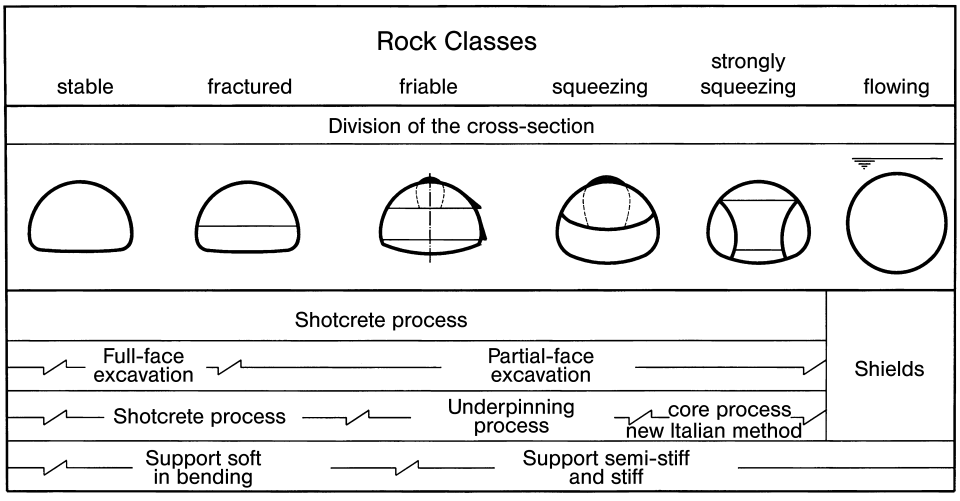


Figure 4-1 Correlation of shotcrete tunnelling and other methods into rock classes

For tunnels driven using conventional shotcrete methods, the construction process technology and the selection of suitable support measures are of great importance. The technical and economic success of a tunnel drive is influenced not only by the geological and hydrological conditions, but also the following factors:

- A suitable construction method, i. e. division of the cross-section.
- A suitable operational method, i. e. construction planning along the tunnel including all the logistics.

Handbook of Tunnel Engineering. Volume I: Structures and Methods. First English Edition.
Bernhard Maidl, Markus Thewes, Ulrich Maidl.
© 2013 Ernst & Sohn GmbH & Co. KG. Published 2013 by Ernst & Sohn GmbH & Co. KG.

Numerous construction methods have been developed and these are illustrated in Fig. 4-1 according to the division of the entire cross-section for partial excavation. The basics of full-face excavation are dealt with in section 3.2.

The decision whether to divide the cross-section is essentially determined by the geological conditions, although larger sections may still be divided even in rock that will stand up for reasons of process technical or to suit the machinery. Another factor is that changing the process during the drive can be expensive and time-wasting, particularly a change from top heading to side headings or vice versa when the change has to take place within a section of a drive.

4.2 Top heading process

The top heading is excavated first and the bench and invert are brought up behind as required. The various methods are shotcrete tunnelling, underpinning method, crown pilot heading method and shotcrete tunnelling with longitudinal slots.

4.2.1 Shotcrete tunnelling method

For a divided cross-section in stable rock with properties ranging from fractured to friable, the shotcrete method is used. After excavation by blasting or mechanical excavation, support is installed that is weak in bending, consisting of shotcrete and steel arches or lattice elements in combination with rock bolts. For the already mentioned reasons, the cross-section is typically divided into top heading, bench and invert, with the advance of the top heading and bench being decided dependent on the geological conditions encountered, the external requirements and the deformation measured during the drive. The top heading and bench can be carried out with or without invert vault according to the conditions of the rock mass. Fig. 4-2 shows the situation in the Himmelberg Tunnel in friable rock, where a support core and an invert vault were necessary.

4.2.2 Underpinning method

In very friable to squeezing conditions, it can be advantageous to use the underpinning method. Excavation in this case also starts with the top heading, although the shotcrete layer is applied thicker to limit deformation and is thus designed to be stiffer (Fig. 4-3).

There are a range of variants for the underpinning method, which are based on the geological conditions and the operational requirements (see also Section 3.3.2). In principle, any tunnel drive with the top heading excavated in advance and support that is no longer weak in bending can be categorised as an underpinning method. The basic difference between the two processes is summarised in the following section:

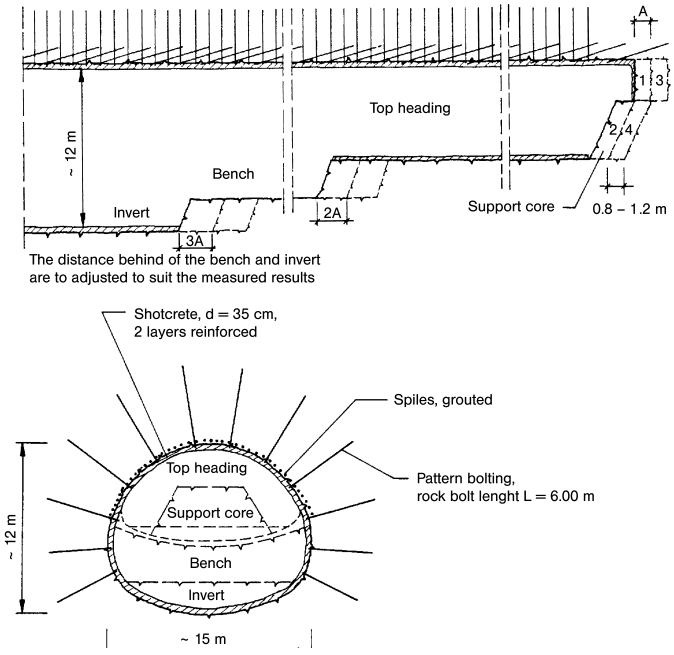


Figure 4-2 Application of a top heading in the Himmelberg Tunnel in friable rock.

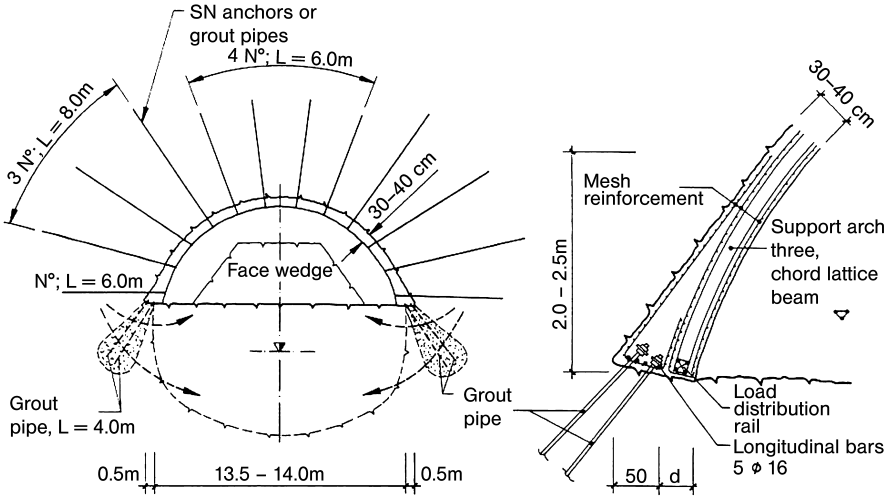
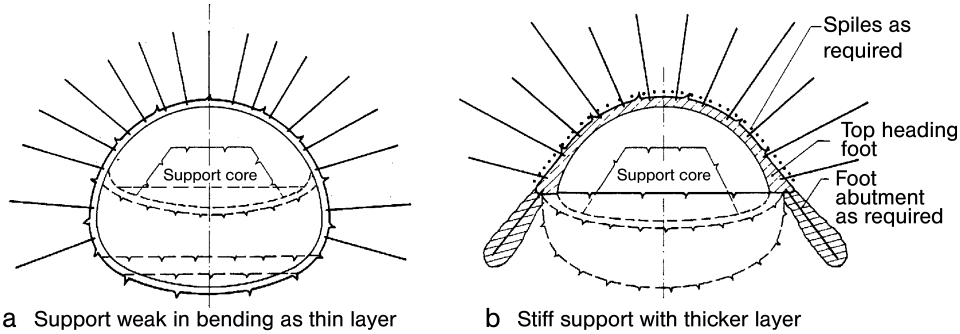


Figure 4-3 Support measures – top heading and the thickening at the foot of the top heading for fault zones encountered during the construction of the Landrücken Tunnels, central contract



a Support weak in bending as thin layer (shortcrete method)

b Stiff support with thicker layer (underpinning method)

Figure 4-4 Differentiation of shotcrete and underpinning methods

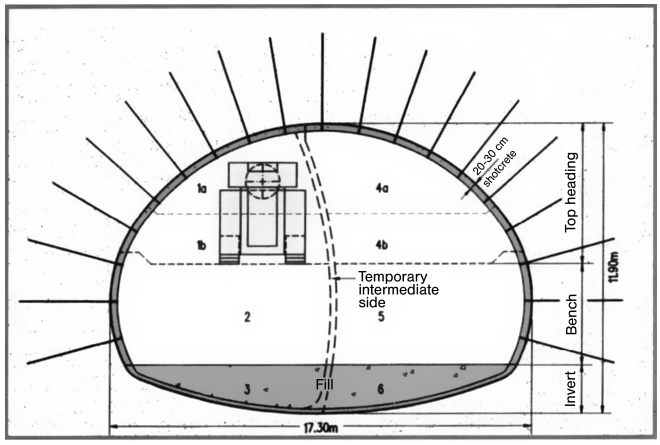
– In shotcrete tunnelling (Fig. 4-4 a), the tunnel drive can be planned with the thinnest possible shotcrete layer with little bending resistance, with more deformation being permitted in order to form a structurally active ring in the surrounding rock mass. The dimensions of the top heading and bench, which are excavated in advance (excavation area, round depth, top heading invert vault, invert vault), are then closely related to the dimensioning of the temporary support and the advance rate, which are dependent on the stand-up time of the rock mass.
– The underpinning method (Fig. 4-4 b) is used in friable to squeezing conditions, particularly with shallow cover, in other words conditions under which the formation of a structurally active ring in the rock mass cannot be guaranteed. But specification requirements for low settlement also demand thicker shotcrete layers, foot thickening, foot piles and perhaps grouting. Under the stated conditions, a shotcrete layer that is weak in bending is no longer achievable and thus not responsible. The use of the underpinning method can comply with the desire for greater safety. In the course of excavation, the shotcrete support layer in the top heading is underpinned with the tunnel structure being verified with calculations, so this case can no longer be considered a support layer that is weak in bending with closed invert, but an underpinning. If there is a danger of the abutments of the top heading support failing, they should be strengthened with grouting or piles.

If the conditions become worse still, particularly combined with the support of a large face, then the cross-section will have to be divided further according to Fig. 4-5. The division can either be by excavating a half side or by advancing a heading in the crown, in which case the crown beam process represents a special development.

Alternatively, the crown beam process permits the retention of an advanced top heading with the use of various types of screen or canopy for support as described in more detail in Chapter 2.

4.2.3 Crown pilot heading with crown beam

This process was developed by B. Maidl in 1982 for the Westtangente Tunnel in Bochum [217] and was also used very successfully in the Schulwald Tunnel in very friable to squeezing ground types (Fig. 4-6). In this tunnel, it was not practical to drive the entire top heading as the stability of the face could no longer be ensured [25].



Excavation phases in 4-lane section

Figure 4-5 Division of the cross-section for the Altstadt Tunnel, Arnsberg.

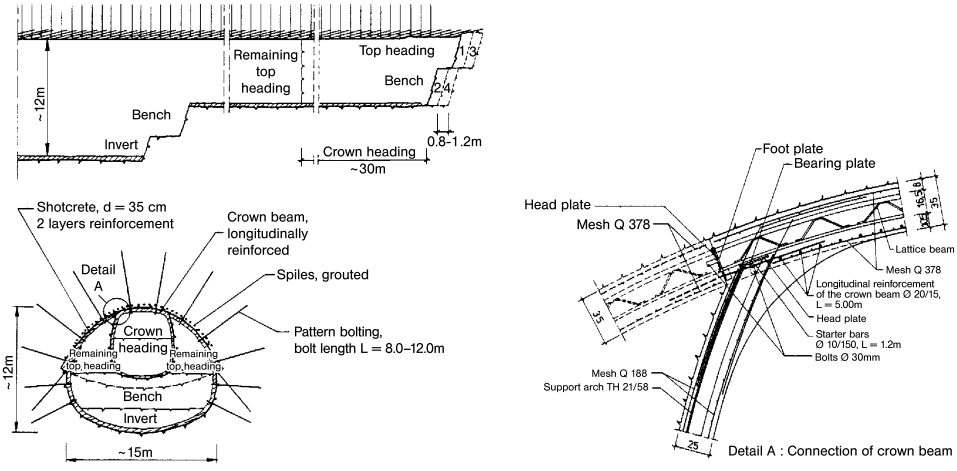


Figure 4-6 Application of the crown pilot heading method with crown beam at the Schulwald Tunnel

The crown pilot heading has about half the cross-sectional area of the top heading and is advanced about 30 to 40 m in front of the widening. If required, the crown pilot heading can also be divided into top heading and bench/invert with inclined face, and the anchoring of the face of the crown pilot heading and an invert vault could also be necessary depending on the geological conditions encountered. The crown pilot heading also has three layers of longitudinal reinforcement with 32 20/15 diameter bars running along the tunnel in 35 cm thick concrete, which acts as a longitudinally load-bearing crown beam.

The construction sequence for excavation and support in the Schulwald Tunnel was as follows:

I. Crown pilot heading:

– Top heading: Excavation and sealing shotcrete $d = 7$ cm as face support,
Outer layer of reinforcement, erection and spraying of the steel arches.

Installation of spiles if required, l = 3.0 m.
Shotcrete in crown d = 25 cm, sides d = 20 cm.
Installation of rock bolts, l = 8.0 – 12.0 m.

– Bench: Same steps as top heading but no spiles.
Next top heading round, next bench round.
Ring closure.
Second reinforcement layer in the sides and shotcrete d = 25 cm.
Construction of crown beam: inner reinforcement (steel mesh and 32 bars dia. 20/15, l = 5 m), shotcrete crown d = 35 cm.

II. Remainder of top heading:

Excavation left and sealing shotcrete 7 cm as face support.
Outer layer of reinforcement, connection and spraying of the support arches.
Reinforcement and shotcrete, top heading feet.
Installation of spiles if required.
Shotcrete d = 25 cm and setting of the anchor plates.
Round right, next round left, next round right.
Installation of the foot piles, inner reinforcement layer and shotcrete to d = 35 cm, alternating sides.
Removal of the support at the sides of the crown heading.

III. Bench:

Excavation and sealing as required.
Outer reinforcement layer, connection and spraying in of the support arches.
Installation of rock bolts, l = 6 m.
Inner reinforcement layer and shotcrete to d = 35 cm.

IV. Invert:

Support and sealing as required.
Installation of the temporary drainage.
Outer reinforcement layer, shotcrete.
Inner reinforcement layer, shotcrete d = 35 cm.

The advanced crown pilot heading reduces the size of the face and thus reduces the danger of face collapses. (Fig. 4-7). It is also useful for advance probing and water drainage. The crown beam provides additional support while the rest of the top heading is driven, with its load-bearing action along the tunnel having the effect of limiting settlement in the unsupported area (which can be shown to make up the largest part of overall settlement) when the remainder of the top heading is driven. The bearings for the crown beam are provided by the pipe-like support to the crown heading at the front and by the already load-bearing support at the back. The excavation of the remainder of the top heading can be performed synchronously or alternately, with the top heading support bearing being provided either by thickened footing (with or without foot pile) or as an invert vault. The excavation of the bench required special measures at the Schulwald Tunnel because of the squeezing rock mass. The footings of the top heading were already highly loaded and not capable alone of supporting additional loading from the underpinning during the bench advance. This demanded particular

skill of the miners and special attention to the underpinning of the top heading feet in order to ensure the necessary safety for the excavation of the bench and invert. One important measure at this stage of construction is the fastest possible closure of the invert for the entire cross-section, meaning that the bench and invert have to be advanced immediately after each other. In this case, it had to be borne in mind that the cross-sectional area of more than 100 m² would scarcely allow for emergency support with timber if a collapse had occurred.

Figure 4-7 Crown pilot heading method in the Schulwald Tunnel.

In this method, the advance can be changed over from top heading to crown heading immediately, and a change from crown heading to top heading advance only requires repetition of the enlargement to the face of the crown heading. This makes the crown heading method an especially adaptable construction process, which can thus also be used when unfavourable geological conditions, which make the excavation of the entire top heading impractical, are encountered unexpectedly without having been prepared. Without having to change to the core method with side headings, this method of tunnelling is to be recommended under very changeable geological conditions and particularly when tunnelling below buildings that are sensitive to deformation [185].

It should be mentioned that with hindsight, the use of a shield machine would have been an alternative worth considering for the Schulwald Tunnel with 4.5 km to be driven, particularly because a division into two bores and thus a shield drive without more risk would have been practical and interesting in terms of time and cost savings compared to the solution described above.

4.2.4 Shotcrete tunnelling with longitudinal slots

When deformations are very large, into the range of metres, the shotcrete layer with the integrated construction elements like steel or lattice arches and rock bolting can be preserved from destruction by providing systematic deformation slots (Fig. 4-8 and Fig. 4-9). Calculation methods can be found in section 3.7.

The width of the slots can be up to 40 cm. It can be assumed that the convergences that occur will deform the steel arches, which are fitted with yielding lap joints and thus represent a type of predetermined failure point.

Fax Order Form to +49 (0) 30 47031 240 - Ernst & Sohn Berlin or order online at: www.wiley.com

Quantity	Order-No.	Title	Price* €
	978-3-433-03048-6	Maidl, Bernhard / Thewes, Markus / Maidl, Ulrich: Handbook of Tunnel Engineering I - Structures and Methods	89,00
	906954	Publishing index Ernst & Sohn 2013/2014	for free
	Ernst und Sohn	monthly E-Mail-Newsletter	for free

Invoice and delivery address ☐ privat ☐ business

Company			
Contact person			Telephone
UST-ID Nr. / VAT-ID No.			Fax
Street number			E-Mail
Country		Zip-Code	Location

We guarantee you the right to revoke this order within two weeks. Please mail to Verlag Ernst Sohn, Willey-VCH, Boschstr. 12, D-69469 Weinheim

Wilhelm Ernst & Sohn
Verlag für Architektur und
technische Wissenschaften
GmbH & Co. KG
Rotherstraße 21, 10245 Berlin
Deutschland
www.ernst-und-sohn.de

Ernst & Sohn
A Wiley Brand

Date/ Signature

* In EU countries the local VAT is effective for books and journals. Postage will be charged. Whilst every effort is made to ensure that the contents of this leaflet are accurate, all information is subject to change without notice. Our standard terms and delivery conditions apply. Prices are subject to change without notice. Date of Information:October2013 (homepage_Probekapitel)