

2nd Edition

Mechanised Shield Tunnelling

Bernhard Maidl
Martin Herrenknecht
Ulrich Maidl
Gerhard Wehrmeyer

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