

Contents

<i>Foreword</i>	xv
<i>Authors</i>	xvii
<i>Glossary</i>	xix
<i>Abbreviations</i>	xxi
<i>Notation</i>	xxiii
<i>Introduction</i>	xxv

1 The Art of Achieving Agreement **1**

<i>1.1 Key Factors</i>	<i>1</i>
<i>1.2 The Power of Progressive Modification</i>	<i>2</i>
<i>1.3 Summaries of Featured Case Histories</i>	<i>5</i>
1.3.1 The Channel Tunnel (1988–1991)	5
1.3.2 The Mansion House (1989–1991)	6
1.3.3 Limehouse Link (1991–1993)	6
1.3.4 Heathrow Express Cofferdam (1994–1995)	7
1.3.5 Heathrow Airport Multi-Storey Car Park (1995–1996)	7
1.3.6 Boston Central Artery (1991–2001)	8
1.3.7 Irlam Railway Bridge Embankment (1997–1999)	8
1.3.8 Heathrow Airport Airside Road Tunnel (ART) (2001–2003)	8
1.3.9 Wembley Stadium Arch (2004–2005)	9
1.3.10 Crossrail Blomfield Box (2012–2014)	9
1.3.11 Crossrail Moorgate Shaft (2014–2015)	10
1.3.12 Heathrow Airport Terminal 5 Tunnels (2005–2006)	10

<i>References</i>	<i>11</i>
-------------------	-----------

2	Channel Tunnel Cut and Cover Works (1988–1990)	13
2.1	<i>Introduction</i>	13
2.2	<i>Key Aspects of Design and Construction</i>	14
2.2.1	Overview	14
2.2.2	Geology	15
2.2.3	Design Uncertainties	16
2.3	<i>Achieving Agreement to Use the OM</i>	19
2.3.1	Creating Opportunity	19
2.3.2	Finding the Key	20
2.4	<i>Implementation of the OM</i>	21
2.4.1	Development of Progressive Modification	21
2.4.2	Construction Sequence, Form and Geometry	22
2.4.3	Design Constraints	23
2.4.4	Addressing Uncertainty	25
2.4.5	Instrumentation and Monitoring	26
2.4.6	Castle Hill East – The OM Stage 1: Initiation	26
2.4.7	Measured Performance at CHE	29
2.4.8	Sugarloaf Hill – The OM Phase 2: Development	30
2.4.9	Castle Hill West – The OM Phase 3: Conclusion	31
2.4.10	Landslip Loading	33
2.5	<i>Connection with the NATM Tunnels</i>	37
2.5.1	Interface Coordination	37
2.5.2	The OM and ‘Most Probable’ Conditions	37
2.6	<i>Conclusions</i>	38
	<i>References</i>	38
3	Mansion House (1989–1991)	39
3.1	<i>Introduction</i>	39
3.2	<i>Key Aspects of the Design and Construction</i>	41
3.2.1	Foundations in the Building’s History	41
3.2.2	The Challenge Presented by the DLR	42
3.3	<i>Achieving Agreement to Use the OM</i>	45
3.3.1	Addressing Complexity	45
3.3.2	Creating the Solution through the OM	47
3.3.3	Introduction of the OM Traffic Light System	49
3.4	<i>Implementation of the OM</i>	50
3.4.1	Managing Risk	50
3.4.2	The Profound Influence of Soil/Structure Interaction	52
3.4.3	Instrumentation and Monitoring	56

3.4.4	Temperature-Induced Cyclic Movements	58
3.4.5	Development of Progressive Modification	60
3.4.6	Critical Observations, Trigger Levels and Contingencies	61
3.5	<i>Results</i>	62
3.5.1	Overview	62
3.5.2	Detailed Assessment	63
3.5.3	The Benefit of Hindsight	65
3.6	<i>Conclusions</i>	65
	<i>References</i>	67
4	Limehouse Link (1991–1993)	69
4.1	<i>Introduction</i>	69
4.2	<i>Key Aspects of Design and Construction</i>	69
4.2.1	Overview	69
4.2.2	Geology	71
4.2.3	Original Design	73
4.2.4	Value Engineering	75
4.3	<i>Achieving Agreement to Use the OM</i>	76
4.3.1	Overcoming Traditional Barriers	76
4.3.2	The Key to Consensus	78
4.4	<i>Implementation of the OM</i>	79
4.4.1	Extending the Process of Progressive Modification	79
4.4.2	Sequence for Each Implementation of the OM	79
4.4.3	Observations, Trigger Levels and Contingencies	82
4.4.4	Measured Performance	84
4.4.5	Increasing Beneficial Design Changes	86
4.4.6	Personnel and Communication	87
4.4.7	Achieving Simple and Effective Monitoring	88
4.4.8	Construction Plant and Resources	89
4.5	<i>Limehouse Basin Construction</i>	89
4.5.1	Reaching the Practical Limits of the OM	89
4.5.2	Monitoring Becomes Intensive	92
4.5.3	Implementation of the OM in Limehouse Basin	92
4.5.4	Added Value Still Achieved	93
4.6	<i>Risk and Insurance</i>	94
4.7	<i>Conclusions</i>	95
	<i>References</i>	96

5 Heathrow Express Cofferdam (1994–1995)	97
5.1 <i>Introduction</i>	97
5.2 <i>Key Aspects of Design and Construction</i>	97
5.2.1 <i>Overview</i>	97
5.2.2 <i>Geology – Conditions Prior and Post Collapse</i>	99
5.2.3 <i>Contractual Conditions</i>	101
5.2.4 <i>The Cofferdam</i>	103
5.3 <i>Achieving Agreement to Use the OM</i>	104
5.3.1 <i>Safety and Innovation</i>	104
5.3.2 <i>Progressive Modification Offers the Way Forward</i>	104
5.4 <i>Implementation of the OM</i>	106
5.4.1 <i>The Recovery Solution</i>	106
5.4.2 <i>Cofferdam Configuration</i>	108
5.4.3 <i>Innovations in Piled Wall Design and Construction</i>	109
5.4.4 <i>Design Development</i>	113
5.4.5 <i>A Bespoke Design for Progressive Modification</i>	115
5.4.6 <i>Observations, Trigger Levels and Contingencies</i>	116
5.4.7 <i>Measured Performance and Design Improvements</i>	118
5.5 <i>Conclusions</i>	119
<i>References</i>	120
 6 Heathrow Airport Multi-Storey Car Park 1A (1995–1996)	 123
6.1 <i>Introduction</i>	123
6.2 <i>Key Aspects of Design and Construction</i>	123
6.2.1 <i>Overview</i>	123
6.2.2 <i>Geology</i>	125
6.2.3 <i>Tunnel Construction</i>	125
6.2.4 <i>Car Park Structure</i>	126
6.3 <i>Achieving Agreement to Use the OM</i>	127
6.4 <i>Implementation of the OM</i>	127
6.4.1 <i>Traffic Lights, Trigger Levels and Contingencies</i>	127
6.4.2 <i>Risk Assessments</i>	128
6.4.3 <i>Predicted Ground Movements</i>	130
6.4.4 <i>Measured Settlements</i>	131
6.5 <i>Effects on the Building and Remedial Measures</i>	136
6.5.1 <i>Damage Assessment</i>	136
6.5.2 <i>Remedial Measures</i>	137
6.5.3 <i>Structural Response: Actual vs Predicted</i>	137
6.5.4 <i>Background to the Risk Assessment</i>	138

6.5.5	Evaluation of Actual Response	139
6.5.6	Key Lessons Learned	141
6.6	<i>Conclusions</i>	145
6.6.1	A Triple Irony	145
6.6.2	Beware the Oddball – Reflections on Peck (1998)	146
	<i>References</i>	146
7	Boston Central Artery Tunnel Jacking (1991–2001)	149
7.1	<i>Introduction</i>	149
7.2	<i>Key Aspects of Design and Construction</i>	149
7.2.1	The Project	149
7.2.2	Geology	152
7.2.3	Original Design Concept	153
7.2.4	Innovations in Tunnel Jacking	154
7.3	<i>Achieving Agreement to Use the OM</i>	159
7.3.1	A Dramatic Simplicity	159
7.3.2	‘A Rose by Any Other Name’	162
7.4	<i>Implementation of the OM</i>	162
7.4.1	The Primary Objective	162
7.4.2	Solving the Spatial Challenges	163
7.4.3	The Process for Tunnel Jacking	163
7.5	<i>Construction Activities Causing Ground Movements</i>	167
7.5.1	Installation of Diaphragm Walls Forming the Thrust Pits	167
7.5.2	Jet Grouting of the Low Level In-Situ Strut	167
7.5.3	Bulk Excavation of the Thrust Pits	168
7.5.4	Installation of Vertical Freeze Pipes	169
7.5.5	Heave and Lateral Movement of the Ground during Freezing	169
7.5.6	Ground Movements during Tunnelling Operations	170
7.5.7	Longer-Term Ground Movements during Thawing and Consolidation	172
7.6	<i>Instrumentation and Monitoring</i>	173
7.6.1	Railway Track Monitoring	173
7.6.2	Diaphragm Wall Monitoring	173
7.6.3	Ground Movement and Groundwater Monitoring	174
7.7	<i>Managing Interfaces</i>	175
7.7.1	Tunnel Launch Pads	175
7.7.2	Jet Grouting	176
7.7.3	Ground Freezing	176

7.8	<i>Fostering a Collaborative Approach</i>	176
7.8.1	Teamwork	176
7.8.2	Extending the Limits of Progressive Modification	179
7.9	<i>Results</i>	180
7.10	<i>Conclusions</i>	182
	<i>References</i>	183
8	Irlam Railway Embankment (1996–1998)	185
8.1	<i>Introduction</i>	185
8.2	<i>Key Aspects of Design and Construction</i>	186
8.2.1	Overview	186
8.2.2	Geology	187
8.2.3	Bridge Assessment	189
8.2.4	Project Constraints	191
8.3	<i>Evaluation of Embankment Options</i>	192
8.3.1	Identifying Viable Options	192
8.3.2	Potential Adverse Effects on Bridge Foundations	194
8.4	<i>Achieving Agreement to Use the OM</i>	198
8.5	<i>Implementation of the OM</i>	200
8.5.1	Trigger Levels and Contingency Measures	200
8.5.2	Instrumentation and Monitoring	202
8.5.3	Pre-load Embankment Construction	205
8.5.4	Removal of Pre-Load and EPS Embankment Construction	208
8.6	<i>Conclusions</i>	211
	<i>References</i>	213
9	Heathrow Airport Airside Road Tunnel	215
9.1	<i>Introduction</i>	215
9.2	<i>Key Aspects of Design and Construction</i>	215
9.2.1	Portal Structures and Tunnels	215
9.2.2	Geology	217
9.2.3	Base Case Design	218
9.2.4	Construction Sequence	219
9.2.5	Retaining Wall Design	219
9.3	<i>Achieving Agreement to Use the OM</i>	221
9.3.1	Promoting Innovation	221
9.3.2	Addressing the Issue of Precedent	223
9.4	<i>Implementation of the OM</i>	223
9.4.1	A Big Challenge at a Small Scale	223

9.4.2	The Breakthrough Concept	225
9.4.3	Instrumentation, Trigger Levels, Contingencies and Measured Performance	227
9.5	<i>Innovation in Blinding Struts</i>	229
9.5.1	Interface with the Piccadilly Line Tunnel	229
9.5.2	Implementing Innovation	232
9.6	<i>Conclusions</i>	234
	<i>References</i>	237
10	Raising the 133 m High Triumphal Arch at the New Wembley Stadium (2002–2004)	239
10.1	<i>Introduction</i>	239
10.2	<i>Key Aspects of Design and Construction</i>	239
10.2.1	Overview	239
10.2.2	Foundations and Geotechnics	242
10.2.3	Arch Raising	244
10.3	<i>Achieving Agreement to Implement the OM</i>	246
10.3.1	Creating Opportunity	246
10.3.2	Assessment of Foundation Behaviour during Arch Raising	248
10.3.3	Preliminary Pile Load Tests	250
10.4	<i>Establishing Trigger Levels and Contingency Measures</i>	251
10.4.1	Foundation Analysis	251
10.4.2	Trigger Levels and Contingency Plans	254
10.5	<i>Implementation of the OM</i>	255
10.5.1	Initial Surveys	255
10.5.2	Observed Pile Group Deformation	257
10.6	<i>Conclusions</i>	259
	<i>References</i>	261
11	Crossrail Blomfield Box (2012–2015)	263
11.1	<i>Introduction</i>	263
11.2	<i>Key aspects of Design and Construction</i>	263
11.2.1	Overview	263
11.2.2	Geology	265
11.3	<i>Achieving Agreement to Use the OM</i>	269
11.3.1	Potential Hazards	269
11.3.2	Design Conditions	271
11.4	<i>Implementation of the OM</i>	273
11.4.1	Dewatering Systems – Potential Failure Scenarios	273

11.4.2	Instrumentation and Monitoring	275
11.4.3	Traffic Light System for the OM	277
11.4.4	Dewatering System, Observations Outside of the Blomfield Box	278
11.4.5	Displacement of Contiguous Pile Retaining Wall	279
11.4.6	Dewatering System, Observations Inside the Blomfield Box	281
11.4.7	Dewatering System, Modifications during Final Phase of Excavation	282
11.4.8	Summary of Changes Introduced through Implementation of the OM	283
11.5	<i>Conclusions</i>	285
	<i>References</i>	286
12	Crossrail Moorgate Shaft (2012–2014)	287
12.1	<i>Introduction</i>	287
12.2	<i>Key Aspects of Design and Construction</i>	287
12.2.1	Overview	288
12.2.2	Geology	291
12.3	<i>Achieving Agreement to Use the OM</i>	291
12.3.1	Design Objectives and Constraints	291
12.3.2	Creating Opportunity	293
12.3.3	Verification Process	296
12.4	<i>Implementation of the OM</i>	297
12.4.1	Key Steps and Activities	297
12.4.2	Verification Point 1	301
12.4.3	Verification Point 2	301
12.4.4	Verification Point 3	305
12.4.5	Summary of Changes Introduced through Implementation of the OM	308
12.4.6	Reflections on the Role of Analysis and Bayesian Updating	309
12.5	<i>Conclusions</i>	310
	<i>References</i>	312
13	Reflections on the Advantages and Limitations of the Observational Method	313
13.1	<i>The Legacy of Terzaghi and Peck</i>	313
13.2	<i>Advantages and Limitations of the OM</i>	314
13.2.1	Lessons Learned from the Case Histories	314

13.2.2	The Importance of Simplicity	315
13.2.3	Key Limitations	315
13.2.4	Heathrow Terminal 5 Tunnels – An Illustrative Case History	318
13.3	<i>Progressive Modification – Solving the Issue of the ‘Most Probable’</i>	320
	References	324
14	Some Observations on the Way Forward	325
14.1	<i>The 1996 Overview</i>	325
14.2	<i>Commercial and Contractual Environment</i>	327
14.2.1	Overview	327
14.2.2	Design and Build	329
14.2.3	Developing Greater Collaboration	329
14.2.4	Value Engineering Clauses	330
14.3	<i>Instrumentation and Monitoring</i>	331
14.3.1	General Considerations	331
14.3.2	Performance Limits and Traffic Lights	333
14.4	<i>Progressive Modification – A Comprehensive Approach</i>	335
14.5	<i>Peer Review</i>	336
14.6	<i>Recommendations for OM Practitioners</i>	337
	References	338
	Index	341