

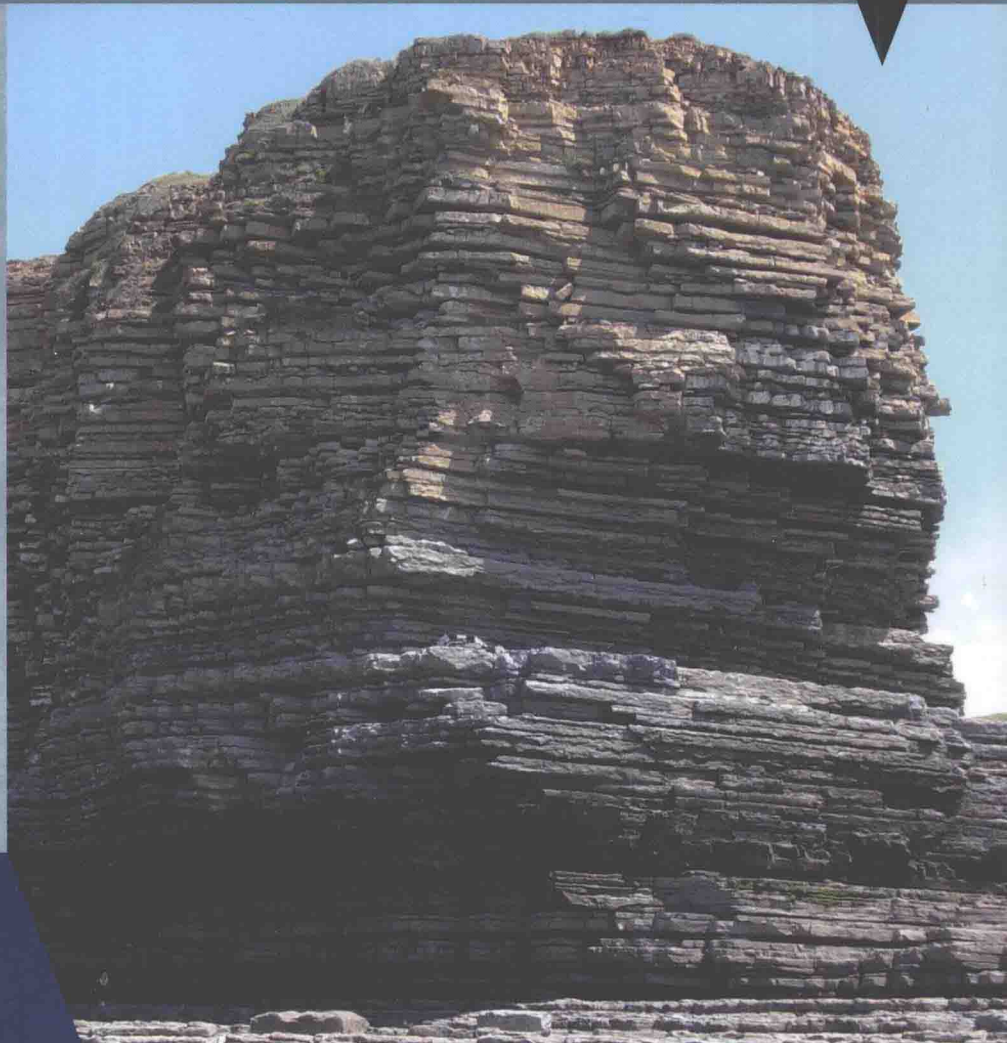


ISRM

International Society  
for Rock Mechanics

ISRM Book Series

1



# Rock Engineering Risk

*John A. Hudson*  
*Xia-Ting Feng*

 CRC Press  
Taylor & Francis Group  
A BALKEMA BOOK

---

# Rock Engineering Risk

---

**John A. Hudson**

*Department of Earth Science and Engineering,  
Imperial College London, UK*

**Xia-Ting Feng**

*Institute of Rock and Soil Mechanics,  
Chinese Academy of Sciences, Wuhan, China*



**CRC Press**

Taylor & Francis Group

Boca Raton London New York Leiden

---

CRC Press is an imprint of the  
Taylor & Francis Group, an **Informa** business

A BALKEMA BOOK

The photograph on the front cover is of a limestone and mudstone rock mass in South Wales, UK, as an example of the discontinuous, inhomogeneous and anisotropic nature of most rock masses.

*CRC Press/Balkema is an imprint of the Taylor & Francis Group, an informa business*

© 2015 Taylor & Francis Group, London, UK

Typeset by V Publishing Solutions Pvt Ltd., Chennai, India

Printed and bound in Great Britain by CPI Group (UK) Ltd, Croydon, CR0 4YY

All rights reserved. No part of this publication or the information contained herein may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, by photocopying, recording or otherwise, without prior permission in writing from the publisher. Innovations reported here may not be used without the approval of the authors.

Although all care is taken to ensure integrity and the quality of this publication and the information herein, no responsibility is assumed by the publishers nor the authors for any damage to the property or persons as a result of operation or use of this publication and/or the information contained herein.

Published by: CRC Press/Balkema

P.O. Box 11320, 2301 EH Leiden, The Netherlands

e-mail: Pub.NL@taylorandfrancis.com

www.crcpress.com – www.taylorandfrancis.com

*Library of Congress Cataloging-in-Publication Data*

Hudson, J. A. (John A.), 1940-

Rock engineering risk / John A. Hudson, Department of Earth Science and Engineering, Imperial College London, UK, Xia-Ting Feng, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, China.

p. cm

Includes bibliographical references and index.

ISBN 978-1-138-02701-5 (hardcover : alk. paper) – ISBN 978-1-315-73857-4

(ebook : alk. paper) 1. Rock mechanics–Risk assessment. 2. Structural failures.

I. Feng, Xia-Ting. II. Title.

TA706.H79 2015

624.1'5132–dc23

2015008976

ISBN: 978-1-138-02701-5 (Hbk)

ISBN: 978-1-315-73857-4 (eBook PDF)

#### DISCLAIMER

No responsibility is assumed by the Authors or Publisher for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions or ideas contained in the material herein.

---

# Preface

---

The purpose of this book is to describe the subject of risk as it relates to the design and construction of engineering projects located on or within rock masses. Traditionally, such projects include facilities such as building foundations, dams, slopes, tunnels, caverns and mines; but, more recently, other increasingly complex rock engineering projects are being developed, constructed and operated, such as geothermal energy, radioactive waste disposal, CO<sub>2</sub> storage and hydraulic fracturing for shale gas. In all these projects, there are risks involved in the separate aspects of site investigation, modelling, design and construction—together with their cumulative effect on the operation of the whole project.

Our previous 2011 book, “Rock Engineering Design”, published by CRC Press/Balkema (Taylor & Francis Group), was also concerned with the design of projects constructed on or in rock masses, i.e., slopes, dams, hydroelectric schemes, mines, and repositories for radioactive waste disposal. That book covered rock engineering design methodologies, associated flowcharts, the information required, technical auditing of design, a rock slope case example, an underground hydroelectric powerhouse case example, Protocol Sheets for auditing rock engineering design, and examples of the use of Protocol Sheets. This new book, “Rock Engineering Risk”, covers the related and important subject of risk using the Frontispiece flowchart in which the risks are considered in terms of the uncertainties associated with ‘before construction’ and ‘during construction’ factors.

The emphasis in the book is on the physical aspects of these subjects, the rock mechanics and the rock engineering, rather than the financial aspects, although of course there are financial ramifications associated with the mitigation of the physical risks. Chapters 1–5 provide information on the subject of risk and the approaches to reducing risk, especially in the context of design and construction for underground rock engineering, although the general principles apply also to surface rock engineering. Chapters 6 and 7 contain two detailed, major case examples from China relating to long tunnels at great depth and a hydropower cavern complex. These two Chapters contain a wealth of information relating to the practical risk reduction methods described in the earlier chapters and the experiences of their application during both tunnelling and cavern construction.

Both our previously published book on ‘rock engineering design’ and this book on ‘rock engineering risk’ are outputs from the International Society for Rock Mechanics (ISRM) Commission on Design Methodology. The earlier ‘rock

engineering design' book was generated when John A. Hudson was President of the ISRM (2007–2011), and this new book on 'rock engineering risk' was generated while Xia-Ting Feng was President of the ISRM (2011–2015).

We are pleased to report that this book is the first in the newly established CRC Press/Balkema ISRM Book Series.

John A. Hudson and Xia-Ting Feng,  
2015

---

# Acknowledgements

---



## ISRM *International Society for Rock Mechanics*

We are especially grateful to Professor E.T. Brown of Golder Associates in Australia who originally recommended that the ISRM Design Methodology Commission should focus on ‘rock engineering risk’ in the 2011–2015 ISRM Presidential tenure period—following the earlier 2007–2011 research on ‘rock engineering design’. The risk subject certainly required attention and we hope that now, four years later, the Commission has indeed made a worthwhile contribution through the publication of this book.

Thus, the ISRM Design Methodology Commission was active in the period 2011–2015 and the authors, as respectively Commission President and Commission Co-President, are significantly indebted to the ISRM Commission Members listed below who actively took part in discussions held in association with ISRM symposia, made many suggestions and provided reference material.

*Dr Conrad Felice, Mr Erik Johansson, Prof. Frederic Pellet, Prof. Wulf Schubert, Prof. Alexandros Sofianos, Prof. Ove Stephansson, Prof. Leslie G. Tham, Dr Antonio Samaniego, Dr Mostafa Sharifzadeh, Prof. Resat Ulusay, Mr Lauri Uotinen, Dr Philippe Vaskou, Dr Christophe Vibert, Dr Thierry You, Dr Yingxin Zhou.*

The authors are additionally grateful to Professor Qian Qihu, Academician of the Chinese Academy of Engineering and President of the Chinese Society for Rock Mechanics and Engineering for his continuing support of the ISRM Design Methodology Commission’s work.

Also, the authors are indebted to Dr Chin-Fu Tsang (former DECOVALEX Project Chairman) and Dr Lanru Jing (DECOVALEX Project Secretary) for their assistance in providing some of the DECOVALEX historical material in Chapter 5. The authors appreciate and thank the DECOVALEX2015 Funding Organisations for their financial and technical support of the DECOVALEX project work described in that Chapter. The statements made in this book are, however, solely those of the authors and do not necessarily reflect those of the DECOVALEX Funding Organisations.

In addition, we thank the following personnel who contributed to the content of Chapters 6 and 7 describing the major tunnel and hydropower case examples; their help has significantly enhanced the content and value of the book. Dr Qiu Shili and Dr Zhang Yongjie wrote the first drafts of Chapters 6 and 7, respectively, and Dr Qiu Shili also assisted with some of the diagram preparation. Professor Jiang Quan provided ideas and considerable information relating to risk assessment of underground cavern groups. Professors Zhang Chunsheng, Hou Jing and Chen Xiangrong were involved with the geological conditions and design information for the Jinping II Project. Professor Chen Bingrui, Dr Xiao Yaxun and Mr Feng Guangliang took part in the rockburst monitoring and warning system in the headrace tunnels and water drainage tunnel at the Jinping II Project site, and Professors Wu Shiyong, Wang Jimin and Zeng Xionghui also provided support for that aspect of the work.

\* \* \* \* \*

Lastly, we express our profound thanks to Carol Hudson for her meticulous checking of all the details of not only the original manuscript, but also both the initial and final proofs of the book. We may not have eliminated all the errors but, through Carol's help, there are far fewer.

---

## About the authors

---



*John A. Hudson and Xia-Ting Feng at an International Society for Rock Mechanics (ISRM)  
Task Force meeting of the Commission on Design Methodology  
held at the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, China.*

*ISRM President 2007–2011: John A. Hudson  
ISRM President 2011–2015: Xia-Ting Feng*

### **PROFESSOR JOHN A. HUDSON**

John A. Hudson graduated from the Heriot-Watt University, UK, and obtained his PhD at the University of Minnesota, USA. He has spent his professional career in consulting, research, teaching and publishing in engineering rock mechanics, and was awarded the DSc. degree by the Heriot-Watt University for his contributions to the subject. He has authored many scientific papers and books, and was the editor of the 1993 five-volume “Comprehensive Rock Engineering” compendium, and from 1983–2006 editor of the International Journal of Rock Mechanics and Mining Sciences. Since 1983, he has been affiliated with Imperial College London as Reader, Professor and now Emeritus Professor. In 1998, he became a Fellow of the UK Royal Academy of Engineering and was President of the International Society for Rock Mechanics (ISRM) for the period 2007–2011. In 2015, the 7th ISRM Müller Award was conferred on Professor Hudson in recognition of “an outstanding career that combines theoretical and applied rock engineering with a profound understanding of the basic sciences of geology and mechanics”.



**PROFESSOR XIA-TING FENG**

Xia-Ting Feng graduated in 1986 from the Northeast University of Technology and obtained his PhD in 1992 at the Northeastern University, China. He was then appointed and acted as Lecturer, Associate Professor and Professor at the same university. In 1998, he was admitted by the Hundred Talents Programme to the Chinese Academy of Sciences (CAS). Subsequently, he permanently joined CAS's Institute of Rock and Soil Mechanics at Wuhan, China. In 2003, he obtained the support of the China National Funds for Distinguished Young Scientists; in 2010, he became a Chair Professor of the Cheung Kong Scholars' Programme, Ministry of Education, China; and, in 2009, he was elected as President of the International Society for Rock Mechanics for the period 2011–2015. He is currently Director of the State Key Laboratory of Geomechanics and Geotechnical Engineering in Wuhan. Additionally, in 2012, Professor Feng became the Co-President of the Chinese Society for Rock Mechanics and Engineering. He has made original contributions to the subject of 'intelligent rock mechanics' and his methods have been applied to large rock engineering projects in China and other countries.

---

# Contents

---

<i>Preface</i>	xvii
<i>Acknowledgements: International Society for Rock Mechanics</i>	xix
<i>About the authors</i>	xxi
<b>I Introduction and background</b>	<b>I</b>
1.1 The previous book “Rock Engineering Design” and this book “Rock Engineering Risk”	1
1.2 Rock engineering risk	3
1.3 Governing flowchart for the book	6
1.4 Structure and content of the book	7
1.5 Chapter summary	8
<b>2 Uncertainty and risk</b>	<b>9</b>
2.1 Introduction	9
2.2 Approaches to risk management	16
2.3 Epistemic and aleatory uncertainties	21
2.3.1 Explanation of the terms ‘epistemic’ and ‘aleatory’	21
2.3.2 Procedures for dealing with epistemic/aleatory uncertainties and Eurocode 7	25
2.4 Chapter summary	27
<b>3 Rock Engineering Systems (RES), auditing and Protocol Sheets</b>	<b>29</b>
3.1 Introduction to the systems approach and auditing concepts	29
3.2 Reducing epistemic uncertainty using the rock engineering systems approach	30
3.3 A review and explanation of the Rock Engineering Systems (RES) methodology	31
3.3.1 The interaction matrix	32
3.3.2 Coding the interaction matrix, and the Cause–Effect plot	36

3.3.3	Mechanism pathways	43
3.3.4	Step-by-step evolution of the interaction matrix	48
3.4	Examples of Rock Engineering Systems (RES) applied to rock mechanics and rock engineering design	56
3.4.1	Natural and artificial surface rock slopes	56
3.4.1.1	Surface blasting	56
3.4.1.2	Natural slopes	60
3.4.1.3	Instability of artificial rock slopes	78
3.4.2	Underground rock engineering	79
3.4.2.1	Underground blasting	79
3.4.2.2	Tunnel Boring Machines (TBMs)	82
3.4.2.3	Tunnel stability	85
3.4.3	Underground radioactive waste disposal	90
3.4.4	Use of the RES interaction matrix in other subject areas	92
3.5	Further development of the RES methodology	105
3.6	Auditing and Protocol Sheets	107
3.6.1	'Soft', 'semi-hard' and 'hard' technical audits and the audit evaluation	108
3.7	Chapter summary	109
<b>4</b>	<b>Rock fractures and <i>in situ</i> rock stress</b>	<b>111</b>
4.1	Introduction	111
4.2	Rock fractures	112
4.2.1	The spectrum of brittle and ductile rock deformation	112
4.2.2	Multiple deformational sequences	114
4.2.3	The risks associated with different types of rock mass	116
4.3	<i>In situ</i> rock stress	122
4.3.1	The stress state in a rock mass	122
4.3.1.1	<i>In situ</i> rock stress scales	123
4.3.2	Stress perturbation factors	124
4.3.2.1	Rock inhomogeneity	124
4.3.2.2	Rock anisotropy	126
4.3.2.3	Rock fractures	127
4.3.2.4	The influence of a free surface	129
4.3.3	Evidence of <i>in situ</i> stress variability	131
4.3.3.1	Stress vs. depth compilations	131
4.3.3.2	The ways ahead for improving the understanding of rock stress variability	132
4.3.4	A case study of modelling <i>in situ</i> rock stress at the Olkiluoto site, western Finland	133
4.4	Chapter summary	137

<b>5</b>	<b>Radioactive waste disposal: overcoming complexity and reducing risk</b>	<b>139</b>
5.1	The disposal objective	139
5.1.1	An example of radioactive waste repository statistics	140
5.2	Features, Events and Processes	143
5.3	Thermo-Hydro-Mechanical (THM+) processes	143
5.3.1	The THM+ issues in context	144
5.3.2	The excavation, operational and post-closure stages	147
5.3.2.1	The excavation stage	147
5.3.2.2	Operational stage	148
5.3.2.3	Post-closure stage	149
5.3.2.4	Heterogeneity and multiple stage data needs	149
5.3.2.5	Modelling phases and scaling	151
5.3.3	The use of numerical computer codes	152
5.3.3.1	The nature of numerical codes	153
5.3.3.2	Uncoupled and coupled codes	153
5.3.3.3	Technical auditing of numerical codes	154
5.3.3.4	Capturing the essence of the problem	155
5.3.3.5	The overall Technical Auditing (TA) procedure and risk	158
5.3.3.6	Validation	163
5.3.3.7	The future of numerical codes	164
5.4	The DECOVALEX programme	164
5.4.1	The development of the DECOVALEX programme	165
5.4.2	Research work in the current DECOVALEX phase: D-2015	166
5.4.2.1	Task A: The Sealex <i>in situ</i> experiment, Tournemire site, France	166
5.4.2.2	Task B1: The HE-E <i>in situ</i> heater test, Mont Terri Underground Research Laboratory, Switzerland	167
5.4.2.3	Task B2: The EBS experiment at Horonobe, Japan	168
5.4.2.4	Task C1: THMC modelling of rock fractures	169
5.4.2.5	Task C2: Modelling water flow into the Bedrichov Tunnel, Czech Republic	170
5.5	Underground Research Laboratories (URLs)	172
5.5.1	The purpose of URLs	172
5.5.2	The Swedish Äspö URL	172
5.6	Chapter summary	176

<b>6</b>	<b>Risks associated with long deep tunnels</b>	<b>179</b>
6.1	Introduction	179
6.1.1	Development of long deep tunnels	179
6.1.2	Flowchart to develop risk management for long, deep tunnels	184
6.2	Epistemic uncertainty analysis of design and construction for long deep tunnels	187
6.2.1	Geological settings	187
6.2.1.1	Geological factors relating to rockbursts in deep tunnels	187
6.2.1.2	Geological conditions exhibiting squeezing or large deformation behaviour	189
6.2.2	Rock stress	194
6.2.3	Hydrogeology	196
6.2.4	Properties of the rock mass	198
6.2.5	Project location	200
6.2.6	Excavation and support methods	200
6.3	Aleatory uncertainty analysis of design and construction for long deep tunnels	203
6.3.1	Detailed geology variations	203
6.3.2	Rock stress variations	205
6.3.3	Local water variations	208
6.3.4	Mechanical behaviour of the rock mass after excavation and in the long term	210
6.4	Methods to assess and mitigate risk for long deep tunnels	212
6.4.1	Rockbursts	212
6.4.1.1	Rockburst risk assessment	212
6.4.1.2	Risk mitigation concepts in rockburst prone tunnels	216
6.4.1.3	New approaches and optimisation of the risk-reduced construction procedures	218
6.4.2	Water inrush	229
6.4.2.1	Procedures for water inflow assessment	230
6.4.2.2	Assessment of water inrush potential	231
6.4.2.3	Assessment of tunnel water inflow	232
6.4.2.4	Treatment technologies for tunnel water inrush	232
6.4.3	Large deformations of weak rock in deep tunnels	233
6.4.3.1	Large deformation assessment	235
6.4.3.2	Treatment technologies for large deformations	241
6.4.4	Long term stability	250
6.4.4.1	Long term stability assessment in deep tunnels	250
6.4.4.2	Treatment technologies to ensure long term stability in deep and long tunnels	254

6.5	Illustrative example: Assessment and mitigation of risk for deep tunnels at the Jinping II Hydropower Station, China	254
6.5.1	Epistemic uncertainty analysis of headrace long deep tunnels	257
6.5.1.1	Geological setting	257
6.5.1.2	Rock stress	259
6.5.1.3	Hydrology	262
6.5.1.4	Properties of the rock mass	264
6.5.1.5	Specific project location	268
6.5.1.6	Excavation and support method	269
6.5.1.7	Water inrush	272
6.5.1.8	Rockbursts	273
6.5.1.9	Large deformations	278
6.5.1.10	Long term stability	279
6.5.2	Aleatory uncertainty analysis of the headrace tunnels	279
6.5.2.1	Geological variations at different chainage intervals	279
6.5.2.2	Rock stress variations affecting the three-dimensional stress field	282
6.5.2.3	Local water variations based on prediction in advance	282
6.5.2.4	Mechanical behaviour of the rock mass after excavation and in the long term	282
6.5.3	Assessment and mitigation of local risk during the construction of the headrace tunnels	289
6.5.3.1	Water inrush	289
6.5.3.2	Rockburst: monitoring, <i>in situ</i> tests, warning and mitigation	296
6.5.3.3	Large deformation: monitoring and treatment	304
6.5.3.4	Long term stability	310
6.6	Chapter summary	316
<b>7</b>	<b>Risks associated with hydropower cavern groups</b>	<b>319</b>
7.1	Introduction	319
7.1.1	Development of large hydropower cavern groups	319
7.1.2	Current status of design and risk management for large rock caverns	321
7.1.3	Why is a new method of risk management required?	323
7.1.4	Outline flowchart for risk management for large hydropower cavern groups	324
7.1.5	Initial and final risk management for assessing and mitigating the risks for a large hydropower cavern group	325

7.2	Database of 60 large hydropower cavern groups in China	325
7.2.1	Principles for establishing a database	325
7.2.2	Content of the database	326
7.2.3	Statistical analysis of key issues	330
7.2.3.1	Lithological character and rock mass quality	330
7.2.3.2	Structure and strength of the rock mass	330
7.2.3.3	Stress conditions	330
7.2.3.4	Arrangement of cavern group by size	337
7.2.3.5	Excavation scheme and parameters	337
7.2.3.6	Support parameters	347
7.2.3.7	Monitoring	352
7.2.3.8	Rockbolt stresses	352
7.2.3.9	Stress in cable anchors	352
7.2.3.10	Relaxation depth of the surrounding rock	352
7.2.3.11	Fractures in the surrounding rock mass	356
7.2.3.12	Typical failure modes	363
7.2.3.13	Effect of loss of cable anchors and rockbolts	368
7.2.3.14	Measures used to reduce local risks	369
7.3	Epistemic uncertainty analysis	371
7.3.1	Geological setting	371
7.3.2	<i>In situ</i> rock stress	373
7.3.3	Hydrogeology	377
7.3.4	Properties of the rock mass	379
7.3.5	Specific project location	380
7.3.6	Excavation and support method	382
7.4	Aleatory uncertainty analysis	383
7.4.1	Detailed geology variations	383
7.4.2	Rock stress variations	386
7.4.3	Local water variations	387
7.4.4	Mechanical behaviour of the rock mass after excavation and in the long term	389
7.5	Risk assessment method for a large hydropower cavern group	390
7.5.1	Principles	390
7.5.2	Method for assessment and mitigation of overall risk for a large hydropower cavern group before construction	390
7.5.2.1	Method to determine the membership degree of the assessment index	393
7.5.2.2	Weight vector determining method	406
7.5.2.3	Determining the overall risk frequency	411
7.5.2.4	Determining overall risk consequence	413
7.5.2.5	Overall risk control analysis	413
7.5.3	Method for assessment and mitigation of local risk for a large hydropower cavern group before construction	414

	7.5.3.1	Large deformation local risk assessment model before construction	414
	7.5.3.2	Index membership degree determining method	416
	7.5.4	Method for assessment and mitigation of local risk for a large hydropower cavern group during construction	430
7.6		Illustrative example: Assessment and mitigation of risk for the underground powerhouse at Jinping II Hydropower Station, China	432
	7.6.1	Epistemic uncertainty analysis	432
	7.6.1.1	Geological setting	432
	7.6.1.2	Rock stress	433
	7.6.1.3	Hydrology	434
	7.6.1.4	Specific project location	434
	7.6.1.5	Excavation and support method	434
	7.6.2	Assessment and mitigation of overall risk before construction	435
	7.6.2.1	Assessment	435
	7.6.2.2	Risk mitigation measures	437
	7.6.3	Assessment and mitigation of local risk before the construction	437
	7.6.3.1	Assessment	437
	7.6.3.2	Risk mitigation measures	440
	7.6.4	Aleatory uncertainty analysis	440
	7.6.4.1	Estimation of geological conditions at different layers	440
	7.6.4.2	Estimation of three dimensional stress field	442
	7.6.4.3	Local water variations	442
	7.6.4.4	Mechanical behaviour of the rock mass after excavation and in the long term	443
	7.6.5	Assessment and mitigation of local risk during construction	449
	7.6.5.1	Construction of the main powerhouse layer I	449
	7.6.5.2	Construction of main powerhouse layer II and transformer chamber layer I	452
	7.6.5.3	Construction of main powerhouse layer III and transformer chamber layer II	461
	7.6.5.4	Construction of main powerhouse layer IV and transformer chamber layer III	472
	7.6.5.5	Construction of layer V of the main powerhouse	479
	7.6.5.6	Construction of layers VI, VIII and IX of the main powerhouse	485



7.6.5.7	Construction of layer VII of the main powerhouse	487
7.6.5.8	Construction of different types of tunnel	492
7.6.5.9	Overall evaluation of the complete construction and final design	496
7.6.6	Important points	497
7.6.6.1	Optimisation of bench height of layers II and III, and the excavation procedure for layers IV–IX	497
7.6.6.2	More than ten local warnings and reinforcement improved the main powerhouse and transformer chamber	499
7.6.6.3	Support reinforcement for different types of tunnel	499
7.6.6.4	Overall evaluation of the complete construction process and final design	500
7.7	Chapter summary	502
<b>8</b>	<b>Concluding remarks</b>	<b>505</b>
	<b>Appendix A: Cavern risk events during construction</b>	<b>507</b>
	<b>Appendix B: The Chinese ‘Basic Quality’ (BQ) system for rock mass classification</b>	<b>525</b>
B1	Introduction	525
B2	Terminology and symbols	525
B2.1	Terminology	525
B2.2	Symbols	526
B3	Classification parameters for the rock mass basic quality	526
B3.1	Classification parameters and the method of their determination	526
B3.2	Qualitative classification of rock mass solidity	526
B3.3	Qualitative classification of rock mass integrity	529
B3.4	Determination and classification of quantitative indices	529
B4	Classification of rock mass basic quality	530
B4.1	Determination of the rock mass basic quality class	530
B4.2	Qualitative characteristics of the basic quality and the basic quality index	530
B5	Engineering classification for a rock mass	531
B5.1	General rules	531
B5.2	Engineering rock mass classification	531