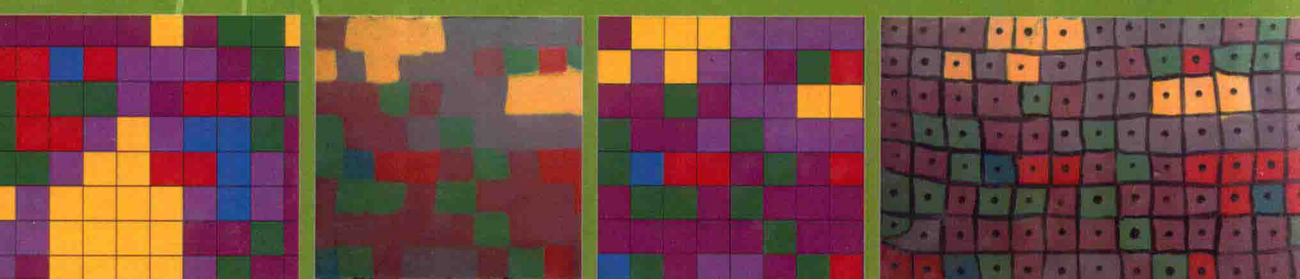
# RISK AND RELIABILITY IN GEOTECHNICAL ENGINEERING



EDITED BY
KOK-KWANG PHOON
JIANYE CHING

CRC Press
Taylor & Francis Group
A SPON BOOK

# RISK AND RELIABILITY IN GEOTECHNICAL ENGINEERING

EDITED BY
KOK-KWANG PHOON
JIANYE CHING

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business
A SPON BOOK

The pictures on the book cover were contributed by Lina Ximena Garzón from her PhD thesis "Physical Modeling of Soil Spatial Variability," Universidad de Los Andes, Bogotá, Colombia.



CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742



Printed on acid-free paper
Version Date: 20141009

International Standard Book Number-13: 978-1-4822-2721-5 (Hardback)



**Library of Congress Cataloging-in-Publication Data**

Risk and reliability in geotechnical engineering / [edited by] Kok-Kwang Phoon and Jianye Ching.
pages cm
Includes bibliographical references and index.
ISBN 978-1-4822-2721-5 (alk. paper)
1. Geotechnical engineering. 2. Reliability. 3. Rock mechanics. 4. Soil mechanics. I. Phoon, Kok-Kwang, editor. II. Ching, Jianye, editor.

TA706.R48 2014
624.1'51--dc23 2014023520

**Visit the Taylor & Francis Web site at**
**http://www.taylorandfrancis.com**

**and the CRC Press Web site at**
**http://www.crcpress.com**

# RISK AND RELIABILITY IN GEOTECHNICAL ENGINEERING

# Preface

*Risk and Reliability in Geotechnical Engineering* was originally conceived as an update to our 2008 Taylor & Francis book *Reliability-Based Design in Geotechnical Engineering—Computations and Applications*. However, R&D in this domain has gained pace over the past 6 years and it is the collective opinion of the contributors that it is timely to write a new book. One important milestone that took place after 2008 is the recognition by the broader structural community that geotechnical reliability is fundamentally distinctive from structural reliability in various important aspects. A new Annex D on "Reliability of Geotechnical Structures" will be included in the third edition of ISO2394 (2015) to emphasize the need to be sensitive to the practical needs of geotechnical engineering in the general application reliability principles. In other words, one expects more attention to be paid on realism in research and the practice of geotechnical reliability.

There is little doubt that the evaluation of the subsurface condition (including soil/rock properties) is one key aspect that distinguishes geotechnical engineering from structural engineering practice. Soils and rocks are naturally occurring geomaterials that cannot be produced according to factory specifications. Dealing with variability is the norm, not the exception, in geotechnical engineering practice. Site investigation is mandated by building regulations in many countries, in part because it is important to appreciate variable subsurface conditions in geotechnical design. Given the diversity of site conditions and the associated diversity of local practices that evolved to deal with these site-specific conditions, it is also possible for geotechnical variability to be comparable or even larger than the variability in the loadings. This variability is already considered in existing practice, albeit implicitly, through the application of a sizeable factor of safety and other risk mitigating measures (e.g., observational approach, integrity test, load test). Information is clearly collected prior to the design (site investigation) and during the construction process (quality assurance). It is very useful to quantify the value of this information for design and risk mitigation in a unified way. At present, reliability-based designs can be viewed as a simplified form of risk-based design where different consequences of failure are implicitly covered by the adoption of different target reliability indices. Explicit risk management methodologies are required for large geotechnical systems where soil and loading conditions are too varied to be conveniently slotted into a few reliability classes (typically three) and an associated simple discrete tier of target reliability indices. Some of these issues are examined in this book in the context of realistic geotechnical examples covering piles, slopes, retaining structures, dams, embankments, and soil liquefaction.

This book focuses on making these important reliability and risk methodologies more accessible to practitioners and researchers by presenting those soil statistics which are necessary inputs, by explaining how calculations can be carried out using simple tools, and by presenting illustrative or actual examples showcasing the benefits and limitations of these analyses. In short, this book adheres closely to the educational theme that has made the previous 2008 book a success. The reader will find "need to know" information for a non-specialist to calculate and interpret the reliability index and risk of geotechnical structures in a realistic and robust way. It will suit engineers, researchers, and students who are interested in the practical outcomes of reliability and risk analyses without going into the intricacies of the underlying mathematical theories.

# Acknowledgments

This book is a collaborative project among some of the top practitioners in our georisk community. It owes its success to all the contributors who have invested significant efforts to make the chapters useful and accessible to the nonspecialists.

The editors are grateful for the patience exercised by everyone in meeting our deadlines and responding to our review comments. We would also like to thank our senior editor from Taylor & Francis, Tony Moore, for helping us to steer this book project to fruition.

The pictures on the book cover were contributed by Lina Ximena Garzón from her PhD thesis "Physical Modeling of Soil Spatial Variability," Universidad de Los Andes, Bogotá, Colombia.

We welcome any constructive comments and suggestions from the readers. Please submit your views to our email addresses below.

Email of Kok-Kwang Phoon: kkphoon@nus.edu.sg

Email of Jianye Ching: jyching@gmail.com

# Editors

**Kok-Kwang Phoon** is a distinguished professor and head of the Department of Civil and Environmental Engineering, National University of Singapore (NUS). He is a professional engineer in Singapore and past president of the Geotechnical Society of Singapore. His main research interests include statistical characterization of geotechnical parameters and reliability-based design in geotechnical engineering. He is the recipient of numerous research awards, including the ASCE Norman Medal in 2005, the NUS Outstanding Researcher Award in 2010, and the John Booker Medal in 2014. He is the founding editor of *Georisk* and chair of TC304 (Engineering Practice of Risk Assessment and Management) in the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). He was former chair of ASCE Geo-Institute Risk Assessment and Management Committee. He is fellow of ASCE and fellow of the Academy of Engineering Singapore.

**Jianye Ching** is a professor in the Department of Civil Engineering, National Taiwan University (NTU). His main research interests include geotechnical reliability analysis and reliability-based design, basic uncertainties in soil properties, random fields and spatial variability, and geotechnical design codes. He is the secretary of TC304 (risk) in the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). He is the recipient of the Outstanding Research Award and the Wu-Da-Yu Memorial Award from the National Science Council of Taiwan, Republic of China.

# Contributors

**Ashraf Ahmed** is a lecturer in the Department of Civil Engineering, Aswan University, Egypt. He earned his PhD in 2012 from the University of Nantes, France. His main research interests include risk analysis, geotechnical reliability analysis and design, and spatial variability of soil properties. He is the recipient of the 2012 best paper award from the journal *Georisk* (Assessment and Management of Risk for Engineered Systems and Geohazards). Email: Ashraf.Ahmef@gmail.com

**Luis Altarejos-García** graduated at Universidad Politécnica de Valencia (UPV), Spain, with a PhD in civil engineering. He is a university professor at Universidad Politécnica de Cartagena (UPCT) and partner at iPresas Risk Analysis, a spin-off company from the UPV that provides consultancy services for enhanced governance, safety and security assessments, and investment prioritization in critical infrastructures. He is a certified project manager professional (PMP) from the Project Management Institute (PMI) and a registered professional engineer in Spain. He has been a member of the Technical Committee on Computational Aspects of Analysis and Design of Dams from the Spanish National Committee on Large Dams (SPANCOLD) since 2009. He has worked worldwide as a consultant in several projects for public institutions, hydropower companies, and mining groups, mainly in water management infrastructures, such as canals, pipes, spillways, and dams. He has also been a consultant for the World Bank in dam safety projects. Email: luis.altarejos@upct.es

**Gregory B. Baecher** is a Glenn L. Martin Institute Professor of Engineering at the University of Maryland. He earned a BSCE from University of California, Berkeley and a PhD from the Massachusetts Institute of Technology. His principal area of work is engineering risk management. He coauthored with J. T. Christian in *Reliability and Statistics in Geotechnical Engineering* (Wiley, 2003), and with D.N.D. Hartford *Risk and Uncertainty in Dam Safety* (Thos. Telford, 2004). He is a recipient of the ASCE Middlebrooks and State-of-the-Art Awards, and a member of the US National Academy of Engineering. Email: gbaecher@mac.com

**Richard J. Bathurst** graduated from Queen's University, Ontario, Canada, in 1985 with a PhD in geotechnical engineering. He is currently professor of civil engineering and research director at the GeoEngineering Centre at Queen's-RMC in Kingston, Ontario, Canada. He holds adjunct positions at the University of Waterloo and Edith Cowan University in Australia. His primary areas of research are reinforced soil wall and slope technologies with specific emphasis on the development of static and seismic design methods, reliability analysis, and LRFD calibration. He has authored or coauthored more than 300 papers and 20 book chapters. Dr. Bathurst is president of the Canadian Geotechnical Society, past-president of the International Geosynthetics Society, past-president of the North American

Geosynthetics Society and an elected fellow of the Engineering Institute of Canada and Canadian Academy of Engineering. Dr. Bathurst is the editor of the technical journal *Geosynthetics International*. Email: bathurst-r@rmc.ca

**Zijun Cao** is currently an associate professor in the School of Water Resources and Hydropower Engineering, Wuhan University, China. He earned his PhD in geotechnical engineering from City University of Hong Kong in 2012. His main research areas include probabilistic site characterization with particular interests in the quantification of uncertainties in soil properties, efficient probabilistic analysis, and risk assessment of slope stability, practical reliability-based design of geotechnical structures. Email: zijuncao@whu.edu.cn

**John T. Christian** delivered the Terzaghi Lecture in 2003 and is the current chairman of the Civil Engineering Section of the National Academy of Engineering (NAE). He has served as the editor-in-chief of the journal *Geotechnical and Geoenvironmental Engineering*, and now serves as its ombudsman. He is a pioneer in the use of computer methods and coauthored the first general, user-friendly computer program for analysis of slope stability with circular and noncircular failure surfaces. His distinguished career includes chairing the NAE's review of Boston's "Big Dig" project, service on NAE committees on New Orleans Regional Hurricane Projects and the Louisiana Coastal Restoration Project, probabilistic studies of the stability of an earth dam and of the seismic behavior of mine waste slopes, as well as numerous publications. He is the 1996 winner of the ASCE Thomas A. Middlebrooks Award. Email: jtchrist36@comcast.net

**J. Michael Duncan** is a professor emeritus of civil engineering at Virginia Tech. He has been a consultant on geotechnical engineering projects since 1965, and has supervised 45 PhD students at University of California, Berkeley and Virginia Tech. He has authored more than 300 geotechnical engineering publications, including the textbook *Soil Strength and Slope Stability*, coauthored with Stephen G. Wright. He is a member of the National Academy of Engineering and a distinguished member of American Society of Civil Engineers. He has been a member of the Panama Canal Geotechnical Advisory Board since 1986. Email: jmd@vt.edu

**Ignacio Escuder-Bueno** graduated from Universitat Politècnica de València (UPV), Spain, earned his Master of Science in civil engineering from the University of Wisconsin-Milwaukee (UWM), and a PhD in civil engineering from UPV. He is a university professor at UPV as well as promoter and founder associate of iPresas, a technology-based UPV spin-off company. He is a registered professional engineer in Spain, and has worked internationally as a consultant in numerous works related to safety studies, risk analysis, or design projects concerning more than 70 dams. He is chairman of the International Committee on Dams Computational Aspects of the International Commission on Large Dams (ICOLD) since 2011, secretary general of ICOLD European Club since 2010, and full member of the Spanish National Committee on Large Dams (SPANCOLD) since 2007. He has promoted and chaired the International Week on Risk Analysis, Dam Safety, Dam Security, and Critical Infrastructure Management (2005, 2008, and 2011). Email: iescuder@hma.upv.es

**Robert B. Gilbert** is the Brunswick-Abernathy professor in civil, architectural and environmental engineering at the University of Texas at Austin. He joined the faculty in 1993. Prior to that, he earned a BS (1987), MS (1988), and PhD (1993) in civil engineering from the University of Illinois at Urbana-Champaign. He also practiced with Golder Associates Inc. as a geotechnical engineer from 1988 to 1993. His expertise is the assessment, evaluation, and management of risk in civil engineering. Applications include building foundations, slopes, pipelines, dams and levees, energy production systems, landfills, and groundwater and soil remediation systems. Email: Bob_Gilbert@mail.utexas.edu

**Mahdi Habibi** is currently a PhD candidate in the Department of Civil, Architectural, and Environmental Engineering at the University of Texas at Austin. He earned a BS (2003) and MS (2006) in civil engineering from the University of Tehran, Iran. He worked for three years as a practicing geotechnical engineer with Pars Geometry Consultant Co. in Tehran. Email: mhabibi@utexas.edu

**Charng Hsein Juang** is currently the Glenn Professor of the Glenn Department of Civil Engineering at Clemson University, South Carolina, and a fellow of American Society of Civil Engineers (ASCE). He also holds a chair professorship at several overseas universities: Tongji University, Shanghai China; Wuhan University, Hubei China; and National Central University of Taiwan. Dr. Juang earned his BS and MS from Cheng Kung University and his PhD from Purdue University. He has authored more than 200 refereed papers, including over 150 journal papers, with a Google Scholar h-index at 29 and a citation count of over 2600. Dr. Juang has received five best paper awards from various civil engineering societies including the TK Hsieh Award from the Institution of Civil Engineers. His latest research interests focus on liquefaction, excavation, slope stability, reliability, and robust geotechnical design. Dr. Juang is an editor-in-chief for *Engineering Geology*, an international research journal. Email: hsein@clemson.edu

**Sara Khoshnevisan** is currently a PhD student at Clemson University, South Carolina, majoring in geotechnical engineering, having earned her BS in mining engineering from Tehran University, Iran, and her MS in civil engineering from Clemson University, South Carolina. Khoshnevisan is a student member of the American Society of Civil Engineers and a member of Phi Kappa Phi. Her research interests focus on liquefaction, supported excavation, reliability, and robust geotechnical design. Email: khoshnevisan.sara@gmail.com

**Dian-Qing Li** is a professor in the State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, China. His main research interests include risk and reliability in geotechnical engineering, risk and uncertainty in dam safety, embankment dams, and slopes. He is a member of TC304 (risk) in the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) and a member of the American Society of Civil Engineers Technical Committee on Risk Assessment and Management. Currently, he is an editorial board member (EBM) of *Georisk*, and an EBM of ASCE-ASME journal, *Risk and Uncertainty in Engineering System*. He is the recipient of the 2012 National Science Fund for Distinguished Young Scholars, China, and the 2013 Young and Middle-Aged Leading Scientists, Engineers, and Innovators, Ministry of Science and Technology, China. Email: dianqing@whu.edu.cn

**Bak-Kong Low** earned his BS and MS in civil engineering from the Massachusetts Institute of Technology, and PhD from the University of California at Berkeley. He is a fellow of the American Society of Civil Engineers, and a registered professional engineer of Malaysia. He currently teaches at the School of Civil and Environmental Engineering at the Nanyang Technological University (NTU) in Singapore. Apart from his long teaching and research career at NTU, he had done research while on sabbaticals at Hong Kong University of Science and Technology (Sept.–Dec. 1996), University of Texas at Austin (Jan.–April 1997) and Norwegian Geotechnical Institute (May–Aug. 2006). His research interests and publications in soil and rock engineering can be found at http://alum.mit.edu/www/bklow. Email: bklow@alum.mit.edu

**Adrián Morales-Torres** is a civil engineering graduate and earned a master degree in hydraulic engineering and environment from the Universidad Politécnica de Valencia (UPV), Spain. In 2010, he received the most outstanding graduate award by the Civil Engineers Association in Valencia. Currently, he is completing his PhD in civil engineering about risk-informed decision making in dam safety management at UPV. Since 2009, he has worked as researcher in UPV and has participated in different works related to dam safety management and risk analysis for more than 30 dams in Spain. In addition, he has been part of the SUFRI European project (Sustainable strategies of urban flood risk management with non-structural measures to cope with the residual risk, 2009–2011) and he is currently developing a decision support tool for the $E^2$STORMED European project (Improvement of energy efficiency in the water cycle by the use of innovative storm water management in smart Mediterranean cities, 2013–2015). Email: admotor@upvnet.upv.es

**Trevor L.L. Orr** is an associate professor at Trinity College Dublin (TCD). His main research interests include geotechnical design and design codes, geotechnical risk and reliability, tunneling, and underground structures. He has been closely involved in Eurocode 7, the European standard for geotechnical design, since the initial work started in 1981. He is currently a member of CEN's Sub-Committee 7 for the development of Eurocode 7 and is a convenor of its Evolution Group 3: Model Solutions. He is a coauthor of two books on Eurocode 7, including the *Designers' Guide to Eurocode 7* published by the Institution of Civil Engineers (ICE), London, and has presented many papers and invited lectures on Eurocode 7. He was awarded the Crampton Prize for his paper on Eurocode 7, published in the ICE journal *Geotechnical Engineering* in 2012. He is an editor of the ICE journal *Geotechnical Engineering* (2015–2017). Email: torr@tcd.ie

**Iason Papaioannou** is a postdoctoral research associate and lecturer at the Engineering Risk Analysis Group of the Technische Universität München (TUM), Germany. He is co-founder and partner at Eracons, a company specialized in consulting and software development for reliability assessment of engineering structures. His research interests include random fields and spatial variability, reliability assessment, and Bayesian analysis of numerical models with emphasis on applications to geotechnical structures. He studied civil engineering at the National Technical University of Athens (NTUA) and computational mechanics at the Technische Universität München (TUM). He earned his doctoral degree from TUM in 2012. His thesis was awarded the Bauer prize for the best PhD thesis of the Faculty of Civil, Geo, and Environmental Engineering of TUM. He is currently secretary of the Geotechnical Safety Network (GEOSNet). Email: iason.papaioannou@tum.de

**Francisco Silva-Tulla** completed his engineering degree at the University of Illinois, Champaign–Urbana and graduate studies at MIT. Dr. Silva has 43 years of professional experience including 39 years as a consulting engineer, participating in engineering and environmental projects, and studies in roles ranging from complete responsibility (program or project management, design, plans and specifications, budget control, construction supervision, quality control, and long-term surveillance) to specialized services (supervision of work performed by other engineering firms; guidance and leadership to groups of consultants; quality assurance; value engineering; expert witness and litigation support; dam and levee safety, risk assessments, soil and groundwater exploration, sampling, analysis, and characterization; and environmental assessments and impact studies). Dr. Silva's experience includes work for the mining, construction, chemical, petrochemical, petroleum, power, transportation, manufacturing, and waste disposal industries as well as U.S. and foreign government agencies. A large part of his professional experience relates to earth structures (especially embankments, dams, levees, dikes, slopes, landfills, and excavations) and the safety of constructed facilities (including probabilistic risk assessments and dam safety). Dr. Silva also has corporate management experience at the operating group level in consulting organizations with up to US$700M annual revenues. Email: silva@alum.mit.edu

**Matthew D. Sleep** is an assistant professor of civil engineering at the Oregon Institute of Technology. Prior to Oregon Tech, Matthew earned his PhD at Virginia Tech researching slope stability, levees, transient seepage, and reliability. Dr. Sleep has worked for the United States Army Corps of Engineers and private consulting. He currently teaches and continues research on reliability and transient seepage. Email: matthew.sleep@oit.edu

**Abdul-Hamid Soubra** is a professor of geotechnical engineering in the Department of Civil Engineering, University of Nantes, France. His main research interests include reliability analysis of geotechnical structures, spatial variability of soil properties, and the stability problems in geotechnical engineering. He serves as an associate editor of international journals (e.g., *Journal of Geotechnical and Geoenvironmental Engineering. ASCE* and *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*) and is a member of the Risk Assessment and Management (GI-RAM) of the American Society of Civil Engineers. He is the recipient of the 2012 best paper award from *Georisk*. Email: Abed.Soubra@univ-nantes.fr

**Daniel Straub** is professor for engineering risk and reliability analysis at Technische Universität München (TUM), Germany. His interest is in developing physically based stochastic models and methods for the decision support of infrastructure, environmental, and general engineering systems, with a particular focus on Bayesian techniques. Daniel earned his Dipl.-Ing. degree in civil engineering in 2000 and his PhD in 2004 from ETH Zürich, Switzerland, and consequently was a postdoc and adjunct faculty at UC Berkeley, before joining TUM in 2008. He has also been frequently active as a consultant to the industry on reliability and risk assessments for structures, infrastructures, and the oil and gas industry. His awards include the ETH Silbermedaille and the Early Achievement Research Award of IASSAR (International Association for Structural Safety and Reliability), and he is an honorary professor at the University of Aberdeen, United Kingdom. Email: straub@tum.de

**Bruno Sudret** has been a professor of risk, safety, and uncertainty quantification at the Department of Civil, Environmental and Geomatic Engineering of the Swiss Federal Institute of Technology (ETH Zürich, Switzerland) since 2012. He has been working in probabilistic engineering mechanics and uncertainty quantification methods for engineering systems since 2000, first as a postdoctoral fellow at the University of California at Berkeley, then as a senior researcher at EDF R&D (France). From 2008 to 2011 he worked as the director of research and strategy at Phimeca Engineering (France), a consulting company specialized in structural reliability. As a young researcher he received the "Jean Mandel" prize awarded by the French Association of Mechanics in 2005. He is a member of the Joint Committee on Structural Safety (JCSS) and of the Board of Directors of the International Civil Engineering Risk and Reliability Association (CERRA). He also serves on the editorial board of the ASCE-ASME *Journal of Risk and Uncertainty in Engineering Systems*. Email: sudret@ibk.baug.ethz.ch

**Xiao-Song Tang** is currently working as a lecturer at Wuhan University, China. He earned his Bachelor of Engineering in 2008 from Sichuan University (Chengdu, China) and his PhD from Wuhan University (Wuhan, China) in 2014. From 2012 to 2013, he studied as an exchange PhD student at the National University of Singapore (NUS) supervised by Professor Kok-Kwang Phoon. His main research interests include uncertainty modeling of correlated geotechnical parameters using copulas and reliability analysis of geotechnical structures. Email: xstang@whu.edu.cn

**Yu Wang** is an associate professor in the Department of Architecture and Civil Engineering, City University of Hong Kong. He earned his PhD in geotechnical engineering from Cornell University, New York. His main research interests include geotechnical risk and reliability (e.g., probabilistic characterization of geotechnical properties, reliability-based design in geotechnical engineering, and probabilistic slope stability analysis), seismic risk assessment of critical civil infrastructure systems (e.g., water supply systems), soil–structure interaction, and geotechnical laboratory and in situ testing. Dr. Wang was the president of the American Society of Civil Engineers (ASCE)–Hong Kong Section in 2012–2013. He is also a member of several international technical committees (TCs), including an ASCE Geo-Institute TC on risk and two ISSMGE (International Society of Soil Mechanics and Geotechnical Engineering) TCs on risk and in-situ testing, respectively. He is the recipient of the inaugural Wilson Tang Best Paper Award in 2012. Email: yuwang@cityu.edu.hk

**Jie Zhang** is an associate professor in the Department of Geotechnical Engineering at Tongji University, China. His teaching and research encompass geotechnical reliability, Bayesian updating of geotechnical systems, and civil engineering risk assessment. Dr. Zhang is a corresponding member of TC304 in the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE), and the secretary of the Young Scientists Committee of Risk and Insurance Research Branch, China Society of Civil Engineering. He is a recipient of the Natural Science Award from the Minister of Science and Technology of China in 2011, and the Outstanding Reviewer Award from Computers and Geotechnics in 2013. Email: cezhangjie@gmail.com

**Limin Zhang** is professor of geotechnical engineering and associate director of the geotechnical centrifuge facility at the Hong Kong University of Science and Technology. His research areas include slopes and embankment dams, geotechnical risk assessment, pile foundations, multiphase flows, and centrifuge modeling. He is chair of Geotechnical Safety Network (GEOSNet), vice chair of the International Press-In Association, editor-in-chief of the international journal *Georisk*, associate editor of the American Society of Civil Engineers' *Journal of Geotechnical and Geoenvironmental Engineering*, and editorial board member of six other journals. He received the Mao Yi-Sheng Soil Mechanics and Geotechnical Engineering Award and the Overseas Young Investigator Award from the National Natural Science Foundation of China. He has published over 150 international journal papers. Email: cezhangl@ust.hk

# Contents