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Computational Geomechanics and Hydraulic Structures

Springer

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Foreword I

With the increasing demand of people for improved life quality, a large number of mega projects spring up in our modern society. The successful construction and sustainable operation of these mega projects mark not only the progress in modern science and technology but also the significant development of human society and civilization.

It is well known that the safety, reliability, and sustainability of a project depend on an elaborate, skillful, and accurate design. Structural computation is, in turn, a fundamental tool for its design, which provides the theories, methodologies, and procedures for profoundly understanding the structural performances of the project.

Over the past three decades, China, a populated country, has witnessed rapid economic and social development and risen to be a middle-income country. In the process, the mega projects, such as high dams, motorways, high-speed trains, ultra-long and deeply buried large-scale tunnels, and UHV grids, played crucial roles.

To exploit and utilize the hydro and water resources of the rivers, China has designed and built a great number of mega water resources and hydropower projects including the Three Gorges, Ertan, Xiaolangdi, Longtan, Xiaowan, Shuibuya, Pubugou, Guangzhao, Xiluodu, Jinping-I, Jinping-II, and South-to-North Water Diversion. These projects challenge the computational methods to tackle with high dams, high and steep cut slopes, large and long hydraulic tunnels with high velocity flow, deep overburden underground cavern clusters under complicated engineering and hydrogeological conditions.

Computational methods have experienced remarkable advancement over the past thirty years. They have evolved from the traditional empirical and semiempirical material mechanics methods as well as rigid body limit equilibrium methods to the nonlinear finite element method, non-continuum discrete element method, and other numerical calculation methods. This should be attributed to not only the development of modern computer technology but also the design and construction of various mega projects. On one hand, the computational methods offered credible and reliable scientific demonstration to the design of mega projects. On the other hand, these mega projects promoted the development of modern geomechanics and computational methods.

Professor Chen Sheng-Hong has long been engaged in the research and development of computational methods and computer software for geomaterials and hydraulic structures. Paying special attention to laboratory experiments and in situ testing validation, he links the theories with practice and has made considerable innovative and practical research achievements. He harvested pragmatic results in the fields like standard adaptive software of the finite element method and initiated the block element analysis and composite element method which are influential both in China and abroad. These methods cover reinforcement analysis, feedback analysis, reliability analysis, seepage field and thermal field analysis, and multifield coupling analysis. He also has realized the synergy of methods, models, parameters, and hydraulic engineering structure safety. His theory and methodology have been verified and widely applied in the dam construction works, underground works, and artificial high slope works. They have offered solutions and scientific demonstrations to the crucial technological challenges in the design of the key national hydropower projects, such as Three Gorges, Longtan, Shuibuya, Guangzhao, Xiluodu, Jinping-I, Pubugou, Xiaowan, and contributed greatly to the success of project construction.

Professor Chen Sheng-Hong has won many science and technology awards of the provincial, ministerial, and national levels as well as those of national industry authorities and associations. He was honored as the Distinguished Professor of the Wuhan University of Hydraulic and Electric Engineering, and the Excellent Professor of Wuhan University, the Ministry of Water Resources, and the Ministry of Education. He is also granted the special government allowance of the State Council.

Professor Chen Sheng-Hong was invited as guest professor of Swiss Federal Institute of Technology in Lausanne (EPFL, Switzerland) and Parma University, Italy. He also worked as the guest professor in the Université des Sciences et Technologies de Lille (Université Lille1, France) on a long-term basis. He opens lectures overseas every year to teach advanced modern numerical computation methods and programs. Since 2000, he acted as the member of Computational Aspects of Analysis and Design of Dams, International Committee of Large Dam.

As the undergraduate and postgraduate schoolmate living in a same residence, as well as the partner in the construction of many mega hydraulic projects, I and Prof. Chen Sheng-Hong are good friends and colleagues. I am proud of his achievements in academic theory and engineering technology related to the geomechanics and hydraulic structures. I shall thank him for his valuable research findings to our breakthrough in the key technology projects of high dams, high and steep cut slopes, and large underground works. I am lucky to have read most of the manuscripts of this great book before publishing and deeply impressed by its rigorous theory, clear logic, as well as innovative and pragmatic contents. The book has both historical texture and broad international vision. I am convinced that the book can not only serve as the reference to technicians engaged in geomechanics and hydraulic structures but also positively promote the health development of computational methods.

Beijing, China
November 2017

Prof. Zhou Jianping
Vice President, International Commission on Large Dams;
Chief Engineer Power Construction Corporation of China

Foreword II

During the visit of my friend Prof. Chen Sheng-Hong to Lille last year (June–July, 2017), he kindly presented me with an advanced draft of *Computational Geomechanics and Hydraulic Structures* and asked me to write a foreword. I was greatly impressed by the extensive area covered in this book, by the scientific and engineering basis of his works, and by the quality of the presentation. I accepted his invitation with great pleasure.

From our first encounter in 20 years ago at Lille when he worked in the Université des Sciences et Technologies de Lille (Université Lille 1, France) as the guest professor until today, we have met regularly either in China or in Europe, including his regular 1- to 3-month stay in Lille as guest professor in our university. We succeeded in building a strong cooperation through yearly academic visits, Ph.D. co-supervision, joint paper publication in international journals and conferences, and the organization of lectures for postgraduate students and young researchers. He is an enthusiastic, hardworking, and interdisciplinary engineering scientist and university educator. I highly appreciated the scientific and the engineering quality of the work of Professor Chen as well as that of his students. I am also proud of that for years our university has opportunity to provide resources for a portion of his theoretical researches and academic writings, which contribute to a part of the coverage in this book.

Through this book, Prof. Chen enhances our library by a synthesis of more than 30 years of academic and professional experience in the field of computational geomechanics and their use in the assessment of both the safety and performances of hydraulic structures throughout their lifecycle covering design, construction, and exploitation stages. At each stage, engineers have to deal with multiple analysis and decision-making challenges, which are related to the complexity of the hydraulic structures geometry, nonlinear behaviors of geomaterials, multiphysics and transient phenomena as well hydro-thermo-mechanical coupling. To cope with these challenges, engineers need to enhance the conventional analysis tools by advanced computational methods in order to consider complex issues, which could highly influence the safety and performances of hydraulic structures.

The works of this book resulted in significant advances in (i) the major issues of the finite element method (FEM) in the analyses of hydraulic structures inclusive error estimation and mesh refinement, thermomechanical and hydromechanical coupling, reinforcement mechanism and modeling, parametric inverse and feedback design, and safety calibration; (ii) the fundamentals of the block element analysis (BEA) and its enhancement inclusive hybrid techniques, seepage analysis and reinforcement analyses, as well as stochastic and dynamic analyses; (iii) the fundamentals of the composite element method (CEM) and its use in the reinforcement, seepage, and thermal analyses.

It is remarkable that Prof. Chen has conducted a huge state-of-the-art study in the field of computational geomechanics and hydraulic structures, and he crossed it with his own academic and professional expertise in the computation methods, laboratory tests and field observations, material properties and parametrical inverse, safety calibration, and countermeasure design. He also presents his research philosophy and skill with engineering cases such as the most famous hydraulic projects of Three Gorges, Longtan, Shuibuya, Xiaowan, Guangzhao, etc. All these resulted in this exceptional book, which I believe will be an important reference book in the field of computational geomechanics and hydraulic structures. I would like to outline that this book constitutes a kind of "encyclopedia" on the computational geomechanics methods and their applications.

In conclusion, this book should be found in every public or private engineering library, particularly in universities. Engineers and postgraduate students can find comprehensive information about the fundamentals of the computational methods in geomechanics as well as scientific and practical recommendations for the efficient use of these methods in the analysis of hydraulic structures. Thanks to Prof. Chen for this great contribution.

Lille, France
January 2018

Prof. Isam Shahrour
Distinguished Professor
former Vice President Université Lille 1

Preface

Hydraulic structures, particularly large underground caverns and high dams with their vicinal high cut slopes, play core roles in hydraulic projects. Following the rapid progress in the construction of mega hydraulic projects, China has reached international level in the theories and technologies related to the project investigation, research, design, construction, and management. The largest work completed in the world, the Three Gorges Project, is installed with electric power generator capacity of 22,400 MW; the world highest arch dam (Xiaowan, H = 294.5 m; Jinping-I, H = 305 m), the world highest concrete-faced rockfill dam (CFRD) (Shuibuya, H = 233 m), the world highest roller compacted concrete (RCC) gravity dam (Guangzhao, H = 200.5 m; Longtan, H = 192 m) are all erected in China.

Initiated in the 1960s and classified as a sub-discipline within computational mechanics, computational geomechanics uses numerical methods to study the phenomena governed by the principles of geomechanics. It is a successful paradigm of interdisciplinary development supported by the applied mathematics and mechanics as well as the computer science, and driven by engineering practices. Since the 1980s, Chinese scientists and engineers have made significant contributions to the research and application of computational geomechanics attributable to the impetus from the demands of civil engineering, environmental engineering, mining and transportation engineering, and hydraulic engineering. Today, modern computational geomechanics has profound influences on the design of giant and complex engineering structures that would be previously very difficult or even impossible to be appropriately analyzed using traditional calculation tools.

This book is mainly focused on the development and application of representative computational methods to estimate the performance and safety of hydraulic structures from their planning and design phases to construction and service phases, on which the author has been working since the mid-1980s. In addition, this book is intended to show how to achieve a good correlation between the numerical computation and the in situ behavior of the hydraulic structure, which is actually attributable to a close collaboration of the author and his colleagues, friends, and students with field engineers. In this book, the heuristic and visualized style is attempted to disseminate the research philosophy and road map. The organization of various matters with typical methods (FEM, BEA, CEM) as warps and others (physical fields and engineering practices) as woofs is meant to clearly and logically elucidate the following aspects related to the subject of this book.

- Modeling of materials. The results of computational geomechanics for hydraulic structures are significantly dependent on the models of rock-like materials characterized by structure planes (rock discontinuities and concrete joints) and mitigation countermeasure components (e.g., reinforcement, drainage, and cooling). In the selection of constitutive models (relations) toward the definition of rock-like materials, these characteristics should be simplified in a rational way for the feasible and credible simulation of hydraulic structures (Chap. 2). This philosophy is followed throughout the generation of computation meshes (Chap. 3), the establishment of typical computational methods (Chaps. 4, 9 and 14), and the approaches of joints and reinforcement components (Chap. 6).
- Input of parameters. It is well known that the unsuccessful computation with regard to hydraulic structures is often blamed on the inappropriate input parameters defined in the material model. This is due to the difficulties arise from laboratory and in situ tests in addition to environmental (stress/water content/temperature) dependence. The laboratory test is suffered from stochastic variation whereas the in situ test possesses poor representativeness entailed by sample amount and high cost. Therefore, it is paramount to be involved in the investigation and experiment works as deeply as possible toward a correct interpretation of experimental data and a realistic evaluation of inputting parameters. On the aspects of computation technique, parametric back or inverse analysis is a supplementary approach to handle this issue subject to well-installed instruments, good understanding of construction procedure, as well as sufficient engineering experience (Chap. 7).
- Diversification of methods. Nowadays, there are a variety of modern computational methods available for geomechanics and hydraulic structures (Chap. 1), although only three of them are representatively elaborated in this book (i.e., FEM, BEA, and CEM). They may be roughly distinguished into entirely different two classes according to their conceptualization of rock-like materials, i.e., the continuum or discontinuum, each of them reflects one extreme aspect of the hydraulic structure encountered. The selection of the most representative ones is, however, an open question. This is actually dependent on the problem type, the material, the work situation, etc. Take a large rock block system for example, to understand its post-failure movements, the DDA or DEM would be a good choice because they permit decoupling of the block system. On the other hand, when the safety margins with respect to collapse/serviceability limit states are demanded, and suggestions concerning the seepage/stabilization countermeasures are expected, the BEA would be more appropriate attributable to its competent strength parameters and clearly allowable safety factors stipulated in the design codes/specifications.

Where the structural issue is very important and complex, it is suggestible to exercise diverse methods (at least two) in addition to traditional tools. This philosophy is followed throughout the whole book, and our readers will find that several typical projects are studied by the FEM or/and BEA (CEM) in addition to traditional LEM or/and TLM, plus geomechanical physical test.

Theoretically, "all-encompassing" methods covering continuum and discontinuum as well as finite and infinitesimal deformation, may be charming. Entailed by the professional experience of the author, however, I have to say that this is actually not very attractive and practical because it, if exists, would be too "precise" and "delicate" to be competent to the "roughly estimated parameters" and complex hydraulic structures.

– Standardization of preprocess. The computation procedure should been developed as not only to easily and reliably collect input data, but also to allow for the standardized discretization of the hydraulic structure. The mesh density (size) dependent on the structural configuration, exerted action, as well as the construction manner and sequence, will significantly affect the calibration of the local safeties (e.g., strength, allowable seepage gradient, cracking potentiality) of a hydraulic structure. This is why the automatic block identification and mesh generation (Chap. 3) and the adaptive refinement technology (Chap. 5) are looked at as important contents in this book. From the standpoint of a practitioner in the field of hydraulic engineering, automatic grid generation and adaptive refinement in grid-dependent computational methods (e.g., the FEM) may help to overcome the cumbersome preprocessing burden as well as to keep the balance between computation effort and precision, by appropriately stipulated discretization error tolerances in design codes/specifications for different structure types and grades, rather than to pursue computation precision solely.
– Coupling of fields. Very often, groundwater appears in and affects hydraulic structures. In addition, concrete placed onto the foundation undergoes strong temperature fluctuation before and after being loaded. As a result, hydraulic structures exhibit complex performances involving hydro-thermo-chemo-mechanical fields which demand appropriate handling. Although various and sophisticated coupling models with regard to the movement of water and heat through the material skeleton and fractures (discontinuities and joints) are available in the environmental engineering and nuclear power engineering, yet in the hydraulic engineering normally only partial coupling of temperature or/and seepage toward the deformation/stress needs to be taken into account attributable to the lower action level (Chap. 2). Full coupling, particularly of hydromechanical, is only sometimes encountered where the stress level in the rock mass is high (e.g., arch dam abutments). Under such circumstances, the coupling model should be rationally elaborated as simple as possible and its coupling parameters should be accessible by experiments (Chap. 2) or in situ back analysis (Chap. 8) subject to the conditions permitted for the project.

- Interpretation of results and calibration of safety. Once the analysis has been accomplished, it is necessary to display the results in such a way that they can be easily understood and interpreted, based on which the safety calibration with respect to the strength/seepage/temperature according to the design codes/ specifications is undertaken. The calibration criteria may be both of local and/or overall (Chap. 4).
- Validation by test/observation and feedback. It is also highly important to check the validation of computational solutions by comparing them with in situ observed data. This is particularly presented in the study of Xiaowan Project (Chap. 8) where the comparison of the FEM computation with the instrumentation data is comprehensively carried out for the arch dam, and in the study of Longtan Project (Chap. 9) where an abutment slope failure accident is captured by the BEA.

This book may be looked at as an advanced continuation of the *Hydraulic Structures* by the author published in 2015 which mainly deals with the investigation, planning, design, construction, and management of hydraulic structures. I was planning to finish my professional activities by that book and to launch a new writing life that I have been dreaming since my childhood. However, the publication of the *Hydraulic Structures* was so welcome by the readers, and I was deeply touched and proud of. Encouraged by my friends, colleagues, and students that I am liable to further present the research achievements and engineering experiences of my team, I have to continue technical writing and now, I feel in relief by contributing this continuation book.

The basis of this book is established on my studies and practices conducted in China over the decades with the help of my students partially recited as Dr. Chen Shangfa, Dr. Wang Weiming, Dr. Xu Minyi, Dr. Fu Shaojun, Dr. Xu Qing, Dr. Wang Shufa, Dr. Qiang Sheng, Dr. Hu Jing, Dr. Cheng Zhao, Dr. Xia Huaixiao, Dr. Li Yongming, Dr. Fei Wenping, Dr. Qin Weixin, Dr. Feng Xuemin, Dr. Zheng Huifeng, Dr. He Zegan, Dr. Xu Guisheng, Dr. Peng Chengjia, Dr. Fu Chenghua, Dr. Xue Luanluan, and Dr. He Ji et al. I am so proud to see that most of them are now successful university professors, consultant engineers, and enterprise managers. In my engineering consultant and education works, I am very fortunate to have chance to collaborate with Prof. Zhou Jianping (Chief Engineer of Power Construction Corporation of China), Prof. Zou Lichun (Deputy President of Kunming Engineering Corporation Limited, PowerChina), Prof. Yang Jiaxiu (Deputy President of Guiyang Engineering Corporation Limited, PowerChina), Prof. Feng Shurong (President of Zhongnan Engineering Corporation Limited, PowerChina), Prof. Wang Renkun (Chief Engineer of Chengdu Engineering Corporation Limited, PowerChina), Prof. An Shengxun (Deputy President of Northwest Engineering Corporation Limited, PowerChina), et al. In the international education and academic activities, the collaboration with my lifetime friends, Prof. Peter Egger (EPFL, Switzerland) and Prof. Isam Shahrour (Lille University 1, France), is the most important. In addition, I am really grateful to Wuhan University for providing tolerant ivory tower and allowing time for me, to complete this book.

Greater challenges await us in the next prospective decades. From 2011 to 2050, under the state policy guidance for developing her vast western area, tens of mega hydropower projects will be built in China. For example, the Motuo hydropower project will be installed with generator capacity larger than 40,000 MW. These milestone projects will further give strong impetus to push the technology of hydraulic engineering in China up to an unprecedented level, and to provide ever vast room for the progress in computational geomechanics. By the publishing of this book, the author does wish to encourage our successors to take on historical responsibilities by conducting more advanced and practical researches on the relevant topics.

Wuhan, Hubei, P.R. China Sheng-Hong Chen

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