# Experiments and Research on Fracture Behaviors of Dam Concrete

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# 序 I

大坝是国家的重要基础设施之一。在中国乃至世界的大坝建设中，混凝土坝是使用最多、最广的一种坝型，其主要优点是承载能力强、使用寿命长、断面相对较小、可经受水流漫顶等。但在混凝土坝建设中，早期处于引领地位的欧美等一些国家曾发生过坝体混凝土开裂漏水、溃坝等重大事故，造成工程功亏一篑和巨大生命财产损失。这使得大坝混凝土开裂成为导致其耐久性和抗震性能大幅降低、使用寿命急剧缩短、严重影响其正常运行和发挥工程效益的世界级难题。因此，施工期混凝土的开裂控制和运行期的裂缝控制是大坝混凝土工程的重大关键技术问题之一。

2002年3月，正值长江三峡水利枢纽二期大坝工程施工进入到高峰期，泄洪坝段混凝土局部出现了一些裂缝，为探讨长江三峡泄洪坝混凝土施工期裂缝成因和预防及处理对策，由清华大学、中国葛洲坝集团公司和烟台大学三方合作启动了"大体积混凝土裂缝仿真断裂分析研究"课题。该课题紧密结合当时正在施工的主体大坝的原材料及浇筑工艺，开展了大量的室内、现场试验和模拟计算研究，并以此为基础，持续开展了长达15年之久的国内外协同攻关和相关研究工作。

研究工作在清华大学水电工程系和中国葛洲坝集团公司试验中心两地同步展开，并进行了广泛的考察调研、查新，较大规模地制备了全级配混凝土试件，系统实施了三峡大坝泄洪坝段混凝土断裂力学性能试验。试验用混凝土试件在三峡施工现场仿真制作，共浇筑试件377件，混凝土方量达23.1$m^3$。试验工作在清华大学水电工程系高坝大型结构国家专业实验室与宜昌葛洲坝集团公司试验中心分别进行，采用了先进的测试技术，自主研制了关键试验装置，在大坝混凝土断裂性能方面取得重要技术创新研究成果。

在三峡大坝混凝土断裂性能试验数据成果的基础上，还与美国西北大学先进水泥基材料研究中心（ACBM）主任、美国工程院院士、中国工程院外籍院士Professor Surendra. P. Shah，德国莱比锡应用技术大学教授、混凝土结构和材料专家Professor Volker Slowik等，对三峡大坝混凝土断裂性能的计算机模拟开展了国际合作和系统研究。其研究成果揭示了三峡大坝混凝土断裂机理，并得出了系统的断裂参数，使得该研究成果具有更深的意义和更广泛的应用价值。

作为时任中国长江三峡工程开发总公司的总工程师，我一直关注该项课题的研究进展，先后考察了宜昌葛洲坝试验中心的试件场区、试验装备和试验情况，听取了研究团队的研究工作方案介绍，共同探讨了研究和试验过程中可能出现的问题和解决措施，提出了全面做好此项试验研究的相关意见和建议。我与研究团队的主要负责人也是此书的主要作者赵志方博士和周厚贵总工程师是在三峡工程的建设之中相识的，他们的刻苦学习与勇于攻关的精神和勤奋努力与扎实工作的作风给我留下了深刻的印象。

本书正是对上述课题试验和研究成果的全面系统的总结，其主要创新点是：提出了大坝混凝土软化曲线简便适用的确定方法，并研发了大坝混凝土软化曲线的专用计算软件；利用裂缝扩展路径上应力集中和应力释放的现象，采用新颖的电测技术，观测断裂全过程

中裂缝起裂、稳定扩展和失稳破坏的规律，提出了起裂点和裂缝扩展长度的测试方法；通过大坝混凝土断裂机理的揭示，利用软化曲线从机理上解释断裂能的尺寸效应；发现了大坝混凝土双K断裂参数无尺寸依赖性，从而完善了大坝混凝土的断裂准则；优化了大坝混凝土配合比，形成了一整套有效控制大坝裂缝的施工技术和工艺。

相信此书的出版能为广大的坝工建设者提供一个大坝混凝土防裂、控裂乃至建造无裂缝大坝的工程理论和工程实践的典型案例，并对今后大坝工程建设技术进步产生较大的促进作用。

中国工程院院士 张超然

2017年2月17日

# Preface I

Dams are vital infrastructures in a country. As for dam construction in China and throughout the world, concrete is the most widely used material in their construction. The main advantages of concrete dam are its strong carrying capacity, long life, small cross-section, and good resistance to water overtopping, etc. However, dam concrete cracking, leakage, failure and other major accidents which occurred during their construction in Europe and the United States were commonplace in early development. This often resulted in the complete ruin of these dams and the loss of peoples lives and property. Thus, dam concrete cracking is a worldwide problem resulting in a significant reduction in durability, seismic performance and service life and has a serious impact on their normal operation and benefits. Consequently, concrete cracking control during the construction period and crack control during the operation period is one of the key technical problems in concrete dam engineering.

In March 2002, when the second phase of dam construction of the Yangtze River Three Gorges Project entered construction peak, some cracks were found in the concrete of the flood discharge dam. To explore the cause of this cracking, crack prevention and treatment countermeasures during the construction period of the Three Gorges flood discharge dam, Tsinghua University, China Gezhouba (Group) Corporation (CGGC) and Yantai University, all located in China, jointly launched the project Fracture Simulation Analysis of Mass Concrete. Using the raw materials and pouring process of the main dam under construction, many laboratory tests, field tests and simulation studies were carried out. Based on this, domestic and international collaborative research and related research work has been pursued for 15 years to try to solve the key technical problems.

The research work was carried out synchronously at the Department of Hydraulic Engineering of Tsinghua University and Test Center of CGGC. The research group made investigation and research, novelty search, prepared the fully graded concrete specimens on a large scale, systematically conducted fracture experiments of Three Gorges Dam concrete. Concrete specimens were prepared at the construction site of the Three Gorges Dam. A total of 377 specimens, with concrete volumes of up to 23.1 cubic meters were produced. The tests were performed in the National Professional Laboratory of High-dam Large-scale Structure of Tsinghua University and Test Center of CGGC, respectively. Advanced testing technology was employed, key test equipment was developed independently and important innovation achievements were made about fracture behaviors of dam concrete.

On the basis of fracture experiments data of the Three Gorges Dam concrete, they also worked with Professor S. P. Shah and Professor Volker Slowik, etc. Professor Shah, the director of the Advanced Cement-based Materials Research Center at Northwestern University, Evanston, Illinois in the United States, is a member of National Academy of Engineering of the United States and a foreign member of the Chinese Academy of Engineering. Professor Volker Slowik is an expert of concrete structures and materials worked at Hochschule für Technik, Wirtschaft und Kultur in Leipzig, Germany. They helped to carry out further international cooperation and systematic research on the computer simulation of the concrete fracture behavior of the Three Gorges Dam concrete. The research results revealed fracture mechanisms of the Three Gorges Dam concrete and obtained systematic fracture parameters, which gave the research results more meaningful and wider application values.

As the chief engineer of the China Three Gorges Corporation, I have been paying close attention to the research progress of the project. I have observed and studied the test specimen area, test equipment and test situation of Test Center of CGGC in Yichang, listened to presentations by the research group, discussed the problems and solutions that might occur in the research and testing process with them, and put forward relevant opinions and suggestions to comprehensively carry out this experimental study. I met the directors of the research team, also the main authors of this book, Dr. Zhifang Zhao and chief engineer Hougui Zhou, during the construction of the Three Gorges Dam project. I was very impressed by their hard work, study of key technical problems, diligence and professionalism.

This book is a comprehensive and systematic summary of the above-mentioned research achievements. The main innovations which resulted are as follows: The simple and applicable method for determining the softening curve of dam concrete was proposed and the corresponding specialized software was developed. Based on the phenomenon of stress concentration and stress release on the crack propagation path, the rule of crack initiation, stable propagation and unstable failure was observed by employing the innovative electrical measuring technology. The methods for testing crack initiation and crack propagation length were also proposed. The size effect of fracture energy was explained by revealing the dam concrete fracture mechanism from the viewpoint of the softening curve. It was discovered that the double-K fracture parameters of dam concrete were size independent, thereby improving the fracture criterion of dam concrete. The dam concrete mix proportions were optimized and formed a set of construction technology to effectively control dam cracks.

I believe that the publication of this book will provide most of the dam builders with a typical case of engineering theory and engineering practice for dam concrete crack mitigation and the control and even construction of non-crack dams. It will definitely play an important role in promoting the progress of dam construction technology in the future.

Chaoran Zhang

Member of the Chinese Academy of Engineering

February 17, 2017

# Preface Ⅱ

Cracking of concrete dams is one of the common problems during the construction period and operation period of the hydropower station. Cracks will greatly reduce a dam's durability and seismic performance. Severe cracking can shorten its service life. In this book, the process of cracking in dams is explained and explored by employing theoretical fracture mechanics. With the aid of fracture mechanics, the author has provided a tool to predict and control cracking of dams and other massive concrete structures.

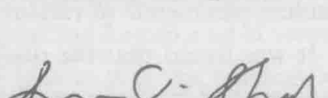
Based on the actual needs of dam construction in China, in March 2002 a project was initiated to explore the causes, prevention and control of cracks of the flood discharge dam of the Three Gorges Project at Yangtze River. It was set up during the dam construction period, under the guidance of chief engineer Mr. Hougui Zhou and Professor Qingbin Li. The co-author Dr. and Professor Zhifang Zhao presided over the implementation of testing and research task Fracture Simulation Analysis of Mass Concrete. This project was jointly carried out by Tsinghua University, China Gezhouba (Group) Corporation and Yantai University. It was comprised of conducting large-scale fracture tests of dam concrete. Testing of large concrete specimens for evaluating fracture parameters was never done before and posed many technical challenges.

Three types of fracture test specimens, namely, the uniaxial tension test specimen, three-point bending notched beam, and wedge-splitting test specimens were employed. Specimens made with normal size aggregates as used in building and road construction, as well as specimens with large aggregates used in dam construction were tested. To compare these two sets of tests, specimens were made with wet-screening concrete. The maximum specimen size of wedge-splitting test specimens were: 1.2m long, 1.2m high and 0.25m thick. The fracture parameters of various types of dam concrete were measured and analyzed systematically. It was found that the double-K fracture parameters of dam concrete proposed by Professor Xu and studied by Professor Zhao can be used as a valid fracture parameters. The tested double-K fracture parameters of dam concrete were used to accurately simulate concrete cracks in the Three Gorges Dam. This study provided a method for the safety assessment and crack control of the Three Gorges Dam. In addition, the study helped optimization of concrete mix proportions.

I met Dr. Zhao at the 11th International Fracture Conference held in Turin, Italy, in March 2005. Her presentation: The *Experiments for Determining the Double-K Fracture Parameters of Concrete of the Three Gorges Dam* attracted my attention and received the praise of the conference Chair Professor A. Carpinteri. She introduced her comprehensive and systematic fracture experimental study of the Three Gorges Dam concrete. Since fracture mechanics of concrete was one of the important research directions of NSF's Advanced Cement-Based Materials Research Center (ACBM Center), I invited her to come to the United States in 2007 to pursue research under my supervision. During her visit, we jointly completed the project"Computer Simulation of Fracture Behaviors of Dam Concrete." Utilizing the comprehensive and systematic fracture tests of dam concrete of the Three Gorges Dam, we conducted the inverse analysis and finite element simulation of the test data. We proposed a simple and suitable method for determining the softening curve of dam concrete. The softening curve can explain the measured size effect of fracture energy. Dr. Zhao has used modern digital technology to explore this world-class engineering problem. Research results were published in international journals and have been widely cited by scholars.

During her stay at the ACBM Center at Northwestern University in America, Dr. Zhao carried out fruitful research in concrete fracture mechanics combining theory, test techniques, and computer simulations of dam concrete fracture. As an outstanding and promising scholar, in 2013 I invited Dr. Zhao to come to ACBM center to participate in a Sino-US cooperation project on "High Volume Mineral Admixture Mass Concrete." I recommended that Dr. Zhao visit University of Illinois at Urbana-Champaign to cooperate with Professor David A. Lange, who has carried out temperature-stress tests of concrete in the early stage. I also suggested that she visit Iowa State University to cooperate with Professor Kejin Wang, who is an expert on fly ash mass concrete. Dr. Zhao is keen on continuing her study of crack prevention and crack control of dams at her own Tsinghua University and Zhejiang University of Technology as well with active international collaboration.

This book, EXPERIMENTS AND RESEARCH ON FRACTURE BEHAVIORS OF DAM CONCRETE, co-authored by eminent scholars: Dr. Zhao and Zhou with its systematic study of the fracture behaviors of dam concrete will effectively guide dam safety assessment, crack control, and dam safety. It will provide a useful reference for college teachers and students as well as the engineering and technical personnel who are engaged in scientific research, design, construction, and management of dam concrete.



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# Summary

Fracture of dam concrete is one of the main hidden dangers affecting and endangering dam safety during their construction and operation. To master and reveal the fracture characteristics and mechanism of mass concrete, while seeking to prevent and control cracks in dam, it is necessary to carry out concrete fracture experiments of large size and fully graded aggregate concrete specimens, together with corresponding tests on the physical and mechanical properties of concrete based on large-scale project. In 2002 the second phase of the Three Gorges project was at its peak, which resulted in a rare engineering opportunity for this important research. Thus Tsinghua University, China Gezhouba (Group) Corporation (CGGC) and Yantai University entered into a cooperative research agreement for "Fracture Simulation Analysis of Mass Concrete", they further agreed to study the key technical problems involved in the cracking and fracture of mass concrete structures to provide the basis for engineering construction and operations.

After the research program was begun, it took two and a half years to complete the preliminary experiments and research necessary to obtain the initial achievements. The experiments were simultaneously conducted at the National Professional Laboratory of High-dam Large-scale Structure of Tsinghua University and Test Center of China Gezhouba (Group) Corporation. At a later stage, research work also was conducted in the United States and Germany, with collaboration of academicians, professors or leading experts from Northwestern University, Evanston, IL, University of Illinois, Urbana-Champaign, IL, and Iowa State University, Ames, IA in America and the Hochschule für Technik, Wirtschaft und Kultur Leipzig in Germany, resulting in the research achievements set forth in this book.

This research initially determined the double-K fracture parameters of dam concrete of the Three Gorges Project. Its related achievements won the Hubei Science and Technology Progress Award in 2005. In the same year, the *Norm for Fracture Test of Hydraulic Concrete* (DL/T 5332-2005) was jointly edited by CGGC based on these fracture experimental test data becoming the basis for support of the national standard in China.

The research achievements have been well-received by Professor Alberto Carpinteri, Professor of science in construction at the Polytechnic University of Turin who was director of the Istituto Nazionale di Ricerca Metrologica (INRiM) in Turin, Chair of the 11th International Fracture Conference held in Turin of Italy in 2005, as well as have been fully affirmed by distinguished Professor Surendra. P. Shah, the Walter P. Murphy Emeritus Professor of Civil and Environmental Engineering at Northwestern University. He invited a research group member to cooperate with Northwesterns' Advanced Cement-based Materials (ACBM) Center to further study the computer simulation of the Three Gorges Dam concrete fracture behavior. These



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achievements have been published in well-known international journals, such as *Cement and Concrete Research*.

This book reveals that by employing uniaxial test, three-point bending notched beam test and wedge-splitting test, the fracture parameters and fracture mechanism of dam concrete and wet-screening concrete were investigated on which the effects of mix proportions, specimen sizes and coarse aggregate sizes are considered. Accordingly, the fracture behaviors of the Three Gorges Dam concrete were achieved, as well as helpful suggestions and solutions to mitigate and prevent cracking of dam concrete in the future. Its sixteen chapters include various topics on dam concrete: state-of-the-art review of concrete softening curve; determination of softening curve of dam concrete by inverse analysis based on cracking strength criterion, and comparison between this method with the Direct Tension (DT) method; research on fracture behaviors of dam and wet-screening concrete by DT method; prediction for tensile softening curve of dam concrete over neural network method; size effect of fracture energy and softening curve determined by the inverse analysis method; effect of aggregate size on softening curve; determination of dam concrete's fracture energy and comparison of fracture energy between the fracture work method and softening curve method; effect of tested curve tail section processing on fracture energy of dam concrete; experimental research on double-K facture parameters of the Three Gorges dam concrete; double-K facture parameters of dam concrete with various graded aggregates; analysis and research on crack prevention in hole roof for the Three Gorges project; construction technology and practice of no cracks concrete dam.

During this research and while writing this book, various people including our collaborative research advisor, academician Guofan Zhao of Dalian University of Technology supported and provided the funds for working in Shandong Province to purchase advanced equipment DH5937 to conduct fracture experiments. The academicians Chaoran Zhang of China Three Gorges Corporation, Chuhan Zhang of Tsinghua University and other experts have personally visited the site several times to inspect and direct these experiments. Their kind assistance greatly improvd the experiments and quality of the research. Additionally, Yangtze River Scholars, Professor Qingbin Li of Tsinghua University, Professor Shiliang Xu of Dalian University of Technology, Professor Kejin Wang of Iowa State University, Professor Volker Slowik of Hochschule für Technik, Wirtschaft und Kultur Leipzig, Dr. Seung Hee Kown of Northwestern University and Professor Jun Zhang of Tsinghua University provided tremendous help and direction for this research. The experimental research received assistance from Duanming Wang, Jingang Ma, Kaiyan Tan, Yongjun Song, Ke Zhang, Shouyang Zhao and Yanlin Zhang of CGGC, as well as Fude Zhang and Wencui Zhang of Tsinghua University. Dr. Zhigang Zhao, a teacher of Zhejiang University of Media and Communications has devoted himself to develop the necessary computer program since 2002, thus making great contributions to this research and was awarded not only the Chinese national software copyright, but the Science and Technology Achievement Award from Zhejiang Province. Our American friend, Henry Landan helped us to refine the book in English. The postgraduates Bin Zhang, Dongming Zhu, Ruixin Jin, Jiamin Dai, Jianping Chen, and Jintao Cai of Zhejiang University of Technology helped to draw some figures for the book, and we sincerely appreciate their valuable contributions.

Finally, We especially extend our profound respect and thanks to professors Chaoran Zhang and S. P. Shah for taking time from their busy schedules to write the Prologues for this book.

Zhejiang University of Technology devoted large amount of manpower, materials and funds to the research and publication of this book. This book was funded by the Monograph and Postgraduate Textbook Publication Fund of Zhejiang University of Technology. It is highly appreciated.

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The authors also wish to state that readers' suggestions and comments are encouraged and we warmly welcomed.

Authors
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