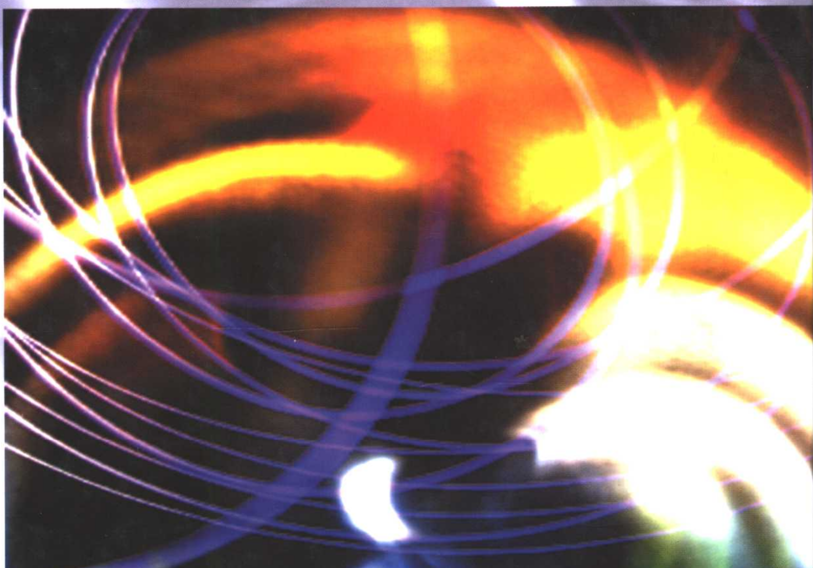
光纤传感技术在大坝工程中的应用

Applications of the Optical Fiber Sensing Technology in Dam Engineering

蔡德所　著



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内 容 提 要

本书以国家和地方重点科学技术项目为基础，专题研究了光纤传感技术在大坝工程中的应用。思想新颖、内容丰富、多学科交叉渗透明显。涉及的主要内容有大坝随机裂缝、板间缝与周边缝位移、温度、挠度以及边坡深部变形等监测项目的分布式光纤传感技术。

本书可供从事水利电力、建筑、道桥、海洋钻井平台、隧道、核电站等工程的科技人员使用，以及有关大专院校教师参考，也可作为大学生和研究生的教学参考书。

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序

工程结构物的损伤识别和早期诊断，是城市与工程减灾对策的重要内容之一。这一点在大坝、核电站等重大工程上尤为明显，这些工程既代表了巨额投资和巨大效益，同时又蕴含着潜在的成灾风险。因此，安全监测显得尤为重要。

大坝安全监测的常规仪器已有百年历史，实用经验多、应用范围广，并与现行规范配套，现阶段仍是大坝安全监测的主要手段。然而，常规观测仪器存在若干根本性缺陷：对测点物性有影响，耐久性较差，易受强电磁场干扰，信息量有局限等。因此，研究大坝工程安全监测的高新技术非常必要。在各国竞相发展的安全监测高新技术中，光纤传感检测技术以其独特优势而处于中心地位。蔡德所博士正是瞄准这一国际前沿课题潜心钻研、直面工程、勇于创新，在近八年的水电工程现场试验研究的基础上，完成了他的这本专著，我感到由衷的高兴！综观全书，从板间缝、周边缝光纤测缝计的研制到智能化系统的集成；从随机裂缝的捕捉到大坝混凝土结构温度场的分布式光纤传感；从光强衰减方程的推导到光纤传感监测信号的小波分析；从边坡深部变形的分布式光纤监测技术到混凝土面板堆石坝面板挠度监测的光纤陀螺方法等，作者敏锐的思维、宽阔的眼界、扎实的基础、吃苦的精神处处可见。他带领课题组以长江三峡工程、清江隔河岩工程、古洞口面板堆石坝、鱼跳面板堆石坝等工程为背景，进行了多项探

索性的、相当艰苦的现场试验和应用研究，这些成果是对大坝安全监测领域的新贡献，也是国内第一部专题讨论大坝工程中光纤传感技术的专著。它的出版，必将对水利水电工程安全监测技术的革新与发展产生积极的推动作用和深远影响。

中国工程院院士

2002年10月26日

于哈尔滨

前　言

筑坝技术尽管已有几千年历史，但大坝工程并非一门严密的科学，因为工程中或工程的运行环境中，包含着许多随机的或不确定的因素，因此，加强大坝安全监测至关重要。安全监测的任务在于随时了解大坝的“健康状况”，核心是及时发现、预报异常状态，特别是险情，以确保大坝安全。为此，安全监测系统自当具有及时、无遗漏捕捉一切工程险情信息的能力。

大坝安全监测的常规仪器已有百年历史，但存在若干根本性缺陷，首先是点式测量，信息量十分有限。在大坝渗流、温度、应力应变、裂缝、挠度等方面无法实现分布式监测，因此，会漏掉一些对大坝安全至关重要的信息；其次是电信号，易受强电磁场干扰，测量精度受影响；不适合易燃、易爆、高温、雷击区等恶劣环境；再次是不便远距离遥测、监控等。因此，开展大坝工程安全监测的高新技术研究非常必要。随着光纤和有关器件在内的光纤基本结构的飞速发展，光纤传感检测技术以其独特优势而处于主导地位。全光纤系统分布式传感技术具有以下优点：①能实现分布式检测，大大降低传统的点式检测的漏检率。②精巧、柔软，不影响埋设部位的材料性能和力学参数，有利于监测值的代表性。③灵敏度高，抗雷击、抗电磁干扰。④传感与信息传输集于一身，易于构成自动化遥测系统等。

1992 年在成都科技大学攻读博士学位期间，作者受到导师刘浩吾教授光纤传感检测技术研究内容的影响，1996 年创建“光纤传感技术研究室”，同年进入哈尔滨工业大学博士后流动站，专题

进行光纤传感器技术在大坝工程中的应用研究。国外一些发达国家对光纤传感器技术的应用研究已取得丰硕的成果，不少光纤传感器系统已实用化，成为替代传统传感器的商品。国内不少部门和单位对光纤传感器技术也进行了多年研究，取得了不少研究成果，但大多处于预研阶段，离实用化尚有一定的距离。针对这一国情和宜昌水电城的区位优势，作者选择了以水电工程为依托开展光纤传感器技术应用研究的主攻方向，让实验室成果尽快走向工程应用，解决工程实际问题。本书正是总结了作者及其课题组近八年的探索性实践，把它奉献给广大工程技术人员和读者，抛砖引玉、以资参考，共同推动大坝安全监测理论、方法及其仪器设备的创新和不断发展。

本书第一章简单讨论了大坝风险意识、大坝事故和大坝安全监测的常规方法；第二章对光纤传感器技术的研究现状进行了综述，涉及到结构损伤评估、裂缝、应力应变、温度、弯曲和位移检测等；第三章介绍了光纤传感器的基本原理；第四章主要以沙牌RCC拱坝平面和整体石膏模型为背景，提出了小比尺模型随机裂缝分布式光纤传感监测技术；第五章针对混凝土面板堆石坝板间缝、周边缝的监测，专门研制了光纤测缝计及相应的智能化系统；第六章讨论了光纤测缝计的光强衰减方程与率定方程；第七章着重介绍了大坝裂缝监测的光纤传感技术现场试验研究，包括三峡工程、古洞口混凝土面板堆石坝和鱼跳混凝土面板堆石坝工程；第八章采用小波分析对裂缝光纤传感监测信号进行了初步的定位分析；第九章介绍作者利用率先引进的光纤分布式测温系统，监测三峡工程左厂14坝段常态混凝土温度场的部分成果；第十章研究了高混凝土面板堆石坝面板挠度监测的光纤陀螺方法；第十一章

提出了边坡深部变形监测的线型和螺旋型分布式光纤传感器技术。为方便广大工程技术人员和读者，作者给出了附录 1 和附录 2，简单介绍了光学基础知识和光纤的基本特性。

本书的成果是作者与同事们团结协作、艰苦创业共同获得的，参加本书内容研究的主要成员有何薪基、蔡顺德、张存吉、廖乃高、蔡永强等，还有作者的研究生。

本书的研究内容多学科交叉渗透，跨度大、难度高。桂林激光研究所、湖北华中精密仪器厂、中国航天集团上海光纤中心、宜昌市长途电信局工程中心、四川大学水电学院等单位是作者的合作伙伴，多年来给了作者大力的支持，在此表示衷心感谢！本书是作者在主持国家自然科学基金项目、国家电力公司重大项目、国家科委“九五”攻关项目小题、国家教育部科学技术研究重点项目等十项国家和地方科学研究课题的基础上完成的。因此，作者也要感谢国家自然科学基金委员会、国家电力公司、国家教育部、中国长江三峡工程开发总公司、三峡大学、湖北清江水电开发有限责任公司、葛洲坝水电集团公司、广西壮族自治区水利厅、广西水利电力职业技术学院等单位给予的资助、帮助和鼓励！三峡大学水工结构省级重点学科资助了该专著的出版。作者还要感谢妻子刘秀珍女士长期以来对作者事业的理解、关心和无私奉献！

光纤传感技术涉及许多学科的专门知识，由于作者水平有限，书中错误和疏漏之处在所难免，敬请各位专家和广大读者批评指正。

蔡德所

2002 年 12 月 16 日

于南宁

作 者 简 介

蔡德所，男，1952年11月出生于武汉市。博士后，教授，博士生导师;湖北省有突出贡献中青年专家，国家电力公司跨世纪学术带头人。毕业于武汉水利电力学院，1991年获武汉水利电力大学结构力学专业硕士学位，1995年获四川大学岩土工程专业博士学位，1997年破格晋升为教授，2001年被确认为武汉大学博士生导师、三峡大学“三峡学者特聘教授”。曾任武汉水利电力大学（宜昌）系主任，科学技术处处长。现挂任广西壮族自治区水利厅副厅长，兼自治区水利厅代总工程师。

现主要从事水利水电工程、岩土工程方面的管理、科研和教学工作。主要研究方向为水电工程安全监测的光纤传感技术及计算机数值模拟。近年来，在光纤传感技术研究方向共主持国家自然科学基金项目、国家电力公司重大项目、教育部科学技术研究重点项目、水利部“948”项目等纵横向科研课题12项，其中获湖北省科技进步二等奖1项、湖北省自然科学优秀论文二等奖2项、黑龙江省高校科技进步三等奖1项。在《水利学报》、《岩土工程学报》等刊物上发表科研论文56篇，出版专著4部。

Introduction

This book, building on the national and local key programs of science and technology, specializes in application of the optical fiber sensing technology in dam engineering. With its innovative thinking, substantial content and evidently interdisciplinary studies, the book mainly presents the distributed optical fiber sensing technology in monitoring of dam random cracks, displacement of slab cracks and peripheral joints, temperature, deflection and deep deformation of landslide.

This book can be used as a reference book to technicians and scientific researchers who work in engineering of hydraulics, electric-power, construction, road and bridge, oceanographic platform, tunnel and nuclear power station etc., to teachers of universities and colleges, and to undergraduates and postgraduates as well.

Foreword

The damage detection and early diagnosis in engineering structures is one of the important measures to decrease disasters, especially in great projects of dams and nuclear power stations, which involve huge investments, enormous profits, and potential risks of disaster as well. Therefore, safety monitoring becomes particularly important.

In dam safety monitoring, conventional techniques possessing one-hundred-year history, more experience and a wide variety of applications, is still the main equipment at the present time after being equipped with current criterion. However, there exist some defects, including poor durability, finite information, being easily disturbed by intensive electromagnetic field, and having influence on measured point, etc. For this reason, it is very necessary to exploit high new techniques for dam safety monitoring. Nowadays in the international competition of high new monitoring techniques, the fiber optic sensing technology with its unique superiority plays a leading role. Here, I am heartily pleased with that it is on this international leading subject that Dr. Cai Desuo has been devoting himself to researching with great courage and originality, and that he has finally finished the book building on nearly eight-year studies of field experiments on hydroelectric engineering. Taking a broad view of the book, from the development of fiber optic crack meter for measuring slab deflection and peripheral joints to the integration of intelligent system, from random cracks detection to distributed fiber optic temperature field sensing in dam concrete structure, from applications of OTDR analytic software to wavelet analysis of fiber optic sensing signal, from distributed fiber optic sensing technology for deep deformation monitoring of landslide to fiber optic gyroscopic method for slab deflection monitoring of concrete-faced rockfill dam, can we find that everywhere it reveals author's keen thinking, broad vision, firm knowledge and spirit of bearing hardship. Basing on Three Gorges Project, Qingjiang Geheyan engineering, Gudongkou concrete-faced rockfill dam and Yutiao concrete-faced rockfill dam, Dr. Cai has led the researching group to carry out several exploratory and very hard field experiments and practicing studies, which have made contribution to the field of dam safety monitoring. This is the first book at home on fiber optic sensing technology in dam engineering, and its publication will produce driving force and profound influence on the innovation and developments of safety monitoring technology in hydraulic and hydroelectric projects.

Member of Chineses Academy of Engineering

Prof.WangGuangyuan

26/10/2002,

Haerbin

Preface

It is very important to enhance dam monitoring because dam engineering, a not rigorous science, involves many random or uncertain factors in it or its operating environment even though dam construction technology has developed for several thousand years. The task of dam monitoring is to keep informed of the dam's condition, to detect and predict the unusual phenomenon especially the hazard so as to ensure the dam safety. Therefore the monitoring system must posses the property of forecasting all engineering hazards without delay and omission.

However, of the conventional instrument which has one hundred year of history, some basic defects remain. First, the dot measuring method offers a lower information density. It fails to perform distributed monitoring of seeping water, temperature, stress variation, crack and deflection, neglecting some important information. Second, the electrical signal is easily interfered by intensive electromagnetic field and influences therefore the measuring accuracy. Third, it is not applicable to rough environment of flammability, explosion hazard, high-temperature, and lightning stroke. Last, it is not easy for remote measuring and surveillance. For this reason, to exploit high new monitoring techniques is very necessary. As the rapid advancing of optical fiber and its relative components, the optical fiber sensing technology, with its unique superiority, is in the lead. This technology posses the following advantages: first, the omission factor can be lowed greatly by performing distributed measurement; second, for its delicacy and softness the material performance and mechanical parameter of the embodied part are not influenced, making the monitoring value accurate; third, high sensitivity, electromagnetic resistance, and lightning stroke resistance can be realized; last, sensing and information transmitting can be incorporated to form a automatic remote measuring system.

When studying for a doctorate in Chengdu Science and Technology University in 1992, I was influenced by Professor Liu Haowu, my advisor, and his research on optical fiber sensing technology. In 1996, I set up the laboratory of optical fiber sensing technology and at the same time entered into the postdoctoral program of Harbin Institute of Technology to make the monograph of application of the optical fiver sensing technology in dam Engineering. Great achievements have been witnessed in this field by some developed countries, and many optical fiber sensor systems have been applicable to replace the conventional sensor. Much work has also been carried out for a few years by many departments at home, but much results are just in a developing stage. In this case, with the superiority of Yicang hydroelectric town, I building on the hydroelectric engineering, focus on the studies of optical fiber sensing technology to make the test results applicable as soon as possible and to overcome the actual construction problems. This book has summed up the exploratory practice of nearly eight years, and is to be supplied to technicians and readers as a reference for promoting together the theory, method and instrument of dam monitoring.

In this book, chapter 1 discusses the risk awareness of the dam, dam accidents and conventional monitoring techniques; chapter 2 makes a researching overview of the present condition of the optical fiber sensing technology including structure damage evaluation, cracks, stress variation, temperature, bending and displacement etc.; chapter3 introduces the basic principles of the optical fiber sensor; chapter 4 puts forward the small scale model distributed optical fiber sensing for random cracks monitoring based on the RCC arch dam plane and monolithic plaster model; chapter 5 introduces the developments of optical fiber crack meter and relative intelligent system according to measuring slab cracks and peripheral joints in concrete-faced rockfill dams; chapter 6 discusses the light intensity attenuation equation and rating equation of the optical fiber crack meter; chapter 7 introduces the field experiment researches on distributed optical fiber sensing technology for dam crack monitoring including the Three Gorges Project, Gudonglou Concrete-faced Rockfill Dam, and Yutiao Concrete-faced Rockfill Dam; chapter 8 analyses the optical fiber sensing signal by using wavelet analysis; chapter 9 introduces partly the results of monitoring concrete temperature field of monolith 14 in the left bank factory of the Three Gorges Projects by using distributed optical fiber temperature sensing system, which is firstly introduced from abroad; chapter 10 studies the fiber optic gyroscopic method for slab deflection monitoring of the high concrete-faced rockfill dam; chapter 11 puts forward the linear and spiral distributed optical fiber sensor for deep deformation monitoring of landslide. In addition, I also provide appendices A and B for engineering technicians and readers, introducing briefly the fundamental knowledge of optics and the basic properties of optical fiber.

This book is the result of the great effort of both my colleagues and mine, mainly including He Xinji, Cai Shuende, Zhang Cunji, Liao Naigao, Cai Yongqiang and my postgraduates.

This research is interdisciplinary with substantial content, wide range and much profundity. Here, I want to express my sincere gratitude to my collaborators, Gulin Laser Research Institute, Hubei Huazhong Precision Instrument Factory, China Aerospace Science & Industry Crop. Shanghai Optical Fiber Center, Hydroelectric Institute of Sichuan University, and Yichang Telecommunication Bureau Engineering Center for their substantive support. This book is also based on the ten national and local projects directed by me, of National Natural Science Foundation, key programs of the State Power Corporation, key state construction projects in the Ninth Five-Year Plans of the State Science Commission and key projects of Science and Technology Research of State Education Ministry.

Therefore I gratefully acknowledge assistance and encouragement from the National Natural Science Foundation, the State Power Corporation, State Education Ministry, China Three Gorges Project Corporation, Three Gorges University , Hubei Qingjiang Hydroelectric Developing Co. Ltd., Gezhouba Project Hydroelectric Group Corp., Water Resources Department of Guangxi Zhuang Autonomous Region, and Guangxi Hydraulic and Electric Polytechnic. The Provincial Key Subjects of Hydraulic Structure Engineering of Three Gorges University for their Financial aid in publishing this book. Besides, I am grateful to my wife, Ms. Liu Xiuzhen, for her understanding, solicitude and selfless devotion to my work..

The optical fiber sensing technology deals with such a wide range of disciplines that some inaccuracies and deficiencies are unavoidable in this book. I would welcome critical comments from experts and readers for its improvement.

Dr. Cai Desuo

October 16th, 2002

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目　　录