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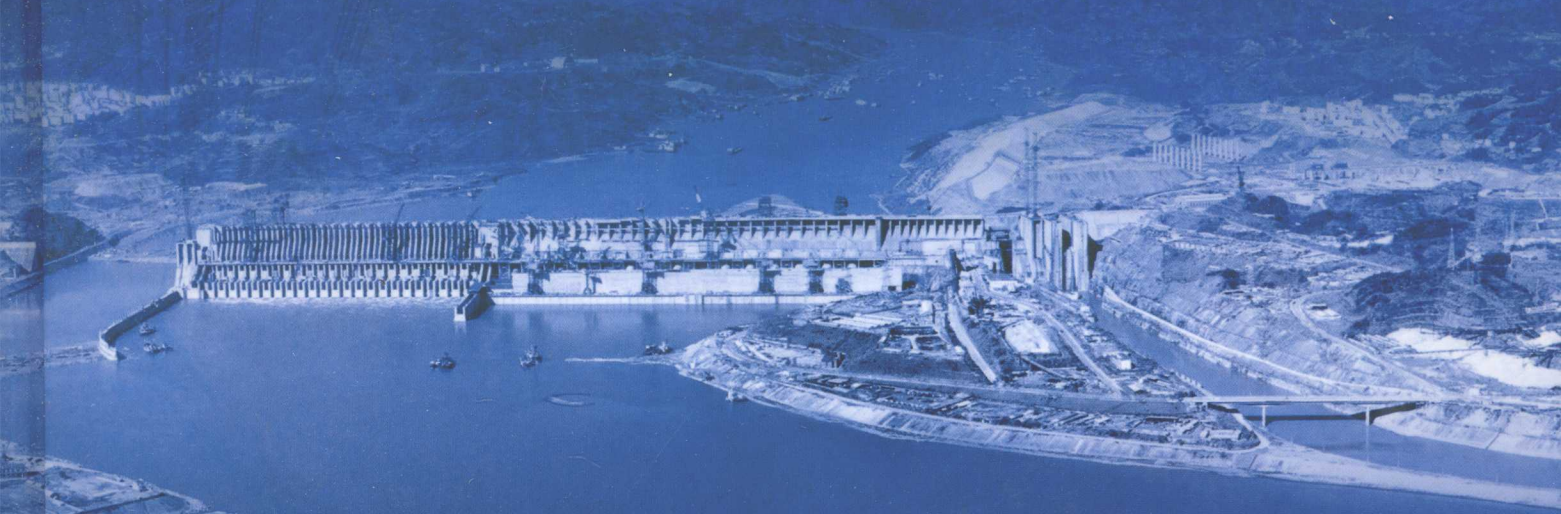
大坝的安全监控理论和试验技术

吴中如 等 著



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内 容 提 要

本书共8章，主要内容有：综述性论文；水工结构分析和模型试验与原位检测技术；大坝原位检测量的多种监控模型及其建模理论与方法；大坝结构形态的反分析；大坝与岩土边坡的健康诊断标准；大坝健康诊断和综合分析；大坝安全综合评价专家系统；大坝病险的运行风险分析与预警等。

本书可供从事大坝安全性研究的所有从业人员阅读、参考。

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吴中如教授简历

吴中如教授于1939年重阳节出生于江苏省宜兴市，1952～1958年在宜兴市和桥中学读书，1963年毕业于华东水利学院河川系，先后在中国水利水电研究院等单位工作，现任河海大学教授、博士生导师，水利部科学技术委员会委员，中国水利学会名誉理事，中国水力发电工程学会理事，Council of ISHMII (International Society for Structural Health Monitoring of Intelligent Infrastructure)。1997年当选为中国工程院院士。曾任第十届全国政协委员。

吴中如教授长期从事大坝安全监测、监控和水工结构领域的教学和科研工作。大坝安全是关系国计民生的大事，大坝安全监测、安全分析、反馈分析和综合评价等需要综合应用水工、数学、力学、计算机、传感技术等多学科理论，是近期发展起来的一门边缘学科。至2009年底先后主持国家重点科技攻关项目子题6项，国家自然科学基金三峡重大项目课题以及国家自然科学基金重点项目等基金6项，973项目课题1项，三峡临时船闸、升船机和左岸厂房等安全监测工程，龙羊峡、丹江口、佛子岭、水口等大型工程科研项目60多项。至今，先后获国家、省部科技进步奖16项（国家奖4项，省部级特等奖1项、一等奖3项、二等奖4项、三等奖4项），其中“高坝安全监测技术及反馈”（负责7个子题中的4个子题）获1995年国家科技进步二等奖，“混凝土坝变形观测量的数学模型研究及其应用——安全监测与预报”获1990年国家科技进步三等奖，“大坝与坝基安全监控理论和方法及其应用研究”获2004年国家科技进步二等奖，“重大水工混凝土结构隐患病害检测与健康诊断”获2007年国家科技进步二等奖，“三峡水利枢纽二期工程蓄水、通航和发电技术研究与实践”获2004年度湖北省科技进步特等奖，“佛子岭连拱坝原型结构性态分析”、“三峡水工建筑物安全监测与信息分析研究”、“重大水工混凝土结构隐患病害检测与健康诊断”分别获1988年安徽省、2002年与2006年江苏省科技进步一等奖，“混凝土坝变形观测量的数学模型研究及其应用”、“龙羊峡大坝安全监测与反馈”、“青铜峡水电站大坝原型观测资料分析和结构性态分析”、“大坝安全综合评价专家系统”等分别获1988年水电部、1992年能源部、1997年宁夏回族自治区与2000年江苏省科技进步二等奖。至2009年，在国内外学术刊物上发表“Deterministic and Hybrid Models for Safety Supervision of Concrete Dams”、“Diagnosis and Evaluation of

Dam Health”等学术论文240多篇，撰写科研报告60多份；出版《水工建筑物安全监控理论及其应用》（河海大学出版社，1990年；经补充修改后由高等教育出版社2003年再版）、《大坝安全综合评价专家系统》（北京科技出版社，1997年）、《变形监测分析与预报》（测绘出版社，1998年）、《三峡水工建筑物安全监测与反馈设计》（中国水利水电出版社，1999年）、《大坝原型反分析及其应用》（江苏科学技术出版社，2000年）、《碾压混凝土坝安全监控理论及其应用》（科学出版社，2001年）和《重大水工混凝土结构病害检测和健康诊断》（高等教育出版社，2005年）等著作。在创建变形监控指标拟定的理论和方法，构建大坝安全综合评价专家系统，建立了完整的监控模型体系，发展和完善了反分析理论，并将成果成功应用于实际工程，取得了显著的社会经济效益等方面作出重要贡献。

由于吴中如院士的突出贡献，先后获国家级有突出贡献的中青年专家、水利部特等劳动模范、全国高等学校先进科技工作者和全国模范教师等光荣称号，是一位长期工作在工程科学技术第一线并作出重大贡献的工程科学技术专家。

目前担任《中国科学》E辑编委，《水利学报》、《岩石力学与工程学报》编委，《河海大学学报（自然科学版）》编委会副主任，《Water Science and Engineering》主编等。

序　言

我国人均水资源占有量贫乏而又时空分布严重不均匀，水能资源丰富但主要分布在西南地区，为了利用这些水资源和水能资源，我国至今有水库大坝（即横跨河床的所有永久性的挡水与泄水建筑物、水库周围垭口的挡水建筑物及这些建筑物的地基和附属设施）8.70万多座，其中15m以上坝高的大坝2.63万多座，形成水库总库容约6345亿m^3，约占多年平均径流总量的1/4。这些水库防洪保护了约3.1亿人、大中城市132座和农田4.8亿亩（0.32亿hm^2），年供水约2400亿m^3，灌溉2.4亿亩（0.16亿hm^2）耕地，为100多座大中城市供水，水电装机量已超过1.70亿kW（约占技术开发量的31%）；在防洪、灌溉与供水、发电、航运和养殖等方面产生了巨大的社会经济效益。然而由于多种原因，约有3.7万多座水库为病险水库，严重影响工程效益的发挥，甚至危及下游人民的生命财产安全。与此同时，为了利用西南地区丰富的水能资源，已建、正建与待建几十座高坝大库，如已建的240m高的二滩拱坝，正建的溪洛渡（坝高278m）、锦屏一级（高305m）与小湾（高292m）等拱坝，以及江坪面板堆石坝（高221m），两河口（高293m）、双江口心墙坝（高314m）等，这些大坝无论是高度、规模和技术难度等都远远超过了已有“各类技术规范”，亟待从已运行的水库大坝中吸取经验教训，制定相应的设计、施工和运行规范。

水库大坝与世界上一切事物一样，都存在“生老病死”的生命期，对水库大坝这种特殊的水工建筑物，尤其是大江大河上建造的水库大坝，应经历规划设计、施工建造、运行监测、病害老化、除险加固、退役报废等过程，在这一过程中，关键是规划设计、施工建造、运行监测所构成的闭路循环。以往普遍存在“重建轻管”，忽视运行监测。经过几十年的实践，尤其是对3.7万余病险水库大坝的安全分析评价与补强加固，以及西南地区修建200～300m级的高坝大库所面临的众多科学技术问题，亟待依据已建大坝采集的海量原位监测资料分析、反演与反馈分析，建立多种监控模型与指标等，据此对病险大坝作出安全分析与评价、预报、风险分析直至为除险加固与退役报废等科学决策提供技术支持，同时也为西南地区修建

高坝大库提供更合理的设计分析理论与方法和更精确的计算参数。

本人的已故恩师陈久宇教授，敏感地认识到大坝运行监测是1：1的模型试验，原位监测资料真实反映大坝的工作性态，于20世纪70年代在国内首先开辟运行监测资料分析，建立统计模型和变形参数的反演分析等，据此定量评估大坝的运行状态。在1984年陈久宇教授病故后，本人继续他的事业，在国家重大科技攻关项目、国家自然科学基金、973项目以及重大工程科研项目等资助下，继续和发展了陈久宇教授开创的事业，在国内外学术刊物和国际学术会议上，至今本人独著以及与顾冲时、陈国启、郑东健、苏怀智、包腾飞等老师和研究生（80多人）合作共发表240多篇论文，选择其中的代表性论文124篇，汇编成《大坝的安全监控理论和试验技术》一书。按科学技术内容与其解决的理论、方法与技术，本书大致归纳为8章。第一章综述大坝安全监控理论与方法和测控技术等。第二章主要介绍水工结构与地下洞室稳定的分析方法和模型试验与原位监测技术。第三章主要介绍大坝的变形、应力应变、裂缝、渗压与渗流量等原位监测量的多种监控模型及其建模理论与方法。第四章介绍基于实测资料反演坝体、坝基与库盘的物理力学参数和反馈分析实际安全度的方法。第五章介绍拟定混凝土坝变形监控指标与裂缝转异、岩土边坡的稳定判据等诊断标准的理论与方法。第六章介绍大坝健康诊断与综合分析的理论与方法。第七章介绍大坝安全综合评价、实时分析、在线监控与反馈分析专家系统的逻辑模型与物理模型。第八章介绍大坝病险的运行风险分析与预警的系统、模型与方法等。

这里要指出的是：①本书除了收录作者独著或第一作者的论文外，还收录了作者和同仁与研究生（80多名）合作撰写的论文，因此本书是集体创作的成果；②由于论文发表的历时长，学术刊物多，论文的编辑要求不尽一致，因此，在保证论文内容相同的前提下，做了少部分修改；③本书的出版得到国家科技支撑计划课题“基于风险的大坝安全评价技术开发”（20006BAC14B03）、国家重点基础研究发展规划（973）项目“灾害环境下重大工程安全性的基础研究”（2002CB412707）等资助。在编辑出版过程中，河海大学王绍泉副研究员做了大量的编辑工作，在此，谨表深切的谢意。

限于作者的水平，难免有不妥之处，希望读者批评指正。

吴中如

2009年5月

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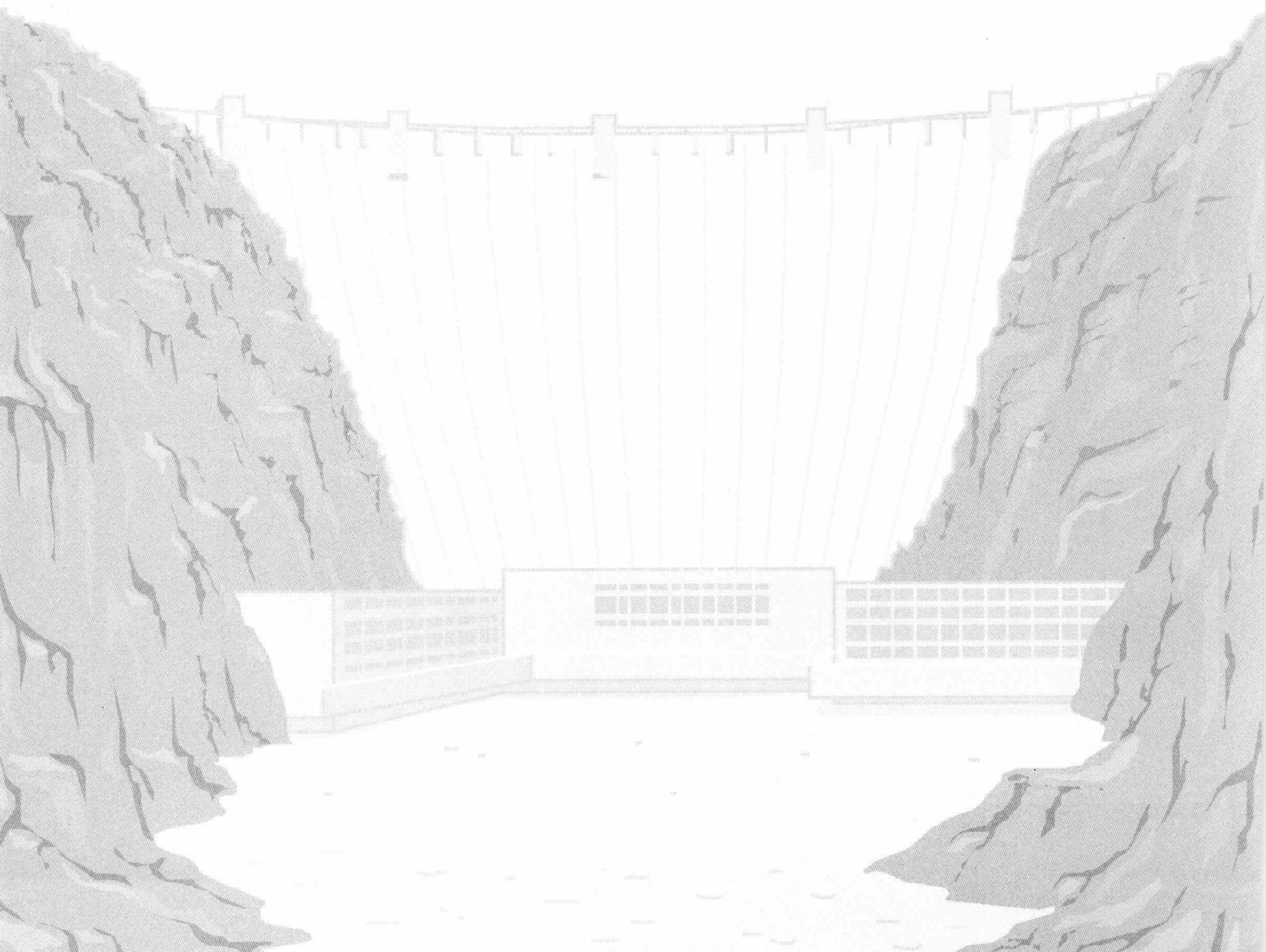

Review of safety and management of dam in china

【Abstract】 Dam is key infrastructure of national economy construction and social development in China. It is of very significance to improve and strengthen dam safety consciousness and management level. Dam safety situation is reviewed and safety management is outlined in this paper, and new notion is presented for the improvement of dam safety and management.

1 Introduction

China is a country with abundant water resources. The theoretical potential hydro-energy is up to 6.98 GW. The technical development hydro-energy in China reach 541 GW, ranking first in the world. In order to make use or water resources and hydro-energy, more than 87thousand dams have been built in China, among them there are 26300 dams higher than 15m. The total storage capacity of reservoirs in China is about 634 Gm^3. The total installed capacity of hydropower stations has broken 170 GW in China. The annual water supply ability is 240 Gm^3. Irrigated area is about 240 million acres. There are about 310 million people, more than 132 large or middle-scale cities and 480 million acres of farmland in the protected areas. The dams play an important role in national economic construction and social development and stability in China.

However, for various reasons, parts of dams have unsafe factors, and there are a great number of ill dams and dangerous dams in China. Such a situation not only influences the role of dams but also threats seriously both the lives and properties of people who live in the downstream areas. Even more it can lead to a burst of flood. For example, in Aug. 1975, Ban Bridge Reservoir and Shimantan Reservoir were broken due to great storm scouring, leading to disaster. Therefore, the management of dam safety must be improved. These reservoirs must be maintained and strengthened in time, so that we can make full use of them. On the other hand, it can improve the level of management of dam safety.

2 Overview of dam safety stitation in China

2.1 History of dam safety

Since People's Republic of China is founded, there are more than 87thousand dams in various types, including about 510 large dams with storage capacity over 0.1Gm^3 and about 3260 middle ones with storage capacity of 0.01～0.1Gm^3. The rest 83315 dams are small ones. The majority of these reservoirs were built in 50's, 60's and 70's. They laid a solid foundation for the construction of water conservancy and hydropower and played an important role in the economic construction. But limited by conditions at that time and short of scientific technical consideration, there are some problems such as low flood control standard, poor engineering quality and hidden dangers for a large number of reservoirs.

According to incomplete statistics, there were two high tides of dam failure. One happened during the end of 50's and the beginning of 60's and most of these reservoirs were of middle and small size. Another happened in 70's because of social upheaval. After 80's, because dam safety manage-

本文在中国工程院主办的第21世纪土木工程国际学术会议论文集上发表，2000。

ment was strengthened and reservoirs with potential danger were reinforced, the failure of dam has decreased.

2.2 Situation of dam safety

Since 80's, Ministry Of Water Resources and Ministry Of Energy (the State Power Corporation of China) organized respectively Dam Safety Supervision Center and Dam Safety Monitoring Center. Statute and code of dam safety management were set down and issued. The safety management was strengthened and periodic inspection of Dam was performed. Dangerous reservoirs were also be strengthened.

On the other hand, the reservoirs built in the two tides have worked for above 30—40 years. Therefore, they may become aged gradually, especially for dangerous reservoirs, and there will occur new dangerous reservoirs in future. According to incomplete statistics, the rate of dangerous reservoirs in large and middle size is 30% and 40% in small reservoirs. The funds only for strengthening reservoirs are over 12,000 million Yuan. Therefore, it will be a tough task to manage, maintain and strengthen reservoirs.

3 Management of dam safety

Strengthening dam safety management is key measure to assure dam operation safely. It includes mainly dam safety management system, legislation, periodic inspection of dam, registration of dams, consolidation treatment of dangerous reservoirs, etc.

3.1 Dam safety management system

At present the dams in China are principally divided into two parts: water resources and hydropower. The dams of water resources, whose main function is flood control and irrigation, come under the jurisdiction of MWR. The dams of hydropower, whose main function is to generate electric power, come under the jurisdiction of the State Power Corporation of China. Ministry of Energy and Ministry of Water Resources (the State Power Corporation of China) organized respectively Dam Safety Supervision Center and Dam Safety Monitoring Center. Two centers are responsible for the Ministry of Water Resources and the State Power Corporation of China and perform the function of dam safety management. Then, monitoring centers of dam safety were also founded in Safety Organizations of Drainage Area, the water conservancy or hydraulic power bureaus of every province, city, and autonomous region. It formed system of safety management of water conservancy dams and hydropower dams.

3.2 Safety legislation

After establishment of two centers, statute and code of dam safety management were set down and issued by Ministry of Water Resources and the State Power Corporation of China. It includes "Statute for Dam Safety Management of Hydropower Station", "Practical Code For Safety Inspection of Existing Dams". "Guidelines for Dam Safety Register of Hydropower Station", "Technical Code of Concrete Dam Safety Monitoring", "Water Code of People's Republic of China", "Flood Control Regulations of People's Republic of China." The above-motioned documents formed the perfect legislation system of dam safety management in China. China Dam safety management stepped on the track of legislation management.

3.3 Periodic inspection of dam safety

According to "Appraisal Methods of Dam Safety" and "Statute for Dam Safety Management of Hydropower Station", dams were inspected periodically. It lasted 12years to compete the first round periodic safety inspection of 96 hydropower stations, from 1987 to 1999. Specialists were invited to-

gether by the department responsible for the work to form consulting group. Through the first round periodic safety inspection, dam project grade, design standard, strength and stability, operation mode, ageing, durability, landside and monitoring system were checked. It showed that there are some dams with unsafe factors, such as inadequate discharge capacity, serious dam body cracks, and excessive foundation seepage amount and reservoir slope slide. So measures must be taken in order to change this situation. At present the second round periodic safety inspection has been carried out. 129 dams are arranged to perform the periodic safety inspection in the second round inspection. Since 1995, safety inspection has been performed on large reservoirs and effect has been obtained. However, compared with what is required, the present work of assessment of dam safety still has a long way to go.

The practice proves that it is an effective approach to understand the dam safety condition and improve the dam safety management. The periodic inspection has become an important institution.

3.4 Registration of dam safety

According to "The Registering Methods of Dams" and "Guidelines for Dam Safety Register of Hydropower Station", since 1997, Dam Safety Supervision Center of MWR is responsible for the registration of dams. Now the registration of large reservoirs has almost been finished. The registration of middle reservoirs is in process. For small reservoirs, the registration is in reparation.

Registration of 110 dams of hydropower stations was finished. Among them, 100 dams were assessed as grade A.

3.5 Consolidation treatment of dangerous reservoirs

According to the problem found in dam periodic inspection, rehabilitation and treatment of hydropower stations were extensively implemented, including heightening the dams, treating the cracks in dam bodies, taking measures to treat the seepage of dams and foundations, implementing modification of monitoring devices and so on.

43 reservoirs were first defined as essential dangerous reservoirs, and now 37 reservoirs have been treated. In 1992, another 38 reservoirs were defined as essential dangerous reservoirs and the treated plan has been carried out. 8 reservoirs have been treated. In the future, another dangerous reservoirs will also be strengthened.

Rehabilitation and treatment of dam play an important role in improving the level of dam safety and making full use of project profit.

4 Dam safety moniforing

With the development of science and technology, the whole level of dam safety monitoring technology in China produced a qualitative leap.

Dam safety monitoring plays the role of ear and eye in the aspect of ascertaining the operation regularity, detecting the latent deficiencies in time, verifying design and building construction.

4.1 Dam safety monitoring instruments and data automatic acquisition

(1) Dam safety monitoring instruments.

China began to develop and manufacture the related monitoring instruments since the middle of fifties. With the efforts for the past decades, especially for recent ten years, China has made great progress in the performance and automation. More than 10 kinds of instruments, such as the Carlson-type, the vibrating-wire, capacitive-type and the step motor-type have been developed.

At the early stage of seventies, China began to study and produce laser-collimating system, applied successfully in the projects such as Fengman, Taipingshao, etc. In recent years, GPS technolo-