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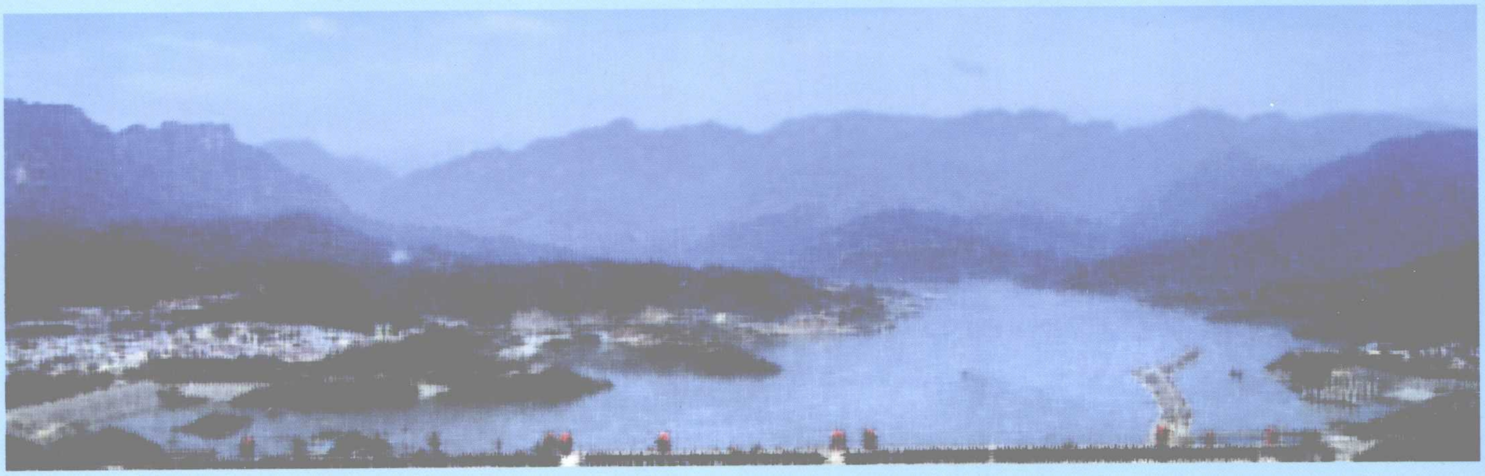
STUDY OF RESERVOIR-INDUCED SEISMICITY



Yuping Mao, Yongping Ai, Zhixiang Li, Ran Chen, Xiaolin Hu, Liming Xie, Hong Fu, Min Wu, Maoxian Li, et al.

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水库诱发地震研究

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FOREWORD

This book is sponsored by the project of "Reservior - Induced Seismicity (RIS) Monitoring and Prediction Study for Complex Tectonic Region" (2006SG01), which is financed by Science and Technique Department of Yunnan Province, P. R. China, and conducted by Earthquake Administration Bureau of Yunnan and Yunnan Lancang River Hydropower Development Co. Ltd. The book is also an important part of the study results of project, "RIS Monitoring and Prediction Study for Complex Tectonic Region".

The suggestion and sponsoring of "RIS Monitoring and Prediction Study for Complex Tectonic Region" was based on that large scale reservoir construction has begun since late 20th centuary in China, most of the reservoirs were constructed and are constructing in the Western China where the seismotectonic background is complex, the RIS problems appear very obvious and complex.

The aims of the projects are to comprehensively research the active rules of RIS, to research the genetic process and mechanism of damage reservoir - induced earthquakes (RIE), and to design the tectonic - physical model of damage RIE and RIE monitoring and prediction system for Hydro - Power Construction Area of median - downstream Lancangjiang River where the seismotectonic environment is very complex, more than ten reservoirs are under construction and going to be constructed.

The book is presented to ones who are interested in reservoir - induced seismicity!

Authors

May 2008

Introduction in Chinese（中文引文）

人类于20世纪初开始修建坝高100 m以上的水库，至今已有百年历史，其中大规模建设开始于20世纪中叶。

根据Sinpson（1976），1973年《大坝的世界登记》（I. C. O. L. D.，1973），给出了当时全世界已建和在建的坝高100 m以上水库326座，其中当时已建265座，在建61座；到2003年，全世界拥有坝高100m以上水库670座（其中坝高150 m以上的大型水库155座），以11座/年的速率增加。

众所周知，水库诱发地震问题是从1938年马拉松水库4.7级地震和1939年美国米德湖（Lake Mead）4.6级地震后提出（Gupta，1992；丁原章，1989）。1962年3月19日中国广东新丰江水库大坝左岸河源一带发生的6.1级地震被认为是第一例6级以上水库诱发地震（丁原章，1989）。此后5年内，赞比亚－津巴布韦的卡里巴水库、希腊克里马斯塔水库、印度柯依纳水库相继诱发了6级多地震。这些6级以上强烈地震造成了大的破坏和经济损失。因此，也是从20世纪中叶开始，人类社会开始了对水库诱发地震的重视和科学研究。

1986年对世界29个国家（包括中国）33770座水库的统计认为，有116座诱发过地震（李华晔，1999）。

到21世纪初，世界范围已经发生水库诱发地震（2级以上）近140例，包括6级以上4例、5.9～4.5级36例、4.4～3.0级43例，2.0～2.9级的51例，这些地震分布于30多个国家，其中中国发生十多例。举世瞩目的长江三峡水库自2003年首次蓄水至135 m水位后已经出现水库诱发地震（姚运生，2006）。

1. 过去半个世纪的水库诱发地震观测与研究

经过过去近半个世纪相关各国研究者的共同努力，对水库诱发地震问题开展了大量的观测、基础研究、预测技术研究工作。

1）水库诱发地震观测方面

美国米德湖的地震观测开始于1938年（水库1935年蓄水）。20世纪50年代以后，一些国家开始在已发生地震的水库设置地震台网详细测定地震运动学和动力学参数，研究地震与蓄水及地质构造的关系。除地震学观测外，1978～1980年Zoback和Fletcher在美国蒙蒂塞洛水库开展了水压致裂应力测量和地震应力降观测；Taiwani等1977年开始对蒙蒂塞洛水库和若卡西水库进行过水化学组分、水氡、水位等方面的测量，研究它们与地震时空分布关系，预报了两次2～4级地震（胡毓良，1983）。

中国的水库诱发地震监测开始于1962年，新丰江水库6.1级地震后，新丰江水库区建立了地震观测网，并连续运行至今，是中国第一个运行时间最长的水库诱发地震监测网。

中国现行“水工建筑抗震设计规范”要求：“在兴建高水头大水库时，如库区地质构造复杂，并有较近期活动断裂分布，应研究产生诱发地震可能性。对产生诱发地震可能性大的水库，应尽量在蓄水前由有关部门建设地震台进行监视。”

根据杨晓源（2000），经过近40年的发展，中国的水库诱发地震监测经历了四个阶段：

第一代水库地震监测：人工值守观测，使用的是观测地方性天然构造地震的短周期地震仪。20世纪60年代建设的广东南水水库，80年代的广西大化水库、云南鲁布格水库，90年代的四川铜街子水库、广西岩滩水库等均采用这种观测。

第二代水库地震监测：非专用无线遥测组网观测。20世纪70年代末至80年代初，无线遥测技术先后用于改造后的新丰江水库地震台网，80年代建设的青海龙羊峡水库台网，90年代建设的湖北丹江口水库台网、云南漫湾水库台网，福建水口水库台网等。

第三代水库地震监测：水库地震专用遥测台网观测。四川二滩水库地震监测台网建设研制出适合于水库地震观测的宽带遥测设备，配置了高采样率的地震数据采集和实时处理设备，先后用于湖北隔河岩水库台网、黄河小浪底水库台网、湖北三峡水库前期观测台网等。

第四代水库地震监测：综合观测和数字地震遥测。湖北三峡水库地震监测网使用了由测震、形变和地下流体三大项目组成的监测系统，是中国水库地震监测的第四个里程碑。这种观测模式还用于金沙江中下游建设的溪糯渡水库、向家坝水库、白鹤滩水库等水库台网建设。

2）研究方面

随着水库诱发地震观测的开展，对某一水库的专项研究、水库诱发地震震例与水库诱发地震特征、成因机理研究随之进行。

（1）水库诱发地震的震例报道和对某一水库的专项研究。

目前对印度 Bhatsa 水库、Osman Sagar 水库、Bhakra 水库、Koyna 水库，美国 Mead 水库、Oroville 水库、Clark Hill 水库、Keowee 水库、Jocassee 水库、Manticello 水库，赞比亚 - 津巴布韦 Kariba 水库，希腊 Kremasta 水库、Marathon 水库，新西兰 Benmore 水库，巴西的 Carmo do Cajuru 水库（Porto Colombia 大坝和 Volta Grande 大坝）、Marimbondo 水库、Capivara 水库、Paraibuna - Paraitinga 水库、Sobradinho 水库，俄罗斯 Toktogul 水库，埃及 Aswan 水库等水库均有不同数量的研究文章出现。中国的广东新丰江水库、广东南水水库、湖南黄石水库、湖南东江水库、长江三峡水库、湖北丹江口水库、湖北前进水库、湖北清江隔岩河水库、贵州东风水电站库、贵州乌江渡水库、贵州引子渡水库、浙江湖南镇水库、浙江乌溪江水库、浙江珊溪水库、江西柘林水库、辽宁参窝水库、四川铜街子水库、四川二滩水库、青海龙羊峡水库、新疆克孜尔水库、广西大化岩滩梯级水库、福建水口水库、四川大桥水库、云南漫湾水库、云南大朝山水库、吉林白山水库、河北潘家口水库等 28 个水库有不同程度的研究。

这些研究的特点是，对有诱发地震发生的大型水库、发生有较大诱发地震（一般 4.0 级以上）的水库有相对较多的研究。主要包括中国的广东新丰江水库、长江三峡水库、湖北丹江口水库、福建水口水库等，印度 Koyna 水库（Shivaji Sagar 湖），美国 Oroville 、Jocassee 、Mead、Manticello 等水库，塔吉克 Nurek 水库，赞比亚 - 津巴布韦 Kariba 水库等。

（2）水库诱发地震震例与水库诱发地震特征、成因机理综合研究。

除各水库的专项研究，还出现了对水库诱发地震震例与水库诱发地震特征、成因机理综合研究，其中代表性研究有：

1983 年地震出版社出版的《中国诱发地震》（国家地震局编）以 22 位作者论文集的方式，对广东新丰江水库、湖北丹江口水库、江西柘林水库、贵州乌江渡水库、浙江乌溪江水库、广东南水水库、湖南黄石水库、湖北前进水库 8 个水库的诱发地震和中国水库诱发地震的地质条件、分类、成因机理进行了讨论。

丁原章 1989 年的《水库诱发地震》介绍了 41 例水库诱发地震，其中中国 7 例、亚洲 13 例、欧洲 10 例、非洲 4 例、北美 7 例、澳洲 4 例、蓄水后地震活动减少的 3 例，研究了水库诱发地震的分类、成因机理。

Gupta（1992）在《Reservoir - Induced Earthquakes》一书中介绍了 41 例水库诱发地震，分析了水库诱发地震的分类、成因机理。

除上述研究外，一些研究论文也分析了水库诱发地震特征和成因。

2. 当前水库诱发地震研究存在的问题

虽然水库诱发地震研究已经取得了很多成果，对水库诱发地震有了不少认识。但仍然存在许多问题，主要表现在：

（1）受资料积累影响，水库诱发地震研究还处于初期阶段。

1980 年，Allen 在“国际地震预报和地震危险估价讨论会”上的“水库地震的危险”报告认为，当时对水库地震的认识还很少，还不了解这些地震为什么会发生，因而不能有把握地认识那些可能发

生水库地震的地区（胡毓良，1981）。

胡毓良（1983）在“水库地震研究的新进展”一文中指出：“水库地震的研究近年来虽然取得了一些进展，但还处于积累资料的阶段，特别应当加强对水库地震实例的详细观测与研究，只有积累相当数量准确可靠的资料，才可能进一步推动这门学科向前发展。”

Gupta（1992）在《Reservoir - Induced Earthquakes》一书中写到，虽然过去30年对水库诱发地震有了一定了解，但还有许多问题需要研究，不仅水库诱发地震现象还没有完全理解，如何评价一个水库的潜在诱发地震危险和最大地震的确定问题仍未解决。

易立新（2003）在“水库诱发地震研究的历史、现状与发展趋势”一文中，对20世纪水库诱发地震研究情况进行了回顾：20世纪60年代接连发生破坏性水库诱发地震之后，掀起了一个这方面研究的高潮。至20世纪80年代后期，水库诱发地震方面的研究渐入低潮，突出的表现是发表的文献显著减少。

陈光祥（2004）认为，水库诱发地震是一个较复杂的问题，是地震科学研究中的新课题，目前国际上还处于研究阶段，因此尚不能十分准确地预测、预报。

（2）水库诱发地震的诱震因素及其关系的认识还不统一。

自水库诱发地震引起关注以来，水库诱发地震产生原因、决定水库诱发地震发生和发展的因素等问题一直是研究的重要方面。到目前为止，这些方面的认识还不统一。

孙君秀（1996）等许多研究者认为，水库诱发地震是多种因素综合作用的结果，这些因素包括库深、库容、应力状态、断裂活动、介质岩性、地震活动背景。

李华晔（1999）认为，水库蓄水对地震不仅有诱发作用，而且在一定地质环境下会有某些抑制作用，加强这方面的研究是非常必要的。完全查清库区地质构造条件是一项较为困难的工作，在分析地质背景资料时应慎重对待，以便找出可能诱发水库地震的地质构造特征，做出符合实际的结论。

李兴强（2002）认为，诱发水库地震有很多因素，中国研究水库地震自20世纪60年代开始也提出不同的诱发理论。他在从地球动力学理论角度研究了大型水库蓄水后水库可能诱发地震的问题。

从地质构造角度，虽然库区地质构造环境与水库诱发地震的关系已得到一定程度认同，易立新（2003）认为，众多研究是对水库诱发地震的地质环境条件进行归纳、总结，并且大部分是在区域尺度上进行研究，着重从发震库区的断裂力学性质、岩性特征、地震活动性以及构造应力场方面进行归纳总结。在综合分析水库工程特征、构造特征和环境条件方面有待深化，有些基本问题还有待于作出回答。

（3）水库诱发地震成因机理仍然处于争论之中。

由于对决定水库诱发地震发生和发展的因素的认识不统一，因此水库诱发地震机理仍处于争论之中。

于品清（1984）认为，有关水库地震的成因问题，国内外广大水库地震研究人员曾从区域地质背景、库区水文地质条件、水的作用和地震活动等方面进行了不少研究，并提出了种种不同的看法。

李祖武（1984）认为，对水库地震持以不同成因观，就会对其发展趋势作出不同的估计。水库区的地震活动的震源虽浅，也有些不同于构造地震的特征，但其性质仍属于构造地震。故水库区地震的发生与发展主要取决于有利的地质条件和应变能的聚集，而库水所产生的静压力、孔隙压力以及天体运转是次要的。

易立新（2003）认为，在水库诱发地震机理方面存在不同认识。水库与地质环境的相互作用非常复杂，库水重力荷载作用、孔隙压扩散作用、地下水对断层物质的浸润、软化作用等，在发震中都起一定作用，但在何种条件下哪一种作用是主导因素？目前还没有明确答案。

（4）有效的水库诱发地震预测技术尚未形成。

水库诱发地震问题出现后，水库诱发地震预测需求也随着产生。一个时期以来，在水库诱发地震中长期预测技术研究上已经做出了很大努力。根据易立新（2003）研究，这方面工作主要有：

胡毓良等（1979）提出根据岩性、渗透条件和岩体稳定性评价诱发地震的可能性。

Packer，（1979；1982）提出概率预测法，选择库深、库容、应力状况、库区断层活动性和库区优势岩性条件，通过统计发震水库和不发震水库给出拟建水库的诱发地震概率。

于品清（1984）认为，水库地震发生的地质背景和构造条件与天然地震很相似，有关天然地震的理论和方法基本上可以引用，其预测预报经验可以借鉴。水库地震发生的关键因素是库区的水文地质条件和库水的作用。

陶振宇（1987）用固—液耦合分析方法对湖南东江水库进行过预测。

Thomas Vladut 20 世纪 80 年代提出的水库诱发地震危险预测方法（Risk Prediction Methods On RTS），在 1988 年召开的国际大坝会议上被认为是一识别水库诱发地震危险的较成熟技术。

常宝崎（1989）从模糊集理论角度提出了水库诱发地震的综合模糊评判法。

黄润秋和许强（1995）提出水库诱发地震震级的人工神经网络预测模型。

江雍熙（1995）从岩体结构理论和水文地质垂直分带方面，提出水库诱发地震的多成因理论及评价方法。

夏其发（2000）从工程地质学角度，研究了水库诱发地震危险性评价的工作程序和方法。

易立新和车用太（2000）提出水库诱发地震的水文地质概念模型。

张秋文等（2001）认为，目前国内外诱发地震预测与评估方法可以归纳为确定性预测和不确定性预测两大类。确定性预测对水库诱发地震进行明确的预测，即水库要么会发生诱发地震、要么不会发生，如地质环境预测法；不确定性预测法以概率的形式给出诱发地震发生的可能性，如灰色聚类法、模式识别法和逻辑信息法等。

根据上述情况，由于对水库诱发地震产生因素和成因机理的认识还处于探索阶段，因此出现了从不同角度提出的多种水库诱发地震预测理论。

3. 关于“复杂构造区水库诱发地震监测预警研究”和本书的主要工作

根据众多地震灾害实例（包括天然地震和水库诱发地震），除水库大坝外，地震还对水库周围的社会和自然环境产生破坏，因此，水库地震安全应由大坝地震安全、水库周围社会和自然环境地震安全组成。

除科学意义外，水库诱发地震研究还是水库地震安全研究的需求。就水库地震安全而言，由于首先注意到的是 1906 年美国旧金山 8.5 级地震等天然地震对水库大坝的破坏，因此该领域中首先关注的是天然破坏性地震对水库大坝安全影响研究，即大坝地震安全研究。20 世纪中叶，由于在新丰江等水库相继发生 6.1 级诱发地震，对水库大坝产生影响，之后开展了水库诱发地震及其对大坝地震安全影响的研究。但水库诱发地震可能对水库周围社会和自然环境的地震安全影响一直未得到重视。

20 世纪初，旧金山 8.5 级大地震对震区一些水库大坝产生破坏，提出了水库地震安全问题，当时人类水库建设处于初期，地震科学也还处于胚胎期，因此未得到充分认识。此后随着上世纪中叶水库建设迅速发展、巨型水库不断增多、建设国家不断增加，水库与人类生存关系日趋紧密，地震对大坝和水库地震安全影响实例不断增加，水库地震安全问题也就日趋突出，同时随着地震科学技术发展，含水库诱发地震在内的地震对水库大坝的安全影响逐步得到重视。经过努力，水库大坝地震安全研究不断深入，相关研究技术不断发展，研究成果不断丰富。

地震科学经过近百年发展，目前尚处于探索研究时期。建立在地震科学基础上的水库诱发地震研究也才经历半个世纪，由于观测资料不足，至今对水库诱发地震的孕育过程缺乏了解，水库诱发地震机理处于争论阶段。近几年提出的灾害预警问题，在 2004 年印尼巨震海啸造成了巨大伤亡后，更加引起了国际社会重视，也对水库诱发地震研究提出更高要求。

就中国而言，由“西部大开发”推进的中国当前和今后一个时期大规模水电站建设不可避免地进入了地质构造复杂、构造稳定性较差的中国西部，水库诱发地震已经成为可能影响电站建设和运行安全的不可忽视的重要问题。根据破坏性水库诱发地震（$M \geqslant 3.5$，烈度 $I_0 \geqslant$ Ⅵ）影响的特殊性、复杂构造区发生破坏性水库诱发地震的可能性，为了进一步分析水库诱发地震震例和已有研究资料，研究

水库诱发地震活动规律、破坏性水库诱发地震孕育过程和发震机理，建立破坏性水库诱发地震构造物理模型，探索复杂构造区破坏性水库诱发地震监测及预警技术，作者2004年向云南省科学技术厅提出并申请了“复杂构造区水库诱发地震监测预警研究”科技攻关项目（2006SG01）。

“复杂构造区水库诱发地震监测预警研究”项目的研究目标是：实现系统研究水库诱发地震活动规律、破坏性水库诱发地震孕育过程和发震机理，建立破坏性水库诱发地震构造物理模型，设计云南澜沧江中下游梯级开发区水库诱发地震监测预警技术系统。项目2006年获云南省科学技术厅资助，由云南省地震局和云南华能澜沧江水电有限公司共同承担。

为了进一步推进水库诱发地震研究，作者在收集研究大量资料基础上，结合“复杂构造区水库诱发地震监测预警研究”项目的研究成果，编辑了本书。

本书是“复杂构造区水库诱发地震监测预警研究”项目成果之一，在内容上由世界水库建设与水库诱发地震、中国诱发地震的水库、世界其他地区诱发地震的水库、水库诱发地震机理研究四章构成。

（1）世界水库建设与水库诱发地震。回顾了20世纪世界和中国百米高坝水库建设的时间和分布特点、水库诱发地震灾害特点、水库地震安全问题及其研究技术，认为由于人类社会发展需要，人类水库建设速度不断加快、数量不断增加、大型水库比例不断增大，水库建设向地质构造复杂的地区发展，来自于天然地震和水库诱发地震的水库地震安全、水库诱发地震对大坝及水库周围社会的地震安全影响越来越明显。因此，人类对水库地震安全问题越来越重视，对水库诱发地震及其预警技术的科学研究，特别是水库诱发地震震例研究、引起水库诱发地震的主要因素、水库诱发地震成因机理、水库诱发地震预测等需求越来越大。

（2）中国诱发地震的水库。对中国28座水库资料进行了分类研究（包括震级分类、增强和减弱活动方式分类、确定属诱发地震活动和有争议的分类），其中包括诱发6.1级地震1座、诱发4.0～4.9级地震6座、诱发3.0～3.9级地震6座、诱发2.0～2.9级地震6座；认为有诱发地震活动的22座，有争议的6座；蓄水后库区地震活动增强的25座、蓄水后库区地震活动减弱的3座。对各水库按照水库工程性特点、蓄水前库区及其周围历史地震活动、蓄水后地震活动特点、库区地质构造特点、诱发地震的成因认识，分别进行了描述。

（3）世界其他地区诱发地震的水库。共不同程度地研究了16个国家的42座水库。其中对印度Koyna水库（Shivaji Sagar湖），美国Oroville、Mead 、Keowee水库，塔吉克Nurek水库，加拿大Manic 3、LG3水库，巴基斯坦Tabelar水库，澳大利亚Gordon和Pedder水库 等6个国家的9座水库（其中诱发大于6级地震1座、诱发5级多地震2座、诱发4级多地震2座、诱发3级多地震2座、蓄水后库区地震活动水平减弱的1座）从水库工程性特点、蓄水前库区及其周围历史地震活动、蓄水后地震活动特点、库区地质构造特点、诱发地震的成因认识，分别进行了描述。

（4）水库诱发地震机理研究。为了比对研究已有水库诱发地震影响因子和成因机理的认识程度，从目前认为是水库诱发地震的影响因素的水库规模（含坝高、库容等）、水位、水库地区天然地震活动水平、库区岩性、构造环境、断层性质、成因机理方面，对已有不同研究者的观点和结论进行了汇集、比对。根据本书70个震例所反映的实际资料，从地震地质的角度，提出并研究了水库诱发地震中的断层响应现象及其在水库诱发地震过程中的作用。根据部分水库的断层资料，提出了它们的概念性构造模型。从水库诱发地震时间过程角度，对水库诱发地震提出了新的划分。根据水库水位与诱发地震活动过程关系，提出水库蓄水以后的水位变化和后期地震活动（频度变化、震级变化）之间存在呼应关系。从水库库水重力机械作用（包括水库存续的静态重力作用，水位上升的加载和水位下降的卸载构成的动态性重力作用）和水库诱发地震活动过程关系角度，对水库诱发地震活动进行了划分。根据水库诱发地震中的断层响应、发生诱发地震水库的构造模型、库水重力机械作用在水库诱发地震活动过程中的作用，认为在静态、动态库水重力机械作用与库区不同性质的先存断层（包括小规模裂隙）的应力作用耦合关系下的断层破裂及其过程，是水库诱发地震及其活动过程的主要机理。提出了水库诱发地震的构造物理机理及其概念模型。

4. 本研究的新发现与创新

与过去的相关研究相比，本研究提出以下值得注意的问题：

（1）水库诱发地震过程中的断层响应现象。

（2）水库诱发地震时间分布特点的意义。

（3）水库蓄水以后的水位变化和后期地震活动（频度变化、震级变化）之间存在呼应关系。

（4）库水重力机械作用（包括水库存续的静态重力作用，水位上升的加载、水位下降的卸载构成的动态性重力作用）与先存断层（包括小规模裂隙）应力作用耦合关系下的断层破裂及其过程，是水库诱发地震的主要机理作用。

上述发现对进一步揭示水库诱发地震机理可能是十分重要的。在创新方面，本研究表现为：

（1）根据水库诱发地震时间分布特点，对水库诱发地震进行了新的划分。

（2）提出了断层性质与断层响应关系。

（3）从库水重力的机械性作用（包括水库存续的静态重力作用，水位上升的加载和水位下降的卸载构成的动态性重力作用）与在水库诱发地震过程关系角度，对水库诱发地震活动进行的新的划分。

（4）根据水库诱发地震中的断层响应、发生诱发地震水库的构造模型、库水重力机械作用与断层应力作用耦合关系，提出了水库诱发地震构造物理机理及其概念模型。

（5）根据水库诱发地震灾害的特点，提出了水库地震安全问题基本构成，对水库诱发地震灾害预警研究具有重要意义。

5. 关于本书的英文表述

在中国，水库地震安全研究开始于20世纪50年代末，包括当时的四川紫坪铺水库建设前期的龙门山断裂研究和三峡工程早期的构造环境和相关断层研究。此后的工作包括以活断层研究和地震危险性研究为内容的水库及其周围地区构造稳定性研究。这些工作首先是为拟建的水库选取一个地震安全性较高的场地，其次是评价水库大坝可能遭受的最大地震影响，其中主要是来自天然地震的影响。自1962年广东新丰江水库6.1级地震后，开始了水库诱发地震研究。因此，中国是开展水库地震安全和水库诱发地震研究较早的国家，经过过去四十多年努力，中国的科学家们在水库诱发地震研究领域取得了丰富的研究成果。

Chen和Talwani（1998）认为，自1962年新丰江6.1级水库诱发地震以后，中国已有18例4.8～2.2级水库诱发地震震例发生在不同地质构造带，对这些地震都有一些不同程度的研究，但大多数研究都是用中文编写的各种工程技术报告、期刊论文和书籍，而详细的英文研究成果很少。

为了让更多的研究者共享中国水库诱发地震研究和本书的研究成果，本书以英文形式编辑出版。

最后，用在水库诱发地震研究中作出重要贡献的印度科学家Gupta在20世纪90年代初出版的《Reservoir－Induced Earthquake》一书的前言结束语，结束本引言：“We close this introduction to RIS by quoting Allen（1982）‘from a purely economic point of view, not to speak of public safety, the problem of RIS deserves far more attention than it currently is receiving in most parts of the world’.”

本书献给已经、正在和将要为水库诱发地震研究作出贡献的人们！

Preface

The construction of reservoirs with dam height ≥100 m of the human race began in the early 20th century, and up to now it has lasted about 100 a. The large number construction has begun since the median 20th century.

According to I. C. O. L. D. in 1973, there were about 326 reservoirs with dam height ≥100m in the world, including 265 reservoirs finished and 61 reservoirs under construction. In 2003, there were about 670 reservoirs with dam height ≥100 m in the world, including 155 large reservoirs with dam height ≥150 m. The increasing rate of reservoirs with dam height ≥100 m was 11 annually during this period.

It is well known that the problem of reservoir – induced seismicity (RIS) has been paid attention since the occurrences of earthquake of *M*4. 7 occurred at Marathon Reservoir in Greece in 1938 and earthquake of *M*4. 6 occurred at Lake Mead in U. S. A. in 1939 (Ding, 1989; Gupta, 1992). The dam height and capacity of Marathon Reservoir is 67m and 0.67×10^8 m^3, the dam height and capacity of Lake Mead is 221 m and 375×10^8 m^3.

It was the first time that RIS was proposed by Carder (1945) for Lake Mead (Gupta, 1972). Since then, a number of RIS cases have been cited by Caloi (1966), Galanopoulos (1967), Adams (1969), Comminakis et al. (1968), Guha et al. (1968), Narain and Gupta (1968), Gupta et al. (1969), Rothe (1968, 1969 and 1970), Gough and Gough (1970), and others.

By the early 1970s, only over a dozen cases of RIS were reported (Gupta, 1992).

Up to 1986, statistics of 33770 reservoirs in 29 countries including China indicated 116 reservoirs which occurred RIS (Li, 1999).

Up to the early 21th century, more than 140 RIS cases were determined in the world(Yao, 2006), including 4 cases of $M \geq 6.0$, 36 cases of *M*4. 5 ~5. 9, 43 cases of *M*3. 0 ~4. 4, and 51 cases of *M*2. 0 ~2. 9. The RIS cases distribute in more than 30 countries, and more than 10 of them are found in China. It was reported that the RIS phenomenon occurred Sanxia Reservoir (Three Gorge Reservoir) in Hubei, China when the water depth approached 135 m.

The earthquake of *M*6. 1 occurred at Xinfengjiang Reservoir in Guangdong on 19 March 1962 is considered the first RIS case of $M \geq 6$ (Ding, 1989). During 5 years after Xinfengjiang earthquake, 3 other earthquakes of $M \geq 6$ occurred at Kariba Reservoir at Zambia – Zimbabwee Border, Kremasta Reservoir in Greece and Koyna Reservoir in Indian. These earthquakes caused large damages and economic losses. Therefor, much more attentions have been paid to the RIS study since the median of 20th century.

For a long time, the role of reservoirs in inducing earthquakes was not well understood untill the fluid injection investigation in early 1960's at Rocky Mountain Arsenal in Colorado, and the application of Evans (1966) on mechanism of inducing earthquakes by increasing fluid pressure which is the work of Hubbert and Rubey in 1959 (Gupta. 1992).

1. RIS Monitoring and Study in Last Half Century

A lot of monitoring works, basic studies and prediction technique studies in the RIS field have been carried out by the researchers in the world during the past half century. The major achievements are follows:

1.1 Monitoring of RIS

The earliest earthquake monitoring of RIS began in the Lake Mead area in 1938. Since the 1950s of 20th century, the RIS monitoring has been carried in most countries to determine seismological motion and earthquake dynamic parameters of RIS, and also to study the relationship among earthquake and water filling and geology. Beside the earthquake monitoring, the seismic stress dropping survey and hydro - pressure - breaking stress survey were carried at Menticello Reservoir of U. S. A. during the period of 1978 ~ 1980 by Zoback and Fletcher. Talwaini et al. surveyed the hydro - chemical composition at Menticello Reservoir etc. based on the relationship between earthquake spatial - temporal distribution and the hydro - chemical composition, they predicted two earthquakes of $M2 \sim 4$ (Hu, 1983).

The RIS monitoring in China began after the Xinfengjiang $M6.1$ earthquake in Guangdong occurred at the vicinity of Xinfengjiang Reservoir dam on 19 March 1962. After the occurrence of Xinfengjiang $M6.1$ earthquake the station network was set up in Xinfengjiang Reservoir area, which was renewed in the early 1980s and work today. The Chinese Hydroconstruction Design Code regulated that the RIS study and earthquake monitoring should be carried in the high dam construction area where there is large probability of RIS occurrence, geological condition is complex, and active faults are developed.

The Chinese RIS monitoring has processed following four periods in the last 40 years(Yang, 2000):

(1) The First Period of RIS Monitoring, which was characterrized by manual operations. Some monitoring stations were set up at Nanshui Reservoir in Guangdong in 1960s, Dahua Reservoir in Guangxi in 1980s, Yantan Reservoir in Guangxi and Tongjiezi Reservoir in Sichuan in 1990s.

(2) The Second Period of RIS Monitoring, named as unspecialized remote monitoring model, which was quoted from the technique for monitoring nature earthquake. For example. the monitoring networks during 1970s to 1990s at Long Yangxia Reservoir in Qinghai, Danjiangkou Reservoir in Hubei, Manwan Reservoir in Yunnan, Shuikou Reservoir in Fujian, etc.

(3) The Third Period of RIS Monitoring, which was specially manufactured by the Ertan Reservoir Monitoring Seismic Network Study in Sichuan and 5 ~ 9 stations were designed at Geyanhe Reservoir in Hubei, Long yangxia Reservoir in Qinghai, etc.

(4) The Fourth Period of RIS Monitoring, is characterized by the establishment of Sanxia Reservoir - Induced Seismicity Monitoring System in Hubei, which is composed of seismology and deformation and underground fluid monitoring techniques. It has also been used at Xinuodu Reservoir, Xiangjiaba Reservoir, and Baihetan Reservoir.

1.2 RIS Study

Accompanied with the RIS monitorings, a lot of basic studies were also carried out, including special studies for some reservoirs, RIS cases investigations, the RIS characters and genesis studies.

(1) RIS Case Reports and Special Studies for Some Reservoirs. Up to date there are many research articles for some reservoirs. These reservoirs include Bhatsa Dam in India; Lake Mead, Oroville Reservoir, Clark Hill Reservoir, Lake Keowee, Lake Jocassee, Manticello Reservoir in U. S. A.; Lake Kariba, at Zambia - Zimbabwe bonndary; Lake Kremasta in Greece; Lake Benmore in New Zealand; Lake Marathon in Greece; Carmo do Cajuru Reservoir (Porto Colombia dam, Volta Grande Dam), Marimbondo Reservoir in Brazil; Osman Sagar Reservoir, Bhakra Dam and Koyna Dam in Indian; Toktogul Reservoir in Tadijk; Aswan Dam in Egypt. There are also some research articles or data for 28 Chinese reservoirs, including Xinfengjiang Reservoir and Nanshui Reservoir in Guangdong; Dahua Reservoir and Yantan Reservoir in Guangxi; Shenwo Reservoir in Liaoning; Danjiangkou Reservoir, Qianjin Reservoir and Panjiakou Reservoir in Hubei; Shiquan Reservoir in Shanxi; Manwan Reser-

voir and Dachaoshan Reservoir in Yunnan, Shuikou Reservoir in Fujian, Tongjiezi Reservoir, Ertan Reservoir and Daqiao Reservoir in Sichuan, Geyanhe Reservoir and Sanxia Reservoir in Hubei, Zhelin Reservoir in Jiangxi; Dongjiang Reservoir and Huangshi Reservoir in Hunan; Wujiangdu Reservoir, Dongfeng Reservoir and Yinzidu Reservoir in Guizhou; Wuxijiang Reservoir and Shanxi Reservoir in Zhejiang; Kezier Reservoir in Xinjiang; Longyangxia Reservoir in Qinghai; Jiangkou Reservoir in Chongqing.

Generally, there are more study materials for the reservoirs which are in large scale or induced larger earthquake ($M \geq 4.0$). The reservoirs include Chinese Xinfengjiang Reservoir in Guangdong, Danjiangkou Reservoir in Hubei, Shuikou Reservoir in Fujian, Sanxia Reservoir in Hubei; Lake Mead, Lake Kariba, Koyna Dam, Oroville Reservoir, Lake Jocassee, Manticello Reservoir, Nureck Reservoir etc in other countries.

A lot of these study articles concern the characters of post - impoundment seismicity and the relationship between seismicity and water level. The detail geological data of reservoir are comparatively few.

(2) Comprehensive Studies on the Characters of RIS Mechanism. Beside of the studies on the special reservoirs, some comprehensive studies on characters of RIS genesis and mechanism are also reported. Their representations include:

The book of "Reservoir - Induced Earthquakes in China" in Chinese was authored by State Seismological Bureau of CHINA in 1983, containing 22 articles that study eight chinese reservoirs including Xinfengjiang Re servoir, Danjiangkou Reservoir in Hubei, Zhelin Reservoir in Jiangxi, Qianjin Reservoir in Hubei, Nanshui Reservoir in Guangdong, Wujiangdu Reservoir in Guizhou, Wuxijiang Reservoir in Zhejiang, Huangshi Reservoir in Hunan. The geological conditions, classification, genesis and mechanism of RIS cases in China were also analyzed in the compiling book.

Another Chinese book of "Reservoir - Induced Earthquakes" was published in 1989, in which 41 RIS cases were introduced, including 20 cases of Asia (7 cases of China), 10 cases of European, 4 cases of Africa, 7 cases of North America, 4 cases of Australia, 3 cases of seismic decrease (Ding, 1989).

In 1992, the book of "Reservoir - Induced Earthquakes" was published, in which 41 RIS cases were also introduced, and the characteristics and mechanism of RIE were discussed (Gupta, 1992).

Beside of the books, some comprehensively specialized articles on RIS have also been published. For example:

Gupta H. K. and Rajendran K., Large water reservoirs in the vicinity of the Hymalaya Foothills and reservoir - induced seismicity.

Chen L., Talwani P., Reservoir - induced seismicity in China.

Assumpcao M., et al., Reservoir - induced seismicity in Brazil;

Simpson D. W., et al., Induced seismicity study in Soviet Central Asia.

Ohtake M., Seismicity change associated with the impounding of major artificial reservoirs in Japan.

Baecher B. G and Keeney R. L., Statistical examination of reservoir induced seismicity.

Gupta H. K. and Rastogi B. K., et al., Common features of reservoir associated seismic activity.

Bock G., Load - induced stresses and their relation to the initial stress field.

Talwani P. and Rastogi B. K., Mechanism for reservoir induced seismicity. Earthquake Notes.

Roeloffs E. A., Fault stability changes induced beneath a reservoir with cyclic variations in water level;

Rothe J. B., Fill a lake, start an earthquake.

Kisslinger C., A review of theories of mechanisms induced seismicity.

Hubbert M. K. and Rubey, W. W. Role of fluid pressure in mechanics of overthrust faulting.

Simpson D. W., et al., Seismicity changes associated with reservoir loading.

Stuart - Alexander D. E., et al, Impoundment - induced seismicity associated with large reservoirs.

Castle R. O., et al., Tectonic state: its significance and characterization in the assessment of seismic effects associated with reservoir impounding.

2. Problems on RIS Study

Although much more progresses have been achieved in RIS study, and much more knowledges on RIS have also been obtained, some important problems exist still in RIS study.

2.1 RIS Study in the Initial Period of the Datum Accumulation

It was proposed that we know few about why RIS occurred and cann't be sure the reservoirs which may induce earthquakes (Allen, 1980; Hu, 1981).

In 1983, a cursory section on induced seismicity in a publication of the U. S. National Academy of Sciences, which concerned the dam safety, stated that there is a question of whether a reservoir may induce earthquakes. To date there is no universally accepted proof that this can occur, but it is possibale that should be given consideration (Gupta, 1992).

Hu (1983) pointed that although the RIS study gets some progresses recently, but it still in the period of datum accumulation. More work should be carried out in detail monitoring and study for RIS cases to accumulate abundant and accurate data. It is very important to develop the RIS research.

Gupta (1992) stated that the phenomenon of RIS is not yet fully understood. Frequently asked questions are how to assess the potentiality of reservoir – induced earthquakes at a given reservoir site, and what would be the magnitude of the largest induced earthquake. During the past three decades, some knowledges on RIS had been gained, but there still are a lot on RIS to be learned.

Yi (2003) stated that the RIS has been studied in world after occurrences of some damage RIS earthquakes during 1960s. The studies during this period were majored in geology, seismology, physical mechanism of RIS and techniques of risk evaluation and prediction of RIS. However, RIS studies were silent and a few articles were published after the late of 1980s.

Chen (2004) concluded that the RIS is a complex problem. It belongs to a new item of earthquake study. RIS is still in the scientific search period in the world. It can't be predicted accurately today.

2.2 The Inducing Factors of RIS and Their Complex Relationships

Sun (1996) stated that the RIS is controlled by the numeral factors. She made the statistic analysis to 22 states of 6 factors, which include water depth, capacity, stress regime, fault activity, petrology and historic seismicity.

Li (1999) stated that water filling can not merely induce earthquakes, but can decrease seismicity in certain geological conditions. It should be necessary to study these phenomena. It is difficult to investigate the detail geological environment of a reservoir. Therefore, it should be careful to analyze the geological data in the reservoir area in order to conclude the geological characteristics of RIS practically.

It has been generally accepted that there are relationship between RIS and geological structure of reservoir. It is concluded, however, that the numerous studies on geological environment of RIS were summarized in the large region, and majored in regional fault dynamics, petrology, tectonic stress regime and seismicity. Some basic questions are still waited to answer. The more attention should be paid to the comprehensive studies on the characters of reservoir construction, and geological structures and environment in order to find the major factor of RIS among the reservoir construction characters, strata feature, geological structures and tectonics, underground water and stress conditions (Yi, 2003).

2.3 Unclearness of RIS Mechanism

The genesis and mechanism of RIS have been in argument in the last half century because there were no concord knowledge on RIS occurrence and its progress.

Yu (1984) reported the numerous different suggestions on RIS genesis based on regional geological background, hydrogeological condition of reservoir, water actions and earthquake activity.

Li (1984) concluded that the different RIS progress should be evaluated by different RIS genetic idea. The occurrence and progress of RIS should be depend firstly on geological condition and strain energy accumulation, secondly on water load pressure and pore – pressure and others including earth rotation.

Yi (2003) stated that there are different opinions on RIS mechanism. The interactions between reservoir and geological environment should be very complex. The water load, pore – pressure, softening and lubricating of fault plane under the action of underground water are critical to RIS occurrence. However, which one should be the most key factor to RIS is still puzzle upto now.

2.4 Lack of Effective Techniques for RIS Prediction

The social need for RIS prediction has appeared since RIS problem occurred. Up to now a lot of efforts have been made in the search of the long – period prediction technique.

Talwani (1997) pointed out that despite the progress attained in explaining the mechanism of RIS, it is not possible to predict the future occurrence of reservoir – induced seismicity because of the practical difficulties in accurately mapping the rock beneath the reservoir, key parameters such as in situ stresses, permeability of the rock masses and geometry of fracture system can't be deter mined.

According to Yi (2003), the major research results of RIS prediction include follows:

The possibility of RIS was evaluated by means of study on rock petrology and its permeating condition, and geological stability (Hu, 1979).

In 1979 and 1982, Packer and Baecher suggested probability method of RIS prediction, which use the data of water depth, capacity, stresses regime, fault activity, petrology in the reservoir area.

In 1984, Hu stated that the geological background and tectonic conditions of RIS are similar to nature earthquakes. The study idea and method, and prediction experience on nature earthquakes can be used to predict RIS. The reservoir action and hydrogeology were considered to be the main factors in RIS prediction.

In 1989, Chang suggested the indistinct judge theory of RIS.

In 1995, Huang and Xu suggested the nerve net model of RIS prediction.

In 1995, Wang suggested the multiple factor method of prediction for RIS by means of rock structure and vertical hydrogeological zoning.

In 2000, Xia suggested the program and method of RIS risk evaluation by means of engineering geology, which is the comprehensive study of regional engineering geology, tectonics, hydrogeology and seismology.

In 2001, Zhang summarized the numerous RIS prediction methods and classified the methods into certain predition and uncertain prediction.

In 2003, Yi stated that RIS study is still in the period of datum accumulation and cases comparing search, there still are not good theory and method to predict RIS risk.

Based on above introduction, the reason of occurrence of different RIS prediction ideas should be that the study on RIS genetic factors and mechanism has been in the search period.

3. Major Endeavors of This Book

The reservoir seismic safety (RSS) from RIS is the key problem that RIS study should answer (Mao et al., 2007).

The initial RSS problems were noted in dam damages caused by some large nature earthquakes such as San Fracisco Earthquake of $M8.5$ on 18 April 1906. The dam seismic safety from nature large earthquake has been studied since then. By the median of 20th century, some reservoirs including Xinfengjiang Reservoir induced damage earthquakes and caused dam damage. Therefore, to study the dam seismic safety from RIS was suggested.

The reservoir construction and earthquake science were in the initial period when the RSS problem faced after San Fracisco Earthquake of $M8.5$ in the early 20th century and the RSS problems were not completely noted. In the median 20th century, the rapid reservoir construction began so that the numbers of large reservoirs and reservoir construction countrys increased. The large construction rate results in the relationship between reservoir and human life was close more and more. RSS cases increase sharply. Consequently, the RSS problem has been obvious day by day. The seismology techniques were developed, causing more attention to RSS from not only the nature earthquakes but also the RIS. More and more RSS study techniques and study results have been gotten by the efforts of globle researchers.

Scientific earthquake study only experiences one century and still in the exploring period. The RIS study which depends on techniques of studying earthquake only experienced half century. Because of lack of survey date, the genetic progress and mechanism of RIS are still in argument. The prediction of disasters which was suggested recently and emphasized by the large earthquake and tsunami occurred in 2004, suggesting new requirement to RIS study.

This book is authored by collecting studing results in order to improve the RIS study on the base of the previous and recent studies. This book is composed of four chapters.

(1) The Chapter 1, Globle Reservoir Construction and RIS Disasters, summarized the data and distribution characters of construction of high dam reservoir in China and other countries, the RSS problem and its study technique, and RIS disaster features. It is concluded that the rate and numbers of large reservoir construction are increasing with the needs of social development. The reservoir construction has enterred the regions where the conditions of tectonics and seismology are complex. The risk of RSS from nature earthquakes and RIS, and the safety of reservoir and society in the reservoir region become more serious. The needs of study and prediction for RIS disasters have became very important.

(2) The Chapter 2, Reservoir of RIS in China, described the character of dams and reservoirs, historic seismicity, reservoir - induced seismicity, tectonic environment, and knowledge of RIS genesis of 28 reservoirs in China.

(3) The Chapter 3, Some RIS Reservoirs in Other Countries, shown some data of 42 reservoirs in 16 countries. Nine reservoirs from six countries are studied in the features of dams and reservoirs, historic seismicity, reservoir - induced seismicity, tectonic environment, and knowledge of RIS genesis. The nine reservoirs include Indian Koyna Dam (Shivaji Sagar Lake), Oroville Reservoir, Mead Reservoir and Keowee Reservoir in U. S. A., Nurek Reservoir in Tadijk, Manic 3 and LG. 3 Reservoirs in Canada, Tabelar Reservoir in Parkistan, Lake Gordon and Lake Pedder in Australia.

(4) The Chapter 4, Mechanisms Research of RIS, collected and compared the former research results of RIS genetic factors which include reservoir scale, water level, seismicity background, petrology, tectonics, fault property, and hypothesis of RIS mechanism. Based on the data of 70 RIS cases which are studied in this book, the following research conclusion are shown:

The faulting response in RIS processes and its role in RIS progresses are suggested in terms of seismogeology.

Based on the data of some RIS reservoirs, their conceptual fault models are sketched.