三峡坝区
水库诱发地震研究
——茅坪钻孔的现场测试与分析

·李方全　张伯崇　苏恺之　等

地震出版社

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李方全　张伯崇　苏恺之 等著

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内 容 提 要

本书为三峡工程坝区水库诱发地震研究的论文集。第一部分主要论述茅坪 800m 深钻孔中各项原地测量的方法和结果；第二部分主要是关于岩石力学实验室研究和断层滑动准则的论文；第三部分是在原地应力测量结果的基础上进行的应力场数值分析的有关论文；第四部分是以原地应力测量结果为基础，用断层滑动准则讨论水库蓄水后不同深度诱发地震的可能性。

本书可供三峡工程设计、科研单位参考，也可供水利、水电部门设计科研单位、高等院校有关专业教师、研究生以及关心三峡工程的人士们阅读参考。

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长江三峡工程坝址附近地壳应力状态及其随深度的变化，不仅是三峡水库诱发地震研究中的重要内容，而且也是研究该区构造应力场和区域地壳稳定性的重要资料。三峡工程地质、地震问题专家组经论证，为了解深部应力，钻孔至少应为800m，最好更深。国家地震局地壳应力研究所李方全和张伯崇两位研究员领导的课题组，经过几年的努力，在茅坪花岗岩体内800m深的钻孔中作了全孔取芯、超声波井下电视全孔照相、井径和井温测量、水压致裂应力测量、初始孔隙水压力测量和渗透率测量，取得了坝址附近地下深部的丰富资料。他们还进行了岩石摩擦性状和孔隙水压力影响的实验室试验和地应力场的数值分析等项工作。在上述实测数据和实验数据的基础上，对三峡水库蓄水诱发地震的可能性进行定量化评价。他们的工作为三峡水库诱发地震的评价提供了重要资料和宝贵意见。这里汇编出版的有关各项研究工作的成果，不仅对三峡工程的设计和决策提供了重要依据，也为其它大型水库诱发地震的预测提供了一个良好的范例。这本文集无论在原始资料的提供、研究问题的思路与方法上的论述都极富科学价值，值得有关专业人员和关心三峡工程的人士阅读和收藏。

茅坪花岗岩体内800m深钻孔中水压致裂原地应力测量的结果表明：地下294m以上，水平较大主应力为最大主应力，垂直主应力为最小主应力，而且水平较大主应力偏高，水库蓄水后，可能在一些方向有利的小断层或节理面上出现局部逆断层滑动而导致小的地震活动；在294—708m深度范围内，由于在577—592m深处存在破裂带，应力随深度的分布相当离散，但总的趋势是水平较大主应力为最大主应力，水平较小主应力为最小主应力，这种应力状态有利于走向滑动，但根据实验室得到的断层滑动准则，上述实测应力状态在水库蓄水后尚不致引起小断层或节理面的走向滑动；708m以下，应力随深度变化较有规律，总体上是垂直主应力为最大主应力，水平较小主应力为最小主应力，这种应力状态有利于正断层型的滑动，按800m以上实测数据线性回归，约900m以上的应力状态在水库蓄水后不致产生正断层型滑动。但在约900m以下，若应力按800m以上测量数据线性回归并向深部外推，则水库蓄水后在产状有利的断层或节理面上将产生正断层类型的滑动。

本文集第13篇文章中提出了应力随深度变化的规律是否可以外推到800m以下的深度是一个重要问题。由于破碎带的干扰，294—708m深度段内应力随深度变化相对离散，在临近800m深度的几个测点上数据才刚刚趋于稳定。文章作者建议在三峡水库修建前将原有800m深钻孔加深到1500m，以便了解应力随深度变化的规律，并进一步测定孔隙水压力值，这是一个值得重视的建议。尽管现在估计800m以下的深度不致有较大的产状适合的大断层或节理带存在，但外推应力状态可能使产状有利的正断层活动也是不容忽视的问题。

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名誉所长、研究员　胡海涛

前 言

本文汇集了国家"七五"重大攻关课题"长江三峡水库诱发地震研究"中的子课题"三峡工程地应力、孔隙水压、渗透率现场测试"（课题编号 16-2-3-3）研究的主要成果.

三峡工程地质、地震专家组第二次扩大会议记要强调指出:"鉴于地应力测量和地应力研究不仅是水库诱发地震研究中的重要内容，且对地质与地震课题中其它专题也有重要意义，应作为重点加强研究."

由于经费限额，测点数量和测量深度存在矛盾. 在 1987 年 12 月 3 日召开的地应力测量技术方案专家论证会上，多数专家认为，为了取得可靠的应力状态数据，钻孔深度至少应为 800m，重点应放在对大坝安全构成影响较大的坝址附近. 课题任务书要求：在钻孔中应进行超声波井下电视全孔照相；用水压致裂法进行地应力测量，测量段争取达到 10 段；选择不同方向裂隙带进行 4 段左右孔隙水压力绝对值测试；采用压水法进行两段渗透性测试；在钻孔中安装孔隙水压测量仪，进行孔隙水压力连续相对观察；进行综合研究，提出"三峡工程重点地段地应力、孔隙水压力、渗透性现场测试综合研究报告".

根据任务要求，为了研究拟建的三峡水库坝址（三斗坪）区附近水库蓄水后诱发地震的可能性，我们在拟建坝址上游（库内），距坝址约 1.8km 的茅坪镇钻了一口深度为 800m 的钻孔. 在钻孔中不同深度进行了 16 次水压致裂法原地应力测量；进行了 6 个层位的孔隙水压力绝对值测量；用瞬时压力法及压水法进行了 5 段渗透率测试；同时还进行了全井井径测量、超声波井下电视全井照相及全井井温观测；并在钻孔中安装了孔隙水压测量仪进行孔隙水压力变化的连续观测.

为了根据实测的原地应力状态估计水库蓄水后诱发地震的可能性，进行了应力场的计算和断层滑动准则的研究. 我们测试了库区的三种主要岩石（花岗岩、灰岩和砂岩）的力学参数，并对三种岩石的摩擦性状和孔隙水压的影响进行了试验研究，试图据此确定天然断层或其它不连续面的滑动准则. 我们还利用茅坪钻孔的花岗岩岩芯进行了声发射凯赛效应测量，并用此法测得的垂直向主应力与静岩压力计算的结果作了对比.

我们还进行了坝址附近地质构造条件、区域水文地质及区域构造应力场的研究，搜集了有关资料并进行了野外地质考察.

在对上述成果进行综合研究之后，我们主要根据原地应力测量、孔隙水压及渗透率测量的结果，也结合岩石力学试验、坝址附近应力场的数值模拟结果及测量点附近的地质构造条件，对三峡水库坝址区附近蓄水诱发地震的可能性进行了讨论.

虽然本文集中所发表的仅仅是"一孔"之见，然而这是建立在非常宝贵的实测资料基础之上的，我们认为这些资料无疑对三峡水库诱发地震的研究是很有意义的.

本研究工作得到三峡工程地质、地震专家组、国家科委工业局、地矿部环境司、国家地震局震害防御司、国家地震局地质所以及国家地震局地壳应力研究所领导的大力支持和帮助，在此谨致谢意. 在本研究工作进行中、报告及文章编写及修改过程中得到很多专家的指导和帮助，在此一并致以衷心的感谢.

李方全　张伯崇　苏恺之

A brief introduction to 《Reservoir Induced Earthquake Risk in the Yangtze Gorges Dam Area —In Situ Tests in Borehole at Maoping and Analysis》

This volume represents an assessment of reservoir induced earthquake risk in the Yangtze Gorges dam area on the bases of in–situ stress measurements, pore–fluid pressure and rock permeability tests, as well as experiment of rock mechanics. All the site testing and experiment data have been collected in this book. The work was supported by the National Committee of Science and Technology as one of the important research projects of the National Seventh 5–Year Research Plan (No.16–2–3–3).

The physical mechanism of reservoir seismic inducement, so far, is still a problem waiting to be further explored. One emphasizes the role of reservoir water loading that might change the pre–existing stress state underneath so that give rise to earthquakes. While the other suggests seismicity might be induced by reduction of the effective normal stress acting on some pre–existing weak planes, caused by the pore–fluid pressure increase due to reservoir impoundment. Numerical modelling of the stress field due to reservoir loading has demonstrated that the stress changed only at very shallow part underneath the reservoir. Many evidence show that pore–water pressure increase due to reservoir impoundment should be the main cause of seismic inducement. On this consideration, in the first part of the book the authors described the method and techniques used for engineering site testing at a 800m depth drillhole near Maoping and their results. The second part discusses a study on the fault slip criteria,as it is necessary for assessing fault stability when the stress state on the fault plane is known. The third part of this book describes the numerical modelling of the regional stress field, with a brief introduction to the regional geological structure. The finite element and boundary element methods used here are also discussed. Finally, the authors came to a discussion on risk of reservoir induced earthquake in the Yangtze Gorges dam area.

Rock Friction Behavior and Fault Slip Criteria

According to the Coulomb criteria, the shear strength of a plane of weakness (or, of a fault) with zero cohesion is given by

$$\tau = \mu S_n \tag{1}$$

where τ is the shear strength of the plane, μ is the coefficient of sliding friction, and S_n is the normal stress acting on the plane. It can be expressed in terms of effective principal stresses. In this case, the ratio of effective principal stresses $(S_1 - P_o)/(S_3 - P_o)$ is given by

$$(S_1 - P_0)/(S_3 - P_0) = [(\mu^2 + 1)^{1/2} + \mu]^2 \tag{2}$$

where S_1 and S_3 are respectively the maximum and minimum principal stresses, and P_0 stands for pore fluid pressure. The intermediate principal stress, S_2, here is assumed to be acting parallel to the fault plane and at right angle to the direction of shear. The normal line of the weak plane favourably oriented makes an angle, ψ, with the axis of S_1, and the value of ψ is determined by

$$\psi = \frac{1}{2}(\pi / 2 + \tan^{-1}\mu) \tag{3}$$

Based on various rock experimental data, J.Byerlee suggested that $\tau = 0.85\ S_n$ for rocks under moderate stress (S_n less than 200 MPa). For fault planes with little gouge, this value may be appropriate to valuating their strength; however, for those with thick gouge, their strength should be lower than the high values of experimental results. For instance, a double-shear friction experiment with the Laxiwa granite showed that the friction strength was given by $\tau = 0.66\ S_n$ when the sliding surface possessed clay gouge or rock powder; or, $\tau = 0.66(S_n - P_o)$ if the effective stress was taken into consideration (B.Zhang et al., 1988).

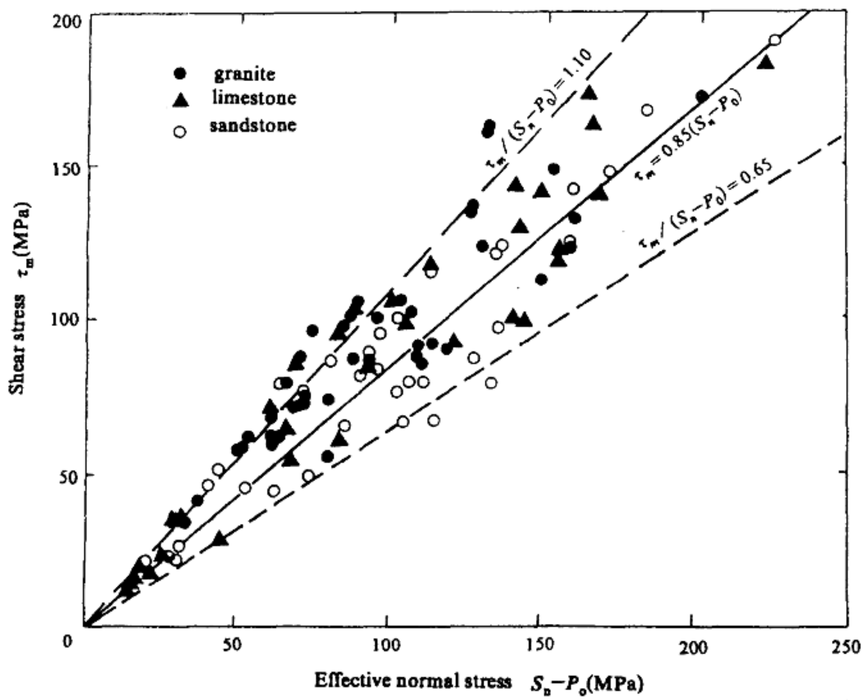

Fig.1 Data of triaxial friction experiment with three type of rock samples taken from the Yangtze Gorges engineering area. The friction coefficients are also given.

Three types of rock samples taken from the Yangtze Gorges area have been studied by triaxial friction experiment and the results are given in Fig.1. The maximum friction coefficient varies from 0.65 to 1.10, and the average taken to be 0.85. From the above, the authors suggest that the fault slip criteria of this area can be given as

$$\tau = \mu(S_n - P_o) \quad , \tag{4}$$

and $\quad 0.65 < \mu < 0.85$.

i.e. taking the friction coefficient $\mu = 0.65$ as the lower limit, and $\mu = 0.85$ as the upper limit.

In–Situ Stress State and Fault Stability Assessment

In–situ stresses have been measured in a 800m drillhole at Maoping in the engineering area, by using hydro–fracturing technique. The results are summarized in Fig.2. As shown, the maximum and minimum horizontal principal stresses S_H and S_h have been determined at different depths by using hydrofrac technique. The linear relation of the stresses increase with depth has been regressed using the least square method with the measuring data. The vertical principal stress S_v was calculated as the geostatic (overburden) pressure.

It can be seen from Fig.1 that in the shallowest part above 294m in depth, the three principal stresses show a relation as

$$S_H > S_h > S_v$$

that is a stress state in favour of reverse faulting. But in depths of 294m—708m, the relation becomes

$$S_H > S_v > S_h$$

that is favourable for strike–slip. While in the region below 708m in depth, the stress relation is in favour of normal faulting, i.e.

$$S_v > S_H > S_h \quad .$$

Based on these measuring results, fault stability has been discussed in this book by delineating approximately the critical area of stress required for initiating different types of faulting.

1. Reverse faulting

As mentioned above, in the shallowest part (above 294m), the minimum principal stress is S_v , which is calculated as the geostatic pressure and the result is coincident with that obtained by sample test using the Kaiser effect. The initiation of reverse faulting requires S_H to reach a critical value which is determined here by the friction coefficient and pore fluid pressure. In Fig.2, the critical area of S_H required for reverse faulting before reservoir impounding is delineated as the doted area by taking $\mu = 0.65$—0.85, and P_o equals the hydrostatic pressure. However, the pore fluid pressure will increase during and after reservoir impoundment. The shaded area in Fig.2 represents the critical values of S_H required when the water level of the reservoir reaches 150m and P_o increased by 1.5 MPa correspondingly.

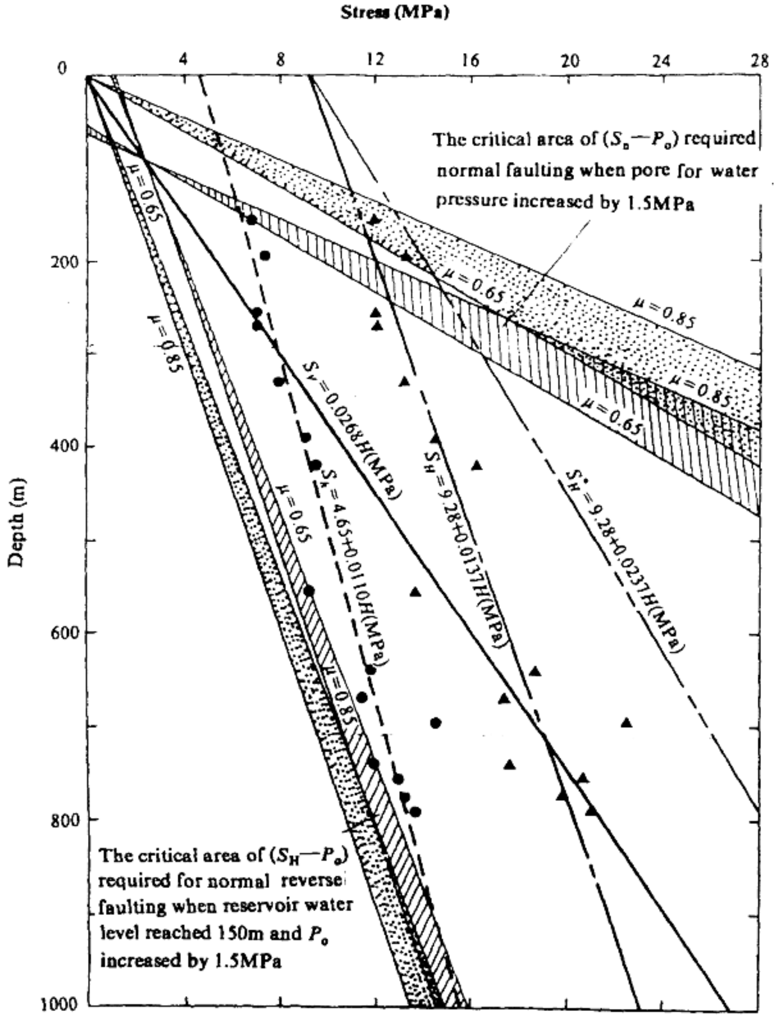

Fig.2 Data of in–situ stress S_H(black circles) and S_h(delta) measured at Maoping 800m drillhole. Their linear relation of stress increase with depth are also given. The critical areas of stress required for normal and reverse faulting are delineated as the doted and shaded zones. See text for the details.

2. Normal faulting

At depths below 708m, S_v becomes the maximum principal stress, and the initiation of normal faulting requires the horizontal minimum principal stress to be less than a critical value as shown by the doted and shaded areas on the lower left in Fig.2, for the two cases before and after reservoir impoundment, respectively.

3. Strike–slip faulting

The stress relation at depths between 294m–708m is in favour of strike–slip. To discuss the stability of faults or weak planes in this region, the authors use a graphical method as shown in Fig.3. The maximum and minimum effective stresses, $(S_H - P_o)$ and $(S_h - P_o)$, are used to draw the Mohr's stress circles to represent the stress state of some measuring points that are considered as the "most dangerous" points that have been found. The critical area of stress required for fault slip is delineated as the doted zone by using the frictional sliding criteria given before. Fault slip would occur on favourably oriented weak planes when the stress circles reached the critical area.

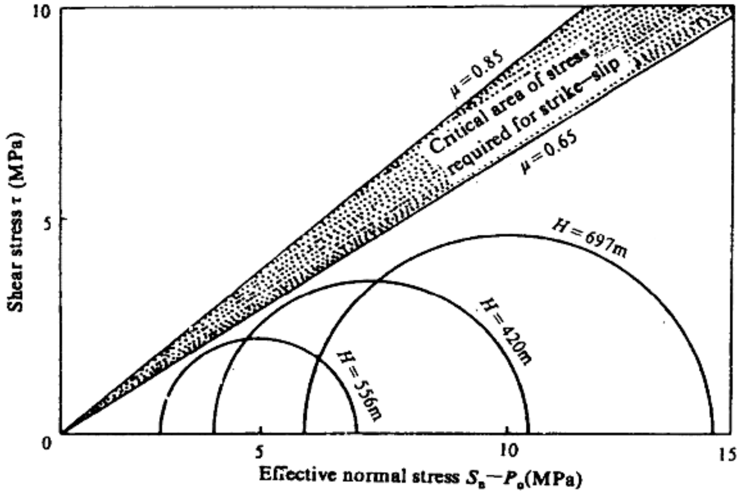

Fig.3 The critical area of stress required for strike–slip, and the stress state measured at depths given by H. See text for the details.

From the above, the authors come to a discussion on the fault stability and earthquake risk that induced. Firstly, after reservoir impoundment, micro–seismicity may be induced in the shallowest part of the engineering area by small reverse faulting on weak planes with low dip–angles (less than 28.5°) and NNE trending. Secondly, although the stress state at depths between 300m—700m is in relation favourable to strike–slip, the magnitude of the effective stresses would not reach the critical area shown in Fig.3. However, the stress variation with depth is scattered in the region between 450m—550m due to the existence of fracture zones. In this region, stress state of some individual points may reach the critical area required for mormal faulting after reservoir impounding, giving rise to small earthquakes. Below 700m in depth, the tendency of stress increase with depth is in favour of normal faulting, but the stress magnitude of most measuring points between 700m—900m may not reach the critical values during and after reservoir impounding, so that only small events may be induced occasionally. Finally, if the linear relation of stress increase with depth obtained in Fig.2 can be extrapolated down below 900m, then the general tendency is very likely to initiate normal faulting on those weak planes trending NWW with high dipangles greater than 61.5°.

An important problem is, just as the authors have pointed out, that both the stress magnitude and the detailed features of geological structure at depths below 1 km need to be further studied in this area.

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茅坪800m

钻孔中的现场测试

水压致裂应力测量及井温观测

李方全　祁英男　刘　鹏　毛吉震　张志国　张　钧

一、引　言

对于水库诱发地震，尽管对水的诱发机制有各种不同的看法，但几乎所有的研究都认为，地壳构造应力场的存在是产生水库诱发地震的基本条件。因此，研究构造应力场及其在蓄水前后的变化是研究水库诱发地震的一项十分重要的工作。

为了研究拟建的三峡水库坝址区在水库蓄水后诱发地震的可能性，我们在拟建坝址区附近的茅坪打了一深度约为800m的钻孔，进行了水压致裂应力测量、孔隙水压和渗透率现场测试，在钻孔中还同时进行了井径测量、超声波井下电视观测和井温观测。

三峡工程地质、地震专家组第二次扩大会议纪要强调指出："鉴于地应力测量和地应力研究不仅是水库诱发地震研究中的重要内容，且对地质与地震课题中其他专题也有重要意义，应作为重点加强"。1987年12月3日召开的地应力测量方案专家论证会进一步明确，地应力测量工作首先要为水库诱发地震的研究服务，其次也应考虑到地壳稳定性评价有关课题的需要。

这里主要介绍水压致裂应力测量的原理、方法及茅坪800m深钻孔的原地应力测量结果，并介绍了井温观测结果，最后对这些结果进行了讨论。

二、水压致裂应力测量

1. 水压致裂法应力测量的方法和原理

应力测量的方法很多，最常用的方法就是所谓的"套芯法"。但是，由于"套芯法"需要使用比较复杂的仪器来测量钻孔或孔壁的变形，因而测量深度受到限制。水压致裂是近年来发展起来的能够测量地壳深部应力的可靠而有效的方法。由于水压致裂法测量应力不需要"套取岩芯"，也不需要精密复杂的井下仪器，因此可以在深井中测量应力[1][2]。

目前这一方法的测量深度已达5100m。由于操作简便，且无须知道岩石的弹性参量，因此近年来其应用发展很快，取得了大量成果。利用水压致裂法原地应力测量资料研究深井注水或水库蓄水后断层或软弱带的稳定性，在国外已有几个成功的例子。如美国兰吉利油田注水和抽水控制地震的试验，以及蒙蒂西洛水库诱发地震机制的研究[3][4]。

(1) 水压致裂法地应力测量方法

水压致裂法测量钻孔中的应力，是利用一对可膨胀的橡胶封隔器，在选定的测量深度封隔一段裸露的岩孔，然后通过泵入流体对这段钻孔增压，压力持续增高直至钻孔围岩产生破裂，继续加压以使破裂扩展（图1）。压裂过程中记录压力、流量随时间的变化，根据压力时间曲线（图2）即可求出原地主应力的大小。主应力方位可根据印模确定的破裂方位而定。