冯志刚，韦国建，张汉猛，等. 西南某水电站断裂构造和层间溶蚀带组合岩溶渗漏研究[J]. 中国岩溶，2022，41(5)：728-735.
DOI: 10.11932/karst2021y33

西南某水电站断裂构造和层间溶蚀带组合岩溶渗漏研究

冯志刚[1,2]，韦国建[3]，张汉猛[3]，许 国[1,2]

(1. 南宁市勘测设计院集团有限公司，广西 南宁 530022；2. 南宁市浅表地质大数据工程技术研究中心，广西 南宁 530022；3. 中国能源建设集团广西电力设计研究院有限公司，广西 南宁 530007)

摘 要：西南某水电站坝址基岩为碳酸盐岩，坝区断层构造和岩溶较发育。水库蓄水后，坝址右岸抗力体1 315 m排水洞出现持续渗漏。随库区水位升高，涌水量逐渐加大至约1.9 $m^3 \cdot s^{-1}$，水库无法正常蓄水。为查明库水渗漏途径，有针对性地采取措施减少渗漏量，开展了岩溶渗漏研究。通过工程地质测绘、岩溶水文地质调查、钻探、压水试验、孔内电视、孔内电磁波CT等勘察手段，结合前期平硐、基坑开挖和物探等勘查成果，并利用灌浆孔灌浆过程试验数据，最终查明库水渗漏通道：在水压力作用下，库水沿断裂构造F_{12}下渗，在深部沿层间溶蚀带绕过防渗帷幕，呈30°倾角向下游逐步抬升，最终通过竖向岩溶发育带，从1 315 m排水洞地质薄弱点涌出。通过对灌浆帷幕采取补强措施，封堵了主要渗漏通道，库水渗漏得到有效控制，达到了设计要求。

关键词：岩溶；断裂构造；溶蚀带；补强灌浆；碳酸盐岩；渗漏

中图分类号：TV738; P642.25 **文献标识码：**A

文章编号：1001—4810(2022)05—0728—08 **开放科学(资源服务)标识码(OSID)：**

0 引 言

碳酸盐岩在我国尤其是西南地区广泛分布[1−2]，岩溶对工程建设产生了很多困扰[3−6]。在水利水电建设领域，岩溶渗漏是岩溶区最常见的库水渗漏形式，很多学者开展了相关研究[7−13]，在实际工程施工中，对岩溶渗漏采取必要的治理措施，取得了一些成功的经验[14−16]。

我国西南某水电站位于云贵高原斜坡地带，最大坝高167.5 m，正常蓄水位1 450 m。电站蓄水后，右岸抗力体1 315 m排水洞出现了多处涌水，且随库区水位升高，渗漏量逐渐加大至约1.9 $m^3 \cdot s^{-1}$，水库无法正常蓄水。如无法有效地减小渗漏量，将造成重大经济损失，因此，查明库水渗漏途径，及时采取措施对渗漏进行治理是非常必要的。

1 区域地质构造

水库工程区位于杨子地台之滇东—黔西台褶带中部(图1)，近场区规模最大的断层是F_{38}，长61 km，总体走向NW，略向SW凸成弧形。断层倾角40°~50°，倾向弧形内侧，断面光滑平直，断层破碎带一般宽数米。

2 坝区工程地质条件

2.1 地形地貌

坝址处河流流向25°~30°，河面宽20~33 m，坝址

基金项目：南宁市科学研究与技术开发计划项目(ZC20211003)；南宁市创新创业领军人才"邕江计划"资助项目(2020016)
第一作者简介：冯志刚(1979—)，男，博士，正高级工程师，主要从事岩土工程和特殊性土工程特性研究。E-mail: fengzhigang@foxmail.com。
收稿日期：2022—01—01

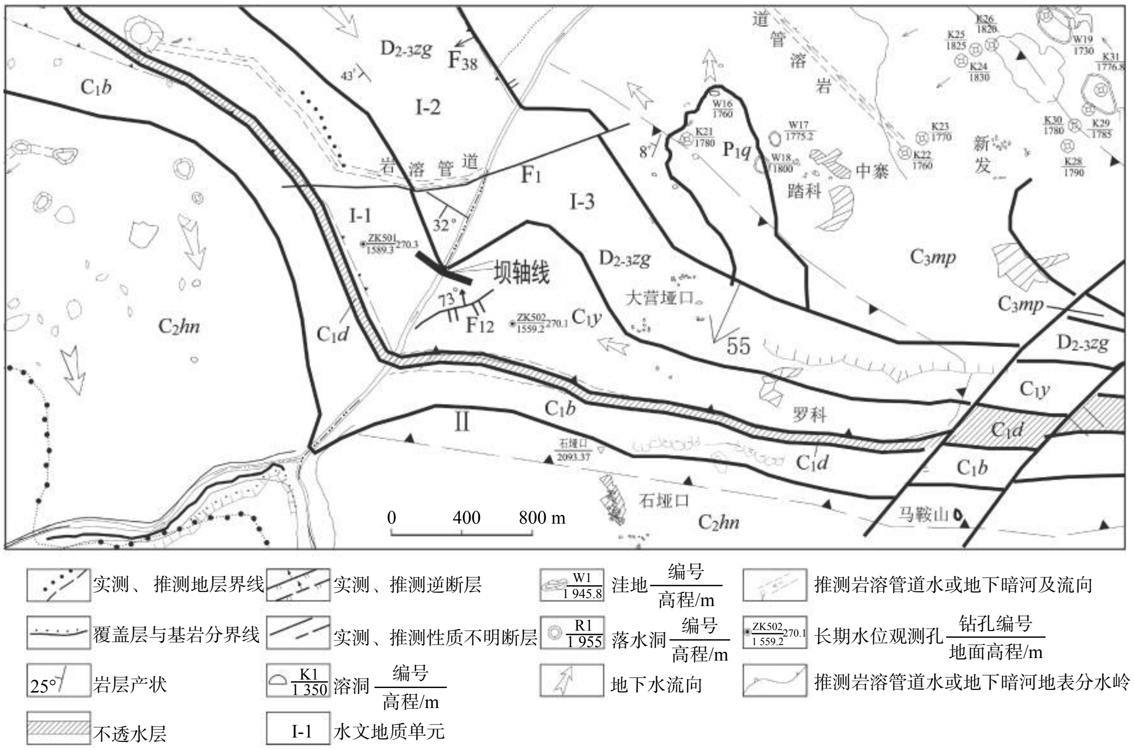

图 1　近坝区综合地质平面图

Fig. 1　Comprehensive geological plan near the dam area

区最高海拔大于 1 900 m，相对高差 600~750 m。河谷呈基本对称的“V”字型，两岸地形陡峭，坡度 30°~53°，部分库区陡崖连续分布。

2.2　地层岩性

坝址区主要出露石炭系和泥盆系沉积岩，其中，可溶岩为石炭系岩关组 (C_1y) 灰岩、泥盆系宰格群 ($D_{2\text{-}3}zg^{2\text{-}2}$) 灰质白云岩夹灰岩和 ($D_{2\text{-}3}zg^{2\text{-}1}$) 白云岩，非可溶岩为石炭系下统大塘组 ($C_1d$) 页岩、泥灰岩、砂岩互层，属相对隔水层。坝址区上游分布石炭系下统摆佐组 (C_1b) 灰岩、白云质灰岩和石炭系中统黄龙群 (C_2hn) 白云岩、灰质白云岩、灰岩。坝址区下游分布石炭系上统马平群 (C_3mp) 灰岩。

2.3　地质构造

坝址位于 F_{38} 断层南侧东西向构造带内，为轴向 NNE 的大水塘斜歪背斜北东端核部区域，平面上岩层呈“S”型平缓扭曲，岩层整体横切河流倾向上游。

3　水文地质特征

3.1　地表水

根据现场地质调查，除两岸近坝冲沟上段（高程 1 500 m 以上）见较明显水流痕迹外，其他地段未见地表水出露。

3.2　地下水

近坝区地下水类型主要为岩溶水，赋存于岩溶裂隙和管道中，受岩性、矿物成分、岩溶发育程度、构造等影响，地下水多以泉水、暗河形式出露。

根据坝区右岸 ZK502 钻孔地下水位长期观测结果，坝址右岸地下水位较低，枯水期地下水位略高于河水面，水力坡降 0.077，说明坝区右岸深部岩溶裂隙、管道连通性相对较好。

4　岩溶发育特征

4.1　地表岩溶

坝址区岩溶发育呈现峡谷区岩溶特征，坝址两岸上部 I 级夷平面分布有岩溶漏斗、洼地、落水洞等地表岩溶地貌，洼地直径一般为 50~200 m，深度一般在 10~50 m。坝址周边地表可见溶蚀裂隙、沟槽和溶穴等。

4.2　地下岩溶

前期平硐、钻探、基坑开挖和物探等勘查成果显示，河床及两岸分布较多溶穴、槽状溶洞和层间溶蚀，

按其延伸趋势推测它们是相互连通的。右岸地下岩溶大致从清水河边沿小断层向下游山体延伸，近岸附近呈近水平管道状。为查明库水渗漏通道，在坝址区开展了大量的钻探及物探工作，揭露了大量的溶蚀裂隙和涌水点（图 2，图 3）。

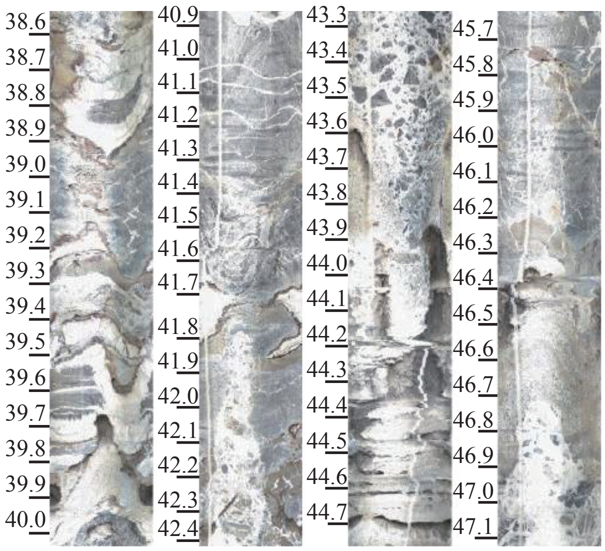

图 2 R1U55 孔深部岩溶裂隙发育情况

Fig. 2 Development of deep karst fissures in borehole R1U55

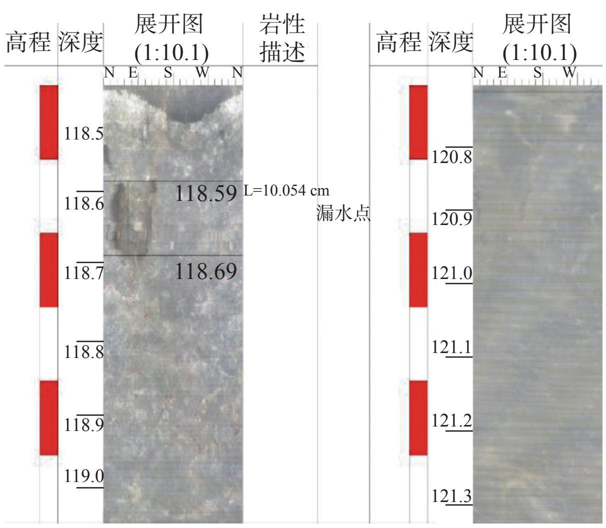

图 3 RBQ-5 孔内电视陡倾角裂隙涌水点

Fig. 3 Water inrush point of steep dip fissure in RBQ-5 borehole television

5 坝区右岸渗漏情况

当库水位上升至 1 325 m 时，坝区右岸抗力体 1 315 m 排水洞 HPR1（第一道横向排水洞）与 ZPR2（第二道纵向排水洞）交叉口以右约 22.0 m 位置，底板部位的地质薄弱点 Y2-1 开始冒浑水，之后 Y2-2、Y2-3 和 Y1 依次出水，一周后 Y3 开始涌水（图 4）。

随着库区水位迅速升高，大量泥质充填物从各涌水点涌出，之后水质逐步变清，渗漏量逐步增大。在库水抬升至 1 357 m 前后，对 Y1 和 Y2 设置反滤。后随库水位升高，依次出现 Y4-Y9 涌水点。库水位达到 1 357 m 时，Y3 涌水量大于 700 $L\cdot s^{-1}$。库水位基本稳定在 1 366.5 m 时，测得总渗流量约 1.9 $m^3\cdot s^{-1}$。

6 坝区库水渗漏途径

6.1 岩体渗透性

为了进一步查明坝区库水渗漏途径，在坝址右岸布置了 15 个钻孔，孔底高程在 1 133.3~1 249.9 m 之间。对坝基帷幕底高程以下进行了 121 段钻孔压水试验，统计结果见表 1，坝轴线处右岸岩体透水性分布示意见图 5。

试验结果表明，右岸坝基帷幕底高程以下，在 1 140~1 250 m 高程（孔深 150~180 m）范围内未发现连续 3 段以上 $q\leqslant 1$ Lu 的区域。坝基帷幕底高程以下 $q\geqslant 3$ Lu 渗透区域呈带状分布，主要分布于 1 200 ~1 260 m，q 值为 3~75 Lu，往右岸逐渐减小至 2~8.82 Lu。

6.2 勘查数据分析

为查明右岸库水渗漏通道，在右岸 1 293 m 和 1 340 m 高程灌浆排水洞的灌浆帷幕线一带布置检查孔，孔底高程 1 200 m 左右。采用压水试验和孔内电视等勘探手段，记录灌浆孔的简易压水试验数据和灌浆过程中异常情况。

6.2.1 1 293 m 灌浆排水洞勘查结果

压水试验实验中，布置的 8 个深部检查孔中有 7 个钻孔在 1 200~1 260 m 高程出现孔口涌水现象，表明在此高程范围存在与库水相连的溶蚀带。8 个检查孔均能正常灌浆，最大灌浆压力 3 MPa。未发现与下游 1 315 m 排水洞涌水通道存在水力联系。

6.2.2 1 340 m 灌浆排水洞勘查结果

在 1 340 m 高程布置了 6 个检查孔。在检 4 孔以左以 10 m 间距、以右以 2 m 间距布置了数百个灌浆孔，局部地段 2~3 排灌浆孔，并在灌浆过程中出现失水、掉钻、吕荣值明显变大等异常部位加密灌浆，并及时记录异常情况。勘查结束后通过对各钻孔数据进行整理分析，得出以下主要结论：

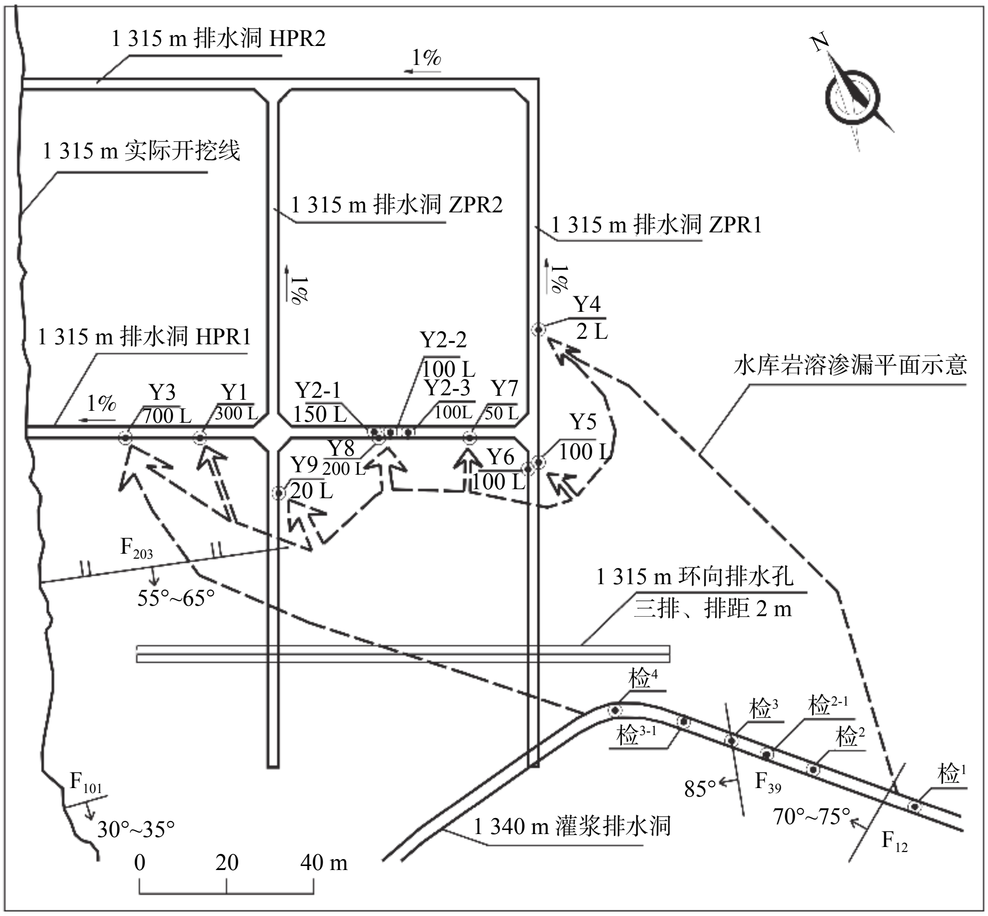

图 4　1 315 m 排水洞和 1 340 m 灌浆排水洞平面示意图

Fig. 4　Plane schematic diagram of 1,315 m drainage tunnel and 1,340 m grouting drainage tunnel

表 1　右岸坝基帷幕以下压水试验结果统计表

Table 1　Statistical result of water pressure tests under the right dam grouting curtain

序号	吕荣值q/Lu	试验段数	占比/%
1	≥3	28	23.1
2	1~3	79	65.3
3	≤1	14	11.6

（1）检 4 孔以左无大的构造断裂破碎带发育，灌浆孔在灌浆过程中，大部分孔无失水、掉钻等异常情况，部分孔揭示 1 240~1 270 m 高程存在溶蚀发育带。各孔均能顺利完成灌浆，未发现与 1 315 m 排水洞相连的涌水通道。

（2）检 4 孔—检 3 孔之间的多个钻孔钻至 1 300~1 310 m 高程时，返水呈黄色，且多含有泥沙，但未出现失水，吕荣值 q 基本小于 3.0 Lu，推测此处为岩层不整合带（$D_{2\text{-}3}zg^{2\text{-}2}$），与库水之间无明显水力联系。不整合带位于原灌浆帷幕底高程之上，前期施工已封堵其渗漏通道，灌浆效果较好。钻至高程 1 245~1 270 m 时，多个钻孔出现失水，压水试验无法加到预定压力。当 1 315 m 排水洞各出水口阀门关闭后，多个钻孔，特别是检 4 孔右侧附近的钻孔，出现涌水现象，说明检 4 孔部位存在库水绕过帷幕线的渗漏通道，且与下游 1 315 m 排水洞有较强的水力联系。

（3）检 3 孔—检 1 孔之间的钻孔，大部分是在 1 315 m 排水洞各涌水口关闭阀门以后施工的。当钻至 1 290~1 310 m 高程时，揭示岩层不整合带（$D_{2\text{-}3}zg^{2\text{-}2}$），检 3 孔—检 1 孔之间的钻孔未出现失水、掉钻等异常情况，吕荣值较小，表明与库水之间无明显水力联系。

断层 F_{12} 以左至检 2 孔间约 20 m 洞段，在高程 1 220~1 260 m，钻孔涌水概率较大，存在一溶蚀带。特别是断层 F_{12} 以左 8 m 范围，几乎每个钻孔均出现涌水现象。出现涌水的高程在 1 240~1 260 m 之间。说明断层 F_{12} 以左至检 2 孔间存在库水绕过帷幕线的渗漏通道。对该部位的钻孔 YGKT-23 孔和 RWM-Ⅲ-8 进行灌浆后，1 315 m 排水洞各地质薄弱点涌水量明显减小，渗透压力从 0.49 MPa 下降到了 0.1 MPa，

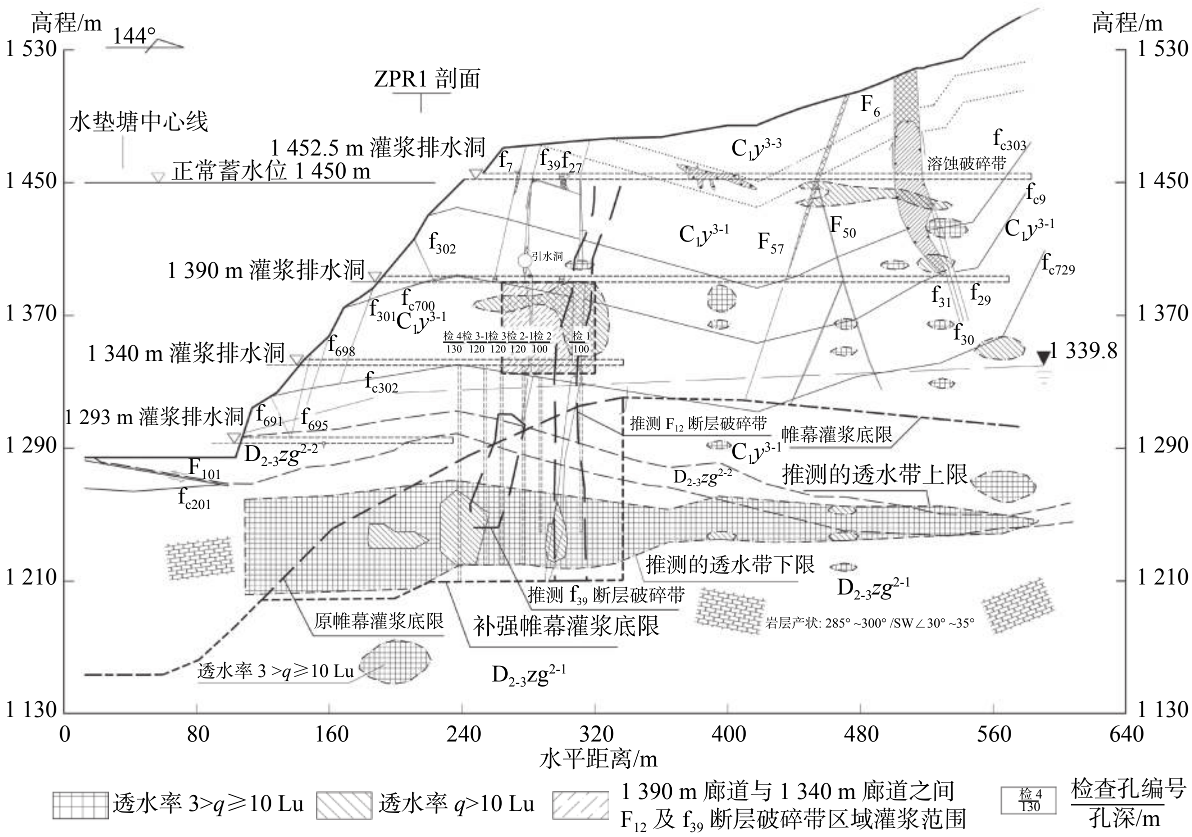

图 5 坝轴线处右岸岩体透水性分布示意图

Fig. 5 Permeability distribution in the right rock body along dam axis

说明断层 F_{12} 至检 2 一带为库水绕帷幕向下游 1 315 m 排水洞渗漏的主要通道。

6.3 渗漏途径研究

右岸 1 315 m 涌水区域以层面溶蚀为主，局部发育溶槽、溶沟和溶洞。在大坝灌浆帷幕线上游右岸岩体中，只有断层 F_{12} 位于水库水面线以下。根据 1 340 m 灌浆排水洞各检查孔和灌浆孔的涌水情况，结合右岸抗力体地质特性、地下水位观测数据及岩体透水性试验结果，判断 1 315 m 涌水的岩溶渗漏路径如下：

库水经断层破碎带 F_{12} 下渗，至深部岩石层面溶蚀带后，往下游以 30°倾角沿溶蚀带逐步抬升，并在 1 220~1 260 m 高程、检 4 孔附近和断层 F_{12} 至检 2 孔一带绕过帷幕线。局部遇竖向溶槽、溶沟、溶洞等地质薄弱地带，向上渗流，最终从 1 315 m 排水洞地质薄弱点涌出（图 4，图 6）。

7 渗漏处理措施及效果

7.1 渗漏处理措施

本项目的岩溶渗漏处理是勘察与治理交叉的动态调整过程，勘察与灌浆封堵动态交互进行。

对在勘察和灌浆过程中发现的主要渗漏通道的区域进行了封堵灌浆。在 1 340 m 灌浆排水洞检 4~检 3 及检 2~检 1 之间，布置 3 排灌浆孔，排距 1.6 m，孔距 2 m（局部加密至 1 m），孔深 130~140 m；检 3~检 2 之间，布置 2 排灌浆孔，排距 1.6 m，孔距 2 m，孔深 130 m。

根据右岸 1 452.5 m 廊道及 1 390 m 廊道勘探孔勘察成果，在 1 390 m 廊道和 1 340 m 廊道之间发育 F_{12} 断层及 f_{39} 断层，该区域岩溶发育，压水试验渗漏量大，局部出现掉钻、漏水到下层廊道的现象。前期坝基施工帷幕灌浆时，该区域耗灰量较大。该地段地质条件较差，岩溶较发育，为确保帷幕截水可靠性，封堵岩溶渗漏隐患，在该区域增加一排补强灌浆帷幕，孔距 2.0 m，孔深 55 m，孔斜 5°。

除上述部位外，在右岸其他部位也实施了一定数量的灌浆封堵措施，此处不再赘述。

7.2 治理成效

经过大量的灌浆封堵处理后，右岸 1 315 m 廊道渗漏量逐渐减少至约 38 $L\cdot s^{-1}$，较封堵前大为减小，压

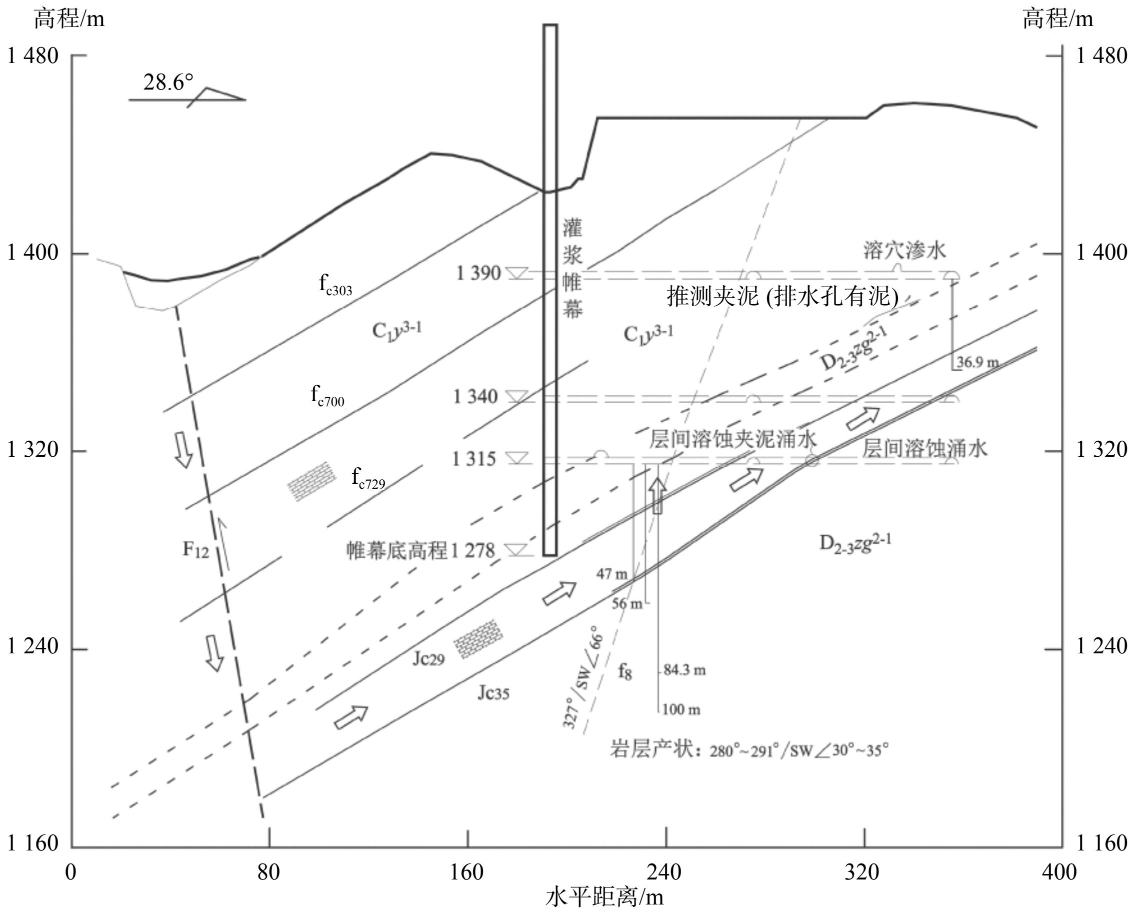

图 6　ZPR1 渗水通道剖面示意图

Fig. 6　Schematic diagram of ZPR1 seepage channel

力由 0.49 MPa 下降到 0.1 MPa，洞壁基本无滴水现象。治理达到了设计要求。

8　结论和建议

（1）西南某水电站区断层和岩溶较发育，水库蓄水后，右岸抗力体 1 315 m 排水洞出现了总渗漏量约 1.9 $m^3 \cdot s^{-1}$ 的岩溶渗漏。岩溶渗漏处理是一个勘察与治理交叉、动态调整的过程。采用钻探、水文试验、钻孔电视、孔内电磁波 CT 等手段，对坝区右岸进行了勘察，通过对勘察成果和灌浆过程试验数据进行分析，最终查明了岩溶绕帷幕渗漏通道。库水在水压力作用下，沿断裂构造 F_{12} 下渗，在深部沿层间溶蚀带绕过防渗帷幕，呈 30°倾角向下游逐步抬升，最终通过竖向岩溶发育带，从 1 315 m 排水洞地质薄弱点涌出；

（2）采取补强灌浆措施处理后，达到了预期效果，为碳酸盐岩区水利水电工程岩溶渗漏治理提供了一个成功的范例；

（3）在水利水电勘察设计工作中，一般按照孔内连续 3 段压水试验 $q \leqslant 3$ Lu（或 $q \leqslant 1$ Lu）确定防渗底限，进行坝基防渗设计。

从本次勘察成果可知，在坝基帷幕底高程以下仍存在透水性较大的区段，在存在导水断裂情况下，库水绕过防渗帷幕产生渗漏。因此，对于岩溶区水利水电工程，不仅要查明防渗底限，还需综合相关勘察成果，对局部断裂构造进行分析，判定库水通过断裂沿深部溶蚀带产生渗漏的可能性，进而采取有效措施进行处理。

参考文献

［1］　李大通，罗雁. 中国碳酸盐岩分布面积测量［J］. 中国岩溶，1983，2（2）：147-150.
LI Datong, LUO Yan. Measurement of carbonate rocks distribution area in China［J］. Carsologica Sinica, 1983, 2（2）：147-150.

［2］　曾中磊. 滇中地区岩溶水文地质特征［J］. 人民珠江，2016，37（8）：39-43.
ZENG Zhonglei. Karst hydrogeological characteristics in central Yunnan［J］. Pearl River, 2016, 37（8）：39-43.

［3］　刘鹏瑞，刘长宪，姜超，王芳，陈钰，贾龙. 武汉市工程施工引发

岩溶塌陷机理分析[J]. 中国岩溶, 2017, 36(6): 830-835.
LIU Pengrui, LIU Changxian, JIANG Chao, WANG Fang,CHEN Yu,JIA Long. Mechanism of karst collapse caused by engineering construction in Wuhan City[J]. Carsologica Sinica, 2017, 36(6): 830-835.

[4] 肖明贵. 桂林市岩溶塌陷形成机制与危险性预测[D]. 长春: 吉林大学, 2005.
XIAO Minggui. The forming mechanism and forecast of fatalness about karst subsidence in Guilin City[D]. Changchun: Jilin University, 2005.

[5] Fares M Howari, Raed Aldouri, Abdulali Sadiq. Gravity investigations of recent sinkholes and karst pits of Dahal Al-Hamam, State of Qatar[J]. Environmental Earth Sciences, 2016, 75(5): 440.

[6] Zhanfei Gu, Qi Liu, Yaoru Lu, Zhengning Shi,Gaoyu Su,Dexiang Luan. Analysis and prevention of sinkhole collapses during the reconstruction and extension of Guang-Qiing freeway, China[J]. Environmental Earth Sciences, 2016, 75(5): 788.

[7] 冯志刚, 刘谢伶. 构造条件对水库岩溶渗漏的影响研究[J]. 红水河, 2018, 37(5): 69-71,75.
FENG Zhigang, LIU Xieling. Study on influence of tectonic conditions on karst leakage of reservoirs[J]. Hongshui River, 2018, 37(5): 69-71,75.

[8] 吕耀成, 李钰强, 张富荣, 巨广宏. 莲花台水电站岩溶发育特征及工程意义[J]. 中国岩溶, 2019, 38(4): 502-507.
LYV Yaocheng, LI Yuqiang, ZHANG Furong, JU Guanghong. Karst features of the Lianhuatai hydropower station and engineering significance[J]. Carsologica Sinica, 2019, 38(4): 502-507.

[9] 赵博超, 朱蓓, 王弘元, 赖柄霖. 浅谈岩溶塌陷的影响因素与模型研究[J]. 中国岩溶, 2015, 34(5): 515-521.
ZHAO Bochao, ZHU Bei, WANG Hongyuan, LAI Binglin. Influence factors and mathematical models of karst collapses[J]. Carsologica Sinica, 2015, 34(5): 515-521.

[10] 万伟锋, 王泉伟, 邹剑锋, 苗旺. 东庄水库岩溶渗漏几个关键问题的探讨[J]. 人民黄河, 2015, 37(2): 99-103.
WAN Weifeng, WANG Quanwei, ZOU Jianfeng, MIAO Wanf. Discussion on several key problems about karst leakage of Dongzhuang reservoir[J]. Yellow River, 2015, 37(2): 99-103.

[11] 余波, 徐光祥, 郭维祥, 等. 岩溶水库防渗处理关键技术[M]. 北京: 中国水利水电出版社, 2020.
YU Bo, XU Guangxiang, GUO Weixiang, et al. Key technology of anti-seepage treatment of karst reservoirs[M]. Beijing: China Water & Power Press, 2020.

[12] 沈春勇. 水利水电工程岩溶勘察与处理[M]. 北京: 中国水利水电出版社, 2015.
SHEN Chunyong. Investigation and treatment of karst in water conservancy and hydropower project[M]. Beijing: China Water & Power Press, 2015.

[13] 刘浩, 田茂中. 贵州冗赖水库岩溶成库条件分析[J]. 中国岩溶, 2019, 38(4): 515-523.
LIU Hao, TIAN Maozhong. Karst geological conditions of the planned Ronglai reservoir in Guizhou Province[J]. Carsologica Sinica, 2019, 38(4): 515-523.

[14] 龚大庆, 向能武, 曾剑华. 构皮滩坝址5、6号岩溶系统的发育特征及处理[J]. 人民长江, 2007, 38(9): 103-105.
GONG Daqing, XIANG Nengwu, ZENG Jianhua. Development characteristics and treatment of No. 5 and No. 6 karst systems at Goupitan dam site[J]. Yangtze River, 2007, 38(9): 103-105.

[15] 卢晓鹏, 谭光明. 清华洞暗河堵洞成库与防渗技术[J]. 中国岩溶, 2012, 31(2): 179-184.
LU Xiaopeng, TAN Guangming. Reservoir building by cave-plugging and the seepage-proofing technique in the Qinghuadong underground river[J]. Carsologica Sinica, 2012, 31(2): 179-184.

[16] 李元奇. 马洞水库岩溶渗漏处理方案[J]. 水利科技与经济, 2014, 20(2): 97-98.
LI Yuanqi. Treatment scheme of karst leakage in Madong reservoir[J]. Water Conservancy Science and Technology and Economy, 2014, 20(2): 97-98.

Study on karst leakage caused by the combination of fault structure and interlayer corrosion zone of a hydropower station in southwest China

FENG Zhigang[1,2], WEI Guojian[3], ZHANG Hanmeng[3], XU Guo[1,2]

(1. *Nanning Survey and Design Institute Group Co., Ltd., Nanning,Guangxi* 530022, *China*; 2. *Nanning Research Center of Big Data Engineering Technology in Shallow Geology*, *Nanning*, *Guangxi* 530022, *China*; 3. *China Energy Engineering Group Guangxi Electric Power Design Institute Co., Ltd.*, *Nanning*, *Guangxi*, 530007, *China*)

Abstract A hydropower station in southwest China is located in the middle part of the fold belt between the eastern Yunnan platform and the western Guizhou platform on the Yangzi platform. The largest fault in the near field area is F38, which is 61 km long and generally protrudes to the northwest in an arc shape. The dam site is located in the east-west structural belt on the south side of F38 fault, which is the core area of the northeast end of Dashuitang oblique anticline with an axial direction of NNE. At the dam site, the river flow direction is 25°-30°, and the valley is basically in symmetrical V shape. The dam area is dominated by carbonate rocks, and faults and karst are relatively developed. There are karst funnels, depressions, sinkholes and other surface karst forms in the upper level of planation surface on both sides of the dam site. Early investigation results of adits, drilling, foundation pit excavation and geophysical prospecting show that there are some karst caves, trough-like caves and interlayer corrosion in the riverbed and both sides, which are interconnected according to their extension trend. Since the reservoir starts to store water, continuous leakage has occurred in the 1,315 m drainage tunnel of the resistance body on the right bank of the dam site. With a rapid rise of the reservoir water level, a large number of muddy fillings gush out from each water inflow point. Then the water gradually becomes clear, the leakage gradually increases to about 1.9 $m^3 \cdot s^{-1}$, and the reservoir cannot store water normally. In order to find out the leakage path of reservoir water and take measures to reduce leakage, karst leakage research is carried out. 15 boreholes are arranged on the right bank of the dam site, with the borehole bottom elevation from 1,133.3 m to 1,249.9 m, and the borehole water pressure tests of 121 section are carried out below the bottom elevation of the dam foundation curtain. Results show that the permeability area of Lugeon value q≥3 Lu below the curtain bottom elevation is distributed in a band, mainly between 1,200 m and 1,260 m, where Lugeon value gradually decreases from q=3-75 Lu to 2-8.82 Lu toward the right bank. Inspection holes are arranged along the grouting curtain line of the grouting drainage tunnel at the elevations of 1,293 m and 1,340 m on the right bank, and the bottom elevation of the holes is about 1,200 m. The water pressure test, borehole television, the data of simple water pressure test and abnormal records during the grouting process are analyzed comprehensively. 8 inspection holes of the 1,293 m grouted drainage tunnel can be grouted normally, and no hydraulic connection with the water gushing channel of the 1,315 m downstream drainage tunnel is found. 6 inspection holes are arranged in the 1,340 m grouting drainage tunnel, and hundreds of grouting holes are arranged at intervals of 10 m to the left and 2 m to the right of borehole inspection-4. There are 2-3 rows of grouting holes in local sections, and the abnormal tunnel sections are densely grouted. The exploration results of 1,340 m grouting drainage tunnel show, (1) There is no large structural fracture zone developed in the left of inspection-4. Grouting is successfully completed in each hole, and no channel connected with water inrush at 1,315 m is found. (2) For the multiple boreholes between inspection-4 and inspection-3, porous water loss occurs when the drilling is at the elevation of 1,245-1,270 m, and the water pressure cannot be added to the predetermined pressure in the test. After the valves are closed at each water outlet of 1,315 m drainage tunnel, the water gushing phenomenon appears in many holes, especially holes near the right side of the inspection-4, which indicates that there is a leakage channel for reservoir water to bypass the curtain line at the inspection-4 position, and there is a strong hydraulic connection with the downstream 1,315 m drainage tunnel. (3) Most boreholes between inspection-3 and inspection-1 are drilled after the valves of water inlets of the 1,315 m drainage tunnel are closed. In the tunnel section of about 20 m from the left of fault F_{12} to inspection-2, the probability of borehole water inflow is relatively high when the drilling reaches 1,220-1,260 m, where there is a corrosion zone. Especially in the area 8 m from the left of fault F_{12}, the water inflow phenomenon occurs in almost every borehole between the elevation about 1,240-1,260 m, which shows that the section from the left of fault F_{12} to inspection-2 is the main channel for the reservoir water to leak around the curtain to the 1,315 m drainage tunnel downstream. According to the water inflow conditions of each inspection hole and grouting hole of the 1,340 m grouting drainage tunnel, combined with the geological characteristics of the right bank resistance body, exploration results and rock permeability test results, the karst leakage path of 1,315 m water inflow is judged as follows: reservoir water infiltrates through the fault fracture zone F_{12}, reaches the dissolution zone of the deep rock bedding plane, and then gradually lifts along the dissolution zone at a dip angle of 30° downstream, and bypasses the curtain line at the elevation of 1,220-1,260 m near inspection-4 and from the fault F_{12} to inspection-2. After encountering the geological weak zones such as vertical solution grooves, solution ditches and solution caves, reservoir water of the local area seeps upward and finally gushes out from the geological weak point of 1,315 m drainage tunnel. The treatment of karst leakage in this project is a dynamic interactive process of investigation and grouting. With the measures of grouting curtain reinforcement, the main leakage channel is blocked, and the reservoir water leakage is effectively controlled. The leakage of the right bank 1,315 m corridor gradually reduces to about 38 $L \cdot s^{-1}$. There is basically no water dripping on the tunnel wall, and the treatment meets the design requirements.the treatment meets the design requirements.e design requirements.

Key words　karst, leakage, fracture, corrosion zone, reinforcement grouting, carbonate rock

（编辑 张 玲）