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前置挡墙对董箐水库下泄水温的影响

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摘要:为明确前置挡墙对水库下泄水温及坝前水温分布的影响,以董箐水库为例,构建三维水温-水动力数学模型。模拟不同挡墙高程下的下泄水温和坝前水温分布,分析前置挡墙高程与下泄水温、坝前水温分布间的变化规律。结果表明,下泄水温的改善效果与挡墙高程密切相关:挡墙高程低于取水口高程时,挡墙高程的变化对下泄水温几乎无影响;挡墙高程高于取水口高程一定高度时,挡墙高程越高,下泄水温越高;挡墙高程480 m时,4月下泄水温最大升温1.11 ℃。下泄水温的提高度与挡墙和取水口位置对应的坝前垂向水温差线性相关。坝前垂向水温分布也受挡墙的影响,挡墙高程高于取水口高程一定高度时,随着挡墙高程的增加,分层期温跃层厚度增加位置上升。下泄水温的改善效果与挡墙高程的关系较为复杂,下泄水温提高度增长较快位置分别出现在挡墙高程471 m和475 m处。考虑方案的工程可行性,挡墙高程471 m为改善下泄水温的最优选择。研究可为前置挡墙的设计及工程优化提供方法和参考。

关键词:水库;水温分层;下泄水温;前置挡墙;数学模型

中图分类号:TV697.2 **文献标志码:**A **开放科学(资源服务)标志码(OSID):**

水电站建设带来的水环境和水生态问题越来越受到重视。作为水环境评价最重要的影响因子之一,水温对水生系统中的物理、化学和生物过程起着重要作用,是水环境研究的基本要素,影响范围极广[1]。大型水库蓄水后,易形成水温分层[2],表底层温差可高达20 ℃[3]。已建成水库大多取水口位置较低且不易改变,导致低温水下泄,继而对库区及下游造成严重的环境影响:低温水下泄最直接的危害是使农作物遭受“冷害”减产[4-5];推迟鱼类的产卵期[6-8];水温分层引起水质参数分层,导致水质恶化[9],对水生态产生不利影响[10]。水库低温水下泄成为目前研究的一个热点问题。对此,采用一系列工程措施来改善下泄低温水所带来的负面影响是有必要的。

分层取水是国内目前改善水库下泄水温不利影响的重要工程措施,主要包括叠梁门、隔水帷幕、前置挡墙、浮式取水口、机控分层取水及多层取水口取水[11]。前人关于低温水下泄改善措施展开了一系列研究:张少雄等[12]模拟了糯扎渡水电站采用叠梁门后,不同引流流量和取水口开启组合下的下泄水温改善效果;杨大超等[13]分析了取水口高程对坝前水温结构的影响;高学平等[14-15]分别研究了叠梁门对多层取水口水力特性的影响,及浮式管型取水口对下泄水温的影响;任华堂等[16]分析了不同取水口高程对库首水体温跃层、均温层位置和下泄水温的影响;薛刚[17]模拟了龙羊峡采用孔口分层取水对下泄水温的影响;练继建等[18]展开了隔水幕布对下泄低温水改善研究。许多研究验证了分层取水能够改善下泄低温水,但关于前置挡墙对下泄水温影响的研究相对较少。

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董箐水库泄流量大、水位深，取水口位置较低且无法改变。采用前置挡墙可改善下泄水温，但前置挡墙为新型工程措施，其对下泄水温的影响程度和坝前水温的改变量均待评估，挡墙高程选择也有待深入研究。本文以董箐水库为例，采用数值方法，分析不同前置挡墙高程对水库下泄水温和坝前水温结构的影响，评价其对下泄水温的改善效果，讨论合理的前置挡墙布置方案。

1　工程概况

董箐水库位于贵州北盘江下游贞丰县与镇宁县交界处，是北盘江流域梯级开发的第 3 个电站。水库正常蓄水位 490 m，以发电为主，兼有防洪、供水、养殖和改善生态环境等综合效益。取水口中心线高程 459.5 m，取水口高度为 9 m，前置挡墙修建在取水口前 13.5 m 处，包围取水口，使温度相对较高的水体通过挡墙顶部流入取水口，以达到改善下泄水温的目的。实际工程采用扶臂式钢筋混凝土挡墙，墙顶高程 470 m，挡墙两侧与进水口边墩相接，剖面结构见图 1。

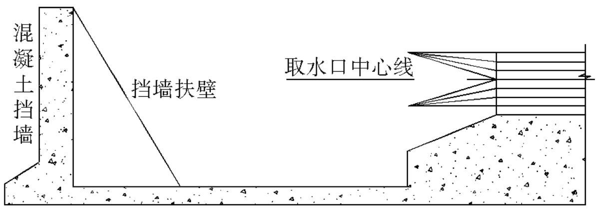


图 1　前置挡墙剖面结构

Fig. 1　Schematic diagram of section of front retaining wall structure

2　计算方法

数值方法理论严密，发展较为成熟，由于较高的精度和灵活性已经成为水温预测和分析使用最广泛的一种方法，在水库水温-水动力场耦合的数值方法计算上取得了较为丰硕的成果[19-21]。本文采用 Delft3d 水动力模块进行模拟。

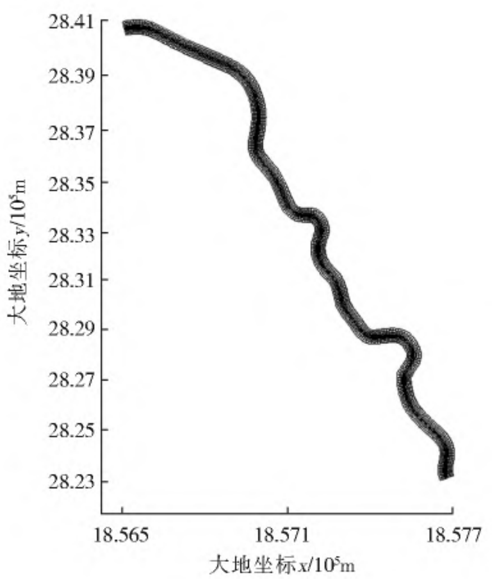
2.1　计算区域及网格划分

2.1.1　计算区域

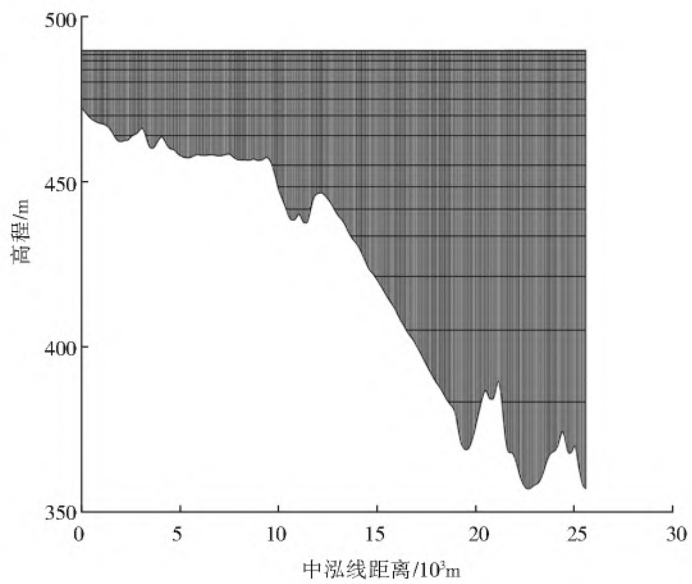
数值计算区域的选择需要遵循的原则如下：计算区域应涵盖的研究区域，并非尽可能地减小边界条件对研究区域的影响，但在具体实施过程中，计算区域往往受到各种条件的限制(如原始资料和监测资料)。在董箐水电站的水温数值模拟中，分别自坝前向上延伸 24、26、28、30 km 作为计算区域，对水库水温结构及下泄水温进行对比。考虑到在向上延伸 26 km 及以上时，水库水温结构及下泄水温趋于稳定，因此选取自坝前向上游延伸 26 km 作为计算区域。

2.1.2　网格划分

根据选定的计算区域，对董箐水库划分网格见图 2。董箐水库约 26 km 的计算区域的网格数划分为 330(纵向)×15(横向)×16 层(垂向)，纵向网格尺寸为 14～84 m，横向为 58～80 m，垂向为 0.8～28.0 m。计算网格的正交性均满足数值计算要求。



(a) 平面网格



(b) 纵向网格

图 2　平面网格及纵向网格

Fig. 2　Planar and longitudinal mesh

2.2　边界条件

2.2.1　表面和底部边界条件

$$\frac{\partial T_s}{\partial t}=\frac{\varphi_n}{\rho_w c_p \Delta z_s} \quad (1)$$

式中：T_s 为水体自由表面的温度，℃；Δz_s 为水体表层网格的厚度，m；φ_n 为通过水气界面辐射到水体表层的总热通量，J/($m^2 \cdot s^{-1}$)。

垂向速度 w 在 z 坐标系，忽略水体在表面和底部的质量通量，即无水通过。

$$w|_{z=0}=0, w|_{z=h}=0 \quad (2)$$

$$v\frac{\partial u}{\partial z}|_{z=0}=\frac{1}{\rho_0}\left|\overrightarrow{\tau_s}\right|\cos\theta \quad (3)$$

$$v\frac{\partial v}{\partial z}|_{z=0}=\frac{1}{\rho_0}\left|\overrightarrow{\tau_s}\right|\cos\theta \quad (4)$$

式中：v 为垂向涡黏性系数。θ 为风力形成的角度，风应力大小的计算公式为

$$\left|\overrightarrow{\tau_s}\right|=\rho_a C_d U_{10}^2 \quad (5)$$

式中：ρ_a 为空气密度，kg/m^3；U_{10}^2 为水面上方 10 m 处的风速，m/s；C_d 为水面风拖曳系数。

2.2.2　入口及出口边界条件

入口边界采用董箐水库上游逐日流量和逐日水温。逐日流量根据董箐水电站设计平水年各月典型日出力过程推求，入流水温采用天然河道水温，由于董箐水库为典型的日调节水库，采用入/出流边界的流量大小相等。具体入流流量及入库水温过程见图 3。

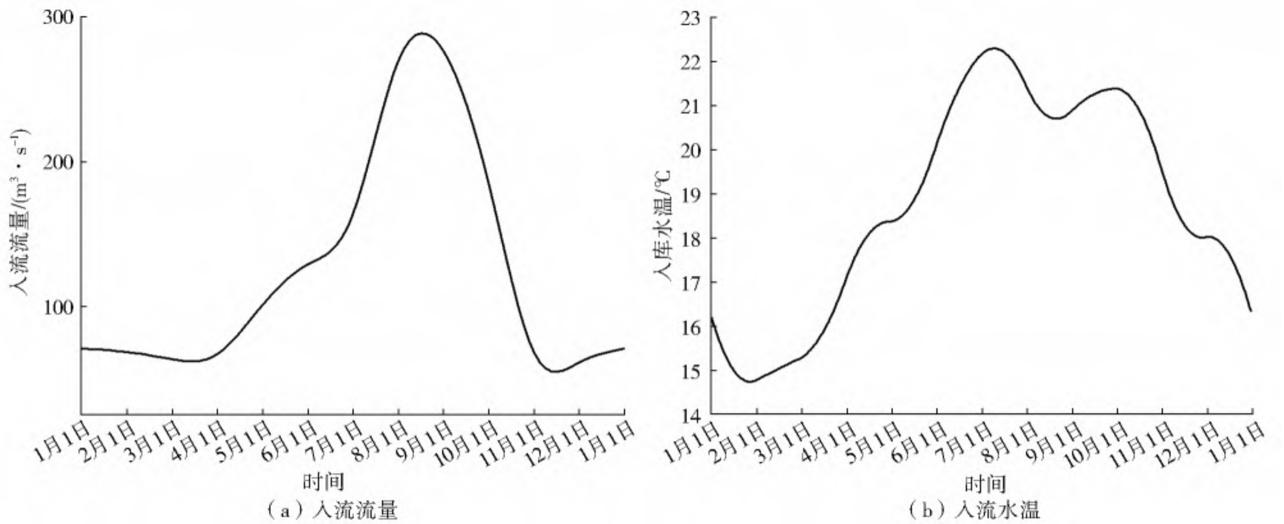


图 3　入流流量及入流水温

Fig. 3　Incoming flow rate and incoming water temperature

2.2.3　其他边界条件

气温、风向风速、云量、湿度及辐射以兴仁站的气象数据参考计算，数据来自中国气象数据网查询。

2.3　模型验证

图 4 中将模拟无挡墙的中层(高程 430 m)、表层(高程 475 m)坝前全年水温与 2012 年实测数据对比分析，在中层和表层计算得到的水库水温与实测值及其变化趋势较为吻合，绝对误差最大为 0.63 ℃，因此该数学模型计算精度可满足要求。

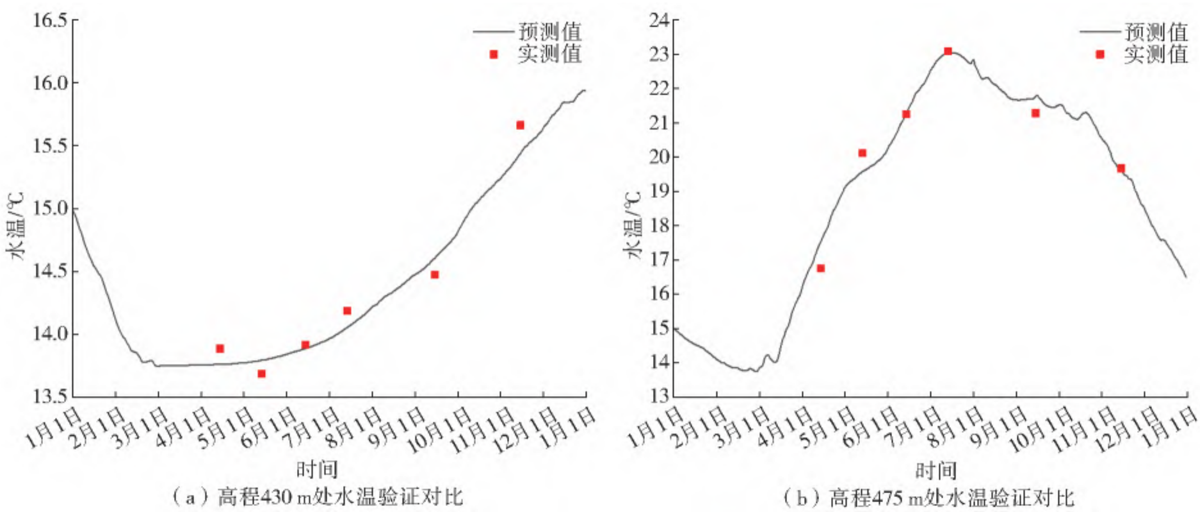


图 4　水温对比

Fig. 4　Water temperature comparison chart

3　计算工况

本文在水库水位变幅不大的前提下，讨论挡墙高程改变对下泄水温及坝前水温结构的影响。挡墙布置具体方案见表1。

表1　挡墙高程方案

Tab.1　Elevation scheme of different retaining wall

工况	取水口中心线高程/m	挡墙顶部高程/m	工况	取水口中心线高程/m	挡墙顶部高程/m
1	459.5	无挡墙	5	459.5	465
2	459.5	450	6	459.5	470
3	459.5	455	7	459.5	475
4	459.5	460	8	459.5	480

4　计算结果及分析

4.1　不同挡墙高程下泄水温

针对董箐水库对下游地区无明显的调节目标，选取前置挡墙运行后对下泄水温的提高度作为一项评价指标，即各挡墙运行方案下的下泄水温减去无挡墙的下泄水温，进而评价下泄水温的改善效果。该水域水生生物对水温的敏感时期为3—6月，因此以3—6月的下泄水温进行分析。取水口高程均为459.5 m，以无挡墙的水库下泄水温作为参考标准，表2展示了各高程挡墙3—6月平均下泄水温的提高度。

表2　取水口高程459.5 m不同挡墙高程方案平均下泄水温提高度

Tab.2　Average degree of increase of released temperature across retaining wall options(Inlet elevation=459.5 m)　单位：℃

月份	挡墙450 m	挡墙455 m	挡墙460 m	挡墙465 m	挡墙470 m	挡墙475 m	挡墙480 m
3	−0.01	−0.01	−0.01	0.01	0.16	0.22	0.23
4	−0.02	−0.02	−0.01	0	0.41	0.96	1.11
5	−0.01	0	0	0	0.18	0.45	0.61
6	0.01	0.01	0.02	−0.01	0.11	0.47	0.76

由表2可知，挡墙高程越高，下泄水温改善效果越明显，挡墙高程为480 m时升温效果最明显，4月下泄水温提高了1.11 ℃。

挡墙高程低于取水口高程，即挡墙高程分别为450、455、460 m时，3—6月的下泄平均水温均无明显升高，其中，6月下泄平均水温的提高度分别为0.01、0.01、0.02 ℃，水库下泄水温的改善效果较为一致。这说明挡墙高程低于取水口高程时，改变挡墙位置对下泄低温水影响不大。

当挡墙高程为465 m时，挡墙高程虽然高于取水口上缘高程，但受水流在挡墙上游沿垂向扩散影响，取水口引入水流主流区和无挡墙相比变化不大，下泄水温也几乎不受影响。

挡墙高程高于取水口高程一定高度，即挡墙高程范围在470～480 m时，随着挡墙高程的增加，3—6月平均下泄水温随之升高。将挡墙高程470、475、480 m的相同月份下泄平均水温进行对比发现：3月水库下泄平均水温提高度分别为0.16、0.22、0.23 ℃；4月水库下泄平均水温提高度分别为0.41、0.96、1.11 ℃；5月水库下泄平均水温提高度分别为0.18、0.45、0.61 ℃；6月水库下泄平均水温提高度分别为0.11、0.47、0.76 ℃。下泄水温随挡墙高程的增加而升高。

4.2　各工况坝前水温分布

在不同挡墙运行方案下，绘制典型月份的坝前(上游距挡墙500 m处)垂向水温分布见图5。

由图5(a)可知，1月坝前水温呈现出稳定的混合型，不同挡墙高程的坝前垂向水温分布较为一致，1月下泄水温无明显变化，坝前垂向水温分布也无明显变化，说明坝前垂向水温分布在混合期间不受挡墙高程改变的影响。

由图5(b)、5(c)可知，4、6月坝前垂向水温呈现出稳定的分层型，表层水温高，底层水温低。取水口高程为459.5 m，挡墙高程由450 m逐渐增加到465 m，坝前水温分布较为一致，温跃层的位置也无明显变化，当挡墙高程由465 m逐渐增加到475 m时，温跃层位置明显上升、厚度增加；当挡墙高程由475 m增加到480 m时，4、6月温跃层位置出现小幅上升，厚度小幅增加，水库水温整体下降。这也说明了挡墙高程高于取水口高程一定高度时，随着挡墙高程的增加，而取水口取到更多的表层高温水，坝前水温结构发生变化，温跃层也随之变化。

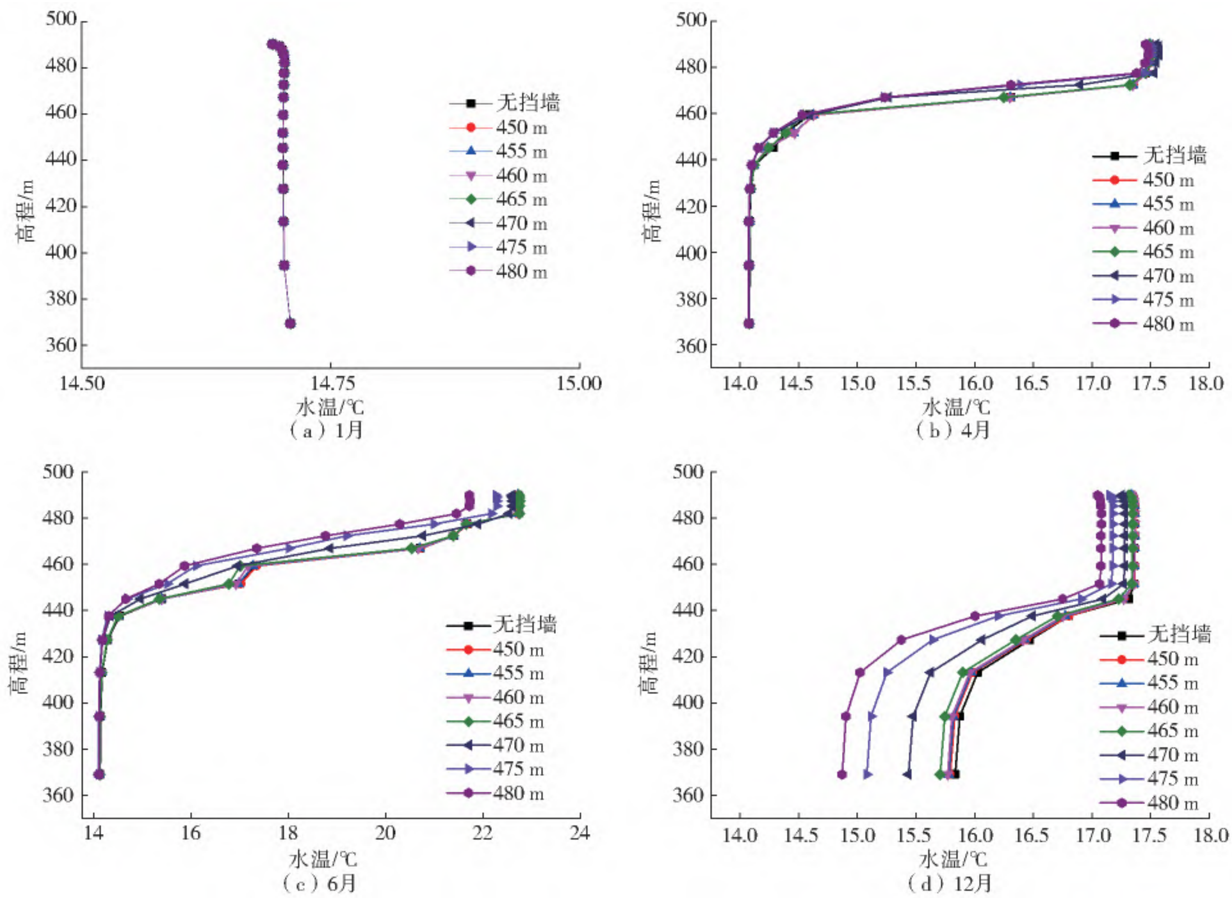


图 5　各工况 1、4、6、12 月坝前垂向水温分布

Fig. 5　Vertical water temperature distribution diagram in front of the dam in each working condition

由图 5(d)可知：12 月坝前水温呈现出过渡型，由于取水口高程为 459.5 m，挡墙高程范围为 450～465 m 变化时，12 月坝前垂向水温几乎无影响；随着挡墙高程由 470 m 增加到 480 m，水流从表层流动增加，底层水流流动性变弱，垂向热交换量减小，12 月和 4 月坝前底层水温之差逐渐减小，挡墙高程越高，坝前底层水温越低。其中：底层升温最低点在高程 394 m 处，无挡墙时水温为 15.83 ℃；挡墙高程为 480 m 时水温为 14.90 ℃。

4.3　下泄水温改善效果分析

表 3 中：挡墙高程分别为 465、470、475、480 m 时，4 月份挡墙位置对应的坝前水温和取水口位置对应的坝前水温差值分别为 1.15、2.17、2.70、2.78 ℃，下泄平均水温提高度分别为 0、0.41、0.96、1.11 ℃；5 月挡墙位置对应的坝前水温和取水口位置对应的坝前水温差值分别为 1.90、3.10、3.62、4.35 ℃，下泄平均水温提高度分别为 0、0.18、0.45、0.61 ℃。分别以 4、5 月挡墙位置对应的坝前水温和取水口位置对应的坝前水温差值为 X，对应下泄水温的提高度为 Y，做皮尔逊相关性分析，发现挡墙高程由 465 m 增加至 480 m，相关性系数均为 0.97，显著性水平均小于 0.05。下泄水温的提高度与挡墙位置对应的坝前水温和取水口位置对应的坝前水温差值显著相关。

下泄水温由挡墙和取水口位置以及坝前水温分布共同决定。除混合期外，在同一月份，坝前水温表层均高于底层，随着挡墙高程的增加，挡墙位置对应的坝前水温和取水口位置对应的坝前水温差值随之增加，下泄水温的提高度增加。下泄水温的提高度取决于挡墙位置对应的坝前水温和取水口位置对应的坝前水温差值。

表 3　下泄水温提高度和温差关系(挡墙高程 465～480 m)

Tab. 3　Table of the relationship between the increase of released temperature and temperature difference (retaining wall 465-480 m)

月份	挡墙高程/m	温差/℃	提高度/℃	相关性系数	显著性水平
4	465	1.15	0	0.97	0.03
4	470	2.17	0.41		
4	475	2.70	0.96		
4	480	2.78	1.11		
5	465	1.90	0	0.97	0.02
5	470	3.10	0.18		
5	475	3.62	0.45		
5	480	4.35	0.61		

4.4　最优工况选择

图 6 展示了 4—6 月下泄水温提高度和挡墙高程的关系。以生物量较丰富且对水温敏感的 4 月为例，挡墙高程为 450～465 m，下泄水温提高度几乎无变化，挡墙高程 470 m 较 465 m 下泄水温升高 0.42 ℃，挡墙高程 475 m 较 470 m 下泄水温升高 0.54 ℃时，挡墙高程 480 m 较 475 m 下泄水温升高 0.15 ℃，5、6 月也呈相同的趋势。挡墙高程由 470 m 增加至 475 m 时，下泄水温的提高度增长最快。

为进一步研究最优的挡墙高程方案，设置挡墙高程 471、472、473、474 m 进行加密计算，分析挡墙高程自 465 m 起，挡墙高程增加所带来的下泄水温提高度增长率 $\Delta T/\Delta H$，结果见表 4。以 4 月为例，挡墙高程分别为 465、470、471、472、473、474、475、480 m 时，提高度的增长率分别为 0、0.08、0.16、0.02、0.03、0.06、0.28、0.03 ℃/ m。5、6 月也呈现相同趋势。这说明挡墙高程由 465 m 增至 480 m，下泄水温提高度的增长率呈现先增加再减小再增大再减小的趋势，挡墙高程 475 m 时带来的下泄水温提高度增长最快，471 m 次之。

结合实际董箐水库运行水位不低于 480 m，挡墙上水深最少应保证在 5.9 m 以上，挡墙高程最高为 474.1 m，因此挡墙高程 471 m 为最优选择。

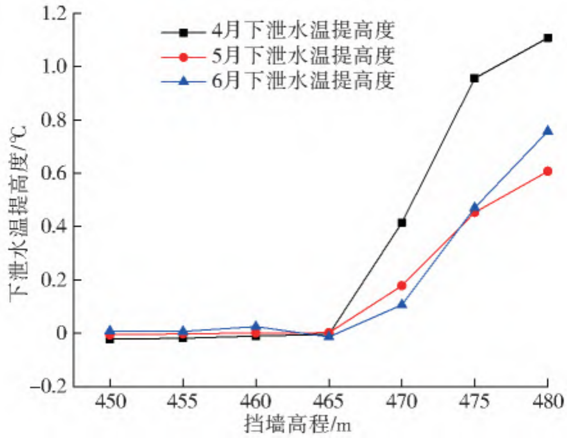


图 6　下泄水温提高度和挡墙高程关系

Fig. 6　Vertical The relationship between the increase of the released temperature and the retaining wall

表 4　下泄水温提高度增长率(挡墙高程 465～480 m)

Tab. 4　The rate of increase of released temperature(retaining wall 465-480 m)　　单位：℃/m

月份	挡墙 465 m	挡墙 470 m	挡墙 471 m	挡墙 472 m	挡墙 473 m	挡墙 474 m	挡墙 475 m	挡墙 480 m
4	0	0.08	0.16	0.02	0.03	0.06	0.28	0.03
5	0	0.04	0.07	0.01	0.02	0.04	0.13	0.03
6	0	0.02	0.08	0.02	0.03	0.06	0.17	0.06

5　结　论

针对董箐水库，模拟了不同高程挡墙下的水库下泄水温、坝前垂向水温，并用实测数据对模型中的参数进行验证，分析了挡墙对下泄水温和坝前水温的影响规律。

(1)前置挡墙可以用来改善下泄低温水对环境造成的负面影响。

(2)当挡墙高程低于取水口高程时，挡墙高程变化对水库下泄水温几乎无影响。

(3)当挡墙高程高于取水口高程一定高度时，挡墙高程决定了下泄水温，随着挡墙高程的增加，水库 3—6 月下泄水温随之升高，挡墙高程越高，改善效果越明显。

(4)当挡墙高程低于取水口高程时，坝前水温分布不受挡墙影响；当前置挡墙的顶部高程高于取水口高程一定高度时，随着挡墙高程的增加，更多的表层高温水下泄，温跃层位置上升，厚度增加。挡墙高程的增加减弱了坝前底层水体的垂向热交换。

(5)当挡墙高程高于取水口高程一定高度时，挡墙对下泄水温的提高度与挡墙和取水口高程之间对应的坝前垂向水温差值有关，差值越大，下泄水温的提高度越大，存在线性相关关系。

(6)通过分析加密计算方案，下泄水温提高度增长率存在 2 个极值点，在挡墙高程 475 m 和 471 m 处提高度的增长率最大。考虑工程可行性，挡墙顶部高程设置为 471 m 为最优选择。

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The effect of the front retaining wall on the released water temperature of Dongqing reservoir

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Abstract：Water，environment，and ecology problems brought by the construction of hydropower plants are getting more and more attention. Water temperature is one of the most important influencing factors for water environment assessment. Water temperature plays an important role in the physical，chemical and biological processes in aquatic systems，and is a fundamental element of water environment research，with a very wide range of influence. Large reservoirs after storage，easy to form water temperature stratification，the temperature difference between the surface and bottom layer can be as high as 20 ℃. Most of the completed reservoirs have low intake locations and are not easy to change，resulting in low-temperature water released，which in turn causes serious environmental impacts on the reservoir area and downstream. The most direct harm of low-temperature water released is to reduce crop yields，delay the spawning period of fish. Water temperature stratification causes stratification of water quality parameters，resulting in water quality deterioration，which harms water ecology. Reservoir low-temperature water released has become a hot issue in the current research. In this regard，it is necessary to adopt a series of engineering measures to improve the negative impact caused by the low-temperature water released.

Taking Dongqing reservoir as an example，a three-dimensional water temperature-hydrodynamic mathematical model was constructed to simulate the temperature of water released from the reservoir and the water temperature distribution in front of the dam under different retaining wall elevation，and to analyze the variation law between the front retaining wall elevation and the temperature of water released and water temperature in front of the dam.

The results show that the improvement effect of the released temperature is closely related to the retaining wall elevation. When the retaining wall was lower than the intake，the change of the retaining wall elevation has almost no effect on the released temperature. When the retaining wall was higher than the intake by a certain height，the higher the retaining wall elevation is，and higher the released temperature. When the retaining wall elevation is 480 m，the maximum increase of the released temperature in April is 1.11 ℃. The increase of the released temperature is linearly related to the difference of the vertical water temperature in front of the dam corresponding to the location of the retaining wall and the water intake. The vertical water temperature distribution in front of the dam is also affected by the retaining wall，when the elevation of the retaining wall is higher than the water intake elevation by a certain height，as the elevation of the retaining wall increases，the thickness of the thermocline increases and the position rises. The relationship between the improvement effect of the released temperature and the height of the retaining wall is more complicated，and the location of the faster growth of the released temperature increase occurs at the retaining wall elevation of 471 m and 475 m.

The front retaining wall can be used to improve the negative impact on the environment caused by the low temperature of water released. When the retaining wall elevation is lower than the intake elevation，the change of retaining wall elevation has almost no effect on the temperature of the water released from the reservoir. When the retaining wall elevation is higher than the water intake elevation by a certain height，the retaining wall elevation determines the temperature of water released，with the increase of the retaining wall elevation，the temperature of the water released from March to June increases，the higher the retaining wall elevation，the more obvious the improvement effect. When the retaining wall elevation is lower than the water intake elevation，the water temperature distribution in front of the dam is not affected by the retaining wall. When the top elevation of the former retaining wall is higher than the water intake elevation by a certain height, with the increase of the retaining wall elevation, more surface high temperature water is released, and the temperature leap layer position rises, and the thickness increases. The increase of the retaining wall elevation weakens the vertical heat exchange of the bottom water body in front of the dam. When the retaining wall elevation is higher than the water intake elevation by a certain height, the degree of improvement of the water temperature released by the retaining wall is related to the difference in the vertical water temperature between the retaining wall and the water intake elevation, the larger the difference, the greater the degree of improvement of the lower released water temperature, and there is a linear correlation. Analyzing the encrypted calculation scheme, there are two extreme points for the growth rate of the lower released water temperature increase, and the growth rate of the increase is greatest at the height of the retaining wall 475 m and 471 m. Considering the engineering feasibility, the top elevation of the retaining wall is set to 471 m as the optimal choice.

Key words: reservoir; thermal stratification; temperature of water released; retaining wall; mathematical model

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to the flexural capacity of the normal section, the maximum bending moment of the section in the area where the stress exceeds the limit was obtained. The maximum bending moment on the section was deduced according to the calculation formula of normal stress of flexural members. Finally, the area where the tensile stress exceeded the tensile strength of concrete could be rechecked by comparing the calculated normal stress results with the finite element stress calculation results. In addition, based on the finite element calculation results of each node of the bottom plate of the lock chamber, the anti-sliding stability of the lock chamber structure could be calculated.

The first five vibration modes of sluice chamber structure were mainly reflected in the vibration of beam and frame bridge structure. The results show that the fundamental frequency of natural vibration was 6.33 Hz under the condition of no water and normal water storage, and the natural frequency did not decrease obviously after considering the effect of hydrodynamic pressure. Under the earthquake action of normal water storage condition, large tensile stress appeared at the joint of side hole beam and frame bridge and the joint of frame bridge and pier, and its maximum tensile stress exceeded the standard value of dynamic tensile strength of concrete, but considering the local reinforcement, the tensile stress met the safety demand. Simultaneously, large compressive stress appeared at the corner of the frame bridge and other geometric mutation, and the maximum compressive stress did not exceed the standard value of concrete dynamic compressive strength, which met the safety requirements. Under the most unfavorable seismic condition, the safety factor of the anti-sliding stability of the whole sluice chamber was 1.68, which met the safety requirements.

According to the Guidelines for Sluice Safety Evaluation (SL 214—2015), the seismic safety of the sluice met the standard requirements, and its seismic grade was Grade A.

Key words: chamber structure; numerical simulation; mode decomposition response spectrum method; seismic response; seismic safety review