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低调节性能水库防洪优化调度分段试算法改进

王翌旭[1]，刘强[2]，钟平安[1]，赵克明[1]，姚超宇[3]

（1. 河海大学水文水资源学院，南京 210098；2. 中国电建集团华东勘测设计研究院有限公司，杭州 310014；
3. 中国电建集团中南勘测设计研究院有限公司，长沙 410014）

摘要：基于水库实时防洪调度的操作流程，以最大化实时调洪库容为准则，提出腾库预泄段、过渡维持段、削峰蓄洪段、安全消落段、期末消落段等 5 阶段划分原则；以最大削峰准则为目标，构建各分段优化出库过程的确定方法，形成低调节性能水库防洪优化调度改进分段试算法。以富春江水库为对象，开展改进分段试算法模拟调度并与原分段试算法进行对比，实例结果表明：改进分段试算法与原分段试算法相比优势明显，克服了原方法调洪计算中频繁突破库容、泄流能力上下限的问题，算法稳定性能良好；减少了闸门操作频次，增强了优化调度方案的可操作性；削峰效果更加显著，同等条件下削峰率提升 13.3%。

关键词：水库防洪；优化调度；最大削峰准则；改进分段试算法

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水库防洪优化调度方法是防洪减灾非工程措施中的研究热点。国内外学者针对水库优化调度方法开展了广泛研究：Windsor[1] 以线性规划求解水库调度问题，但处理非线性约束比较困难；Foufoula-Georgiou 等[2] 提出了动态规划算法（DP）用于水库群优化调度，但容易出现“维数灾”问题。为了降低“维数灾”，产生了大量的基于 DP 的改进方法，如 IDP[3]、DDDP[4-5]、动态规划的改进算法在一定程度上减轻了“维数灾”，但失去了 DP 的遍历性，常常只能得到局部最优解。此外，DP 及其改进算法是递推算法，要求求解的问题满足无后效性，而防洪调度问题中的河道洪水演进等都是有后效问题[6-7]。逐步优化算法（POA）[8-9] 是基于过程迭代的优化算法，可以较好地适应无后效问题，但也不能保证获得全局最优解。近年来智能算法被广泛应用于水库防洪优化调度中，Oliveira 等[10]、畅建霞等[11]、邹强等[12]、徐刚等[13]、王建群等[14-15]、崔东文等[16] 将遗传算法、粒子群算法、蚁群算法、狼群算法、鲸鱼算法等运用在水库优化调度中，这类启发性进化算法虽然在一定程度上减轻了动态规划等的“维数灾”，但存在最优解不稳定和易陷入局部最优解的缺陷[17-19]，对于类似防洪的水量优化调度，得到的水库放水过程时常出现“锯齿”波动、可操作性差等问题。

钟平安[20] 证明了最大削峰准则和最小成灾历时的最优解特性，其后根据最大削峰准则的最优解特性，提出了一种从“理想最优解”出发，逐步引入约束条件的分段试算法[21]。该算法计算速度快，计算结果可操作性强，应用于防洪库容比较大的高调节性能水库具有良好的效果。但对于周调节以下的低

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作者简介：王翌旭(1996—)，男，湖南衡阳人，主要从事水资源规划与管理研究。E-mail：maybecrazy@163.com
通信作者：钟平安(1962—)，男，安徽无为人，教授，博士，主要从事水资源规划与管理研究。E-mail：pazhong@hhu.edu.cn

调节性能水库，由于调节库容小，按“理想最优解”调洪演算，经常会突破水位的上下边界，导致“理想最优解”的出库过程剧烈变形，最后甚至不能通过分段试算逼近最优解。

针对分段试算法的上述问题，本文提出适应低调节性能水库的改进分段试算方法并以富春江水库为例验证改进方法的有效性。

1　水库防洪优化调度模型

1.1　目标函数

采用最大削峰准则构建目标函数，原始目标函数为

$$\min_{\Omega}\{\max_{t\in[1,T]}[q(t)]\} \tag{1}$$

文献[20]对该目标函数进行了详细讨论，推导出等价形式为

$$\min F=\sum_{t=1}^{T}[q(t)]^2 \tag{2}$$

式(1)和(2)中：$q(t)$为t时刻的水库出库流量，$\mathrm{m^3/s}$；T为调度期时段数，h；Ω为策略空间。

1.2　约束条件

（1）水量平衡约束

$$V(t)=V(t-1)+\left(\frac{Q(t)+Q(t-1)}{2}-\frac{q(t)+q(t-1)}{2}\right)\Delta t \tag{3}$$

式中：$V(t-1)$、$V(t)$分别为第t时段始、末水库的蓄水量，$\mathrm{m^3}$；$Q(t-1)$、$Q(t)$分别为第t时段始、末入库流量，$\mathrm{m^3/s}$；$q(t-1)$、$q(t)$分别为第t时段始、末出库流量，$\mathrm{m^3/s}$；Δt为时段长，h。

（2）水库最高水位约束

$$Z(t)\leqslant Z_{\mathrm{m}} \tag{4}$$

式中：$Z(t)$为t时刻计算水库水位，m；Z_{m}为允许最高水位，m，该值设置体现了水库自身安全和上游库区淹没损失。

（3）水库泄流能力约束

$$q(t)\leqslant q(Z(t)) \tag{5}$$

式中：$q(Z(t))$为t时刻水库水位$Z(t)$对应的下泄能力，$\mathrm{m^3/s}$。

（4）出库流量变幅约束

$$|q(t)-q(t-1)|\leqslant\nabla q \tag{6}$$

式中：∇q为相邻时段出库流量变幅的允许值，$\mathrm{m^3/s}$，该值设置的作用是避免下游水位陡涨陡落，有利于下游堤防和航运安全。

（5）调度期末水位约束

$$Z_T\geqslant Z_{\mathrm{e}} \tag{7}$$

式中：Z_T为调度期末计算水库水位，m；Z_{e}为调度期末水库的控制水位，m。调度期末水位反映水库防洪和兴利的协调关系。

（6）最大出库流量约束

$$q(t)\leqslant Q_{\max} \tag{8}$$

式中：$Q_{\max}$为入库流量过程的最大值（洪峰流量），$\mathrm{m^3/s}$，此约束的设置是为了避免出现人造洪峰。

2　改进分段试算法

2.1　原分段试算法

文献[20-21]证明了在给定可用防洪库容$V_{防}$条件下最大削峰准则的“理想最优解”为调度期内的出库流量尽可能均匀。原分段试算法寻优过程是：首先以“理想最优解”为起点一段计算，然后依次引入约束条件，根据水库水位触及上下边界的状况将全过程分段，最后逐段调整出库过程，通过迭代最终得到可操作性强（尽可能减少闸门调整频率）的最优解。原分段试算法的初始“理想最优解”为

$$q(t)=\frac{1}{T}\left[\sum_{t=1}^{T}Q(t)\cdot\Delta t-V_{防}\right] \tag{9}$$

初始“理想最优解”俗称“削平头”，其原理见图1，对于库容较小的低调节性能水库，文献[21]中的全过程整体试算法可能会产生以下问题：（1）图1中$[0,t_1]$段为腾库预泄，水库水位下降。但当水库库容较小时有可能会将水库放空，计算水位低于库容曲线、泄流能力曲线下限，导致计算错误。（2）图1中$[t_1,t_2]$段为蓄水削峰，如果前期$[0,t_1]$由于其他约束条件没有预泄到位，则该段蓄量将超过可用防洪库容$V_{防}$。当水库库容较小时，计算水位可能突破库容曲线上限，导致迭代计算无法正常进行。（3）频繁受上下限水位约束影响，使得迭代过程的“连续性”遭到破坏，从而导致迭代失败，或者产生出库过程“畸形”，降低了调度结果的合理性和可操作性。

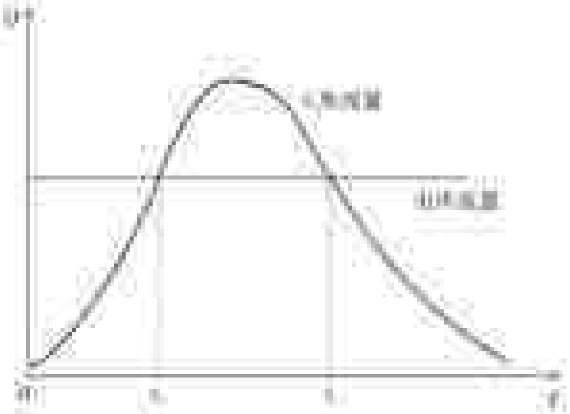

图1　“理想最优解”示意图

Fig. 1　Schematic diagram of the"ideal optimal solution"

2.2　改进分段试算法

针对原分段试算法的上述问题，对低调节性能水库提出改进分段试算法，其步骤如下。

2.2.1　防洪调度期阶段划分

首先，根据低调节性能水库的调洪水位形成机制和实时防洪调度决策的一般流程，建立“概念性”分段原则，将原分段试算法中全调度期初始“理想最优解”改成分阶段确定“理想最优解”；然后，根据实时入库洪水过程进行试算，动态确定各阶段的起讫时间。本文将防洪调度期分为 5 段，见图 2，各阶段的主要功能如下：

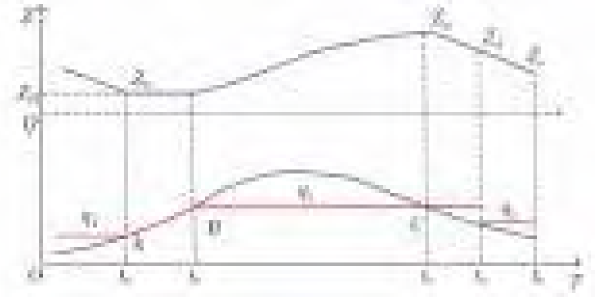

图 2　改进分段试算方法示意图

Fig. 2　Schematic diagram of the improved stage-wise trial-and-error method

(1)$[1,t_1]$为腾库预泄段，预泄腾库，提升水库的调洪能力；(2)$[t_1,t_2]$为过渡维持段，保持预泄效果，等候洪峰段出现；(3)$[t_2,t_3]$为削峰蓄洪段，利用水库的预泄库容和设计防洪库容共同消减洪峰；(4)$[t_3,t_4]$为安全消落段，洪峰过后，及时将水库水位消落到安全水位以下；(5)$[t_4,t_5]$为期末消落段，进一步将水库水位消落到期末控制水位。

2.2.2　腾库预泄段最优出库过程试算

(1)为防止预泄水量超过水库库容，在模型中增加预泄深度约束，即给定预泄最低水位 Z_x(对于低调节性能水库可设为死水位)，从起调水位 Z_0 到 Z_x，水库预泄的蓄水量为

$$V_x=f_{Z\text{-}V}(Z_0)-f_{Z\text{-}V}(Z_x) \tag{10}$$

式中：$f_{Z\text{-}V}(\cdot)$是水库水位库容函数。

(2)为了减少闸门操作次数和实现最大预泄流量最小化，在总出库水量一定的条件下，需要保证腾库预泄段出库流量尽可能均匀，参见图 2，腾库预泄段平均出库流量试算步骤如下。

①预泄终止点 t_1 点的特征为出库流量等于入库流量，t_1 点可通过试算得到，首先假定预泄时段数为 m，腾库预泄段平均出库流量为 q_1，则

$$q_1=\frac{1}{m}\left(\sum_{t=1}^{m}Q(t)\cdot\Delta t+V_x\right) \tag{11}$$

②若 $Q(m-1)\leqslant q_1\leqslant Q(m)$，则 $t_1=m$，q_1 为腾库预泄段“理想最优解”，$q(t)=q_1$，$t\in[1,t_1]$，然后转③；否则，令 $m=\{t\,|\,Q(t-1)\leqslant q_1\leqslant Q(t)\}$，转①。

③根据 $Q(t)$和 $q(t)$在$[1,t_1]$腾库预泄段进行逐时段调节计算，逐时段检验泄流能力约束、出库流量变幅约束和最大出库流量约束等，对不满足约束条件的采用文献[21]的方法进行逐时段修正，最后得到腾库预泄段的出库流量 $q(t)$、腾库预泄段终止时刻 t_1 以及 t_1 时刻的水库水位 $Z(t_1)$。

2.2.3　削峰蓄洪段最优出库过程试算

削峰蓄洪段是最大削峰准则防洪优化调度的关键控制段，在可用调洪库容和入库洪水一定的条件下，出库流量尽可能均匀(削平头)是“理想最优解”，削峰蓄洪段平均出库流量试算步骤如下。

(1)计算可用调洪库容，为了应对后续来水，实现设计调洪库容的分级使用，需给定调度期最高控制水位 Z_m(式(4))，t_3(图 2)，是调洪最高水位出现时刻，为了实现最大削峰准则，前期预泄腾空库容应当用于削峰蓄洪段，所以削峰蓄洪段的起调水位为 $Z(t_1)$，削峰蓄洪段可用调洪库容为

$$V_m=f_{Z\text{-}V}(Z_m)-f_{Z\text{-}V}(Z(t_1)) \tag{12}$$

(2)削峰蓄洪段的平均出库流量应当不小于腾库预泄段的平均出库流量，不大于洪峰流量，因此可假定初始平均出库流量为

$$q_2=\frac{Q(t_1)+Q_{\max}}{2} \tag{13}$$

(3)根据 q_2，结合来水 $Q(t)$确定削峰蓄洪段的左右边界 t_2 和 t_3，计算所需要水库调蓄的库容为

$$\Delta V=\sum_{t=t_2}^{t_3}[Q(t)-q_2]\Delta t \tag{14}$$

(4)给定试算精度 ε，若 $|\Delta V-V_m|\leqslant\varepsilon$，则得削峰蓄洪段的起始时间 t_2 和终止时间 t_3，削峰蓄洪段的“理想最优解”$q(t)=q_2$，$t\in[t_2,t_3]$，转下一步(5)；否则，按式(15)调整 q_2，转上一步(3)。

$$q_2\Leftarrow q_2+\frac{\Delta V-V_m}{t_3-t_2} \tag{15}$$

(5)根据 $Q(t)$和 $q(t)$在$[t_2,t_3]$削峰蓄洪段进行逐时段调节计算，逐时段检验泄流能力约束，对不满足约束条件的采用文献[21]的方法进行逐时段修正，最后得到削峰蓄洪段的出库流量 $q(t)$、削峰蓄洪段的起始时间 t_2 和终止时间 t_3，以及水库调洪最高水位 $Z(t_3)$。

2.2.4　过渡维持段出库过程确定

t_1 为预泄的终止时间，t_2 为蓄洪的起始时间，为

保证将预泄的腾空库容用于削峰蓄洪段，过渡维持段的出库过程确定步骤如下：

（1）一般采用来多少放多少，保持水位不变的策略，即 $q(t)=Q(t)$。

（2）根据 $Q(t)$ 和 $q(t)$ 在 $[t_1,t_2]$ 过渡维持段进行逐时段调节计算，逐时段检验泄流能力约束，对不满足约束条件的采用文献[21]的方法进行逐时段修正，最后得到过渡维持段的出库流量 $q(t)$ 和过渡维持段由于泄流能力不足占用的预泄库容 V_z。

（3）若 $V_z=0$，转 2.2.5；否则改变削峰蓄洪段的调洪库容 $V_m \Leftarrow V_m - V_z$，转第 2.2.3 重新确定削峰蓄洪段的出库过程。

2.2.5　安全消落段出库过程确定

t_3 为削峰终止时间，也是调洪最高水位出现时间，为了水库防洪安全，水库水位应尽快回到安全水位以下，为此在最高控制水位和洪水资源利用回蓄水位（期末水位）之间增设安全水位 Z_A，在水库回落到该水位之前，维持出库流量 q_2 不变，见图 2 的 $[t_3,t_4]$ 段，该段的主要计算任务是确定 t_4，可以通过试错实现，步骤如下：

（1）计算安全消落段的消落水量

$$V_s=f_{Z\text{-}V}(Z(t_4))-f_{Z\text{-}V}(Z_A) \tag{16}$$

（2）假定 t_4，计算 $\Delta V_s=\sum\limits_{t=t_3}^{t_4}(q_2-Q(t))\Delta t$

（3）若 $|\Delta V_s - V_s| \leqslant \varepsilon$，$t_4$ 即为所求，转 2.2.6；否则，转（2）。

2.2.6　期末消落段出库过程确定

达到水库安全水位，表明本次洪水的防洪调度任务基本完成，水库调度转为洪水资源利用阶段，应适时减小出库流量，尽可能将水库水位消落到期末控制水位 Z_e，步骤如下：

（1）计算期末消落段的消落水量

$$V_H=f_{Z\text{-}V}(Z_e)-f_{Z\text{-}V}(Z(t_4)) \tag{17}$$

（2）计算 $[t_4,t_5]$ 平均出库流量

$$q_3=\frac{1}{t_5-t_4}\left(\sum_{t=t_4}^{t_5}Q(t)\Delta t+V_H\right)$$

（3）若 $q_3 \leqslant q_2$，则 $q(t)=q_3$，$t\in[t_4,t_5]$；否则 $q(t)=q_2$，$t\in[t_4,t_5]$。

改进分段试算法的计算流程见图 3。

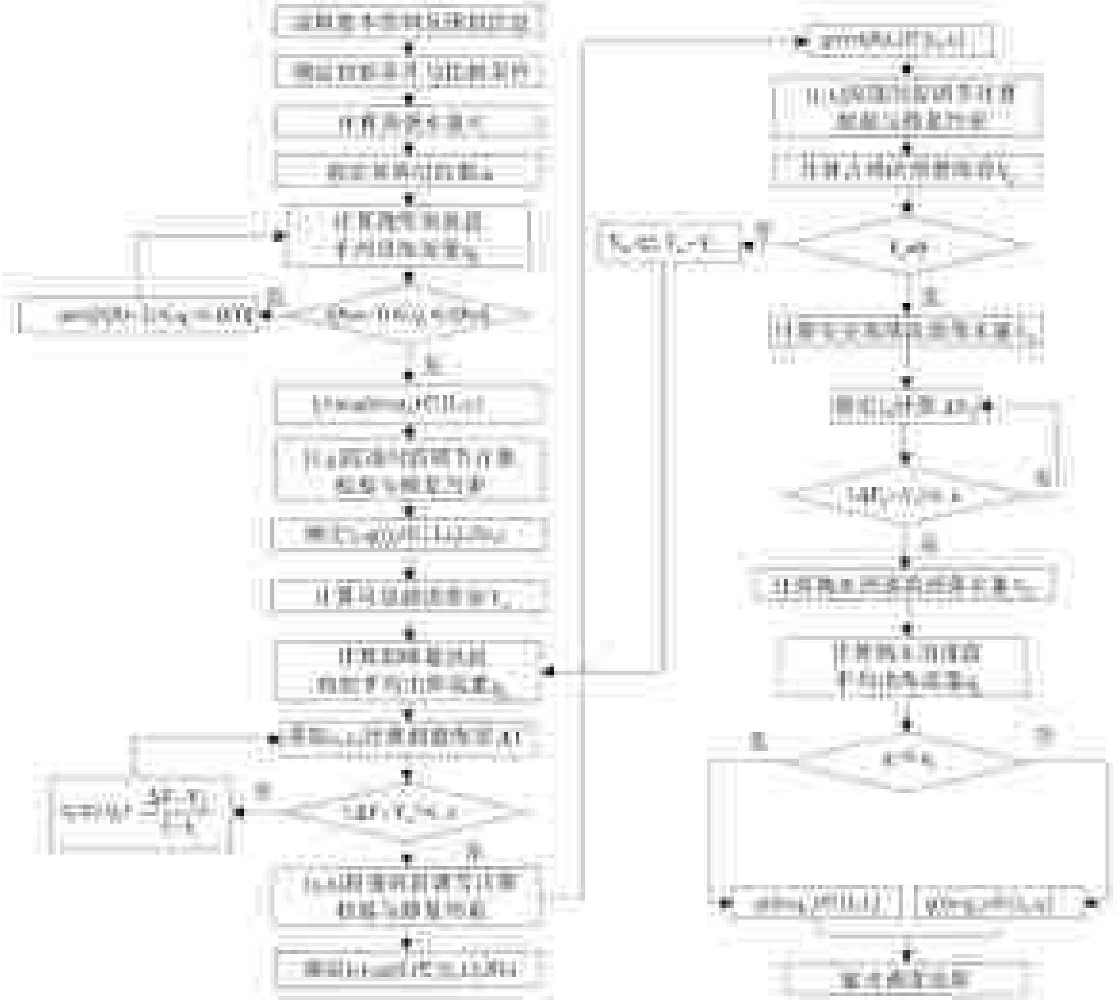

图 3　改进分段试算法计算流程

Fig. 3　Algorithm flow chart of the original stage-wise trial-and-error method

3　应用实例

富春江水库是一座以发电为主，兼顾防洪、航运、城市供水的日调节水库。水库正常蓄水位和汛限水位均为 23.00 m，死水位 21.50 m，防洪高水位 23.50 m，设计洪水位 24.70 m，校核洪水位 28.20 m。

选取富春江水库 20170624 号洪水开展模拟调度。调度期为 72 h；时段长取 1 h；调度期初坝前水位 23.00 m；当前面临时刻的出库流量 6 000 m^3/s；出库流量允许变幅 5 000 m^3/s；预泄最低水位 21.50 m；调洪最高控制水位 23.20 m；安全水位 23.00 m；期末控制水位 22.80 m。

采用上述计算条件，分别应用原分段试算法和改进分段试算法进行模拟调度，图 4 为改进分段试算法的调度结果，图 5 为原分段试算法调度结果。表 1 为两种方法控制水位与削峰率对比。

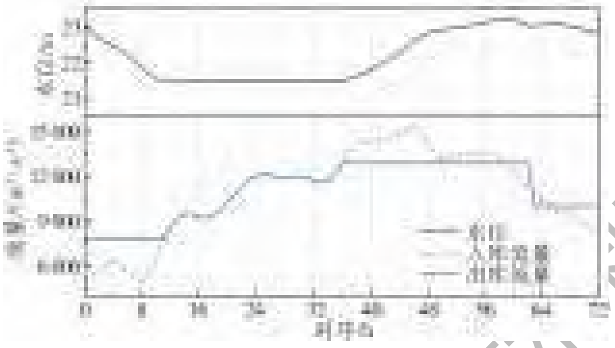

图 4　改进分段试算法调度结果

Fig. 4　Operation results of the improved stage-wise trial-and-error method

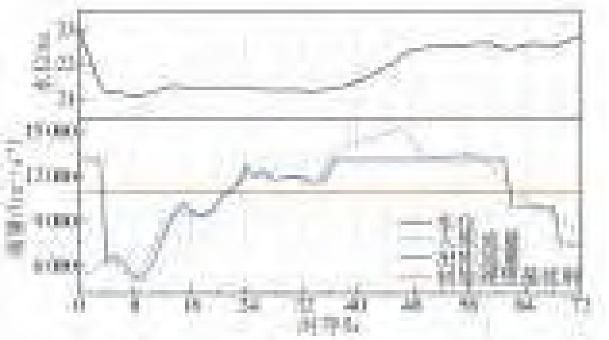

图 5　原分段试算法调度结果

Fig. 5　Operation results of the original stage-wise trial-and-error method

由图 4、5 和表 1 可得如下结果：

(1)改进分段试算法调度结果中，各种水位约束均得到严格满足，而原分段试算法的最低水位为 21.12 m，最高水位 23.00 m，均与给定的控制条件有一定的偏差，主要原因是原分段试算的分段是根据全过程“理想最优解”的调洪演算结果确定的分段数，参见图 5。由于初始“理想最优解”的出库流量较大，在腾库预泄段，预泄水位很快跌破“最低水位”，可供流量调整的时段数少，实现“离散”条件下最低水位的精准控制困难；在削峰蓄洪段，由于缺少改进分段试算法的“过渡维持段”，削峰蓄洪段的起调水位不确定性增加，也难以实现最高水位的精准控制。

表 1　两种方法控制水位与削峰率对比

Tab. 1　Comparison of water level control and peak shaving rate by two methods

方法	改进分段试算法	原分段试算法
最高水位/m	23.20	23.00
最低水位/m	21.50	21.12
期末水位/m	22.80	22.80
最大出库流量/$(\mathrm{m}^3\cdot\mathrm{s}^{-1})$	12 900	13 200
削峰率/%	16.20	14.30

(2)从出库过程看，改进分段试算法出库过程规整，阶段清晰，各阶段的出库过程符合事前预期，结果合理，可操作性强。原分段试算法调度结果出库过程“锯齿”比较严重(由于短时段试算)，预泄时段少，预泄流量大(库容小水库水位快速消落到下限水位的原因)。

(3)由于改进分段试算法水位控制“精准”，可调防洪库容利用充分，所以削峰率为 16.2%，优于原分段试算法调度的削峰率 14.3%，削峰率提升 13.3%。

4　结　论

本文针对原分段试算法应用于周调节以下低调节性能水库效果不佳的问题，提出了改进分段试算法，与文献[21]中原分段试算法相比具有以下优点：

(1)能够较好地适应低调节水库库容小、调节性能低的特点，克服了调洪计算中突破库容曲线、泄流能力的上下限导致计算错误的问题，算法的稳定性好。

(2)改进分段试算法计算原理简单，分段迭代过程完整清晰，能得到合理的可操作性强的调度方案。

(3)改进分段试算法在富春江水库的防洪调度中模拟调度，效果良好，具有实用价值。

本文没有考虑水库的补偿调度，下一步将开展适用于低调节性能水库防洪补偿调度的改进分段试算方法研究。

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Improved stage-wise trial-and-error method for optimal flood control operation of reservoirs with a low regulation capacity

WANG Yixu[1], LIU Qiang[2], ZHONG Pingan[1], ZHAO Keming[1], YAO Chaoyu[3]

(1. *College of Hydrology and Water Resources, Hohai University, Nanjing* 210098, *China*;
2. *PowerChina Huadong Engineering Corporation Limited, Hangzhou* 310014, *China*;
3. *PowerChina Zhongnan Engineering Corporation Limited, Changsha* 410014, *China*)

Abstract: The storage of a reservoir with low regulation capacity is often small, and the reservoir water level is sensitive to changes in the outflow process. In flood control optimization process operation, small changes in outflows may lead to large variations in the reservoir water level, resulting in the reservoir water level frequently approaches the upper and lower controlled boundaries. To meet the maximum and minimum water level constraints, it will cause severe fluctuations of the reservoir outflow process and affect the operability of the optimal solution.

The maximum peak-reduction criterion is taken as the objective function, considering the constraint conditions such as the mass balance, the maximum and minimum water levels, the discharge capacity, the fluctuation of the outflow period, and the return storage level at the end of the operation horizon. The optimized dispatching model is developed for reservoir flood control. Based on the operation process of the real-time flood control operation of the reservoir and the mechanism that the reservoir water levels frequently approach the upper and lower controlled boundaries in the flood control operation, the improved stage-wise trial-and-error method with low regulation capacity is proposed. The maximization of real-time flood regulation capacity and the operability of the optimal operation solutions is taking into account in this method and proposes the principle of "conceptual" segment. The whole operation period is divided into five stages including the pre-discharge stage, maintenance stage, flood storage stage, safety drawdown stage, and final drawdown stage. Based on the principle of segmented mass balance, with the principle of homogenizing the outflow process, a segmented trial calculation strategy and implementation process for dynamically determining the start and end times of each stage are proposed using the real-time flooding process of the storage. Furthermore, the uniform outflow process iterative optimization method is proposed.

Taking the Fuchunjiang Reservoir as the research subject, the simulation operation of the improved stage-wise trial-and-error method was carried out. The results were compared with the original stage-wise trial-and-error method and reveal the following:

(1) It was found that with the improved stage-wise trial-and-error method, various constraints are strictly met. However, the original stage-wise trial-and-error method had a certain deviation from the given water level control conditions. The lowest water level was 0.38 m higher, and the highest water level was lower by 0.2 m, and the adjustable flood control storage capacity was not fully used.

(2) From the perspective of the outflow process, the improved stage-wise trial-and-error method had a regular outflow process with clear stages, and the outflow process at each stage conformed to pre-expectations, with reasonable results and strong operability. The "sawtooth" in the outflow process of the original stage-wise trial-and-error method operation results was

more serious, especially in the pre-release stage, where the pre-release period was short and large.

(3) Due to the "precision" water level control of the improved stage-wise trial-and-error method and the full utilization of the adjustable flood control storage capacity, the peak reduction rate was 16.2%, which was better than the 14.3% peak reduction rate produced by the original stage-wise trial-and-error method, and the peak reduction rate was increased by 13.3%.

To address the poor performance of the original stage-wise trial-and-error method applied to reservoirs with low regulation capacity under weekly regulation, an improved stage-wise trial-and-error method was proposed, which had the following advantages compared with the original one:

(1) It could better adapt to the characteristics of reservoirs with small storage and low regulation capacity. It may overcome the shortcoming that the upper and lower limits of reservoir storage capacity and discharge capacity were frequently broken in the original one, which brought a good stability performance to the algorithm.

(2) The calculation principle of the improved stage-wise trial-and-error method was simple, and the segmentation iteration process was complete and clear. A reasonable and operability operation solution could be easily obtained.

(3) The case study in Fuchunjiang Reservoir proved that the improved stage-wise trial-and-error method achieved good application results in the flood control operation.

Key words: flood control of reservoirs; optimal operation; the principle of maximum flood peak reduction; improved stage-wise trial-and-error method

(上接第 580 页)

To ascertain the source of sulfate pollution during the water diversion period in the SNWD-ERP in Shandong province, monitoring points in NSL and its surrounding rivers and groundwater distribution were sampled to analyze the characteristics of hydrochemical and sulfate concentration distribution in NSL. The $\delta(^{34}S_{SO_4})$ value was used to calculate the contribution rate of each direct source in the diversion water period, and combining with the $\delta(^{18}O_{SO_4})$ value to explore the sources of sulfate in NSL and the major sources of sulfate in inflowing rivers in the diversion water period. The variety rules of sulfate sources in NSL are analyzed to search for the potential sources of sulfate pollution and appropriate treatment techniques were investigaled to reduce sulfate concentration and ensure the safety of water supply, and provide data support in the SNWD-ERP.

The main result were as follows: (1) in the diversion water period, the pH of NSL and its inflowing rivers was alkalescence, and groundwater was neutral. The sulfate concentration in NSL gradually increased from south to north, even as high as 631.50 mg/L in the Nanyang sub lake (NE). The main water types of NSL were Na^+-$SO_4{}^{2-}$-Cl^- and Na^+-$SO_4{}^{2-}$-HCO_3, which was mainly affected by carbonate weathering. But the water types in groundwater were Ca^{2+}-$SO_4{}^{2-}$-Cl^-, which was mainly affected by the dissolution of evaporite salt and the weathering of silicate. (2) Evaporite dissolution has the largest sulfate contribution rate in NSL, reaching 52.18 %. But the direct source of sulfate in Nanyang sub lake was mainly carried by rivers, especially Zhuzhaoxin River, Old Canal, and Wanfu River. The contribution rate to Nanyang Lake sulfate was much higher than that of evaporite dissolution, and contribution rate of water transfer in NSL from Jiangsu was only 5.34 %. (3) For the inflowing river, sewage inflow was the main source of sulfate in the Baima River, Chengguo River, Panlong River, and Dongyu River, and the main sulfate source in Zhuzhaoxin River, Wanfu River, Old Wanfu River, Guangfu River, and Old Canal were evaporite dissolution, while the Zhushui River sulfate was affected by both sewage and evaporite dissolution. (4) Based on the analysis of the source of sulfate in the Nansi Lake basin during the water transfer period, a reasonable sulfate prevention and control system was constructed. For rivers with a high contribution rate, the "river chief system" should be adopted to assign responsibility to people, and reasonable treatment measures should be taken before the water is transferred and used.

Key words: Nansi Lake; sulfate; diversion water period; $\delta(^{34}S_{SO_4})$; $\delta(^{18}O_{SO_4})$