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小浪底水库浑水异重流出库理论判别

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摘 要：浑水异重流是多沙河流水库中泥沙常见的运动形式，在小浪底水库拦沙运用初期对减少库区泥沙淤积起到重要作用。异重流持续运移至坝前实现排沙出库所满足的条件对多沙河流水库的运行管理至关重要。本文引入河流功的概念研究小浪底水库异重流出库的动力因素。在忽略水沙交换的情况下，异重流运动受控于河床纵比降和自身水沙动力。用潜入点至坝前的平均河床纵比降J_0与异重流临界比降J_c的比值J_0/J_c表示相对河床纵比降，代表异重流运动的地形条件；用异重流平衡速度u和持续时间T的乘积与潜入点至坝前的径向距离L比值uT/L表示异重流持续运动的相对距离，代表异重流水沙动力因子；进而确定相对河床纵比降J_0/J_c和自身水沙动力因素uT/L双参数构成的异重流出库判别图。分析小浪底水库1999年建库至2023年的逐日水沙资料，确定了92场次异重流过程，从整体上看，水量和沙量越大的洪水过程能够产生较为明显的异重流排沙过程。采用该判别图能成功将大部分能否到达坝前的场次异重流进行区分，同时为多沙河流水库异重流高效排沙提供了可靠依据。

关键词：浑水异重流；小浪底水库；出库；判别

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小浪底水库控制了黄河主要的泥沙来源，洪水挟沙入库频繁产生异重流，高水位运行时利用异重流排沙被认为是小浪底水库在拦沙运用期间控制淤积的重要手段[1–2]。李国英[3]提出在小浪底库区人工塑造异重流，加大小浪底水库的排沙量。围绕小浪底水库异重流排沙，曲少军等[4]提出调整异重流出库时的排沙流量，以达到下游河道少淤甚至不淤的排沙效果；部国明等[5]采用多元非线性拟合方法提出了调水调沙期异重流排沙比的预测方法；王婷等[6]确定了高水位异重流出库条件及排沙影响因素。较为成熟的数值模拟已经能够对水库异重流工程实践提供技术支撑，包括采用零维水库法基础上考虑底坡的异重流倒灌公式处理干支流交换[7–8]、小浪底水库异重流全周期[9–10]、黄河河口水沙异重流[11]、局部分级时间步长提高计算效率。同时，在已知的物理机制基础上建立起来的数值模型，还可以高效地分析异重流特征。Hu 等[13]对比了三方程与四方程模型差异；An 等[14]数值模拟雷诺数、密度弗劳德数、含沙量对异重流潜入的影响；Cao 等[15]考虑泥沙输运、河床冲淤，采用双层模型对水库异重流进行全耦合模拟；Hu 等[16]模拟论证了三方程模型对自加速异重流的适用性；胡鹏等[17]模拟确定了水卷吸和泥沙侵蚀经验关系式的适用性和对异重流模拟的影响；章若茵等[18]利用SCHISM模型模拟异重流潜入及垂向结构受入口水沙条件影响的变化；谢晓云等[19]采用大涡模拟分析了刚性植被对双层密度层化异重流的影响。在量化单因子对异重流运动的影响方面，水槽试验仍是分析异重流特征较为直观的方法。已有水槽试验研究确定了异重流形成（潜入）[20]、结构[21]与运动特征[22]等规律，以及河床地形[23–25]、进口流量[23]、出口流量[26]、排沙历时[26]、植被[27]、含沙量[28]等因素对异重流运动和排沙效率的影响。异重流运动机理是异

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重流排沙的理论基础，异重流与上层清水掺混[29–31]和河床[32]的水沙交换与冲淤[33]方面仍是今后的研究重点。

异重流排沙的前提是异重流能持续运动到坝前，取决于其是否满足持续运动的条件，即维持异重流在水库中持续向前运动到达坝址而排出水库所要满足的水沙搭配情况[34–35]。入库水沙、水库运用方式、水库边界条件均会对异重流能否到达坝前产生影响[36]。目前，确定了异重流持续运动条件的定量经验关系，主要包括基于流量与含沙量及组成[37]、水流功率与库区平均水深[36]的定量经验关系。李书霞等[38]基于均匀流的异重流流速与单宽流量、含沙量及库底坡降之间的关系式，给出了异重流传播速度的具体计算方法。由于欠缺力学机制层面的解释，经验方法在普适性和适用性方面略显不足。

国内外对于浑水异重流三方程与四方程模型研究，对异重流持续运动条件的分析很有启发性。Parker[39]认为异重流的沿程冲刷是其长距离输运的基础，通过考虑冲刷对异重流驱动力的增益确定了自加速异重流的动力来源于沿程冲刷的泥沙。由连续方程、动量方程、泥沙输运方程构成的三方程模型模拟自加速异重流时存在能量不闭合的情况，因此Parker等[40]通过添加紊动能输运方程实现紊动能的封闭进而建立了四方程模型。三方程与四方程模型相比，弱化了异重流与底层床沙和上层水体水沙交换的反馈作用，但三方程在机理上的局限并没有妨碍其在国内水库浑水异重流研究中的广泛应用。本文认为水库浑水异重流持续运动即为异重流出库，在确定异重流出库条件时，对异重流与环境的水沙交换不做显式考虑，引入河流功的概念研究小浪底水库异重流出库的动力因素。

1　小浪底异重流特点

小浪底水利枢纽是黄河干流三门峡以下唯一能够取得较大库容的控制性工程，既可较好地控制黄河洪水，又可利用其淤沙库容拦截泥沙，进行调水调沙运用，以减缓下游河床的淤积抬高，运用以来发挥了巨大的社会效益和经济效益。从1999年9月开始蓄水运用至2023年底，小浪底水库已运用21 a，多年平均入库水量为255.39×10^8 m³，入库沙量为3.375×10^8 t；出库沙量为1.439×10^8 t，淤积三角洲顶点已经推进至坝前附近，全库区累计淤积量为34.448×10^8 m³，淤积纵剖面变化如图1所示。按库段进行统计，随着淤积不断向坝前推进，从库尾到坝前，各段淤积体均经历先增长后稳定的过程，如图2所示。图2中，“HH+数字”表示库区断面号，断面号从坝前到库尾按顺序布置。

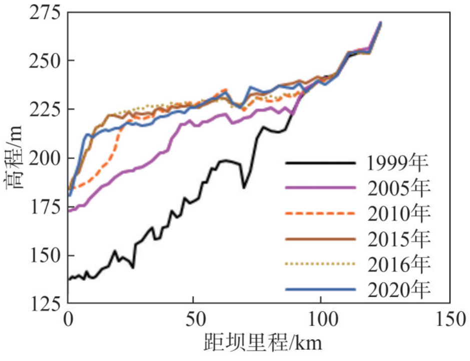

图1　小浪底水库库区纵剖面（深泓点）

Fig. 1　Longitudinal profile of Xiaolangdi Reservoir (thalweg)

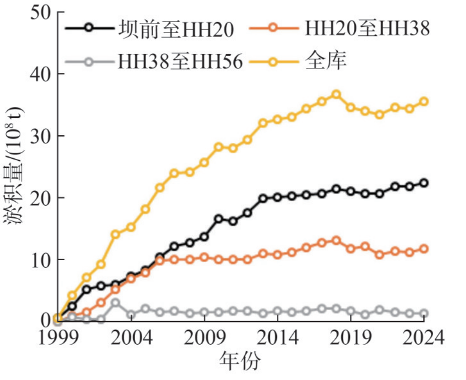

图2　小浪底水库淤积量逐年变化

Fig. 2　Annual sedimentation changes of Xiaolangdi Reservoir

水库浑水异重流运动具有明显的非恒定性，表现在流量大小和含沙量大小的变化上。异重流在潜入后向坝前传播过程中，结构复杂，异重流躯干与头部之间存在物质和能量的输送，头部厚度和运动速度的变化受到后续动力作用影响明显。如开闸式异重流[41]，头部缺少后续动力支撑而在沿程与环境水体掺混、拖尾过程中减速导致异重流快速消失。因而需要以场次异重流为整体分析异重流的运动。本文采用三门峡和小浪底水文站实测日均数据作为入库和出库水沙条件，以入库日均含沙量为指标对小浪底水库浑水异重流的场次进行界定。以日均含沙量超过20 kg/m³、输沙率超过10 000 kg/s作为场次异重流选入标准并确定异重流的入库起止时间。入库含沙量较低的水沙过程历时一般较短，形成的异重流在向坝前移动过程中衰减，无法到达坝前。由于缺少坝前监测资料，假定到达坝前的异重流均实现排沙出库。出库含沙量偏低时排沙比接近0，同时，打开底孔泄洪时水流会携带闸门附近少量浮泥出库引起出库水流有少量含沙，因此，从工程角度用出库日均含沙量超过1 kg/m³作为判别异重流是否出库的标准。按照场次异重流划分条件确定的两场异重流时间间隔较短时，同时将两场进行合并

为额外的一场异重流进行考虑。2000年以来,满足设定标准的异重流共有92场,其中,运移至坝前的出库异重流55场次。

小浪底浑水异重流场次平均流量和平均含沙量关系如图3所示。从图3可看出,两者之间没有明显的相关关系,小流量和低含沙量的异重流较多,出库和未出库异重流的分布没有差异,无法用场均流量和含沙量对出库和未出库异重流进行区分。小浪底水库异重流场次入库沙量与水量关系如图4所示。场次水量和场次沙量具有一定的正相关关系,但出库和未出库异重流的分布没有差异,也无法用场次水量和场次沙量对出库和未出库的异重流进行区分。

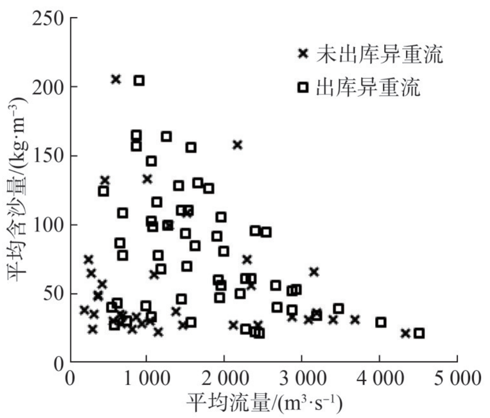

图3 小浪底水库异重流场次平均含沙量与平均流量关系

Fig. 3 Relationship between event-averaged sediment concentration and discharge of turbidity currents of Xiaolangdi Reservoir

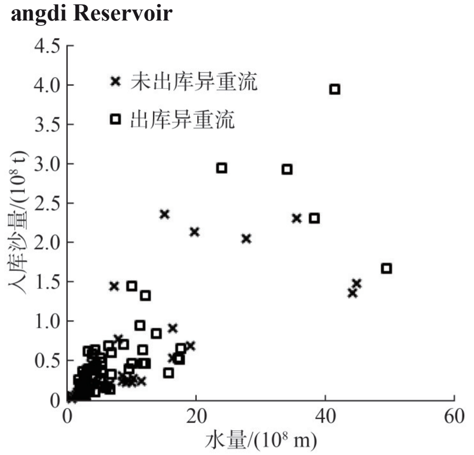

图4 小浪底水库异重流场次入库沙量与水量关系

Fig. 4 Relationship between incoming sediment load and runoff of turbidity currents of Xiaolangdi Reservoir

统计异重流场次沙量频次分布如图5所示,未出库异重流场次沙量主要集中在0.8×10^8 t以下,各区间分布较为均匀,而出库异重流场次沙量主要集中在0.2×10^8～3.2×10^8 t区间,为钟形分布。统计异重流场次水量频次分布如图6所示,未出库异重流场次水量主要集中在1×10^8～16×10^8 m^3区间,而出库异重流场次水量主要集中在4×10^8～16×10^8 t,两者水量分布均为钟形分布。从整体上看,异重流的水量和沙量越大,出库的几率越高:沙量超过0.8×10^8 t的24场异重流中,22场出库;水量超过8×10^8 m³的36场异重流中,30场出库。

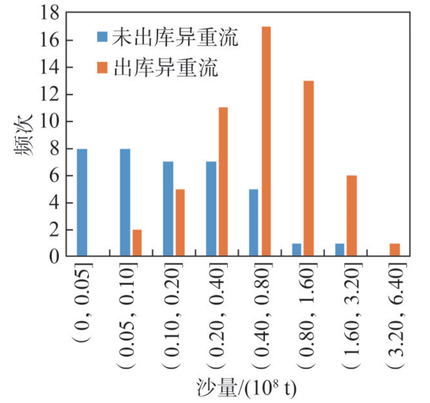

图5 小浪底水库异重流场次沙量频次分布

Fig. 5 Frequency distribution of incoming sediment load for turbidity currents of Xiaolangdi Reservoir

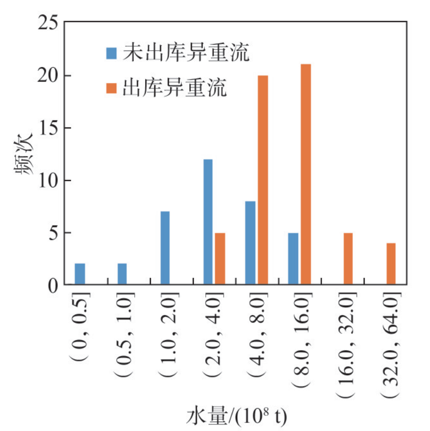

图6 小浪底水库异重流场次水量频次分布

Fig. 6 Frequency distribution of incoming water volume for turbidity currents of Xiaolangdi Reservoir

2 异重流出库条件

异重流的运动需要不断克服阻力做功,因此引入河流功的概念。假定异重流运动从潜入到停滞的沿程能量耗散为异重流功,将运动到坝前时的异重流功定义为临界功。异重流功需要超过临界功,才能运动到坝前。小浪底水库不同运用阶段,三角洲淤积体不断发展,不同淤积体之间在前坡段、顶坡段的纵比降存在明显差异,相同规模的异重流,在不同年份能否出库的情况存在明显差异,在进行对比时,需要考虑河床纵比降差异的影响。

按异重流场次平均讲,从潜入点到出库径向距离做功应大于某一临界功:

$$\gamma' Q_s J_0 L T > W_C \tag{1}$$

式中,Q_s为输沙率,γ'为容重,J_0为从潜入点到坝前的

河床纵比降，T 为持续历时，L 为径向距离，W_C 为临界功。假定异重流为均匀流，不等式(1)可以转化为：

$$uTJ_0 > \frac{W_C}{\gamma' cBhL} \tag{2}$$

式中，h 为异重流厚度，B 为异重流宽度，c 为体积含沙量，u 为异重流速度。按照量纲和谐原理，式(2)右侧同样可以认为是3个表征变量 U_S、T_S、J_S 的函数：

$$\frac{W_C}{\gamma' cBhL} = f(U_S T_S, J_S) = U_S T_S J_S \tag{3}$$

假定 $U_S T_S/L$、J_S/J_c 可用待定参数 K 表示，其中 J_c 为异重流临界比降，则式(3)可转换为：

$$f(U_S T_S, J_S) = \frac{U_S T_S}{L} \cdot \frac{J_S}{J_c} \cdot J_c L \triangleq K J_c L \tag{4}$$

将式(4)代入式(2)得：

$$\frac{uT}{L} \cdot \frac{J_0}{J_c} > K \tag{5}$$

式(5)为由 uT/L、J_0/J_c 确定的异重流能否出库的理论表达式。在忽略水沙交换的情况下，异重流能否出库受控于河床纵比降和自身水沙动力。将相对河床纵比降 J_0/J_c 和自身水沙动力因素 uT/L 双参数构成异重流出库的判别条件，用以区分能否到达坝前的场次异重流。

小浪底水库为河道型的水库，假设异重流近似为均匀流状态，假定异重流在沿程传播过程中保持宽度不变，那么异重流厚度调整与流速调整相协调。小浪底水库库区淤积体为典型的三角洲淤积形态，纵向形态规则，具有明显的顶坡段、前坡段，各段纵比降均可采用单一数值表示。忽略异重流与床面、上层清水的物质和动量交换，长距离输运的异重流满足下列基本平衡方程：

$$RgchJ = u_*^2 \tag{6}$$

式中：R 为泥沙颗粒的水下比重，取1.65；g 为重力加速度；u_* 为异重流摩阻流速，引入摩擦系数的概念来计算摩阻流速，即 $u_*^2 = C_d u^2$，其中，u 为异重流的平均速度，C_d 为摩擦系数，假定异重流维持恒定均匀流状态，参考文献[10]，C_d 取为0.005。则可以确定均匀流流速 u 与异重流厚度 h，表示如下：

$$u = \left(\frac{RgcJQ}{C_d B}\right)^{1/3},\ h = \frac{Q}{Bu} \tag{7}$$

式中，Q 为异重流流量。为了体现在不同坡度下的运用差异，引入异重流不稳定平衡态概念，表示异重流能够稳定运移的最弱运动状态，在确定异重流水沙条件后，该状态对应的临界比降记作 J_c，选择该状态的参照流速 u_c，假定 $C_d = 0.088 Re^{-1/4}$（Re 为雷洛数），同样通过采用上述平衡方程，推导得出：

$$J_c = \frac{0.027\,83 u_c^{7/4} h^{-5/4}}{Rgc} \tag{8}$$

至此，已经建立了描述异重流动力机制的模型架构，在给定的条件下，通过计算驱动力因素以及阻力因素的相互关系，可以判断异重流运移的后续发展方式，为异重流排沙期间的水库调度提供依据。

3 场次异重流出库判别

假定异重流在沿程输移过程中为恒定均匀流，忽略异重流与床面、上层清水的物质和动量交换时，确定平衡状态下异重流持续运移判别指标中各变量的经验表达式，利用实测资料构建小浪底水库的异重流持续运移判定分区图，如图7所示，对小浪底水库92场异重流进行逐一概化分析，确定各场异重流历时、场均入库流量与体积含沙量，根据场次异重流入库时段坝前平均水位确定异重流潜入点位置，由纵剖面地形确定异重流潜入点至坝前距离、整体平均河床纵比降，根据实际淤积纵剖面，一般按三角洲顶点划分纵剖面的陡坡段和缓坡段，确定缓坡段河床平均纵比降 J_M，计算异重流在缓坡段的速度 u_M 与厚度 h_M，采用 u_M 确定异重流动力驱动的相对距离 uT/L、异重流临界纵比降 J_c。

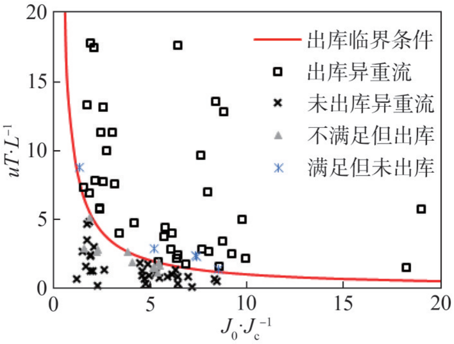

图7　小浪底水库场次异重流出库判别图

Fig. 7　Discriminant diagram of sediment discharge with turbidity currents in Xiaolangdi Reservoir

以2003年8月10日至17日的一场异重流为例说明计算过程。该异重流历时8 d、场次平均流量为599 m^3/s、体积含沙量为0.016 3、异重流潜入点距坝沿程距离为83.14 km、平均河床纵比降为0.000 55、缓坡 J_M=0.000 146、过流宽度为500 m，代入式(7)得 $u=u_M$=0.349 m/s、h_M=3.44 m，按 u_c=max(u, 0.25 m/s)代入式(8)得 J_c=0.000 357，最终得到 uT/L=2.90、J_0/J_c=1.54。统计的92场异重流 J_0 在0.000 267～0.005 210之间，缓坡流速在0.184～1.205 m/s之间，变化范围较大，预测结果代表性较强。对92场异重流进行判别，结果如图7所示。

图7中未出库异重流场次处于坐标系的左下方，出库异重流场次处于坐标系的右上方，从而论证了异

重流能够出库可以采用J_0/J_c和uT/L两个参数进行判定,异重流能否出库的临界条件可以近似用K=12的双曲线进行表示,未出库的37场异重流中有33场位于该曲线左下方,出库的55场异重流中有45场位于该曲线右上方,该判别图基本上能够对异重流出库和未出库进行比较好的区分。没有成功判别的14场异重流均位于曲线附近,其中,4场未出库的异重流位于曲线右上方,10场出库的异重流位于曲线左下方。判别未成功的4场未出库的异重流均处于水库水位明显抬升阶段,出库流量远小于入库流量,初步认定是异重流沿程输运过程中被支流分水分沙,导致异重流动力减小从而未能出库;对于判定未成功的10场出库异重流,其中,5场异重流发生在2004年至2006年水库降水冲刷期,异重流受到水库降低水位冲刷影响,入库含沙量比入库控制站实测值明显偏大,导致有足够的动力出库,另有5场异重流发生在2003、2007、2010—2013年,这几年水库发生异重流次数较多,5场异重流或与前期异重流时间间隔短,或前期有长时间的输沙未达到本文异重流统计阈值的过程,使得该5场后续异重流沿程获得额外泥沙补给,增强了自身动力,进而实现出库。

在相对河床纵比降J_0/J_c和自身水沙动力因素uT/L双参数构成的坐标系中,随着参数uT/L、J_0/J_c的增大,异重流更容易推进至坝前,整个坐标区域可分为两个区域:远离坐标轴和0点的动力区和靠近坐标轴和零点的惯性区。在动力区,异重流可以完全依靠自身势能可以快速到达坝前;在惯性区,异重流自身能量不足,存在明显减速情况。对于实际场次异重流事件,当头部向前推进过程依赖后续异重流躯干提供能量,仍可能实现排沙。不能实现异重流出库的场次洪水主要位于该坐标系的左下方。

本文提出基于理论的判别图,是对异重流理论分析的探索研究,后续工作需要通过更多的观测数据来验证模型的准确性和适用性。该方法假定异重流运动为恒定均匀流,适用于河道型水库,该类水库异重流运动路径单一,异重流宽度沿程变化较小。本文出发点是浑水异重流的河流功,从能量角度判定异重流出库,理论上较前人相关研究更进了一步,后续需要对异重流河流功的表达式进行完善。小浪底库区支流可能会造成异重流分流分沙、不同异重流之间相互作用、水流的冲刷等情况,对异重流出库判别均能产生影响,后续将论证该判别方法在其他水库异重流的适应性。

4 结　论

本文对小浪底水库建库以来的主要异重流排沙场次过程,根据异重流受力分析确定相应动力因素,提出了适用于多沙河流水库异重流运移至坝前的无量纲因子。最后,利用实测资料构建了小浪底水库的异重流持续运移判定分区图,确定了判定条件。得到以下主要结论:

1)确定小浪底水库异重流运动的关键因子为地形条件和自身水沙动力。入库洪水的含沙量增加、流量增加、历时增加,坝前水位降低,都会使异重流更容易到达坝前。

2)提出无量纲因子相对河床纵比降J_0/J_c和异重流持续运动的相对距离uT/L表征异重流持续运行到坝前的双控制变量。其中:潜入点至坝前的平均河床纵比降与异重流临界比降的比值J_0/J_c表示相对河床纵比降,指示异重流运动的地形条件;异重流平衡速度和持续时间的乘积与潜入点至坝前的径向距离比值uT/L表示有持续异重流持续运动的相对距离,指示异重流水沙动力因子。

3)基于双控制变量构建的异重流出库判定分区图,能够有效判定异重流是否出库。

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Theoretical Discrimination of Turbidity Current Venting in Xiaolangdi Reservoir

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Abstract:

Objective The Xiaolangdi Reservoir, as a representative sediment-loaded river reservoir, shows that turbidity current venting plays a crucial role in mitigating reservoir sedimentation during initial sediment retention operations. Understanding the mechanical conditions under which the turbidity current reaches the dam for effective sediment discharge or venting presents a critical operational challenge in managing sediment-loaded river reservoirs. The theoretical identification of turbidity current venting provides direct technical support for water and sediment regulation strategies, which form the objective of this study.

Methods Turbidity current venting and the turbidity current reaching the dam were considered equivalent situations. The turbidity current events were selected based on the conditions that, for the inflow, the daily sediment concentration exceeded 20 kg/m³ and the daily sediment transport rate exceeded 10 000 kg/s, which were used as the thresholds for turbidity current event occurrence. For practical significance, a daily sediment concentration greater than 1 kg/m³ for the outflow was employed as the standard to determine whether sediment discharge occurred. The concept of river work was introduced, as the movement of the turbidity current needs to overcome resistance to perform work, referred to as turbidity work. It was assumed that the energy dissipation of turbidity current movement from plunging to cessation was equal to turbidity work, and the turbidity work when it reached the dam was defined as critical work. Therefore, the theoretical discrimination of turbidity current venting was that the turbidity current work needed to exceed the critical work before reaching the dam. The turbidity current movement was controlled by its sediment content and the longitudinal gradient of the riverbed, by neglecting the water and sediment exchange and mixing processes. The ratio J_0/J_c of the average longitudinal gradient J_0 of the riverbed from the plunge point to the dam and the critical gradient J_c of the turbidity current is utilized to represent the relative longitudinal gradient of the riverbed, indicating the topographic conditions of turbidity current movement. The ratio uT/L, where u is the turbidity current equilibrium velocity, T is the duration, and L is the radial distance from the plunge point to the dam, is utilized to represent the relative distance of motion, indicating the dynamic factor of the turbidity current. The theoretical discrimination is expressed as $J_0/J_c \cdot uT/L > K$, where K is a parameter related to a specific reservoir. Therefore, the discriminant diagram of turbidity current venting, composed of the relative longitudinal gradient of the riverbed (J_0/J_c) and its hydrodynamic factor (uT/L), was determined.

Results and Discussions A total of 92 turbidity current events were identified, of which 55 resulted in sediment discharge. Statistically, flood events with higher sediment concentrations and larger water volumes produced turbidity currents with more significant sediment discharge. There was no clear correlation between the event-averaged flow discharge and sediment concentration, and these parameters cannot be directly employed to distinguish between turbidity currents that reached the dam and those that did not, i.e., for discrimination purposes. A clear positive correlation existed between the event water and sediment amounts; however, these two parameters failed to serve as effective discriminants. The sediment amount of turbidity current events that did not reach the dam was primarily concentrated below 80 million tons, whereas that of the events that reached the dam was mainly distributed in the range of 0.2～320.0 million tons, exhibiting a bell-shaped distribution. The water volume of turbidity current events that did not reach the dam was mainly concentrated in the range of 0.1～1.6 billion m^3, while that of the reached events was mainly concentrated in the range of 0.4～1.6 billion m^3, both showing bell-shaped distributions. The larger the water and sediment amounts in a turbidity current event, the higher the probability of its reaching the dam. The entire coordinate area of the discriminant diagram was divided into two regions, namely the dynamic region at the top left and the inertial region at the bottom right. As the parameters J_0/J_c and uT/L increased, the density current was more likely to advance toward the dam and occupy the dynamic region. In the dynamic zone, the turbidity current quickly reached the dam by its potential energy. In the inertia zone, a significant deceleration of the turbidity current occurred due to insufficient potential energy. For most turbidity current events in the inertia zone, the head of the current was still able to reach the dam due to the energy supplied by the trunk of the turbidity current. The flood events in which the turbidity current did not reach the dam were mainly located in the lower left corner of this coordinate system. The critical condition for the sediment discharge of turbidity currents was represented by a hyperbolic curve with K=12 for the Xiaolangdi Reservoir. This discrimination chart effectively distinguished the outflow of density currents. Thirty-three of the 37 non-vented events were located at the lower left of the curve, and 45 of the 55 vented events were located at the upper right of the curve. The discrimination diagram effectively distinguished sediment discharge by turbidity currents.

Conclusion Most of the turbidity current events since the establishment of the Xiaolangdi Reservoir were successfully identified using the discriminant diagram. The proposed theoretical sediment discharge conditions effectively predict the sediment discharge of multiple floods that have already occurred. The discriminant diagram also provides a dependable basis for achieving efficient sediment discharge of turbidity flow in the reservoir of the sediment-laden river.

Key words: turbidity current; Xiaolangdi Reservoir; sediment discharge; discrimination

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