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中国鲤科鱼类游泳能力综合分析和应用*

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摘 要: 该研究利用学术论文数据库筛选出中国鲤科鱼类游泳能力相关论文115篇,并用Origin软件进行了数据统计分析,旨在归纳和分析中国鲤科鱼类游泳能力并建立估算方法,可为正处于规划阶段和可行性研究阶段的过鱼设施流速设计提供依据. 结果表明:(1)鱼类游泳速度与鱼体长度具有显著的非线性相关关系,据此建立了一系列幂函数经验公式,可为游泳能力和过鱼设施研究及设计提供依据.(2)依据所得到的经验公式和协方差分析可知,喜流水型鲤科鱼类的游泳能力>广适型>喜静水型. 根据该研究得到的经验公式并结合行业规范和文献资料,对正处于规划阶段和可行性研究阶段过鱼设施流速设计的建议如下:西南地区以裂腹鱼成鱼为主要过鱼对象的过鱼设施进鱼口吸引流速范围为0.61~0.76 m/s,通道内最高流速阈值为1.28 m/s;长江中下游以四大家鱼成鱼为主要过鱼对象的进鱼口吸引流速范围为0.76~0.93 m/s,通道内最高流速阈值为1.49 m/s,以四大家鱼幼鱼为主要过鱼对象的进鱼口吸引流速范围为0.42~0.62 m/s,通道内最高流速阈值可为0.82 m/s.

关键词: 鲤科;过鱼设施;鱼道;游泳能力;游泳速度;流速;鱼长度

Comprehensive analysis and application of Chinese Cyprinidae swimming ability*

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Abstract: In order to provide an estimation method and basis for the fish swimming ability and for the flow velocity design of fish passing facilities in the planning stage and feasibility stage, by searching the papers related to the swimming ability of Chinese Cyprinidae from the internationally recognized academic paper network database, we selected 115 and then compared them with the critical swimming speed, burst speed and total length as describing indexes by using software Origin 9.0. Results indicated: (1) The relationship between fish swimming speed and fish length is allometric rather than isometric. It is recommended that the power function can be used to fit the correlation between fish swimming speed and total length. (2) Based on the empirical formula and the covariance analysis, swimming ability of rheophilic Cyprinidae > swimming ability of semi-rheophilic Cyprinidae > swimming ability of limnophilic Cyprinidae. According to the *Design code for fish passage facilities in hydropower projects* in China, *Guideline for*

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fishway in water conservancy in China and literature references about fish passage facility design, as well as the empirical formula in this study, the flows for fish passing facilities in the planning and feasibility stages in southwest China and the middle and lower reaches of the Yangtze River were recommended as follows. In the southwest China, the attraction flow velocity range of the fish passing facility entrance with adult Schizothoracinae fishes as the target species is 0.61-0.76 m/s, and the maximum velocity of the passage and pool is 1.28 m/s. In the middle and lower reaches of the Yangtze River, the attraction flow velocity range of the fish passing facility entrance with adult four major Chinese carps as the target species is 0.76-0.93 m/s, and the maximum velocity of the passage and pool is 1.49 m/s. The attraction flow velocity range of the fish passing facility entrance with juvenile four major Chinese carps as the target species is 0.42-0.62 m/s, and the maximum velocity of the passage and pool is 0.82 m/s.
Keywords: Cyprinidae; fish passage facility; fishway; swimming ability; swimming speed; flow velocity; fish length

虽然水利水电工程具有防洪、发电、航运等重要功能,工程造成的河流破碎化却对鱼类生存和繁衍产生了深远影响[1-3]. 随着西南水电开发、三峡大坝以及全国其他水利水电工程逐步建成,我国鱼类保护问题迫在眉睫. 修建过鱼设施可以缓解工程阻隔带来的负面作用[4-6].

鲤科(Cyprinidae)鱼类是鲤形目中分布最广、种类最多的一个类群. 中国有鲃亚科(Barbinae)、鲌亚科(Culterinae)、鲤亚科(Cyprininae)、鱼丹亚科(Danioninae)、鮈亚科(Gobioninae)、鳅鮀亚科(Goblobotinae)、鲢亚科(Hypophthalmichthyinae)、野鲮亚科(Labeoninae)、雅罗鱼亚科(Leuciscinae)、鳑鲏亚科(Rhodeinae)、裂腹鱼亚科(Schizothoracinae)、鲴亚科(Xenocyprininae)共 12 个亚科. 目前国外已建过鱼设施大部分是以鲑科(Salmonidae)鱼类为主要过鱼对象[3],而中国过鱼设施的主要过鱼对象大部分是鲤科鱼类[4]. 通过聚焦研究鲤科鱼类可解决我国大量过鱼设施对鱼类基础数据的共性需求.

我国过鱼设施相关的设计标准已对鱼类游泳能力数据提出明确要求[7-8]. 鱼类游泳能力是过鱼设施流速设计的关键基础数据,其中鱼类的临界游泳速度和爆发游泳速度是最重要和最常用的参考指标,临界游泳速度反映了鱼类在较长时间内持续运动的游泳能力,其测试方法是 Brett 提出的递增流速法,爆发游泳速度反映了鱼类在较短时间内快速运动的游泳能力,其测试方法包括递增流速测试法、尾部触碰测试法、鱼类自主游动观测法等[9-11]. 鱼的长度是影响鱼类游泳能力重要的因子[6,9,12]. 虽然我国众多学者分别各自测试了一定量的鱼类游泳能力数据[13-14],但未见有论文对现有成果进行全面、深入、定量地分析. 本研究的目的是通过分析我国鲤科鱼类游泳能力,为正处于规划阶段和可行性研究阶段的过鱼设施流速设计提供估算方法和依据.

1 材料与方法

分别以"鱼,游泳行为""鱼,游泳能力""鱼,游泳速度""鱼,游泳特性""fish, swimming performance""fish, swimming ability""fish, critical swimming speed""fish, prolonged speed""fish, swim, burst"和"fish, swim, sprint"等关键词组合在国内外公认的学术论文数据库中查找相关论文. 数据库包括:中国知网、Google scholar、ISI web of science、Elsevier Science Direct、Springer、Taylor & Francis 和 Wiley 等. 筛选出包含中国鲤科鱼类游泳能力数据的论文. 本研究数据包含鱼类 4446 尾、69 种、43 属、12 亚科、1 科(鲤科)、文献 115 篇(其中中文论文 80 篇[13-92],英文论文 35 篇[93-127]).

在鱼类研究领域内,鱼类身体的长度的表达方式通常有全长 L_t(自吻端至尾鳍末端的长度)、叉长 F_t(自吻端至尾叉的长度)和体长 L_b(也常称作标准长 L_s,自吻端至椎骨末端的长度)3 种类型,但并不是所有文献都报道了上述 3 种长度. 对于上述 115 篇文献来说,大部分鱼类的全长是可获得的(由原文直接提取原始数据或联系作者获取原始数据),剩余部分鱼类的全长可根据全球鱼类著名网站 Fishbase 中的"体长—全长相关关系"或"叉长—全长相关关系"进行数据转换而得到. 因此本研究选取全长(自变量)作为鱼类长度的表达方式并进行游泳能力数据分析,游泳能力的具体分析指标(因变量)为临界游泳速度和爆发游泳速度,数据统计分析使用 SPSS 22.0 软件,数据绘图使用 Origin 9.0 软件. 考虑到将鲤科鱼类分类学层次以属或者种来划分,会因划分类别过多导致细分类别的样本量较少,难以形成有效分析. 因此本研究按亚科来划分鲤科鱼类. 依据 Fishbase 中有关鱼类栖息地的描述以及鱼类栖息地、繁殖和摄食习性研究人员的野外研究经验来判断不同鱼种对水流环境偏好,将本文涉及的鱼种分为 3 类:喜流水型鱼类、广适型鱼类、喜静水型鱼类,

然后分析三类鱼的游泳能力是否存在显著差异. 由于该三类鱼的全长不同,且全长亦对游泳能力产生影响,因此本研究采用协方差分析检验三类鱼的游泳是否存在显著差异,显著水平设置为 0.001.

速度大小的单位通常以 m/s 来表达,本文相关指标有鱼类的绝对临界游泳速度 $U_{crit\text{-}a}$(单位为 m/s)和绝对爆发游泳速度 $U_{burst\text{-}a}$(单位为 m/s). 但由于不同鱼的长度不同,为了从一定程度上排除鱼体长度对速度值的影响,在研究鱼类游泳能力时通常也会用相对速度(单位为鱼长度/s,本文相关指标有鱼类的相对临界游泳速度 $U_{crit\text{-}r}$(单位为 TL/s)和相对爆发游泳速度 $U_{burst\text{-}r}$(单位为 TL/s))来表达研究结果和发现[11,14]. 在本研究调研的 115 篇文献范围内共有 31 篇文献拟合了鱼类游泳速度与长度之间的相关关系,其中 21 篇文献使用了线性拟合(或称直线函数拟合)[36,40,45,48,51,56,58,63-64,67,73-74,78-79,85,88-90,112,115,125],10 篇文献使用了非线性拟合(包含幂函数[108,110,123]、多项式函数[36,41,59,116]、数据取 ln 或 lg 对数之后的线性函数[82,121,127]). 除了本文研究的中国鲤科鱼类之外,其他鱼种(例如鲑科、鲟科(Acipenseridae)、狗鱼科(Esocidae)等)游泳速度与体长的相关关系均使用这几种拟合方法[6,12,128].

将本文收集的数据分别使用直线函数和幂函数拟合,通过比较拟合后 R^2 值的大小得出优选的拟合函数. 结果表明,非线性函数拟合效果明显优于线性函数拟合效果(参照图 1 中的数据拟合,幂函数拟合的 R^2 值相比直线函数拟合的 R^2 值可提升 0.057~0.214,提升幅度 17%~46%). 因此,本研究选取幂函数来模拟鱼类游泳速度与全长的相关关系.

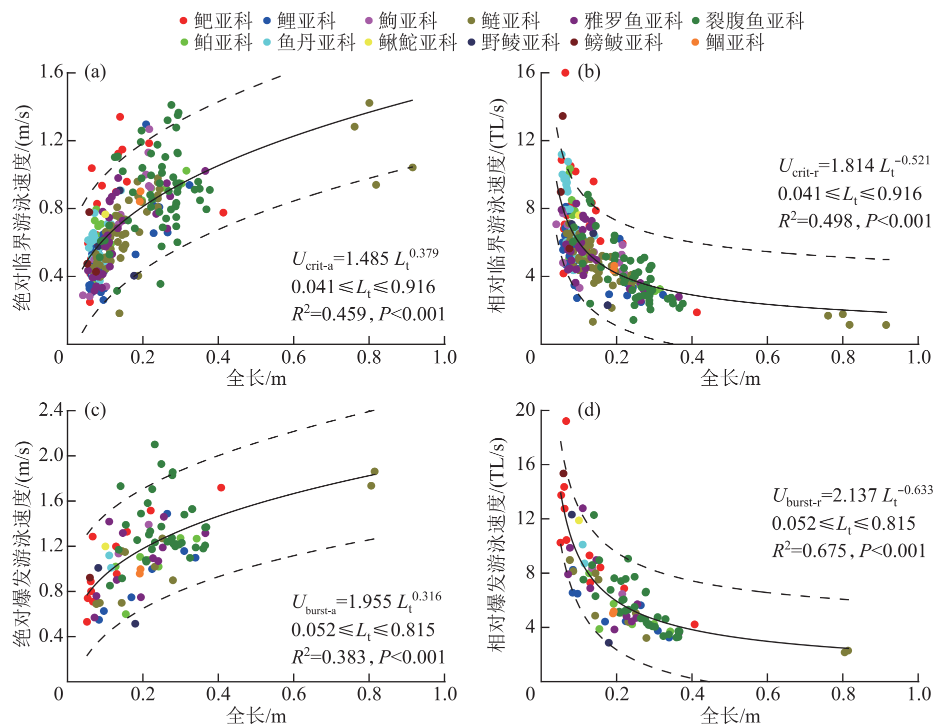

图 1 鲤科鱼类游泳速度 U 与全长 L_t 的相关关系(绝对临界游泳速度 $U_{crit\text{-}a}$,相对临界游泳速度 $U_{crit\text{-}r}$,绝对爆发游泳速度 $U_{burst\text{-}a}$,相对爆发游泳速度 $U_{burst\text{-}r}$,图中虚线是根据拟合曲线(实线)推求的 95% 预测区间)

Fig.1 Relationship between swimming speed U and total length L_t of Cyprinidae (absolute critical swimming speed $U_{crit\text{-}a}$, relative critical swimming speed $U_{crit\text{-}r}$, absolute burst speed $U_{burst\text{-}a}$, relative burst speed $U_{burst\text{-}r}$, dash lines are 95% prediction band derived from the fitted curve)

2 结果

本研究得到的鲤科鱼类的绝对临界游泳速度(U_{crit-a},m/s)与全长(L_t,m)相关关系为 $U_{crit-a}=1.485\ L_t^{0.379}$,$0.041\leqslant L_t\leqslant0.916$;绝对爆发游泳速度($U_{burst-a}$, m/s)与全长($L_t$, m)相关关系为 $U_{burst-a}=1.955\ L_t^{0.316}$, $0.052\leqslant L_t\leqslant0.815$. 得到的所有经验方程(具体详见图 1 中的相关说明)可为鱼类研究学者和过鱼设施工程设计人员提供鲤科鱼类游泳能力估算方法,亦可为其他鱼种研究提供借鉴. 对于本研究得到的结果,有如下 4 点需要注意和说明:(1)本研究主要为正处于规划阶段和可行性研究阶段的过鱼设施流速设计提供估算方法和依据,而水利水电工程过鱼设施专项设计阶段所需的鱼类数据仍应以目标过鱼对象野外现场的实际测试结果为主. (2)部分数据点分布于经验方程的预测区间之外,这可能是由于实验设备差异、实验环境差异、人员操作不稳定等方面造成,也可能是由于鱼类个体差异造成. (3)本研究总结的经验方程,使用时需符合鱼全长定义域范围,具体可见图注说明. (4)本研究中鱼全长以小于 0.4 m 的个体居多,因此当实际应用过程中的鱼全长更大时,由本研究经验方程计算得到的数据结果存在一定的不确定性.

以鱼类全长作为横坐标,游泳速度作为纵坐标,分析三类水流环境偏好的鲤科鱼类游泳能力(图 2),由图可知:不论以鱼类绝对游泳速度(m/s)还是相对游泳速度(TL/s)作为参照来看,总体来说喜流水型鱼类的游泳速度的拟合曲线均在图中相对较高的位置,广适型鱼类游泳速度的拟合曲线均在图中中间位置,喜静水型鱼类的游泳速度的拟合曲线均在图中相对较低的位置,三类水流环境偏好的鲤科鱼类游泳能力的幂函数经验公式可见图 2. 协方差分析显示:水流环境偏好是影响鱼类绝对临界游泳速度(m/s)和绝对爆发游泳速度(m/s)的重要因子($P<0.001$),对于上述两项鱼类游泳能力指标,喜流水型鱼类的和广适型鱼类之间均有显著差异($P<0.001$),喜流水型鱼类的和喜静水型鱼类均有显著差异($P<0.001$),广适型鱼类和喜静水型鱼类均无显著差异($P=0.013$ 和 $P=0.443$). 即喜流水型鱼类的游泳能力>广适型>喜静水型,但广适型鱼

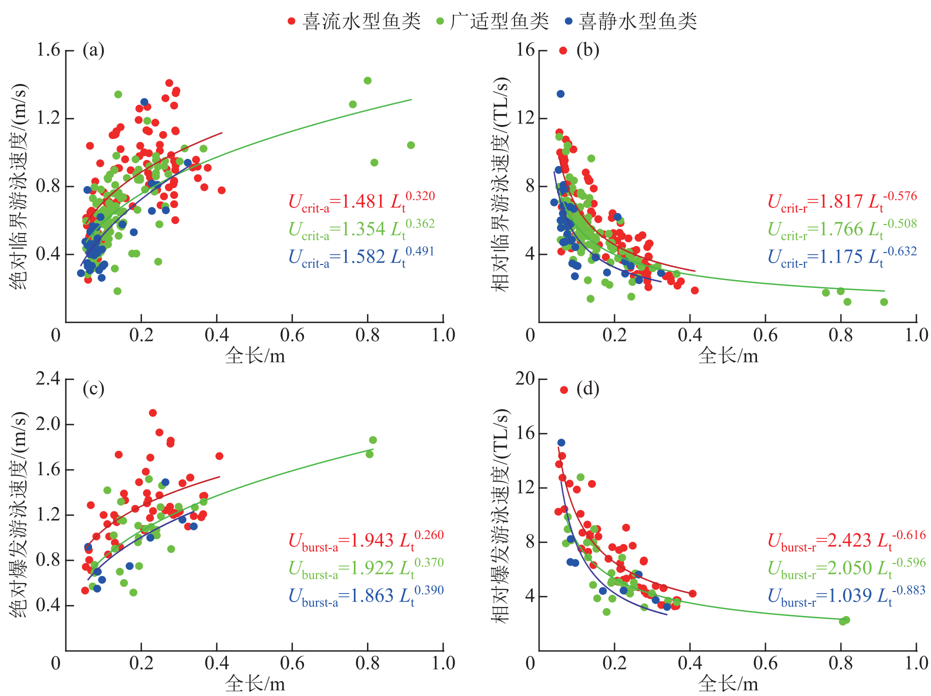

图 2 三类水流环境偏好的鲤科鱼类游泳速度 U 与全长 L_t 的相关关系(绝对临界游泳速度 U_{crit-a},相对临界游泳速度 U_{crit-r},绝对爆发游泳速度 $U_{burst-a}$,相对爆发游泳速度 $U_{burst-r}$)

Fig.2 Relationship between swimming speed U and total length L_t of Cyprinidae

(Three species types that prefer different flow environment, absolute critical swimming speed U_{crit-a}, relative critical swimming speed U_{crit-r}, absolute burst speed $U_{burst-a}$, relative burst speed $U_{burst-r}$)

类的游泳能力与喜静水型之间的差异不显著.

3 讨论

3.1 三类水流环境偏好的鲤科鱼类游泳能力差异和过鱼设施流速设计

大江大河的上游江段水体中的鱼类主要以喜流水型鱼类为主,如西南地区过鱼设施常见的过鱼对象裂腹鱼[112,118,120];江河的中下游江段和通江湖泊水体中的鱼类以广适型和喜静水型鱼类为主,如“四大家鱼”(广适型)和棒花鱼 *Abbottina rivularis*(喜静水型). 在拟合函数有效 L_t 范围内,以 L_t 每变化 0.001 为间隔,根据 3 类水流偏好的鲤科鱼类游泳速度拟合曲线分别计算所有长度规格的三类鱼的临界游泳速度和爆发游泳速度,然后对相同长度规格鱼的游泳速度做减法,并对减法得到的所有数值取平均值,最终计算可得:喜流水型鱼类的绝对临界游泳速度比广适型鱼类高 0.10 m/s,喜流水型鱼类的绝对临界游泳速度比喜静水型鱼类高 0.15 m/s;喜流水型鱼类的绝对爆发游泳速度比广适型鱼类高 0.21 m/s,喜流水型鱼类的绝对爆发游泳速度比喜静水型鱼类高 0.28 m/s. 根据我国《水利水电工程鱼道设计导则》和《水电工程过鱼设施设计规范》[7-8]的建议:鱼道进口区域水流速度小于鱼类感应流速时,应采取补水等措施. 但上述两个文件未曾对补水量和流速进行具体的量化分析. 有文献[129]调研并总结了一些鱼类的趋流行为,并认为过鱼设施进鱼口的吸引流速宜约为 0.7 倍临界游泳速度(m/s).《水利水电工程鱼道设计导则》和《水电工程过鱼设施设计规范》建议鱼道流速不应超过鱼类最大游泳速度. 因此经过计算并建议,以过喜流水型鱼类为主的过鱼设施的进鱼口吸引流速可以比以过广适型鱼类为主的高 0.10 m/s,以过喜流水型鱼类为主的过鱼设施的进鱼口吸引流速可以比以过喜静水型鱼类为主的高 0.15 m/s;以过喜流水型鱼类为主的过鱼设施的最高流速阈值可以比以过广适型鱼类为主的高 0.21 m/s,以过喜流水型鱼类为主的过鱼设施的最高流速阈值可以比以过喜静水型鱼类为主的高 0.28 m/s. 此外,前文协方差分析结果显示,广适型鱼类游泳能力与喜静水型之间的差异不显著,因此该两类鱼的过鱼设施流速设计在规划阶段和可行性研究阶段可考虑设置为近似值.

3.2 西南地区和长江中下游等重要地区过鱼设施的重要过鱼对象的游泳能力和流速设计

《中华人民共和国国民经济和社会发展第十四个五年规划和 2035 年远景目标纲要》提出:“建设雅鲁藏布江下游水电基地. 建设金沙江和雅砻江流域等清洁能源基地”. 因此西南地区典型短距离洄游鱼类裂腹鱼过坝能力研究显得尤为重要. 目前西南地区雅砻江、金沙江、澜沧江等流域已建设了大量水电站,更多的水电站正在规划和建设之中,这些水电站已经配建或正在设计过鱼设施,其中需要的过鱼种类最多的就是裂腹鱼类. 西南水电站对裂腹鱼造成的影响主要是成鱼过坝繁殖洄游的问题.《中华人民共和国长江保护法》第五十四条要求:“……组织实施长江干流和重要支流的河湖水系连通修复方案……逐步改善长江流域河湖连通状况”. 因此,应加快研究长江中下游(原)通江湖泊的生物连通性修复问题. 四大家鱼(青鱼 *Mylopharyngodon piceus*、草鱼 *Ctenopharyngodon idella*、鲢 *Hypophthalmichthys molitrix*、鳙 *Aristichthys nobilis*)作为长江中下游广布种和经济种,其成鱼由湖入江产卵(繁殖洄游)和幼鱼由江入湖育肥(索饵洄游)已长期被(原)通江湖泊的水闸阻隔,近年来一直处于争议的鄱阳湖建闸问题也包含四大家鱼过闸相关问题. 目前野外资源中[130-132]:喜流水型鱼类裂腹鱼亚科鱼类成鱼(性成熟个体)的常见规格约 0.2~0.4 m,广适型鱼类四大家鱼成鱼(性成熟个体)的常见规格约 0.5~0.9 m,四大家鱼幼鱼入湖育肥的常见规格约 0.1~0.3 m. 该数据也符合我国目前已建和已设计的过鱼设施的裂腹鱼和四大家鱼目标过坝规格范围. 依据我国需求的目标过鱼规格和本文所得喜流水型及广适型拟合曲线(图 2),鱼类游泳能力预测结果如表 1.

依据表 1 结果,并根据我国《水利水电工程鱼道设计导则》、《水电工程过鱼设施设计规范》和联合国粮食及农业组织 FAO[7-8,129]的过鱼设施流速设计方法,本研究对中国西南地区和长江中下游正处于规划阶段和可行性研究阶段的过鱼设施的流速设计建议如表 2 所示.

除了西南地区和长江中下游以外,黄河流域和珠江流域等重要流域也都修建了大量水利水电工程,并且未来还有大量的过鱼设施建设需求. 对于黄河流域来说,其上游的鲤科鱼类亦以喜流水型的裂腹鱼亚科为主,因此其过鱼设施流速设计可参考表 2 中的西南地区过鱼设施流速设计值;黄河下游则以广适型的四大家鱼和喜静水型的鲤为主,因此其过鱼设施流速设计可参考表 2 中的长江中下游过鱼设施流速设计值或者适当低于该值. 对于珠江流域来说,其主要的鲤科鱼类以喜流水型的鲃亚科、广适型的鲌亚科以及四大家

鱼为主,因此其过鱼设施流速可设计为小于西南地区过鱼设施流速且大于长江中下游过鱼设施流速.

表 1 基于鱼类游泳能力拟合方程的典型鱼种预测结果

Tab.1 Typical species swimming ability prediction results based on big data fitting equation

鱼	全长/m	临界游泳速度/(m/s)	爆发游泳速度/(m/s)
喜流水型鲤科鱼类成鱼(如裂腹鱼)	0.2~0.4	0.87~1.08	1.28~1.53
广适型鲤科鱼类成鱼(如四大家鱼)	0.5~0.9	1.08~1.33	1.49~1.85
广适型鲤科鱼类幼鱼(如四大家鱼)	0.1~0.3	0.60~0.89	0.82~1.23

表 2 西南地区和长江中下游过鱼设施流速设计建议值

Tab.2 Recommended velocity design values for fish passing facilities in southwest China and the middle and lower reaches of the Yangtze River

流域	目标过鱼对象	洄游目的	进鱼口流速/(m/s)	通道内最高流速阈值/(m/s)
西南地区	喜流水型鲤科鱼类成鱼(如裂腹鱼及形态学和生态习性相近鱼种)	繁殖洄游	0.61~0.76	1.28
长江中下游	广适型鲤科鱼类成鱼(如四大家鱼及形态学、规格和生态习性相近鱼种)	繁殖洄游	0.76~0.93	1.49
长江中下游	广适型鲤科鱼类幼鱼(如四大家鱼及形态学、规格和生态习性相近鱼种)	索饵洄游	0.42~0.62	0.82

4 总结

通过聚焦研究鲤科鱼类可解决我国大量过鱼设施对鱼类基础数据的共性需求,本研究以 4446 尾鱼的数据验证了鱼类游泳速度与鱼体长度具有显著的非线性相关关系,并据此建立了中国鲤科鱼类游泳能力估算方法(一系列幂函数经验公式). 虽然本研究整理了我国鲤科鱼类中共 12 个亚科鱼类的数据,并对喜流水型鱼类、广适型鱼类和喜静水型鱼类分别进行了归纳和统计分析,也对西南地区流域、长江流域、黄河流域等地区过鱼设施提供了流速设计建议值,但有 3 方面还需要注意:(1)不同流域水利水电工程过鱼设施的过鱼对象有所差别,本研究旨在解决最基础的共性问题—鲤科鱼类的数据需求问题,在实际过鱼设施设计中还应考虑其他主要目标过鱼种类的游泳能力. (2)本研究主要是为正处于规划阶段和可行性研究阶段的过鱼设施流速设计提供估算方法和依据,而水利水电工程过鱼设施专项设计阶段所需的鱼类数据仍应主要以目标过鱼对象野外现场的实际测试结果为主. 此外,出于对文献数据进行统计分析的目的,本文流速设计建议值均精确到小数点后两位. 但在实际工程应用问题中,由于环境条件和鱼类个体存在一定差异,初步的流速设计结果无需过于强调数字精度. (3)目前我国已建过鱼设施约 200 座,然而过鱼设施运行效果的评估案例数量远少于建设数量[133],且评估主要以鱼类实际过坝数量为主要评价指标,而鲜见对鱼类游泳能力、过鱼设施流速和鱼类过坝数量进行综合分析,鱼类游泳能力理论试验数据和野外过鱼设施流速有多大程度是匹配的却不得而知,因此建议未来研究应重点关注该问题,通过对已建过鱼设施进行监测来实现对过鱼设施流速设计和鱼类游泳能力试验数据等方面进行回顾性评价和优化设计.

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