•河流保护与治理•

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有植被弯曲分汊河道水流特性研究

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摘　要:弯曲分汊河道以其独特的平面形态形成了一套复杂的水沙运动规律,对河道稳定、防洪及航运都有深远影响。植被作为维持河流生态系统完整与健康的重要因素,对河道水流特性影响较大。植被影响下的弯曲分汊河道水流运动是一种特殊而复杂的水流问题,而目前针对其水流特性的相关研究较少。本文基于物理模型开展不同来流及不同植被密度影响下的弯曲分汊河道概化试验,分析了有植被弯曲分汊河道水流的运动特性,主要包括水面高程、水面比降、表层流速分布及水流动力轴线变化等。试验结果表明:弯曲分汊河道水位受流量影响较大,随着流量的增加水位呈现阶梯式增长,而随着植被密度的增加水位抬高并不显著;来流相同条件下,弯曲分汊河段分流区、汊道段以及汇流区流速受植被影响差异较大;右汊有植被条件下,受植被阻水作用影响,分汊段右汊水流动力轴线逐渐向凹岸侧偏转,且植被密度越大,水流动力轴线越靠近凹岸侧。研究成果一定程度上可为相关的河道整治、河流生态修复等提供理论参考。

关键词:弯曲分汊河道;植被;水流特性;恒定流

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自然界的许多河流,如中国的长江、珠江,新西兰的怀马卡里里河,欧洲的莱茵河,南美洲的亚马孙河等,都存在着大量的弯曲分汊河道[1]。弯曲分汊河道作为一种典型河型,以其独特的平面形态形成了一套复杂的水沙运动规律,表现在河道主流线会大幅摆动,汊道之间发生冲淤交替,并时常伴随航槽出浅、堤岸崩塌等问题,对河势稳定、防洪、航运、沿岸经济发展均有着重要影响[2]。植被往往生长在弯曲分汊河道的洲滩甚至河道中,对河道水流特性影响较大。有植被的河道水流是一种特殊而复杂的水流:一方面,河道岸滩上的植被通过其根系保护土壤,起到固岸护滩的作用[3–5],河道中的植被能减小水流流速,床面切应力相应减小,从而保护河床不受侵蚀[6];另一方面,河道中的植被会增大水流阻力,减小水流流速,导致泥沙淤积[7–9],水流在行进过程中通过植被产生紊流脉动,将部分能量转化为紊动动能,消耗了自身能量,升高河道水位,河道的过流能力减小,导致洪水泛滥的风险增大[10–11]。植被与水流相互作用在维持河流生态功能方面发挥着重要影响。

国内外学者对弯曲分汊河道水流运动进行了研究。Momplot等[12]通过水槽试验探讨了主支汊在分离角为90°时的水流特性,发现分离区水流结构更为复杂,不仅具有经典的二维水流结构,还具有螺旋状的三维水流结构。华祖林等[13]研究了不同支汊宽度比及不同入流流量对分汊口水流分离区特征尺寸的影响。Hsu等[14]通过分析分汊河道分流区的试验成果,建立了分流区能量损失系数与分流比、弗劳德数、相对水深间的关系。孙志林等[15–16]基于积分形式二维连续方程、二维阻力公式、无因次宽深比关系与时变水流挟沙能力公式,建立了分汊河道水力几何形态理论关系,提出了分汊河道平衡水深计算方法。Ashmore等[17]提出了分汊河道水位流量关系的预测方法。Martino[18]、White[19]、Pujol[20]等研究了植物对三维水流结构、水流紊动特性及流速分布特性的影响。Huthoff[21]、Wu[22]等提出植被河道水流阻力、流速分布的计算方法。Martin-Vide等[23]通过考虑滩槽交界面上表观剪切应力的作用,建立了有植被弯曲复式河道的

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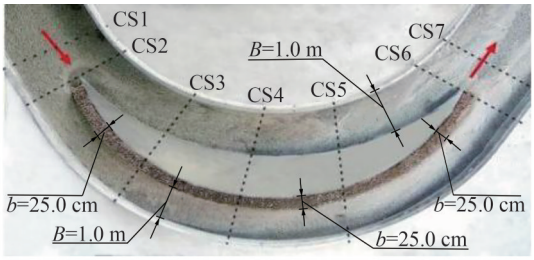
流量计算方法,从而改善流量的计算精度。

尽管国内外学者在弯曲分汊河道水流运动方面做了大量研究,但涉及植被的较少[24],且植被对河道影响的研究主要集中于边界条件较为简单的单一河道。因此,本文通过开展物理模型试验,对植被影响下弯曲分汊河道的水流运动特性进行分析研究,可为河道防洪、河流生态修复等提供一定的理论支持。

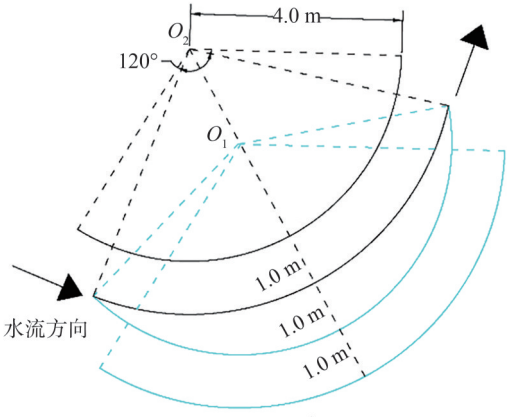
1 试验概况

1.1 水槽

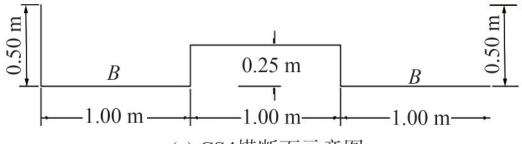
试验在四川大学山区河流保护与治理全国重点实验室进行,选取了有代表性的长江叙泸段余家湾河段进行概化模型设计,并依据长江中下游弯曲分汊河段泥沙沉积过程及植被发育形成设定了试验方案,即在一较为规则的弯曲分汊河段中进行全动床系列试验。试验中,支汊凸岸侧有大量细颗粒泥沙落淤,有利于植被发育形成。因此,设计了支汊有植被布设的系列过程试验,图 1 为试验水槽示意图。水槽由进口直线段、中部圆弧段及出口直线段构成,中部圆弧段采用双同心圆结构,整体水槽沿圆心连线 O_1O_2 呈对称分布;水槽中,进、出口直线段宽均为 2 m,圆弧段左、右汊河道宽度 B 均为 1.0 m,弯顶处江心洲宽度为 1.0 m。试验研究范围为横断面 CS1～CS7 之间的河段(其中,CS1、CS2 位于分流区,CS6、CS7 位于汇流区),纵向比降为 3‰,横向无比降[24–25],河床初始铺沙坡度与纵向比降保持一致。由于弯曲分汊河道各汊道水沙运动与河床演变相互作用、彼此影响,试验将植被统一布置于右汊河道,植被布设宽度 b 为 25.0 cm,与右汊河道宽度 B 之比为 1∶4。图 2 为试验植被模型示意图。试验选取刚性圆杆作为模拟材料,用以表征河道中非淹没刚性植被,植被杆件直径 d 为 0.8 cm,杆件长度为 30.0 cm。



(a) 水槽实拍图



(b) 圆弧段示意图



(c) CS4横断面示意图

图 1 试验水槽示意图

Fig. 1 Sketch of the flume

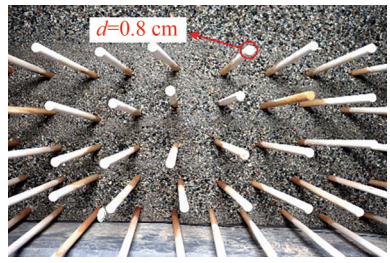


图 2 试验植被示意图

Fig. 2 Schematic diagram of experimental vegetation

图 3 为初始沙床级配。天然沙的级配区间为 0.5～10.0 mm。床沙代表粒径 D_{16}、D_{50} 及 D_{84} 分别为 0.226、0.690 和 2.556 mm,初始铺沙厚度为 15 cm,水槽中江心洲高度为 25 cm。

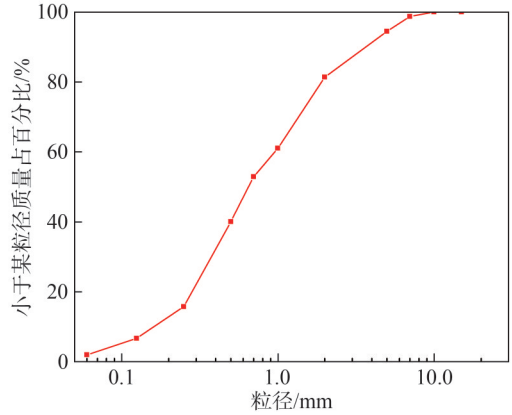


图 3 初始床沙级配

Fig. 3 Grading composition of initial bed sediment

1.2 测量方法

1.2.1 水位测量

在试验研究段布设 7 个横断面进行水位测量,其中在横断面 CS1、CS2、CS6、CS7 各布置 3 个测量点,距左岸分别为 5、95、195 cm;分汊段 CS2～CS6 各布设 6 个测量点,左汊测量点距左岸分别为 5、50、95 cm,右汊测量点距右岸分别为 5、50、95 cm。采用瑞士堡盟集团的超声波测距传感器(UR18.DA0–IA1B.7BO),其测距范围为 100～1 000 mm,重复精度为 0.5 mm,分辨率小于 0.3 mm,采样频率设置为 2 次/s,每个测量点测量时间为 30 s。

1.2.2　流速测量

采用武汉大学智慧水业研究所与武汉大水云科技有限公司联合研发的AiFlow视频测流系统进行表层流速测量。该系统在实验室流体力学研究中基于粒子图像测速(PIV)技术进行了改进[26],以漂浮粒子或水面波纹为示踪剂,以自然光为主要光源,采用数码相机或摄像机作为图像采集设备,并通过对研究区域示踪粒子图像的相关匹配处理,得到研究河段的二维表层流速。目前,该测量方式已在多种情况下使用并取得了较好的结果[27–29]。此外,该系统分辨率为0.01 m/s,测量范围为0.10～20.00 m/s,误差范围为±0.05 m/s。

1.3　方案设置

为探究清水环境下弯曲分汊河道的水流运动特性,试验采用恒定流。试验设置小、中、大3级流量,分别为55、70、90 L/s;同时,选取无植被、低密度、高密度3种植被覆盖条件,对应植被密度依次为0.00、0.02、0.08。两个变量交叉组合,共设置9组试验工况。各组试验保持边界条件相同,统一恒定冲刷时间为8 h,试验方案设置如表1所示。植被密度 Φ 的表达式为:

$$\Phi = \frac{\pi}{4} nd^2$$

式中,n 为单位面积植株数目,单位为 cm^{-2}[30]。

表1　试验方案设置

Tab. 1　Experimental scheme settings

工况编号	植被密度 Φ(右汊)	时间/h	流量/(L·s^{-1})
A_1			55
A_2	0	8	70
A_3			90
B_1			55
B_2	0.02	8	70
B_3			90
C_1			55
C_2	0.08	8	70
C_3			90

本文中,水流特性均为河床冲刷稳定后进行测量所得的结果。

2　试验结果

2.1　水面高程

在水流特性中,水面线能够较为直观地反映水流的情况,图4为各工况下弯曲分汊河道水面线。由图4可见,整体上左、右两汊水面线变化情况基本相同,研究段范围内水位呈较为显著的波动趋势。受支汊植被影响,左、右汊水面高程整体随植被密度的增加而增大,且右汊直接受植被阻水作用,增加幅度较左汊更为显著。与受植被影响相比,弯曲分汊河道水面高程仍受流量影响较大,随着流量的增加水位呈阶梯式增长,随着植被密度的增加水位抬高并不显著。具体而言,分流区水流从CS1行至CS2,水位有所降低,这是受江心洲顶托作用影响,其上游产生壅水,CS1处水位有所抬高,水流行至分汊口断面CS2时,顶托作用消失,水位随之降低。在汊道进口段CS2～CS4,左、右汊水面变化有所差异。左汊总体上随上游流量的增加,水位沿程增大,在大流量(90 L/s)条件下,水流漫滩,受弯道离心力作用,水流向右汊沿程转移,导致分汊口断面CS2至CS3水位沿程呈较小的降低趋势;右汊在中、小流量(70、55 L/s)条件下水位变化不大,大流量条件下(90 L/s)水面高程沿程降低,同时受到左汊的侧向水流补给,CS3～CS4的水位变化幅度较CS2～CS3更小。在汊道出口段CS4～CS6,左汊最高水位普遍位于CS5处,而右汊则出现在弯顶断面CS4处,其原因是左汊流路较短,容易受江心洲下游汇流区壅水的影响,而右汊流路较长,汇流区壅水产生的影响波及不到CS5。在汇流区CS6～CS7,左、右汊两股水流相互冲击顶托,水位沿程有所增加,一定程度上呈逆坡衔接。

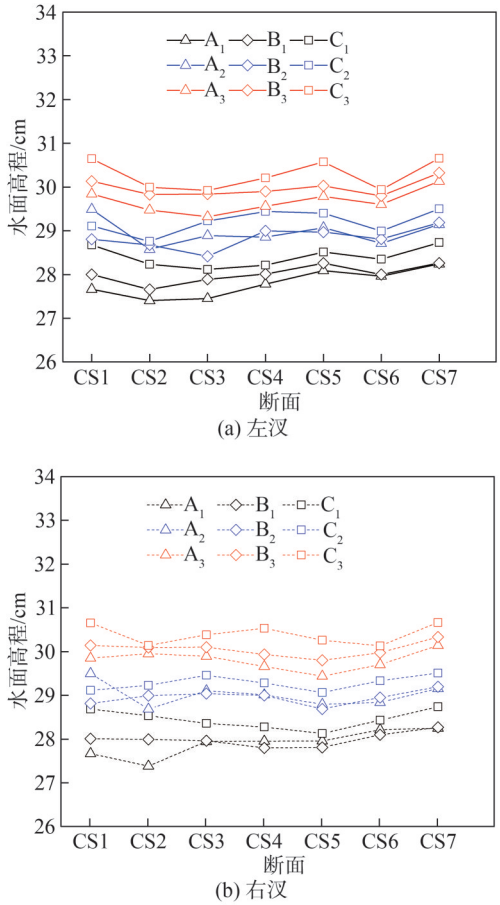


图4　各工况下弯曲分汊河道水面线

Fig. 4　Water surface profiles of curved bifurcated river channels under various conditions

2.2 纵比降

图5为各工况下水面纵比降(顺水流方向,水位壅高为正、跌落为负),量化了顺水流方向水位变化情况。由图5可见,整体而言,左、右汊纵比降在分流区CS1～CS2、汇流区CS6～CS7均呈现出沿程增大的特点,而在分汊段CS2～CS6的变化情况有所差异;同时发现右汊植被密度的变化对弯曲分汊河道纵比降的影响较小。对于左汊道,由于其为主汊道,纵比降变化较为明显,从分汊口断面CS2至弯顶断面CS4,水面纵比降逐渐增大,而从弯顶断面CS4至汇流口断面CS6,水面纵比降呈减小的趋势。对于右汊道,作为支汊同时受植被直接作用影响,水面纵比降变化较小,从分汊口断面CS2至汇流口断面CS6,水面纵比降呈先减小后增大的趋势,并在弯顶断面CS4处取得极小值。左、右两汊道纵比降变化幅度及变化趋势的差异在于左、右汊流路长度不同,导致汇流区壅水及弯道离心力两者的影响程度不同。对于左汊,汇流区壅水的作用大于弯道离心力;对于右汊,弯道离心力的作用大于汇流区壅水,且右汊植被的存在减少了过流面积,断面流速的三维性较强,一定程度上进一步增大了弯道离心力的作用,使其在右汊占据主导地位。

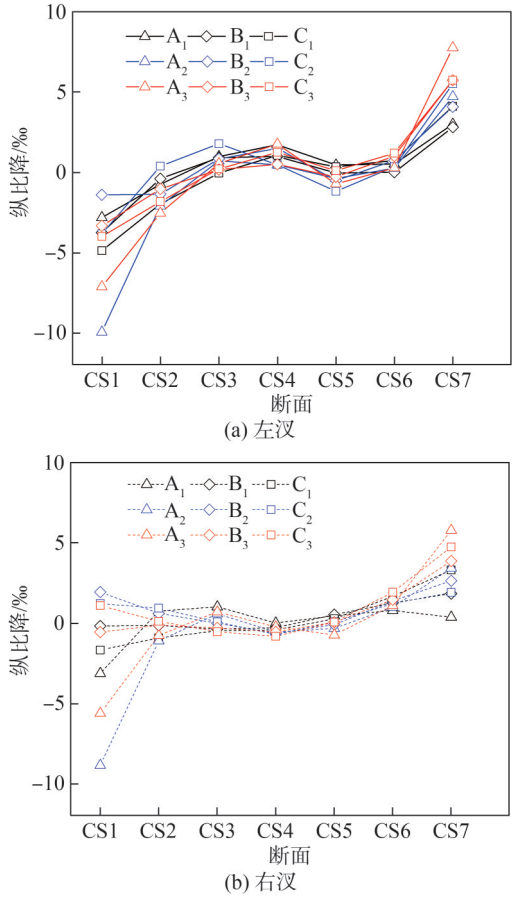


图5 各工况下水面纵比降

Fig. 5 Longitudinal gradients of water surface under various conditions

2.3 横比降

弯曲分汊河道左、右汊兼有弯道水流的水动力特性。由于弯道水流的曲线运动,水流在离心力作用下会产生水面超高及水面横比降,图6为各工况下水面横比降(横比降为正时表示凹岸高于凸岸,为负时表示凸岸高于凹岸)。由图6可见:在相同流量条件下,各断面横比降随支汊植被密度的增加而增大,且左汊增大幅度较为显著;在同一植被密度下,随着流量的增加,各断面横比降显著增大,其中尤以左汊增大更为明显,右汊受植被覆盖的影响,断面横比降增幅相对较小。总体而言,弯曲分汊河道横比降受流量影响较为剧烈,而植被密度对其影响相对较小。具体而言,水面横比降呈“几”字形分布,呈先增大后减小的趋势,其中左汊最大横比降出现在弯顶断面CS4处,而右汊最大横比降则出现在汊道进口段CS3处。对于左汊,弯曲河道离心力的作用使水面横比降均为正值;对于右汊,在分汊口断面CS2和汇流口断面CS6处,受植被影响,凸岸侧水位高于凹岸侧,水面横比降为负值,随着水流行至汊道段CS3～CS5,弯道的离心力作用有所增加并超过植被对水位的影响,汊道段CS3～CS5水面横比降为正值。

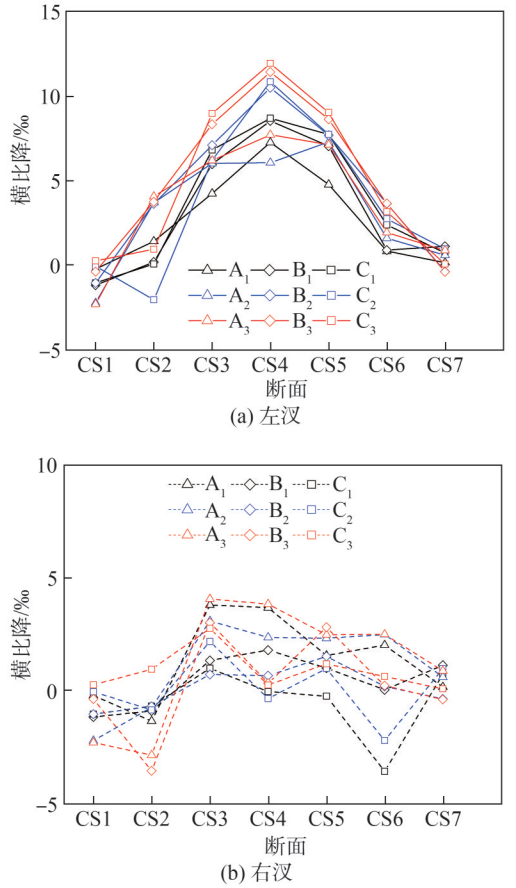


图6 各工况下水面横比降

Fig. 6 Transversal gradients of water surface under various conditions

2.4　表层流速

水流、河床相互作用并达到稳定状态后,不同工况下流速为55 L/s时水流表层流速分布如图7所示。因中流量(70 L/s)、大流量(90 L/s)条件下,水流表层流速分布变化情况与小流量(55 L/s)相似,图7仅展现小流量条件下水流表层流速分布。由图7可见,整体上,在流量相同条件下,随着右汊(支汊)植被密度的增加,由流线的矢量长度可知,CS1处流速值未发生显著变化,分汊段CS2～CS6左、右汊流速发生了不同程度的变化,CS7处流速变化亦较小。

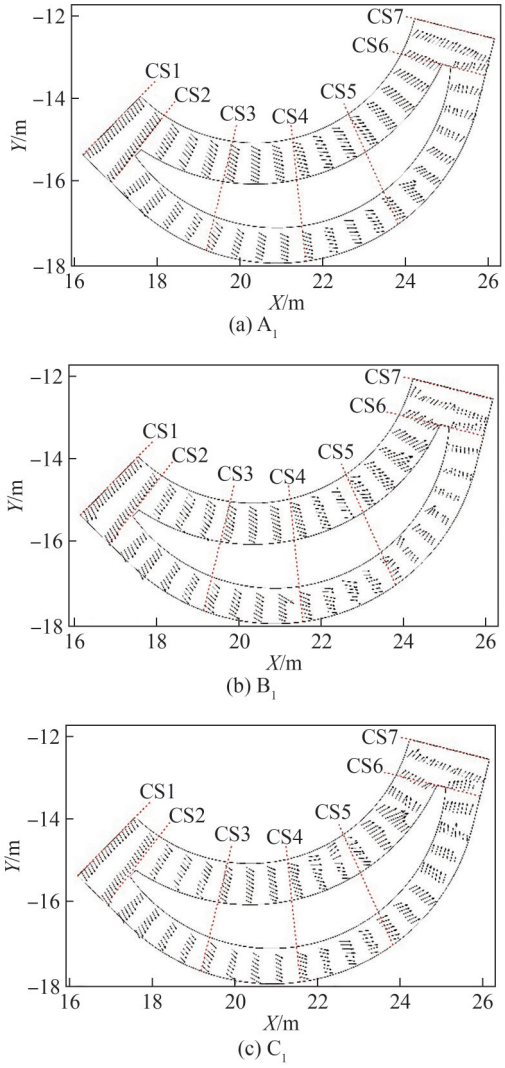


图7　不同工况下流量为55 L/s时表层流速分布

Fig. 7　Surface velocity distribution of flow at a discharge of 55 L/s under different conditions

具体而言,水流行至分汊口断面CS2时,右汊(支汊)植被的存在对其流速值影响较小,但对CS2处流向造成一定的影响,表现为右汊受植被影响,流速向凹岸侧偏转,且植被密度越大,流速偏转角越大,而左汊流速偏转角随植被密度变化较小。在汊道进口段CS2～CS4,随着植被密度的增加,左汊分流增大,流速值增大;右汊过流减少,流速值随植被密度增加呈减小趋势;左、右汊流速偏转趋势基本与分汊口断面CS2相似。在汊道出口段CS4～CS6,受弯道离心力作用,随植被密度的改变,左、右汊流速偏转角比上游更小;左汊流速值随植被密度增加而增大,右汊呈相反的变化趋势。水流行至CS7时,流速值随植被密度的增加未发生显著变化,流向受分汊河段左、右汊流速偏转的影响,表层流速发生了一定程度的偏转。

2.5　水流动力轴线

水流动力轴线一般指沿程各断面最大垂线平均流速所在点的连接线,本文仅测量了水流表层流速,水流动力轴线采用沿程最大表层流速的连接线。图8为不同流量下水流动力轴线分布。由图8可见,流量相同时,小流量(55 L/s)、中流量(70 L/s)及大流量(90 L/s)条件下,水流动力轴线呈相似的变化趋势,但仍存在较小的差异。总体而言,右汊(支汊)无植被时,水流动力轴线在分流区CS1处偏靠凸岸,进入弯曲分汊段后,左、右

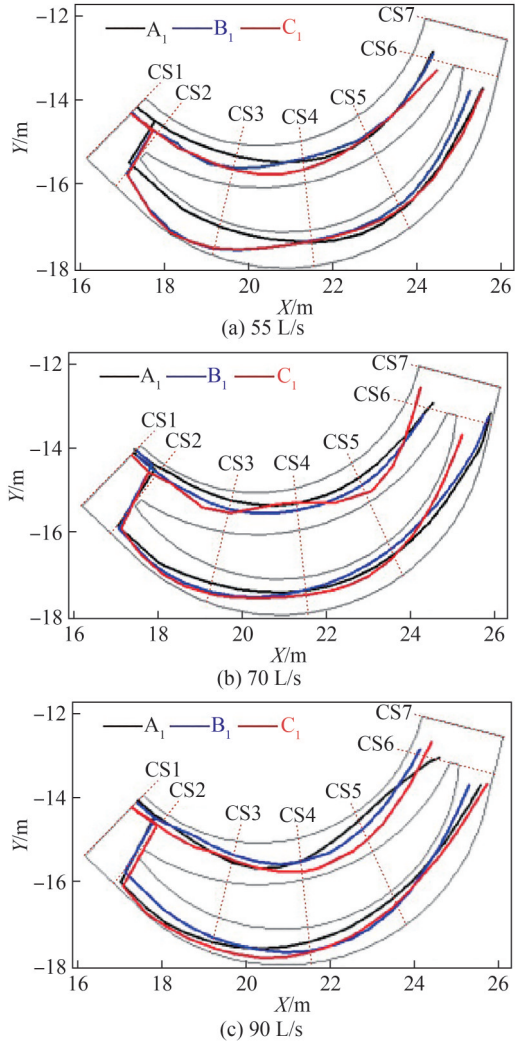


图8　不同流量下水流动力轴线分布

Fig. 8　Distribution of hydrodynamic axis under different flow rates

汊随即逐渐向凹岸过渡，其中右汊水流行至紧靠凹岸后，受边界作用影响，水流发生偏转并向凸岸折回。这一现象与天然河湾的水流动力轴线变化趋势一致。右汊（支汊）在有植被条件下，受植被阻水作用影响，分汊段右汊水流动力轴线逐渐向凹岸侧偏转，且植被密度越大，水流动力轴线越靠近凹岸侧；同时，右汊有植被覆盖后，左汊分流增大，水流动量增加，由于惯性力的作用，水流倾向于走直趋中，水流动力轴线亦向凹岸侧偏移，且偏移量随植被密度的增加而增大。

具体而言，图 8 中不同流量条件下弯曲分汊河段水流动力轴线的差异表现在：小流量条件下，右汊（支汊）是否有植被布设对水动力轴线影响较为显著，而随着右汊植被密度的增大，水流动力轴线变化较小，即小植被密度曲线（工况 B_1）与无植被密度曲线（工况 A_1）相比，水流动力轴线向凹岸侧偏转，而大植被密度曲线（工况 C_1）与小植被密度曲线（工况 B_1）相比，水流动力轴线未发生明显变化。中、大流量条件下，3 种植被密度下的水流动力轴线变化基本一致，左汊水流随着右汊植被密度的增加而倾向于走直趋中，水流动力轴线向凹岸侧偏移；右汊由于植被密度的增加，阻水面积加大，水流在进入汊道进口段后先偏转至凹岸，随后在汊道出口段偏转至植被附近。

3 结 论

本文基于物理模型，开展不同来流及不同植被密度下弯曲分汊河道概化试验，分析了有植被弯曲分汊河道水流的运动特性，主要结论如下：

1）弯曲分汊河道水位受流量影响较大，随着流量的增加水位呈现阶梯式增长，而随着植被密度的增加水位抬高并不显著；支汊植被及其密度的变化对弯曲分汊河道纵比降的影响较小，而各断面横比降随支汊植被密度的增加而增大，且左汊增大幅度较为显著。

2）来流相同条件下，弯曲分汊河段分流区、汊道段及汇流区流速受植被影响有差异，具体表现为分流区断面平均流速随植被密度的增加而增大，汊道段左汊断面平均流速与分流区变化相同，汊道段右汊则呈相反的变化趋势，汇流区断面平均流速随植被密度的增加无显著变化。

3）右汊在有植被条件下，受植被阻水作用影响，分汊段右汊水流动力轴线逐渐向凹岸侧偏转，且植被密度越大，水流动力轴线越靠近凹岸侧；上游来流较小时，支汊植被的布设对弯曲分汊河段水流动力轴线影响较为显著，随着流量的增加，弯曲分汊河段水流动力轴线受植被的影响作用逐渐减弱。

本文研究成果适用于特定水流条件（流速为 0.15～0.35 m/s）与植被密度条件（Φ 为 0.02～0.08）。此外，本文进行的是刚性非淹没植被影响下的水流特性研究，其他形式植被影响下的水流特性尚需进一步深入研究。

参考文献：

[1] 钱宁，张仁，周志德. 河床演变学[M]. 北京：科学出版社，1987.

[3] Lawler D M.Advances in the continuous monitoring of erosion and deposition dynamics:Developments and applications of the new PEEP-3T system[J].Geomorphology, 2008,93(1/2):17–39.

[4] Wang Chao,Yu Jiyu,Wang Peifang,et al.Flow structure of partly vegetated open-channel flows with eelgrass[J].Journal of Hydrodynamics,2009,21(3):301–307.

[5] Pollen－Bankhead N, Simon A. Hydrologic and hydraulic effects of riparian root networks on streambank stability: Is mechanical root-reinforcement the whole story[J].Geomorphology,2010,116(3/4):353–362.

[6] TAL M,PAOLA C.Dynamic single-thread channels maintained by the interaction of flow and vegetation[J].Geology,2007,35(4):347–50.

[7] Bennett S J,Wu Weiming,Alonso C V,et al.Modeling fluvial response to in-stream woody vegetation: Implications for stream corridor restoration[J]. Earth Surface Processes and Landforms,2008,33(6):890–909.

[8] Bouma T J,van Duren L A,Temmerman S,et al.Spatial flow and sedimentation patterns within patches of epibenthic structures:Combining field,flume and modelling experiments[J].Continental Shelf Research,2007,27(8):1020–1045.

[9] Rominger J T,Lightbody A F,Nepf H M.Effects of added vegetation on sand bar stability and stream hydrodynamics[J]. Journal of Hydraulic Engineering,2010,136(12):994–1002.

[11] Gurnell A M,Van Oosterhout M P,De Vlieger B,et al. Reach-scale interactions between aquatic plants and physical habitat:River Frome,Dorset[J].River Research and Applications,2006,22(6):667–680.

[12] Momplot A,Lipeme Kouyi G, Mignot E,et al.A new flow structure in a dividing open channel[J].La Houille Blanche, 2015,101(5):78–83.

[13] Hua Zulin,Yan Ming,Gu Li,et al.Characteristic dimension of separation zones in the bifurcation of braided rivers[J]. Journal of Hydroelectric Engineering,2013,32(5):163–168. [华祖林，严明，顾莉，等. 分汊河道分汊口水流分离区特征尺寸初步研究[J]. 水力发电学报，2013,32(5):163–168.]

[14] Hsu C C,Tang C J,Lee W J,et al. Subcritical 90° equal-width open-channel dividing flow[J]. Journal of Hydraulic Engineering,2002,128(7):716–720.

[15] Sun Zhilin,Gao Yun,Xu Dan.A theory of equilibrium depth

of branching rivers[J]. Journal of Harbin Engineering University,2019,40(1):61–66.[孙志林,高运,许丹. 分汊河道平衡水深方法[J]. 哈尔滨工程大学学报,2019,40(1):61–66.]

[16] Sun Zhilin,Yang Zhongtao,Gao Yun,et al.Hydraulic geometry of branching channels in Yangtze estuary[J]. Journal of Zhejiang University(Engineering Science),2014,48(12):2266–2270.[孙志林,杨仲韬,高运,等. 长江分汊河口水力几何形态[J]. 浙江大学学报(工学版),2014,48(12):2266–2270.]

[17] Ashmore P,Sauks E.Prediction of discharge from water surface width in a braided river with implications for at-a-station hydraulic geometry[J].Water Resources Research, 2006,42(3):2005WR003993.

[18] Martino R,Paterson A,Piva M.Double-average mean flow and local turbulence intensity profiles from PIV measurements for an open channel flow with rigid vegetation[J]. Environmental Fluid Mechanics,2012,12(1):45–62.

[19] White B L,Nepf H M.Shear instability and coherent structures in shallow flow adjacent to a porous layer[J].Journal of Fluid Mechanics,2007,593:1–32.

[20] Pujol D,Nepf H.Breaker-generated turbulence in and above a seagrass meadow[J].Continental Shelf Research,2012,49:1–9.

[21] Huthoff F. Theory for flow resistance caused by submerged roughness elements[J].Journal of Hydraulic Research,2012, 50(1):10–17.

[22] Wu Weiming,Shields F D,Bennett S J,et al.A depth-averaged two-dimensional model for flow, sediment transport, and bed topography in curved channels with riparian vegetation[J]. Water Resources Research,2005,41(3):2004WR003730.

[23] Martín–Vide J P,Moreta P J M,López–Querol S.Improved 1-D modelling in compound meandering channels with vegetated floodplains[J]. Journal of Hydraulic Research, 2008,46(2):265–276.

[24] Liu Xingnian,Wang Sen,Zhang Bin,et al.The effect of emergent vegetation on flow, bedload transport,and bed morphology in a diffluence-confluence unit on a meandering channel[J].Journal of Hydrology,2024,638:131488.

[25] Wang Sen,Li Kunfang,Liu Xingnian,et al.Flow and sediment characteristics in meandering branch channel under the effects of vegetation[J].Advanced Engineering Sciences,2025,57(1):29–36.[王森,李坤芳,刘兴年,等.植被影响下的弯曲分汊河道水沙特性[J]. 工程科学与技术,2025,57(1):29–36.]

[26] Zhao Haoyuan,Chen Hua,Liu Bingyi,et al.An improvement of the Space-Time Image Velocimetry combined with a new denoising method for estimating river discharge[J].Flow Measurement and Instrumentation,2021,77:101864.

[27] Le Coz J,Hauet A,Pierrefeu G,et al.Performance of image-based velocimetry(LSPIV) applied to flash-flood discharge measurements in Mediterranean rivers[J].Journal of Hydrology,2010,394(1/2):42–52.

[28] Lee M C,Leu J M,Chan H C,et al.The measurement of discharge using a commercial digital video camera in irrigation canals[J].Flow Measurement and Instrumentation,2010,21(2):150–154.

[29] Muste M,Hauet A,Fujita I,et al.Capabilities of Large-scale Particle Image Velocimetry to characterize shallow free-surface flows[J].Advances in Water Resources,2014,70:160–171.

[30] Nepf H M. Flow and transport in regions with aquatic vegetation[J].Annual Review of Fluid Mechanics,2012,44:123–142.

Flow Characteristics in Meander Branch Channel with Vegetation

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Abstract:

Objective This study addresses the insufficient understanding of the flow characteristics of such channels in existing research and provides theoretical support for channel regulation and ecological restoration engineering practices to clarify the flow movement laws of meandering branching channels under the coupled effects of discharge and vegetation density.

Methods A generalized physical model test was conducted using the Yujiawan reach of the Xulu section of the Yangtze River as the prototype at the State Key Laboratory of Hydraulics and Mountain River Engineering. The flume was composed of inlet and outlet straight sections and a middle arc section, with the left branch, right branch, and central bar each having a width of 1 m and a longitudinal slope of 3‰. The riverbed was paved with natural sand with particle sizes ranging from 0.5 mm to 10.0 mm. Rigid non-submerged vegetation, with a diameter of 0.8 cm and a length of 30 cm, was arranged in the right branch. Nine groups of clear water steady flow tests were designed using three discharge gradients

(55, 70, and 90 L/s) and three vegetation density gradients (0, 0.02, and 0.08). Each test was subjected to constant scouring for 8 hours until the riverbed reached a stable state. Ultrasonic distance-measuring sensors were utilized to measure the water surface elevation at seven cross-sections. The AiFlow video current measurement system, based on improved Particle Image Velocimetry (PIV) technology, was adopted to obtain the surface flow velocity. The variation characteristics of water surface elevation, longitudinal and transverse water surface gradients, surface flow velocity distribution, and the hydrodynamic axis of the channel were systematically analyzed.

Results and Discussions The water level of the meandering branching channel was influenced more significantly by discharge than by vegetation density. A stepwise increase in water level was observed with increasing discharge, whereas only a slight rise in water level occurred with increasing vegetation density, and the magnitude of increase in the right branch was slightly greater than that in the left branch. The water level in the diversion area increased due to the backwater effect of the central bar, decreased at the branching mouth with the disappearance of the backwater effect, and then increased along the flow direction in the confluence area due to flow impact and backwater effects. Vegetation exerted a minimal influence on the longitudinal gradient of the channel. The longitudinal gradients in both the diversion and confluence areas increased along the flow direction. In the branching section of the left branch, the longitudinal gradient increased gradually from the branching mouth to the bend apex and then decreased progressively from the bend apex to the confluence mouth. In the branching section of the right branch, the longitudinal gradient first decreased and then increased, reaching a minimum at the bend apex. The transverse gradient of each cross-section increased slightly with increasing vegetation density, with a more pronounced increase in the left branch. The transverse gradient was strongly affected by discharge and increased sharply with increasing discharge. The transverse gradient in the left branch remained positive, whereas that in the right branch was negative at the branching and confluence mouths and positive within the branching section. Under the same inflow conditions, vegetation produced significantly different effects on flow velocity across different channel sections. The flow velocity in the diversion and confluence areas was less affected by changes in vegetation density, whereas clear differentiation was observed in the branching section. With increasing vegetation density, the diversion ratio and flow velocity in the left branch increased, whereas the discharge through the right branch decreased and the flow velocity was reduced. In addition, vegetation in the right branch caused the flow velocity at the branching mouth to deflect toward the concave bank, and the deflection angle increased with increasing vegetation density. The flow-blocking effect of vegetation in the right branch was identified as the primary cause of hydrodynamic axis deflection. Under vegetation cover conditions, the hydrodynamic axis of the right branch in the branching section deflected toward the concave bank, and higher vegetation density brought it closer to the concave bank. Simultaneously, the hydrodynamic axis of the left branch also deflected toward the concave bank due to the increased diversion ratio. The influence of vegetation on the hydrodynamic axis depended on discharge, being significant under low discharge conditions and gradually weakening with increasing discharge. Under low discharge, the hydrodynamic axis showed a noticeable deflection when vegetation density increased from 0 to 0.02, but only slight changes were observed when the density increased from 0.02 to 0.08. Under medium and high discharge conditions, the variation trends of the hydrodynamic axis under different vegetation density gradients remained generally consistent.

Conclusions The study revealed the regulatory mechanisms of discharge and vegetation density on the flow characteristics of meandering branching channels. It clarified the variation patterns of water surface morphology, flow velocity distribution, and the hydrodynamic axis of such channels under the water-blocking effect of vegetation. The research results can provide theoretical references for flood control and regulation, the rational configuration of beach vegetation, and river ecological restoration engineering in meandering branching channels. The findings are only applicable to scenarios involving rigid, non-submerged vegetation, with a flow velocity of 0.15～0.35 m/s and a vegetation density of 0.02～0.08. Further experimental studies are required to investigate the effects of other vegetation types, such as flexible and submerged vegetation, on the flow characteristics of meandering branching channels.

Key words: meander branch channel; vegetation; flow characteristics; steady flow

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