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河道采沙坑位置对桥墩局部冲刷特性影响试验研究

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摘　要:河道中采沙坑的存在会影响桥墩稳定性,对两者影响关系研究较少,需进一步深入研究。本文共开展两种水流强度、4种采沙坑位置与无采沙坑结构的桥墩局部冲刷试验,分析了不同工况的冲刷地形特征和桥墩局部紊流结构变化规律。试验结果表明:1)随着采沙坑与桥墩模型间的距离越近和水流强度越大,桥墩冲刷坑的坑深及截面面积越大,采沙坑上游倾角相等,且与泥沙休止角基本一致。2)随着采沙坑与桥墩模型间的距离越近,桥墩冲刷坑的最大坑深逐渐增大;当L_k/D为7时,高水流强度下桥墩冲刷坑的最大坑深比低水流强度下增加约38.6%。3)随着采沙坑与桥墩模型间的距离越近,桥墩上游流速减速越明显,涡量在桥墩冲刷坑内越大;当L_k/D为7、冲刷坑内最大深度处的涡量约为无采沙坑(即L_k/D=0)的2.2倍时,加剧了桥墩局部冲刷。4)随着L_k/D越近和水流强度越大,1阶模态越小,桥墩周围的紊动加剧,能量越趋于分散。随着模态阶数的升高,能量减小的速度变快,低阶模态是整个流场的主要载体。

关键词:圆形桥墩;矩形采沙坑;局部冲刷试验;运动摄像恢复结构(SFM)方法;粒子图像测速;本征正交分解(POD)方法

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桥梁的修建增强了水流局部紊动,破坏泥沙运动平衡和原有河床形态。Lin 等[1]总结了桥梁失稳的案例,发现局部冲刷造成的失稳比例占64%,揭示了冲刷对桥梁结构安全性的影响。随着现代建筑材料需求增加,河流采沙成为工程用沙的重要来源。河床采沙会导致河床结构变化加剧,威胁桥梁安全,甚至造成桥梁水毁[2−4]。采沙坑一旦形成将长期存在、发展和演变,加剧水流对河床及桥墩周围的冲刷,故研究存在采沙坑的情况下桥墩周围水沙运动规律对于河湖治理具有重要现实意义。

河床地形结构是影响桥墩安全的关键因素,许多学者对此开展了广泛的研究[5−6]。梁发云等[7]对桥墩冲刷后的地形采用单点测量方法,分析不同时段地形冲刷的动态变化。Yagci 等[8]进行不同结构桥墩模型冲刷试验,利用激光扫描床面形态三维结构,分析桥墩形状与冲刷强度关系。Bouratsis 等[9]开发水下双目三维地形测量技术,分析桥墩周围实时三维结构演变规律。Hamidi 等[10]运用水沙数值模型模拟桥墩周围冲刷形态,与经验数据的对比表明该模型桩心间点的冲刷深度偏高。Das 等[11]测量了桥墩周围不同位置的冲刷深度,分析圆柱体中心附近和圆柱体下游附近的最大和最小冲刷深度。对于存在采沙坑的情况下,齐梅兰等[12]在水槽试验中观察到采沙坑的存在加剧了桥墩局部冲刷。Majedi−Asl 等[13]通过试验研究河床采沙对桥墩群周围水流水动力的影响,认为采沙坑的存在导致桥墩群周围的冲刷加剧,并提出估算冲刷深度的非线性方程。Lade 等[14]研究了局部冲刷动态演化过程,发现存在采沙坑时,局部冲刷的空间演化速度更快,冲刷深度和体积也会增加。然而,由于水沙运动复杂性及采沙坑存在的干扰,河床冲刷过程更为复杂,特别是河床结构形态仍需进一步深入研究。

紊流携沙运动是河床演变的主要驱动力,很多学者对桥墩局部冲刷流场开展大量的研究[15−16]。为研究水流条件和局部冲刷的关系,Beheshti 等[17]运用声学多普勒流速仪(ADV)研究复杂桥墩水平面和垂直面

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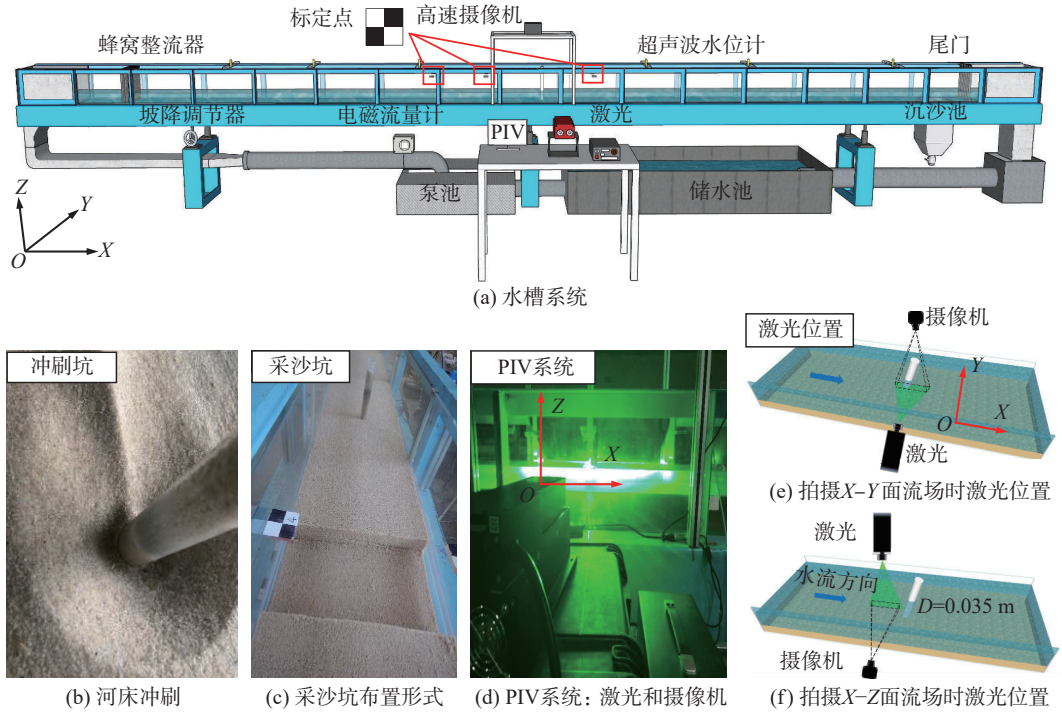
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的时均流速、紊流强度和雷诺应力，指出冲刷坑发展与冲刷坑后涡流有关，并随紊动强度增大而增大。Unger 等[18]通过粒子图像测速（PIV）技术研究了桥墩周围的流动特性，结果表明，桥墩周围存在的马蹄涡加剧冲刷坑尺寸的增大，桥墩上游的向下射流是造成冲刷的主导因素。Dipankar[19]、Feng[20]等将本征正交分解（POD）方法应用到圆柱绕流分析中，可以更加精细地观察到圆柱后缘尾迹旋涡脱落的方向和强度。Guan 等[21]对圆形桥墩局部流场开展分析，发现桥墩周围涡强度随冲刷深度增大而增大。Lade 等[22]在沙床河道中进行试验，研究采沙坑对圆形桥墩周围水动力学的影响，该研究表明采沙坑的开挖增加了冲刷孔区域马蹄形涡流的强度，同时也增大了桥墩后侧尾涡流的脱落频率。虽然桥墩冲刷被广泛研究，然而对于存在采沙坑时桥墩周围紊流结构及两者相互影响规律的研究尚不充分。

综上所述，以往的研究主要集中在紊流结构和桥墩周围坑深变化规律，对存在采沙坑时桥墩局部冲刷影响规律缺乏足够数据和定量研究。本文开展不同采沙坑位置对桥墩冲刷影响的定量试验研究。采用运动摄像恢复结构（SFM）方法重构床面三维地形，并通过 PIV 技术获取桥墩周围的流场，定量分析采沙坑布设在不同位置和无采沙坑结构对桥墩冲刷坑流场和地形的影响关系。研究结果可为研究采沙对桥墩局部冲刷的影响，提供新的思路和数据支撑。

1　试验设计

为了研究不同位置采沙对桥墩冲刷特性影响，在长、宽、高分别为 15.0、0.4、0.4 m 且变坡范围为 0～2% 的矩形循环明渠水槽中开展试验，试验水槽示意图如图 1 所示。图 1 中：X 轴为沿水流流向，即流向；Y 轴为沿水槽宽度方向，即横向；Z 轴为水深方向，即垂向。水槽侧壁和底板均为透明钢化玻璃，整体尺寸误差为±0.2 mm，其底板和两侧边壁均由钢化玻璃构成。水槽通过 JFC 水流自动测控系统控制变频器调节其频率，来改变流量，并利用位于水槽下方的泵池抽取储水池中的水，以实现水循环的持续输送。水槽下方管道旁安装电磁流量计负责显示流量数值，精度为±0.5%。水流通过水槽入口后，先经过 3 个矩形蜂窝整流器以消除水泵产生的大尺度水流结构，保证水流的平稳。沿水槽长度中心线上方，等间距依次安装 6 个横跨水槽宽度方向的超声波水位计测量瞬时水深，其精度为±0.5 mm。水槽末端配有活动尾门，通过调节尾门开闭度达到恒定均匀流条件。



(a) 水槽系统　(b) 河床冲刷　(c) 采沙坑布置形式　(d) PIV系统：激光和摄像机　(e) 拍摄X–Y面流场时激光位置　(f) 拍摄X–Z面流场时激光位置

图 1　试验水槽示意图

Fig. 1　Schematic diagram of experimental tank

试验选用中值粒径 d_{50}=0.5 mm、密度 ρ_s=2 650 kg/m^3 的均匀天然沙，铺设厚度为 0.12 m，长度约为 9 m。选用直径 D=3.5 cm 的单桥墩有机材质模型，桥墩模型直径 D 保持小于水槽宽度的 0.1 倍，以避免侧壁对试验结果造成影响[23]。同时，桥墩模型直径与床沙平均直径的比值 $D/d_{50}>50$，可避免泥沙颗粒粒径大小对冲刷深度影响。中间 3 m 为试验段，其距离水槽入口和尾门出口均为 6 m，水流平稳且减少尾门影响。试验开

展坡降 J=0.002，动床（水流强度 U/U_C=1.280>1，U_C 为临界平均流速，称为 Case1280 组次）和清水（水流强度 U/U_C=0.508<1.000，称为 Case508 组次）冲刷试验[24]，每个组次各包含 4 种无量纲化相对横向距离（L_k/D=7、14、21、28，k=1、2、3、4）和无采沙坑（L_k/D=0）5 组工况，其中，L_k 为矩形采沙坑中轴线平面与桥墩模型对称轴平面之间的距离。采沙坑是长 0.35 m（沿 X 轴方向）、宽 0.40 m（沿 Y 轴方向）、深 0.05 m（沿 Z 轴方向）的矩形坑。两种水流条件（Case1280、Case508）合计 10 组恒定流冲刷试验，试验水流条件如表 1 所示，试验布设平面图如图 2 所示。表 1 中，H_1/D 为无量纲化初始矩形采沙坑深度，H_1 为初始矩形采沙坑深度。鉴于目前的篇幅及试验工作量，本文未考虑采沙坑不同深度对桥墩冲刷的影响。

表 1 试验水流条件

Tab.1 Flow conditions of experiments

组次	$L_k\cdot D^{-1}$	$H_1\cdot D^{-1}$	流量 Q/(L·s^{-1})	平均流速 U/(m·s^{-1})	弗劳德数 Fr	水流强度 $U\cdot U_C^{-1}$	雷诺数 Re
Case508	7	1.4	6.3	0.146	0.168	0.508	5 053
	14	1.4	6.3	0.146	0.168	0.508	5 053
	21	1.4	6.3	0.146	0.168	0.508	5 053
	28	1.4	6.3	0.146	0.168	0.508	5 053
	0（无采沙坑）	0（无采沙坑）	6.3	0.146	0.168	0.508	5 053
Case1280	7	1.4	10.3	0.348	0.401	1.280	12 058
	14	1.4	10.3	0.348	0.401	1.280	12 058
	21	1.4	10.3	0.348	0.401	1.280	12 058
	28	1.4	10.3	0.348	0.401	1.280	12 058
	0（无采沙坑）	0（无采沙坑）	10.3	0.348	0.401	1.280	12 058

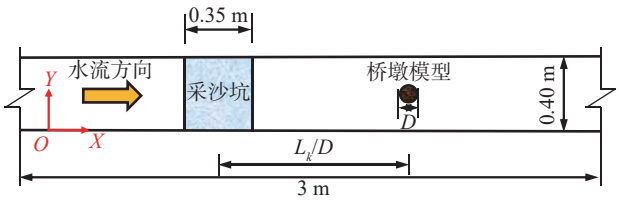


图 2 不同 L_k/D 的试验布设示意图

Fig. 2 Schematic diagram of the test layout under different L_k/D values

为分析二维瞬时流场，利用高分辨率 PIV 系统沿 $X-Y$ 和 $X-Z$ 面内测量了桥墩模型周围的瞬时二维流场。拍摄 $X-Y$ 面流场时，将高速摄像机架设在桥墩模型正上方，而激光则沿横向进行摆放，照射高程约为水深的 0.7 倍，摄像机在墩柱背光侧难以拍摄到示踪粒子，因此流场分析为激光照射的墩柱迎光侧区域（图 1(e)）；拍摄 $X-Z$ 面流场时，激光设备架设在桥墩模型对称轴的正上方，摄像机则沿横向放置，由于激光照射在墩柱边壁处会产生反射，得到的流场数据不精确，因此研究重点为桥墩上游侧的流动信息（图 1(f)）。在拍摄过程中，采用密度为 1 000 kg/m^3、平均直径为 10 μm 的空心玻璃微珠作为试验的示踪粒子。流场计算采用多重网格迭代图像变形算法，通过高斯拟合得到亚像素精度。最小诊断窗口为 32 像素×32 像素，相邻窗口重叠度为 50%，最终得到相应的速度场，每种工况拍摄约 5 000 个瞬时流场。

为分析试验段床面三维地形结构特征，在试验水槽边壁水槽的不同位置粘贴 6 个由 5 cm×5 cm 正方形棋盘格组成的标定点（图 1(a)），其具体坐标如表 2 所示。待流场拍摄完后，放干河床，使用尼康 D7200 相机环绕目标区域拍摄冲刷试验前后地形，每对相邻照片的重叠率保持在 80% 左右，照片数约为 300 张，其中，约有 150 张照片含有棋盘格标定点，以提高三维地形重构准确性。

表 2 地面标定点的坐标

Tab. 2 Coordinates of ground control points

X/m	Y/m	Z/m
0.025	0.025	0.289
0.038	0.375	0.292
1.186	0.025	0.258
1.202	0.375	0.252
2.643	0.025	0.328
2.642	0.375	0.323

2 分析方法

2.1 地形分析方法

冲刷地形基于 SFM 方法进行重构。本文采用 VisualSFM[25] 开源软件进行三维地形重构，利用尺度不变特征变换法[26]识别提取地形特征点，并进行特征点匹配[27]。将相机拍摄的照片群（图 3）根据照片自带的位置信息进行排序和特征点识别，匹配不同照片的特征点得到同名点，特征点匹配过程如图 4 所示。基于匹配特征点，依次获得模型的稀疏点云和密集点云的 SFM 重构图分别如图 5(a)、(b) 所示，可见结果精度较高[28]。



图3　实测地形照片群

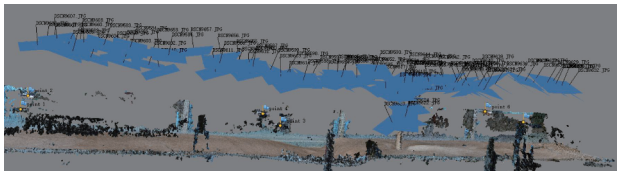
Fig. 3　Measured terrain photo group



(a) 第1帧图像　(b) 第2帧图像　(c) 匹配结果

图4　特征点匹配过程

Fig. 4　Process of feature point matching



(a) 稀疏重构



(b) 密集重构

图5　SFM方法的重构过程

Fig. 5　Reconstruction process of SFM method

2.2　流场分析方法

为获取桥墩附近流场信息，使用式(1)计算拍摄的瞬时流场，以获得时间平均速度场，从而分析桥墩周围的流动特性。

$$\begin{cases} U=\dfrac{1}{N}\sum_{i=1}^{N}u_i, \\ V=\dfrac{1}{N}\sum_{i=1}^{N}v_i \end{cases} \tag{1}$$

式中，U和V分别为拍摄范围内的平均流向流速和横向流速，N为用于分析的快照的总数量，u_i和v_i分别为拍摄范围内的瞬时流向流速、横向流速。使用式(2)计算涡量ω：

$$\omega=\frac{\partial v_i}{\partial x}-\frac{\partial u_i}{\partial y} \tag{2}$$

式中，x为水流方向的长度，y为垂直方向的长度。

为了更深入了解桥墩局部流场的流动特性，本文采用快照POD(snapshot POD)方法[29]将PIV设备获得的瞬时流场分解为平均流场和脉动流场，并对脉动流场进行模态分解，从中提取具有较高能量的前几阶模态[30]，即：

$$\varphi_i=\sum_{k=1}^{N}A_i^k u_k \tag{3}$$

式中：φ_i为求解得到的第i阶POD模态，即一个空间上的正交基函数；u_k为第k个流场快照，包含了在某一时刻整个流场空间所有网格点上的物理量信息；A_i为第k个流场快照u_k在构成第i阶模态时所具有的能量值系数。

水动力场的特征模态可由以下积分方程求得：

$$\int_{\Omega}C(x,y)\varphi(y)\mathrm{d}\Omega=\lambda\varphi(x) \tag{4}$$

式中：Ω为空间区域；$C(x,y)$为空间两点间的协方差核函数，定量描述了流场中任意两个空间点x和y处，物理量随时间的同步变化关系；$\varphi(y)$和$\varphi(x)$分别为积分核作用的对象和输出，是与式(3)类似的POD模态在空间点y和x处的值；λ为对应的特征值，与对应模态所具有的能量值直接相关。将流场快照的内积关系代入式(4)的协方差核函数，推导出离散特征值矩阵：

$$\boldsymbol{RA}=\lambda\boldsymbol{A} \tag{5}$$

式中：$\boldsymbol{A}$为一个每一列包含式(3)中构建第i阶模态所需的所有系数A_i的特征值矩阵；$\boldsymbol{R}$为一个$N\times N$的矩阵，R_{ij}为矩阵$\boldsymbol{R}$中第i行、第j列的元素，其表达式为：

$$R_{ij}=\frac{1}{N}(\boldsymbol{u}_i,\boldsymbol{u}_j),\ i,j=1,2,\cdots,N \tag{6}$$

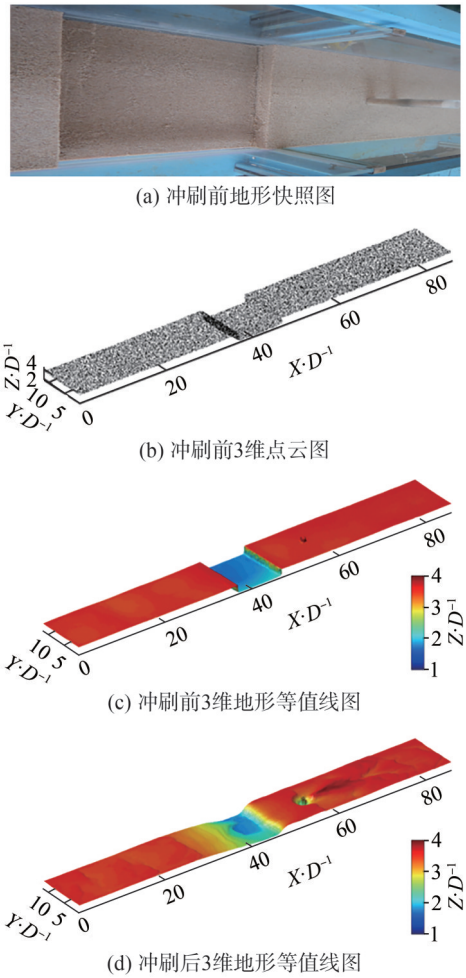
式中，$(\boldsymbol{u}_i,\boldsymbol{u}_j)$为第$i$、$j$个流场快照向量的内积。

所求的特征值维度只有N阶，远小于空间点M的量级，可通过求解矩阵$\boldsymbol{R}$的特征值及特征向量得到POD模态。

3 结果分析

3.1 冲刷地形基本特征

以Case508的L_k/D=14工况为例，利用一系列冲刷前地形快照图(图6(a))，采用SFM方法可得到冲刷前三维地形点云图(图6(b))。



(a) 冲刷前地形快照图

(b) 冲刷前3维点云图

(c) 冲刷前3维地形等值线图

(d) 冲刷后3维地形等值线图

图6 Case508的L_k/D=14工况时桥墩冲刷地形图

Fig. 6 Case508 condition pier scour topographic map of L_k/D=14

图6中，X/D、Y/D、Z/D分别为沿水流流向、横向、水深方向的无量纲数值。由图6(b)可见，采用SFM方法得到的冲刷前三维地形点云密集且均匀分布。为定量分析冲刷地形特征，需对研究区域进行网格化。将铺沙范围划分为1 mm×1 mm的网格，并采用插值方法对网格中的点云数据进行处理，得到网格点上的插值结果，冲刷前后的三维地形等值线图分别如图6(c)、(d)所示。由图6(c)、(d)可见，经过网格化和插值处理的三维点云重构的床面结构与实际布置的结构相吻合，表现出较好的重构效果。

3.1.1 不同工况的整体冲刷地形特征

水流强度和无量纲化相对横向距离L_k/D是影响河床地形形态的两个重要原因。图7为冲刷试验前不同L_k/D(L_k/D=7、14、21和28)及无采沙坑(L_k/D=0)下三维地形图。图7中：上一行图是试验中实际工况的地形快照，因为工况长度为3 m，照片拍不全，仅截取了工况中采沙坑和桥墩关键部分照片；下一行图是根据上一行实际工况重构后的地形图。图8展示了两种水流条件下冲刷后的河床地形三维重构云图，图8(a)、(b)分别对应水流强度Case508和Case1280各5组工况。由图8可见：当水流强度U/U_C=0.508 < 1即清水冲刷(Case508)时，水流流速未达到泥沙启动流速，采沙坑上游泥沙未运动，床面地形较为平整。桥墩模型附近由于紊流的作用且无泥沙补给，下游出现明显的“鱼鳍状”沙丘结构且范围可长达数米。当U/U_C=1.280 > 1即动床冲刷(Case1280)时，水流流速已达到泥沙启动流速，采沙坑上游泥沙发生运动，床面出现明显的沙波形态，且采沙坑整体结构有向下游迁移的趋势。下游的“鱼鳍状”沙丘由于泥沙输移，冲刷逐渐减弱，当采沙坑距离桥墩最近时，冲刷床面变化不明显。图8(b)中，L_k/D=7、14的采沙坑与桥墩冲刷坑已有一定贯通，表明床面下切更多会使桥墩暴露更大范围，对桥墩的稳定性产生不利影响。

为研究桥墩局部冲刷坑结构特征，两种水流条件下沿水槽长度纵向X–Z面和水槽宽度横向Y–Z面绘制无量纲化河床高程，分别如图9、10所示。

从图9(X–Z面)来看：Case508水流条件下，由于清水冲刷，水流流速低于泥沙启动流速，桥墩上游床面高程较为平整；Case1280水流条件下，由于水流流速高于泥沙启动流速，床面沙粒输移使床面地形高低起伏。在上游越靠近墩柱处，床面高程逐渐下降，直至桥墩冲刷坑的最大坑深处。两种水流强度下采沙坑上游高程剖面线与纵向X轴的夹角α_{U1}和α_{U2}基本相等，且均与泥沙休止角基本一致[31]，采沙坑下游边缘被冲刷且未保持和上游边缘同样角度，这是由于采沙坑的下游剪应力值高于上游[32]。在下游越远离墩柱处，床面高程逐渐上升，至坑后凸起区为床面高程最大值。高水流强度下，沙堆的高度小于低水流强度，这是由于高水流强度的床面剪切力较大，挟沙能力强，能将泥沙向下游输运，

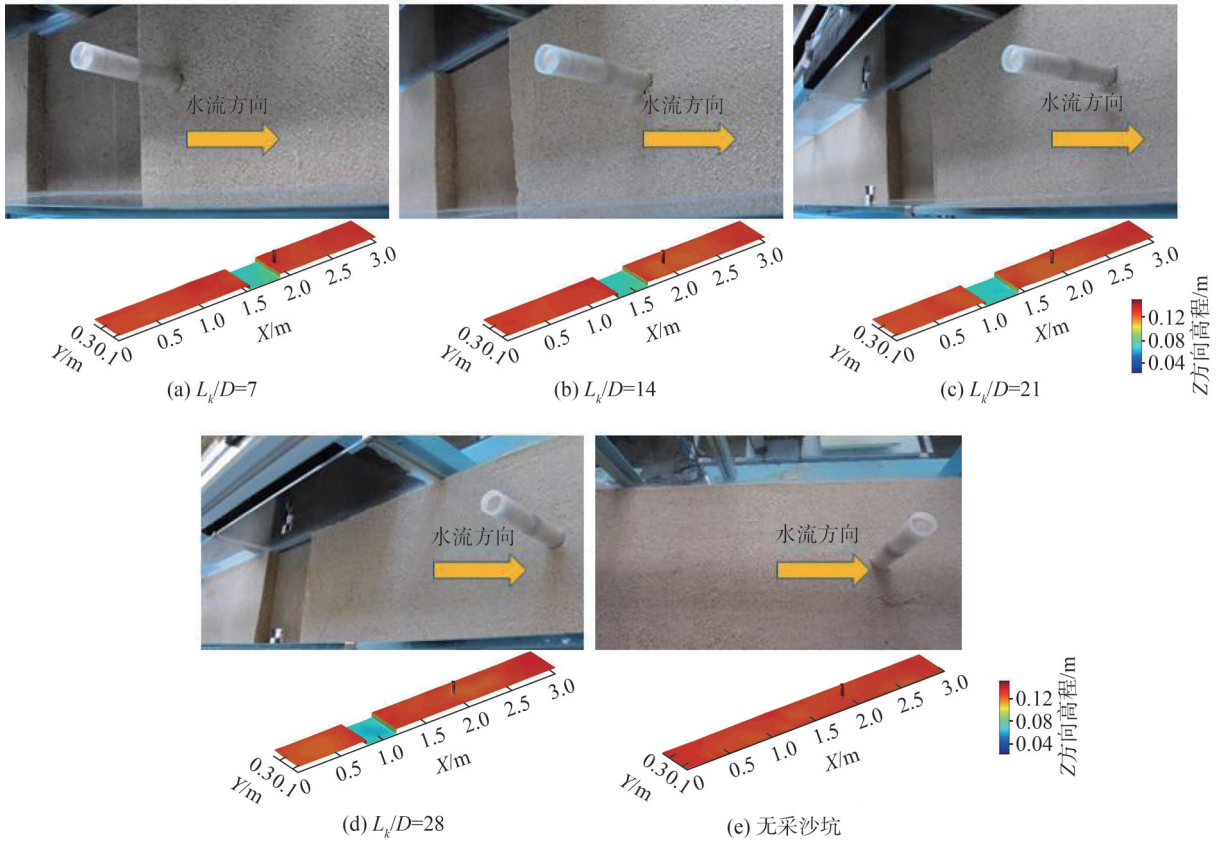


图7　冲刷前的三维地形快照和云图

Fig. 7　Three-dimensional topographic snapshots and cloud images of before scouring

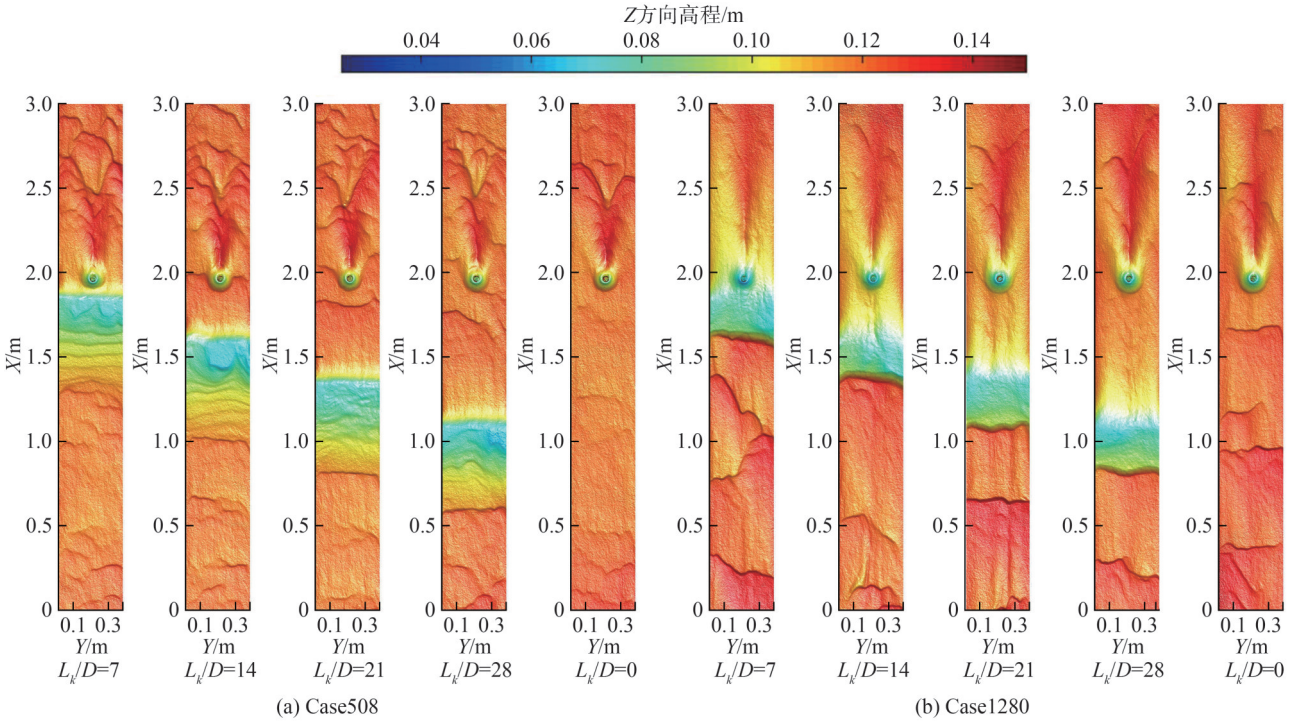
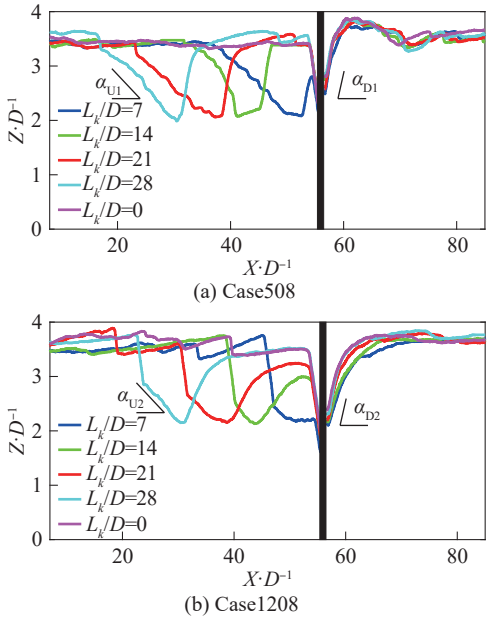


图8　两种水流条件下冲刷后的三维地形云图

Fig. 8　Three-dimensional topographic cloud map after scouring under two kinds of water flow conditions

使堆积高度下降，高程曲线也更为平滑。此时，墩柱下游沙层剖面线趋于平缓，种水流强度下桥墩冲刷坑下游高程剖面线与纵向X轴的夹角$\alpha_{D1}>\alpha_{D2}$，坑深和坑径也越大，这与Aksoy等[33]结论一致。在图9(b)中L_k/D=7下，由于采沙坑和桥墩模型间的距离最近，相互影响下会使墩柱下游曲线最平缓且坑径最大。

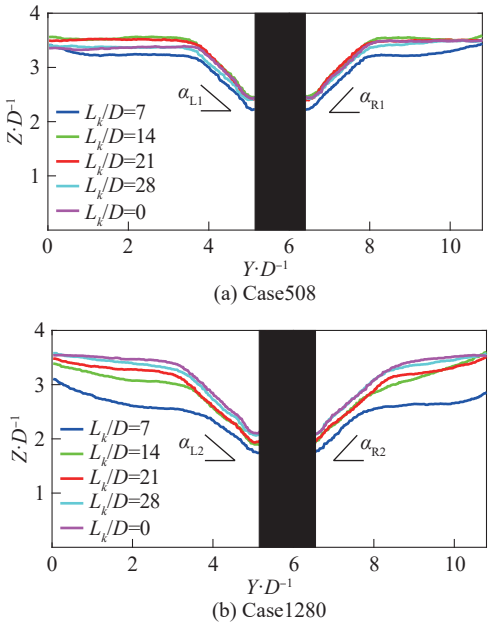


(a) Case508

(b) Case1208

图9 两种水流条件下X–Z面的无量纲化高程

Fig. 9 Dimensionless elevation on the $X-Z$ plane under two flow conditions



(a) Case508

(b) Case1280

图10 两种水流条件下Y–Z面的无量纲化高程

Fig. 10 Dimensionless elevation on the $Y-Z$ plane under two flow conditions

从图10(Y–Z面)分析桥墩局部冲刷坑可知:冲刷坑在沿桥墩模型对称轴基本对称,即高程剖面线与横向Y轴的左右夹角$\alpha_L=\alpha_R$;采沙坑与桥墩模型间的距离越近,桥墩冲刷坑的坑深越大,且高水流强度下河床下切的深度比低水流强度下更大。

图11展示了两种水流条件下不同L_k/D时无量纲化最大坑深(H_2/D)对比。

由图11可知:床面存在采沙坑时,桥墩冲刷深度均增大,即采沙坑的存在加剧了桥墩局部冲刷。当L_k/D相同时,水流强度越大,桥墩冲刷坑的最大坑深越大。随着采沙坑与桥墩模型间的距离越近,最大坑深呈增大趋势,河床下切深度变大,桥墩裸露的面积增大。当L_k/D分别为0、7、14、21、28时,高水流强度下桥墩冲刷坑的最大坑深比低水流强度下分别增加了28.5%、38.6%、35.1%、34.2%、38.6%,平均增加33.9%,尤其当L_k/D=7时增加约38.6%,表明采沙坑的存在对桥墩局部冲刷产生了重要影响。

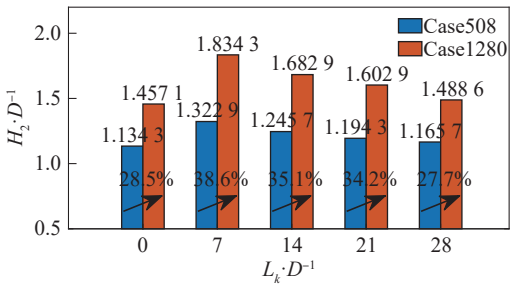


图11 两种水流条件下桥墩冲刷坑的无量纲化最大坑深对比

Fig. 11 Dimensionless maximum pit depth comparison of the pier scour pit under two flow conditions

3.1.2 不同工况的采沙坑和桥墩冲刷坑面积特征

为进一步观察采沙坑和桥墩冲刷坑形态变化特征,选取Case1280的5组试验工况,沿各组试验工况的0.3、0.4、0.6和0.7倍坑深分别截取X–Y面,分析不同坑深对应的坑面积大小、形态特征关系,Case1280的采沙坑面积截面、桥墩冲刷坑面积截面分布分别如图12、13所示。

图12、13中,紫色区域代表冲刷地形的二维截面,黄色区域代表相应坑深对应的坑截面面积,绿色圆圈代表桥墩模型。

由图12可以看出:横向观察同一组工况发现,随着坑深的增大,采沙坑对应坑深的截面面积越大,即黄色区域越大;从竖向即每组工况的同一坑深来看,发现采沙坑与桥墩模型间的距离越近时,同一坑深位置的采沙坑截面面积越大,这表明采沙坑与桥墩模型之间的相互作用导致紊流对采沙坑的剪切冲蚀作用加剧[32]。

由图13可以看出:横向观察同一组工况发现,随着坑深的增大,当截面坑面积未完全包围桥墩模型时,桥墩冲刷坑面积基本以桥墩模型对称轴呈对称增大;而当截面坑面积完全包围桥墩模型时,桥墩冲刷坑截面区域逐渐演变为不规则的心形;对比每组工况的同一坑深同样可以发现,随着采沙坑与桥墩模型之间的距离越近,同一坑深位置处桥墩冲刷坑截面区域越大,坑径也逐渐变大,这正好与图10的结论一致。

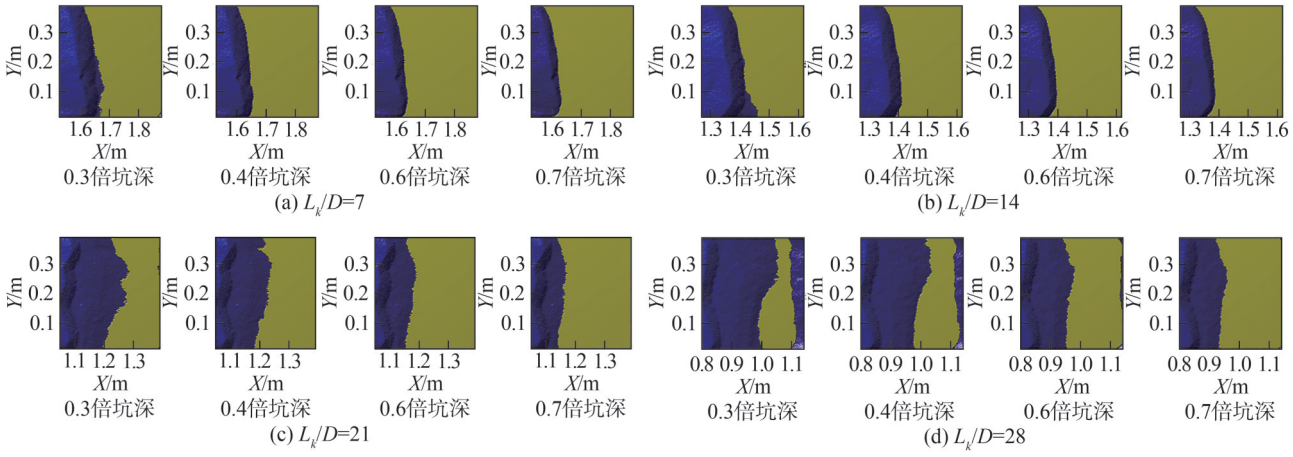


图 12　Case1280 的采沙坑面积截面

Fig. 12　Cross sections of sand pit area of Case1280

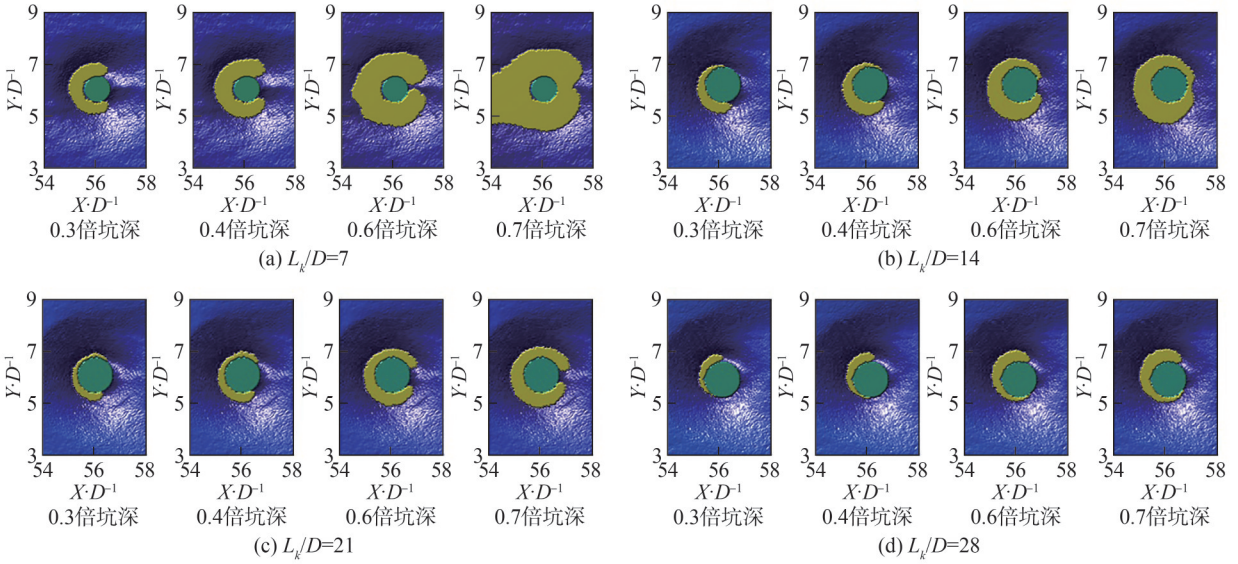


图 13　Case1280 的桥墩冲刷坑面积截面

Fig. 13　Pier scour hole area cross-sectional views of Case1280

为定量分析冲刷坑的形态变化，对冲刷后的桥墩冲刷坑进行不同坑深处面积的定量统计。将其分成 n 等份，设 S_i 为坑深 H_i 处坑面积。不同坑深处坑面积 S_i 是坑 $X-Y$ 截面内网格数（N_i）乘以单位网格面积（n^2），其计算公式如下：

$$S_i = N_i \times n^2 \tag{7}$$

图 14 展示了 Case1280 的不同 L_k/D 下桥墩冲刷坑的最大坑深对应的无量纲化面积截面。由图 14 可以看出：随着采沙坑与桥墩模型间的距离越近，桥墩冲刷坑最大坑深所对应的截面面积越大，这与图 13 的结论相同。L_k/D=0 和 L_k/D=28 的桥墩冲刷坑最大坑深所对应的截面面积较接近；L_k/D=0 和 L_k/D=7 的桥墩冲刷坑最大坑深所对应的截面面积相差较大，L_k/D=7 的桥墩冲刷坑最大坑深所对应的截面面积比 L_k/D=0 时增加约 12%，这同样说明了采沙坑的存在对桥墩局部冲刷产生重要影响。

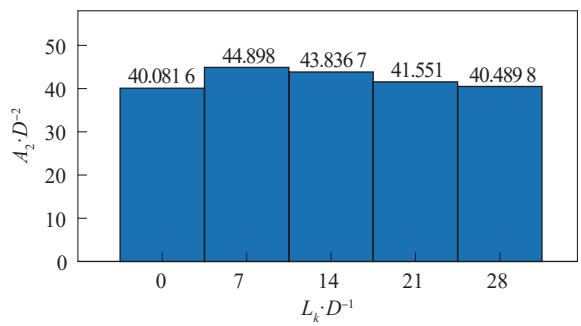


图 14　Case1280 的桥墩冲刷坑最大坑深对应的无量纲化截面面积

Fig. 14　Dimensionless cross-sectional area corresponding to the maximum pit depth of the pier scour pit for Case1280

3.2　湍流与冲刷坑的结构特性

为研究流场与冲刷之间的关系，通过 PIV 系统分别拍摄垂向 $X-Y$ 面和横向 $X-Z$ 面二维流场。本文对 Case1280 中 4 组具有代表性的工况的桥墩周围流场分

布进行详细阐述。在各工况的0.7倍水深位置，对水平面拍摄的近5 000张瞬时流场进行平均，获取$X-Y$面二维流场；对垂直面拍摄的近5 000张瞬时流场进行平均，获取$X-Z$面二维流场。

3.2.1 绕流的流场特性

图15、16分别展示了每组工况$X-Y$面、$X-Z$面无量纲化的平均流向和横向流速云图。

通过图15($X-Y$面)可以观察到：上游来流越靠近墩柱，流向流速沿桥墩模型对称轴两侧基本对称分布；水流因墩柱阻碍减速，至墩柱处趋近于0，而在两侧区域形成偏黄红色区域，对应流速最大值；水流遇到墩柱受阻后，横向流速的极大值点位于墩柱上游上侧，而极小值点在墩柱上游下侧区域出现，且沿桥墩模型对称轴平面呈反对称形态，速度大小为扇形向外扩散逐级递减。

由图16($X-Z$面)可见：底部空白区域为沙层区域，其流速为0；流向流速的极小值主要出现在桥墩周围的冲刷坑内，横向流速的极小值点出现在靠近墩柱上游的冲刷坑内，水流遇桥墩受阻后部分水流向下运动，形成负值区域。总体来看，随着采沙坑与桥墩模型间的距离越近，流向和横向流速在桥墩上游的减速较为明显，在下游水流远离墩柱过程中流速增加越缓慢，即红橙色区域越少，这说明水流流经采沙坑时形成漩涡结构使水流流速降低。

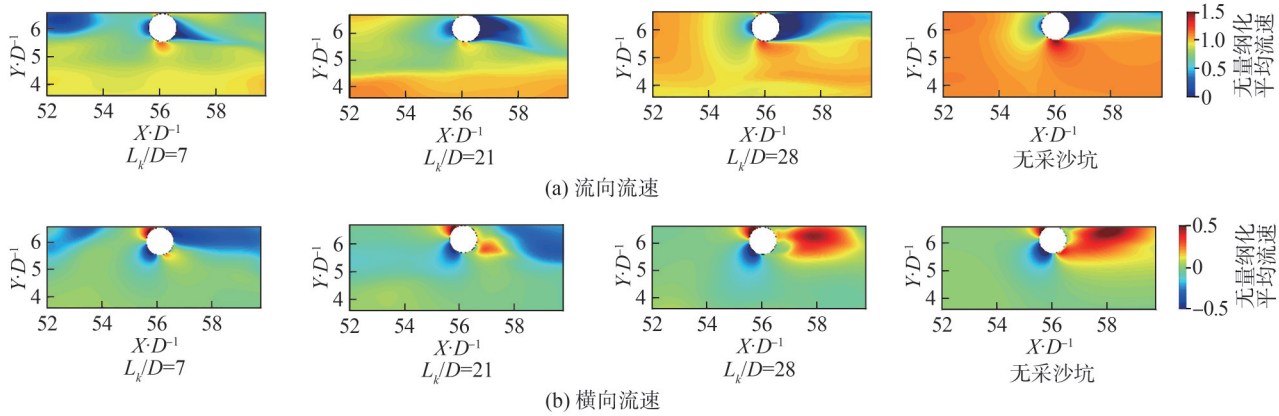


图15 Case1280的桥墩周围$X-Y$面无量纲化平均流向和横向流速云图

Fig. 15 Dimensionless average streamwise and transverse velocities cloud diagram of $X-Y$ plane around the pier of Case1280

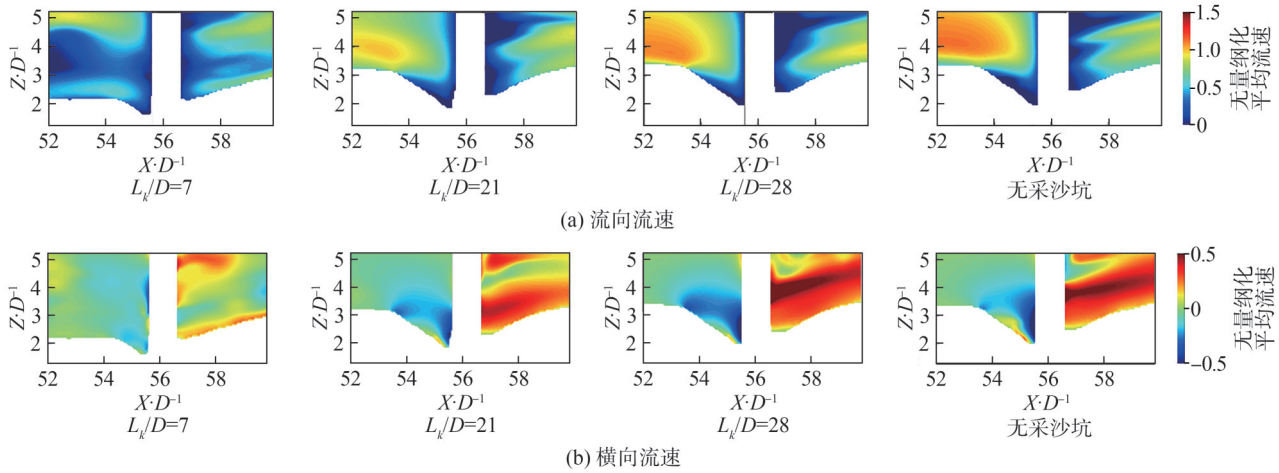


图16 Case1280的桥墩周围$X-Z$面无量纲化平均流向和横向流速云图

Fig. 16 Dimensionless average streamwise and transverse velocities cloud diagram of $X-Z$ plane around the pier of Case1280

图17、18分别为每组工况$X-Y$、$X-Z$面无量纲化的涡量云图。由图17可以发现：$X-Y$面的涡量主要出现在墩柱周围及其下游；且随着采沙坑与桥墩模型间的距离越近，涡量分布区域范围越大。当L_k/D=7时，墩柱与采沙坑之间相互作用，形成较大范围的涡量极值区域，如桥墩上游出现明显的较大涡量。由图18可以发现：$X-Z$面的涡量主要出现在墩柱周围和墩柱上游冲刷坑内，因为在水流撞击墩柱的过程中，一部分水流形成下潜流，存在涡流。随着采沙坑与桥墩模型间的距离越近，墩柱上游冲刷坑内涡量分布区域范围越小，但冲刷坑内的涡量更加密集，即涡量值越接近深蓝表示涡量越接近极小值[34]，这会加剧泥沙输移，使桥墩局部冲刷坑的深度变大，桥墩暴露的区域越大，越不利于桥墩的安全稳定运行。L_k/D=7时涡量是无采沙坑(即L_k/D=0)时的约2.2

倍，也验证了紊流流经采沙坑后，涡量呈倍数增加的结论[35]。总体来看，随采沙坑与桥墩模型间的距离越近，墩柱周围的涡量出现区域范围越大。同时，当采沙坑与桥墩距离较近（即L_k/D=7）时，由于两者的相互作用，涡量分布覆盖桥墩和采沙坑两个区域，也造成了桥墩局部冲刷加剧[36–37]。

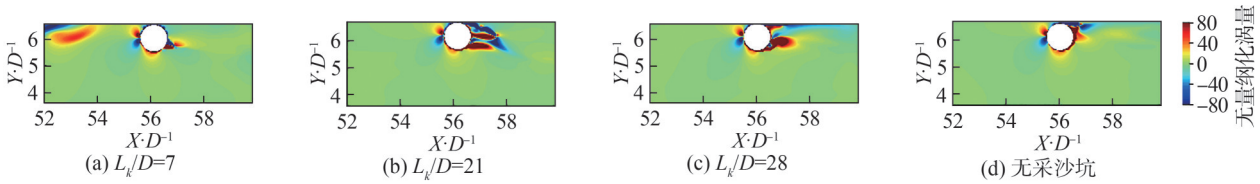


图 17　Case1280 的桥墩周围 *X*–*Y* 面无量纲化涡量云图

Fig. 17　Dimensionless vorticity contour on the *X*–*Y* plane around the pier of Case1280

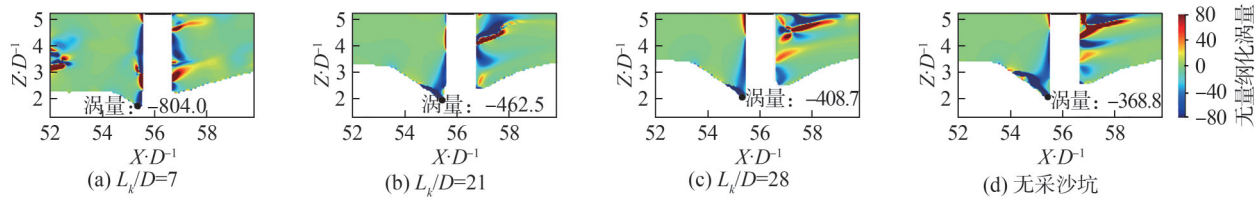


图 18　Case1280 的桥墩周围 *X*–*Z* 面无量纲化涡量云图

Fig. 18　Dimensionless vorticity contour on the *X*–*Z* plane around the pier of Case1280

3.2.2　POD 结果分析

为深入研究河道内不同位置采沙对桥墩周围水流流动特征影响，采用 POD 模态分解方法，对桥墩模型局部流场进行深入分析。图 19 为前 10 阶特征能量分布。

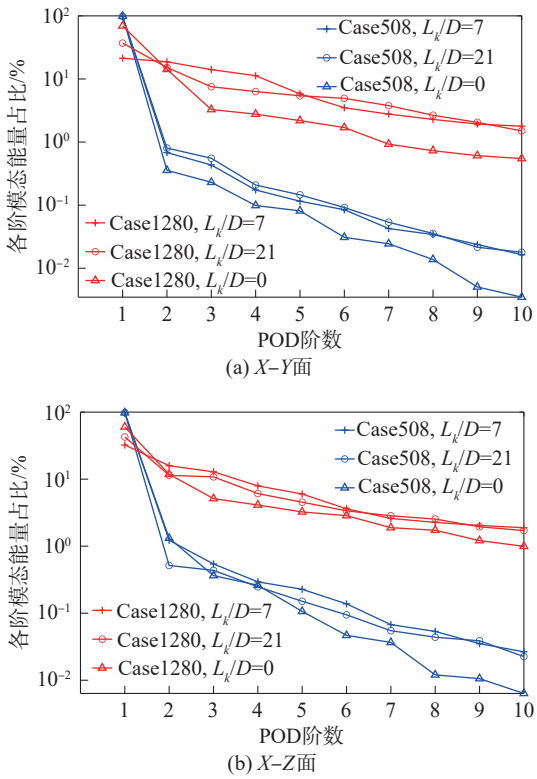


图 19　桥墩周围前 10 阶能量分布

Fig. 19　Energy distribution map of the first 10 steps around the pier

由图 19 可见：随着模态阶数的升高，能量减小的速度越快，低阶模态是整个流场的主要载体[38]；1 阶模态占据了流场中大部分能量，是流动结构中最稳定的模态，而高阶模态则涵盖了小尺度更细微的流动结构。无论是在 *X*–*Y* 面还是 *X*–*Z* 面的能量分布中，清水冲刷时，1 阶模态所占能量远远高于剩余模态之和，也远大于动床冲刷的 1 阶模态所占的能量。同时，随着水流强度增大，水沙运动加剧导致紊动加剧，1 阶模态占比减小。当 L_k/D 相同时，较低水流强度下 1 阶模态所占能量约为 90%，而较高水流强度下 1 阶模态所占能量约为 46%。此外，随着采沙坑与桥墩模型间的距离越近，1 阶模态所占能量越小，这也说明桥墩周围的紊动越剧烈，紊动强度越高，能量越趋于分散。

结合图 8～19 的分析可以看出：采沙坑的存在对桥墩局部冲刷地形和流场均产生了影响。当 L_k/D=28 时，其影响相对较小，与无采沙坑（即 L_k/D=0）时的影响较为接近；随着采沙坑与桥墩模型间的距离越近，采沙坑的存在对桥墩局部冲刷的影响越大，故建议在 L_k/D=28 的位置内不得进行采沙活动，以便保持河床结构平稳，桥墩结构安全稳定。同时，本文未考虑采沙坑不同深度对桥墩局部冲刷的影响，未来可对此开展进一步研究。

4　结　论

本文在两种水流强度下，采用天然均匀沙铺设，在 L_k/D 为 7、14、21、28 和无采沙坑（L_k/D=0）下对比开展明渠桥墩局部冲刷试验。采用 SFM 方法对床面进行精确三维地形重构；借助 PIV 系统分别获取桥墩模型局部垂向 *X*–*Y* 面和横向 *X*–*Z* 面的二维流场；通过快照 POD 方法对流场数据进行模态分解，提取在低维空间中占主要能量的模态，分析在不同水流强度条件下低阶模态能量的变化。主要结论如下：

1)随着采沙坑与桥墩模型间的距离越近和水流强度越大,桥墩冲刷坑的坑深越大,即河床下切深度变大,采沙坑上游倾角相等且与泥沙休止角基本一致。随着采沙坑与桥墩模型间的距离越近,高水流强度下桥墩冲刷坑的最大坑深比低水流强度下的逐渐增大,尤其当L_k/D=7时,最大坑深增加约38.6%。

2)随着采沙坑与桥墩模型间的距离越近,水流强度越大,无量纲化坑深越大时,采沙坑和桥墩冲刷坑截面面积越大,坑径逐渐变大,桥墩暴露的面积也越大;L_k/D=7时的桥墩冲刷坑最大坑深所对应的截面面积比无采沙坑(L_k/D=0)时增加约12%,采沙坑的存在对桥墩局部冲刷产生重要影响,不利于桥墩的安全稳定。

3)随着采沙坑与桥墩模型间的距离越近,流向和横向流速云图中桥墩上游减速越明显,涡量在桥墩冲刷坑内越大。L_k/D=7时冲刷坑内最大深度处的涡量是无采沙坑(L_k/D=0)时的约2.2倍,加剧了桥墩局部冲刷。

4)随模态阶数的升高,能量减小的速度越快,低阶模态是整个流场的主要载体。随着采沙坑与桥墩模型间的距离越近和水流强度越大,1阶模态所占能量越小;1阶模态所占能量在较低水流强度下约为90%,而在较高水流强度下约为46%;桥墩周围的紊动越剧烈,能量越趋于分散。

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Experimental Study on the Influence of River Sand Mining Pit Location on Local Scour Characteristics of Bridge Piers

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Abstract:

Objective The presence of sand pits in a river affects the stability of piers; however, the relationship between the two is poorly understood. In this study, an experimental investigation of local pier scour was conducted under two distinct flow conditions, with four sand pit positions to address this knowledge gap. The characteristics of scour topography and the resulting variations in the local turbulent structure of flow around piers under different working conditions were analyzed.

Methods First, a three-dimensional terrain reconstruction was produced using Visual SFM open-source software, and the scale-invariant feature transformation method was applied to identify, extract, and match the terrain feature points. The images captured by the camera were sorted into a database, and the feature points were identified and matched with the location information from the photograph. Feature points from different photographs were matched to obtain homonymous points. Based on the matching feature points, sparse and dense point clouds were obtained for use in the model. The resulting error was ±0.1 mm and the accuracy was high. Second, to obtain flow field information near a pier, the instantaneous flow field was calculated. The resulting time average velocity field was used to analyze the flow characteristics around the pier. At the same

time, to better understand the flow characteristics of the local flow field around the pier, the Snapshot proper orthogonal decomposition method was used to decompose the instantaneous flow field obtained by the particle image velocimetry device into an average flow field and a pulsating flow field. The pulsating flow field was decomposed, and the first few modes with the highest energy were extracted for comparison.

Results and Discussions The structural characteristics of the local scour pit around the pier were quantitatively studied. Under clear-water scour conditions, the flow velocity was lower than the sediment start-up velocity, and the upstream bed surface elevation of the pier was relatively low. Because the flow velocity was greater than the sediment start-up velocity, sand transport on the bed surface caused the bed surface topography to rise and fall. Along the upstream profile approaching the pier column, the two-dimensional profile of the bed elevation gradually decreased until it reached the maximum pier scour pit depth. The upstream dip angles α_{U1} and α_{U2} of the sand pit were virtually identical and consistent with the sediment repose angle. The scour hole was structurally symmetrical along the axis plane of the pier model, i.e., the angle $\alpha_L = \alpha_R$ was identical between the elevation profile line and the transverse Y axis. The closer the distance between the sand pit and the pier, the greater the depth of the pier scour pit, and the depth of the riverbed under a high flow intensity was greater than that under a low flow intensity. Across the varying distances between the sand pit and the pier model, the maximum pier scour pit depth under high flow intensity was 27.7%−38.6% (average, 33.9%) higher than under low flow intensity. When $L_k/D = 7$, the increase was 38.6%. This shows that the existence of a sand pit has an important influence on the local scour of the pier. The relationship between the size and morphological characteristics of the pit area was analyzed across different pit depths. As pit depth increased, the corresponding cross-sectional area of the sand pit depth also increased. Furthermore, a shorter distance between the sand pit and the pier model resulted in a larger cross-sectional area of the sand pit for the same pit depth, indicating that the interaction between the sand pit and the pier model intensified the shear erosion effect of turbulence on the sand pit. The larger the cross-sectional area of the pier scour pit for the same pit depth, the larger the pit diameter gradually became. The relationship between the flow field and the scour was also studied. The upstream deceleration of the flow approaching the pier became more pronounced in the flow direction and transverse velocity cloud as the distance between the sand pit and the pier model shortened. The velocity increased more slowly, suggesting that a vortex structure formed when the water flowed through the sand pit, reducing the flow velocity as the downstream water flow moved away from the pier. As the distance between the sand pit and the pier model shortened, the vorticity area in the scour pit upstream of the pier was reduced; however, the vorticity in the scour pit intensified. This aggravated the sediment transport and increased the depth of the local scour pit around the pier, resulting in a larger area of the pier being exposed. These conditions were not conducive to the safe and stable operation of the pier. The vorticity at $L_k/D = 7$ was about 2.2 times that at $L_k/D = 0$ when there was no sand pit, which also indicated that the vorticity increased exponentially after the turbulent flow passed through the sand pit. This in-depth study of the influence of sand mining at different positions in a river revealed the flow characteristics around a pier. With an increase in the modal order, the energy decreased faster, and the low-order mode was the main carrier of the whole flow field. The first-order mode accounted for most of the energy in the flow field and was the most stable mode in the flow structure, whereas the higher-order mode covered the smaller-scale flow structure.

Conclusions The results showed that the shorter the distance between the sand pit and the pier model, and the greater the flow intensity, the greater the depth and cross-sectional area of the scour pit around the pier. However, the upstream dip angle of the sand pit was equal and consistent with the angle of repose of the sediment. As the distance between the sand pit and the pier model shortened, the maximum pier scour pit depth gradually increased. When the distance between the sand pit and the pier model was $L_k/D = 7$, the maximum pier scour pit depth under high flow intensity was 38.6% higher than that under low flow intensity. As the distance between the sand pit and the pier model shortened, the upstream deceleration of the flow around the pier became more pronounced, as revealed by the spanwise velocity contours. Furthermore, the vorticity was more intensive in the scour pit around the pier. When the distance between the sand pit and the pier model was $L_k/D = 7$, the vorticity at the maximum depth of the scour pit was about 2.2 times greater than that of the baseline case with no sand pit ($L_k/D = 0$), thereby aggravating local scour around the pier. As the distance between the sand pit and the pier model shortened and the water flow intensity increased, the first-order mode became smaller. The turbulence around the pier was intense under these conditions, and the energy tended to be more dispersed. As the modal order increased, the energy decay rate increased.

Key words: circular pier; rectangular sand mining pit; local scour test; structure from motion method; particle image velocimetry; proper orthogonal decomposition method

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