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重大水利工程对长江中下游干流河槽和岸线地质环境影响研究

姜月华[1,2],程和琴[3],周权平[1,2],倪化勇[4], 金阳[1,2],梅世嘉[1,2], 张鸿[1,2],顾轩[1,2],施斌[5], 顾凯[5],魏广庆[6],李云[1,2],杨国强[1,2],齐秋菊[1,2]

(1. 中国地质调查局南京地质调查中心,江苏 南京 210016;2. 自然资源部流域生态地质过程重点实验室,江苏 南京 210016;3. 华东师范大学,上海 200241;4. 中国地质调查局成都地质调查中心, 四川 成都 610081;5. 南京大学,江苏 南京 210023;6. 苏州南智传感科技有限公司,江苏 苏州 215123)

提要:本文主要采取历史水下地形和水位数据分析、干流河槽现场测量、室内测试和综合评价等方法对重大水利工程影响长江中下游干流河槽和岸线进行了分析和研究,取得如下新进展:(1)创新构建了一套多模态传感器系统,实现陆上和水下一体化水动力、沉积和地貌特征测量与数据采集。(2)调查研究发现,长江干流河槽冲刷强烈,岸线窝崩、条崩发育。(3)悬沙和床沙粗化,河床阻力下降,发育侵蚀型链珠状沙波,长江大桥主桥墩冲刷严重。(4)潮区界显著上移,潮区界变动河段地貌发生重要变化。在此基础上,研究认为应该加强长江中下游干流河槽、沿岸高陡岸坡、支流入汇干流河口、崩岸以及跨江大桥桥墩冲刷等调查、监测和成因机理分析。上述研究成果对长江岸滩防护和修复、航道整治、沿岸防洪、长江大桥桥墩维护等具有重要意义。

关 键 词:长江中下游地区;潮区界;崩岸;窝崩;河槽冲刷;侵蚀和淤积;地质调查工程

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The influence of major water conservancy projects on the geological environment of channel and shoreline in the middle and lower reaches of the Yangtze River

JIANG Yuehua [1,2], CHENG Heqin [3], ZHOU Quanping [1,2], NI Huayong [4], JIN Yang [1,2], MEI Shijia [1,2], ZHANG Hong [1,2], GU Xuan [1,2], SHI Bin[5], GU Kai[5], WEI Guangqing[6], LI Yun[1,2], YANG Guoqiang[1,2], QI Qiuju [1,2]

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作者简介:姜月华,男,1963年生,博士,研究员,主要从事环境地质和水文地质工作;E−mail: 316664105@qq.com。

(1.*Nanjing Center, China Geological Survey, Nanjing* 210016*, Jiangsu,China;* 2. *Key Laboratory of Watershed Eco− Geological Processes, Ministry of Natural Resources, Nanjing* 210016*, Jiangsu, China;* 3. *East China Normal University, Shanghai* 200241*;* 4. *Chengdu Center, China Geological Survey, Chengdu* 610081*, Sichuan,China;* 5. *Nanjing University, Nanjing* 210023*,Jiangsu, China;* 6. *Suzhou Nanzhi Sensing Technology Co., Ltd., Suzhou Industrial Park, Suzhou* 215123*, Jiangsu, China)*

Abstract: Based on the analysis of historical underwater topography and water level data, field measurement, laboratory test and comprehensive evaluation, the influence of major water conservancy projects on the channels and shorelines of the middle and lower reaches of the Yangtze River is studied. Some new progresses have been made. Firstly, a multi− mode sensor system was innovatively constructed to integrate the measurements of land and underwater hydrodynamic, sedimentary and geomorphic characteristics and data acquisition. Secondly, it was found that the main channel of the Yangtze River experienced strong erosion, arc collapse, and strip collapse. Thirdly, the hanging sand and bed sand were coarsened. The resistance of the river bed dropped, which caused the forming of the erosion type chain bead sand wave. The main piers of the Yangtze River Bridge were subjected to serious erosion. Finally, the tidal limit obviously moved up, and the geomorphology of the river changed significantly. On this basis, it is suggested that the investigation, monitoring and mechanism analysis should be strengthened on main river channel, high and steep slope along the bank, the estuary where the tributaries join the main stream, bank collapsing, cross−river bridge pier scour and so on. These results are of great significance to the protection and restoration of the bank and beach of the Yangtze River, the waterway regulation, the coastal flood control, and the maintenance of the piers of the Yangtze River Bridge.

Key words: middle and lower reaches of the Yangtze River; tidal limit; bank collapsing; arc collapsing; channel erosion; erosion and deposition; geological survey engineering

About the first author: JIANG Yuehua, male, born in 1963, doctor, senior researcher, engaged in environmental geology and hydrogeology; E−mail: 316664105@qq.com.

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1 引 言

长江是中华民族的母亲河，自20世纪 60 年代以来，长江流域兴建了以三峡大坝为核心的一系列拦、蓄、引、调大型水利工程，入海河口建设了大规模围垦、深水航道、造船基地、跨江与跨海大桥以及毗连的洋山深水港等重大工程。这些工程不可避免地对长江中下游干流河槽和岸线冲刷产生影响（Luo，2013；Luo et al.,2017；石盛玉等，2017；姜月华等，2017；Zheng et al., 2018；Jiang et al.,2018），从而威胁过江通道、港口码头和水厂等重要基础设施安全（Williams et al., 1984; Carriquiry et al., 2001; Rinaldi，2010；陈敏等，2017；姜月华等，2019）。河槽冲淤演变事关岸线资源开发与利用以及两岸地区人民生命财产安全（齐梅兰，2005；王建等，2007；韩剑桥等，2014；张晓鹤等，2015；吴帅虎等，2016；陆雪骏等，2016；石盛玉，2017）。针对这些影响和威胁如何应对是当前有关政府部门、学术界与公众关注的焦点和难点（Surian，2002；Zheng et al.,2017；Shi et al.,2018）。

长江中下游地区沿江两岸，除了极少数地区出露基岩外基本多为第四系沉积物覆盖。其中，江汉—洞庭盆地和长江三角洲地区第四系沉积物厚度较大，最厚处均超过400 m。第四系沉积物地层结构复杂，沿江两岸的沉积地层结构主要为砂层或泥层或砂泥互层，砂泥互层结构在垂向上通常表现为下细上粗或者下粗上细的特点。由于岩相变化，沉积地层结构在各地是各不相同的。由于沉积物质结构相对较疏松，所以极易遭受侵蚀而发生崩塌地质灾害。资料显示，长江中下游干流河道岸线总长约3600 km，其中，崩岸长度达1520 km，占沿江总长度的41%（刘红星等，2003；王路军，2005），近5年水利部下拨崩岸应急整治经费3.25亿元（陈敏等，2017），用于长江中下游湖北、湖南、江西、安徽和江苏等河道崩岸应急整治。

鉴于长江中下游干流水砂条件的改变以及岸

线崩塌有趋于发展严重的态势，本文通过大量长江干流水域现场剖面测量和样品采集，获得一批最新原始数据，以及开展了以三峡水库为核心的重大水利工程运行过程中河槽床沙与悬沙粒径、潮流、含沙量、床面微地貌时空分布特征及其变化规律的研究和讨论，分析了新的水沙条件下长江河槽床沙粒径、沉积结构、河槽及岸滩冲淤稳定性，阐明了引发河槽地貌变化和河槽冲淤不稳定的主导因素，旨在为长江河槽航道工程与护岸保滩工程的冲淤灾害防治以及长江中下游过江通道等重大工程安全预警提供科学依据。

2　研究方法

本次研究基于长江流域重大水利工程与地质环境多元响应的研究思路，主要采用创新构建的一套多模态传感器系统（图1），实现陆上和水下一体化水动力、沉积和地貌特征测量与数据采集（图2）。多模态传感器系统组合了奥地利生产的Riegl VZ-4000三维激光扫描系统、丹麦生产的SeaBat7125_SV2多波束测深系统、美国生产的EdgeTech 3100P浅地层剖面仪、美国生产的声学多普勒流速剖面仪（ADCP）、全球定位系统（GPS）和实时动态载波相位差分定位仪（RTK）。同时，使用抓泥斗采集床沙样品（用于含沙量、含盐度和悬沙粒径的水样品），利用马尔文公司生产的Master Sizer 2000型激光粒度仪进行粒度分析。2014—2018年共计完成长江宜昌—河口段测线5000 km测量，积累了大量第一手水动力、地形、沉积特征等实测资料，并结合历史水下地形数据（1998年和2013年长江宜昌至上海干流河段，据原交通运输部长江航道局），开展了沿江水下地形、潮流、悬沙浓度及级配组成、沿江跨江大桥冲蚀状况、河岸边坡稳定性等分析与评价，在此基础上，提出了重大水利工程对地质环境影响新认识和新判断。

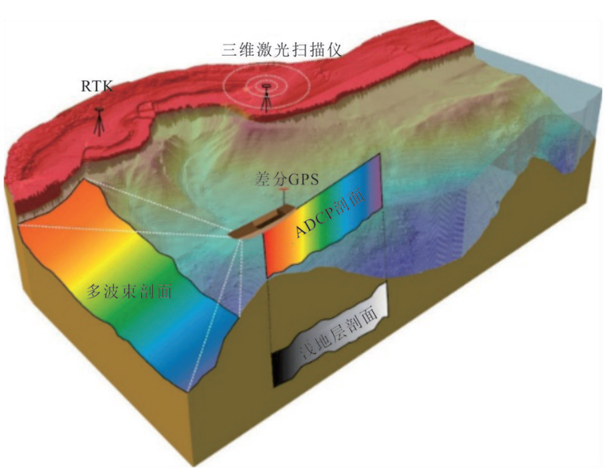

图 1　多模态传感器系统工作示意图
Fig.1　Working schematic diagram of the multimodal sensor system

3　讨论和结果

3.1　干流河槽冲刷及岸线窝崩、条崩发育状况

研究发现，流域大型水利工程特别是三峡大坝建设使长江宜昌以下至上海吴淞口干流河槽整体冲刷强烈（图3）。汉口至湖口、湖口至大通以及大通至吴淞口等河段−5～−10 m河槽、0～−5 m河槽和10 m以深河槽的冲刷贡献率分别占相应河槽总冲刷量60.2%、44.9%和49.1%。典型汇流河段（洞庭湖、鄱阳湖与长江交汇处）大部分横断面呈强烈冲刷状态（图4），主槽大幅摆动，河槽下切刷深，0 m浅滩多数侵蚀后退；−3 m、−5 m以深面积显著增加，冲刷幅度洞庭湖口大于鄱阳湖口。

调查研究显示，坡度在20°~40°、40°~60°和大于60°的水下高陡边坡占比分别为22%、2.5%和

图2　野外测量工作照片
a—正在遥控搭载多波束测深系统、浅地层剖面仪、声学多普勒流速剖面仪和差分定位仪等设备的无人船测量；b—安放浅地层剖面仪；c,d—数据采集
Fig. 2 Photos of field measurement work
a − Remote control unmanned vessel survey with multi−beam sounding system, sub−bottom profiler, acoustic doppler current profiler, real time kinematics and so on; b− Placement of sub−bottom profiler; c and d − Data acquisition

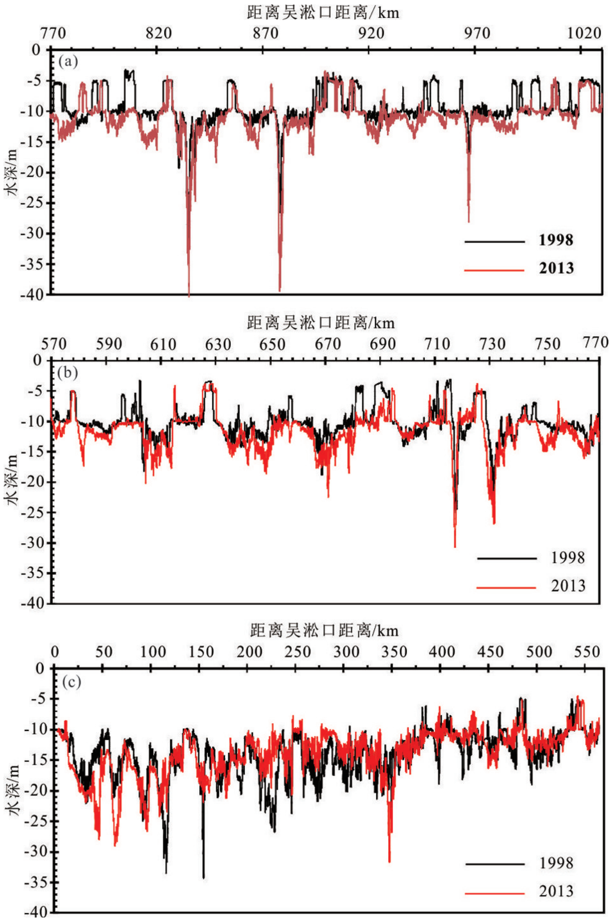

图3 长江汉口至湖口(a)、湖口至大通(b)、大通至吴淞口(c)河段深泓线变化特征

Fig. 3 Variation characteristics of the depth line from Hankou to Hukou (a), Hukou to Datong (b) and Datong to Wusongkou (c) along the Yangtze River

0.8%。坡脚发育深达10 m、长达几千米冲刷槽，极易发生窝崩和条崩。如龙潭、太阳洲、螺山、砖桥等水道边坡发生窝崩(图5)，煤炭洲和蕲春等水道边坡发生条崩，窝崩、条崩总计多达30余处。这些不稳定岸段长度多在1 km以上，其中，武穴市和新厂镇等不稳定岸段长度可达2 km以上。窝崩形态多以“鸭梨”形、“耳”形、“月牙”形为主。

在长江中下游崩岸多以窝崩和条带状崩岸为主。窝崩近岸河槽坡脚较大，常伴有涡旋回流(图6)。条带状崩岸坍塌岸线一般较长，近岸常有冲刷坑或冲刷深槽，水流多为向岸流。水下地形探测发现，在长江下游铜陵太阳洲、扬州嘶马等地崩岸水下地形存在显著的崩塌堆积现象，显示相应岸段存在多期次的崩塌(图7)，这与当地经常性发生塌岸实际情况一致。

2017年11月8日在江苏省扬中市三茅街道指南村泰州大桥上游约1.5 km处的江岸发生的窝崩，造成岸线崩塌540 m，坍失主江堤440 m，崩岸最大进深190 m，坍失房屋9户、涵洞1座，土地9.73 hm^2(图8，图9)，2017—2020年对该岸段的整治已经累计花费达4亿元人民币。

已有的研究表明，窝崩和条崩等的形成主要与向岸流或涡旋回流冲刷作用有关(Osman and Thorne，1988；Thorne and Abt，1993；Youdeowei，1997；唐金武等，2012)，此外，上游来砂减少、水厂抽水、深泓近岸、高低水位突变(王家云和董光林，1998)、堤内积水、堤基加载、河槽形态和岸坡土体特性(长江流域规划办公室，1978)、地质构造(吴玉华等，1997；Wu et al.,2020)、人为采砂(王永，1999)等也是其形成的主要因素。本次工作通过对扬中指南村的窝崩研究发现，其成因机理主要与紧邻窝崩岸段上游的自来水厂抽水以及地下水渗流与涡旋回流冲刷三重作用密切相关。特别是该窝崩段岸带陆上部分的地层存在一古河道(图10)，实施的光纤监测也发现在近堤地下30~60 m深存在地下水渗流变化(图11)导致温度显著变化而引起的部分物质流失，这是有别于其他窝崩成因重要因素之一。

本次研究测量获得中下游干流沿程崩岸增多的结果表明：上述干流河槽整体冲刷幅度超过三峡大坝论证预估和三峡大坝工程前期调研结果，也与最新的“河槽冲刷虽然逐渐向下游过渡，但未来几十年里三峡大坝引起的河槽冲刷有可能在汉口附近停止”也显著不同。

3.2 河槽沉积物粒度、河床阻力及沙波变化状况

河槽表层沉积物及微地貌是河流水动力条件、沉积物、河槽边界与比降等因素相互作用结果，事关堤岸、过江通道、航运及港口安全。三峡大坝截流前，长江中下游河槽表层沉积物从上游向下游基本上呈现波动变细的趋势，平均粒径从细砂(0.3 mm)波动下降至极细砂(0.1 mm)，徐六泾以下河段基本小于0.1 mm(王张峤，2006；徐晓君等，2010；罗向欣，2011；许全喜等，2013；石盛玉等，2017)。2003年三峡大坝截流以来，大坝下游沉积物发生严重侵蚀和粗化，汉口至吴淞口大部分表层沉积物中值粒径为细砂—中砂(0.63～0.5 mm)。同时，河床

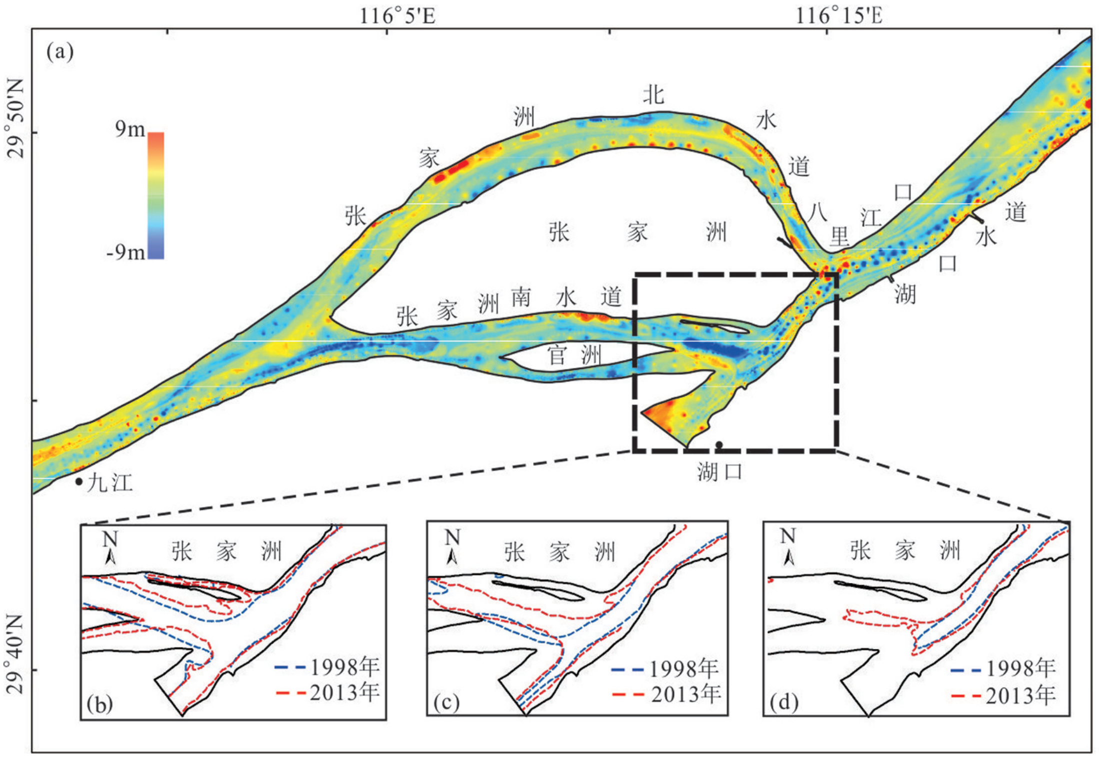

图4 长江与鄱阳湖汇流河段冲淤变化与微地貌特征
a—河道冲淤地形图;b—0 m 等值线;c—5 m 等值线;d—10 m 等值线
Fig.4 Changes in erosion, deposition and microgeomorphic features of the confluence of the Yangtze River and Poyang Lake
a−Scouring and silting topographic maps; b−0 m isobath; c−5 m isobath; d−10 m isobath

沙粒阻力下降,三峡蓄水前后最大河床沙粒、沙波阻力和平均沙粒、沙波阻力分别减小85%和63%(图12),相同水位下过境流量增大,表明在三峡截流泥沙来源减少后,相近挟沙能力下水体含沙量降低使动力对床沙的起动作用相对增强,河槽多处于冲刷环境。

近期研究发现,在长江中下游河槽发育侵蚀型链珠状沙波,一种由链状沙波和伴生底形椭圆形凹坑组成,在形态上椭圆形凹坑如同一粒粒圆珠镶嵌在链状沙波中(图13)。沙波形态一直是河流、河口和浅海环境研究的基础和重点 (Allen, 1980; Knaapen, 2005; 庄振业等, 2009; Van Landeghem et al., 2009; Barnard et al., 2011; 马小川, 2013)。初步推断链珠状沙波是长江九江至吴淞口河槽微地貌适应流域来沙量减少、水动力增强以及边界条件改变而形成的一种新的侵蚀型沙波类型,其发育机制尚需进一步研究。九江至湖口、湖口至大通、大通至徐六泾、徐六泾至吴淞口等河段河槽中沙波地形分别约占河段的80.3%、62.1%、64.3%和27.5%,沙波尺度(已达巨型沙波级)比三峡修建之前显著增大。

受地形因素、河床表层沉积物性质与组成、水动力条件等多因素的影响,沙波发育的尺度、形态与移动速度并不相同(Knaapen et al., 2001; 程和琴等, 2002; Knaapen, 2005; Li et al., 2008; Wu et al., 2009; Franzetti et al., 2013; Naqshband et al., 2014)。单就大型和巨型沙波波高而言,2003年黄石至安庆河段沙波波高一般都<2 m,安庆至芜湖河段波高一般为4~8 m,芜湖至吴淞口的波高局部可达到4~8 m(王哲等,2007),也即当时九江上游至吴淞口河段沙波波高未观测到超过8 m的,但在2014年至2018年的野外观测中,观测到了沙波波高9~10 m的巨型沙波(图14)。显然,长江汉口—吴淞口河槽沙波较2003年以前尺度有增大的趋势。

研究发现,河口河槽最大冲刷深度可达29.6 m;九江至上海干流8座长江跨江大桥主桥墩冲刷深度达10~19 m(图15,图16);在河槽浅滩分布有深

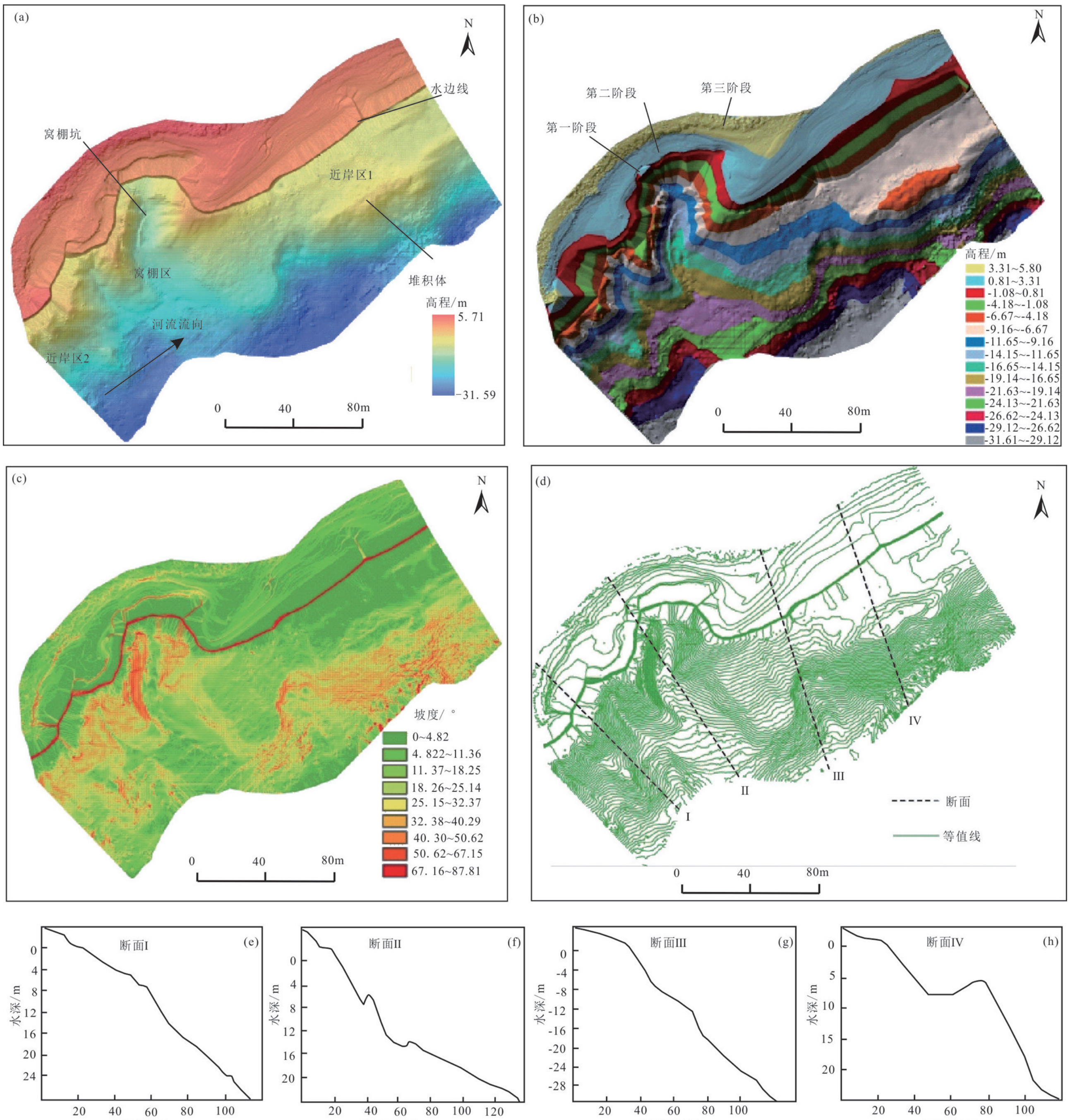

图5 铜陵太阳洲窝崩陆上和水下一体化高精度地貌图

a—基于反距离权重法的陆上水下3维地形数据融合图;b—TIN模型;c—坡度模型;d—高程等值线;
e~h—窝崩区域典型断面图

Fig. 5 Terrestrial and underwater high accuracy geomorphology of the arc collapse in Taiyangzhou, Tongling

a−Three−dimensional terrain point cloud data of non−submerged portions of the slope are integrated with submerged portions based on the method of IDW; b−Model of TIN; c−Model of slope; d−Contour map;e−h− Profile diagram of the Arc collapsing

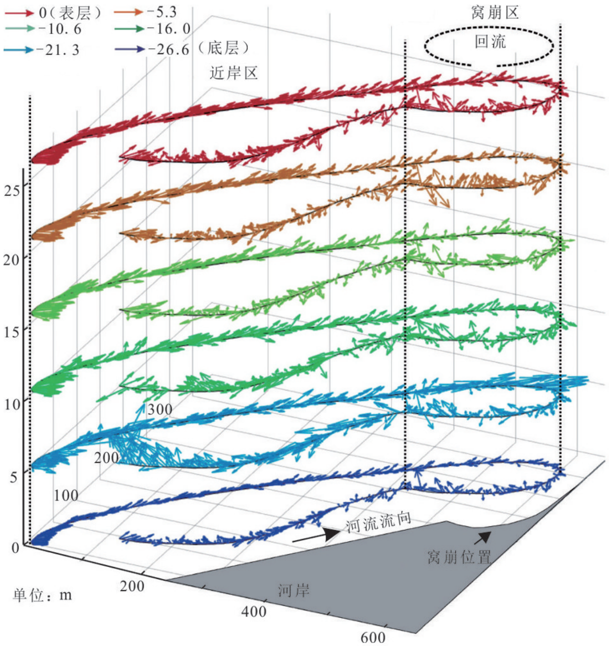

图6 扬中指南村利用声学多普勒流速剖面仪(ADCP)测得的崩岸三维地表水流场图

Fig. 6 A three-dimensional surface flow field map of bank collapsing measured by acoustic doppler current profiler (ADCP) in Zhinan Village, Yangzhong

3~5 m、直径达10~30 m的盗采砂坑。研究认为,这些侵蚀型沙波、巨型沙波、采砂坑和桥墩冲刷等均增加了水上航行和桥梁通行风险,需要引起高度关注。

3.3 潮区界及相应河段地貌变化状况

潮区界是标志河流水位受潮动力作用与否的关键界面(萨莫伊洛夫,1958;沈焕庭等,2008)。安徽大通一直是长江河口潮区界位置(陈吉余等,1979;黄胜,1986;徐沛初和刘开平,1993)。近年来,重大水利工程大幅改变了流域径流和输沙时空分布,尤其以三峡工程的调蓄作用使长江中下游流量过程变得平缓,加之海平面上升影响潮波上溯,引起潮区界位置改变(李佳,2004;李键庸,2007;杨云平等,2012;徐汉兴等,2012;侯成程,2013)。本次研究发现长江洪季潮区界与2005年相比上移82 km,枯季上移约220 km;特大枯水时期,九江站流量8440 m^3/s时,潮区界在九江附近,特大洪水时期,九江站流量66700 m^3/s时,潮区界在枞阳闸与池口之间;自上而下九江流量对潮区界的影响沿程减弱,南京潮差的影响则沿程增强,相近流量/潮差下潮区界位置有变动,变动范围随流量的

图7 江都嘶马利用浅地层剖面仪测得的崩岸水下地形图

Fig.7 Underwater topographic map of bank collapse measured by sub-bottom prsofiler in Jiangdu Sima

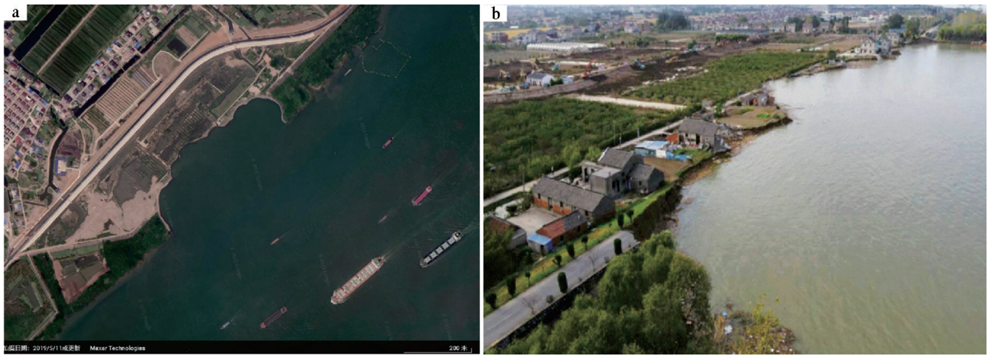

图8 扬中指南村窝崩图片(a—窝崩卫星影像图片;b—窝崩现场照片)

Fig.8 Arc collapsing pictures in Zhinan Village, Yangzhong (a−Arc collapsing satellite image picture;b−Arc collapsing site photograph)

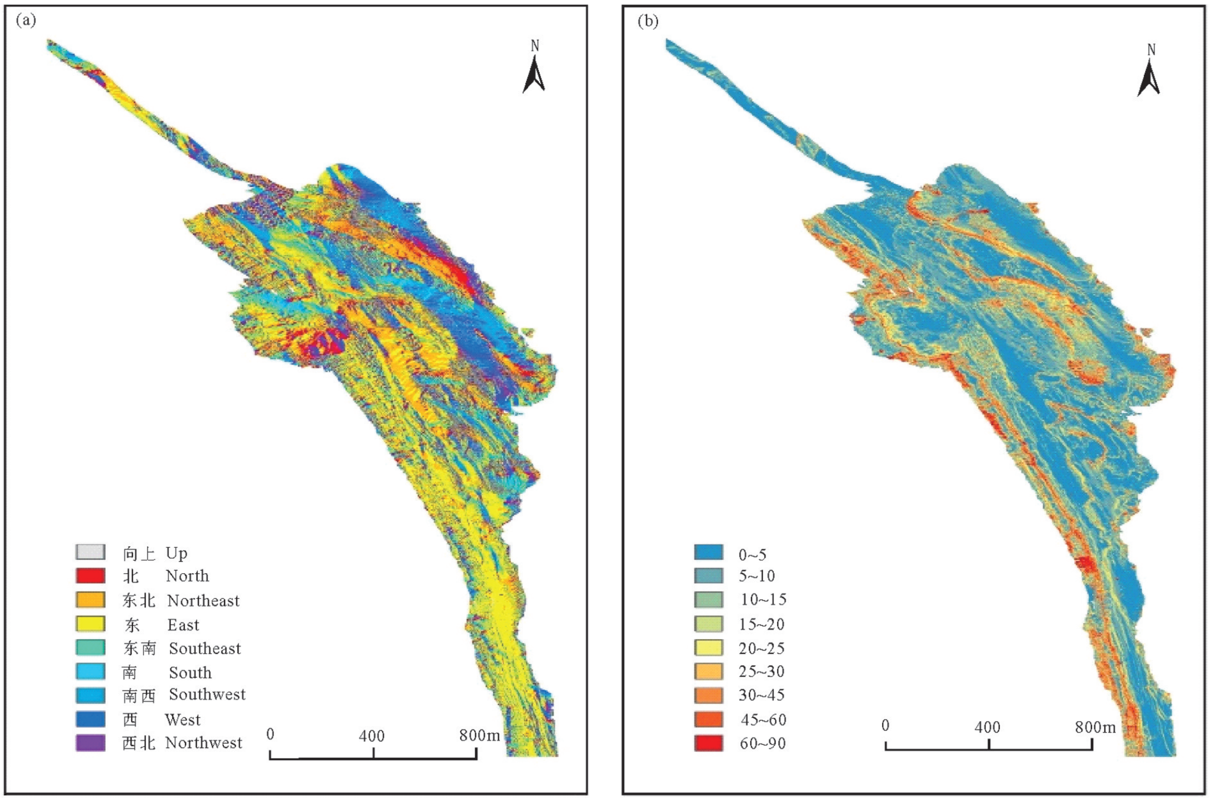

图9 扬中指南村水陆一体化地形坡向(a)和坡度(b)分类图
Fig.9 Classification map of integrated land and water topographic slope direction (a) and slope gradient (b) in Zhinan Village, Yangzhong

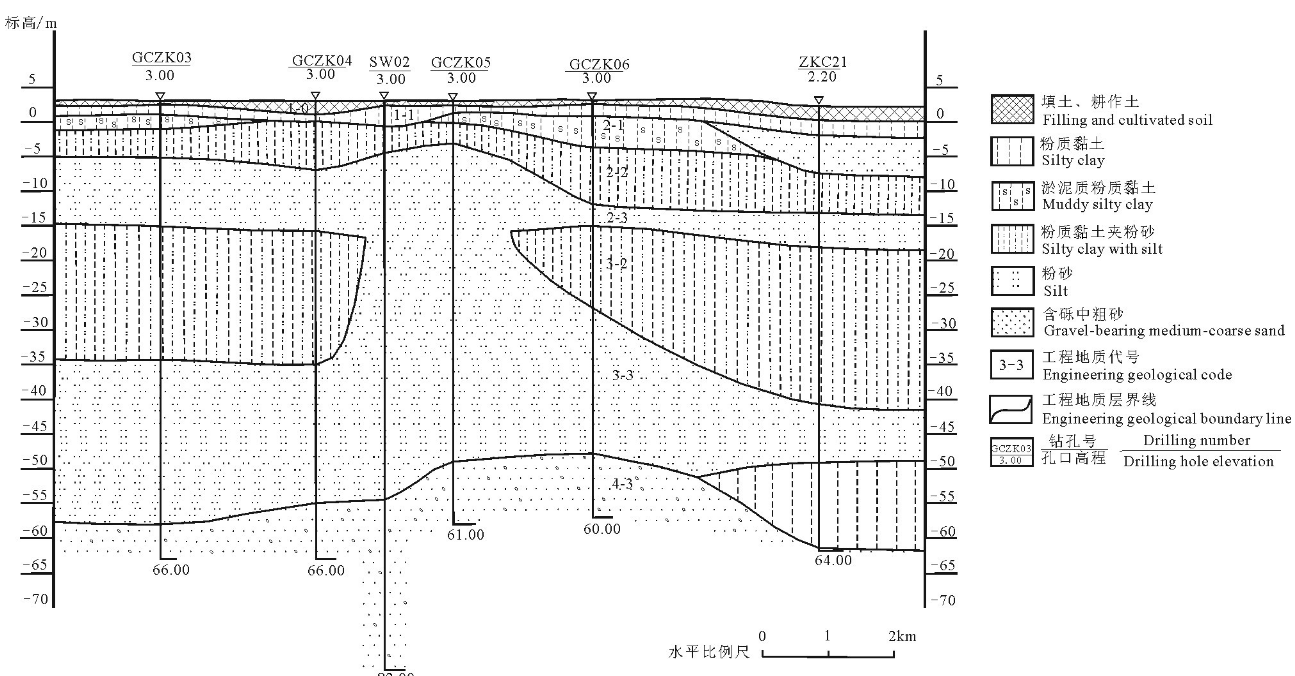

图10 扬中指南村沿江工程地质剖面图
Fig.10 Geological profile of Zhinan Village, Yangzhong along the river

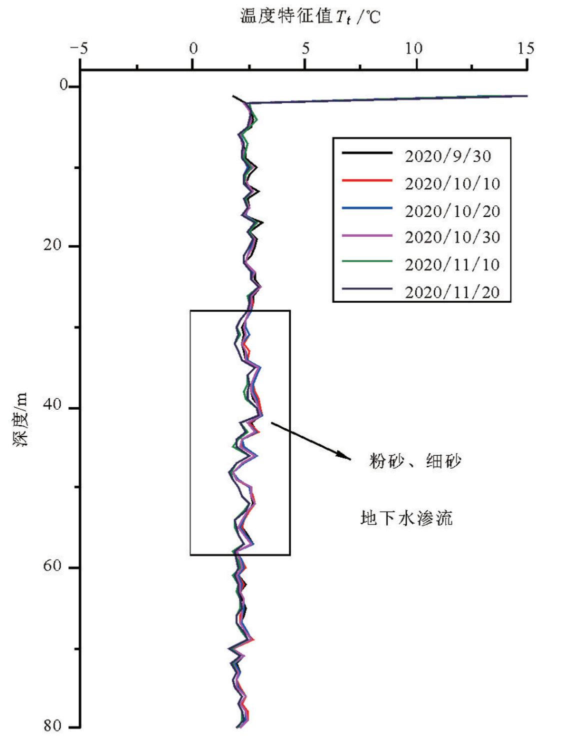

图11 地下水渗流引起的光纤传感器温度变化图

Fig.11 Temperature variation of fiber optic sensor caused by groundwater seepage flow

增大而增大,随潮差的减小而增大;在流域与河口工程建设和气候变暖及海平面上升的持续叠加影响下,未来潮区界或将进一步上移。

潮区界的显著上移导致下泄洪峰顶托上移,安徽安庆至湖北鄂州、黄冈河段两岸城乡洪涝风险增大。此外,变动河段由长期动力条件形成的地貌发生变化,形成稳态转换,变动段冲刷显著。如张家洲南水道全断面表现为冲刷,最大冲刷深度5.08 m;太子矶水道断面河中心浅滩消失,断面由“W”型变为宽而深的“U”型,整体呈冲刷趋势,最大冲刷深度7.58 m(图17)。鄱阳湖、青弋江等支流流域局部侵蚀基准下降2~3 m,枯季旱灾风险增大。大通水文站年输沙量自2007年起逐渐稳定在1.3亿t左右。但与三峡截流初期相比,年均输沙量降低约2.1亿t,有研究发现下游河段沉积地貌演变对三峡截流的响应具有延时性累积效应(戴仕宝等,2005;张珍,2011),因此,在较长的时间尺度下,潮区界变动河段冲刷地貌演变趋势仍将持续。

全流域尺度减沙后变动河段冲刷下切,河槽纵比降减小;潮区界上移壅水,水面坡降降低,径流速

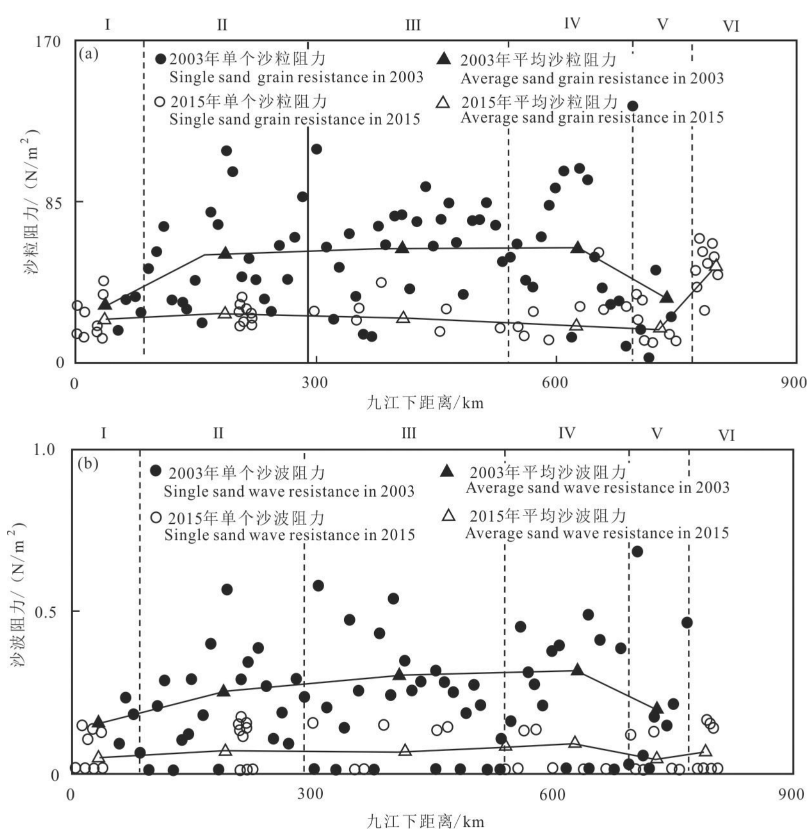

图12 2015年和2003年长江下游河道沙粒阻力(a)和沙波阻力(b)变化图

Fig.12 Changes of sand grain resistance (a) and sand wave resistance (b) in the lower reaches of the Yangtze River in 2015 and 2003

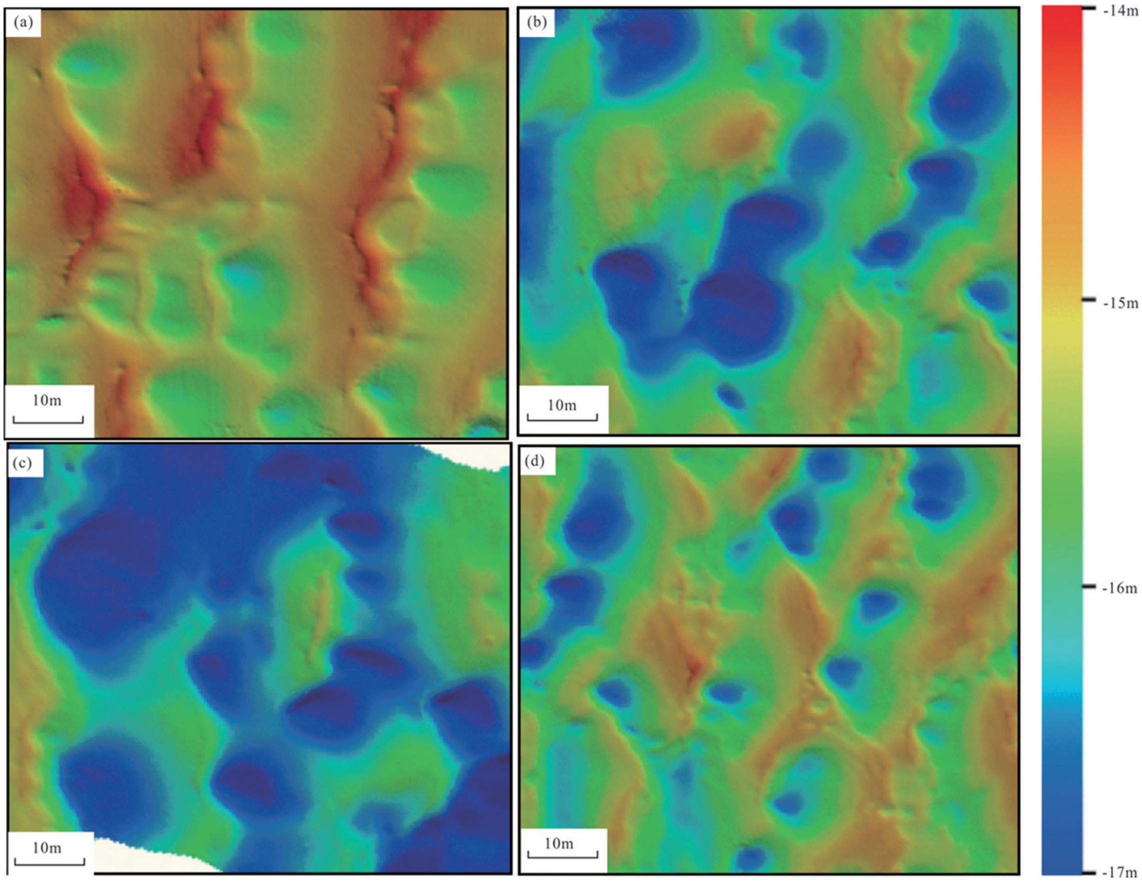

图 13 链珠状沙波多波束图像

a—椭圆形凹坑发育于次级沙波间;b—椭圆形凹坑发育于沙波脊线上;c—椭圆形凹坑发育于波峰两侧,形成了某些"孤立"于其他沙波的链珠状沙波;d—椭圆形凹坑的发育造成相邻两组沙波在形态上连接在一起的"错觉"

Fig.13 Multi−beam image of chain beaded sand wave

a−Oval pits developed between secondary sand waves; b−Oval pits developed on the sand ridge; c−Oval pits developed on both sides of the crest, forming some "isolated" chains of sand waves; d−The development of oval pits creates an "illusion" that two adjacent groups of sand waves are morphologically connected

度减弱,潮流也上溯到原受径流单一控制的河段,导致附近河流地貌系统逐渐向潮汐河口地貌系统转换。同时,航道整治、盗采江砂等人类活动直接导致局部河槽加深(石盛玉等,2017;Zheng et al.,2018;薛嘉伟和赵爽,2018;程和琴等,2020);日益密集的护岸工程虽增强了局部岸线的抗冲能力,

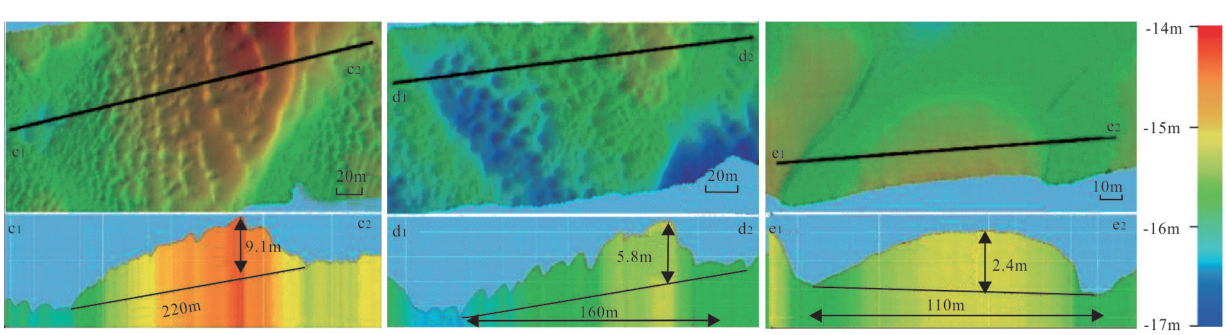

图 14 典型巨型沙波形状与几何参数

Fig.14 Typical shapes and geometric parameters of giant sand waves

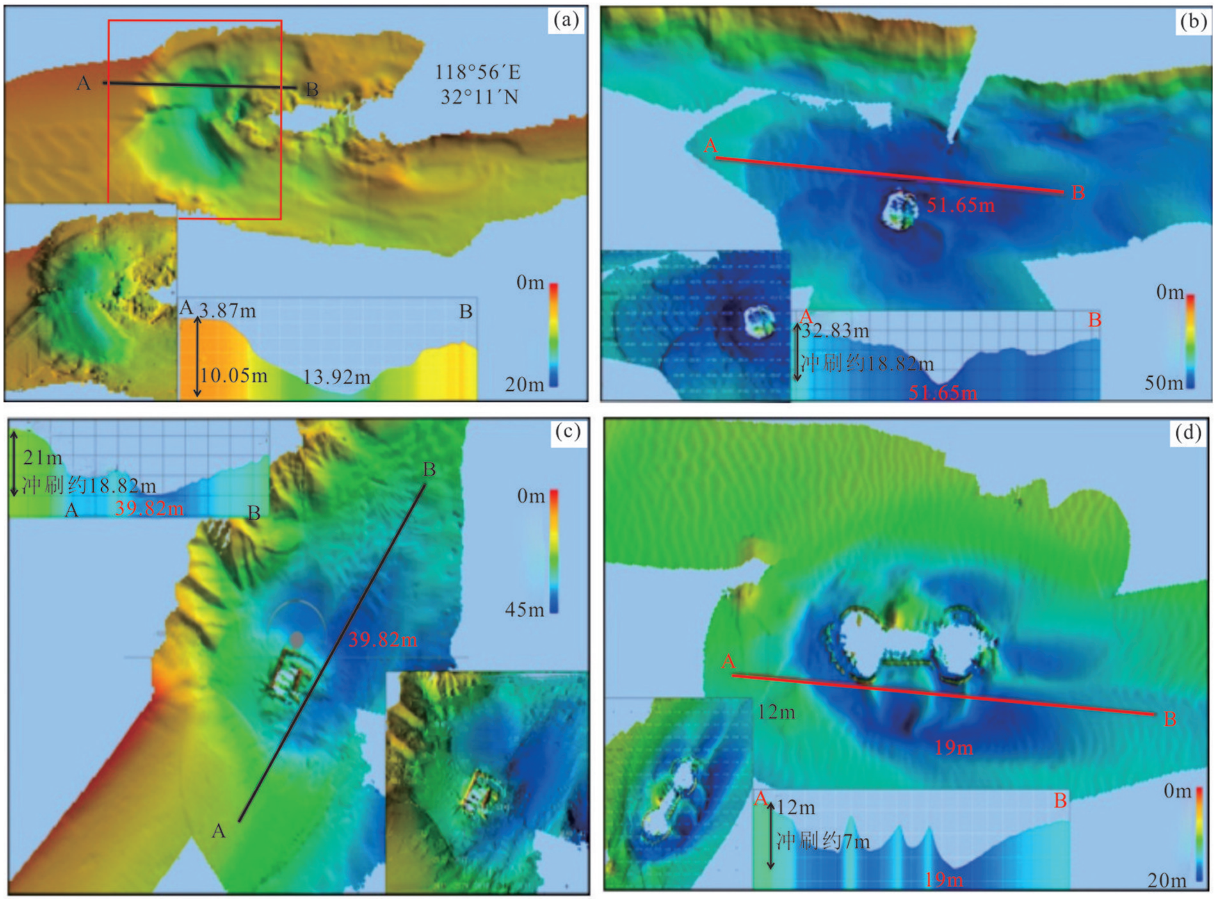

图 15　长江跨江大桥主桥墩冲刷坑在平面和剖面上形态
(a,c—南京长江第四大桥;b,d—南京长江第二大桥)
Fig.15　The plane and sectional shape of scour pit on the main pier of the Yangtze
(a,c–The Fourth Nanjing Yangtze River Bridge; b,d–The Second Nanjing Yangtze River Bridge)

也间接使整体冲刷趋于河槽下切。这都使潮区界变动与地貌系统的过渡范围更大,作用更强。若河口区域继续向上延伸,潮流界上移带来的涨潮流侧蚀作用还可能导致变动河段近岸冲刷环境进一步增强。

4　结　论

本文主要采取历史水下地形和水位数据分析、干流河槽现场测量、室内测试和综合评价等方法对重大水利工程对长江中下游干流河槽和岸线影响进行了分析和研究,取得如下新进展和成果:

(1)受上游重大水利工程影响,长江径流和输沙时空过程大幅改变,影响潮波向上传播,研究发现长江洪季潮区界与2005年相比上移82 km,枯季上移约220 km,潮区界显著上移,潮区界变动河段地貌发生重要变化。

(2)宜昌以下干流河槽冲刷强烈,水下岸坡坡度大于20°的高陡边坡占比高达22%以上,发现窝崩、条崩30余处,长度多在1 km以上,主要分布在龙潭、太阳洲、螺山、砖桥、煤炭洲和蕲春等水道边坡,防洪与航运安全堪忧。

(3)河槽沉积物粗化,河床阻力下降,侵蚀型沙波发育且尺度增大,河口河槽最大冲刷深度达29.6 m,长江大桥主桥墩冲刷深度达10 ~ 19 m,水上与陆桥交通安全风险增大。

(4)建议加强长江中下游干流水下典型高陡岸坡、支流入汇干流河口、崩岸以及跨江、跨海大桥桥墩冲刷等调查和监测,加强干流岸线易崩地段陆上水文地质、工程地质调查与监测,加强岸滩崩岸成因机制分析研究,为长江经济带航道工程与护岸保

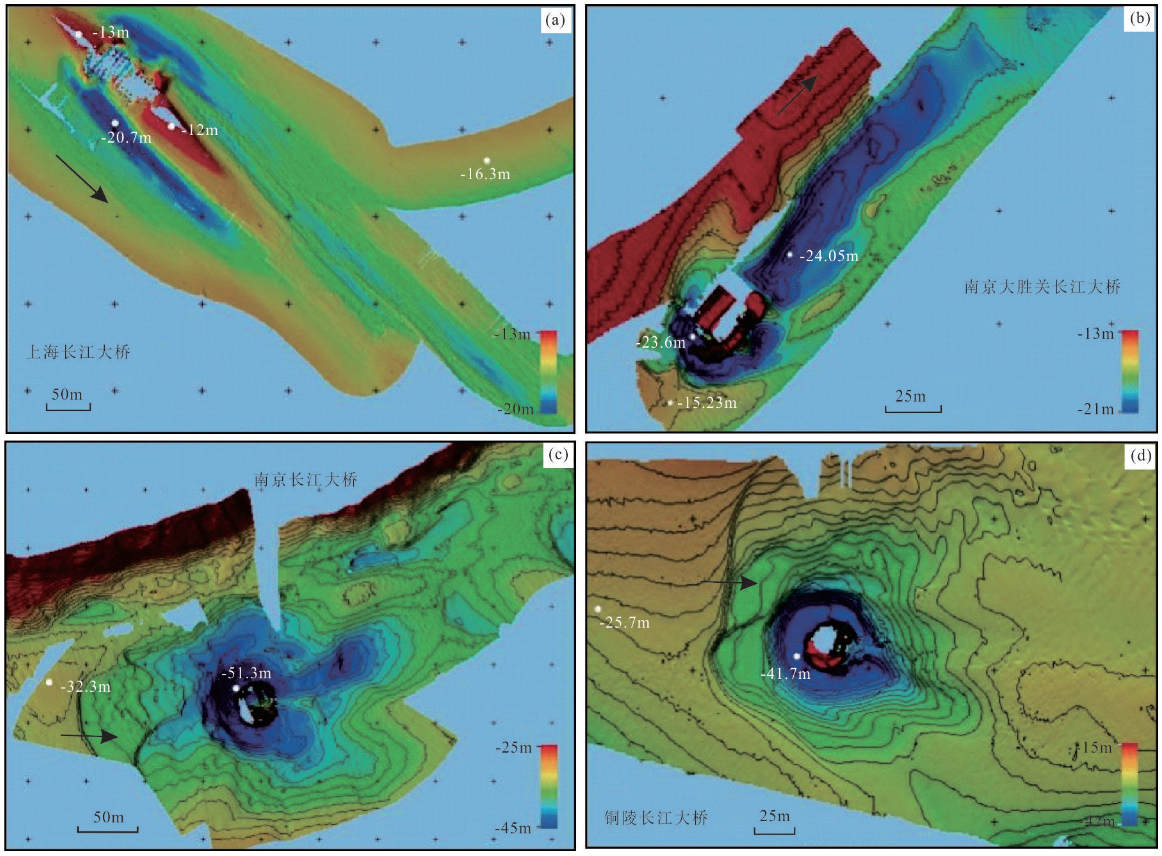

图16上海—铜陵长江大桥桥墩冲刷坑形态

a—上海长江大桥;b—南京长江第三大桥;c—南京长江大桥;d—铜陵长江大桥

Fig.16 Shape of scour pit on piers of Shanghai to Tongling Yangtze River Bridge

a−Shanghai Yangtze River Bridge;b−The Third Nanjing Yangtze River Bridge;c−Nanjing Yangtze River Bridge;d−Tongling Yangtze River Bridge

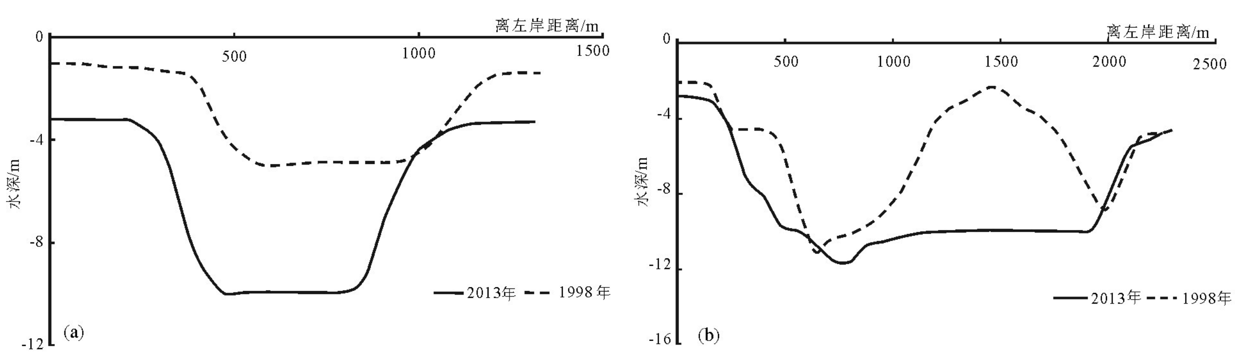

图 17 九江张家洲南水道(a)和安庆太子矶水道(b)断面变化

Fig.17 Cross sections of the southern Zhangjiazhou waterway in Jiujiang (a) and the Taiziji waterway in Anqing (b)

滩工程冲淤灾害防治以及沿江城镇资源与环境安全预警提供科学依据。

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