DOI:10. 3880/j. issn. 1006 - 7647. 2025. 05. 002

堆石混凝土坝建设与技术标准体系发展与展望

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摘要:2025 年初,已建和在建的堆石混凝土坝已达 200 座,其中百米级周源水库堆石混凝土重力坝开工建设,且 NB/T 10077—2024《堆石混凝土坝设计规范》正式实施,标志着堆石混凝土筑坝技术经过 20 余年发展已走向成熟。为此,全面回顾了堆石混凝土筑坝技术从发明伊始到逐步成熟的发展过程,将其分为 4 个发展阶段,详细介绍了不同阶段研究解决的主要技术问题和研究成果,总结了堆石混凝土相关基础研究的主要进展,阐述了典型堆石混凝土坝的建设情况及堆石混凝土坝技术标准体系不断发展与完善的进程,以帮助读者全面了解堆石混凝土坝的发展脉络,为未来的发展指明方向,并促进堆石混凝土坝技术不断进步。

关键词:堆石混凝土;重力坝;拱坝;技术标准;智能建造

中图分类号:TV642 **文献标志码**:A **文章编号**:1006 - 7647(2025)05 - 0013 - 13

Progress and prospects of construction and technical standards for rock-filled concrete dams//JIN Feng(*Department of Hydraulic Engineering*, *Tsinghua University*, *Beijing* 100084, *China*)

Abstract: By early 2025, the number of completed and under-construction rock-filled concrete (RFC) dams had reached 200. Among them, the Zhouyuan RFC gravity dam with a height of 100 m had commenced construction. Concurrently, the *Code for Design of Rock-Filled Concrete Dams* (NB/T 10077-2024) was issued. These events indicate that RFC dam construction technology has achieved maturity after more than 20 years of development. The development process of RFC dam construction technology from its initial invention to gradual maturity was reviewed and divided into four key stages, the main technical problems and research achievements obtained in different stages were introduced, the main progress on fundamental research related to RFC was summarized, and the construction status of typical RFC dams as well as the continuous development and improvement process of the technical standard system for RFC dams were presented, so as to help readers better understand the evolution of RFC dams, point out the direction for future development, and promote the progress of RFC dam technology.

Key words: rock-filled concrete; gravity dam; arch dam; technical standard; intelligent construction

自 2003 年清华大学发明堆石混凝土坝以来[1],堆石混凝土技术从无到有,从小到大,已成功应用于近 300 个工程项目。截至 2025 年 2 月,已建成堆石混凝土坝 160 座,包括松林水库、坪坑水库等 148 座堆石混凝土重力坝,以及佰佳水电站、沙千水库等 12 座堆石混凝土拱坝。当前正在浇筑的堆石混凝土坝有 40 座,包括永丰水库堆石混凝土双曲拱坝与平坦原抽蓄电站下库主坝等工程。此外,百米级周源水库堆石混凝土重力坝已开工建设,还有超过 100 座堆石混凝土坝正在设计中,即将开工建设。

20 余年来,在国家自然科学基金重点项目、国家重点实验室项目等支持下,结合上述工程的设计、施工与运行,人们开展了堆石混凝土坝室内试验、现场试验、理论分析、数值模拟、运行资料分析等科学研究,在总结工程经验的基础上,制订了相关国际标准、行业标准、地方标准、团体标准,形成了比较完善的技术标准体系,堆石混凝土筑坝技术已走向成熟,逐步发展成为主流筑坝技术。

本文将堆石混凝土坝的发展历程,分为早期探索阶段、首部行业标准编写及颁布阶段、100 座堆石混凝土坝建设及标准体系初步建立阶段、200 座堆石混凝土坝建设及行业标准更新阶段等 4 个阶段,详细介绍不同阶段研究解决的主要技术问题和研究成果、典型工程案例及技术标准,以期帮助读者全面了解堆石混凝土坝的发展脉络,为未来技术发展指明方向,并促进堆石混凝土坝技术不断进步。

基金项目:国家自然科学基金重点项目(52039005);国家自然科学基金重大项目(52192670)

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1　早期探索阶段(2003—2019年)

在探索性试验[2-3]基础上，2005年清华大学完善了普通堆石混凝土施工工艺，提出了堆石混凝土坝基本体型，明确堆石混凝土重力坝、拱坝可采用与常态或碾压混凝土重力坝、拱坝相近的设计方法和构造，两者的主要区别在于施工方式[4]。在南华大学开展的1 m×2 m×1.8 m堆石混凝土大块体室内分层浇筑试验(层厚0.6 m)[5]中，以吊斗浇筑模拟泵送浇筑，论证了堆石混凝土的合理施工工序与工艺。通过切割大块体，获得了不同尺寸的堆石混凝土试件，进行了立方体抗压强度与劈拉强度试验、棱柱体抗弯强度与轴心抗压强度试验，以及抗渗、抗冻性能等试验[5-7]，获得了堆石混凝土基本物理力学参数。针对堆石混凝土复合材料特点，开展了细观力学性能探索研究，初步形成了对堆石混凝土力学机理的认识[8-9]。研究了堆石混凝土所需的低水化热自密实混凝土配合比[10]和堆石混凝土的热学性能[11-12]，论证了堆石混凝土坝取消温控措施的可行性。

这些早期研究成果表明：在保证堆石粒径大于300 mm，且自密实混凝土满足相关工作性能要求的前提下，堆石混凝土密实性良好，其抗压强度显著高于填充堆石的自密实混凝土，故采用自密实混凝土抗压强度代表堆石混凝土抗压强度，可简化施工质量控制。

2005年，在北京石景山区建成的世界首座堆石混凝土坝是一座坝高14.5 m的小坝。坝轴线为折线，分为3个坝段，总长81.3 m，大坝体积约为1800 m^3。利用附近现成的洞室开挖料，用人工小车运输、堆铺；利用混凝土罐车运输附近自密实混凝土到坝址，并用混凝土泵车泵送入仓。主要施工期在8月，气候炎热。采用光纤测温监测堆石混凝土水化温升，结果显示堆石混凝土水化热温升较低。因此，除下午阳光直射时不进行自密实混凝土浇筑以外，没有采取其他温控措施。大坝建成后未发现开裂及渗漏现象，迄今运行正常。

首座堆石混凝土坝建成后不久，2006年宝泉抽蓄电站上库开展了堆石混凝土现场试验，并在副坝、基础回填等部位浇筑堆石混凝土约60000 m^3。山西清峪水库大坝、围滩水电站大坝、广东长坑三级水库大坝复建工程相继应用堆石混凝土技术。其中，清峪水库是一座小(1)型水库，坝高42.3 m，坝轴线长203 m，是首座完全按照大坝建设程序设计、施工的堆石混凝土坝，体积45600 m^3。山西省水利厅对该大坝设计文件进行了全面审查，这些设计文件成为后续技术标准编写的核心支撑。这个时期还开展了多项堆石混凝土坝设计与施工工艺的探索研究，自密实混凝土一体化防渗构造、堆石冲洗与表面含泥量控制、施工层面处理等工艺也逐步完善。2008年，以潘家铮院士为组长的《堆石混凝土技术》鉴定专家组充分肯定了堆石混凝土技术的创新性，并建议尽快编写相关技术标准。堆石混凝土坝的研究与应用，因其创新性，一直受到国际关注，如国际坝工主要刊物 *International Water Power & Dam Construction* 在2008年对堆石混凝土研究进展进行了报道[13]。

2　首部行业标准编写及颁布阶段(2010—2014年)

2010年，水利部与水利水电规划设计总院启动了水利行业技术标准《堆石混凝土与胶凝砂砾石筑坝技术导则》的编写工作。编写过程中，根据专家意见将标准名称修改为《胶结颗粒料坝筑坝技术导则》。2014年，SL 678—2014《胶结颗粒料坝筑坝技术导则》正式颁布，其适用范围为中小型水利工程，坝高超过70 m的堆石混凝土坝应进行专题论证。

在首部行业标准编写过程中，黑龙江东升水电站、云南虎跳峡水库、青海那河二级水电站、四川吉牛水电站等20余座堆石混凝土重力坝相继开工建设，特别是蒙山水库堆石混凝土拱坝(世界上首座堆石混凝土拱坝，图1)与佰佳水电站堆石混凝土拱坝(图2)开工建设，为行业标准的编制提供了重要数据支撑。佰佳水电站坝高69 m，2013年开始施工，2015年初步蓄水，2016年建成，运行效果良好，

图1　蒙山水库堆石混凝土拱坝

图2　佰佳水电站堆石混凝土拱坝

是目前建成最高的堆石混凝土拱坝。考虑到堆石混凝土拱坝数量少,工程经验不多,首部行业标准未纳入堆石混凝土拱坝相关设计内容。

为配合行业标准编制,除开展堆石混凝土强度[14-16]等基本力学性能试验外,还开展了其他一系列试验。堆石混凝土断裂性能[17-18]、剪切性能、徐变性能和层面抗剪[19]试验成果表明:堆石混凝土比普通混凝土有更强的断裂性能、抗裂能力及层面抗剪能力;热膨胀系数[20]、水化温升等热学性能试验及堆石混凝土坝温度应力仿真分析成果表明:堆石混凝土水化温升低,一般条件下可取消温控措施[21-22];自密实混凝土充填堆石空隙机理与数值模拟[23-24]结果表明:在保证堆石粒径大于 300 mm 和自密实混凝土具有良好工作性能的条件下,堆石混凝土的密实性有很高的保证裕度。设计与研究人员结合实际工程,在堆石混凝土坝型比选、施工工艺[25]、质量控制及其智能化[26-27]、环境生态[28]与经济效益等方面开展了大量研究,结果表明堆石混凝土坝具有诸多优势,能大幅度降低碳排放量,其造价低于常态或碾压混凝土坝,具有良好推广前景。

本阶段一个重要的研究进展是清华大学系统梳理了堆石混凝土关键科学问题与研究技术路线(图 3)。基于混凝土密实度与超大粒径混凝土性能这两大关键工程难题,梳理出堆石混凝土研究中存在的两大关键科学问题:高自密实混凝土(high performance self-compacting concrete,HSCC)流动堵塞机理和堆石混凝土大尺度非均质复合材料真实性能,并开展了相关的试验与数值方法研究,成功获得了国家自然科学基金重点项目资助,为堆石混凝土基础研究指明了方向。

3 100 座堆石混凝土坝建设及标准体系初步建立阶段(2015—2020 年)

2014 年首部行业标准的颁布促进了堆石混凝土坝的推广应用,2015 年松林水库堆石混凝土重力坝(坝高 90 m,图 4)开始浇筑;之后,溪源水库、坪坑水库、满坪水库、麻柳湾水库等一批坝高超过 70 m 的堆石混凝土高坝相继建成。此外,绿塘水库堆石混凝土拱坝(坝高 54.5 m)不分横缝、通仓浇筑,充分发挥了堆石混凝土的优势,在拱坝结构方面取得了新的突破,龙洞湾水库(坝高 48 m)、沙千水库(坝高 66 m)等堆石混凝土拱坝也采用了类似结构。截至 2020 年初,已建和在建堆石混凝土坝数量达 100 座。

2018 年,华东勘测设计研究院有限公司与清华大学共同主编的能源行业标准 NB/T 10077《堆石混凝土筑坝技术导则》正式颁布,适用于新建、改建和扩建水电工程中 1 级且坝高低于 70 m 的重力坝,2 级及以下且坝高低于 100 m 的重力坝,以及坝高低于 70 m 的拱坝。考虑到堆石混凝土拱坝建设经验较少,该标准仍然未设专门的拱坝章节。该标准在 SL 678—2014《胶结颗粒料坝筑坝技术导则》的基础上,针对堆石混凝土坝设计与施工,制订了更为详尽的规定,还提高了堆石表面含泥量的控制标准(从 SL 678—2014《胶结颗粒料坝筑坝技术导则》规定的 0.5%提高到 0.2%)。2020 年,中国水利水电第八工程局有限公司与清华大学等编写的能源行业标准 DL/T 5806—2020《水电水利工程堆石混凝土施工规范》正式颁布,针对堆石混凝土施工质量控制与验收进行了更为详尽的规定。同年,贵州省颁布了 DB52/T 1545—2020《堆石混凝土拱坝技术标准》,这是首部堆石混凝土拱坝标准,规定了部分横缝拱坝的设计计算方法及相应的应力控制标准;重庆市颁布了 DB50/T 1045—2020《水利水电工程单元工程施工质量验收评定规范 堆石混凝土工程》,这是首部专门针对堆石混凝土单元工程施工质量验收的地方标准。至此,堆石混凝土坝技术标准体系已初步建立。

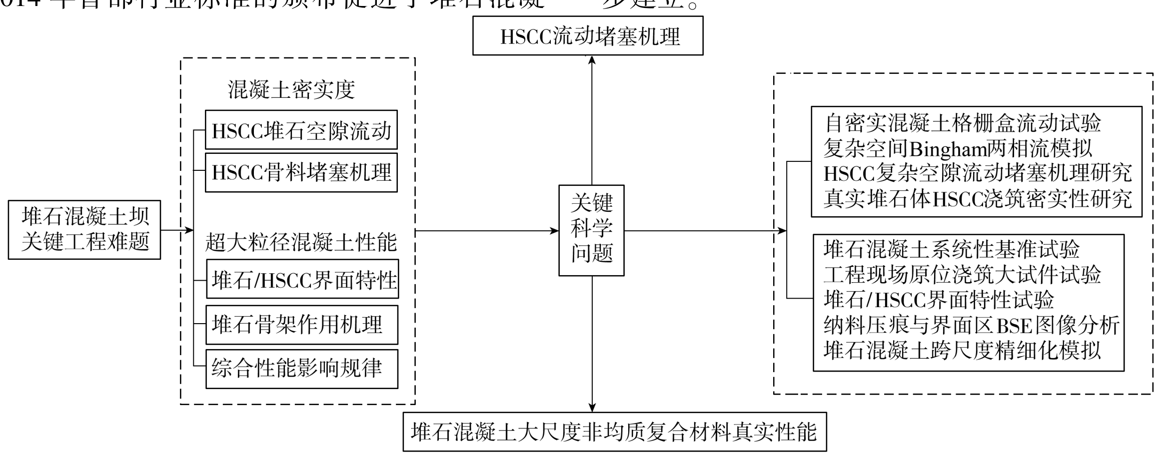

图 3　堆石混凝土关键科学问题与研究技术路线

本阶段堆石混凝土研究重点围绕图 3 所示的技术路线开展。填充试验[29-30]和数值模拟研究[31-38]揭示了自密实混凝土填充及堵塞机理,为堆石混凝土施工工艺参数优化提供了科学依据。强度机理方面,除继续开展大量室内试验[39]和现场试验[40-42]对抗压强度、徐变性能[43]、氯盐侵蚀性能[44]等进行研究外,还分析了施工层面与冷缝[45]、界面区[46]等薄弱环节和浇筑方式[47]等的影响。同时结合大坝质量检测[48],开展了现场芯样试验,揭示了堆石混凝土材料的真实性能。国外研究人员亦已启动堆石混凝土试验研究[49]。本阶段发展了多种细观分析模型,深化了人们对堆石骨架与自密实混凝土相互作用机理的认识[50-52]。为研究堆石混凝土坝真实工作性能,除开展坝体监测资料分析以外,还开展了施工、运行期温度应力仿真分析[53-56],如对绿塘水库堆石混凝土拱坝等工程开展现场试验,并对不分横缝、通仓浇筑拱坝的温度应力进行了深入研究,改进了设计方法[57-58]。堆石混凝土重力坝坝型选择、分缝设计、应力计算、防渗构造等方面也取得了创新成果[59-61],特别是围绕严寒地区堆石混凝土坝的修建[62-64],以及非岩基[65]和软岩地基上堆石混凝土坝的建设[66]开展了针对性研究,还对施工过程中常态混凝土垫层裂缝影响及处理措施开展研究[67]。为了加强对堆石混凝土坝施工质量的控制,针对堆石混凝土坝施工工艺和工序开发的施工质量管理信息系统在堆石混凝土坝工程中初步得到应用。

图 4　松林水库堆石混凝土重力坝

4　200 座堆石混凝土坝建设及行业标准更新阶段(2021—2025 年)

从第 1 座到第 100 座堆石混凝土坝建成历时 15 年;而从第 100 座到第 200 座历时不到 5 年,堆石混凝土坝推广应用进程逐步加快,技术更新亦十分迅速。国家能源局和水利部为适应技术发展,分别启动了堆石混凝土坝相关技术标准的修编工作。2024 年,在充分吸收最新科研成果和工程经验后,能源行业标准 NB/T 10077—2024《堆石混凝土坝设计规范》正式颁布,适用于新建、改建和扩建的水电工程堆石混凝土坝设计。该规范规定:坝高超过 130 m 的堆石混凝土重力坝、坝高超过 100 m 的堆石混凝土拱坝基堆石采用较软岩需要专题论证,特别重要的堆石混凝土坝设计也需要专题论证。新规范将堆石粒径要求放宽至 150~200 mm,并提出了相应的自密实混凝土工作性能要求;增加了堆石级配、吸水率和压碎指标值等要求;增加了板状岩块和软岩的应用条件;增加了拱坝“通仓浇筑不设横缝”的规定;增加了堆石混凝土浇筑充填试验方法;增加了堆石混凝土施工过程数字化监控方法;扩大了堆石混凝土坝坝体分缝间距;提出了新的坝体防渗规定。2025 年,水利行业标准《胶结坝技术规范》即将颁布;能源行业标准 DL/T 5806《水电水利工程堆石混凝土施工规范》也启动修订。特别是 2021 年,国际大坝委员会正式批准了第 190 号技术公报 *Rock-filled concrete dam:design and practice*,这是国际大坝委员会成立近百年来大坝领域第一部以中国原创技术为核心的国际技术标准。

工程应用方面,周源水库堆石混凝土重力坝坝高接近 100 m;已建成的东庄水库二道坝是第一座用堆石混凝土建造的 1 级水工建筑物(图 5);已建成的叶巴滩水电站堆石混凝土二道坝采用通仓浇筑方式(图 6),单仓仓面面积达 5 000 m^2,体积达 10 000 m^3,齿槽仓单仓厚度局部达 4.5 m,浇筑质量良好;平坦原抽蓄电站下库主坝是第一座抽蓄电站堆石混凝土主坝;在建的永丰水库堆石混凝土双曲拱坝坝高 83 m,为目前最高的堆石混凝土拱坝;这些重要工程均采用了堆石混凝土施工管控数智化系统(construction

图 5　东庄水库二道坝

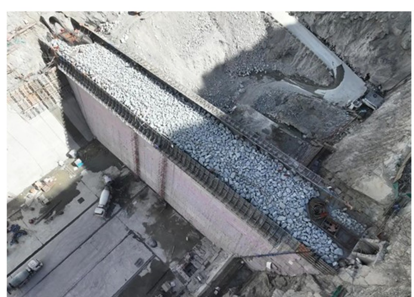

图 6　叶巴滩水电站堆石混凝土二道坝通仓浇筑

information modeling for rock-filled concrete, CIM4R)监控施工质量,表明堆石混凝土筑坝技术已进入智能信息化时代。而安哥拉 Niobonga 堆石混凝土坝的建成及成功运行,标志着中国原创的堆石混凝土坝技术正走向国际舞台。

近年来,堆石混凝土研究聚焦于建立堆石混凝土密实性理论和揭示超大粒径复合材料细观力学机理。在堆石混凝土填充过程物理试验与数值模拟方法[68]基础上,建立了堆石混凝土密实性判别公式[69],提出了堆石混凝土粒径、形状、级配细化要求,为新规范放松堆石粒径要求起到了支撑作用。除传统的堆石混凝土强度[70-72]、耐久性能[73-74]与层面抗剪性能[75-77]等试验以外,发展了 900 mm 原型试件试验方法,建立了尺寸效应公式[78-79];开展了带空隙或缺陷的堆石混凝土试件试验和细观模拟[80-82],并采用深度学习方法进行堆石混凝土缺陷识别;结合堆石混凝土坝体芯样断口分析与强度统计[83],揭示了堆石混凝土强度影响规律,加深了人们对堆石骨架作用机理的认识;开展了堆石混凝土断裂性能试验,揭示了堆石对裂缝扩展的限制作用[84]。此外,基于细观数值模拟[85-90]和复合材料理论,对堆石混凝土弹性模量[91]与强度发展过程开展研究,揭示了堆石混凝土材料破坏过程的细观机理。

围绕堆石混凝土水化温升与堆石混凝土坝温控设计,开展了自密实混凝土与堆石混凝土绝热温升试验[92-97],进行了实际堆石混凝土重力坝[98-102]和拱坝[103-107]的现场施工监测与数值仿真模拟,提出了堆石混凝土坝的结构分缝与温控设计准则,为寒区、严寒区的堆石混凝土坝建设奠定了基础[108-110]。设计人员还在坝型选择[111-112]、重力坝与拱坝结构设计[113-115]方面开展了大量工作,通过堆石混凝土坝抗渗性能研究[116-119],优化了抗渗构造,还开展了堆石混凝土坝抗震性能与设计研究[120]。

在堆石混凝土施工研究方面,不断扩大堆石与自密实混凝土骨料的应用范围,包括使用软岩和石粉代替粉煤灰[121]建造堆石混凝土坝。持续拓展堆石率提升技术路径,一体化浇筑[122-124]、厚层浇筑等工艺不断成熟,同时无损检测技术和质量评定方法[125-127]逐步完善。特别是采用视频图像、传感器、物联网和人工智能技术进行堆石混凝土坝施工质量控制[128],该技术在堆石粒径与密实性监测[129]、层面露出率监测[130]等环节应用效果良好。此外,基于大量工程实践数据的堆石混凝土定额与经济性分析,以及生命期环境效益分析等也取得了重要进展。

除堆石混凝土坝研究以外,关于再生混凝土骨料[131-135]、钢筋混凝土[136]与高强混凝土[137-138]中堆石混凝土的应用研究也在不断深化。

5 结论与展望

5.1 结论

a. 已建、在建堆石混凝土坝数量已达 200 座,在建堆石混凝土坝坝高已达 100 m,相关行业、地方、团体和国际标准已颁布实施,已建立完整的堆石混凝土坝技术体系。

b. 堆石混凝土基础研究围绕混凝土密实度与超大粒径混凝土性能两大工程难题,聚焦 HSCC 流动堵塞机理和堆石混凝土大尺度非均质复合材料真实性能两大关键科学问题,在浇筑密实性判定、堆石混凝土综合性能指标体系、堆石骨架作用与抗裂机理等方面已取得重要进展。

c. 堆石混凝土坝监测资料分析与仿真研究,不仅推动了堆石混凝土坝分缝、防渗等构造设计的不断进步,而且发展了不分横缝堆石混凝土拱坝设计方法,充分发挥了堆石混凝土的优势,在堆石混凝土坝结构方面有所创新。

d. 堆石混凝土一体化、厚层浇筑等施工工艺的持续创新,推动了堆石混凝土坝向更安全可靠、更低碳环保、建造速度更快、综合造价更低的方向迈进,显著提升了工程适用性与经济性。

e. CIM4R 已在多座重要的堆石混凝土坝工程中应用,显著提升了堆石混凝土的施工管理水平,促进了堆石混凝土坝施工质量的不断提高。

5.2 展望

未来堆石混凝土坝技术的发展将围绕理论创新、技术突破与应用拓展展开,重点聚焦以下方向:①堆石混凝土结构宏细观分析模型构建。揭示堆石混凝土结构从早龄期到全运行期的性能演化规律,为严酷条件下高堆石混凝土坝的设计、施工提供技术支撑。②堆石骨架与自密实混凝土相互作用机理研究。揭示堆石骨架对堆石混凝土综合性能的影响机理,通过对堆石形状、级配、堆积方式的优化,提高堆石混凝土力学性能,为高坝建设提供技术支撑。③堆石混凝土动力性能与堆石混凝土坝抗震机理研究。开展大尺寸试件动力性能试验和数值模拟研究,深入认识堆石混凝土动力特性,揭示堆石混凝土坝抗震机理,为强震区高堆石混凝土坝提供技术支撑。④堆石混凝土密实度影响因素、规律研究。研究堆石形状、级配、堆积方式与浇筑层厚对堆石混凝土密实度的影响规律,同时开发基于 AI 的视频图片识别技术,以快速分析堆石体特性,在保证堆石混凝土高密实度的前提下,提升堆石率,降低成本。⑤高自密实性能混凝土工作性能全量仪设备研发。通过

研发能够快速、准确评价高自密实混凝土工作性能的全量仪设备,为重大工程高水平质量控制提供技术手段。⑥堆石混凝土坝无(少)人智能建造技术研发。综合利用信息化、自动化、人工智能等技术,开发智能模板安装、智能堆石入仓、混凝土智能拌合浇筑及层面处理等配套装备,充分发挥堆石混凝土在简化振捣、温控工艺等方面的优势,构建堆石混凝土坝无(少)人智能建造技术体系,推动堆石混凝土坝在重大水利水电工程、高坝工程及国际工程中的广泛应用。⑦堆石混凝土应用场景拓展。针对特殊应用环境,优化堆石混凝土施工工艺,开发相应施工装备,拓展其应用领域。

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(收稿日期:2025-03-19　编辑:骆超)