

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) xx-xx-2009		2. REPORT TYPE Research		3. DATES COVERED (From - To) 09-11-2006 to 25-02-2009	
4. TITLE AND SUBTITLE Working in the Dry Cofferdams, In-River Construction & the USACE Volume : ()				5a. CONTRACT NUMBER DACW27-03-D-0006	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) O'Bannon, Patrick				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Gray & Pape, Inc. 1318 Main St Cincinnati OH 45202-7614				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Corps of Engineers 1000 Liberty Ave Pittsburgh PA 15222-4186				10. SPONSOR/MONITOR'S ACRONYM(S) USACE	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT This study documents and analyzes the history of advances in inland river construction techniques involving cofferdam and in-the-wet construction methods used by the U.S. Army Corps of Engineers. Cofferdams are the traditional solution for constructing a bridge pier, dam foundation, or other structure where the work site is underwater. The study includes a review of early American inland waterway improvements completed without federal participation, examines the origins of the Corps of Engineers' engineering traditions, and documents the Corps' earliest in-river projects, including the 1830s Potomac River Aqueduct, which represented one of the Corps' earliest uses of cofferdams for in-river construction. Particular attention is devoted to the development of cofferdam designs used to create slackwater improvements on the Ohio River and other inland rivers during the late-nineteenth and early-twentieth century. The development of steel sheet pile cofferdams, which permitted larger cofferdams in deeper water, is explored in relationship to the construction of Mississippi River locks and dams in the 1930s.					
15. SUBJECT TERMS Dams, Cofferdams, In-River Construction, History, U.S. Army Corps of Engineers					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 184	19a. NAME OF RESPONSIBLE PERSON Conrad Weiser
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (include area code) 412-395-7220



US Army Corps
of Engineers

Working in the Dry: Cofferdams, In-River Construction, and the United States Army Corps of Engineers



Patrick O'Bannon

Working in the Dry: Cofferdams, In-River Construction, and the United States Army Corps of Engineers

by

**Patrick O'Bannon
Gray & Pape, Inc.**

20100201288

**U.S. Army Corps of Engineers, Pittsburgh District
Pittsburgh, Pennsylvania
2009**

Acknowledgments

This project enjoyed the support and assistance of many people. Conrad Weiser, U.S. Army Corps of Engineers Pittsburgh District, served as the Contracting Officer's Technical Representative for the project. He identified Corps' personnel that could contribute to the study, provided illustrations, and oversaw the entire process. Charles Parrish of the Corps' Louisville District, and Matthew Percy with the Corps' Office of History helped point the research effort in fruitful directions and provided copies of hard-to-find sources. At the U.S. Army Corps of Engineers' Engineer Research and Development Center (ERDC) in Vicksburg, Mississippi, Milton Myers served as a gracious host and introduced me to librarian Helen T. Ingram who retrieved dozens of reports and documents for my review. Mr. Myers also arranged for oral interviews with senior ERDC staff, who generously shared their time and knowledge of cofferdam design and analysis. My particular thanks to Dr. Reed L. Mosher and Mr. Thomas J. Pokrefke, Jr., for patiently explaining some of the intricacies of structural and hydraulic design to me.

Thomas Brankamp at Woolpert, Inc., served as the principal liaison between the Corps and Gray & Pape. At Gray & Pape, Brandon McCuin and Mitchell Sipus assisted in the research effort, Carly Meyer prepared the graphics, and Madonna Ledford and Julisa Meléndez edited the manuscript.

The staff at numerous libraries and research institutions helped ferret out obscure sources and illustrations. At the Public Library of Cincinnati and Hamilton County, Diane Mallstrom, Claire Smittle, and Sherry Lytle in the Rare Books and Special Collections Department made available the voluminous resources of the Corps' former Inland Rivers Library. At the National Archives and Record Center in College Park, Maryland, archivist Ken Schlessinger served as a guide to the mysteries of Record Group 77, while Holly Reed in the Still Picture Branch helped locate fabulous images. Constance Carter, at the Library of Congress, helped locate many rare materials.

Naturally, any errors in this text are solely my responsibility and cannot be blamed upon any of these gracious folks.

Patrick O'Bannon

Preface

In 1897, through the largest federal condemnation action of that century, Congress acquired the seven locks and dams of the Monongahela Navigation Company (MNC). This privately owned, state-chartered system had provided slackwater navigation on the Pennsylvania portion of the Monongahela River since 1841. Federal ownership guaranteed the elimination of tolls levied by the MNC, and consolidation with the two federal locks and dams on the West Virginia portion of the river and the federal lock and dam on the Ohio River. These federal facilities were built and operated by the Pittsburgh District, U.S. Army Corps of Engineers, starting in the late 1870s, with a Congressional directive to extend slackwater navigation to the Monongahela headwaters and the Ohio. At the same time the District was planning and designing the new facilities for the extension, they were assigned responsibility for the existing seven MNC facilities, which entailed immediate repair or replacement of some of the older MNC locks and dams that had worn out from age and the harsh river environment. Army engineers in Pittsburgh had three locks and dams to manage before 1897, but within 10 years, they would have twenty.

Many of the MNC engineers had gained practical experience in small lock and dam construction on the early 1800s canal system, but they had to pioneer open river construction techniques for building more substantial structures for river navigation. The MNC engineers succeeded while many of their contemporaries working on other Ohio River tributaries struggled and some failed. Many of the MNC engineers transferred to the Pittsburgh District in 1897, and brought their experience with them. New lock and dam structures would become larger and more durable, particularly as wood and stone gave way to concrete and steel in the early 1900s. By the 1930s, the District had replaced all of the original MNC facilities with seven of its own, and had long since expanded the system to a total of 15 locks and dams, covering the full length of the 128-mile river. During World War II, it became obvious through increasing demands and age that the earliest District replacements needed themselves to be replaced by newer and larger locks. Planning for an updated system consisting of modern-sized and fewer, higher lift locks began a few years after the war ended.

By the late 1980s, all of the navigation facilities in the middle and upper reaches of the river had been modernized, including some components of the three lower river facilities, Locks and Dams 2, 3 and 4. In 1992, Congress authorized the District's plan to modernize these three older facilities, producing a third generation of locks and dams from the original MNC structures. These new structures would bear little resemblance to the original MNC timber and stone structures, but would be constructed in the river in much the same fashion: inside dewatered tempo-

rary cofferdams. Cofferdam technology had changed somewhat since the 1830s but the same basic issues affecting MNC engineers concerned modern engineers – how to construct a cost-effective temporary structure in the river to create a dry working environment. Foundation characteristics, permeability, structural stability, overtopping, and the vicissitudes of weather and river flow were as critical as they had always been.

District engineers, working on detailed replacement plans for the 1906 Dam 2 in the mid-1990s, made a landmark decision to construct the new dam without use of cofferdams. Working with a team of construction and marine engineers, they conceived and executed a plan for in-the-wet construction that should save both time and money by eliminating the necessity of constructing and removing two stages of cofferdams. The dam would be constructed in two segments of heavily reinforced concrete shells, fabricated in a specially constructed casting basin about 16 miles downriver from Pittsburgh, and 27 miles from their final destination at Monongahela River Locks 2. On a warm summer afternoon in July 2001, District employees gathered at Pittsburgh's Point State Park to see the first segment, as large as a football field, float past as a towboat pushed it to an outfitting pier at Duquesne on the Monongahela River. Here, both segments, in turn, would be outfitted for setdown onto a pre-constructed foundation, all done in-the-wet without cofferdams. Although float-in construction in coastal and lake environments was not new in concept, its use for the new Dam 2 (renamed Braddock Dam) represented the first use of float-in construction on the inland rivers for a major navigation dam.

Innovation is no stranger in the Pittsburgh District. New designs and technology for making locks and dams bigger, and their operations more flexible and easier, have consistently been introduced from the District's first projects on the Mon and Ohio rivers. Movable dams, gated dams, the largest lock chambers in the world, these and more characterize their structures and set standards others would follow in maintaining reliable and efficient movement of traffic on the inland rivers. The historic importance of Pittsburgh's regional industries to iron, steel, glass, coke and coal production, and their role in national development and victory in two world wars is well recognized. What is not so well recognized, however, is the vital dependence of these industries upon the river navigation system. Pittsburgh engineers have had more experience with locks and dams than any other Corps of Engineers district. Although the smallest geographically of the four Ohio River districts, its situation at the steeper headwaters of the Upper Ohio River requires that navigation dams be spaced at closer intervals than further downriver where the slope decreases. The District operates and maintains more locks and dams than any other Corps of Engineers district (23 on the Ohio, Allegheny and Monongahela rivers).

In the process of planning for the modernization of Monongahela Locks and Dams 2, 3 and 4, District compliance with the National Historic Preservation Act led to a cultural resource miti-

gation plan to account for the effects of removing the last remnants of structures constructed nearly a century earlier. Through consultation with the Pennsylvania Bureau for Historic Preservation and the Advisory Council on Historic Preservation, the resulting plan included three basic components: historic documentation, preservation and interpretation. Documentation of has been satisfied through the inclusion of Locks and Dams 2, 3 and 4 in the Historic American Engineering Record collection at the Library of Congress. The HAER documentation also included contextual information on the Monongahela Navigation System, and a separate entry on the construction of new Braddock Dam.

This history of Corps of Engineers cofferdams and in-river construction satisfies the “historical publication” stipulation under the “interpretation” mitigation feature. While other interpretive mitigation activities, such as production of a video, museum exhibit, and signage, are directed towards a general audience, the historical publication involves research and themes of more interest to the historic professional community. Former research on the Monongahela River Navigation System has been narrowly focused on an administrative history - the where’s and when’s of projects. More was needed on the why’s and how’s, and on placing the navigation system into a broader context of the Corps of Engineers inland river navigation systems. There are many directions that research might have taken.

The direction that was eventually settled upon developed during the process of HAER documentation of the new Braddock Dam in-the-wet construction. Questions about the technological innovations that permitted in-the-wet construction at this time led to others on how and why the Corps employed and adapted cofferdam construction over the years. Many Corps historical studies had been performed on inland navigation systems, and individual structures within these systems, but nothing had been done on the cofferdam technology to construct these systems.

The District consulted with historians at the Chief of Engineers Office of History, Ft. Belvoir, Virginia, receiving both encouragement and valuable input on specific research questions and avenues for research and sources. Dr. Marty Reuss, now retired, and Matthew Percy contributed to and improved the scope of work, and Mr. Percy provided welcome guidance during research and review of the draft manuscript. Corps staff from many districts and research facilities, including historians, engineers, librarians, and others, contributed to this body of research, and their time and input were greatly appreciated. Through their knowledge and the talents and diligence of Dr. Patrick O’Bannon and others at Gray & Pape, Inc., the researching, organizing, analyzing and writing of this publication was made possible.

From the 128-mile Monongahela River Navigation System to all 196 lock and dam facilities on 12,000 miles of the inland river navigation system bordering 38 states, the Corps of Engineers contributes significantly to the nation's economy. Hundreds of millions of tons of domestic cargo valued at over \$300 billion move annually through this system. It also facilitates movement of a significant portion of the \$851.5 billion of imports and exports through U.S. ports each year. The efficiency and reliability of this system depends on the ability of the Corps to operate, maintain and construct replacement facilities. While these facilities may be seen, touched, and rightly appreciated, the present study is a tribute to what is essentially an invisible and little known element of Corps history, yet important in its own right.

Conrad Weiser
Pittsburgh District
U.S. Army Corps of Engineers

Contents

Acknowledgments	i
Preface	iii
1 Introduction	1
2 Early American Inland Waterway Improvements	3
The Erie Canal	5
The Western Rivers	6
Antebellum Non-Federal Inland River Improvements.....	7
<i>The Falls of the Ohio</i>	7
<i>Muscle Shoals</i>	8
Antebellum Non-Federal Slackwater Navigation Improvements.....	9
<i>The Monongahela Navigation Company</i>	9
3 Early Federal In-River Construction	11
The Corps of Engineers and the French Engineering Tradition	11
The Corps' Earliest In-River Projects	13
Military Education and the Design of Cofferdams	16
<i>The Potomac Aqueduct</i>	19
4 Cofferdams on the Inland Rivers: The Initial Corps' Projects	26
Rock Island and Des Moines Rapids	26
5 Slackwater Improvement of the Ohio River	31
Davis Island Lock and Dam	32
The Canalization of the Ohio.....	35
The Ohio River Type Box Cofferdam	37
Other Ohio River Innovations.....	45
<i>Lock and Dam No 41 – Incorporation of Existing Structures into a Cofferdam</i>	45
<i>Caissons</i>	45
6 Canalization Projects Prior to World War I	48
Monongahela River	48
Allegheny River.....	50
Kanawha River.....	51
Big Sandy River.....	52
Kentucky River	54
Cumberland River	54
Tennessee River	55
<i>Hales Bar Dam</i>	56
Mississippi River Headwaters	56

Upper White River.....	57
Big Sunflower River	58
Ouachita River	60
Mobile River System.....	62
<i>Coosa and Alabama Rivers</i>	63
Dissemination of Cofferdam Design.....	63
7 Introduction of Steel Sheet Pile Cofferdams.....	65
Steel Sheet Pile Design	65
Early Steel Sheet Pile Cofferdams.....	66
Black Rock Lock Cofferdam	67
Raising the Battleship <i>Maine</i>	70
Troy Lock and Dam	71
Cape Fear River Lock No. 2.....	74
8 Adoption of Steel Sheet Pile Cofferdams.....	77
Resistance on the Upper Ohio.....	77
Ohio River Canalization: 1919-1930	78
Replacement of the First Generation Ohio Dams: 1919-1937.....	80
<i>Deadman Island [Dashields] Locks and Dam</i>	81
<i>Montgomery Island Locks and Dam</i>	83
<i>Gallipolis Locks and Dam</i>	85
<i>The Falls of the Ohio</i>	86
Steel Sheet Pile Cofferdams on Ohio Tributaries.....	88
<i>Monongahela River</i>	88
<i>Allegheny River</i>	89
<i>Kanawha River</i>	93
<i>Persistence of Traditional Technologies: Wilson Dam on the Tennessee River</i>	94
9 Slackwater Navigation on the Upper Mississippi.....	98
From Open River to Slackwater Navigation	98
Upper Mississippi 9-Foot Channel Project Cofferdams.....	101
<i>Ohio River Type Box Cofferdams</i>	105
<i>Double-Wall Wood and Steel Cofferdam – Lock No. 6</i>	105
<i>Single-Wall Cofferdam – Dam No. 6</i>	109
<i>Steel Sheet Pile Cofferdams – Lock and Dam No. 26</i>	110
Continued Use of Traditional Designs – Bonneville Dam	117
10 Post World War II Cofferdam Design and Construction	122
The Tennessee Valley Authority’s Steel Cofferdams	122
Design Theory for Cofferdams	124
Post World War II Corps of Engineers Cofferdams	127
<i>The Columbia and Snake Rivers</i>	127
<i>Monongahela River</i>	128
Ohio River Navigation Modernization.....	130

11	Contemporary In-River Construction Practice.....	133
	Melvin Price Locks and Dam.....	133
	Innovations in Design Methods and Behavior Analysis	136
	Innovative Design Solutions at the End of the Twentieth Century	137
	<i>Point Marion Lock</i>	137
	<i>In-the Wet Construction: Braddock Dam</i>	138
	<i>The Work Continues: Olmsted Locks and Dam</i>	142
12	Conclusion.....	143
13	Bibliography.....	148
	Index.....	164
	Notes.....	169

Figures and Plates

Figures

Figure 1. Schuylkill River Bridge.	4
Figure 2. The falls of the Ohio at Louisville prior to any improvements.	8
Figure 3. Section of sheet pile cofferdam.	16
Figure 4. Potomac Aqueduct.	23
Figure 5. Potomac Aqueduct.	24
Figure 6. Section of Potomac Aqueduct cofferdam.	25
Figure 7. Map of the Rock Island Rapids.	27
Figure 8. Section of Chanoine shutter-dam for navigable pass on the Upper Seine River, France.	33
Figure 9. Map of the Ohio River system showing locations of locks and dams.	35
Figure 10. Use of barge to place cofferdam framework in deep water.	37
Figure 11. Typical section through Ohio River type box cofferdam.	39
Figure 12. Ohio River Lock and Dam No. 48. Section of 1912 cofferdam.	40
Figure 13. Wakefield sheet piling, showing joint formed from three planks.	41
Figure 14. Ohio River Lock and Dam No. 48. Plan of 1912 cofferdam.	44
Figure 15. Ohio River Lock and Dam No. 32. General layout of caissons and cofferdams with typical sections, 1919-1922.	46
Figure 16. Ohio River Lock and Dam No. 32. Section through navigable pass showing steel floating caisson with attached cofferdam, 1919-1922.	47
Figure 17. Big Sunflower River. Plan and section of cofferdam.	58
Figure 18. Big Sunflower River. Cofferdam construction sequence.	59
Figure 19. Ouachita River. Cofferdam section.	60
Figure 20. Ouachita River. Cofferdam construction sequence.	61
Figure 21. Various steel sheet pile sections.	65
Figure 22. Section of Friestadt steel sheet piling showing interlock.	66

Figure 23. Black Rock Lock, Buffalo, New York. Plan and section showing cofferdam.....	67
Figure 24. Black Rock Lock, Buffalo, New York. Details of sheet piling interlocks and connections.....	68
Figure 25. Plan of circular cell cofferdam around wreck of Maine.....	70
Figure 26. Troy Lock and Dam, New York. Plan, sections, and profiles of cofferdam.....	72
Figure 27. Cape Fear Lock No. 2, North Carolina. Cofferdam plan and section.....	74
Figure 28. Typical section through timber-braced arch-webbed steel sheet pile cofferdam.....	79
Figure 29. Ohio River Lock and Dam No. 32. Plan of cellular steel sheet pile cofferdam for construction of bear-traps and bear-trap piers, 1924.....	80
Figure 30. Dashields Locks and Dam, Ohio River. Plan showing circular cell cofferdams, 1928-1929.....	82
Figure 31. Dashields Locks and Dam, Ohio River. Section showing dam masonry and location of circular cell cofferdam and plan showing details of construction between cofferdam cells.....	82
Figure 32. Gallipolis Locks and Dam, Ohio River. Plan showing arrangement of cellular steel pile cofferdams, with detail showing sub-cofferdam and well points at lock land wall, 1933-1937.....	87
Figure 33. Ohio River Lock and Dam No. 41, Louisville, Kentucky. Site plan for 1920s improvements.....	88
Figure 34. Marmet Lock and Dam, Kanawha River. General plan and construction plant layout showing cellular steel pile cofferdam, 1932-1934.....	96
Figure 35. Map of upper Mississippi 9-foot channel project.....	101
Figure 36. Construction of Ohio River type box cofferdam.....	105
Figure 37. Ohio River type box cofferdam. Detail of articulated joint.....	105
Figure 38. Mississippi River Lock and Dam No. 6. Double-wall cofferdam with earth fill, plan and section.....	106
Figure 39. Mississippi River Lock and Dam No. 6. Detail of double-wall cofferdam with earth fill.....	108
Figure 40. Mississippi River Lock and Dam No. 6. Cross section of single-wall cofferdam.....	109
Figure 41. Mississippi River Lock and Dam No. 26. Plan of cofferdam for auxiliary lock.....	112
Figure 42. Mississippi River Lock and Dam No. 26. Typical cross section of cofferdam wall.....	113
Figure 43. Mississippi River Lock and Dam No. 26. Guide pile and bracing system used for driving steel sheet piling.....	114

Figure 44. Mississippi River Lock and Dam No. 26. Plan of Cofferdam No. 1.	115
Figure 45. Mississippi River Lock and Dam No. 26. Design of streamline fin, Cofferdam No. 1.....	116
Figure 46. Mississippi River Lock and Dam No. 26. Closure operations and falsework for Cofferdam No. 3.	118
Figure 47. Section of timber crib cofferdam.....	118
Figure 48. Bonneville Dam, Columbia River site plan with cofferdams.	119
Figure 49. Plan view of a cloverleaf cofferdam.....	124
Figure 50. Map and profile of Ohio River navigation modernization (1969).	130
Figure 51. Lock and Dam No. 26(R) (Melvin Price Locks and Dam) Stage 1 cofferdam plan.	134
Figure 52. Point Marion Lock. Plan of cofferdam showing location of new and old locks and incorporation of old land wall into cofferdam.	138
Figure 53. Point Marion Lock. Section of old land wall showing location of rock anchors.	139

Plates

Plate 1. Potomac aqueduct.....	19
Plate 2. Davis Island Lock and Dam, Ohio River.	34
Plate 3. Constructing lock cofferdam.	38
Plate 4. Monongahela River Lock and Dam No. 7. Lock cofferdam during construction.....	50
Plate 5. Kanawha River Lock and Dam No. 7. General view of timber crib lock cofferdam.....	52
Plate 6. Kanawha River Lock and Dam No. 9. Masonry lock walls in foreground and timber crib cofferdam at rear.....	53
Plate 7. Big Sandy River, Louisa, Kentucky. Needle Dam showing trestles being raised into position.	54
Plate 8. Big Sandy River, Louisa, Kentucky. Needle Dam showing placement of needles from trestle.....	54
Plate 9. Black Rock Lock, Buffalo, New York. Steel sheet pile cofferdam.	69
Plate 10. Constructing circular cell cofferdam around wreck of Maine.....	71
Plate 11. Ohio River Lock and Dam No. 23. View from outer end of navigable pass cofferdam towards locks.	79
Plate 12. Dashields Locks and Dam, Ohio River. View of lock cofferdam.....	81

Plate 13. Dashields Locks and Dam, Ohio River. View toward right shore of cofferdam, 1 October 1928.	83
Plate 14. Dashields Locks and Dam, Ohio River. View downstream of abutment construction showing caissons, 1 October 1928.	83
Plate 15. Montgomery Locks and Dam, Ohio River. Middle lock wall under construction, view upstream.	84
Plate 16. Montgomery Locks and Dam, Ohio River. Upstream arm of steel sheet pile box type cofferdam under construction.	85
Plate 17. Montgomery Locks and Dam, Ohio River. Placing fill in upstream arm of cofferdam.	86
Plate 18. Montgomery Locks and Dam, Ohio River. River arm of steel sheet pile box type cofferdam under construction.	86
Plate 19. Aerial view of crib cofferdam at the Falls of the Ohio (Lock and Dam No. 41).	89
Plate 20. Allegheny River Lock No. 2. Concreting keyway in caisson, 21 February 1933.	89
Plate 21. Allegheny River New Lock No. 2. Caisson workers, 11 March 1933.	90
Plate 22. Allegheny River Lock No. 8. Air locks attached to caisson for construction of dam foundations, 25 June 1930.	91
Plate 23. Allegheny River Lock No. 8. Cofferdam construction, view downstream, 11 March 1933.	92
Plate 24. Allegheny River New Lock No. 2. Cofferdam for lock, looking downstream, 28 November 1932.	93
Plate 25. London Locks and Dam, Kanawha River. View downstream of Lock A cofferdam prior to placement of fill, showing wood spreaders and steel tie rods between walls of steel sheet piling.	94
Plate 26. London Locks and Dam, Kanawha River. Collapse of river arm of Lock A cofferdam.	95
Plate 27. London Locks and Dam, Kanawha River. View of second dam cofferdam.	95
Plate 28. Wilson Lock and Dam, Tennessee River. View of rock excavation in south end corner of Cofferdam No. 1.	97
Plate 29. Wilson Lock and Dam, Tennessee River. View of interior of Cofferdam No. 1.	97
Plate 30. Wilson Lock and Dam, Tennessee River. View of interior of Cofferdam No. 5.	97
Plate 31. Mississippi River Lock and Dam No. 19. Building last crib of Illinois cofferdam.	99
Plate 32. Mississippi River Lock and Dam No. 24. Aerial view of steel pile box cofferdam for first portion of the dam.	102

Plate 33. Mississippi River Lock and Dam No. 4. Detail of lower arm of lock cofferdam before filling.	103
Plate 34. Mississippi River Lock and Dam No. 21. Dewatering the steel pile box type cofferdam for first portion of dam.	104
Plate 35. Mississippi River Lock and Dam No. 15. Construction of Ohio River type box cofferdam. Framework section completed and ready to be dropped into river.	107
Plate 36. Bonneville Project, Columbia River. Tailoring of bottom of crib to conform to bottom conditions.	120
Plate 37. Braddock Dam, Monongahela River. Construction of dam segment in casting basin.	140
Plate 38. Braddock Dam, Monongahela River. Positioning Segment No. 1, December 2001.	141

1 Introduction

Any child who has tried to build an island in a puddle, or dam a freshet or stream, has confronted the difficulty of building in water. You can drop stones or rocks into the water to form a base or foundation for your project, which works well enough if you use large stones, but becomes increasingly problematic as the size of the stones diminishes. If you are working in moving water, the difficulties are significantly greater, since the current tends to wash the stones downstream as soon as they are dropped into the water. What can be frustrating for a child appears seemingly impossible for an adult. How does one construct a foundation for a permanent structure, such as a dam or a bridge pier, when the construction site is underwater?

In December 2006, the Pittsburgh District of the U.S. Army Corps of Engineers engaged Gray & Pape, Inc., through Woolpert, Inc., to document and analyze the history of advancements in inland river construction techniques involving cofferdam and in-the-wet construction technology used by the U.S. Army Corps of Engineers. This document presents the results of those investigations.

The traditional solution to this problem requires the use of a cofferdam. A cofferdam is a temporary, watertight structure erected around a construction site, designed to keep water from inundating the site during construction. Cofferdams can vary in design from simple earthen dikes heaped up around

a construction site, to elaborate and costly structures constructed of steel sheet piling.

Cofferdams are not an invention of the industrial age. Among the earliest written descriptions of cofferdams are those of Marcus Vitruvius Pollio, a Roman writer, architect, and engineer, active during the first century B.C. Vitruvius is said to be the author of *De architectura*, known today as *The Ten Books on Architecture*, a treatise on landscape architecture, architecture, engineering, and town planning. Written ca. 27 B.C., it is the only surviving major book on architecture from classical antiquity.

Vitruvius describes single and double-wall cofferdams in Chapter 12, Book 5, of *De architectura*. The single-wall structure consists of “sides formed of oaken stakes with ties between them... driven down into the water and firmly propped there; then, the lower surface inside, under the water, must be leveled off and dredged, working from beams laid across; and finally, concrete ... must be heaped up until the empty space which was within the cofferdam is filled up by the wall.” The double-wall design was intended for use where concrete was unavailable. It consisted of “double sides, composed of charred stakes fastened together with ties, [with] clay in wicker baskets made of swamp rushes... packed in among the props.”¹

Cofferdams were widely used in Europe prior to the settlement of North America. It is not known where and when the first cofferdam was constructed in what became the United States, but it was likely used for construction of a masonry bridge pier or dam foundation. Wooden bridge piers did not require access to the river bottom for construction, since such piers generally consisted either of wood piles driven into the bottom using a pile driver, or a wooden crib, a box-like structure of logs or sawn timbers filled with rocks and resting directly upon the bottom. Likewise, wooden dams, generally constructed of a series of cribs, did not require foundation work.

Determination of the type of cofferdam to be used is the “first and most important problem to be solved preliminary to the start of construction of a lock or dam.”² A reliable cofferdam minimizes the flow of water into the construction site, permitting the area to be dewatered by pumps or other means. After dewatering, the cofferdam must permit the control of leakage into the construction site. The cofferdam must be economical—inexpensive to construct, readily removed, and offering a maximum reuse of materials. For in-river construction, a reliable cofferdam is crucial, because construction often spans multiple low water seasons. This requires the cofferdam to be capable of surviving overtopping and inundation during the period of high water. This necessitates that the structure be protected against marine hazards, such as flood, ice, and drift, which may damage the structure and flood the construction site.³

Delays or costs caused by leakage or failure of the cofferdam can significantly affect con-

struction. However, “owing to the temporary need of these structures, engineers and contractors are often tempted to use too much economy in their construction to their subsequent regret.”⁴ The design and construction of cofferdams therefore represents something of an engineering high-wire act, striving to balance somewhat contradictory goals—the desire for the least expensive, most easily constructed and removed structure, and the need to protect the enclosed construction site from flood or other vagaries of nature.

The Corps of Engineers has constructed cofferdams for in-river construction projects for more than 150 years. During that period, Corps engineers have developed entirely new cofferdam designs, refined and improved existing designs, introduced innovative approaches to construction, and pioneered the use of scientific methods to analyze the forces and stresses acting upon cofferdams. This study documents the history of the Corps’ use of cofferdams in inland river construction, with particular emphasis upon the evolution of design, construction, and analytical methods.

2 Early American Inland Waterway Improvements

In the neoclassical tradition of the eighteenth and early nineteenth centuries, rivers were most attractive “when they yielded to humanity’s needs, whether as mechanisms of transportation or as sites for nascent towns.”⁵ Wild rivers served little purpose, so many considered America’s waterways untapped or under-exploited raw materials requiring development, control, and management for human benefit.⁶

During the colonial and early national periods, exploitation of America’s rivers required construction in the water. Available technologies did not permit construction of long-span bridges that could cross significant streams in a single span, necessitating the use of shorter spans with support piers built in the stream. Water powered mills and other industrial plants required the construction of dams to assure a reliable supply of water.

In-water construction, on any significant scale, required the use of cofferdams. Carl W. Condit, in *American Building Art: The Nineteenth Century*, suggests that the use of cofferdams in America likely dates from the late eighteenth century. He notes that “to erect adequate timber bridges two structural techniques had to be mastered: one was the method of building substantial masonry piers up from a firm bed in watertight cofferdams; the other was the construction of truss framing. Both had been developed to a sufficient degree in Europe by the mid-eighteenth cen-

tury, and by the end of the century the American carpenters were ready to try their hands.”⁷

Condit cites Timothy Palmer, of Newburyport, Massachusetts, as one of the first American builders to use cofferdams for the construction of masonry bridge piers. In 1794, Palmer designed and constructed the Piscataqua River Bridge at Portsmouth, New Hampshire. Constructed over a tidal stream with a swift and turbulent current, the nearly half-mile-long bridge spanned the main shipping channel upon a Palladian-arched truss set between masonry piers erected inside timber cofferdams.⁸

The most famous of Palmer’s bridges was the 1806 Permanent Bridge over the Schuylkill River in Philadelphia (Figure 1). This structure’s most notable feature was the height of the west pier, which extended 41 feet 9 inches below common high water. The pier was constructed of stone masonry laid up inside a watertight cofferdam similar to those designed and constructed in England by engineer William Weston.⁹

Cofferdams also were used to construct the foundations for masonry dams. The control of water through the use of dams is one of the earliest utilitarian structural techniques. The ancient Egyptians, Mesopotamians, Greeks, and Romans all built dams. In Medieval Europe, dams were used to generate power.

the canal along the natural contours of the land, but in hilly terrain this strategy could significantly increase the length of the canal.¹³

Upon the conclusion of the War of 1812 the United States embarked on a flurry of canal construction. Although ambitious schemes for canals had been urged since the colonial period, by 1816 only about 100 miles of canal existed in the United States, and only three canals were more than 2 miles in length. The longest (27.25 miles), the Middlesex Canal, linked the Merrimack River in New Hampshire with Boston. The Santee & Cooper Canal in South Carolina provided Charleston with access to the Santee River, while the Dismal Swamp Canal linked Norfolk and Albemarle Sounds.¹⁴

The Erie Canal

In 1817, the New York state legislature authorized construction of the Erie Canal.¹⁵ This legislation represented an extraordinary act of faith. In 1817, New York's population did not much exceed a million persons, most of whom lived in the lower Hudson River Valley. Much of the territory between Albany and Buffalo, the projected route for the 364-mile canal, was unsettled wilderness. The longest canal in the nation extended not quite 28 miles. Not only was the Erie to be, by far, the longest canal in the world, but its builders faced engineering problems far greater than any previously encountered by canal builders.¹⁶

Although it presented significant engineering difficulties, the projected route of the canal, from Albany through the valley of the Mo-

hawk River to Lake Erie at Buffalo, offered by far the most attractive water route from the Atlantic seaboard to the interior. At its highest point, near Buffalo, the route rose only 650 feet above the Hudson River at Albany. Ample water supplies were available, and the terrain was less forbidding than further south.¹⁷

Following the legislative authorization, construction began on July 4, 1817. At the same time, the Champlain Canal, connecting the Hudson River and Lake Champlain was authorized. The federal government denied financial aid to either project, so the state of New York assumed the entire responsibility for raising the required funds and directing construction. Even prior to its completion, the Erie Canal proved phenomenally successful. Successive sections of the canal were placed into service beginning in 1819, with the entire canal opened from Albany to Buffalo in 1825. The Champlain Canal was completed in 1823. Traffic crowded the canal from the outset, with revenue from tolls contributing significantly to the financing of its completion.¹⁸

Three major effects of the Erie Canal were immediately apparent. It reduced the cost of shipping goods so dramatically that it virtually guaranteed the commercial prominence of New York City. It compelled rival states and ports to frantic efforts to build their own connections across the Appalachians, and it served as the catalyst for the construction of canals linking Lake Erie and the Ohio River.¹⁹

The Western Rivers

The widespread introduction of the steamboat, in conjunction with the surge in canal construction, sparked a nationwide transportation revolution in the decades following the end of the War of 1812.²⁰ Robert Fulton demonstrated the commercial viability of the steamboat on the Hudson River in 1807, and with the return of peace in 1815, the use of steamboats in the United States expanded rapidly. By this date, steamboats had ceased to be a novelty on the Hudson and Delaware rivers. In the West, the steamboat *New Orleans* successfully traveled from Pittsburgh to New Orleans during the winter of 1811-1812. In 1815, *Enterprise*, built in Brownsville, Pennsylvania, on the Monongahela River, successfully returned upstream to its home port after a trip to New Orleans.²¹

Steamboats proved the most important factor in the rapid industrial development of the Ohio and Mississippi River valleys during the period between 1815 and the onset of the Civil War. No section of the country was so completely dependent upon steam for effective transportation, and in no other part of the world were so many steamboats built and operated. Seventeen steamboats operated on western rivers in 1817. By 1820, that number had risen to 69, and by 1860 735 steam vessels navigated western rivers. Steamboats transported bulk commodities upstream and downstream far more rapidly and at one-quarter of the cost of other forms of river navigation. Steam navigation spurred the

spread of market production throughout the West, directly contributing to the growth and prosperity of river ports such as Pittsburgh, Cincinnati, Louisville, St. Louis, Memphis, and the great entrepot of New Orleans.²²

The physical character of the rivers determined the conditions and set the problems of steamboat construction and operation. Significant efforts were made to design and construct vessels suited to the peculiar conditions found on western rivers, but, from the first, attention also was directed towards the improvement of the rivers themselves. Steam navigation on the western rivers confronted serious perils and hazards. The level of water in the rivers was subject to wide and sudden fluctuations. At Cincinnati, the spread between high and low water could exceed 40 feet within a matter of a few weeks. Vessels forced to tie up for lack of water during the summer faced floods in the fall and spring. Ice closed rivers to navigation in the winter, and constituted a major threat to navigation upon spring breakup. Extended periods of low water made ledges and rock and sand bars a feared threat, while snags (large trees that fell into the water from eroding banks and became caught in the river bed) damaged more steamboats than any other cause. Between 1811 and 1851, more than 40 percent of the steamboats lost on western rivers fell victims to snags or similar obstructions.²³

In the early decades of steam navigation on the western rivers, river improvement efforts were directed towards elimination of specific rapids, rocks, snags, and bars. The goal was conceived in terms of clearing a channel by

removing or cutting through obstructions or bypassing them by means of a canal. As the scale of western river commerce increased, dissatisfaction grew with such limited forms of relief. Navigation interests came to demand a channel not merely cleared of obstructions, but filled with a navigable depth of water year round. These demands led to ambitious proposals for maintaining year-round navigation through the diversion of water from Lake Erie, the storage of water in huge headwater reservoirs, or construction of a slackwater system of locks and dams.²⁴

Antebellum Non-Federal Inland River Improvements

Early efforts to eliminate navigation obstructions on the western rivers were funded by private companies and state governments. These efforts were piecemeal in nature and largely ineffective. The states focused their efforts and funds on intrastate rivers, initiating improvements on tributary streams while the main stems of the nation's river system remained largely untouched. Private ventures lacked the capital, prior to the Civil War, to address more than particular, local problems. After 1824, the federal government assumed responsibility for improvement of navigation on the western rivers and began a program of snag removal and elimination of rocks, bars, and other obstacles.

The Falls of the Ohio

Among the earliest inland river improvement projects in the United States was construction of a canal around the Falls of the Ohio at Louisville, Kentucky (Figure 2). The Falls represented the only permanent obstruction to

navigation on the entire Ohio and, consequently, was the object of improvement schemes dating back as far as 1793. The Falls consisted of a series of rapids formed by limestone ledges that extended for 2 miles along the river, which fell 22 feet over this distance. Three main natural passages existed at the Falls, the Indiana Chute, the Middle Chute, and the Kentucky Chute, the latter two navigable only at high water.²⁵

In 1825, the Commonwealth of Kentucky granted a charter to a private stock company, the Louisville & Portland Canal Company, to build a canal around the falls. The United States government bought shares in the company, which completed the canal and locks in 1830. The canal was 1.9 miles long and 64 feet wide, with three lift locks measuring 198 feet by 50 feet (capable of handling a vessel 183 feet in length), each with a lift of approximately 8 feet. The "first major improvement to be successfully completed on the great central river system of the United States," the Louisville & Portland Canal was gigantic in scale, vastly exceeding the size of the Erie Canal in all but length. The canal proved an immediate financial success; by 1841 revenue from tolls had exceeded the original construction costs, and by 1855 Kentucky began to apply toll revenue to the purchase of company stock, with the intent of turning the stock over to the federal government and making the canal toll free.²⁶

Despite its financial success, the canal proved a source of dissatisfaction and complaint to navigation interests. Floods left heavy deposits of mud in the canal bed. Landslides and projecting rocks along the banks further ob-

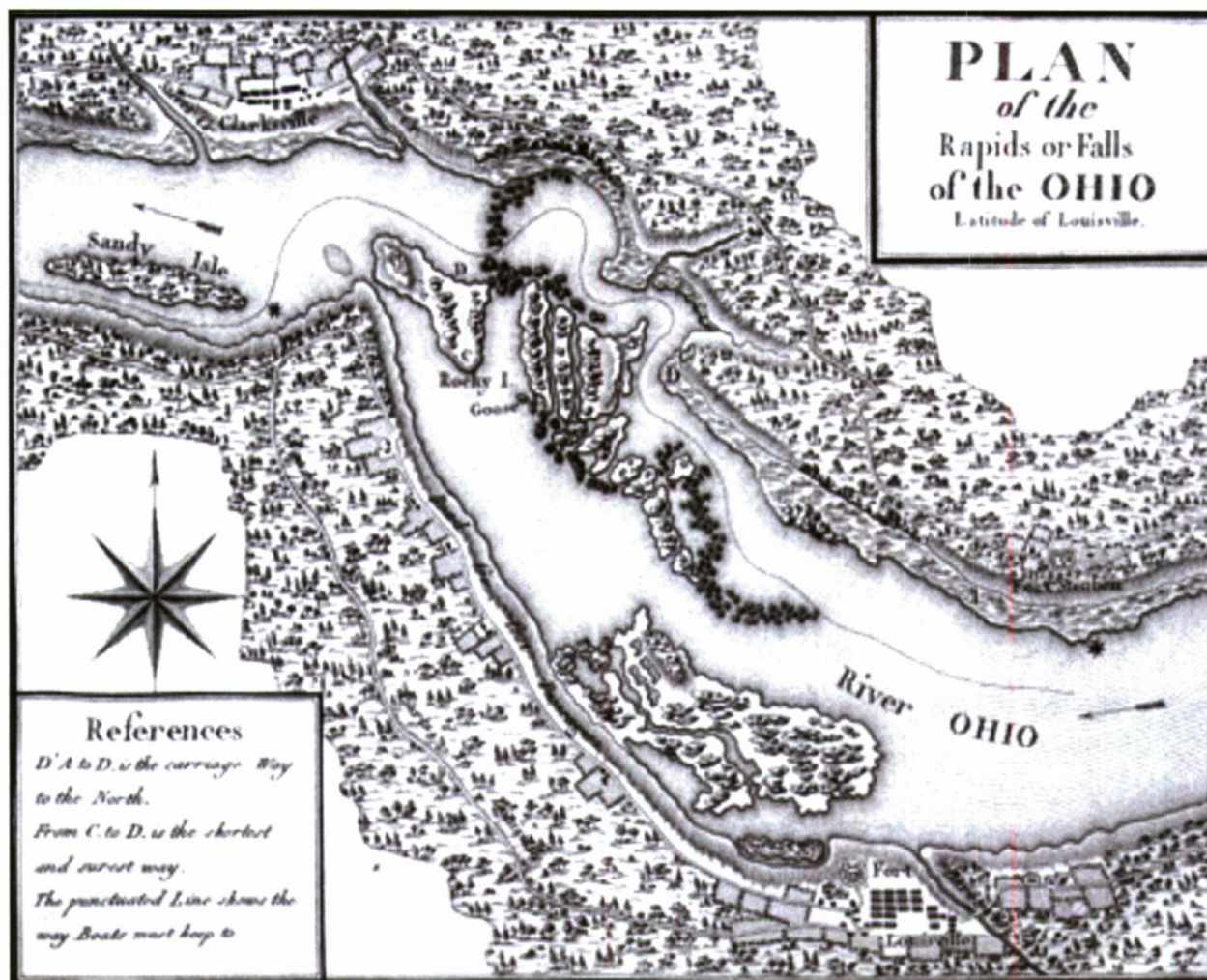


Figure 2. The falls of the Ohio at Louisville prior to any improvements. Map collection, Indiana Division, Indiana State Library.

structed the passage. Tree trunks stranded in the canal proved difficult to remove. The absence of guard locks or gates at the ends of the canal made repairs difficult. The canal had to be closed, sometimes for several weeks, to permit the removal of accumulated mud and debris. The narrow, shallow canal was difficult to navigate during periods of low water and during periods of heavy use had to be restricted to one-way traffic. Such delays and restrictions proved expensive, particularly for larger vessels. These inadequacies paled, however, compared to the inadequate size of the canal and locks. The canal had

scarcely opened before technological innovations and improvements made possible the construction of much larger steamboats. By 1853, over 40 percent of steamboats were too large to pass through the locks.²⁷

Muscle Shoals

Muscle Shoals represented the only barrier to navigation on the Ohio River system comparable to the Falls of the Ohio. Located in northern Alabama approximately 250 miles upstream from the mouth of the Tennessee at Paducah, Kentucky, and about 400 miles

downstream from the head of navigation at Knoxville, Tennessee, these rapids constituted a more formidable obstacle to navigation than the Falls of the Ohio. They comprised a series of rapids extending for 30 miles from Brown's Ferry, located 35 miles upstream from Florence, downstream to Waterloo. The three main rapids, Elk River, Muscle, and Colbert's shoals, had an aggregate fall of 134 feet in 29 miles, with Muscle Shoals accounting for 85 feet in about 14 miles. The water over the shoals ran as shallow as 6 to 18 inches at low stage. The current was swift, and the channel a narrow and tortuous passage through a series of rock ledges and boulders. Upstream navigation proved almost always impossible, while downstream navigation was restricted to about one month a year during the highest freshets.²⁸

Except for these rapids, the Tennessee offered favorable conditions for navigation for a distance of 400 miles upstream from the river's mouth. Improvement or elimination of the rapids would eliminate a commercial bottleneck and provide economic benefits to the entire river. In 1824, Congress granted the state of Alabama permission to improve navigation on the Tennessee and, in 1828, granted the state 400,000 acres of land. Proceeds from the sale of this land were to be applied to the improvement of Muscle Shoals. The state of Alabama began work on a canal extending from Florence to Brown's Ferry in 1831. Less than half the canal was completed, and this portion was quickly rendered useless

when floods cut gaps in its banks. In 1875, the federal government took over the project.²⁹

Antebellum Non-Federal Slackwater Navigation Improvements

The earliest slackwater improvements on the western rivers were state and private ventures begun in the mid-1830s. These improvements sought to provide for year-round navigation through a system of locks and dams, and represented a significant expansion of prior open-channel improvement efforts. Within a decade, slackwater systems operated on a number of Ohio River tributaries, including the lower portions of the Kentucky, the Green, the Licking, the Muskingum, and the Monongahela rivers. Dams placed across the streams at intervals provided a minimum depth of water for navigation. Each dam was provided with a lock to pass vessels up and down the stream. Financial difficulties, imperfect engineering and construction, natural disasters, and inadequate maintenance and repair efforts, delayed the completion and limited the usefulness of these improvements. The dams employed were generally timber crib structures, built directly on the river bottom. The locks were frequently of stone masonry, founded on rock. Construction of many of these locks required some type of cofferdam, usually either a simple earthen dike or a timber crib structure.³⁰

The Monongahela Navigation Company

The most successful of the early western slackwater systems was built on the Monon-

gahela River beginning in 1836. The Monongahela, which joins with the Allegheny River at Pittsburgh to form the Ohio River, taps one of the richest bituminous coal regions in the world. The desire to bring this mineral wealth to market provided a powerful incentive to the improvement of navigation on the Monongahela. Navigation on the unimproved stream was limited to the 57-mile stretch between Brownsville, Pennsylvania and the river's mouth at Pittsburgh. During periods of high water the river was navigable as far upstream as Morgantown, West Virginia, and, on occasion, even to Fairmount. The principal traffic on the river prior to its improvement consisted of rafts of lumber.³¹

Proposals to improve the Monongahela were made as early as 1814, but it was not until 1832 that any real progress occurred. In that year, Congress provided funds for a survey of the river, which was conducted by William Howard in 1833. Howard recommended construction of a system of eight low dams and locks, with lifts of 4.5 to 6 feet, intended for use in low water conditions. Congress declined to commit federal funds to the project, and in 1835 local interests urged the Commonwealth of Pennsylvania to undertake the work.³²

On March 31, 1836, the Commonwealth of Pennsylvania chartered the Monongahela Navigation Company (MNC) to build a slack-water navigation system upstream from Pittsburgh to the Pennsylvania state line, and as far into Virginia as that state would permit. W. Milnor Roberts resurveyed the route in 1838 and recommended the use of 8-foot high dams, rather than the 4.5-foot structures

authorized by the legislature. Local interests opposed Roberts' taller dams, fearing increased and intensified floods, but in 1839 the Pennsylvania legislature approved Roberts' designs. The first construction contracts were let, and Lock Nos. 1 and 2, on the lower river, opened to traffic in 1841.³³

These initial improvements employed log crib cofferdams, dewatered using horse-powered screw pumps, in the construction of timber crib dams and stone masonry locks measuring 50 by 190 feet. In an effort to speed the work, the MNC attached steam engines to the pumps at Lock and Dam Nos. 3 and 4. This innovation enabled the pumps to discharge 2100 gallons per minute, reducing the time required to dewater the cofferdams. When completed to Brownsville in late 1844, these four lock and dam complexes provided 60 miles of 5-foot slackwater navigation. The MNC eventually added a second lock chamber at Lock Nos. 1-4 and gradually extended the entire system upstream, as revenue from tolls provided working capital. Lock and Dam Nos. 5 and 6, completed in 1856, extended the system to New Geneva, Pennsylvania. Lock and Dam No. 7, which completed the system to the Pennsylvania state line, opened in 1883.³⁴

3 Early Federal In-River Construction

During the Washington and Adams administrations, the constitutionality of federal civil works was widely questioned. In 1806, President Thomas Jefferson approved federal construction of the National Road, initially authorized to extend from the Potomac River at Cumberland, Maryland to the Ohio River at Wheeling, Virginia (now West Virginia). Subsequently, in 1808, Secretary of the Treasury Albert Gallatin recommended a \$20 million federal program for the construction of roads and canals. The War of 1812 stopped discussion of this proposal and, indeed, work did not begin on the National Road until 1811, under the supervision of the Treasury Department.³⁵

The War of 1812 exposed the nation's need for an improved defense and transportation system. In 1819, Secretary of War John C. Calhoun proposed the use of federal aid for transportation projects and recommended that the U.S. Army Corps of Engineers be directed to improve waterways and other transportation systems because such work would facilitate the movement of troops and military supplies, while also contributing to national economic development.³⁶

Following Calhoun's 1819 proposal, Congress appropriated \$5,000 in 1820 to continue a survey of the Ohio and Mississippi rivers initially begun by the states. The survey, conducted by General Simon Bernard and Colonel Joseph G. Totten of the U.S. Army Corps

of Engineers, sought to determine the most practical means for improving steamboat navigation from Louisville, Kentucky, at the Falls of the Ohio, to New Orleans. Published in 1821, the survey recommended removal of snags and other obstructions to navigation, use of dikes to increase the depth of water over sandbars, and construction of a canal around the Falls of the Ohio.³⁷

Congress eventually accepted Calhoun's recommendations in 1824, passing the General Survey Act, which authorized the president to use army engineers to survey road and canal routes of national importance. The U.S. Army Corps of Engineers assumed responsibility for supervision of the construction of the National Road in 1825, when Congress authorized extension of the road west of the Ohio River. In 1827, Army engineers began supervising lighthouse construction, previously the responsibility of the states or private parties. Throughout the late 1820s and the 1830s army engineers assumed an increasingly prominent role in surveying, designing, and supervising the construction of internal improvements.³⁸

The Corps of Engineers and the French Engineering Tradition

The origin of the Army Corps of Engineers dates to the establishment of the Continental Army in June 1775, when Congress provided for the inclusion of military engineers.³⁹ French military engineers began arriving in

America to assist their American allies in 1776. Their skill and expertise sparked an affinity for French techniques and methods among American military engineers that significantly influenced the Corps' future approach toward river improvements.

When the Revolution ended in 1783, a political debate ensued as to whether the United States should maintain a standing Army. Those opposed to a peace-time army carried the day and by the end of 1783 the engineers had been mustered out of service. No engineers served in the U.S. Army until 1794, when war with Britain threatened and the need for coastal fortifications and defenses resulted in establishment of a new corps of artillerists and engineers. The Army Corps of Engineers was not permanently established until March 16, 1802, when Congress authorized creation of the U.S. Army Corps of Engineers and the U.S. Military Academy at West Point, New York.

From the beginning, West Point stressed the formal training of Army engineers. The curriculum, which placed heavy emphasis upon mathematics in the institution's early years, was expanded to include engineering in 1808, and by 1812, a professorship of engineering had been established. Sylvanus Thayer, superintendent of the Academy from 1817 to 1833, reorganized the curriculum based upon the course of study of France's *Ecole Polytechnique*. Indeed, the Academy's engineering professor, Claudius Crozet, was a French graduate of the *Ecole Polytechnique*. Cadets relied upon French engineering texts, with

Joseph-Marie Sganzin's *Program D'un Course de Construction* serving as the principal civil engineering text. Compiled from Sganzin's lecture notes at the *Ecole*, where he served as an expert on roads and canals, the text stressed the need for elaborate planning and a reliance upon scientific methods.⁴⁰

The French centralized, government-funded, scientific approach to civil engineering projects stood at odds with contemporary British practice, which was suspicious of army involvement, hostile to regimentation, and indifferent to utopian science. Most British engineering projects were constructed as private investments with no centralized control or standards. Additionally, the French approach towards waterway improvement contrasted sharply with typical British practice. By 1700, the French had constructed an extensive system of coastal canals and improved rivers stretching from Brittany to Flanders. These largely consisted of slackwater improvements, locks and dams placed within the natural river to create pools that provided an adequate depth for navigation. In contrast, British canals frequently deviated from the course of the river and sought level ground, minimizing the need for locks and simplifying the engineering.⁴¹

Early American canal and waterway projects tended to conform to the British approach. Most consulting engineers for early American projects were British, and these engineers brought their preference for experience over science to their work. This led to a rejection of French-style slackwater improvements, with their reliance upon locks and dams, and widespread adoption of British-style canals that

emphasized minimizing lockage and the use of rivers to feed canals. American preference for wooden construction, over more expensive and complex masonry, also narrowed the gap between trained and craft builders, enabling practical craft builders to function as civil engineers responsible for the design and construction of complex waterway improvement projects.⁴²

West Point and its graduates represented the principal bastion of French-style civil engineering in the United States. However, as noted above, until the 1820s, this training and expertise was not employed to improve inland waterways or other transportation systems. Rather, the principal duties of the Corps of Engineers during this period entailed the construction and maintenance of fortifications. Beginning about 1812, some West Point graduates were assigned essentially civil tasks as surveyors and cartographers, and in 1818 the War Department established the Topographical Bureau, attached to the Corps of Engineers within a single engineering department.⁴³

The Corps' Earliest In-River Projects

Before 1824, river and harbor improvements were commonly executed by local or state agencies. Army engineers provided occasional engineering aid to states, localities, and chartered companies after 1816, but prior to the widespread adoption of the steamboat on inland rivers, interior improvement projects were not considered nationally important or technically complicated enough to demand skills of Army engineers. Nevertheless, by

1824, federal participation in internal improvements included the provision of engineering aid through the establishment of the engineering school at West Point, western exploration and mapping, and river and harbor surveys.⁴⁴

The Corps of Engineers participation in internal improvement projects was formally sanctioned in 1824 with passage of the General Survey Act on April 30, 1824 and funded by passage, on May 24, 1824, of "An Act to Improve the Navigation of the Ohio and Mississippi Rivers." The General Survey Act provided that the President employ military and civil engineers to produce survey, plans, and cost estimates for roads and canals of national importance. It "did not authorize construction of a national system of internal improvements, but merely instituted a general scheme for surveying and planning a series of major improvements."⁴⁵

Passage of the General Survey Act neatly coincided with the Supreme Court's March 2, 1824 landmark decision in the case of *Gibbons v. Ogden*. The case arose from an attempt by the State of New York to grant a monopoly on steamboat operations between New York and New Jersey. Robert Fulton and Robert Livingston were granted such rights, and they licensed New Jersey operator Aaron Ogden, a former U.S. Senator and Governor of New Jersey, to operate the ferry between New York City and New Jersey. Thomas Gibbons operated a competing ferry service licensed by a 1793 act of Congress regulating coastal trade. Ogden obtained an injunction

from a New York court against Gibbons to keep him out of New York waters, maintaining that navigation was a distinct form of commerce and was thus a legitimate area of state regulation. Gibbons sued, and the case was appealed to the United States Supreme Court.

The Court found in favor of Gibbons, stating that, "The mind can scarcely conceive a system for regulating commerce between nations which shall exclude all laws concerning navigation." The ruling determined that "a Congressional power to regulate navigation is as expressly granted as if that term had been added to the word 'commerce'."

The Court went on to conclude that Congressional power should extend to the regulation of all aspects of commerce, overriding contrary state law:

*If, as has always been understood, the sovereignty of Congress, though limited to specified objects, is plenary as to those objects, the power over commerce with foreign nations and among the several states is vested in Congress as absolutely as it would be in a single government, having in its constitution the same restrictions on the exercise of the power as are found in the Constitution of the United States.*⁴⁶

Empowered by the *Gibbons v. Ogden* decision and the General Survey Act, on May 24, 1824, Congress passed "An Act to Improve the Navigation of the Ohio and Mississippi Rivers," which authorized the expenditure of \$75,000 to remove sand bars and trees from

the Ohio and the Mississippi. The Corps of Engineers officially began work to improve navigation on the nation's inland rivers.⁴⁷

After passage of the congressional appropriation, Chief Engineer Alexander Macomb dispatched Major Stephen H. Long to the Ohio, charging him to conduct experiments to determine how best to deepen channels across sand and gravel bars. Bars acted as dams, holding back and conserving water during dry seasons. Elimination of a bar would simply stabilize the depth of water at a lower level, precisely the opposite of the desired effect. Bernard and Totten had recommended construction of timber and stone dikes to concentrate the flow of water within a limited space, thus cutting a deeper channel and aiding navigation. Long selected a compacted gravel bar near Henderson, Kentucky, just downstream from the mouth of the Green River, as the site for his experiments. At low river stage, only 15 inches of water covered this bar.⁴⁸

Long sought to determine whether Bernard and Totten's recommendations, based upon Italian and French experience, would work on the Ohio. Bernard and Totten called for the use of low wooden dikes, built into the river so as to concentrate the flow of the stream, increase the velocity of the water passing over the bar, and thereby scour material from the bar, increasing the depth of water for navigation. Long experimented with dams of different lengths, widths, and heights, finally settling upon a "wing dam" approximately 1,200 feet long, consisting of a double row of wood piles connected by wood stringers and filled between with brush and rocks. The dam

extended from one bank at a 45-degree angle downstream. The piles were driven using a windlass-powered, 500-pound pile driver mounted on a flatboat. Completed in 1826 at a cost of \$3,000, the dam functioned as predicted, decreasing the width of the channel and increasing the velocity of the current across the bar. The current scoured away material, nearly doubling the minimum depth of water over the bar to 30 to 36 inches. The structure remained in place until repaired and lengthened by the Corps of Engineers in 1872.⁴⁹

The positive results achieved by Long led to appropriations for additional wing dams, and by 1832 three additional structures had been completed and a fourth was under construction on the lower Ohio. Congress determined to apply this approach to other streams. In 1832, work began on a series of wing dams on the Cumberland River, downstream from Nashville, and in 1836 the first wing dam was built on the upper Ohio.⁵⁰

Between 1824 and 1839, the Corps oversaw a program designed to improve navigation conditions on the Ohio and the Mississippi. This work included the design and construction of wing dams, development and deployment of snag boats—specially designed vessels used to remove dead trees (snags) from the navigation channel, and limited dredging. Between 1839 and 1842, the Corps conducted no work on the inland rivers because funds were suspended during the nationwide economic depression. Work resumed on a limited basis in 1842, but funding fell increasingly victim to sectional politics, and by 1854,

all work halted, not to be resumed until 1866, after the conclusion of the Civil War.⁵¹

In the 1830s, wing dams proved a successful method for increasing the depth of water over bars. The full benefits of such improvements could only be realized by the improvement of all bars, since improving selected bars merely shifted the location of the principal navigational hazards. The elimination of funding in the 1840s precluded any effort to institute a comprehensive improvement program, and through the end of the Civil War, navigation interests had to satisfy themselves with the modest local improvements constructed in the 1830s. However, the loss of funding meant that these improvements did not receive adequate maintenance and repair, and by the late 1830s, several wing dams were reported to have been breached. By 1843, many of the dams on the lower Ohio were reported in a dilapidated condition. After the Civil War, when funding for river improvements again became available, many of the wing dams constructed in the 1830s and 1840s had deteriorated to such an extent that they no longer exercised any influence over the bars. In some instances, the remains of these dams had themselves become hazards to navigation.⁵²

For the most part, the Corps' work on inland rivers prior to the Civil War did not require the construction of cofferdams. The only permanent structures erected by the Corps on the inland rivers during this period were wing dams and the pilings used in their construction were driven from flatboats or floating barges without need of cofferdams.

Military Education and the Design of Cofferdams

The methods of constructing cofferdams were, however, addressed in the civil engineering texts used at West Point. In 1837, Sganzin's *Program D'un Course de Construction* was replaced as the basic civil engineering text in use at the Academy by Dennis Hart Mahan's *An Elementary Course of Civil Engineering, for the Use of the Cadets of the United States Military Academy*. Mahan, an 1824 West Point graduate, had toured France in the late-1820s, studying and examining French civil engineering methods and practices. Mahan returned to the United States in 1830, perhaps the most highly educated officer in the Corps of Engineers, and in 1832 was named professor of engineering at West

Point. Mahan, recognizing that the academy's introductory civil engineering text was then nearly 30 years old, compiled *An Elementary Course of Civil Engineering* from his own notes and sketches. Mahan taught at West Point until his death in 1871, and for much of that time *An Elementary Course of Civil Engineering* served as his basic text. His final revision of the book went through 12 editions and remained a standard reference at West Point until the first decade of the twentieth century.⁵³

The first edition of *An Elementary Course of Civil Engineering* describes the method of constructing a "coffer-dam" (Figure 3) for use in non-moving water more than 4 feet deep.⁵⁴ Mahan defined the cofferdam as "two rows of plank, termed *sheeting piles*, driven into the

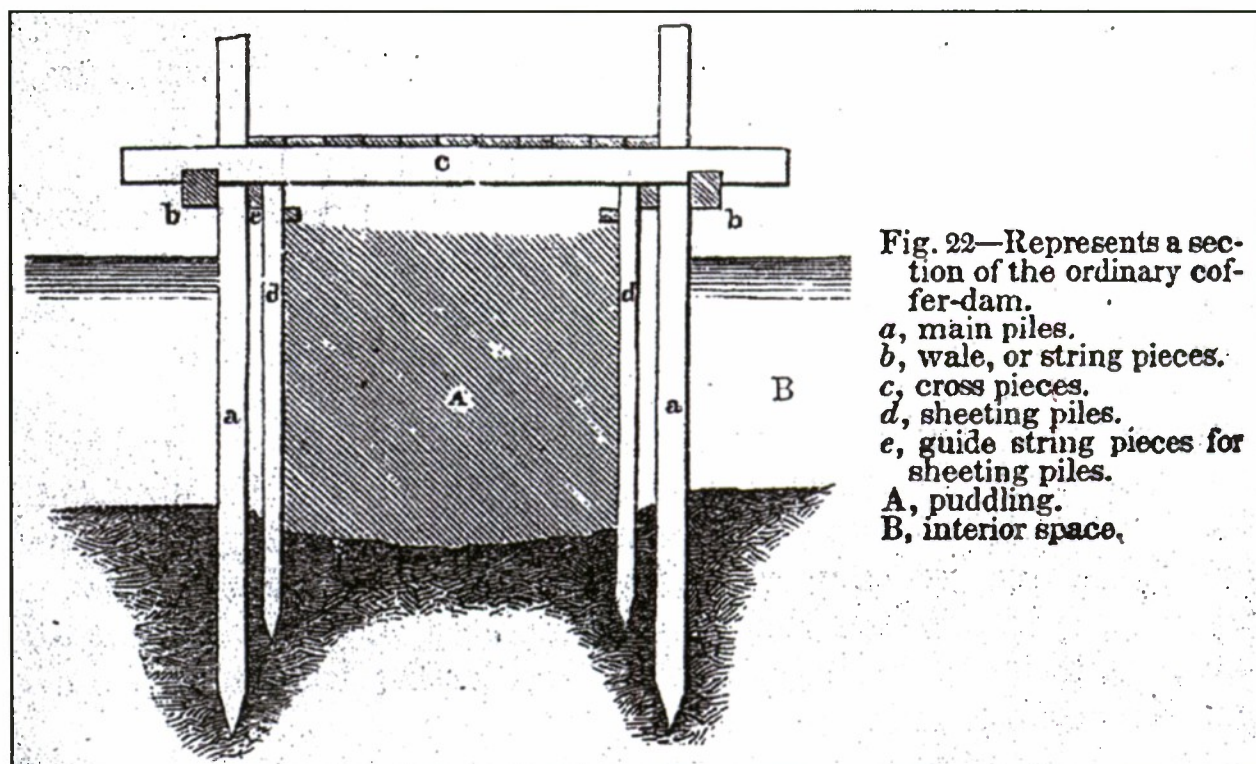


Figure 3. Section of sheet pile cofferdam. From Mahan, *An Elementary Course of Civil Engineering* (1837).

soil vertically, forming thus a coffer work, between which, clay or binding earth is filled in, to form a water-tight dam to exclude the water from the area enclosed.”⁵⁵ He carefully outlined the method for constructing this temporary structure. The work began by driving a row of ordinary piles, spaced about 4 feet apart, around the area to be enclosed. These piles were driven 4 to 6 feet into the bottom and were connected by a string course of stout timbers, termed “wales.” The wales were bolted to the inside face of each pile (the face fronting the area to be enclosed), at least 1 foot above the water surface. A second row of piles was driven parallel and outside the first, the distance between the two rows constituting the thickness of the cofferdam. For water less than 10 feet deep, Mahan recommended a dam 10 feet thick. For every additional 3 feet of depth, the thickness of the dam should be increased by 1 foot. The second row of piles also was connected by wales bolted to the side facing away from the work area. Thus, the wales at each row of piles faced away from the interior space of the cofferdam. A second string course, of smaller size than the wales, was then bolted to the piles opposite the wales. This string course functioned as a guide and support for the sheet piles that made the cofferdam watertight.

With the framework of the cofferdam complete, sheet piles were placed against the second string courses and driven 3 to 4 feet into the bottom. Mahan recommended sheet piles about 9 inches wide and 3 to 4 inches thick. After the sheet piles were driven into place, another string course was positioned against their inner face and spiked or bolted through

the sheet piles, the guide stringers, and into the main piles, securing the sheet piles in place. Notched cross pieces were laid atop the stringers, spaced 3 to 4 feet apart and spiked into place. These cross pieces connected the two rows of piling, preventing them from spreading when fill was placed between sheeting. The cross pieces also served as joists for any scaffolding or bridging constructed atop the dam.

Loose soil and mud on the bottom within the cofferdam was removed, leaving a compact surface for the placement of puddling within the space enclosed by the sheet piling. Puddling consisted of a mix of clay and sand that formed a watertight mass and prevented water from seeping through the cofferdam. Mahan recommended spreading puddling in layers 1 foot thick, compacting each layer before spreading the next. Once the puddling was in place, the water enclosed by the cofferdam was removed by pumps (dewatering).

Mahan believed there were limits to the practical use of cofferdams. He noted that they “cannot be used with economy on a sandy bottom if the depth of the water is above five feet; for the exterior water, by its pressure, will, in most cases, force its way under the puddling, so soon as the interior is freed from water.”⁵⁶ On ordinary soil or clay bottoms he believed a cofferdam would prove effective in up to 10 feet of water, though at this depth he recommended placement of a 3- to 6-foot layer of clay, overlaid by plank flooring and held in place by loose stone, below the puddling.

In situations impractical for the use of cofferdams, Mahan recommended a floating caisson. He described this as a large box with a flat bottom made of heavy scantlings laid side by side and firmly connected to each other. The bottom of the caisson would eventually serve as the bed of the foundation for the structure above. The vertical sides of the caisson were constructed of upright timbers set into a cap piece. The timbers were faced with thick planks and the seams caulked in order to make the caisson watertight. The sides were not permanently attached to the bottom of the structure and could be detached and removed once the masonry pier or foundation was complete, leaving the masonry resting atop the bottom of the caisson.⁵⁷

The descriptions of cofferdams in subsequent editions of *An Elementary Course of Civil Engineering* differed little from that of the first edition. Mahan expanded upon some of his ideas, and clarified some of his language, but the basic method remained unchanged. In the sixth edition, published in 1857, Mahan explained that the top of the cofferdam should provide space for scaffolding and derricks to be used in handling materials and machinery. He also noted that the space enclosed by the cofferdam needed to be large enough to accommodate not only the planned foundations, but also sufficient space around the foundations for the materials and machinery required for their construction.⁵⁸

Mahan also clarified and refined some of his theoretical considerations governing the design of cofferdams. He expanded upon the role that the width or thickness of the cofferdam played in providing stability to the struc-

ture, stating that the width needed to be sufficient to make the cofferdam impermeable to water and, by the weight of the puddling and the resistance of the timber frame, to form a wall capable of resisting the horizontal pressure exerted by the water outside the cofferdam. He explained that the sheet piling needed to be sufficient to resist the pressure of both the puddling, which sought to expand beyond the confines of the cofferdam, and the outside water, which sought to flow into the work area. In order to provide the necessary strength, Mahan proposed placing intermediate string pieces, buttressed by cross bracing, on the interior of the cofferdam frame, connecting the inside and outside rows of piling and creating a stiffer structure. To counteract seepage under the cofferdam, which Mahan termed the “main inconvenience,” he proposed driving the sheet piling at least as deep as the bed of the permanent foundation.⁵⁹

As a result of these refinements, Mahan significantly revised his recommendations regarding the conditions in which cofferdams could be safely employed. The 1837 edition of *An Elementary Course of Civil Engineering* called for considerable precaution in the cofferdams in water more than 10 feet deep. By the 1857 edition Mahan had determined that “with requisite care coffer-dams may be used for foundations in any depth of water, provided a water-tight bottoming can be found for the puddling.”⁶⁰ In water over 10 feet deep, he recommended use of the intermediate structural supports described above to accommodate the increased stresses resulting from the greater depth of water and the weight of the puddling.

The Potomac Aqueduct

Mahan's determination that cofferdams could be safely used in water more than 10 feet deep stemmed directly from the Corps of Engineers experience designing and constructing a series of cofferdams for the Potomac Aqueduct in the 1830s. This structure, one of the largest civil works projects of the antebellum period, measured more than 1,500 feet in length and carried the Alexandria Canal, completed in 1843, across the Potomac River in a 30-foot wide, 5-foot deep wood trough set atop eight massive stone piers (Plate 1).⁶¹

The Potomac Aqueduct was a vital link in the Chesapeake & Ohio Canal system. Begun in 1828, the Chesapeake & Ohio eventually linked Georgetown, just outside Washington, D.C., with Cumberland, Maryland. The Alex-

andria Canal provided a connection along the south bank of the Potomac between Georgetown and the port city of Alexandria, Virginia, crossing the Potomac on the Potomac Aqueduct. The Alexandria branch served as the system's principal outlet to the Potomac. The Corps of Engineers became involved in construction of the aqueduct as a result of a \$400,000 Congressional appropriation for construction of the Potomac Aqueduct.⁶²

In August 1832, Topographical Captain William Turnbull was assigned to determine the proper location of the Potomac Aqueduct Bridge, as well as its character and cost. The site of the aqueduct had been fixed in 1829 by Benjamin Wright and Nathan Roberts, engineers of the Chesapeake & Ohio Canal. Turnbull surveyed a shorter route than Wright and Roberts, which ran at exactly a right angle to the flow of the river, but political

interests in Georgetown forced the use of the original alignment.⁶³

Turnbull oversaw a series of borings for the aqueduct foundations that provided a profile of the river indicating the presence of solid rock under the entire river at an average depth of 28 feet below the average high water level. Based, at



Plate 1. Potomac aqueduct.

least partially, upon the results of these borings, Turnbull designed the aqueduct structure, seeking “the utmost stability” for the foundations and “equal durability” for the superstructure. Turnbull’s design called for 12 stone arches, supported on 11 piers and two abutments. The arches were designed to span 100 feet, with a 25-foot rise. The 11 piers included three abutment piers (every third pier) measuring 21 feet thick at the spring line of the arches, and eight support piers, each 12 feet thick at the spring line. An earthen causeway, 350 feet long, was substituted for the southernmost three arches. As a result, Turnbull modified his design to consist of eight piers (two abutment piers and six support piers), set 105 feet apart at high water.⁶⁴

Advertisements were issued for bids to build Turnbull’s design in January 1833. Turnbull and Alexandria Canal Company engineer W.M.C. Fairfax reviewed the bids and in June 1833, a contract was signed with John Martineau and A. Stewart for construction of the piers and south abutment.⁶⁵ Martineau and Stewart proposed to use a cofferdam of Martineau’s design for construction of the piers. Turnbull believed the design “incapable of being made water-tight, and insufficient to resist the pressure of so great a column of water as must necessarily pressed upon it.” Turnbull’s opinion was shared by his superior, Lieutenant Colonel James Kearney.⁶⁶ Although Martineau and Stewart’s contract stipulated that they were to work under the direction of Turnbull and Fairfax, it provided a specific sum for construction of each cofferdam, which precluded Turnbull from inter-

fering with Martineau’s plans, despite his conviction that the cofferdam design was totally insufficient.

Martineau’s cofferdam design consisted of two circular rims, 80 feet in diameter, supported one above the other by posts. The lower rim rested upon the mud at the bottom of the river, while the upper rim lay at the water’s surface. Each rim was constructed of approximately 25, 10-foot lengths of 12-inch by 14-inch pine timber simply spiked together with iron dogs. In the center of each segment was a rabbet through which a pile was driven to serve as a guide pile. This divided the circumference of each rim into 10-foot panels, which were then infilled with 11-inch thick white pine piles driven into the mud, but not to the underlying rock. In essence, Martineau’s cofferdam consisted of a single row of piles without puddling to prevent leaks and without any shoring to resist the pressure of the surrounding water and mud.⁶⁷

Construction of the cofferdam for the first pier began in September 1833, and the structure was completed in mid-November. The initial effort to pump out the coffer began on December 13, but after an hour the water inside the cofferdam had risen 8.5 inches, equal to the rise of the tide. Clearly, no headway had been achieved. Several other attempts to empty the cofferdam proved no more successful, and operations were halted for the winter. On December 21, 1833, a freshet crushed the cofferdam. Lack of action on the part of Martineau and Stewart led the Alexandria Canal Company’s board of directors to declare the contract abandoned in early January 1834. The board ordered Turnbull and Fairfax to

prosecute the work beginning in the spring of 1834.⁶⁸

Throughout the winter, Turnbull amassed equipment and materials for the spring construction season, including two, 20-horsepower steam engines mounted on floating scows. He built three pile drivers and acquired a fourth from the failed contractors. Two of the pile drivers, powered by horses, were intended for driving heavy oak piles. A lighter unit, for driving sheet piling, was worked by a tread-wheel. The pile driver acquired from the contractors was operated by a hand crank. Sixteen, 18-inch diameter pumps also were constructed. In March 1834, the circular cofferdam was removed. The piles were drawn from the bottom using derricks or shears mounted on scows.⁶⁹

In Turnbull's 1836 report to Secretary of War Lewis Cass, he noted that "[e]xperience in founding upon rock, at so great a depth, is very limited in this country, there being but one example, viz: the bridge over the Schuylkill, at Philadelphia—and that not strictly a fair example, the rock not having been laid entirely bare." Turnbull based the design of his cofferdam upon those used by Peronnet for the bridges of Neuilly and Orleans in France. But Turnbull was aware that the French cofferdams were for relatively shallow foundations that did not require excavation to bare rock, and so modified the French design. The first cofferdam undertaken by Turnbull was for the second pier north from the Virginia shore, the next north of Martineau and Stewart's failed efforts. The construction site

consisted of 18 feet of water atop 17 feet 4 inches of mud.⁷⁰

In May 1834, Turnbull began work on Dam No. 2, a parallelogram with interior dimensions of 82 by 27 feet. The inner row of piles was of white oak, 40 feet long and 16 inches in diameter. Each pile was shod with iron, pointed with steel. The piles were placed 4 feet on center and driven to rock using a 1,700-pound hammer. The piles were connected, on their inside face, with 12-inch by 12-inch pine stringers bolted through the piles. The outer row of piles, set 15 feet from the inner row, was also of white oak, 36 feet in length and 16 inches in diameter. These piles also were placed 4 feet on center, but were neither metal-shod nor driven to rock. As in the inner row, these piles were connected with a 12-inch by 12-inch pine stringer on their outside face.⁷¹

A scaffold was erected atop the stringers to support pile drivers for driving the sheet piling. The sheet piling consisted of 6-inch thick North Carolina heart pine, with the piling for the inner row measuring 40 feet in length and that for the outer row measuring 36 feet in length. The sheet piling was driven in 16-foot long panels formed by bolting a pair of 18-foot long 12-inch by 6-inch guides to a pair of sheet pile planks 8 feet above the foot of the sheet piles. This panel then was suspended above the oak piles and lowered into place, the guides sliding against the faces of the oak piles. The sheet piles were then driven into the bottom until the guides rested upon the mud. Two additional guides were then placed 1 foot above the high water mark and bolted through both the sheet piles and

the main piles. Once the panels were in place, additional sheet piles were driven between the guides to close each panel, working from the ends of the panel towards the center. The closing pile in each panel was wedge-shaped in order to affect a watertight closure. All the sheet piling for the inner wall was driven to rock. The sheet piling for the outer wall was placed in similar fashion, but was not driven to rock. This decision was based upon a desire to "husband the company's funds as much as possible." It was hoped that driving the sheet piling 12 to 15 feet into the mud would provide sufficient support for the puddling.⁷²

Turnbull's report on the progress achieved with various pile drivers illuminates the laborious nature of the construction process. A pair of 1,300-pound hammers was used to drive the sheet piles, one worked by a crank and the other by a tread-wheel. The crank unit required a crew of eight men and a superintendent and delivered a blow from the top of the 40-foot planes every 7.5 minutes. In contrast, the tread-wheel unit required a crew of six men and a superintendent and delivered a blow every 75 seconds, six blows for each blow from the crank unit. The horse-powered pile drivers used to place the principal oak pilings delivered a blow every 1.5 minutes.⁷³

Once the sheet piles were in place, 11-inch square pine timbers were installed between the two walls of piling as ties. Spaced every 12 feet, these ties were dovetailed into the sheet piling. Unfortunately, when the puddling was placed between the two walls, the weight of the material forced the outer wall, which had not been driven to rock, to spring

out, drawing the ties through the dovetails.⁷⁴ Additional ties were installed at every other oak pile, but these too failed to hold the structure together. Long screw bolts then were passed through the stringers attached to both rows of piles, additional stringers were placed outside the sheet piling, notched to the ties and bolted down, and, finally, three 14-inch square ties were placed across the top of the cofferdam to keep the long sides of the structure in place. These ties were placed by driving pairs of pilings outside the cofferdam, connecting the piles with stout pieces of timber bolted in place, and then bolting and strapping the long ties to these anchor points. Turnbull was convinced that these efforts were, at least in part, necessary because the stringers, ties and other timbers salvaged from the failed Martineau and Stewart cofferdam, were of white pine, and unable to resist the stresses placed upon them.⁷⁵

In mid-June 1834, all the oak piles for Dam No. 2 having been driven, work began on Dam No. 1, the location of the failed Martineau and Stewart cofferdam. Turnbull's experience at Dam No. 2, where the expansion of the clay puddling tended to force the inner and outer rows of piles apart, led him to place ties at every oak pile of Dam No. 1, notching the ties to the stringers and bolting them to both the stringers and the oak piles.⁷⁶

At Dam No. 2 pumping began in early September. As the water was removed from the cofferdam, three tiers of additional shores were placed against the stringers. In October, following excavation of approximately 6 feet of mud from within the cofferdam, it was discovered that several oak piles on the south

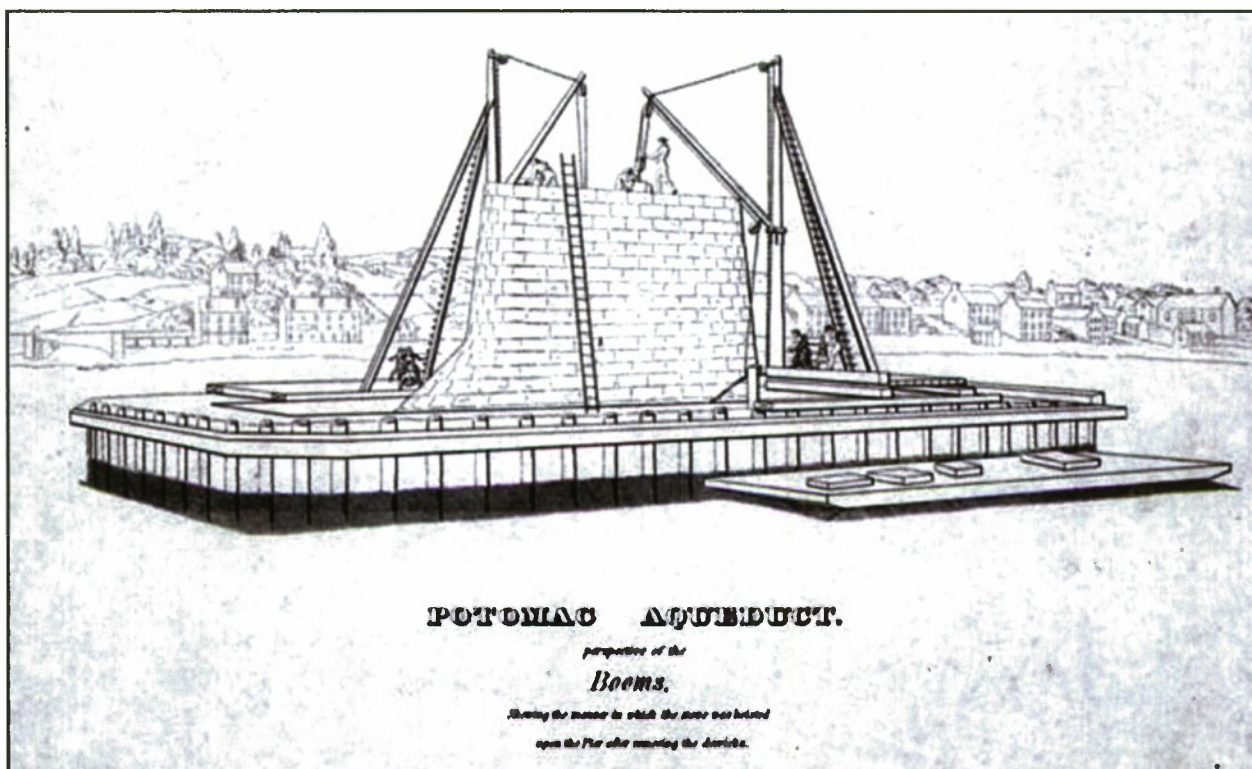


Figure 4. Potomac Aqueduct. Perspective view of pier construction showing cofferdam, 1838.

side of the structure had broken. The number of shores placed at the original surface of the mud was doubled and a fourth tier of shores was placed at the then current surface of the mud. Before this work was completed, a leak at the northeast corner of the cofferdam completely filled the structure. Turnbull attributed the leak to the fact that the sheet piles that framed each panel only penetrated 8 feet into the mud, rather than extending to rock. The pressure of the water outside the cofferdam forced itself through the gap between the rock and the bottom of the sheet piles. Once the puddling settled, the leak stopped and additional puddling was added to replace that which had settled.⁷⁷

This pattern, a major leak beneath sheet piles not driven to rock, followed by settlement of

the puddling into the resulting void, and topping off of the puddling within the cofferdam, repeated itself on several occasions. Turnbull eventually concluded that “it had now become very apparent that the whole mass of mud and sand underneath the puddling would be washed into the dam, and that, on its being replaced by the clay puddling, the dam would become tight.” Turnbull was convinced that “by perseverance, all difficulties could be overcome, and the ultimate success of the work ensured.” He and his workers persevered throughout the last months of 1834, replacing virtually all the material below the puddling. Work on the masonry pier foundations began in early January 1835, but ceased shortly thereafter when the river froze, preventing the delivery of stone to the construction site.⁷⁸

Work resumed in the spring of 1835. As the masonry was carried up, Turnbull determined that it was too dangerous to remove the lowest tier of shores, and they were incorporated into the masonry. As the masonry reached the successive tiers of shoring, the walls of the cofferdam were braced against the masonry and the shores removed (Figure 4). At Dam No. 1, which had been built to the same design as Dam No. 2, the problem of leakage presented itself earlier than anticipated, largely because the puddling placed prior to the cessation of work in early 1835 had become too compact to settle into the voids resulting from leaks and the displacement of the river bottom mud and sand. Consequently, Turnbull's crews had to soften the puddling by pumping water onto it, causing it to settle more readily, and, ultimately to remove and replace much of the material.⁷⁹

In July 1835, work began on the cofferdam for the south abutment. Turnbull's design for this cofferdam incorporated many of the lessons he had learned from his experiences with Dam Nos. 1 and 2. Turnbull believed that the inner row of oak piles were "useless" and "pernicious," since it proved nearly impossible to secure piles of precisely similar

diameters and to drive them in proper alignment. The irregularity of the oak piles, both in terms of their individual dimensions and their collective placement, adversely affected the placement of the sheet piling, leaving gaps that produced leaks. Dam Nos. 1 and 2 also demonstrated the need to drive all piles and sheet piles to rock, since nearly all the leaks occurred in areas where this had not been done.

For the abutment cofferdam, the outer row of oak piles was driven to rock and the entire interior framing, including the stringers, posts, and shores, was assembled on land, launched and floated into position, and sunk to the bottom of the river. Once positioned, sheet piles were driven on opposite sides of the frame and bolted to the frame to hold it in the correct position. The remaining sheet piles were then placed and driven to rock. This design proved effective and was em-

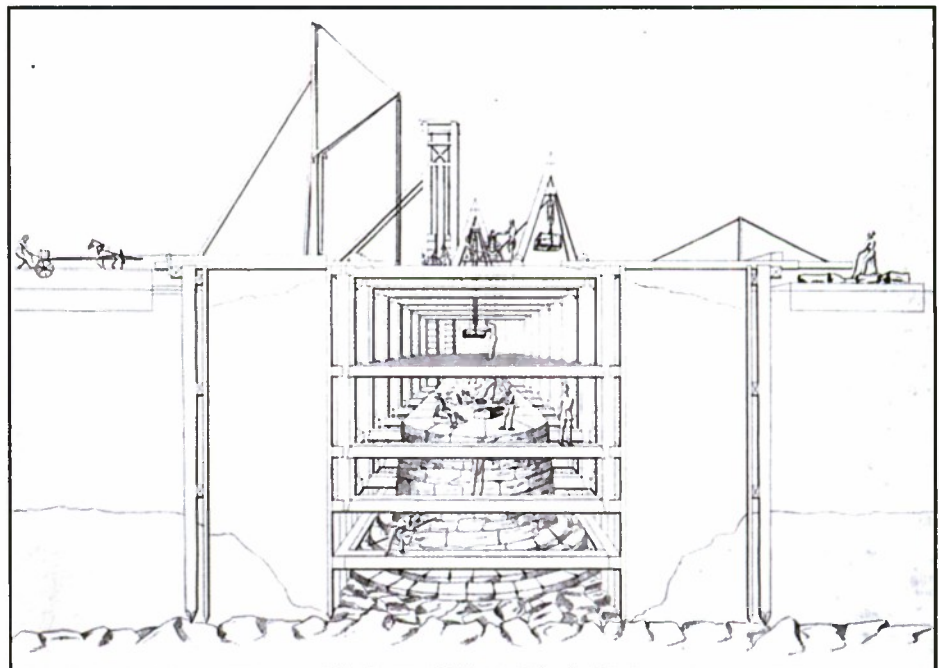


Figure 5. Potomac Aqueduct. Section and perspective view of interior of cofferdam for Pier No. 5, September 1838.

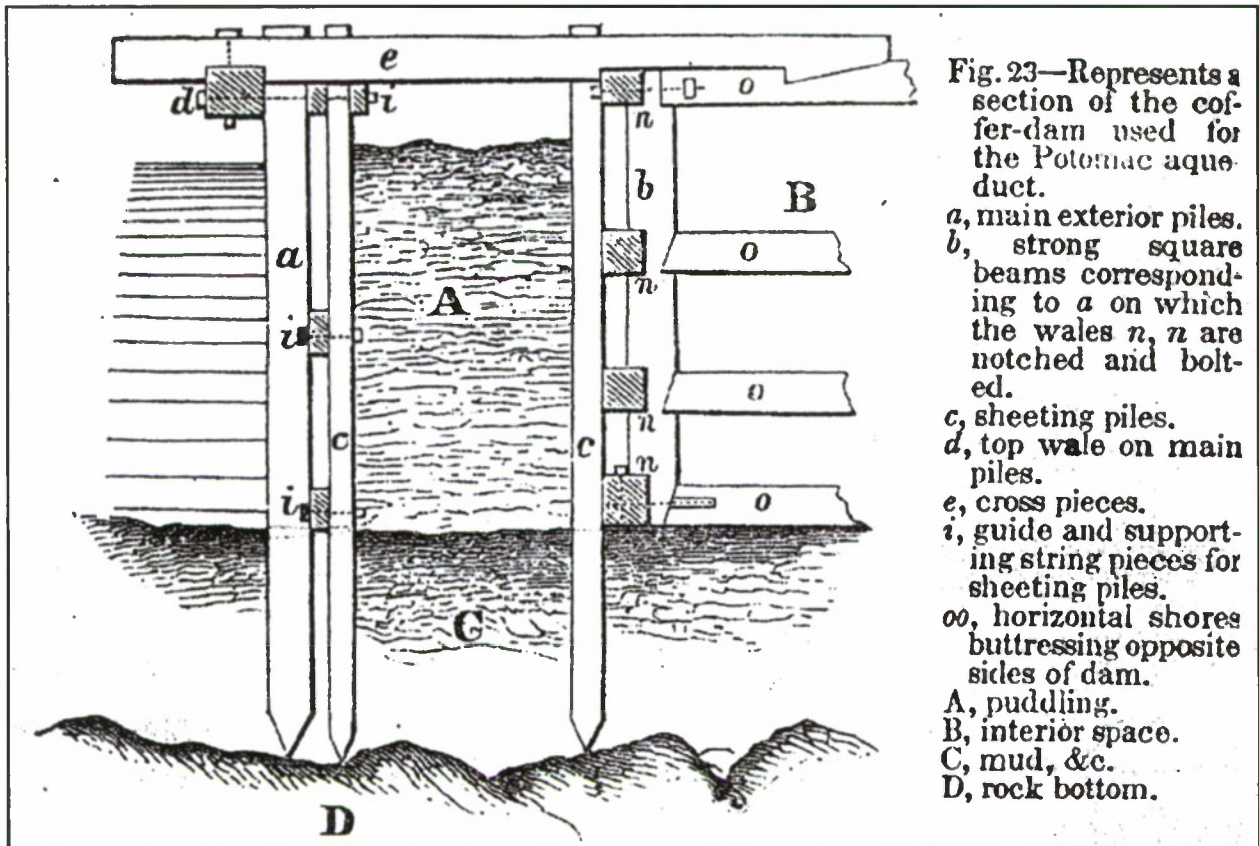


Figure 6. Section of Potomac Aqueduct cofferdam, from Mahan *An Elementary Course of Civil Engineering* (1857).

ployed, with minor alterations, for the remainder of the project (Figure 5).

Turnbull's experience on the Potomac predates the publication of Mahan's *An Elementary Course of Civil Engineering*. Instead, Turnbull employed French practice in the design of his cofferdams, but conditions on the Potomac forced him to adopt new methods and modify the French design vocabulary. His final design, with a single row of oak piles and an interior frame built on shore and floated into position against these piles and sunk in place, and with all oak piles and sheet piling driven to rock, represents adaptability to local conditions and circumstances.

This combination of reliance upon the French-based model of scientific engineering, with a practical adaptation to local circumstances, came to characterize much of the Corps of Engineers work on inland waterways. Indeed, it appears that Mahan's recognition that cofferdams could be used effectively in water more than 10 feet deep stemmed from Turnbull's experience. In later editions of *An Elementary Course of Civil Engineering*, Mahan described in detail the final design of the cofferdams used for the Potomac Aqueduct Bridge, including the horizontal shoring developed by Turnbull to resist the pressure of the puddling (Figure 6).⁸⁰

4 Cofferdams on the Inland Rivers: The Initial Corps' Projects

After a nearly two-decade hiatus, the result of sectional political discord and the Civil War, the Corps of Engineers resumed work on inland waterways in 1866. Inland navigation in the United States confronted five “great obstructions to navigation” — the Falls of the Ohio at Louisville, Kentucky; Muscle Shoals on the Tennessee River in northern Alabama; Sault Ste. Marie in northern Michigan, where Lake Superior flows into the lower Great Lakes; and the Des Moines and Rock Island rapids on the Mississippi. In the decades following the Civil War, the Corps of Engineers designed and constructed improvements at all these obstructions, greatly improving inland navigation. All these improvements, with the exception of the work conducted at the Rock Island Rapids, entailed the construction of canals to bypass the obstructions.⁸¹

Cofferdams were required, at the very least, at the entry points of these canals, but the *Annual Reports of the Chief of Engineers* rarely mentions cofferdams in the descriptions of the work conducted at the Falls of the Ohio, Muscle Shoals, or Sault Ste. Marie. Indeed, while the *Annual Reports of the Chief of Engineers* provide detailed information on the design and construction of Corps projects throughout the United States for the period from 1866 to 1900, cofferdams are rarely mentioned. Their absence from the written

record suggests that their design and method of construction were considered routine and unworthy of comment.

During this period, Corps engineers relied upon two types of cofferdam designs: traditional timber crib cofferdams and pile-supported structures similar to those described by Dennis Hart Mahan. In some circumstances construction methods departed significantly from conventional, textbook practice in order to accommodate local conditions. These construction innovations often represented intuitive, rather than scientific solutions. As a result, Corps engineers found themselves integrating the British tradition of practical experience and trial-and-error with their formal French-based academic training. This is exemplified in the work conducted at Rock Island Rapids, which was described in detail in the 1869 *Annual Report of the Chief of Engineers*.⁸²

Rock Island and Des Moines Rapids

Among the first navigation improvement projects authorized by Congress after the Civil War were those for the Des Moines and Rock Island Rapids on the Mississippi River. The Des Moines rapids, located approximately 200 miles upstream from St. Louis, consisted of an 11-mile chain of rapids with a fall of approximately 22 feet. Rock Island Rapids, located approximately 150 miles upstream from the Des Moines Rapids, had a similar

The bottom of the Mississippi River at Rock Island Rapids consisted of bare rock, with little overlying sand or gravel in which piles could be driven. Under these conditions, conventional European and American practice called for use of 2-inch to 2.5-inch diameter iron rods as substitutes for the principal support piles described by Mahan. The rods were to be placed into holes, drilled about 15 inches into the rock bottom, in two parallel rows, set about 10 feet apart from each other. The rods in each row were set every 5 feet and tied together with wood wales. The two rows of rods were connected with diagonal iron bars that braced the framework of the cofferdam and stiffened the structure. Once the iron framework was in place, sheet piling was placed in the conventional manner, and the interior of the cofferdam filled with puddling.⁸⁶ However, Charles G. Case & Company, contractors for the first Rock Island cofferdam, assumed that the weight of the structure would provide sufficient resistance to the sliding and toppling forces exerted by the river and that the structure would remain in place on the river bottom without the need for the iron framework. Captain P.C. Hains agreed to this proposal, and the first cofferdam was constructed in this manner, a departure from conventional practice.

Hains located the first cofferdam, located at the Duck Creek Chain, “without the use of instruments . . . mainly by the eye,” and Case & Company began construction on September 8, 1867, completing the 205-foot by 450-foot structure by October 15.⁸⁷ A breakwater upstream from the cofferdam protected the structure from steamboats, log rafts, ice, and floating debris. This breakwater consisted of a

series of timber cribs,, loaded with stone and sunk about 30 feet apart across the current of the river and about ten feet upstream from the head of the cofferdam. Timbers were laid between the cribs and sheathing placed along the timbers—one end spiked to the timbers and the other end resting on the bottom at an angle of 45 degrees. In addition to protecting the cofferdam, the breakwater formed a continuous obstruction to the current. The cofferdam was constructed in the eddy of calm water downstream from the breakwater.⁸⁸

The cofferdam at Duck Creek Chain consisted of a framework of 6-inch by 8-inch timbers, 16 feet in length, connected with iron tie rods. The sheet piling comprised 2-inch thick plank-ing.⁸⁹ Work began at the upper corner of the dam, which was framed and sunk into place. The timber frame consisted of two pairs of lower wall timbers, one extending downstream and the other across the current, attached by tie rods, the timbers of each pair secured to each other by the middle tie rods, and the outer ends held at the surface by a float. Rafts were positioned on each side of the line of the cofferdam and additional pairs of lower wall timbers were positioned on stringers fastened by tie rods to the floating ends. The pair of upper timbers then was attached to the fixed part of the dam and sinking planks were spiked to the pair of lower timbers nearest the fixed part of the dam at right angles to their length. The pair of timbers were sunk until the ends of the sinking planks rested upon the bottom. The upper timbers were then raised above the surface and spiked to the sinking plank. The framework created in this fashion was weighted to keep the timbers in place. Sheet piling planks were chamfered to a thin

edge at their lower end and driven to the bottom and spiked to the upper timbers. The space between the framework was then filled with puddle consisting of clay mixed with gravel. This departure from conventional practice proved effective, and was used for all subsequent cofferdams constructed at Rock Island Rapids. The size of the timbers and the thickness of the planking varied according to the depth of the water and the resulting height of the cofferdam. In deep water, three rows of stringers were used, and these were often braced from inside. In general, the upper and lower ends of the cofferdams averaged 10 feet in thickness, while the sides, constructed parallel to the current, were generally 8 feet thick.⁹⁰

Hains laid out the second cofferdam for the Rock Island Rapids improvements in June 1868 at the Moline Chain, using a theodolite to place buoys marking the location. The cofferdam was similar in design and construction to that built the year before at Duck Creek Chain. Cribbs were sunk upstream from the cofferdam and connected with timbers to form a breakwater. Because of the rock bottom, the sheet piles were chamfered "to the thickness of a shingle" and driven against the rock with mallets to form a watertight seal. Tie rods connected the longitudinal members of the frame. The cross section of the cofferdam was described as "foot for foot," it being 1 foot thick for every 1 foot of water depth. However, this calculation proved insufficient because the contractor included the dimension of the framework in his measurements, not just the puddling. As a result, failures were experienced in water over 10 feet deep. Captain Hains noted, however, that the rules formu-

lated by Professor Mahan were reliable. The completed Moline Chain cofferdam measured approximately 260 by 950 feet and enclosed 6 acres.⁹¹

In 1870, the Corps constructed an even larger cofferdam at Campbell's Chain. This structure enclosed 43 acres and measured 1,400 feet long on the upstream end, 1,740 feet on its west side, 2,000 feet on its east side, and 620 feet on the downstream end. The dam, designed and constructed as those described above, was 10 feet thick and 10 feet in height.⁹²

By the end of 1872, the Corps of Engineers, generally working with Charles G. Case & Company as contractors, had constructed ten cofferdams at Rock Island Rapids. The cofferdams, all designed and built in the fashion described, enclosed between 2.26 and 43.07 acres. They were generally constructed in shallow waters ranging from 6 to 14 feet in depth, although at Sycamore Chain, portions of the cofferdam stood in 25 feet of water. Once the water within the cofferdam was pumped out, steam drills and hand tools were used to remove the rock obstructions. When the work was completed, the cofferdams were flooded and removed, along with their protective upstream crib breakwaters, using dredges.⁹³ By July 1879, the work at Rock Island Rapids was essentially complete, with a 200-foot wide, 4-foot deep channel cut through the rock chains. Approximately \$1.2 million had been spent on the project between 1866 and July 1880, with nearly \$900,000 expended between 1866 and 1871, when the cofferdams were constructed. De-

spite the years of effort and substantial cost incurred, calls were made almost immediately upon completion of the work to widen the channel to 400 feet, since it was still too crooked and narrow to permit steamboats to pass each other.⁹⁴

Des Moines Rapids, a nearly continuous set of rapids extending for 11.25 miles just upstream from Keokuk, Iowa, presented a very different engineering challenge to the Corps of Engineers. The river bottom at Des Moines Rapids consisted of a great mass of limestone, forming a natural dam. The rapids were completely impassable at low water and even during high water presented a dangerous combination of shallow depth, swift currents, and intricate channels. The solution proposed by the Corps of Engineers, and reported to Congress in 1867, called for construction of an 8-mile lateral canal, 300 feet wide and 6 feet deep on the Iowa shore. The canal would require two lift locks and a guard lock, each measuring 350 by 80 feet. The remaining rapids would be eliminated by a program of drilling and blasting within the navigation channel, as at Rock Island Rapids.⁹⁵

Contracts were awarded for construction of the canal prism and locks in September 1867, with Charles G. Case & Company receiving some of the work. Construction of the canal required the use of cofferdams, particularly for the locks and at the entrances to the canal. These cofferdams are not described in detail in the *Annual Report of the Chief of Engineers*, unlike the innovative designs employed by Case & Company at Rock Island. This suggests that the first cofferdams at Des Moines Rapids, which were associated with the lateral canal and its locks, and which were

not built directly upon bedrock, likely conformed to Mahan's design and did not represent any innovation or departure from customary practice. In 1875, a large cofferdam enclosing 95 acres was erected for excavation of the navigation channel through the Montrose Chain at Des Moines Rapids. This cofferdam, built upon the bedrock river bottom, is also not described in detail, but by that date, the innovative methods used by Case & Company to build upon bedrock at Rock Island Rapids had been published. In all likelihood, the Montrose Chain cofferdam resembled those constructed between 1867 and 1872 at Rock Island Rapids.⁹⁶

The Corps' experience with the Montrose Chain cofferdam illustrates that these temporary structures were vulnerable to a variety of natural forces. On September 3, 1875, a little over a week after its completion, a crevice in the bedrock beneath the cofferdam led to a leak that undermined the walls and flooded the structure within 40 minutes. Five days later, on September 8, a rise in the river broke and carried away 600 feet of the cofferdam. By October 12, repairs had been completed, but on January 2, 1876 the cofferdam was again carried away by a flood. Repairs were again completed by February 7, 1876.⁹⁷

The improvements to the Des Moines Rapids were completed in 1883. The final project consisted of an 8-mile canal with an additional 4 miles of channel cut through the rocky bottom of the river. The canal opened in August 1877, and by the time the channel improvements were complete in 1883, nearly \$4.4 million had been expended on the project.⁹⁸

5 Slackwater Improvement of the Ohio River

The most important inland river navigation improvements undertaken by the Corps of Engineers in the nineteenth century were on the Ohio River. The Ohio extends for 981 miles, from Pittsburgh, Pennsylvania to its confluence with the Mississippi River at Cairo, Illinois. Prior to its improvement, the river was generally closed to navigation during the low water season that extended from July to October. Fleets of coal barges marshaled at Pittsburgh ready to take advantage of any rise in the water level.⁹⁹ The improvement of the Ohio through the introduction of a series of locks and dam that created a slackwater system, essentially turning the entire river into an enormous canal, produced a number of significant engineering designs and novel construction methods, including the Corps of Engineers' first widespread adoption of a new cofferdam design.

The earliest efforts to improve the Ohio River entailed removal of snags, rocks, and gravel and sand bars within the navigation channel. During low water stages, this channel could be as shallow as 1 foot deep between Pittsburgh and Cincinnati, and only 2 feet deep downstream from Cincinnati.¹⁰⁰ The earliest impetus for improvements resulted from commercial competition between Pittsburgh, located at the head of the Ohio, and Wheeling, West Virginia, located on the National Road. Droughts in 1818 and 1819 hampered navigation on the Ohio and spurred demand for river improvements from Pittsburgh shipping interests who feared the loss of trade

and commerce to Wheeling. Federal involvement on the Ohio began on April 14, 1820, with Congressional funding of a survey intended to determine how to improve navigation between the Falls of the Ohio and the mouth of the Mississippi.¹⁰¹

The completed survey report was submitted to Congress by Brigadier General Simon Bernard and Brevet Lieutenant Colonel Joseph G. Totten in 1822. Bernard and Totten enumerated the hazards on the lower Ohio, including the Falls of the Ohio at Louisville and 21 shoals that prohibited the passage of steamboats for five to six months of the year. As described above, Bernard and Totten recommended wing dams constructed of driven piles to narrow the channel and deepen the water over these shoals. By 1866, the Corps of Engineers had constructed 111 wing and training dikes and 47 back-channel dams on the Ohio. These structures were originally rather crude, but after 1875 they were increasingly of timber crib construction, carefully filled and paved with stone.¹⁰²

In 1866, W. Milnor Roberts was appointed superintending engineer for the Corps of Engineers' work on the Ohio. In 1870, Roberts, expanding upon earlier proposals by Edward Gay in 1828 and George W. Hughes in 1842, recommended creation of a slackwater system, comprised of an estimated 66 locks and dams, to provide a 5-foot deep channel the length of the Ohio.¹⁰³

Roberts resigned in 1870 to become chief engineer of the Northern Pacific Railroad. His replacement, Major William E. Merrill concurred with Roberts' proposal for a slack-water system. In the 1873 *Annual Report of the Chief of Engineers*, Merrill presented a case for the project. He noted that the greatest impediment to navigation on the Ohio was the lack of water. In confined places, the channel might 225 feet wide and only 12-18 inches deep. Merrill proposed a radical program of improvement to secure a 300-foot wide and 6-foot deep channel. He argued that there were only two practical ways to increase the amount of water in the river; either construct huge storage reservoirs on the headwater tributaries that could supply water to the main stream, or use a series of locks and dams to create a series of shallow reservoirs. Merrill noted that the headwater reservoir system, advocated prior to the Civil War by prominent civil engineer Charles Ellet, was entirely novel, and had never been adopted on any river. In contrast to this untried approach, the use of locks and dams represented a widely used and time-tested means of achieving slackwater navigation. The demands of the owners of the fleets of coal barges that passed downriver from Pittsburgh caused Merrill to recommend the use of movable dams. The coal fleets, as the rafts of barges were known, were huge and ponderous, and often measured 100 to 144 feet in width. The barges were bound together with cables and screw clamps and could not be disconnected without significant hazard and cost. Consequently, their owners demanded that any navigation improvements on the

Ohio include navigable passes that would permit the fleets to avoid the use of locks during periods of high water.¹⁰⁴

In 1874, Merrill recommended construction of a series of 13 locks and movable dams fitted with Chanoine wickets extending from Pittsburgh and Wheeling. The Chanoine system, invented in France, comprised a series of timber wickets, measuring approximately 3.5 feet wide and 13 feet tall, that lay on the bottom of the river when water levels were high enough to permit open navigation and, when raised to create a pool, sloped downstream, supported on an iron prop (Figure 8). Merrill recommended the use of Chanoine wickets to create a 250-foot wide navigable pass at each dam, facilitating passage of the coal fleets during high water. In 1875, Merrill recommended extending the proposed system the entire length of the Ohio.¹⁰⁵

Davis Island Lock and Dam

In 1875, Congress appropriated funds for construction of an experimental movable dam, based upon Merrill's recommendations, on the Ohio River at Davis Island, just downstream from Pittsburgh. Between 1878, when construction began, and the completion of the project in 1885, the *Annual Reports of the Chief of Engineers* contain detailed accounts of the design and construction of the lock and dam, which required a series of seven cofferdams.¹⁰⁶ The cofferdams are not described in the *Annual Reports of the Chief of Engineers*, which suggests that they were designed and constructed in conformance with Mahan's principles as outlined in *An Elementary Course of Civil Engineering*. This is scarcely

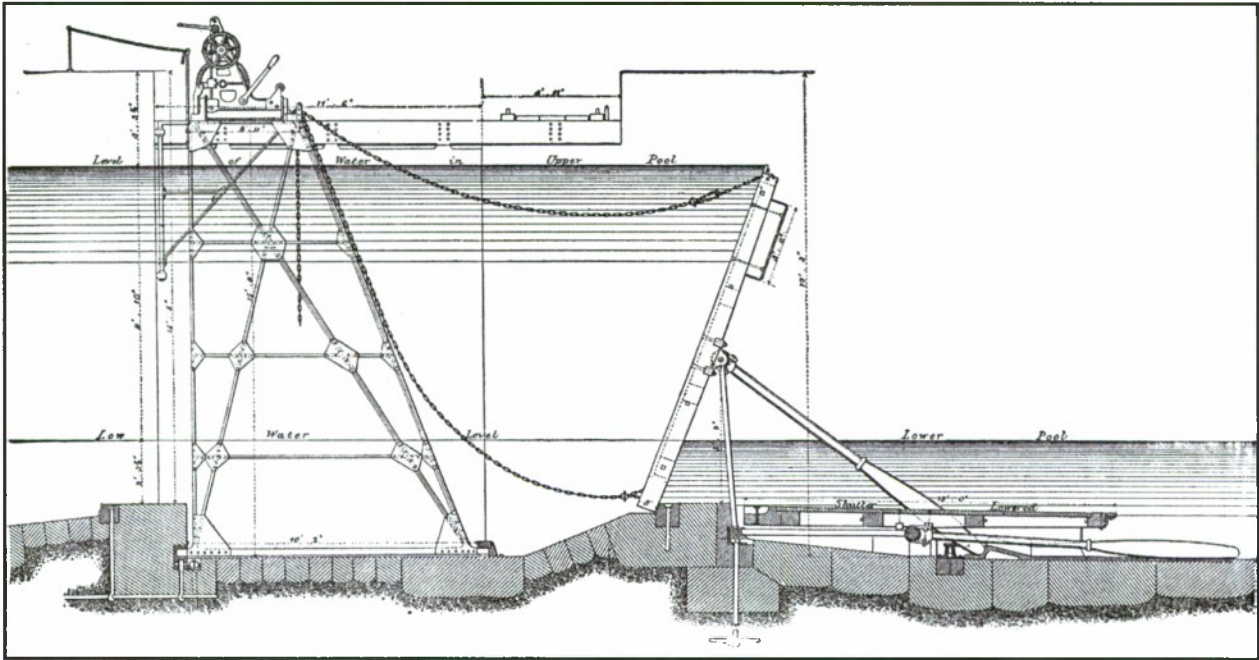


Figure 8. Section of Chanoine shutter-dam for navigable pass on the Upper Seine River, France. Figure 96 in Wegmann, *The Design and Construction of Dams* (1911).

surprising when one considers that Lieutenant Frederick A. Mahan, the resident engineer assigned to the project by Merrill, was Dennis Hart Mahan's son. An 1882 description of the cofferdam constructed for the navigable pass, published in the *Engineers' Society of Western Pennsylvania Proceedings* confirms this assumption. It is assumed that the other six cofferdams constructed for the Davis Island project were similar in design.¹⁰⁷

The navigable pass cofferdam enclosed an area of more than 3 acres immediately to the river side of the lock. The framework of the cofferdam consisted of two rows of 15-inch diameter oak piles, 20 feet in length, driven an average of eight feet into the river bottom, making the cofferdam approximately 12 feet in height. The piles in each row were placed 21 feet on center and the two rows were 15 feet 8 inches apart. Three rows of timber

stringers were spiked to the piles of each row with iron tie rods passing through the stringers and connecting the two rows of piling. Sheet piling was placed against the stringers and driven two feet into the gravel river bottom. A second row of sheet piling was placed against the first, and the joints covered with 1-inch by 6-inch battens to prevent leakage of the puddling. At the top of the sheeting, 2-inch by 10-inch stringers were spiked to each side of the sheeting, forming bearing surfaces for joists that supported a plank deck. The space between the sheet piling was filled with puddling (Plate 2). This design conforms closely to that published 45 years earlier by Mahan. Clearly, the technology of cofferdam construction had advanced little over a span of nearly 50 years.¹⁰⁸

While the design of the Davis Island cofferdams did not depart from common and

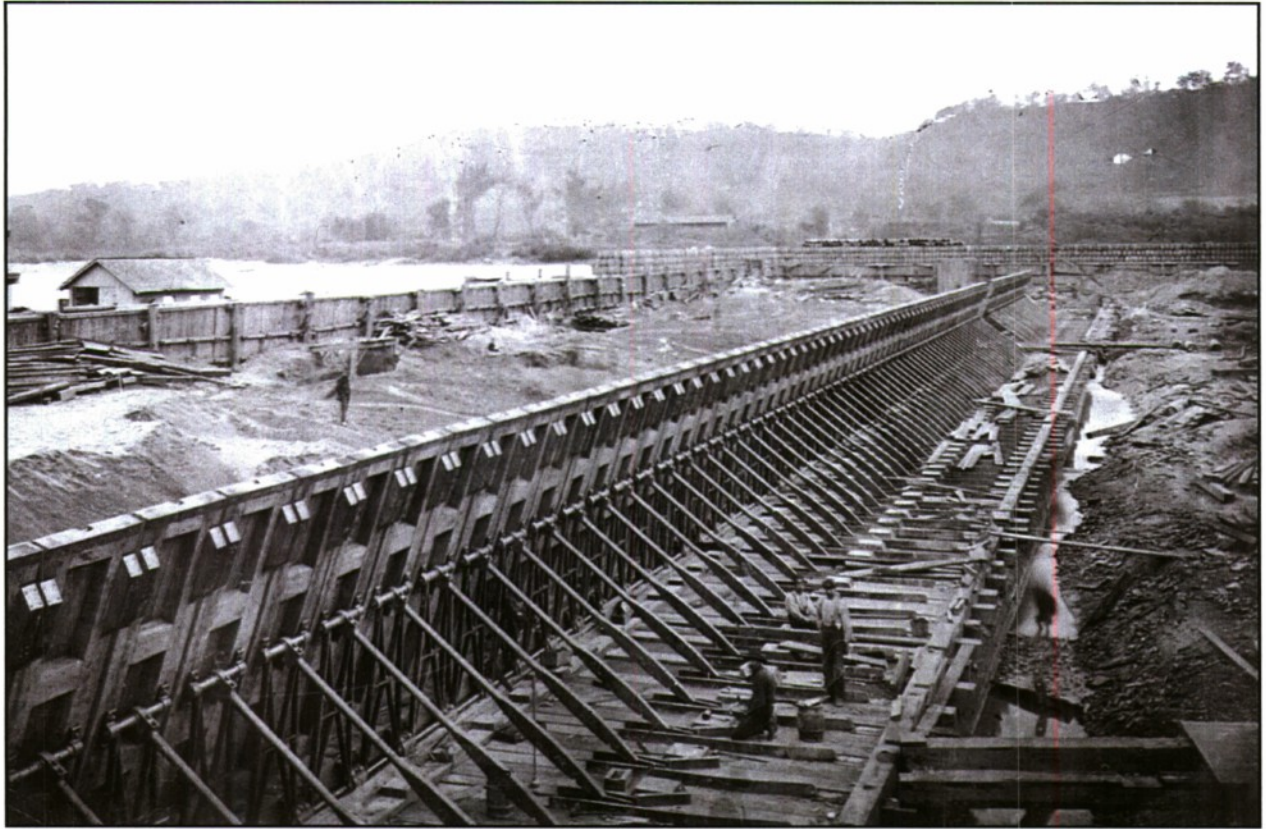


Plate 2. Davis Island Lock and Dam, Ohio River. View of Chanoine weir within cofferdam. The cofferdam is a traditional pile cofferdam, as evidenced by the heavy vertical piles and the relative absence of an interior berm. Ca. 1884. RG 77-RH, Box 124, Ohio River L/D #1 Folder, NARA.

accepted practice, the manner in which the puddling was placed within the cofferdam did represent a technical innovation. The puddling for the lock cofferdam had been placed by hand. Workers shoveled soil on Davis Island into small cars running upon a tramway. The cars were dumped into scows, which carried the soil across the river to the construction site. Workers shoveled the soil from the scows directly into the cofferdam framework. The soil was mixed with water to form puddle and tamped into place in accordance with Mahan's time-tested methods. For the navigable pass cofferdam, however, the puddle was pumped from Davis Island to

the cofferdam. A vat was constructed on Davis Island and soil was placed in the vat, mixed with water at high pressure to form puddle. The puddle was pumped, using a large centrifugal pump, through 900 feet, eventually increased to 1,400 feet, of 4-inch pipe laid on the river bottom between Davis Island and the cofferdam. The pipe sometimes clogged, and sand wore out the pump casing, but the puddle was placed without the need for handling or tamping. The system delivered 25 cubic yards per hour at an estimated cost of \$1.05 per yard, a considerable savings in time and money over hand placement.¹⁰⁹

The Canalization of the Ohio

The Davis Island Lock and Dam proved the technical and economic viability of movable dams on the upper Ohio. In 1888, Congress authorized the construction of five additional locks and dams, which would create a 6-foot deep channel from Pittsburgh to the mouth of the Beaver River. In 1899, 12 additional locks and dams were authorized, extending the 6-foot channel to the mouth of the Muskingum River (River Mile 172) at Marietta, Ohio. In 1901, an additional 20 locks and dams were authorized to extend the channel to Cincinnati. In 1905, as a result of the increasing use of larger barges that drew more water, Congress authorized a study to examine the feasibility of deepening the navigation chan-

nel to 9 feet. The resulting report recommended canalization of the entire Ohio River to a navigable depth of 9 feet. The report further recommended that those locks and dams whose pools would provide harbors for cities be constructed first. The River and Harbors Act of June 1910 adopted the recommended plan for 54 locks and movable dams between Pittsburgh to Cairo (Figure 9). This plan, somewhat modified to total 49 locks and dams, was completed in 1929.¹¹⁰

Given the 981-mile length of the Ohio, it is scarcely surprising that conditions governing the construction of locks and dams varied along the length of the river. The bottom conditions in the upper river were characterized

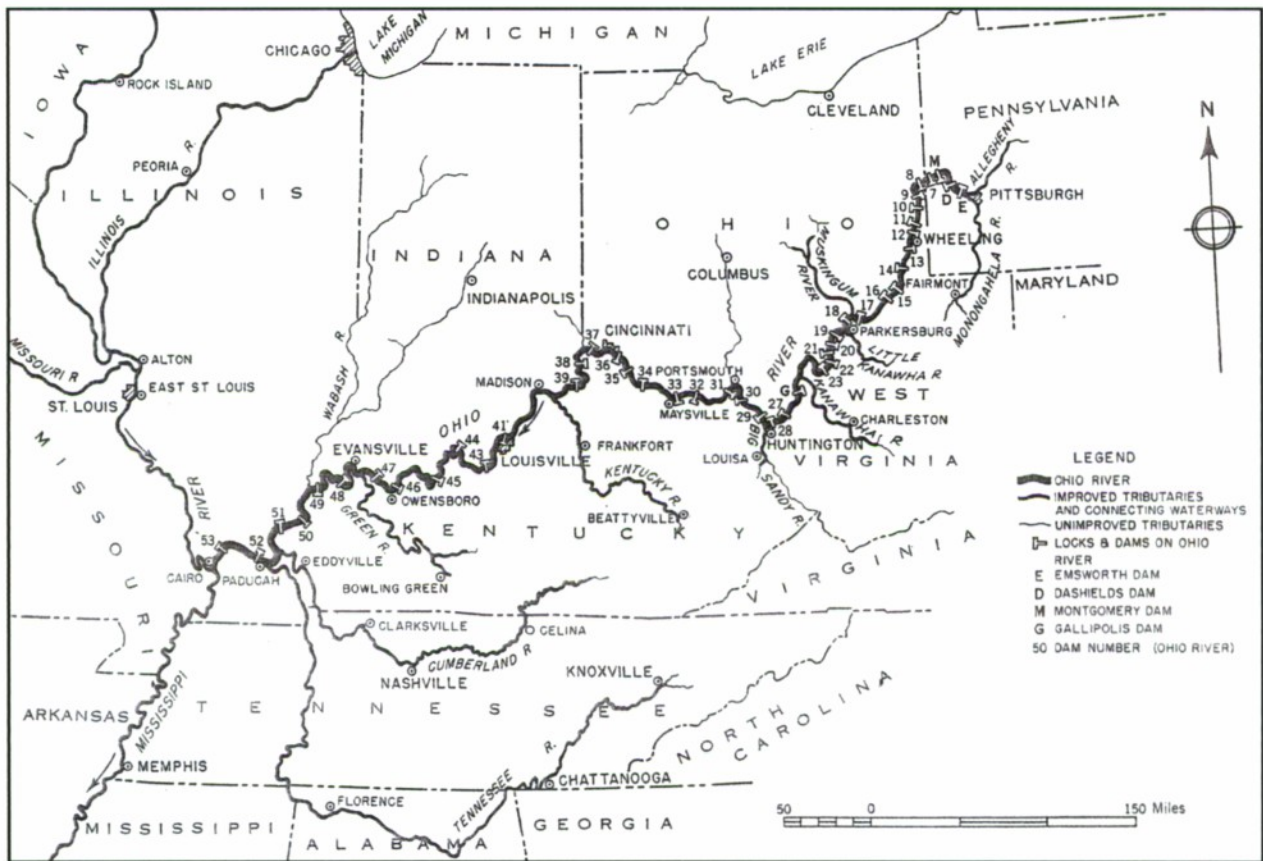


Figure 9. Map of the Ohio River system showing locations of locks and dams. From Loveland and Bailey "Navigation on the Ohio River" (1949).

by coarse gravel and boulders. As one proceeded downstream, the gravel became progressively smaller and the boulders less frequent until, downstream from the mouth of the Kanawha River, the river bottom was characterized by a sand bed, with the exception of some gravel beds upstream from the Falls of the Ohio at Louisville. The variation in bottom conditions directly affected choices regarding the design and construction of cofferdams. The ability to drive sheet piling, and the resulting watertightness of a structure, were dictated to a considerable degree, by bottom conditions.¹¹¹

In 1890, five years after completion of the pioneering Davis Island Lock and Dam, construction began on the second installation on the Ohio, Lock and Dam No. 6, located at the mouth of the Beaver River. Work began on Lock and Dam Nos. 2, 3, 4, and 5, located upstream from Lock and Dam No. 6, in 1896. Lock and Dam No. 6 opened for traffic in the summer of 1904, while the other four installations were completed in 1906 and 1907. All these installations were designed to provide a 6-foot channel. After Congress authorized development of a 9-foot channel in 1907 all five of these installations were modified in order to secure the increased depth.¹¹²

The locks and movable dams constructed on the Ohio between 1890 and 1929 were built to similar designs and employed similar construction methods. In general, they consisted of a single navigation lock, measuring 110 feet by 600 feet, fitted with rolling gates built of steel. The dams included a navigable pass

between 600 and 700 feet wide, fitted with movable Chanoine wickets, a series of bear-trap gates used to regulate the pool height, and overflow and non-overflow weirs. Support facilities included a powerhouse, operating machinery, maneuvering boat and gear, and quarters. On the upper river the dams were built on rock foundations, but downstream from Lock and Dam No. 31 such foundations proved exceptional, and the majority of the dams in the lower river were supported upon wood pilings.¹¹³

In general, each project required four cofferdams; one for the lock, one for the abutment that incorporated one section of the bear-trap foundation, one for 650 feet of the navigable pass, and one for the weir, bear-traps, and remaining 50 feet of the navigable pass. The cofferdam for the lock usually was constructed first, followed by the cofferdam for the navigable pass, and then the cofferdam (or cofferdams) for the weir. It was unusual for work on the lock to be completed in a single season, so this cofferdam generally remained in place over one winter. The cofferdams constructed for the dam generally were built and removed in a single construction season.¹¹⁴

Lock and Dams Nos. 2–6 all employed pile-founded cofferdams similar to those described by Mahan. Sometime after 1905, a new cofferdam design, known as the Ohio River type box cofferdam, was introduced and became widely used. This design represented the first major advancement in cofferdam design in more than 50 years.

The Ohio River Type Box Cofferdam

The Ohio River type box cofferdam was a modification of the pile-founded cofferdam described by Mahan. Corps' engineers believed the new design offered a more economical alternative to pile-founded structures on the upper Ohio. The design consisted of two parallel rows of sheet piling, spaced 16 to 20 feet apart, and held in position by a flexible framework. The framework resembled two parallel rail fences, each panel of which was comprised of a series of horizontal wooden wales bolted to the outside face of vertical sheet piles. At the joints between the 18- to 20-foot long panels the wales were scarfed and aligned vertically at a sheet pile, with steel tie rods passing through the wales

and the sheet pile. This created a hinged joint that allowed each panel to be pushed into the water as the barge was moved forward (Figure 10). The tie rods connected the two rows of the framework and prevented the structure from spreading. Longitudinal and cross bracing were used to prevent the framework from warping and each section was weighted to hold it in place on the bottom.¹¹⁵

Once the framework was resting on the river bottom, additional sheet piling was driven against the inside face of the framework wales, forming two parallel rows of sheet piling (Plate 3). This sheet piling was driven into the river bottom to increase the stability of the structure, but for the most part the design relied upon its weight and mass to hold it in

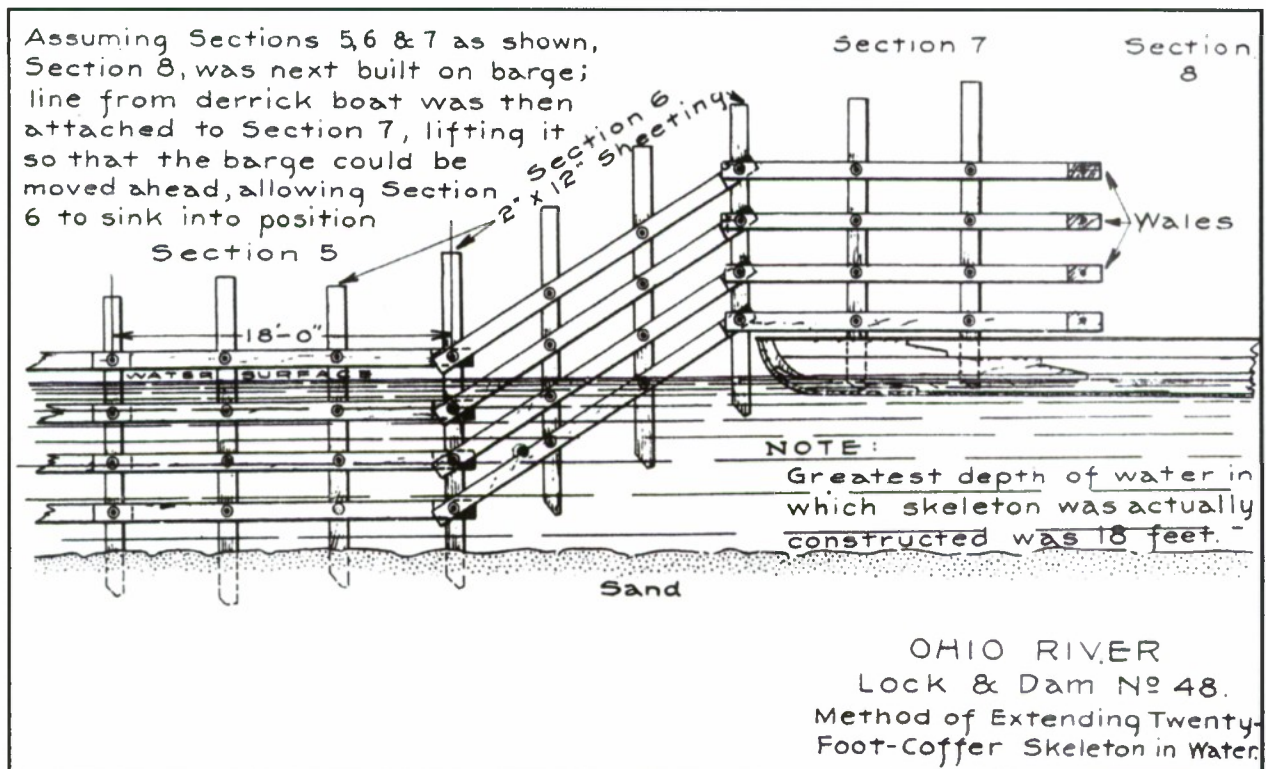


Figure 10. Use of barge to place cofferdam framework in deep water. From Oakes "Ohio River Dam No. 48" (1913).



Plate 3. Constructing lock cofferdam. Placing the sheet piling for an Ohio River type box cofferdam. Note the lightness of the construction and the men in the water. August 14, 1911. RG 77-RH, Box 127, Ohio River L/D #28 – Lock/Lock Cofferdam Folder, NARA.

place. Once the sheet piling was placed the interior of the cofferdam was filled with sand and gravel. The fill was covered with planking, or a layer of concrete, to prevent the fill from washing out in high water and to serve as a working platform. A sand and gravel berm was placed against the inner and outer faces of the structure to increase its stability and deter leakage (Figure 11). It often was necessary to place riprap around the corners of the cofferdam to prevent scour, a condition that results from the increase in the velocity of the current that results when a cofferdam,

or other obstruction, is placed within a stream, constricting the space through which water may flow. The increased current velocity can erode the stream bed, particularly if the bed is comprised of sand, silt, or clay. This erosion can jeopardize the stability of a cofferdam by undermining its foundations.¹¹⁶

The need for berms inside and outside Ohio River type box cofferdams required that the structures be built a considerable distance from the foundation work they protected. This distance varied, based upon the compo-

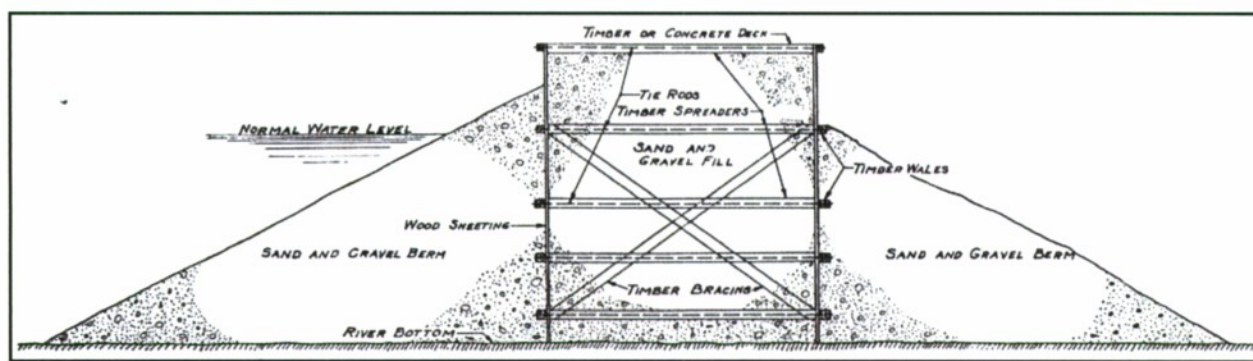


Figure 11. Typical section through Ohio River type box cofferdam. From Dravo Corporation *Locks and Dams* (1947).

sition of the soil used for the berms. In the Pittsburgh vicinity, the material used for berms would stand on a slope of 1:2, or 1:3, while on the lower reaches of the Ohio a slope of 1:5, or 1:6 was required because the downstream river bed contained less gravel and more sand. Consequently, a cofferdam on the upper Ohio could be built closer to the permanent work than one located between Louisville and Cairo.¹¹⁷

The width of the required berm also necessitated the use of construction plants, a floating plant outside the cofferdam and a land plant inside the structure. This doubled the amount of machinery and equipment required and, if it proved necessary for the cofferdam to remain in place for more than one construction season, necessitated removal of the inside plant during the four- to eight-month high water season when the cofferdam was flooded.¹¹⁸

It is unclear when the Ohio River type box cofferdam was first introduced. The *Annual Report of the Chief of Engineers* for 1894 describes work conducted by First Lieutenant Hiram M. Chittenden at the Falls of the Ohio that may represent the first use of the design.

Chittenden was responsible for construction of a new canal basin at the head of the locks and intended to use a cofferdam to remove a ledge of rock, as had been done at Rock Island Rapids. The work required closure of the busy canal for ten days. In order to minimize the length of the closure, Chittenden built the framework of the cofferdam “on a barge ready to be launched into place as soon as the canal was closed to traffic.”¹¹⁹

Box type cofferdams were used in 1905 for the navigable pass cofferdam at Lock and Dam No. 18, and in late 1910 for the lock cofferdam at Lock and Dam No. 9. However, published descriptions of this work did not appear until 1923 and 1915, respectively, and these descriptions do not specifically identify the structures as Ohio River type box cofferdams. In 1913, Major J.C. Oakes published the first known description of the design and construction of a “Ohio River box type” cofferdam, constructed in 1912 for the lock site at Lock and Dam No. 48 (Figure 12). Oakes’ casual designation of the structure as an “Ohio River box type” cofferdam suggests that the design was in use, and known by this designation, prior to 1912.¹²⁰

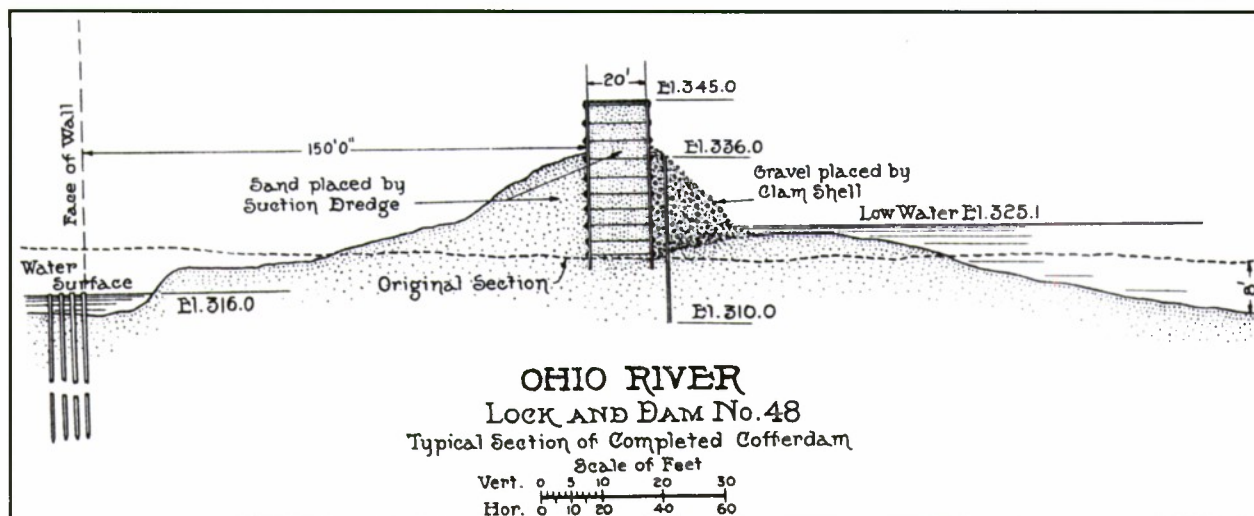


Figure 12. Ohio River Lock and Dam No. 48. Section of 1912 cofferdam. From Oakes "Ohio River Dam No. 48" (1913).

It is clear that the Ohio River type box cofferdam was in widespread use on the Ohio prior to the 1913 publication of the second edition of the massive two-volume *The Improvement of Rivers: A Treatise on the Methods Employed for Improving Streams for Open Navigation*. Written by B.F. Thomas and D.A. Watt, both officers in the Corps of Engineers, the work is a virtual handbook on river construction designs, methods, and techniques, and includes a detailed description of the design.¹²¹

Local conditions and circumstances continued to play a major role in determining the type of cofferdam selected for any given project, even after the adoption of the Ohio River type box cofferdam. At Lock and Dam No. 18, located between Parkersburg, West Virginia and Marietta, Ohio, at River Mile 178, a crib cofferdam, founded upon bedrock, was built in 1903-1904 for construction of the lock. The crib design permitted the cofferdam to be constructed within 10 feet of the lock masonry, facilitating the transfer of materials

into the work area. A box cofferdam, with its associated berm, would have placed the top of the cofferdam some 40 feet from the lock masonry, greatly complicating the movement of materials.¹²²

A pile-founded cofferdam, similar in design to that described by Mahan, was constructed in 1909 for the navigable pass at Lock and Dam No. 37, located opposite Fernbank, Ohio, 12 miles downstream Cincinnati. The largest of the dams built to that date, the pool behind the dam extended 23 miles upstream, improving the harbor at Cincinnati. The cofferdam consisted of two rows of piles, spaced 22 feet apart, with the piles in each row spaced 6 feet apart. On the inner side of each row, lines of waling timber were attached, and a single row of tongue-and-groove Wakefield sheet piling was placed against the waling (Figure 13). Tie rods were placed across the top of the enclosed space and secured by nuts to the outside of the piles. The 20-foot wide space between the rows of sheet piling was filled with dredged gravel and sand and

covered with a plank floor to prevent the fill from washing out in high water. Leaks in the sheet piling generally were controlled by the

silt in the river water, which filled gaps and spaces and choked off any leaks. Dredged material was banked against both walls of sheeting to prevent water from percolating through the river bottom and into the work area. In some places, the outside berm was paved with riprap to prevent scouring by the current. Additionally, a series of 16-foot square, stone-filled cribs, rising 18 feet above low water, as well as a row of three-pile clusters spaced 15 feet apart and bound with wire cables, were placed upstream from the cofferdam to protect it from ice and other drift.¹²³

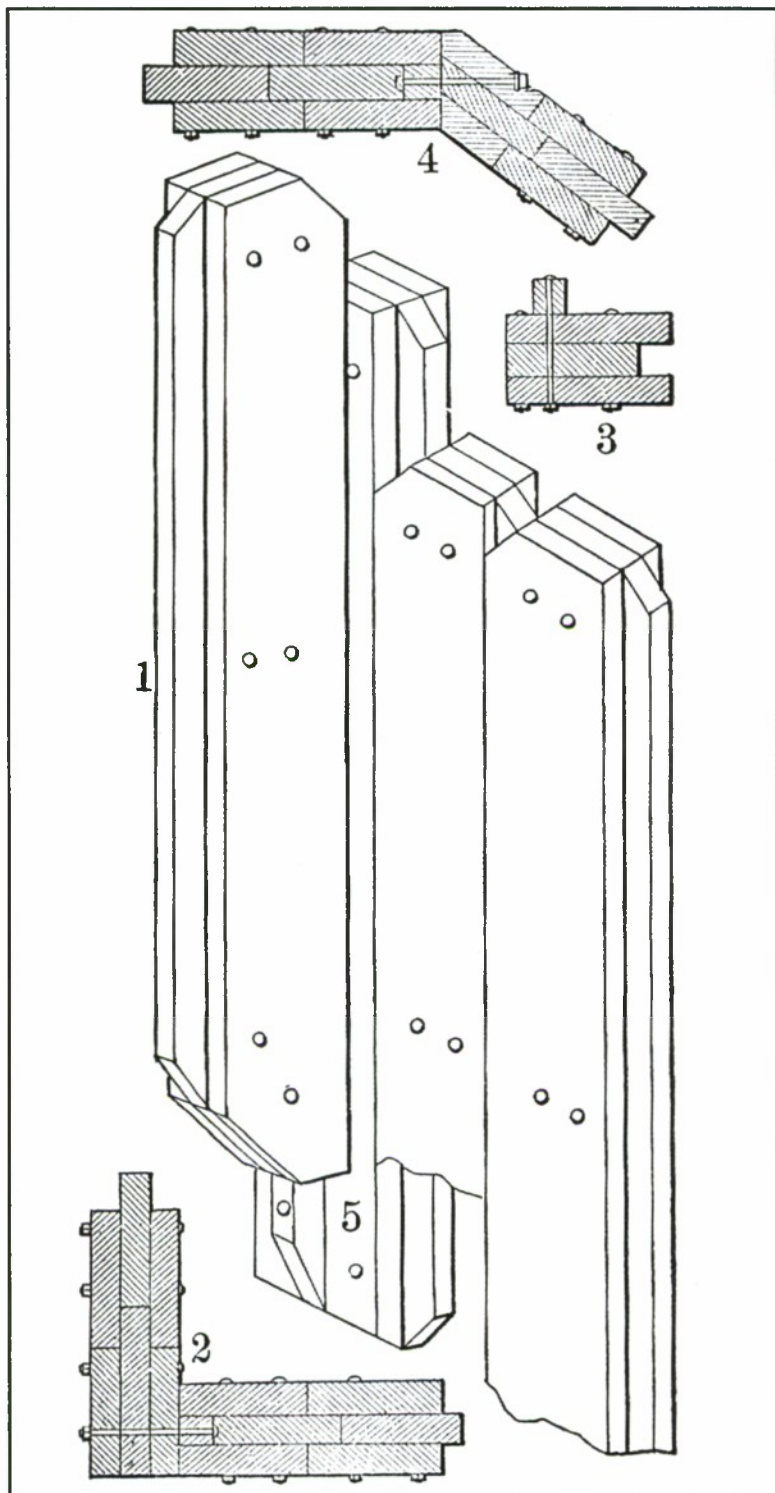


Figure 13. Wakefield sheet piling, showing joint formed from three planks. Figure 131 in Wegmann, *The Design and Construction of Dams* (1911).

At Lock and Dam No. 18 the contractor opted to use a box cofferdam for construction of the navigable pass in 1905. A written description of this cofferdam, published in 1923, does not identify it as an Ohio River type box structure. The account makes no mention of the articulated joints that permitted the framework to be placed continuously from a barge, the defining feature that distinguishes the Ohio River type from other box cofferdams. The cofferdam for the navigable pass rose 18 feet above low water, and was designed to withstand river stages of 14 to 16 feet. It failed when overtopped by a flood, and later analysis indicated that it was only effective at stages of 8 to

10 feet. The government constructed the weir cofferdam, a box type structure, using material salvaged from the lock and pass cofferdams. This structure performed somewhat better than the pass cofferdam, proving effective at river stages up to 12 to 14 feet.¹²⁴

Box type cofferdams were employed in late 1910 for construction of the lock at Lock and Dam No. 9, located at New Cumberland, West Virginia, about 55 miles downstream Pittsburgh, and in 1911 for the lock at Lock and Dam No. 19 were located at Little Hocking, Ohio, about 5 miles downstream from Parkersburg, West Virginia. Neither of these structures is identified as an Ohio River type box cofferdam.¹²⁵

At Lock and Dam No. 9, the National Contract Company of Evansville, Indiana, erected a box type cofferdam rising 16 feet above low water and measuring 20 feet thick. The cofferdam consisted of inner and outer faces constructed of 2-inch sheet piling braced by 6-inch by 6-inch and 6-inch by 8-inch wales spaced 5 feet above each other and tied across the cofferdam with rows of tie rods spaced 5 feet above each other. Spreaders, measuring 3 by 4 inches and 20 feet in length, held the sides of the cofferdam apart, while 2-inch by 10-inch cross bracing stiffened the bents at the ends of the wales. The cofferdam fill consisted of gravel and sand dredged from the lock site. Narrow gauge railroad tracks laid atop the upper and lower arms of the cofferdam facilitated the placement of concrete from two concrete mixing plants.¹²⁶

The lock cofferdam at Lock and Dam No. 19, erected in 1911, measured about 20 feet in

height and 16 feet thick. Two rows of guide piles, spaced about 18 feet apart, and about 16 feet apart within each row, were driven 4 feet into the gravel bottom. Four lines of 6-inch by 8-inch waling were spiked to the piles and 2-inch sheet piling driven a slight distance into the bottom and spiked to the wales. Tie-rods passed through the wales and connected the two sides of the structure. Earthen berms, with a slope of 1:2 were placed against both the inside and outside faces of the cofferdam.¹²⁷

As noted above, the first documented Ohio River type box cofferdam was erected in 1912 at Lock and Dam No. 48, located on the lower Ohio 6 miles downstream from Henderson, Kentucky. The construction of a successful cofferdam at this site was particularly significant given the river bottom conditions. All the locks and dams constructed prior to No. 48 enjoyed "fairly firm foundations, most of them being on rock and a few on gravel."¹²⁸ However, downstream from Louisville the character of the river bottom changed dramatically. Thirteen dams were planned for the lower 400 miles of the Ohio and rock foundations were available at only three of these sites. The remainder required foundations constructed atop fine sand and silt, so fine that the river bottom changed with every stage of the river. These conditions created a concern over both the long-term stability of the works and the ability of the cofferdams to withstand scouring and erosion of the river bed. Corps engineers noted that:

...it has been openly affirmed by some of the contractors who have had ex-

*perience on the Ohio River that it would be impossible to construct coffer-dams in the shifting sands of the lower river that would remain during the period of construction, and, second, that if constructed they could not be made sufficiently impervious against seepage to withstand ordinary pressure heads, and that they could not be pumped out sufficiently to enable the work to proceed.*¹²⁹

The Ohio River Contract Company, the only bidder for the work, constructed the cofferdam for the lock, which enclosed 20 acres, in 1912. Work within the cofferdam ceased for the winter on December 31, 1912, and in January 1913 the works were submerged by a flood, with no particular damage to the cofferdam. This experience “proved that safe coffer-dams can be constructed, maintained, and pumped out without undue trouble at the sites in question as well as in other parts of the river where better foundations exist.”¹³⁰

The lock cofferdam was an Ohio River type box cofferdam, built 150 feet away from the permanent works and enclosing about 20 acres (Figure 14). The lock was located on the Indiana side of the river, with the river wall of the lock at approximately the low water line. This meant that the upstream and downstream arms of lock cofferdam extended into the bank. The cofferdam rose 20 feet above low water and measured 20 feet thick.¹³¹ The structure consisted of two rows of sheet piling tied together with steel rods and timber wales. The construction of those portions of the cofferdam located on land began with the driving of parallel lines of

sheet piling. After the driving began, trenches about 2 feet deep and 20 feet apart were dug parallel to the sheet piles. In these trenches, the framework of the cofferdam was erected. This consisted of timber wales and the pieces of sheeting through which the tie rods passed, the sheeting being driven about 2 feet into the sand. All the wales were scarfed for 2 feet at each end, and bored through the center of the scarf to accept the tie rods. Where the tie rods were spaced 8 feet apart, the wales were 18 feet long, and where the tie rods were spaced 6 feet apart the wales were 20 feet long, thus allowing a 2-foot overlap at each end of the wales. A 20-foot long temporary separator was placed perpendicular to the wales at each tie rod. The remainder of the sheeting was then driven, and after the proper cut-off elevation was marked, the ribbing strips were spiked on and the sheeting cut off to grade. Gaps between adjacent sheet piles were closed with 1-inch by 3-inch battens nailed to the inside of the sheeting. After the sheeting was cut off to the proper elevation, deck joists were spiked to the ribbing strips.¹³²

When the work extended into deep water, the framework for the cofferdam was assembled on a barge, and as each section was completed, it was lifted into the water by a derrick and the barge moved forward prior to placement of the sheet piling by crews standing on the wales of the framework. Bulkheads were built across the interior of the cofferdam at “convenient intervals” and, as the cofferdam was filled, the temporary separators were removed and reused. The space between the rows of sheet piling was filled with sand from within the cofferdam using a 10-inch suction

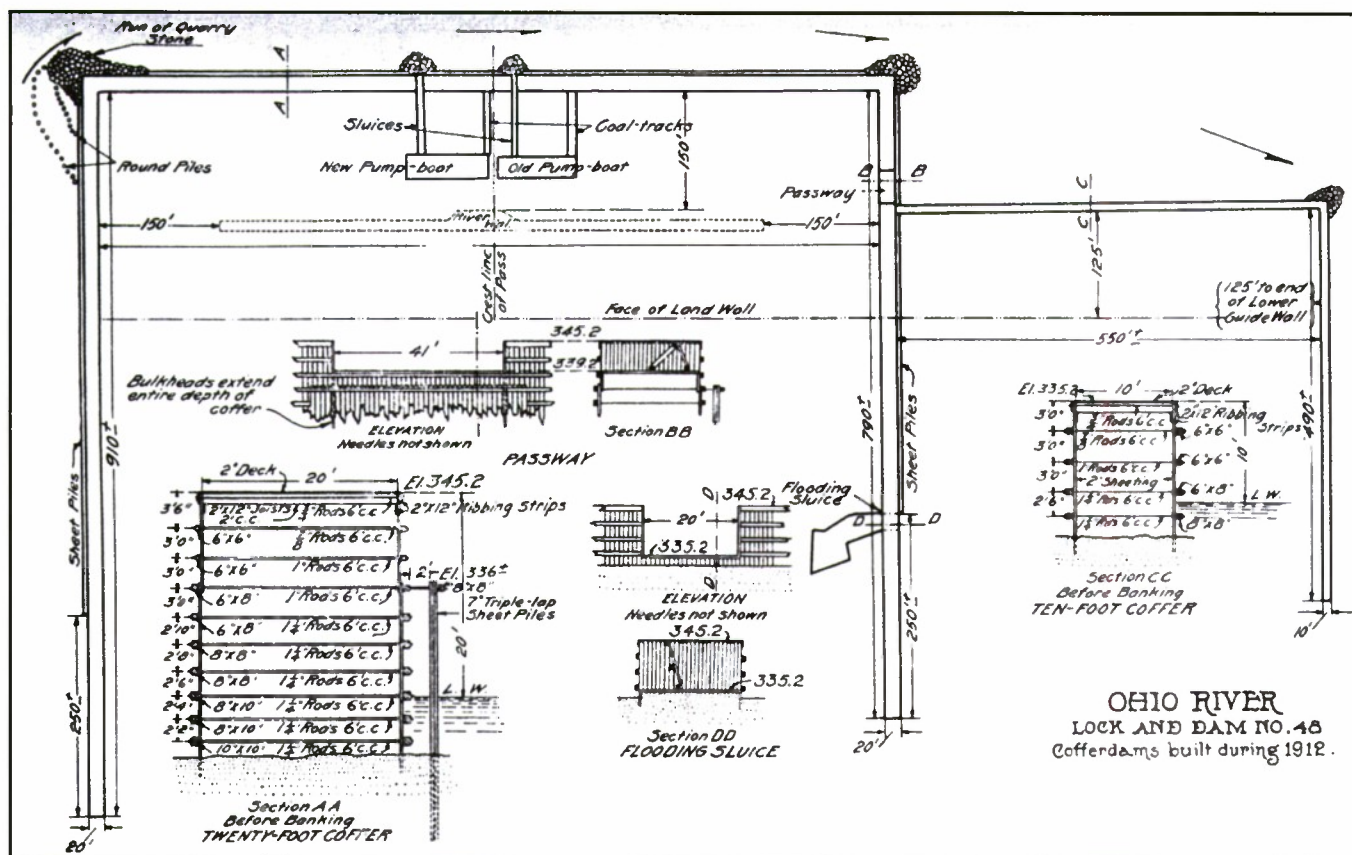


Figure 14. Ohio River Lock and Dam No. 48. Plan of 1912 cofferdam. From Oakes "Ohio River Dam No. 48" (1913).

pump. The inner and outer faces of the cofferdam were heavily banked with sand berms. During construction the framework was extended an average of 38 feet per day, or two wale lengths.¹³³

To increase the stability of the structure and to reduce seepage through the porous river bottom, a line of 26-foot long, 7-inch by 12-inch Wakefield sheet piles was driven around the outside of the cofferdam and bolted to the main structure. Once dewatered, seepage into the work area was controlled using three 15-inch pumps. Both the upstream and downstream outer corners of the structure, considered the areas of greatest weakness, further were protected by clusters of 50 piles driven off the corner. The area

between the piles was filled with brush weighted with sandbags topped by quarry stone riprap piled as high as the top of the cofferdam.¹³⁴

The Ohio River type box cofferdam remained the standard design for the locks and dams constructed on the lower Ohio until the completion of the canalization project in 1929. Lock and Dam No. 53, located about 20 miles northeast of Cairo, Illinois, between Grand Chain and Olmstead, Illinois, was one of the last of the movable dams constructed on the Ohio. Work began on the project in 1924 and was completed in 1929. The river measured more than a mile in width at this location, and bottom conditions required that both the lock and dam be pile-founded structures,

with their concrete foundations poured atop a series of wood piles driven to refusal. Construction of both the lock and dam took place within standard box cofferdams similar in design to those first introduced at least a decade earlier.¹³⁵

Other Ohio River Innovations

In addition to the development of the Ohio River type box cofferdam, the canalization of the Ohio River resulted in other innovations in in-river construction methods. Some of these innovations represented responses to a specific set of conditions and were replicable only in a very limited number of circumstances, while others had more widespread utility.

Lock and Dam No 41 – Incorporation of Existing Structures into a Cofferdam

The canal and locks at the Falls of the Ohio at Louisville, Kentucky, constituted Lock and Dam No. 41. As improved in 1873, the canal measured 86.5 feet in width with twin locks measuring 348 feet long and 80 feet wide. By 1910, these facilities were too small to accommodate the standard coal tows comprised of 15 to 20 barges, each measuring 130 feet long and 24 feet wide, and tow boats averaging 175 feet in length and 26 feet in width. The small size of the locks necessitated that the tows be broken apart and no more than two tow boats or six barges locked through at one time. The canal and locks at Louisville, the most modern on the river, and among the largest in the world in 1873, had become a choke point, slowing traffic to a crawl. To improve the capacity of the canal and locks

and to standardize the locks with those on the remainder of the Ohio, it was determined to construct a new single lift lock, measuring 600 feet by 110 feet, alongside the two existing locks, and to widen the canal to 200 feet between perpendicular walls.¹³⁶

Work began on widening the canal in 1913. The excavation between the old and new canal walls was to be done in the dry behind the old wall, which served as the cofferdam between the new wall excavations and the existing canal. This allowed the work to proceed without interrupting navigation. Once the new canal wall was complete, the old wall and the rock upon which it rested were to be excavated in the wet. The old canal wall measured approximately 7 feet tall and was constructed of cut sandstone, laid with headers and stretchers, laid atop the limestone rock ledge. On October 5, 1915, approximately 720 feet of the rock ledge and sandstone canal wall failed, collapsing into the work area. The pressure of the water had moved the 8-foot wide rock ledge and the sandstone canal wall keyed into the top of the ledge. The Corps engineers concluded that the friction of rock upon rock did not provide safety against sliding, particularly when one rock was stratified limestone.¹³⁷

Caissons

Dravo Corporation received two separate contracts for construction at Lock and Dam No. 32. The site was located at River Mile 381.7, 4.6 miles downstream from Vanceburg, Kentucky. The lock, contracted in 1919 and completed in 1922, was constructed within a typical Ohio River type box cofferdam, and was

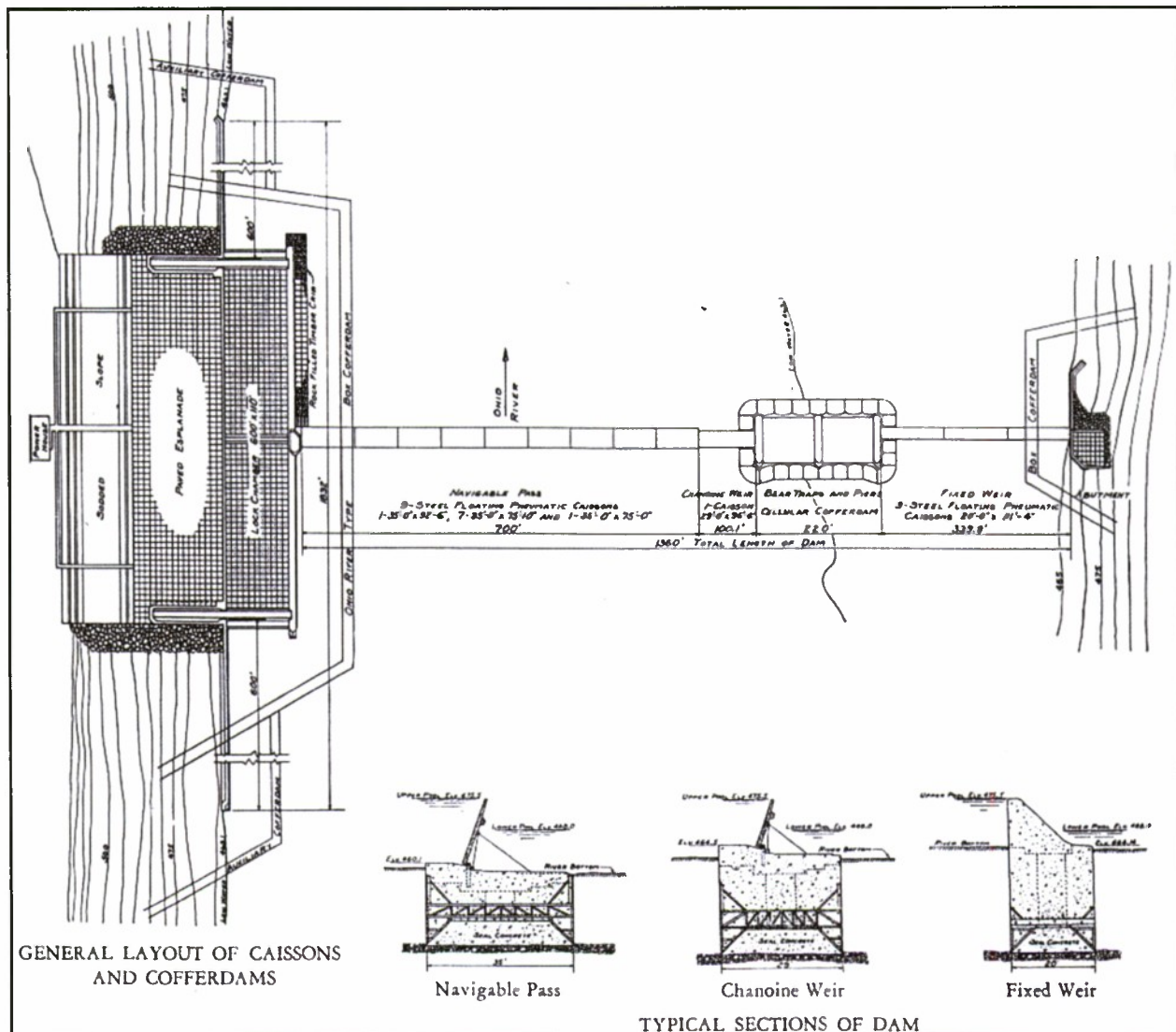


Figure 15. Ohio River Lock and Dam No. 32. General layout of caissons and cofferdams with typical sections, 1919-1922. From Dravo Corporation *Locks and Dams* (1947).

founded upon wood piles driven to refusal. For the dam, contracted in 1922, the Corps of Engineers requested alternate bids for a pile-founded structure and for carrying the dam foundations to rock by means of pneumatic caissons (Figure 15).¹³⁸

Thirteen pneumatic steel caissons were designed, fabricated, and assembled by Dravo's Engineering Works Division in Pittsburgh and towed 372 miles to the dam site. The steel caissons measured between 75 and 111

feet in length and between 20 and 35 feet wide (Figure 16). The first caisson was sunk adjacent to the river wall of the lock. Excavation was accomplished by open dredging with orange peel buckets until the caisson sank to an elevation close to rock. Air locks then were attached to the dredging tubes, compressed air introduced, and the sinking continued through compact gravel and boulders until the caisson reached a depth about 4 feet below where rock was expected. At about 10 feet below this grade, fire clay was encountered,

and borings indicated that this material extended another 35 feet. In the absence of a rock bottom, the first two caissons were carried to the fire clay and sealed. The Corps of Engineers then determined to stop the remaining caissons at the strata of compact gravel, where borings had indicated rock would be found. Given these circumstances, additional protection of the dam foundations was attained by depositing riprap against the downstream face of the foundations.¹³⁹

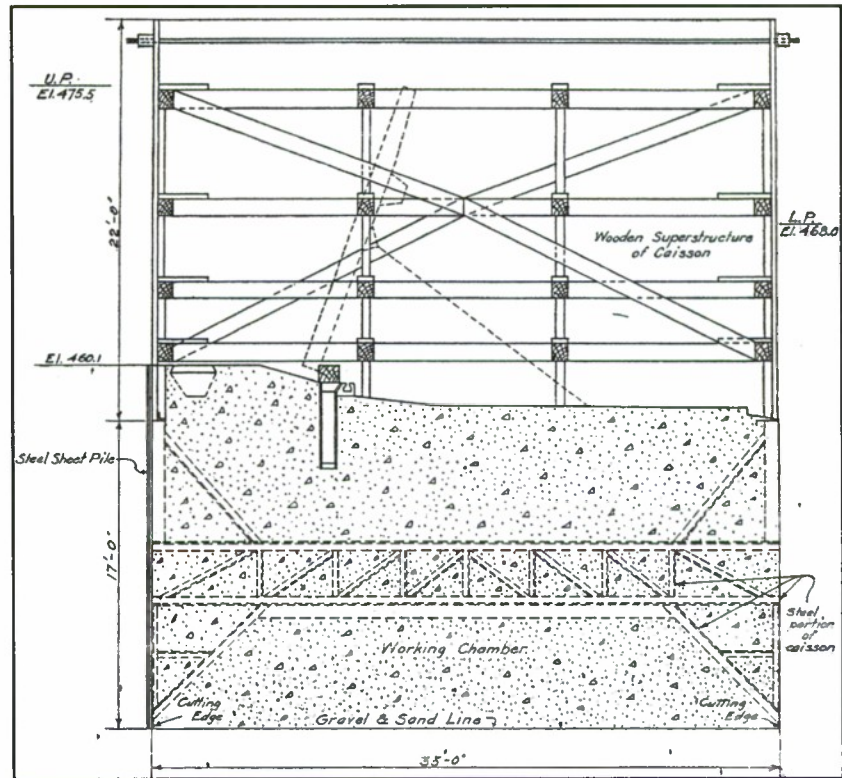


Figure 16. Ohio River Lock and Dam No. 32. Section through navigable pass showing steel floating caisson with attached cofferdam, 1919-1922. From Dravo Corporation *Locks and Dams* (1947).

6 Canalization Projects Prior to World War I

While the Corps of Engineers' major inland river improvement efforts prior to 1930 were concentrated on the Ohio River, the agency also worked on a number of Ohio River tributaries, the Mississippi River headwaters, and several Mississippi tributaries during this period. The earliest of these projects involved rivers where state governments or private firms previously had initiated improvement campaigns. Few of the projects entailed any significant innovations in the design, construction, or use of cofferdams. The following sections discuss the nature of the improvements on various streams and the cofferdam designs and methods employed for these projects, and explores the manner in which innovations in design and construction were disseminated and transferred from one region to another. To avoid confusion, the discussion is organized by tributary, proceeding downstream from the headwaters of the Ohio and then downstream from the headwaters of the Mississippi, rather than chronologically.

Monongahela River

Beginning in the 1830s, the private Monongahela Navigation Company (MNC) constructed a series of seven locks and dams that provided a 5-foot navigation channel from the mouth of the river at Pittsburgh upstream to the Pennsylvania state line. In 1883, the year this system was completed, and two years before completion of Davis Island Lock and Dam on the Ohio, the federal government sought to attain control over the MNC's facilities. The federal government did not acquire

the MNC system until 1897, but prior to that date, the United States completed Lock and Dam Nos. 8 and 9, which extended the 5-foot channel to Morgantown, West Virginia. Upon acquisition of the MNC system, the federal government eliminated tolls, opening the river to free navigation. Traffic increased markedly with the elimination of tolls, creating a demand for larger and more efficient lockage facilities, particularly at the river's five lower locks, all built by the MNC before the Civil War. As a result, the Corps of Engineers embarked upon a program to enlarge the old locks and extend the system further into the West Virginia coal fields. By 1904, six new concrete lock and dam complexes, Nos. 10-15, extended the system to a point 4 miles upstream from Fairmount, West Virginia.¹⁴⁰

Between 1899 and 1917, the Corps of Engineers improved the entire slackwater system on the Monongahela. Of the seven stone masonry locks constructed by the MNC, only Lock Nos. 1, 6, and 7 were founded on a rock bottom. The remaining structures were built upon hewed timbers laid down on the gravel river bottom like railroad ties, with about 10 inches of space between each timber. The Corps rebuilt Lock and Dams Nos. 1 to 6 using fixed concrete dams with movable tops and two parallel locks, each measuring 56 feet by 360 feet, with 8 feet of water over the sills. These lock dimensions became the standard for the entire river. Traffic conditions did not warrant rebuilding the locks upstream from Lock No. 6, which had all been constructed after 1883.¹⁴¹

The fact that much of the work undertaken on the Monongahela involved the reconstruction and enlargement of existing facilities significantly complicated the design and construction of new facilities and necessitated creative and innovative approaches. Work began in 1907 on a replacement of MNC's Lock and Dam No. 5 at Brownsville, Pennsylvania, 57 miles upstream from Pittsburgh. The new structure, 2 miles downstream from the original, included a fixed concrete dam and a pair of 56-foot by 360-foot locks. The cofferdams used for this work incorporated elements of the construction plant and portions of the permanent works. These hybrid structures satisfied the demands and constraints of local conditions, but did not represent a new design easily replicated in other situations. The construction site for both lock chambers was enclosed within a single cofferdam. The river wall of the cofferdam was built against a pile trestle that supported a large gantry crane used to handle heavy material. Hardwood sheet piling driven along the outside face of the trestle effectively incorporated the trestle into the cofferdam structure. The trestle and cofferdam were banked on both sides with clay excavated from the site of the land wall and the resulting river wall proved "practically watertight."¹⁴²

The new Dam No. 5 was a pile-founded structure constructed in three sections. The cofferdam for the first section, begun in 1909 and extending 225 feet into the river from the dam's abutment, incorporated elements of the permanent work. Floating pile drivers drove 30-foot long round piles for the dam

substructure. Once these were in place, wal-ing strips were bolted to the upstream row of piles and a solid row of 30-foot long hardwood Wakefield sheet piling driven between the strips, forming a cofferdam that essentially conformed to Mahan's familiar design. The sheet pile wall extended 225 feet into the river from the shore abutment and then turned downstream, at a right angle, for 60 feet, forming the upstream and river arms of the cofferdam. The downstream arm consisted of a 225-foot long section of apron crib, sunk in its permanent position just downstream from the round piling. The Wakefield sheet piling wall was braced to the cribbing and banking was placed against the downstream face of the crib and the outer face of the Wakefield piling.¹⁴³

At Lock and Dam No. 6 the replacement of the original 1856 lock and construction of a new 56-foot by 360-foot lock, authorized by Congress in 1913, was complicated by the fact that the auxiliary lock chamber was to be located in the same space as the 1856 lock. The design left no space between the old river wall and the middle wall of the new two-lock complex. As a result, Corps engineers used the old river wall as the shore arm of the cofferdam, enclosing the new work site for the new river side lock, much as at Lock and Dam No. 41 at Louisville on the Ohio. In this instance, incorporation of an existing structure into a cofferdam proved successful.¹⁴⁴

The Corps engineers engaged in designing and constructing improvements on the Monongahela in the early twentieth century were largely based in Pittsburgh and were closely

associated, if not actively involved, with the canalization of the Ohio. The fact that they did not employ the Ohio River type box cofferdam on the Monongahela until the improvement of Lock and Dam No. 7 in the 1920s (Plate 4) strongly suggests that local site conditions, including the narrowness of the river, the large amount of existing traffic, and the necessity to construct new locks and dams, in some instances, virtually on top of existing structures, dictated the design of cofferdams. Only when conditions warranted was the new design employed.

Allegheny River

Prior to 1879, the Allegheny River, which together with the Monongahela forms the Ohio River at Pittsburgh, remained virtually unimproved. In 1879, Congress appropriated funds for the removal of rock obstructions and the construction of wing dams on the upper river. In 1885, completion of the Davis Island Dam on the Ohio created a slackwater pool that extended 2 miles upstream from the mouth of the Allegheny. That same year, Congress provided for construction of a lock and dam at Herr's Island, near 21st Street in Pittsburgh.



Plate 4. Monongahela River Lock and Dam No. 7. Lock cofferdam during construction. At far left is a section of Ohio River type box cofferdam framework on a barge prior to being lowered into the water. Behind this section may be seen framework in the water and, to the rear, sections of the cofferdam with the sheet piling in place. Note the steel tie rods in the foreground. 19 December 1923. RG 77-RH, Box 106, Monongahela River L/D #7 – Lock Cofferdam Folder, NARA.

Land acquisition issues delayed the start of work until 1893, and this first improvement on the Allegheny was not completed until 1903. Between 1902 and 1908, Lock Nos. 2 and 3, located at Aspinwall, 7 miles upstream from the river's mouth, and Springdale, 16.7 miles upstream from the mouth, were completed.¹⁴⁵

The work on the Allegheny included the first work by the Dravo Corporation, a Pittsburgh-based contracting company closely associated with inland river construction. In December 1902, Dravo entered into a contract with the Corps of Engineers for construction of Lock and Dam No. 2 on the Allegheny. According to a Dravo Corporation promotional book published in 1947, the lock was constructed within an Ohio River type box cofferdam. Contemporary descriptions of the project do not identify the type of cofferdam employed, but if the Dravo account is accurate, this represents perhaps the earliest use of a box cofferdam with an articulated framework.¹⁴⁶

In 1898, Major Charles F. Powell of the Corps of Engineers proposed extending slackwater navigation to Monterey, 75 miles upstream from Pittsburgh, by means of eight additional lock and dam complexes. However, several existing bridges over the Allegheny lacked sufficient clearance to pass towboats. Work did not begin on Lock and Dam Nos. 4–8 until 1920, after the City of Pittsburgh and the Pennsylvania Railroad agreed to raise the problem bridges.¹⁴⁷

Kanawha River

The Kanawha River is the largest inland waterway in West Virginia, extending approximately 97 miles from the confluence of the New and Gauley rivers to its confluence with the Ohio opposite Point Pleasant, Ohio. The river valley contains significant deposits of coal, but the wildly fluctuating level of the river prevented its use for transportation. In the mid-1820s, the James & Kanawha River Company, chartered by the Commonwealth of Virginia began to improve the waterway through the removal of snags and construction of a system of wing dams and sluices. In the mid-1850s, as coal traffic on the river increased, the company undertook to improve its facilities, but this program of improvement was curtailed by the Civil War.¹⁴⁸

In 1872, the federal government undertook to improve the Kanawha, appropriating \$25,000 for the construction of wing dams and the dredging of sluices. Congress authorized development of a slackwater navigation system on the Kanawha River in 1874, a year before authorization of the Davis Island Lock and Dam. The program called for construction of 12 locks, three fixed dams, and nine movable Chanoine dams, the first Chanoine wicket dams built in the United States, extending from the Falls of the Kanawha approximately 90 miles downstream to the mouth of the river. Construction began in 1875. In 1880, two locks and dams were eliminated from the program. In October 1898, with completion of the last of ten lock and dam complexes, the Kanawha became the first fully canalized river in the United States.¹⁴⁹

All the cofferdams used to construct the Kanawha locks and dams were simple timber crib cofferdams, (Plate 5). The cribs were constructed of logs, spiked together and sheathed on their interior faces. The cribs measured approximately 16 feet by 21 feet, and stood about 20 feet tall, with about 13 feet below water (Plate 6). The actual dimensions varied according to the requirements of the specific job site. The cribs were filled with coarse material dredged from the river bed and banked on the inside with puddle topped with dredged material.¹⁵⁰

Big Sandy River

The Big Sandy River forms part of the boundary between West Virginia and Kentucky. The river extends approximately 29 miles from the confluence of the Tug Fork and Levisa Fork north to its confluence with the

Ohio approximately 8 miles downstream from Huntington, West Virginia.

In 1897, the Corps of Engineers completed a lock and needle dam on the Big Sandy near Louisa, Kentucky. The needle dam design represented an experiment with an alternative type of movable dam. Prior to this date, all of the movable dams constructed by the Corps of Engineers on the upper Ohio and the Kanawha had utilized Chanoine wickets. The needle dam consisted of a row of trestles placed parallel to the current that turned in castings fixed to the dam foundation (Plate 7). The upper part of the trestles was attached to each other by bars and a metal walkway. When the trestles were raised, wooden needles—long narrow pieces of wood—were placed close together on the upstream side of the trestles, resting against the sill of the dam at their base and against the



Plate 5. Kanawha River Lock and Dam No. 7. General view of timber crib lock cofferdam. RG 77-RH, Box 47, Kanawha River L/D #7 Folder, NARA.



Plate 6. Kanawha River Lock and Dam No. 9. Masonry lock walls in foreground and timber crib cofferdam at rear. Note vertical sheet piling inside the timber cribs. RG 77-RH, Box 47, Kanawha River L/D #9 Folder, NARA.

connecting bars at their top (Plate 8). When not in use, the needles were removed and stored ashore and the trestles were lowered to the bottom of the river.¹⁵¹

The cofferdam used for construction of the lock constituted a pile-founded structure. It stood 13 feet above low water and consisted of two parallel rows of piles, set 8 feet apart. The piles in each row were connected by three rows of longitudinal wales. Sheet piling, consisting of 2-inch thick plank driven to bedrock and 1-inch thick plank driven as deep as possible over the joints in the first layer of plank-

ing, was driven against the waling. Delays in the delivery of machinery to the job site forced the use of horse-powered pile drivers for placement of the main piles. Workers armed with wooden hammers drove the sheet piling. At the ends of the cofferdam, the proximity of bedrock to the river bottom prevented driving piles, so wood cribs were built from the outer wall of the cofferdam to the riverbank. The entire structure cost about \$2,750, or \$7.16 per linear foot. Both the navigable pass and weir cofferdams were of similar design.¹⁵²

Kentucky River

The Kentucky River extends for approximately 261 miles from the confluence of the Three Forks of the Kentucky River at Beattyville to its confluence with the Ohio at Carrollton. The river and its tributaries drain much of the central region of the state, with its upper course passing through the coal regions and its lower course passing through the Bluegrass region.

In 1879, the federal government assumed control of five locks and dams on the Kentucky River built by the Commonwealth in the 1830s and 1840s. These works were repaired and improved in order to extend a 6-foot slackwater navigation to Beattyville.¹⁵³ In 1882, Congress appropriated funds for construction of a lock and moveable dam at Beattyville. Because the amount of river traffic upstream from Beattysville was “exceedingly small” the proposed lock was eliminated from the project and a permanent timber crib dam with chutes for navigation was constructed.¹⁵⁴

The cofferdam constructed for the Beattyville Dam was a typical pile-founded structure. The cofferdam arms varied in width from 7 to 10.5 feet, and were internally braced with wood braces and iron tie rods. Cribs lined with sheet piling were required at the shore

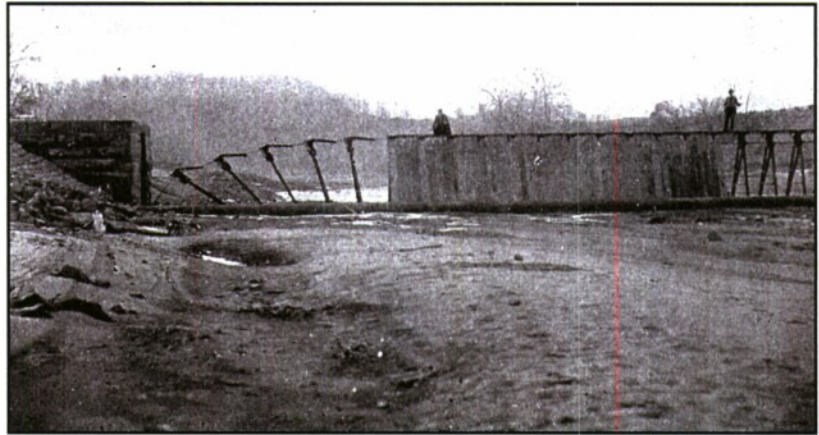


Plate 7. Big Sandy River Louisa, Kentucky. Needle Dam showing trestles being raised into position. Plate DD in Wegmann, *The Design and Construction of Dams* (1911).

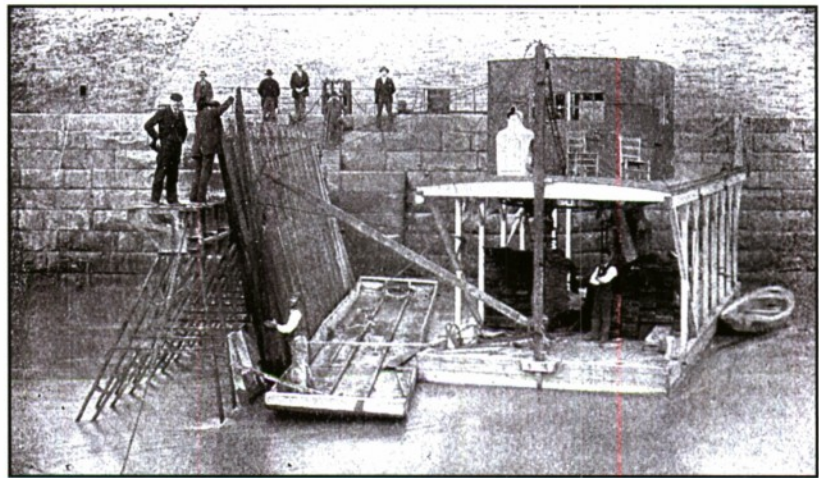


Plate 8. Big Sandy River, Louisa, Kentucky. Needle Dam showing placement of needles from trestle. Plate DD in Wegmann, *The Design and Construction of Dams* (1911).

end of the lower arm of the cofferdam because the rock bottom of the river in this location prevented the driving of piles. The cribs were 26 feet wide and varied in their height above the riverbed from 9 to 23 feet.¹⁵⁵

Cumberland River

The Cumberland River stretches for approximately 678 miles from its headwaters on the Cumberland Plateau in eastern Kentucky to its confluence with the Ohio River at Smithland, Kentucky. In 1884, Congress ap-

proved plans to construct locks and dams on the Cumberland River to achieve a 3-foot deep channel extending 327 miles upstream from the mouth of the river for 4 to 6 months of the year. Construction of Lock and Dam No. 1, located at Nashville, Tennessee, began in 1888. The cofferdam is not described, suggesting it was a standard pile-founded structure or a timber crib.¹⁵⁶

An additional 14 locks and dams were built on the Cumberland, the last completed in 1924. Locks A-F provided a 6-foot deep channel between the mouth of the Cumberland and Nashville. Locks 1-21 extended the navigation system for 196 miles upstream from Nashville. The original project plans called for dredging the open river downstream from Lock F, at Eddyville, Kentucky. However, the pool produced by Lock and Dam No. 52 on the Ohio River, downstream from the Cumberland's mouth, provided sufficient water up the Cumberland to eliminate the need for dredging.¹⁵⁷

The specifications for Locks B and C, located upstream from Clarksville and Cumberland City, Tennessee respectively, permitted the contractor to submit their own cofferdam plans. Box type cofferdams, filled with gravel and banked inside and out, were used. At Lock D, located downstream from Dover, Tennessee, the Corps' plans and specifications called for a box type cofferdam, filled with clay puddle and supported at intervals on the inside by a stone-filled timber crib, the inside wales of the box cofferdam being incorporated into the crib. These projects were

constructed between 1913 and 1915. By this date, published descriptions of the Ohio River type box cofferdam touted the economy of the design, which didn't require large pilings and therefore could be constructed using lighter pile drivers and equipment. Adoption of this design at construction sites with appropriate bottom conditions is not surprising.¹⁵⁸

Tennessee River

The Tennessee River is formed by the confluence of the Holston and French Broad Rivers east of Knoxville, Tennessee and flows for approximately 652 miles through Tennessee, Alabama, and Kentucky to its confluence with the Ohio at Paducah, Kentucky. In 1875, the Corps of Engineers assumed responsibility for completing the failed improvements initiated by the State of Alabama on the Tennessee River at Muscle Shoals. During the 1870s the Corps also began work on a series of improvements on the upper Tennessee River, upstream from Chattanooga, designed to provide a 3-foot channel. These improvements largely consisted of stone wing dams designed to raise the level of water over shoals, a practice begun on the Ohio in the mid-1820s. The dams constructed on the upper Tennessee were of stone, "quarried at the most convenient points and conveyed in flat-boats to the site of the proposed dam, where they are thrown in, care being taken to give the dam the proper direction and to place the stones in as compact a mass as possible." Cofferdams were not used for the vast majority of these improvements.¹⁵⁹

Hales Bar Dam

Prior to World War I the most innovative work on the Tennessee River occurred at Hales Bar Dam, the first main-river, multi-purpose dam built on the Tennessee. In order to improve navigation on the Upper Tennessee and provide electricity to the city of Chattanooga, Jo Conn Guild, a Chattanooga engineer, promoted construction of a privately funded lock and dam that would be turned over to the federal government in return for the hydroelectric power produced over a specified period of time. Congress authorized the project and the first construction contracts were let in 1905, but work, under the auspices of the Chattanooga & Tennessee River Power Company, did not begin on the dam proper until 1909.

Hales Bar Dam was an engineering milestone. It incorporated a 40-foot lift lock, then the highest in the world. Construction of the dam marked the first use of caissons, in dam construction, to penetrate rock and was one of the first instances of pressure grouting a dam foundation. Despite use of innovative construction technologies the dam was plagued with problems, largely resulting from its construction upon a foundation of Bangor limestone, a structure riddled with clay-filled cavities and interconnected caverns. Three different contractors failed to complete the project prior to 1910 because of the difficult foundation conditions. The engineering firm of Jacobs & Davis finally completed the project in 1913, employing diamond-drill core holes for exploration and a series of reinforced concrete pneumatic caissons. The Corps of Engi-

neers approved the use of pneumatic caissons in July 1911.¹⁶⁰

Where employed, two rows of caissons formed the base of the dam. The face (upstream) caissons measured 40 feet by 45 feet, while the toe (downstream) units measured 30 feet by 32 feet. All caissons were built of concrete with a steel cutting edge. The foundation was tested under each caisson by drilling holes 8 to 12 feet into the rock bottom before concreting began. All test holes that showed evidence of crevices or leaks were piped for grouting, which was done from outside the caisson, after the interior of the caisson had been concreted. When the caisson reached its final position, all gravel, sand, and clay was removed from the surface of the rock, leaky test holes were piped for grouting, and the caisson was filled with concrete. Spaces between the caissons were grouted, cleaned out and filled in the open, or covered with a concrete roof and worked under compressed air.¹⁶¹

Problems with leakage under the foundation were never fully corrected. The Tennessee Valley Authority (TVA) acquired Hales Bar Dam in August 1939 as part of the Tennessee Electric Power Company purchase. Unable to overcome the foundation and leakage problems, TVA demolished Hales Bar in 1968 and replaced it with Nickajack Dam, 6.4 miles downstream.

Mississippi River Headwaters

Prior to the 1880s federally funded improvements on the Upper Mississippi entailed the use of wing dams and closing dikes to secure

a desired depth of water. Except at major obstacles, such as the Rock Island and Des Moines rapids, these efforts did not require the use of cofferdams. Beginning in 1883, the Corps of Engineers began construction of 6 dams to impound and store water at the headwaters of the Mississippi River for systematic release to benefit navigation. Although significant as a reservoir system, the headwaters dams did not employ unique technology. Each dam consisted of an earthen embankment and a timber outlet structure founded on timber piles. Discharge sluices were controlled by timber gates.¹⁶² The dam constructed at the outlet of Cross Lake in Minnesota was completed in October 1886 and employed a typical pile-founded cofferdam 8.5 feet wide.¹⁶³ The Sandy Lake Dam, begun in July 1891 and completed in October 1895, relied upon a 12-foot wide pile-founded cofferdam with tie rods to prevent spreading.¹⁶⁴

Upper White River

The headwaters of the White River lie in the Boston Mountains of northeast Arkansas. The river flows through Arkansas and Missouri for approximately 722 miles before its confluence with the Mississippi. Below Batesville, Arkansas the river was navigable to shallow-draft vessels. In 1899, Congress authorized construction of a 4-foot slackwater navigation system on the Upper White River. The project consisted of ten, 36-foot by 160-foot concrete masonry locks with fixed, timber crib dams extending nearly 89 miles upstream from Batesville to Buffalo Shoals.¹⁶⁵

The Corps of Engineers used timber crib cofferdams, for the project. This design was selected over pile-founded structures, because the river bottom provided no hold for pilings. Bottom conditions forced use of a design that used more material and required dredging of the cofferdam site prior to placement of the cribs. For Lock No. 1, the cofferdam was built and sunk in sections 20 to 30 feet long, with an inside width of 10 feet 8 inches. Each section was constructed of 7- to 9-inch diameter oak logs bolted together to an average height of 17 feet. The inner and outer walls of the cribs were tied together every 10 feet by a transverse log wall. The inside faces of the cribs were sheeted with boards driven into the river bottom using hand mauls. A single row of 1-inch thick planking was used for the outer wall and a double-lap of 1-inch and 2-inch planking was used for the inner wall. The cribs were filled by hand with puddle taken from the river bank and delivered to the site in barges.¹⁶⁶

The cofferdam for Lock No. 2 was constructed using sawn 10-inch square timbers, instead of logs. The sawn timbers proved more easily and quickly handled than the rough logs, and proved nearly as inexpensive. The upstream and downstream ends of the cofferdam were constructed using 20-foot cribs, while the river arm consisted of 80-foot sections. These were built on barges, four timbers tall, launched, towed to their location and raised in height as the increasing weight of the timber sunk the crib. Sheet planking and fill were placed in the usual fashion.¹⁶⁷

Big Sunflower River

The headwaters of the Big Sunflower River lie in the bayous and lakes of Northern Coahoma County Mississippi. The river meanders south some 250 miles through the Yazoo/Mississippi Delta paralleling the Mississippi River on the West and the Yazoo River on the East, with which it conflues 10 miles above Vicksburg, Mississippi. Congress authorized improvement of the Big Sunflower through a program of wing dams and snag removal in 1879. Initial efforts sought to increase the channel to a depth of 36 to 40 inches.¹⁶⁸

In 1914, work began on a navigation lock at Little Callao Landing, Mississippi. Corps engineers used a "modified box cofferdam" during construction of the lock. This cofferdam, an Ohio River type box, stood 11-12 feet tall and measured 10 feet thick. The design conformed closely to those previously described, with an articulated framework of timber wales and sheet piles fabricated and placed from a barge. Vicksburg District engineers departed from the standard Ohio River design by developing a jointed system of eye-bolts, shackles, and eye-rods that facilitated placement of the frame and by modifying the system used to assemble and place the framework (Figure 17). These innovations constituted relatively minor refinements and adjustments to the basic design and construction methods devel-

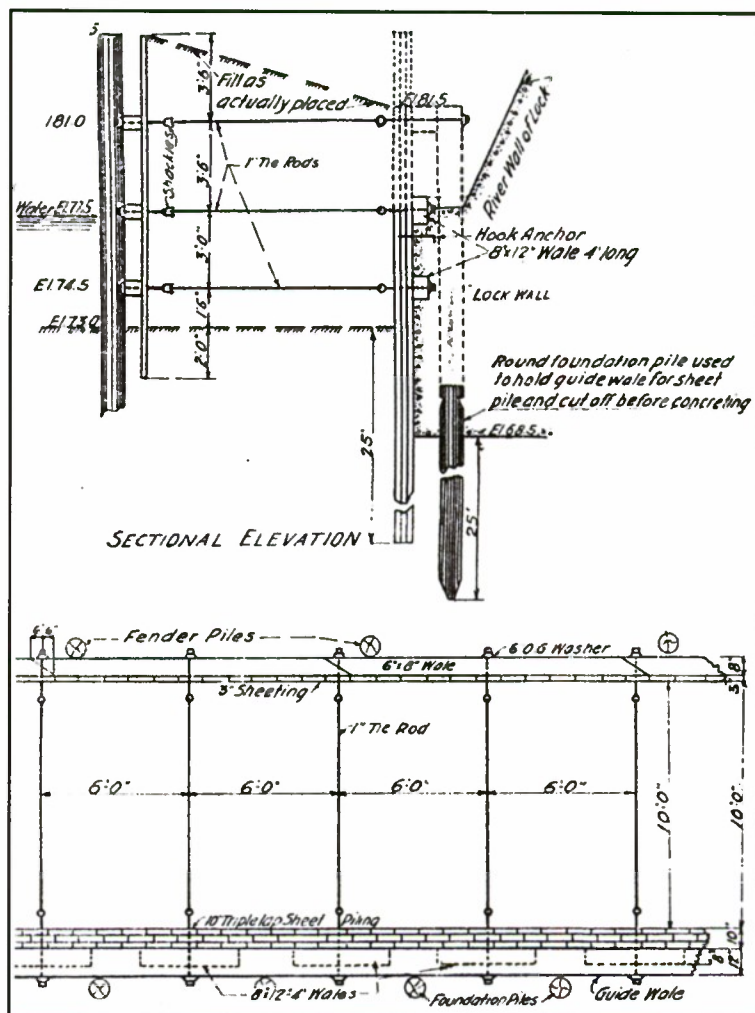


Figure 17. Big Sunflower River. Plan and section of cofferdam. From Thomas "Box Cofferdams" (1917).

oped on the Ohio. Nevertheless, the use of the Ohio River design on a minor tributary of the Mississippi indicates that the details of the design and the conditions in which it offered savings in material and labor, were familiar to engineers throughout the Corps within a decade of its introduction. The fabrication innovations clearly show that Corps engineers did not simply receive and accept new technologies, but analyzed them to determine whether they proved useful under local conditions and felt free to modify them to suit their needs and notions of economy and efficiency.¹⁶⁹

The inner wall of the cofferdam consisted of triple-lap sheet piling with holes bored in every sixth pile. During the driving of the piles, whenever one of these holes passed below the guide wale, an eye-bolt was passed through the hole and bolted to an 8-inch by 12-inch block long enough to bear upon four sheet piles. Tie-rods then were connected to the eye-bolts and temporarily secured to the sheet piling. Fabrication of the outer wall of the cofferdam employed an innovative method of construction. The waling and sheet piles, spaced 6 feet apart, were assembled upon a platform projecting from the side of a

barge. The top wale of the panel under construction was suspended at the proper height from chain hoists supported by trolleys running on a rail hung on brackets secured to the side of the deckhouse. The sheet piles and the ends of the top wales for the adjacent panels were secured to the hanging wale by shackle eyebolts. The second and third wales of the panel under construction, and the ends of the corresponding wales for the adjacent panels were then secured to the sheet piles, the bottom wale resting upon the platform projecting from the side of the barge. The barge was then shifted, and the assembled panel slid

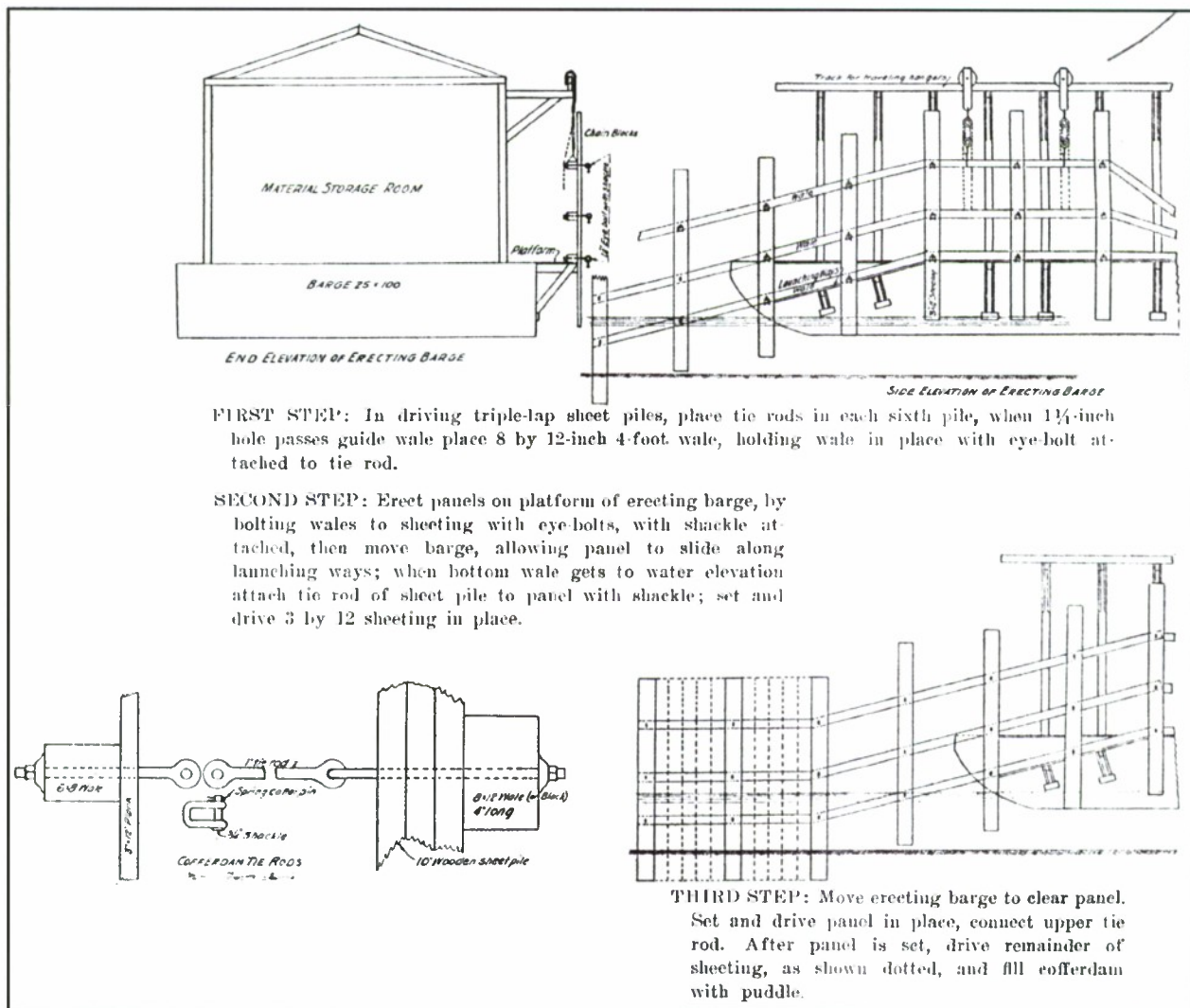


Figure 18. Big Sunflower River. Cofferdam construction sequence. From Thomas, "Box Cofferdams" (1917).

down a sloping way at the end of the platform. The chain hoists were run forward and slacked off as the barge shifted. When any eye-bolt reached the water's surface, the corresponding tie rod was swung over from the inner wall of the cofferdam and connected to the shackle eye-bolt. The intermediate sheet piles were then placed and driven about 2 feet into the bottom (Figure 18). The puddle placed inside the cofferdam walls was largely dredged from the lock site. The lock cofferdam was built in June and July 1914. The dam was built in 1915, using two cofferdams of a similar design.¹⁷⁰

Ouachita River

The Ouachita River originates in the Ouachita Mountains in western Arkansas and flows south and east for approximately 605 miles through Arkansas and Louisiana, joining the Red River just before the Red enters the Mississippi River. In 1902, Congress authorized establishment of a 6.5-foot slackwater channel on the Ouachita River extending 360 miles downstream from Camden, Arkansas to the mouth of the Black River. The Vicksburg District of the Corps of Engineers pursued this work, which entailed construction of six locks and movable dams, and employed new methods of cofferdam construction "to suit the Ouachita's 'sensitive' nature," over the period from 1902 to 1924. By 1984 all of these dams had been re-

placed by four modern locks and dams spaced from Calion, Arkansas to Jonesville, Louisiana.¹⁷¹

Cofferdam construction for the Ouachita project entailed the use of both traditional pile-founded structures and Ohio River type box cofferdams. Photographs of the cofferdam erected in 1911 for Dam No. 8, located near Calion, Arkansas, depict a pile-founded structure similar to Mahan's design. An Ohio River type box cofferdam was used in construction of Lock No. 3, near Riverton, Louisiana. The

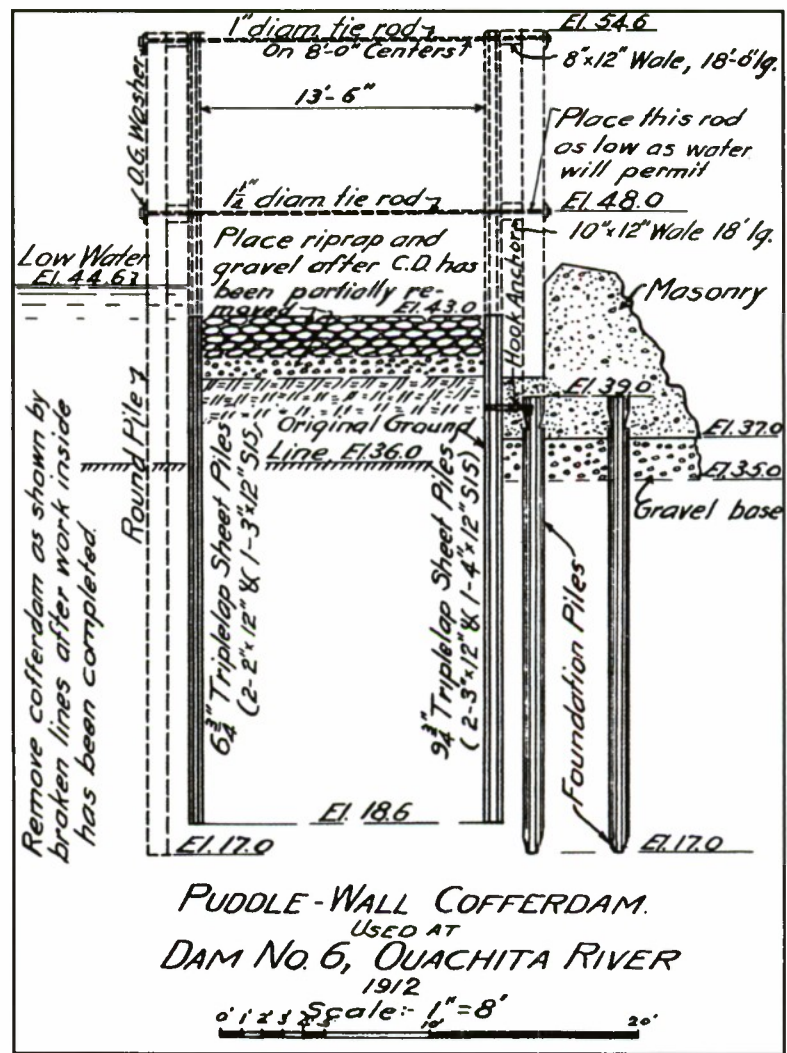


Figure 19. Ouachita River. Cofferdam section. From Thomas, "Box Cofferdams" (1917).

structure stood 19 feet tall and 16 feet wide (Figure 19). The framework consisted of 6-inch by 8-inch wales with 2-inch by 12-inch verticals and 1-inch tie rods spaced at 8-foot intervals horizontally. Three lines of 4-inch by 4-inch horizontal struts were placed within the structure and removed as the puddle was placed. The vertical spacing of the wales and tie rods varied from 2.5 feet at the bottom of the structure to 4 feet at the top, where the pressure of water and puddle were less. Sheet piling consisted of 2-inch by 12-inch plank, with an average penetration of 2.5 feet into the river bed (Figure 20).¹⁷²

Work began on the cofferdam in August 1913, halted because of high water in September 1913, and was resumed and completed in October 1914. Twenty-four days were required to place the 640 feet of cofferdam framing, which was assembled on a raft and barge and launched by hoisting successive panels with a derrick while the raft was moved clear, and then lowering the panels into the water, and another 24 days were spent placing the sheet piling. The Vicksburg District's use of Ohio River type box cofferdams on both the Big Sunflower and the Ouachita clearly indicates that the District was familiar with designs and construction methods developed and

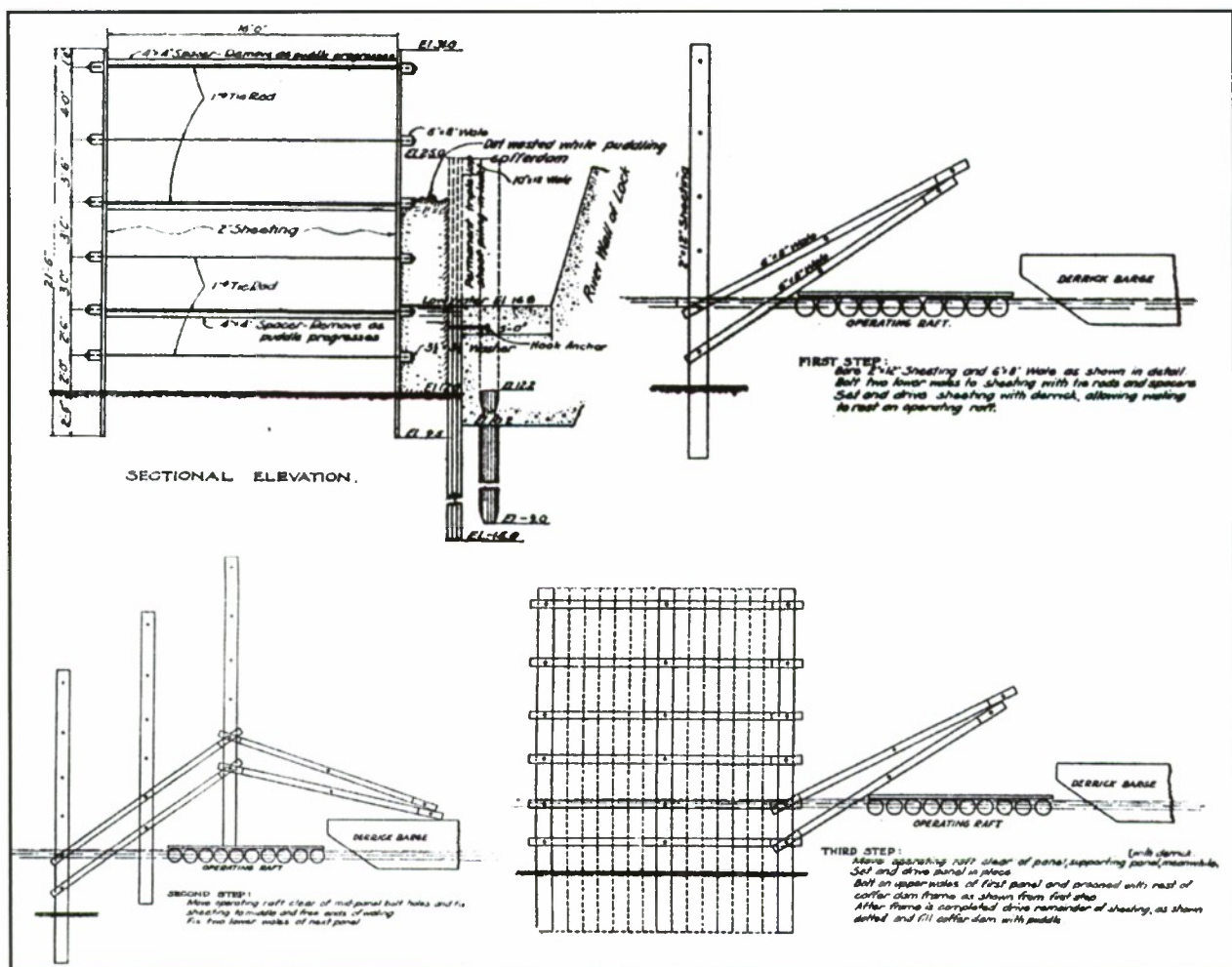


Figure 20. Ouachita River. Cofferdam construction sequence. From Thomas, "Box Cofferdams" (1917).

introduced a considerable distance from the lower Mississippi River.¹⁷³

Mobile River System

In the 1880s, in an effort to develop the coal fields of Central Alabama, the federal government began construction of a slack-water navigation system on a series of rivers that together constitute the Mobile River system in Alabama. The Black Warrior River is an approximately 178-mile long tributary of the Tombigbee River. The Coosa River, originates in northwestern Georgia, is a major tributary of the Alabama River. The Tombigbee and the Alabama join and form the Mobile River about 45 miles upstream from Mobile Bay.¹⁷⁴

Prior to 1888, the only improvement work conducted on the Black Warrior and Tombigbee rivers entailed snag removal and construction of wing dams and dikes. This work did not significantly extend the navigation season or assure unimpeded navigation during that season. In 1888, the Corps of Engineers began a project intended to provide a 6-foot channel on the Black Warrior and Tombigbee from the coal fields of Central Alabama to the Gulf of Mexico. Initial plans called for construction of 20 locks and dams with a total lift of 230 feet. The locks were designed with a clear width of 52 feet and a clear length of 286 feet. Three locks and dams were to be located on the Tombigbee, with six on the Warrior, and 11 on the Black Warrior.¹⁷⁵

While the locks all were similar in design, the lock walls on the Tombigbee and Warrior, built after 1902, were constructed of concrete, while the first three installations on the Black Warrior, built between 1888 and 1895, had cut sandstone walls. Likewise, the design of the dams varied somewhat. On the Warrior River, timber crib dams were constructed during low water without the use of cofferdams. On the Black Warrior, the first three dams were rock fill dams, with the downstream face composed of large, roughly dressed stones, and sheathed timber cribs, built into the upstream face. As on the Warrior, these dams were built during low water seasons without cofferdams.¹⁷⁶

Lock Nos. 1, 2, and 3 were constructed on the Warrior River between 1902 and 1908. After their completion, the locks and dams on all three streams were renumbered to create consecutive numbers. Lock and Dam Nos. 1-3 on the Tombigbee retained their original numbers. Lock and Dam Nos. 1-6 on the Warrior became Nos. 4-9, while those on the Black Warrior became Nos. 10-20. Lock and Dam Nos. 14-16 were constructed between 1908 and 1911.¹⁷⁷

In 1907, Dravo Corporation received a contract from the Corps of Engineers for construction of Lock and Dam Nos. 14 and 15 on the Black Warrior. Crib cofferdams, designed by the Corps of Engineers, were employed. The cofferdams were made up of 6-inch by 8-inch timbers, with the spaces between the timbers covered with 1-inch by 12-inch boards, placed longitudinally. The cribs were floated during construction, placed in position, and built up until the bottom

rested on rock. The cribs were then filled with earth and rock and decked with 2-inch planking. In subsequent work, Dravo used 1-inch and 2-inch vertical sheeting on the outside of the cribs to cut off water, permitting the sheeting to be more accurately fitted to the irregular surface of the river bottom and providing a more stable and watertight design.¹⁷⁸

Coosa and Alabama Rivers

In 1879, Congress authorized construction of slackwater improvements on the Coosa River to provide a 3-foot navigation channel. By 1890, four lock and dam complexes had been completed. Work began on Dam No. 5, near Riverside, Alabama, in 1914. In 1916, a box type cofferdam was constructed to enclose approximately half of the dam foundation. The Corps conducted channel work between 1877 and 1920 between Rome and Riverside. The Corps District Engineer recommended abandonment of the entire Coosa navigation project in 1931 and there has been no maintenance of this project since. Subsequent, non-federal, development of the Coosa focused on the construction of hydroelectric power dams. Alabama Power Company constructed and maintains six power dams on the Coosa.¹⁷⁹

Dissemination of Cofferdam Design

Prior to World War I, the Corps of Engineers employed three basic designs for wooden cofferdams. Pile-founded structures conformed closely to the design first published by Dennis Hart Mahan in the 1830s and frequently were used in conditions where the

river bottom consisted of a considerable depth of sand, gravel, or other material through which the foundation piles could be driven to an adequate depth. Crib type cofferdams were used where bedrock lay close to the river bottom, precluding the use of foundation piles. Crib cofferdams required dredging of the cofferdam site, so that the cribs could rest directly atop the bedrock. This design also required a considerable amount of timber to construct the cribs. Box type cofferdams, including the Ohio River type, were used in conditions similar to those for pile-founded structures. They offered significant savings in over pile-founded structures in terms of the amount of material required and time of construction. Their principal disadvantage, as with pile-founded structures, was the need for extensive interior and exterior berms in order to thwart the movement of water under the structure and into the working area. These berms were expensive to construct and maintain, required that the cofferdam be built a considerable distance from the permanent works, and complicated the delivery and movement of construction materials.

The design parameters for pile-founded and crib cofferdams were common knowledge among engineers in the second half of the nineteenth century. Crib cofferdams represented a folk building tradition scaled up to meet the needs of an industrial society. As noted, the design parameters for pile-founded structures had been published as early as the 1830s. Prior to World War I only the box type cofferdam, and specifically the Ohio River type box with its articulated frame, repre-

sented a significant innovation in cofferdam design and construction.

As described above, the Corps of Engineers began to use box type cofferdams on the Ohio River, and its tributary, the Allegheny River, in the first decade of the twentieth century. The details of both the basic design and the innovative articulated framework that defined the Ohio River type were published in national engineering journals and in the professional journal of the Corps of Engineers, *Professional Memoirs*, beginning in 1912. It is after that date that Ohio River type box cofferdams are first used by Vicksburg District engineers on rivers outside the Ohio River basin.

Thomas C. Thomas, a civilian assistant engineer in the Vicksburg District in 1912, appears to have been responsible for the introduction of the Ohio River type box cofferdam in the Vicksburg District.¹⁸⁰ It seems likely that Thomas read the published articles describing the design and then contacted engineers working in the Ohio basin to obtain detailed design specifications. A review of the basic civil engineering texts in use at the United States Military Academy during the period from 1900 to 1920 indicated that these texts did not include any description of box type cofferdams. The details of the design must have been transmitted informally among Corps engineers through a combination of published articles and correspondence.¹⁸¹

7 Introduction of Steel Sheet Pile Cofferdams

The most significant innovation in the design of cofferdams came in the early twentieth century with the introduction of steel sheet piling. This material, which replaced wood sheet piling, allowed construction of taller cofferdams, permitting work in greater depths of water. Steel sheet piling, while initially more expensive than wood, also offered considerable cost savings since it could be reused and, when no longer usable, sold for scrap.

Steel Sheet Pile Design

Toward the end of the nineteenth century, Bessemer steel mills began hot-rolling I-beams, channels, angles, and other structural shapes, including sheet piling. Designers sought to develop sheet piling with interlocks rolled into the beam during manufacturing, rather than attached afterwards by riveting. Englishman Charles Arthur Fitzherbert Gregson patented a ball and socket interlock in 1889; however, his design was relatively flat in section, offering little resistance to bending and deflection. Gregson also failed to develop a method for rolling his design that would permit it to be manufactured. In 1906, Trygve Larssen obtained a

German patent for a deep, hot-rolled section that greatly increased the strength and efficiency of steel walls and represented a major advancement. Larssen's piling wall assumed a "wave shape" when assembled. All subsequent developments for efficient sheet pile walls are based on this concept. Larssen's initial design still contained a partially fabricated interlock, and it was not until 1914 that a rivetless Larssen interlock appeared in Germany (Figure 21).¹⁸²

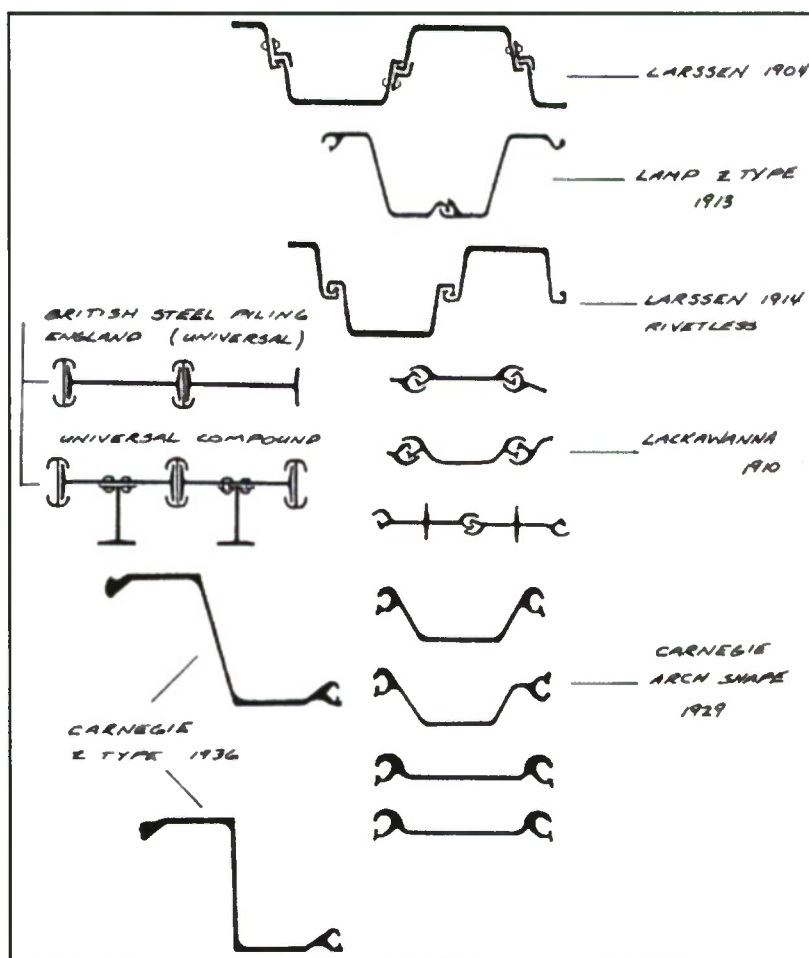


Figure 21. Various steel sheet pile sections. From Pile Buck, Inc. (<http://pz27.pilebuckinternational.com/overview/history.php>)

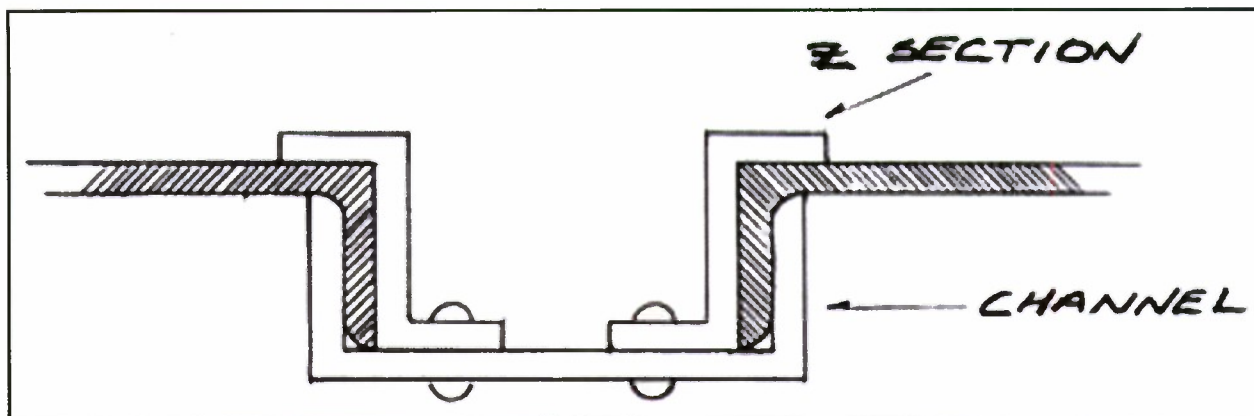


Figure 22. Section of Friestadt steel sheet piling showing interlock.

Despite these European developments, interlocking steel sheet piling was essentially an American invention. In 1902, Luther P. Friestadt of Chicago received a patent for his Z-bar piling, first used by him in 1899. Z-bars were riveted to the web of a rolled channel section, providing a groove into which the flange of a channel could slide, forming a crude but innovative interlock (Figure 22). In November 1901, the contracting firm of George W. Jackson, Inc., also of Chicago, used fabricated-beam type interlocking steel for a cofferdam used in the construction of the foundations of Chicago's Randolph Street Bridge. By 1910 the Lackawanna Steel Company had developed a flat sheet piling shape and several arched types with rolled, integral interlocks. Carnegie Steel Company (later U.S. Steel Corporation) offered three flat sections with rolled-on interlocks and one fabricated section. By 1929, Carnegie's catalogue illustrated four deep-arch, two shallow-arch, and two straight sections (Figure 21).¹⁸³

Early Steel Sheet Pile Cofferdams

Railroad companies were among the first to adopt steel sheet piling for cofferdams, employing the new material for bridge pier cof-

ferdams. In 1904, the Chicago, Burlington & Quincy Railway replaced an old single-track bridge on the line's Monroe-Mexico branch over the Cuivre River at Moscow Mills, Missouri, approximately 60 miles northwest of St. Louis, with a new three-span structure that included two piers in the river. The cofferdams for the piers, designed by the railroad and constructed by the Foundation & Contracting Company of New York, consisted of 30-foot long, 12-inch wide steel channels of the Friestadt pattern. Every other pile had 3 Z-bars riveted to the inner face of the web, forming grooves to receive the flanges of intermediate channels.¹⁸⁴

In 1906, the Norfolk & Western Railroad used steel sheet piling for the cofferdams used in the construction of three stone piers supporting a double-track bridge over a tributary of the Scioto River near Chillicothe, Ohio. The three cofferdams, identical in design and construction, measured 16 feet by 62 feet in plan and required 156 pieces of 16-foot long sheet piling manufactured by the U.S. Steel Piling Company. The piles were driven using an ordinary pile driver with a 2,000-pound hammer mounted on a scow. The piles were driven 14 feet below the water surface, leaving

2 feet exposed above water. The last eight to 12 piles of each cofferdam were assembled prior to being driven. This allowed some play and shifting between the pieces, assuring tight joints. Strips of poplar or pine were driven into the joints between the piles, making the structure nearly watertight. Upon completion of the masonry piers, the piles were pulled and reused in a cofferdam for a Baltimore & Ohio Southwestern Railroad bridge at Ray, Ohio.¹⁸⁵

Black Rock Lock Cofferdam

The Corps of Engineers first used steel sheet piling in the construction of a cofferdam at Black Rock Lock, at Buffalo, New York, in 1908. The 122-foot by 817-foot lock, constructed as an improvement to Black Rock Harbor and channel, was located in a side channel of the Niagara River between Squaw

Island and the main shore. The concrete lock was built on bedrock. Three to 15 feet of water covered the lock site, with bedrock located 35 to 45 feet below the surface of the water.¹⁸⁶

In April 1908, MacArthur Brothers Company of Chicago received the contract for construction of the cofferdam, which covered nearly 6 acres and measured 260 by 947 feet. The government specifications called for construction of a cofferdam consisting of parallel walls of steel sheet piling, but left the details of the design and the method of construction to the contractor, subject to government approval. MacArthur Brothers began work by investigating the types of heavy interlocking steel sheet piles available on the market. Four different manufacturers submitted enough sample material to build single 30-foot square pockets as field tests.¹⁸⁷

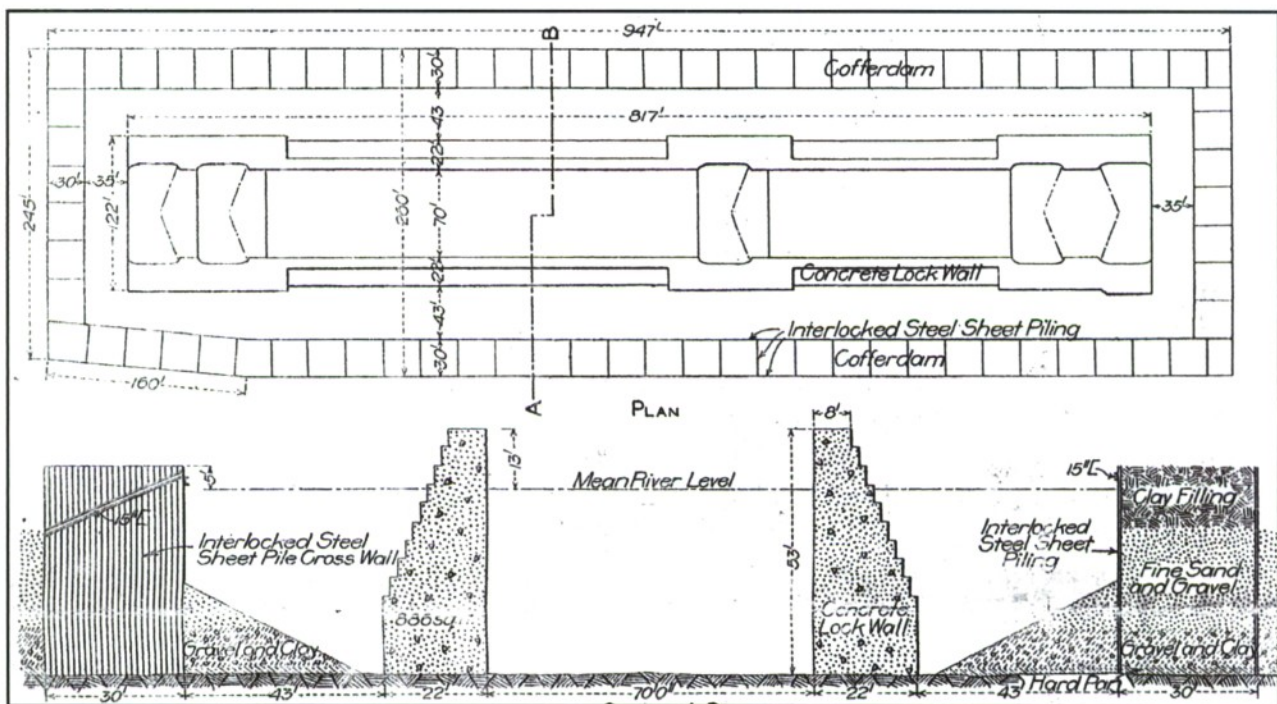


Figure 23. Black Rock Lock, Buffalo, New York. Plan and section showing cofferdam. From *The Engineering Record* (April 3, 1909).

The approved design of the cofferdam consisted of parallel lines of steel sheet piling, set 30 feet apart and connected by transverse bulkheads to create 77 pockets, each measuring nearly 30 feet square and 45 feet tall (Figure 23). A horizontal, 15-inch waling channel was bolted to the top of the pilings at the inner walls and a similar channel, inclined at an angle of 30 degrees, was bolted across the top of each transverse wall to stiffen the structure.

It was believed that placing the fill in the pockets would place significant stresses on the inner and outer rows of piles, while placing the transverse bulkheads in tension. The field tests of various piles were designed to select the pile best adapted to resisting these large tensional stresses. After completion of the field tests, a contract was awarded to the Lackawanna Steel Company for 7000 tons of steel sheet piles in lengths of 46 to 50 feet, the largest order for steel sheet piles placed to that date. The piles, first placed on the market in 1908, consisted of "integral rolled sections, without riveting or other assemblages to form the interlock, and the edges are so shaped that a complete hinged joint is formed between adjacent piles." The joint provided an arc of motion of 44 degrees (22 degrees to either side), permitting a right angle to be constructed using only four piles (Figure 24).¹⁸⁸

A pair of floating scows, fitted with 60-foot leads and Vulcan steam hammers, began

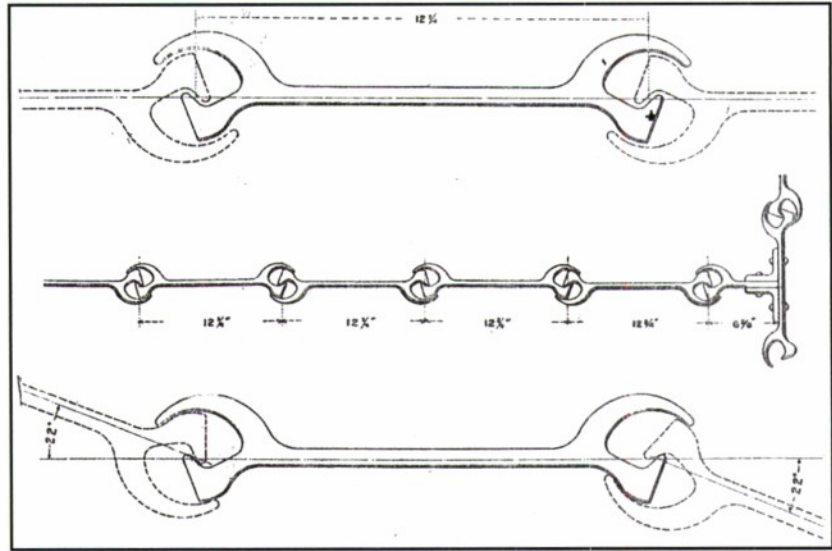


Figure 24. Black Rock Lock, Buffalo, New York. Details of sheet piling interlocks and connections. From *The Engineering Record* (13 June 1908).

driving piles in May 1908. The sheet piles initially were driven using a guide, consisting of wood piles with waling bolted to both sides, to keep them properly aligned. Eventually, the sheet piling was driven without guides, other than 10-foot by 30-foot floats moored with one edge in the line of the sheeting. The contractor assured that the piles were driven vertically, by holding them in position with chain slings, levers, and other devices. The interlocks afforded about a half inch of clearance between piles, allowing for cumulative displacement. Nevertheless, it proved difficult to close the corners of the structure. Assemblies fabricated from short pieces of piles were used to position the last pile. After the last pile was driven, the short pieces were pulled and replaced with permanent piles. On occasion, the contractor had to fabricate piles up to 2 feet in width, the standard width was 12.75 inches, in order to close the gaps. The length of the piles was supposed to conform to the government soundings of the lock site and allow for 5 feet of

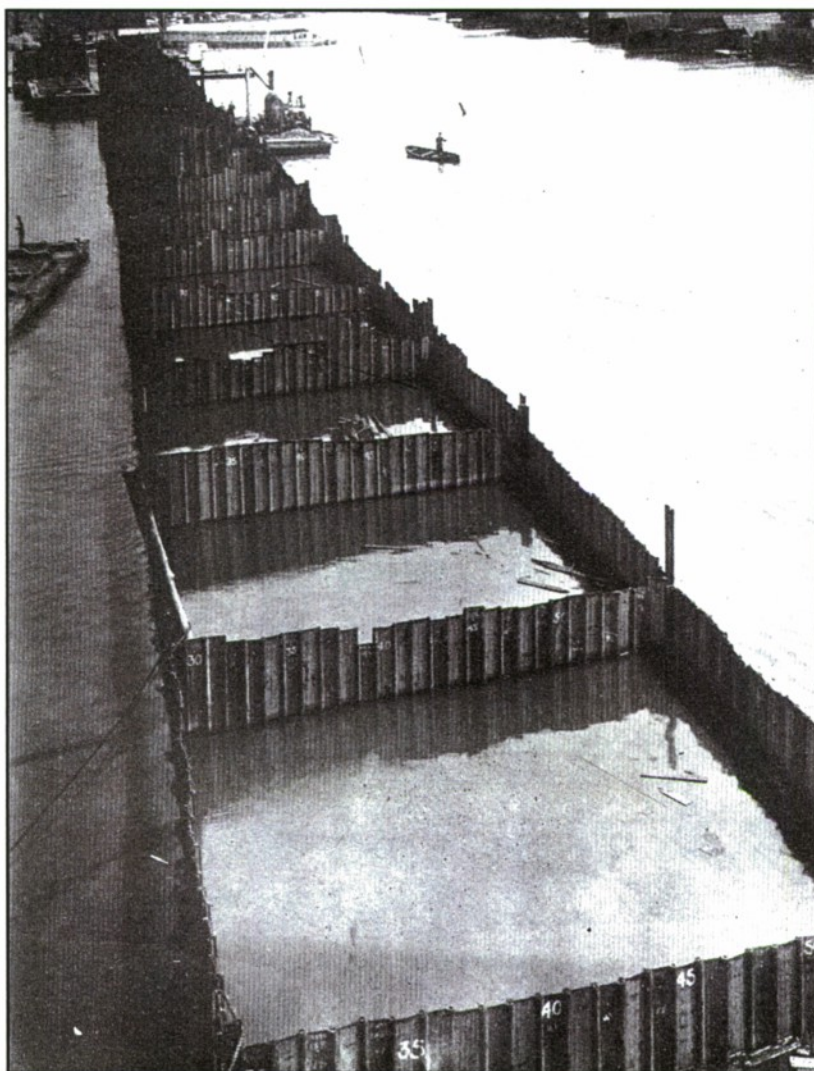


Plate 9. Black Rock Lock, Buffalo, New York. Steel sheet pile cofferdam. Note rectangular plan of cells. Plate JJ in Wegmann, *The Design and Construction of Dams* (1911).

projection above the water. This system did not always work, and the contractor maintained a stock of various length piles, basing the length of each pile to be driven upon the length of the previous pile. After the piles were driven into place, holes were drilled through the web for the attachment of the waling pieces and braces, which were secured using a single 1-inch bolt per pile for the walings and two bolts per pile for the braces. The lower end of the braces could not be drilled or bolted into place until the water was pumped

from the pockets. After the braces were bolted into place, the pockets were filled with clay puddle delivered in scows and placed using clamshell buckets. A 20-foot berm was left against the inside wall of the cofferdam to resist the pressure exerted against the outside of the structure by the water.¹⁸⁹

The 7,000 tons of sheet piling was driven, and the cofferdam closed, in February 1909 (Plate 9). The cofferdam was pumped out by July 1909. While the cofferdam itself proved watertight, greater leakage through the bedrock under the lock site occurred than was anticipated. Considerable time and money were spent trying to address this issue, but the ultimate solution was simply to increase the pumping capacity to a total of 29,000 gallons per minute.

The pumps removed 15 to 16 million gallons per day.¹⁹⁰ In addition, because all the walls of the cofferdam consisted of straight lines of sheet piling, the longitudinal (inner and outer) walls bulged badly between the transverse walls. In one cell, the inner wall, with an unsupported height of about 30 feet, bulged 3.45 feet between the transverse walls. Despite this bulging, the inward movement of the top of the inner and outer walls nowhere exceed about 1 inch.¹⁹¹

Raising the Battleship *Maine*

The second major steel sheet pile cofferdam constructed by the Corps of Engineers was erected in the harbor of Havana, Cuba, in order to raise the battleship *Maine*. The sinking of the *Maine* resulted in the death of 260 American sailors, many of whose bodies were not recovered. The Cuban government wanted the wreck, which it considered an eyesore and a navigational hazard, removed from the harbor. In May 1910, Congress authorized the Secretary of War and the Chief of Engineers to raise and remove the wreck and assure the proper internment of any recovered bodies.¹⁹²

Responsibility for the project was assigned to a board of engineering officers led by Colonel William M. Black. Prior to this assignment Black served as Northeast Division Engineer. The Northeast Division encompassed the Buffalo District, and it is likely that Black was familiar with the design and construction details of the innovative steel sheet pile cofferdam built by the district at Black Rock Lock. The engineering board determined that removal of the wreck required construction of a cofferdam around the sunken ship. The area inside the cofferdam would be dewatered to permit examination of the wreck, removal of bodies and debris, and any repairs necessary prior to removal.¹⁹³

Construction began in December 1910 on an elliptical cofferdam comprised of 20 circular steel sheet pile cells. Each cell measured 54 feet in diameter. The cells were connected by short arcs of sheet piling on their outer faces (Figure 25). Both the cells and the con-

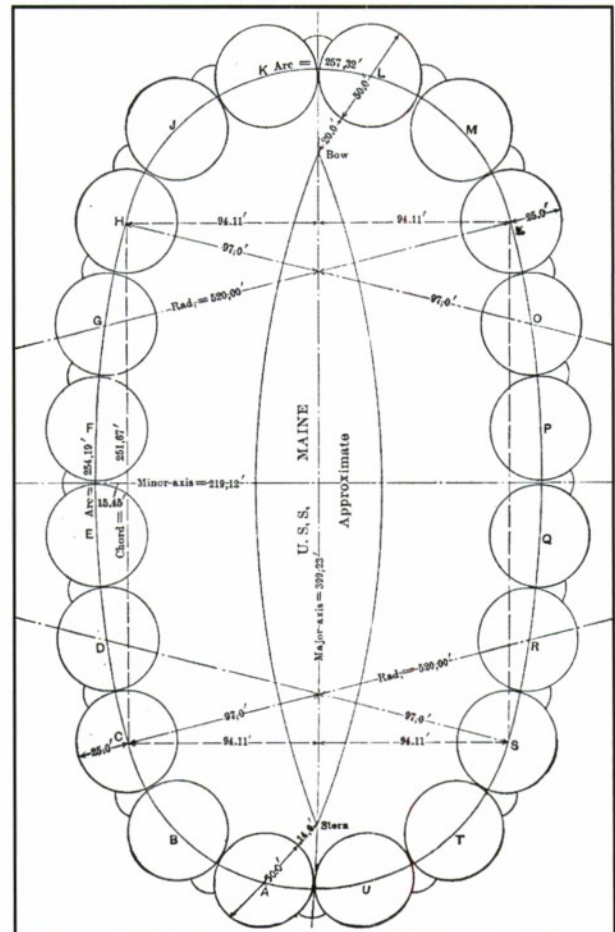


Figure 25. Plan of circular cell cofferdam around wreck of *Maine*. Figure 158 in Wegmann, *The Design and Construction of Dams* (1911).

necting segments were filled with clay dredged from the harbor bottom. Site conditions proved challenging. The average depth of the water around the wreck was about 37 feet. The harbor bottom consisted of about 10 feet of sand and mud atop stiff clay.¹⁹⁴

The sheet piling was purchased from the Lackawanna Steel Company, and consisted of 4,430 tons of 3/8-inch web in lengths of 25, 35, 40, and 50 feet. The design intent was to drive 75-foot long piles into the stiff clay bottom, but because of the impracticality of shipping 75-foot piles, individual 75-foot piles were fabricated from the stock of shorter

piles. The method of construction entailed first driving an ordinary wood pile at the center point of each cell. A floating template was fixed to this pile to guide the placement of the steel piling. A 50-foot length of steel sheet piling was placed against the template and allowed to sink into the mud on the harbor bottom by

its own weight. A 40-foot pile then was threaded through the web of the first pile and suspended until a 35-foot top section was bolted into place. This assembly then was allowed to drop into the mud and the process was repeated, alternating 50- and 40-foot bottom sections. This practice alternated the location of the joints between the individual units that comprised each 75-foot pile, eliminating a potential structural weakness in the cells. After a number of piles were placed, pile driving began, with the piles driven to a depth of 73 feet. Closure of each cell was accomplished by setting the last 15 or 20 piles on the outer face of the cell and driving them as a unit.¹⁹⁵

Pile driving was completed at the end of March 1911 and the filling of the cells and connecting arcs was completed in May 1911 (Plate 10). A stone toe was placed against the

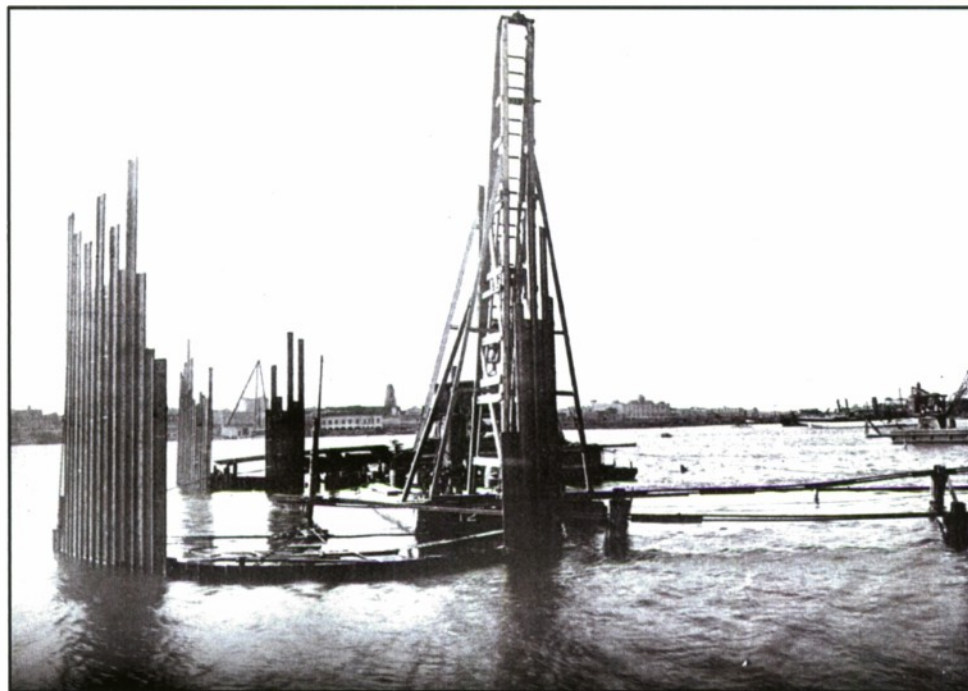


Plate 10. Constructing circular cell cofferdam around wreck of Maine. Plate LL in Wegmann, *The Design and Construction of Dams* (1911).

inside face of the cofferdam, between the cofferdam and the wreck. During dewatering of the cofferdam, an inward movement of the cells was observed. To counteract this force, the cylinders were stiffened with steel bands made from sheet piles, and braces were placed between the cells and the wreck. These consisted of heavy wood beams resting against concrete abutments at the cells. The dewatering was completed in October 1911, and removal of the wreck was finished in February 1912.¹⁹⁶

Troy Lock and Dam

In 1913, the Corps of Engineers erected steel sheet pile cofferdams for construction of a lock and dam on the Hudson River at Troy, New York (Figure 26). The west end of the dam was built behind a timber crib cofferdam. For the lock, the cofferdam was built in

two sections, partly to save time and partly to enable the masonry laid within the first cofferdam to serve as part of the second cofferdam, saving on the required quantity of piling. The first lock cofferdam was placed in the river's main channel. Plans called for it to remain in place for two winters, which necessitated that it be strong and reliable. Since the

cofferdam would block more than one-third of the river, it had to be able to support a head of 27 to 34 feet. This was too high for a crib or pile-founded structure. Additionally, wooden sheet piling could not be effectively driven into the gravel river bed. If the sheet piling was not driven, and reliance was placed upon outside banking of the cofferdam, there

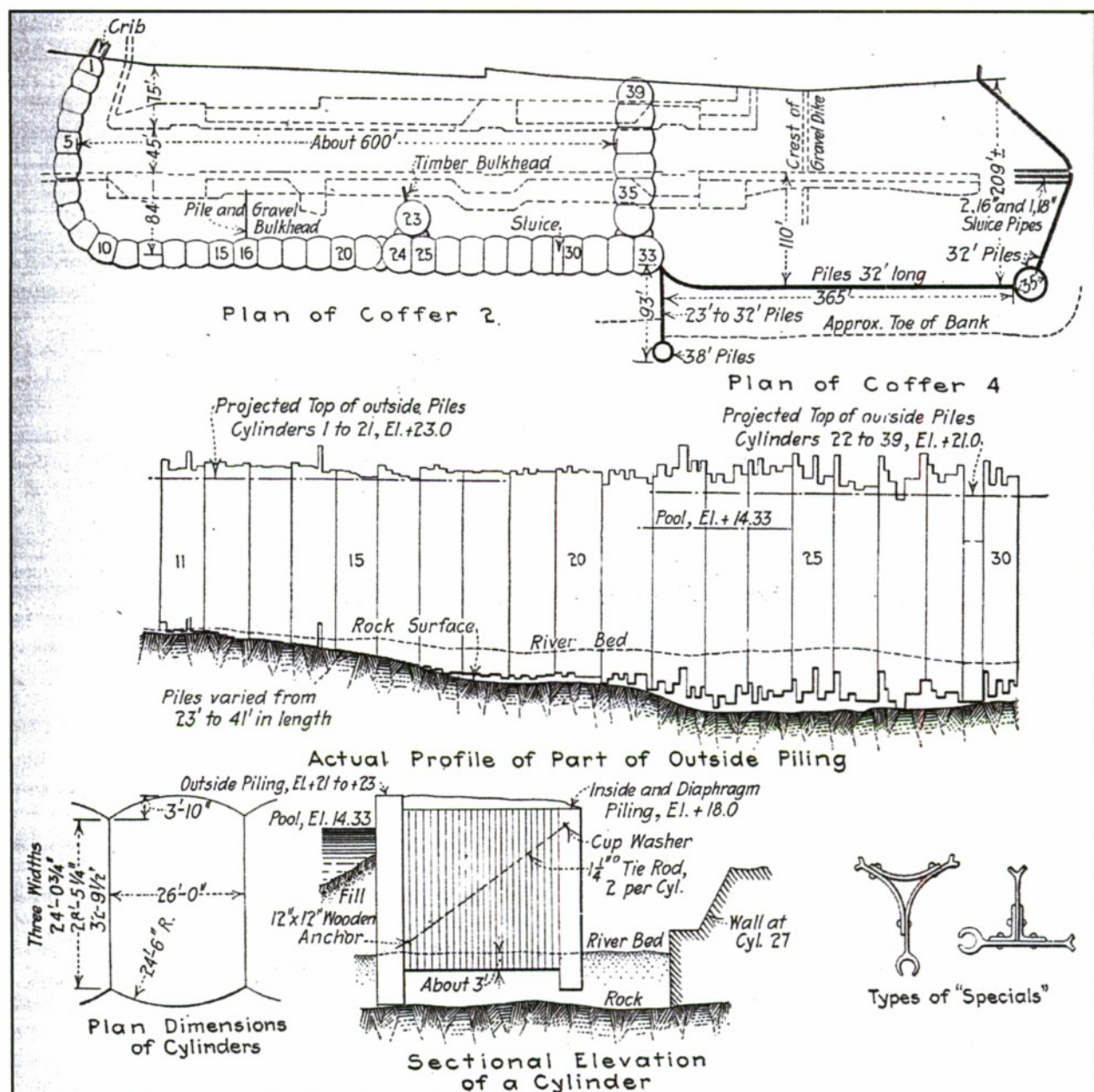


Figure 26. Troy Lock and Dam, New York. Plan, sections, and profiles of cofferdam. From Watt "Steel Sheetpile Cofferdams" (1916).

was a considerable possibility that this banking would be washed away during a flood. Finally, a timber cofferdam would not be easy to remove and offered no resale value on materials. As a result of these considerations, it was determined to build a steel pocket cofferdam. The steel piles could be driven to rock through the gravel riverbed, could be pulled without undue damage and reused, and when the work was completed, could be sold for scrap for approximately one-third their original cost. Once the scrap value was considered, it was calculated that the steel cofferdam could be constructed for about the same cost as a wooden structure.¹⁹⁷

The Albany District conducted trials to determine the most economical size of the pockets and to analyze the expected stresses on the cofferdam. Upon completion of the trials, the pockets were designed to be 26 feet wide, with their outer and inner faces curved on a radius of 24.5 feet. These faces were connected by straight diaphragm walls. The pockets were designed to extend 7 feet above the pool level, with a pressure head of between 21 and 41 feet. This design represented a combination of the pocket designs used at Black Rock Lock and Havana. The curved inner and outer walls reflected the results of the lessons learned at Black Rock Lock, where straight inner and outer walls of sheet piling had bulged dramatically. The success of this cofferdam design, which became known as a diaphragm or semi-circular cell cofferdam, led to the increased use of cellular cofferdams by the Corps of Engineers.¹⁹⁸

The Carnegie Steel Company supplied 1,900 tons of 38-pound steel sheet piling (3,400 pieces). Pile driving for the first lock cofferdam began in July 1913. The piles were placed around a template of two-inch planking, with the best progress resulting from placement of several piles before driving. Maximum penetration was only 8 to 9 feet, because of the compact gravel river bottom. The pockets were closed by setting eight to ten piles on each side of the closure and permitting them to rest on the river bottom. This provided the flexibility required to thread the closing pile into the interlocks. Once the closing pile was placed, the entire set of piles was driven into place. Derrick boats were used to handle and drive the piling. The largest cell measured about 40 feet across and stood 40 feet tall. Considerable care was taken to assure that the fill was placed in the cells progressively. If one cell was filled too much in advance of the adjacent cell, the weight of the fill would distort the diaphragm wall between the cells. Interior and exterior berms were placed to reinforce the structure. Dewatering began in late November 1913, and the last section of the structure was removed in August 1915, after completion of the lock.¹⁹⁹

The second lock cofferdam consisted of a single line of steel sheet piling, salvaged from the first cofferdam. It measured 650 feet in length and attached to the end of the first cofferdam. The piles were only driven to a depth of 5 to 6 feet, and a 28-foot wide earthen bank was used to provide stability and control seepage. Sand was poured into the interlocks of the piling to further reduce seepage. The final cofferdam at the site was used to complete the 500-foot east arm of the

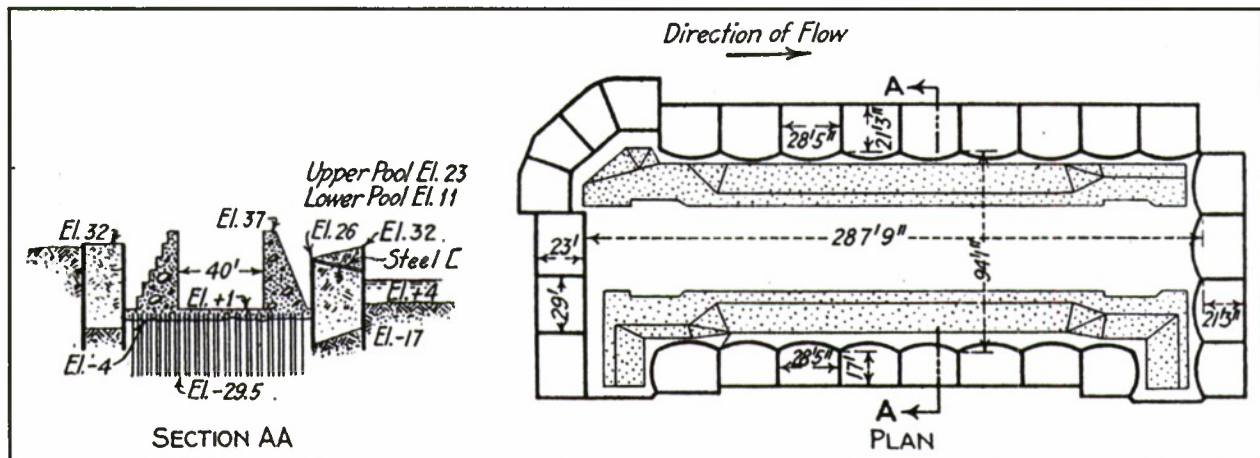


Figure 27. Cape Fear Lock No. 2, North Carolina. Cofferdam plan and section. From *The Engineering Record* (9 September 1916).

dam. The masonry work within this cofferdam was to be completed in a single season, so the cofferdam did not need to withstand a winter. Like the second lock cofferdam, this structure consisted of a single wall of steel sheet piling supported by banking. However, in this instance, the piles were not driven, but simply rested on the river bottom. Thirty-foot diameter anchor cylinders were placed about every 100 feet along the line of piling in order to restrict the damage if high water topped the sheet piling.²⁰⁰

Cape Fear River Lock No. 2

In 1916, the Corps of Engineers employed a “steel pocket cofferdam” in the construction of Lock No. 2 on the Cape Fear River, 72 miles upstream from Wilmington, North Carolina. Like the cofferdam built at Troy, New York, this structure, designed for a 30-foot head, used both straight and curved sections of steel sheet piling. However, this design employed two different types of pockets. At the upper end of the cofferdam, the pockets were rectangular, with the walls tied together with steel cables and rods fastened

to the wales. The remaining pockets were built without ties, the inside wall being curved to reduce distortion in the piling resulting from the pressure of the fill against the piling (Figure 27). Lackawanna Steel Company arch-web piling was used in the straight wall pockets and on the straight, outside walls of the river wall because of its superior strength. The remainder of the cofferdam was constructed of straight-web piling.²⁰¹

In retrospect, this design appears less sophisticated than that used at Troy. The pockets are largely comprised of straight sections of sheet piling, with only the inner face curved, and then only in some locations. The design was a hybrid of the Black Rock and *Maine* cofferdams, suggesting a certain hesitancy in the adoption of steel sheet piling. The District Engineer, Captain Clarence S. Ridley, noted that steel cofferdams were expensive, but that this expense was warranted under certain conditions, such as those at the Cape Fear River site. The narrow Cape Fear River required a narrow cofferdam that would minimally obstruct the river. The Cape Fear location also was subject to rapid rises, which

meant the cofferdam had to be capable of surviving repeated inundations. In Ridley's view, these conditions dictated use of a steel cofferdam.²⁰²

The cofferdam was designed to stand 28 feet above the river bottom of 28 feet. To achieve the desired height and secure the necessary penetration in the sand and clay river bottom, piles 49 feet long were required for the river arm. The piles used in the land arm pockets were 49 feet long for the land side, but only 43 feet long on the river side, making the inside wall 6 feet lower than the outside wall. By thus sloping the tops of the pockets, the amount of fill required was reduced. All piles in the inner wall were spliced just above the elevation of the lock floor, the lower portion remaining as part of the permanent construction after removal of the cofferdam.²⁰³

The piles of the land wall were driven 39 to 48 feet into clay, clay and sand, and marl using two pile drivers mounted on tracks. Pile driving for the river walls was accomplished using a floating rig. Penetration for the river wall was only 18 to 21 feet, so driving progressed more quickly than for the land wall. The curved panels were driven against a floating template held against wooden guide piles by adjustable bracing. Closure of the pockets required considerable care to keep the piles vertical. In four instances, specially fabricated wedge-shaped piles were required to close a pocket. All pockets were closed on their outside face using a group of four piles.²⁰⁴

Diagonal steel channels were bolted to the cross walls to prevent sliding of one interlock on another under the overturning force on

the back of the pockets. Despite this precaution, several pockets experienced significant movement during dredging of the lock pit, tending to turn over in the direction of the lock pit and shearing off the fastening bolts. The pressure against the back wall was relieved by excavation and drainage, and the affected cross walls were tied back to tree anchorages using heavy wire cables. This solved the problem, which had entailed a maximum movement at the top of the affected pockets of 7 feet 6 inches.²⁰⁵

Ridley made careful calculations regarding the cost of the cofferdam in comparison to a wooden structure. Initial calculations, based upon material, shipping, and labor costs, indicated a cost of \$90.19 per linear foot. However, Ridley noted that 17 percent of the piling remained in place as a permanent cut off wall and should not be charged to the cofferdam. Additionally about 75 percent of the piling was salvaged for reuse. Adjustments for these savings reduced the cost to \$40.13 per linear foot. Ridley sought to extrapolate his experience on the Cape Fear to the Ohio, where he believed additional savings could be obtained by lowering the height of the cofferdam and reducing the depth of penetration of the piles. Ridley's final calculations suggested a cost of \$24.03 per linear foot for a steel sheet pile cofferdam on the Ohio. This figure contrasted with an average cost of \$15.00 per linear foot for the wooden cofferdams constructed on the upper Ohio. Ridley pointed out that steel cofferdams did not have to be built as thick as Ohio River type box cofferdams, which required wide berms, thus per-

mitting a smaller cofferdam and a considerable savings of material, reducing the total cost of a steel structure to approximately the cost of a wood structure.²⁰⁶

Ridley had no connection to the Ohio River, his previous duty stations had been in Hawaii, the Philippines, and at Fort Leavenworth, Kansas. His cost comparison between a steel sheet pile cofferdam and the widely used Ohio River type box structure, published in the Corps of Engineers professional journal, appears to have been undertaken solely in the interest of providing an objective, statistical comparison between a widely used design and a new technological development.

8 Adoption of Steel Sheet Pile Cofferdams

Clarence S. Ripley's thorough cost analysis demonstrated that steel sheet pile cofferdams could be built for roughly the same cost as traditional wooden Ohio River type box cofferdams. Nevertheless, the Corps of Engineers proved slow to adopt steel sheet pile cofferdams on the Ohio River, the principal scene of inland river construction prior to 1930. Adoption of steel sheet pile cofferdams on other streams followed their acceptance on the Ohio.

Resistance on the Upper Ohio

By 1915, a year before Ripley published his analysis, 31 of the projected 53 locks and dams on the Ohio were under construction.²⁰⁷ All of these projects used wooden pile-founded or Ohio River type box cofferdams. Wooden cofferdams, particularly the innovative Ohio River type box, which was developed on the Ohio during the same period that steel sheet pile structures were introduced elsewhere, proved admirably suited to conditions on the Ohio. They were reliable, inexpensive and relatively simple to construct, and economical in the use of materials. During the decade and a half prior to the American entry into World War I, Corps engineers working on the Ohio likely saw little reason to experiment with steel sheet pile cofferdams, since current practice fit their needs.

The reluctance to discard accepted practice in favor of a relatively untested new technology is perhaps best exemplified by the attitude of Thomas P. Roberts, chief engineer of the Mo-

nongahela Navigation Company and son of W. Milnor Roberts, who had first proposed canalization of the upper Ohio. Roberts' position was somewhat extreme, and was not held by all Corps engineers working on the Ohio, but his reputation and experience enabled him to wield considerable influence. Roberts was a powerful advocate for the use of Ohio River type box cofferdams and vowed not to use steel sheet piling. In a 1905 presentation to the Engineers' Society of Western Pennsylvania, Roberts noted that he had no experience using steel piling—which had not yet been used for cofferdams by the Corps — “except to listen to the glowing accounts of the sales agents as they set up their models on my office table.”²⁰⁸

Roberts' description of the sales pitch, and his reaction to it, illustrates his preference for field-tested engineering experience, over innovative methods and materials lacking a record of successful employment in varied circumstances:

It is really remarkable how rapidly an agent can surround a pile of books, or a “make believe” pier, with his interlocked aluminum or bronze piles.

When I ask them what is to be done if one of the piles strikes a tree trunk twenty feet down in the gravel they reply, “Pound away until you cut right through it.” When I suggest a large “nigger head” [sic] boulder at the same depth they answer, “That’s easy, now

here's your ink stand, it's the boulder, when I come to it I start a curve and go around it, and get on the line on the other side, see, just as slick as a wink." "But suppose," I interject, "it's a nest of big boulders." "Well," they say, "keep on curving around, you'll get through all right."

That's just it, the books and other authorities, including the learned sales agents, know all about the subject of coffer-dams, excepting as to the trifling point of getting them securely in place at the desired depth, so that the engineer in charge can proceed to pump them out and go along with his work. The unfortunate resident engineer can get more advice up to the time he is ready to start work than he can possibly utilize, but when the boulders, tree trunks and quicksands are encountered, and big springs come boiling up through the fissures in the rock, where is the know-all agent? Most likely at that unblessed moment hundreds of miles away setting up his models on somebody's office table.

Here is the part of the science where each engineer must work out his own salvation, or if he seeks advice will probably get the best from the combined knowledge and experience of his derrick man, blacksmith, pump man, pile driver, and dredge runner.²⁰⁹

Roberts' prestige and influence may have tipped the balance in favor of the continued use of wooden cofferdams on the upper Ohio.

Indeed, the first use of a steel sheet pile cofferdam within the Pittsburgh District did not occur until 1927 at Deadman Island (Dashields) Dam, four years after Roberts' retirement in 1923.²¹⁰

Ohio River Canalization: 1919-1930

The adequacy of existing cofferdam technology and some degree of institutional resistance were not the only factors retarding the adoption of steel cofferdams for Ohio River lock and dam projects. The canalization program was interrupted during World War I, as expertise, materials, and funding were diverted to the war effort. Work on the program resumed in 1919, and one of the first projects begun after the hiatus, Lock and Dam No. 23 at Millwood, West Virginia, in the Huntington District, made use of steel sheet piling in the construction of the project's three cofferdams.²¹¹

The design of the Lock and Dam No. 23 cofferdams clearly indicates that engineers had yet to settle upon a standard approach to the use of steel sheet piling. Dravo Corporation engineers decided that the successful use of steel sheet piling depended upon the effectiveness of the cofferdam bracing. They designed structures that essentially consisted of steel sheet piling walls enclosing the working area, heavily braced by steel tie rods and timber bents (Figure 28). The bracing system blocked free and clear access to the work area and it is not known exactly how the dam was constructed within the closely placed bracing (Plate 11). The horizontal bracing must have been removed as the dam rose, and it is possible that the steel sheet pile walls were

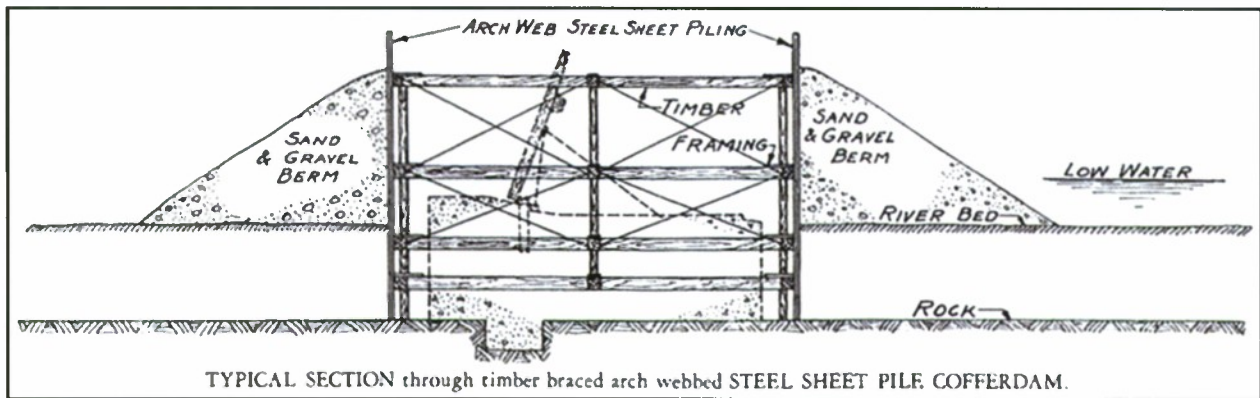


Figure 28. Typical section through timber-braced arch-webbed steel sheet pile cofferdam. From Dravo Corporation *Locks and Dams* (1947).

braced directly to the concrete of the dam as work progressed.²¹²

The design proved strong enough to withstand an ice jam and inundation by silt and sand deposited by flood waters. Dravo touted the fact that the design enabled the cofferdam to be placed closer to the permanent work. This eliminated the need for two sets of derricks, cranes, and other equipment, one inside the cofferdam and one outside. The floating plant delivered and handled all construction materials and equipment, making the work more economical and efficient.²¹³

Dravo Corporation continued to experiment with the design of steel sheet pile cofferdams in their work at Lock and Dam No. 32. Construction of the lock began in 1919, inside a typical wooden Ohio River type box cofferdam. The navigable pass was built using pneumatic caissons (described above). However, the use of caissons proved impractical for con-

struction of the bear-trap weir piers and foundation. The shallow foundations and the absence of rock upon which to found the caissons did not permit the addition of enough weight to the caissons to hold them in place while the bear-traps were constructed. Consequently, in 1924 Dravo designed and built a cellular, steel sheet pile cofferdam for this portion of the work (Figure 29). The concrete

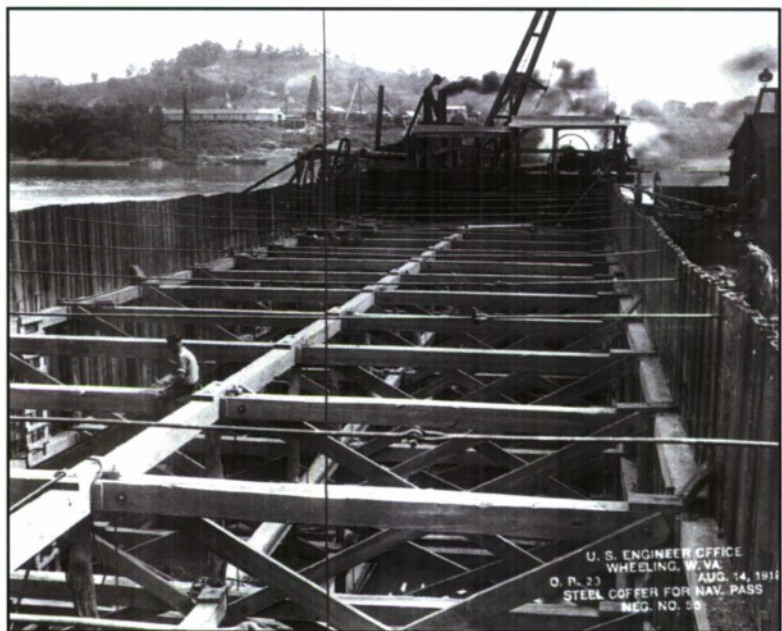


Plate 11. Ohio River Lock and Dam No. 23. View from outer end of navigable pass cofferdam towards locks. View shows a steel sheet pile box type cofferdam under construction. 14 August 1919. RG 77-RH, Box 126, Ohio River L/D #23 Pass, Navigable Cofferdam Folder, NARA.

foundations for the bear-traps and their piers were poured under water. Weep holes in the base of the foundations prevented the concrete from floating when the cofferdam was dewatered.²¹⁴

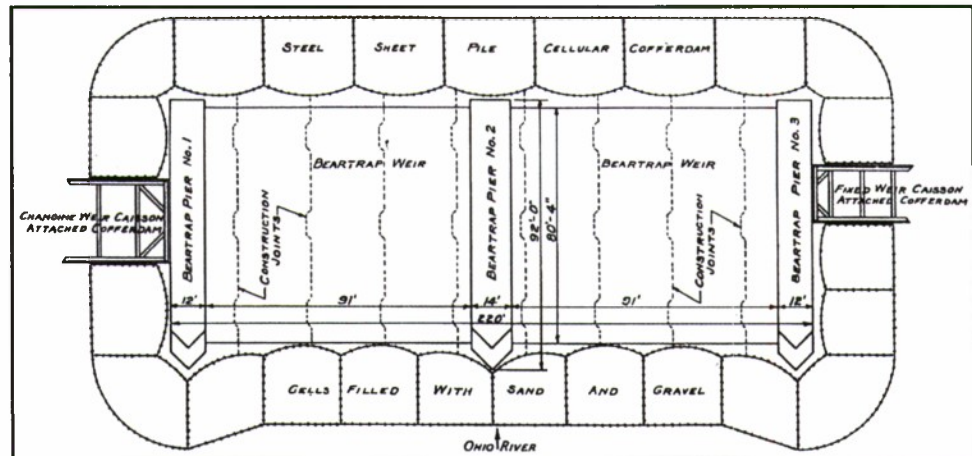


Figure 29. Ohio River Lock and Dam No. 32. Plan of cellular steel sheet pile cofferdam for construction of bear-traps and bear-trap piers, 1924. From Dravo Corporation *Locks and Dams* (1947).

Plan views of the Lock and Dam No. 32 cofferdam depict a structure that fairly closely resembled that built in 1916 by Clarence S. Ridley at Lock No. 2 on the Cape Fear River in North Carolina. The outside and diaphragm walls of the individual cells consisted of straight sections of piling, while the inside cell walls were curved. The corner cells and those at the upstream end of the bear-trap piers were irregular in shape. The various shapes of the cells appear somewhat idiosyncratic, especially compared to the uniform circular cells widely adopted within the next decade. The design suggests that engineers working with steel sheet pile cofferdams had, as late as 1924, yet to settle upon a standard cell design that could be economically and efficiently employed in a variety of conditions.

Replacement of the First Generation Ohio Dams: 1919-1937

In the upper reaches of the Ohio, a variety of factors, including the steep slope of the stream, its rapid fluctuations in stage, the dangers of running ice, and the brief periods

in which open river navigation was possible, combined to make the operation and maintenance of movable dams problematic. The chief advantage offered by movable dams, the ability to permit open river navigation, was only available during limited periods of the year, while their disadvantages were present year round. Fixed dams represented a viable alternative, providing a stable depth of water at less cost and with greater ease of operation and maintenance.²¹⁵ Consequently, in the years immediately following World War I, and before the Ohio River canalization program was complete, the Corps began to replace the original locks and dams on the upper Ohio. Emsworth Locks and Dam, constructed between 1919 and 1922, replaced Lock and Dam Nos. 1 (Davis Island) and 2. Deadman Island, subsequently renamed Dashields Locks and Dam, constructed between 1927 and 1929, replaced Lock and Dam Nos. 3 and 4. Both new dams were fixed crest concrete, gravity dams. As such, they represented a significant departure from previous practice on the Ohio, which had been limited to movable dams since 1875.

Deadman Island [Dashields] Locks and Dam

Construction of Emsworth Locks and Dam employed typical Ohio River type box cofferdams. Deadman Island Locks and Dam, begun five years after completion of work at Emsworth, relied upon steel sheet pile cofferdams. Work began at Deadman Island in May 1927. A conventional Ohio River type box cofferdam was used for construction of the lock (Plate 12), but for the dam the Dravo Corporation employed a circular cell type, steel sheet pile cofferdam, the first constructed on the upper Ohio. The determination to use this design was the result of careful study by the contractor, who described the design as “somewhat similar” to that used in the raising of the *Maine*.²¹⁶

The dam measured 1,585 feet in length, with a 60-foot wide base resting on solid rock 32 feet below lower pool level. Construction proceeded inside five sections of cofferdam, each enclosing an area 80 feet wide and between 210 and 498 feet long (Figure 30). The 40-foot diameter cells, each of which contained 100, 40-foot long steel piles, were placed 42 feet on center. The 2-foot space between cells was closed with two short arcs of sheeting connected to T-piles in the walls of the cells (Figure 31). This detail differed from that of the cofferdam used for raising the *Maine*, which used only a single arc of sheeting to connect adjacent cells. A wooden template served as a guide during driving of the piles. The piles were driven to rock and each cell, and the enclosed spaces between the cells, was filled with sand and gravel



Plate 12. Dashields Locks and Dam, Ohio River. View of lock cofferdam. Note the Ohio River type box construction and the extensive berm between the cofferdam wall and the permanent work. 2 February 1928. Photo 5248, Folder 1, Ohio River Dashields L/D Photographs 1927, Pittsburgh District, USACOE.

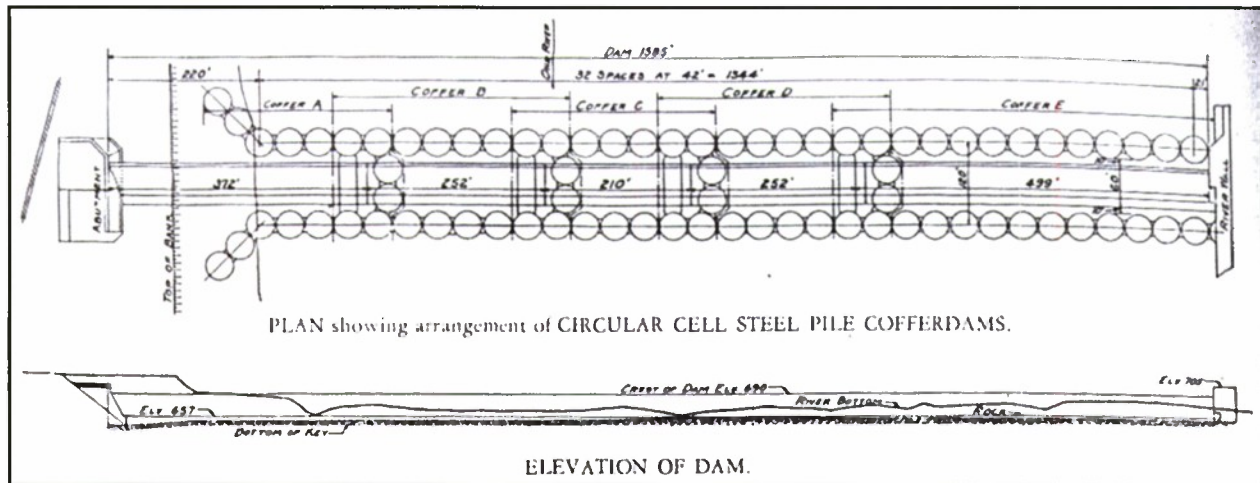


Figure 30. Dashields Locks and Dam, Ohio River. Plan showing circular cell cofferdams, 1928-1929. From Dravo Corporation *Locks and Dams* (1947).

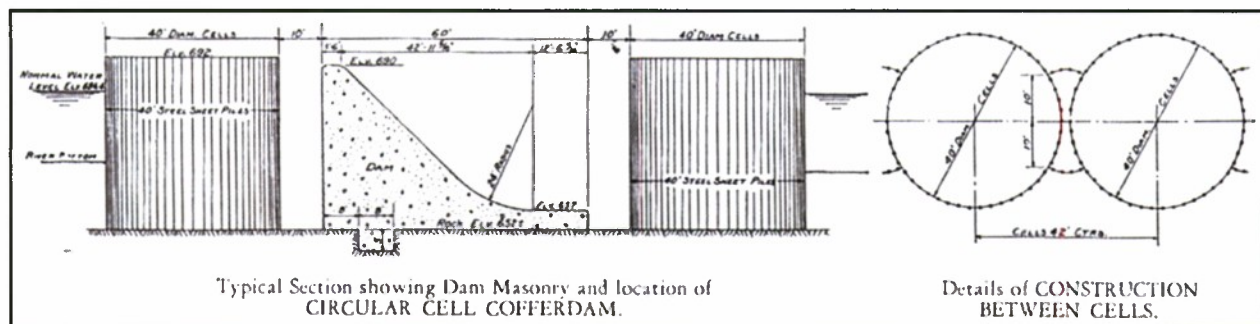


Figure 31. Dashields Locks and Dam, Ohio River. Section showing dam masonry and location of circular cell cofferdam and plan showing details of construction between cofferdam cells. Note the close proximity of the cofferdam to the permanent works, 1928-1929. From Dravo Corporation *Locks and Dams* (1947).

(Plate 13). A berm was placed against the outside of the entire cofferdam, but no interior berm was required and the cells sat only 10 feet from the permanent work.²¹⁷

Another innovation employed during construction of the Deadman Island Dam was the use of a caisson for construction of the abutment. The abutment extended approximately 160 feet into the right bank, which consisted of a high slag fill. A significant amount of excavation was required to carry the abutment into the bank the necessary distance. During excavation, the fill rose 66 feet above the work site on three sides. The dam contractor determined that the threat of cave-ins war-

ranted use of reinforced concrete caissons, in order to assure the safety of the work and eliminate the need for heavy shoring.

Two caissons were employed, with a 1-foot gap between them. The downstream caisson was rectangular in plan, measuring 27 feet by 75 feet, and 30 feet tall (Plate 14). The upstream caisson also measured 27 feet in width and 30 feet in height, but was L-shaped in plan to incorporate the base of the abutment. Each caisson had a chisel-shaped steel cutting edge. As concrete was poured into the caissons in successive horizontal pours, the caisson settled into the sand and gravel bottom of its own weight. Working gangs within the

chamber loosened material and moved it to the center of the caisson, beneath 7-foot diameter openings that admitted buckets used to remove the material. When the caissons had sunk 30 feet to bedrock, the chambers were cleaned, a 3-foot by 5-foot key was channeled into the bedrock, and the chamber and bucket openings filled with concrete. The gap between the caissons was also cleaned and filled with concrete. The remainder of the abutment was then constructed atop the caisson base.²¹⁸



Plate 13. Dashiels Locks and Dam, Ohio River. View toward right shore of cofferdam. 1 October 1928. Photo 5375, Folder 3, Ohio River Dashiels L/D Photographs 1927, Pittsburgh District, USACOE.

Montgomery Island Locks and Dam

The innovative cofferdam design employed at Deadman Island Dam was not used at the next replacement facility constructed on the Upper Ohio. In 1932 work began on Montgomery Island Locks and Dam, located 31.7 miles downstream from Pittsburgh. The new facility replaced movable Dam Nos. 4, 5, and 6. It consisted of a fixed concrete dam with vertical lift gates to regulate the pool height, and a pair of locks measuring 110 by 600 feet and 56 by 360 feet.²¹⁹

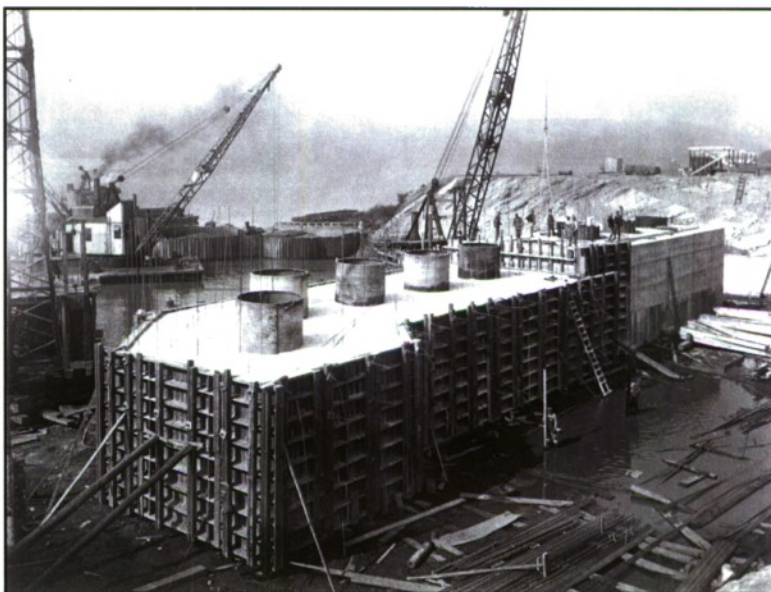


Plate 14. Dashiels Locks and Dam, Ohio River. View downstream of abutment construction showing caissons. 1 October 1928. Photo 5302, Folder 2, Ohio River Dashiels L/D Photographs 1927, Pittsburgh District, USACOE.

The contractor, Booth & Flinn Company of Pittsburgh, originally planned to erect a single cofferdam for the locks and their guide walls, but in order to reduce the amount of pumping required they determined to erect separate cofferdams for the upper and lower guide walls. The cofferdams were of a conventional box type design, with 60-foot steel sheet piling driven to rock or refusal forming the outer walls and wood sheeting of 4-inch by 12-inch fir planks, 24 to 26 feet in length, forming the inner wall (Plate 15). Steel tie rods connected the two walls of the cofferdam (Plate 16). Towers for stationary cableways,

were placed on the upper and lower arms of the lock cofferdam, which resulted in these arms being built 60 and 80 feet wide respectively, instead of the usual 24- to 30-foot width. The cofferdam fill consisted of sand and gravel dredged from the lock site (Plates 17 and 18).²²⁰

The Montgomery Island Locks and Dam cofferdams represent a technological step backwards, compared to the earlier Deadman Island cofferdams. They are a conventional box type cofferdam and differ from traditional



Plate 15. Montgomery Locks and Dam, Ohio River. Middle lock wall under construction, view upstream. Note the cofferdam in the rear with extensive earth berm between the permanent work and the cofferdam wall. 4 November 1932. Photo 6764, Ohio River Montgomery L/D Photographs 1932 - June 1934, Pittsburgh District, USACOE.

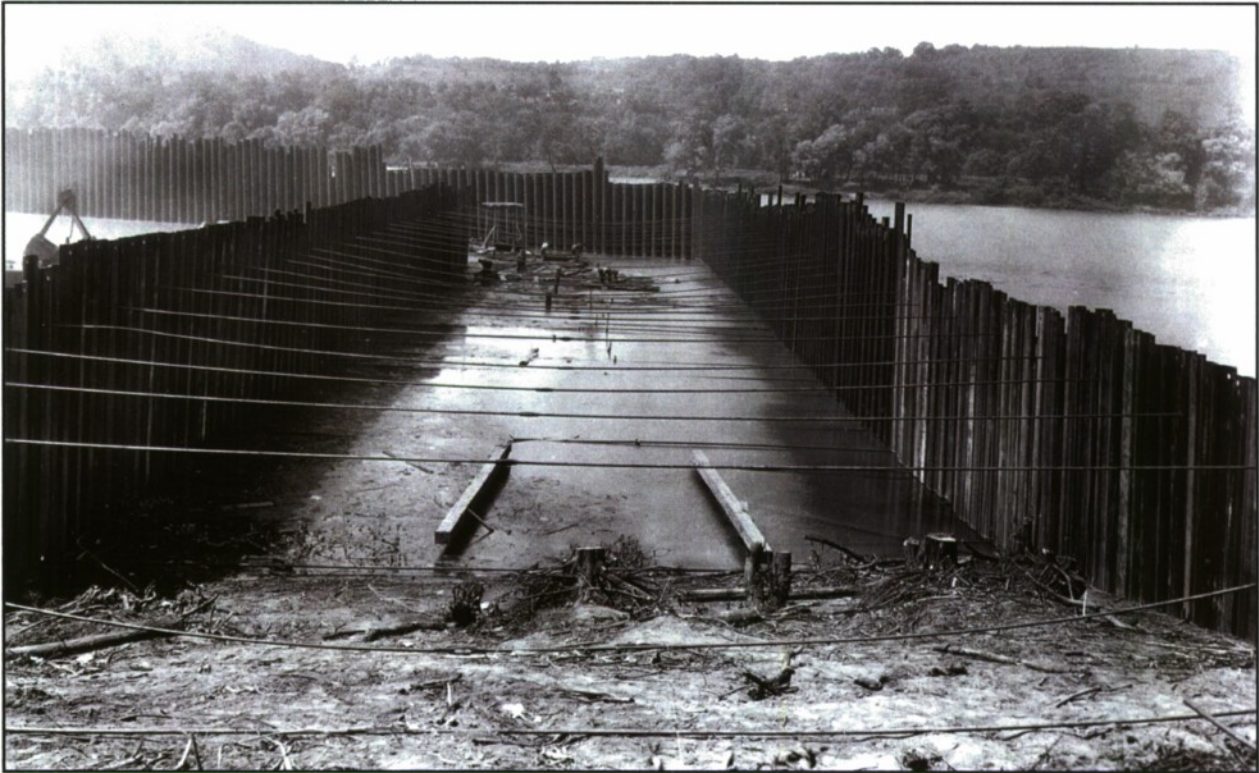


Plate 16. Montgomery Locks and Dam, Ohio River. Upstream arm of steel sheet pile box type cofferdam under construction. Note the metal tie rods between the two walls of the cofferdam. 29 June 1932. Photo 6537, Ohio River Montgomery L/D Photographs 1932 – June 1934, Pittsburgh District, USACOE.

design only in their substitution of steel sheet piling for wood sheet piling.

Gallipolis Locks and Dam

The Corps of Engineers designed Gallipolis Locks and Dam, located on the Ohio River near Gallipolis, Ohio, as part of a larger, more comprehensive system of improvements designed both to eliminate several of the original movable dams on the Ohio (Lock and Dam Nos. 24-26) and to provide a 9-foot navigation channel up the lower reaches of the Kanawha River (see below). At the time of its construction the Gallipolis Dam was the only roller gate dam on the Ohio, and included the largest roller gates in the world.²²¹

Between 1933 and 1936 the Dravo Corporation constructed two locks, measuring 110 feet by 600 feet and 110 feet by 360 feet, within a single diaphragm-type, cellular steel sheet pile cofferdam. The lines of diaphragm piling were spaced at 35-foot intervals. After placement of the fill, a concrete cap was poured to prevent the loss of fill in case of overtopping, and to supply a level working surface.²²²

The dam, constructed between 1935 and 1937, measured 1,149 feet in length and consisted of nine piers with eight roller gates, each gate measuring 125 feet in length and 29.5 feet in height. Three cofferdams, designed to fit site conditions, were used during construction of the dam. The circular steel sheet pile cells in the upstream arms of the

cofferdams consisted of 40-foot diameter cylinders spaced 50 feet on center and connected by short arcs of piling. The downstream arms employed diaphragm cells, with straight cross walls spaced every 35 feet, as well as circular cells with connecting arcs. The entire cofferdam was paved with concrete (Figure 32).²²³

The cofferdams employed during construction of Gallipolis Locks and Dam, like the innovative roller gate dam itself, represented the most advanced approaches to the design and construction of steel sheet pile cofferdams. Between 1927, when Dravo Corporation designed the circular cell cofferdams used at Deadman Island Dam, and their 1933 work at Gallipolis, this Pittsburgh-based firm had secured a position at the leading edge of cofferdam design and construction.

The Falls of the Ohio

In the 1920s, plans were developed to construct a hydroelectric power plant at the Falls of the Ohio. Engineering studies indicated that the pool height created by Dam No. 41 needed to be increased by 6 feet in order to provide the necessary operating head. In 1925, negotiations were completed, and



Plate 17. Montgomery Locks and Dam, Ohio River. Placing fill in upstream arm of cofferdam. Note the use of bulldozers to distribute the fill. 15 July 1932. Photo 6570, Ohio River – Montgomery L/D Photographs – 1932 – June 1934, Pittsburgh District, USACOE.



Plate 18. Montgomery Locks and Dam, Ohio River. River arm of steel sheet pile box type cofferdam under construction. Cranes are placing fill within the cofferdam. Note the timber wales and tie rod connections on the outside face of the sheet piling. 17 August 1932. Photo 6619, Ohio River – Montgomery L/D Photographs. 1932 – June 1934. Pittsburgh District, USACOE.

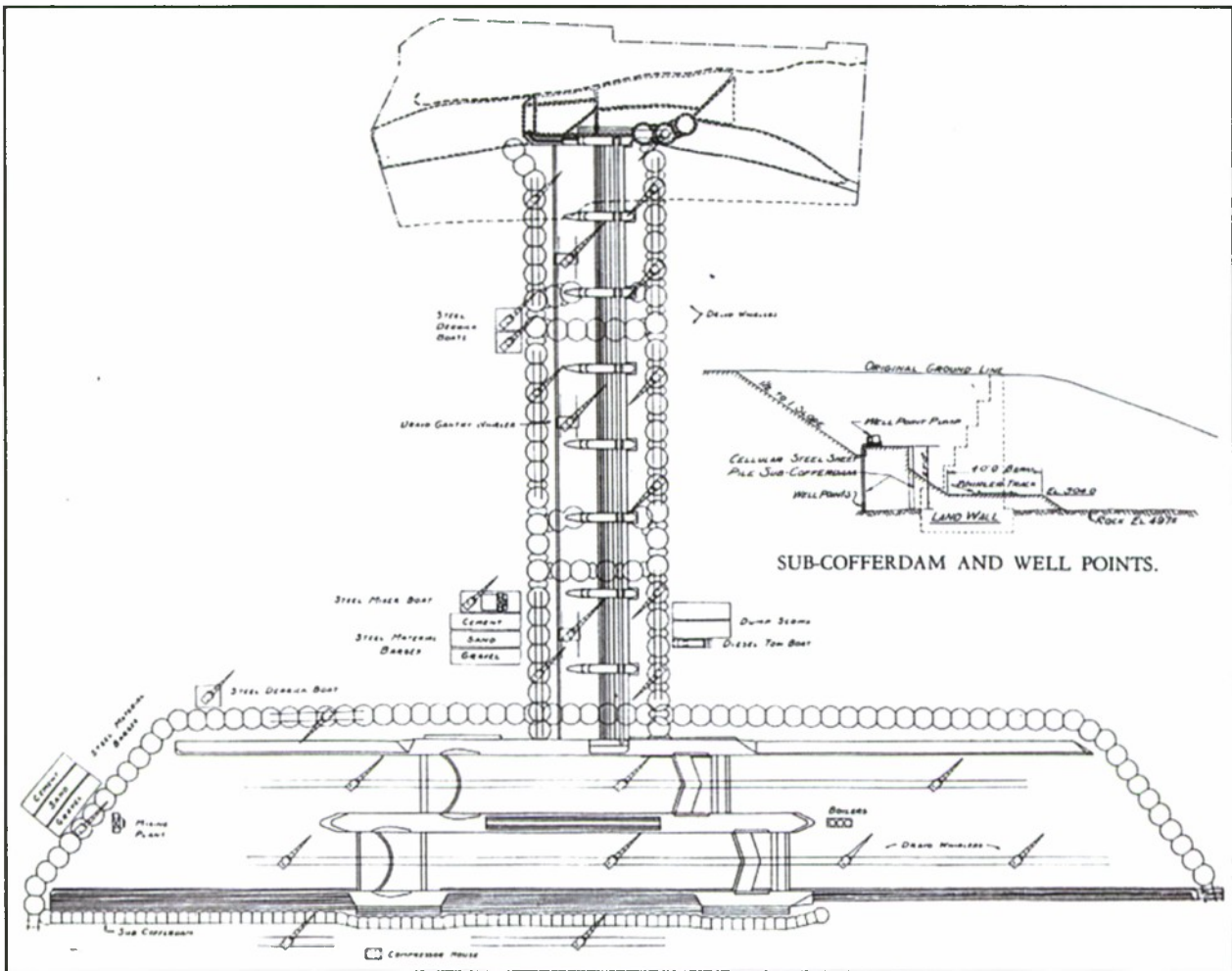


Figure 32. Gallipolis Locks and Dam, Ohio River. Plan showing arrangement of cellular steel pile cofferdams, with detail showing sub-cofferdam and well points at lock land wall, 1933-1937. From Dravo Corporation *Locks and Dams* (1947).

the Corps of Engineers agreed to build a new Dam No. 41, eliminate Dam No. 40, and extend the pool behind the new Dam No. 41 back to Dam No. 39. Plans called for a 8,650-foot long dam with a 534-foot long powerhouse adjacent to the Kentucky shore (Figure 33).²²⁴

As elsewhere on the Ohio, design of the cofferdam for the power plant work entailed consideration of the advantages and disadvantages of different height cofferdams. A taller cofferdam would extend the working season, since the construction site would be

better protected from flooding. A shorter structure would reduce the working season, but would be less costly to construct and less likely to be broken by a flood. Engineers consulted historical records detailing river heights dating back 26 years and determined that a cofferdam sufficiently tall to permit a six-month working season offered the maximum economy and efficiency. Two cofferdam designs were used, a standard crib cofferdam (Plate 19) and an Ohio River type box. Neither represented any innovation in cofferdam design or construction.²²⁵

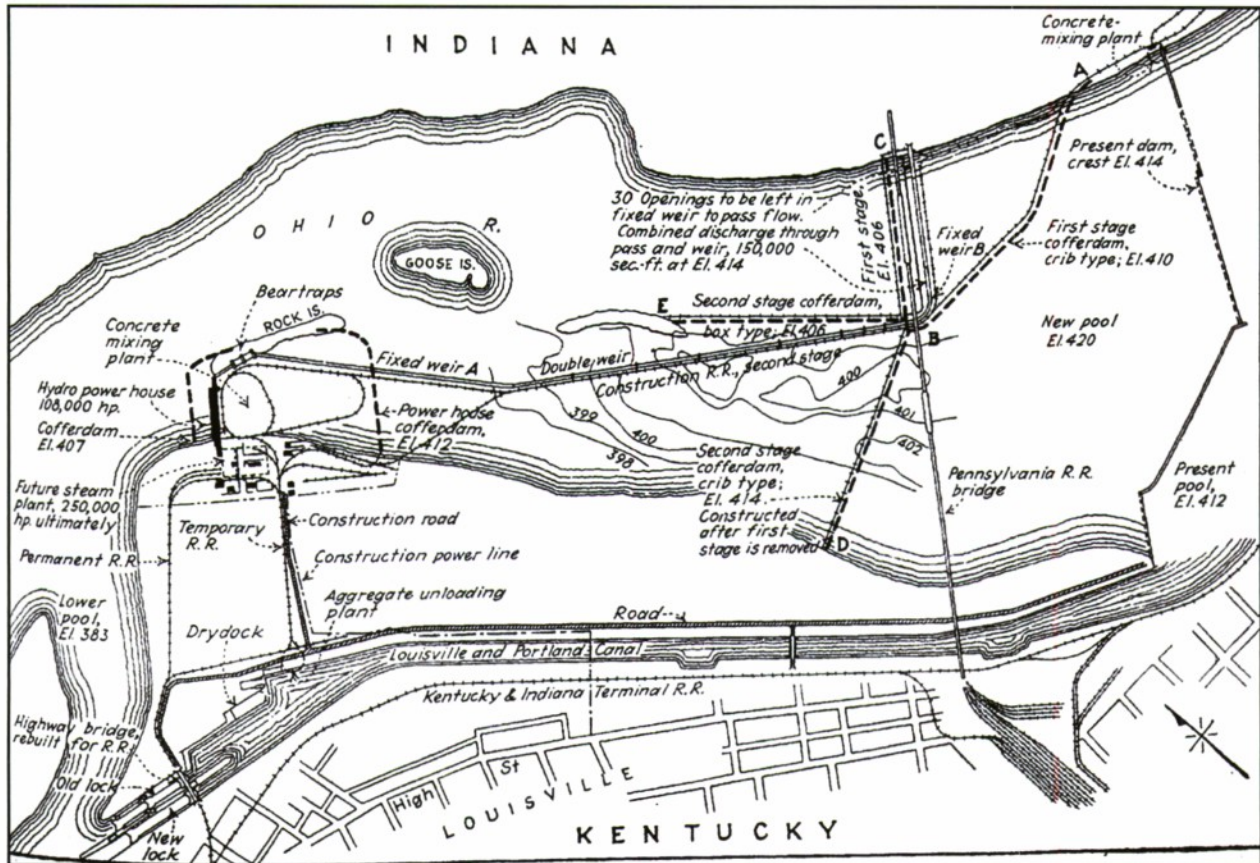


Figure 33. Ohio River Lock and Dam No. 41, Louisville, Kentucky. Site plan for 1920s improvements. From *Engineering News-Record* (May 12, 1927).

Steel Sheet Pile Cofferdams on Ohio Tributaries

Inland river construction during the period between the end of World War I and the onset of the Great Depression was concentrated upon the Ohio, where the principal goals were to complete the canalization of the river and then to upgrade facilities on the upper river. The other major rivers improved by the Corps of Engineers during this period were tributaries of the upper Ohio, the Monongahela, Allegheny, and Kanawha rivers, all of which had been at least partially improved by the construction of slackwater navigation systems prior to World War I. Steel sheet pile cofferdams began to appear in projects constructed

on these streams following their introduction and acceptance on the Ohio.

Monongahela River

The reconstruction and replacement of locks and dams on the Monongahela relied upon pile-founded and Ohio River type box cofferdams through the mid-1920s, at least partially because of Thomas P. Roberts' opposition to the use of steel sheet piling. In 1931-1932, the Corps of Engineers replaced original Locks and Dam No. 4 with a new facility at Charleroi, Pennsylvania, 41.5 miles upstream from the mouth of the river. The new facility consisted of a concrete dam and a pair of pile-founded locks, measuring 56 by 360 feet and 56 by 720 feet, located about 0.5

miles upstream from the old dam. The project's cofferdams, one for the lock and three for the dam, consisted of box cofferdams, 24 feet in thickness, with steel sheet piling instead of traditional wooden sheet piling. The Dravo Corporation designed and built these structures, which closely resembled the design employed by the firm for construction of the locks at Deadman Island on the Ohio in 1927.²²⁶

Allegheny River

The present slackwater navigation system on the Allegheny River, consisting of Lock and Dams Nos. 2–9, facilitates navigation for a distance of 71 miles to East Brady, Pennsylvania. Lock and Dam No. 1, the 1903 Herr's Island Lock and Dam, was removed after the 1935–1938 reconstruction of Emsworth Dam on the Ohio River just downstream from Pittsburgh. This work converted Emsworth into a gated structure, raising the pool height behind the dam by 7 feet and eliminated the need for both the Allegheny and Monongahela Locks and Dams No. 1. Constructed between 1920 and 1938, the Allegheny improvements consist of fixed, concrete gravity type dams, each with a single lock chamber measuring 56 feet by 360 feet.²²⁷



Plate 19. Aerial view of crib cofferdam at the Falls of the Ohio (Lock and Dam No. 41). Note that the cribs are not continuous, but are connected by a single row of wood sheet piling. 9 June 1926. RG 77-RH, Box 129, Ohio River L/D #41 – Cofferdam Folder, NARA.



Plate 20. Allegheny River Lock No. 2. Concreting keyway in caisson. 21 February 1933. Photo 6957, Folder 1, Allegheny L/D #8 Photographs 1929–1943, Pittsburgh District, USACOE.

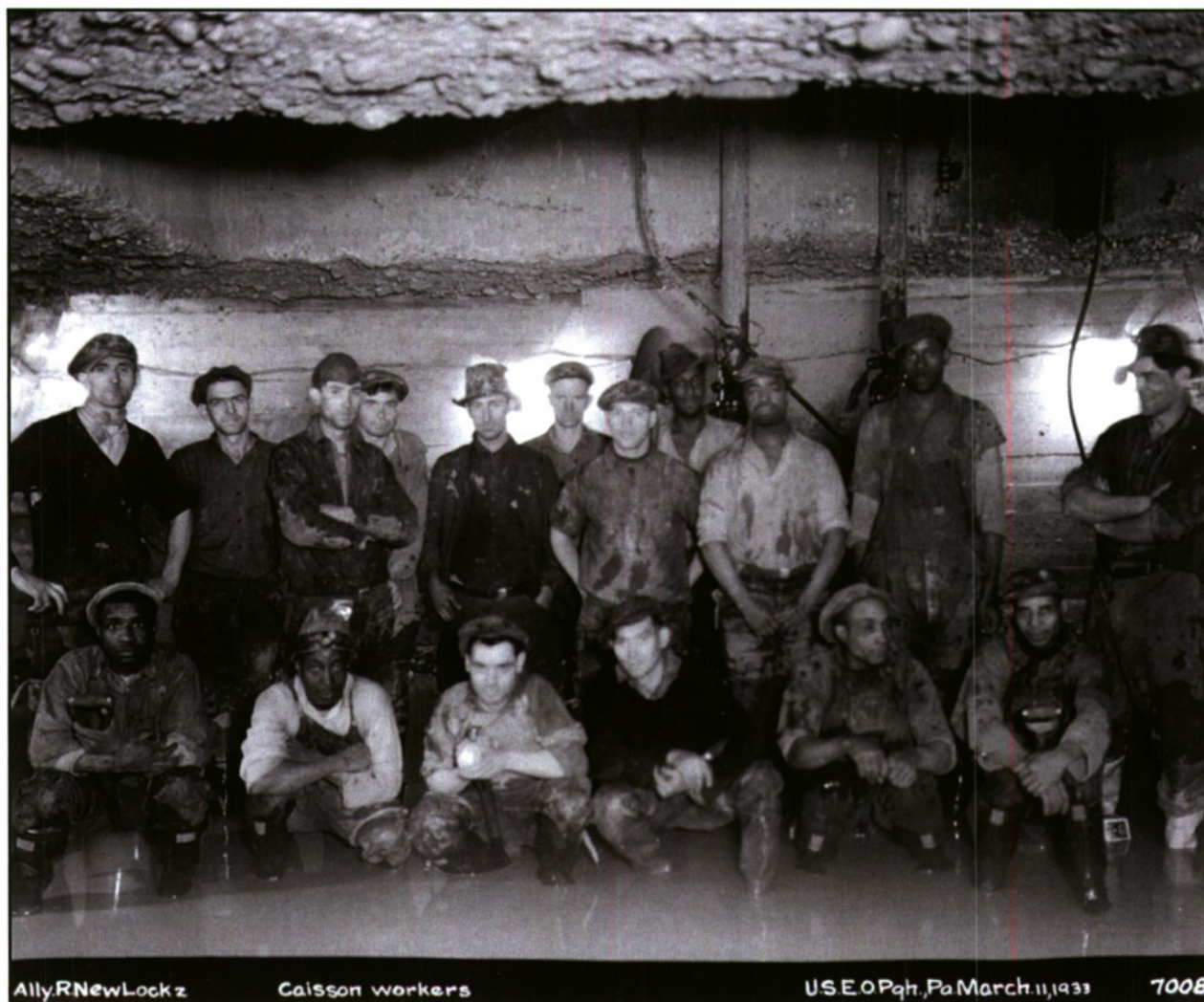


Plate 21. Allegheny River New Lock No. 2. Caisson workers. March 11, 1933. Photo 7008, Folder 3, Allegheny L/D #2 Photographs. 1933-1959, Pittsburgh District, USACOE.

Work began on Lock and Dam Nos. 4 and 5 in 1920, but it was 1927 before the locks opened to river traffic. Construction began on Lock and Dam No. 6 in 1927, Lock and Dam No. 7 in 1928, and Lock and Dam No. 8 in 1929. These three installations entered service in 1933. Lock and Dam Nos. 2 and 3, which by the 1930s were too small to handle the barge traffic then in use, were replaced in 1934.²²⁸

This second generation of navigation improvements on the Allegheny employed several types of cofferdams and both open and

closed caissons. The dams constructed on the Allegheny during this period are fixed crest concrete structures founded on bedrock, piles, or a combination of piles and cribs, depending upon site conditions. Dam Nos. 2, 4, and 8 are founded on bedrock and employ a keyway, an approximately 5-foot wide and 3-foot deep trench cut in the bedrock, to anchor the dam (Plate 20). The keyways of Dam Nos. 2 and 4 were cut by workers inside caissons (Plate 21), rather than cofferdams. The wood and steel caissons were lowered to the river bottom and pumped full of air to drive out the

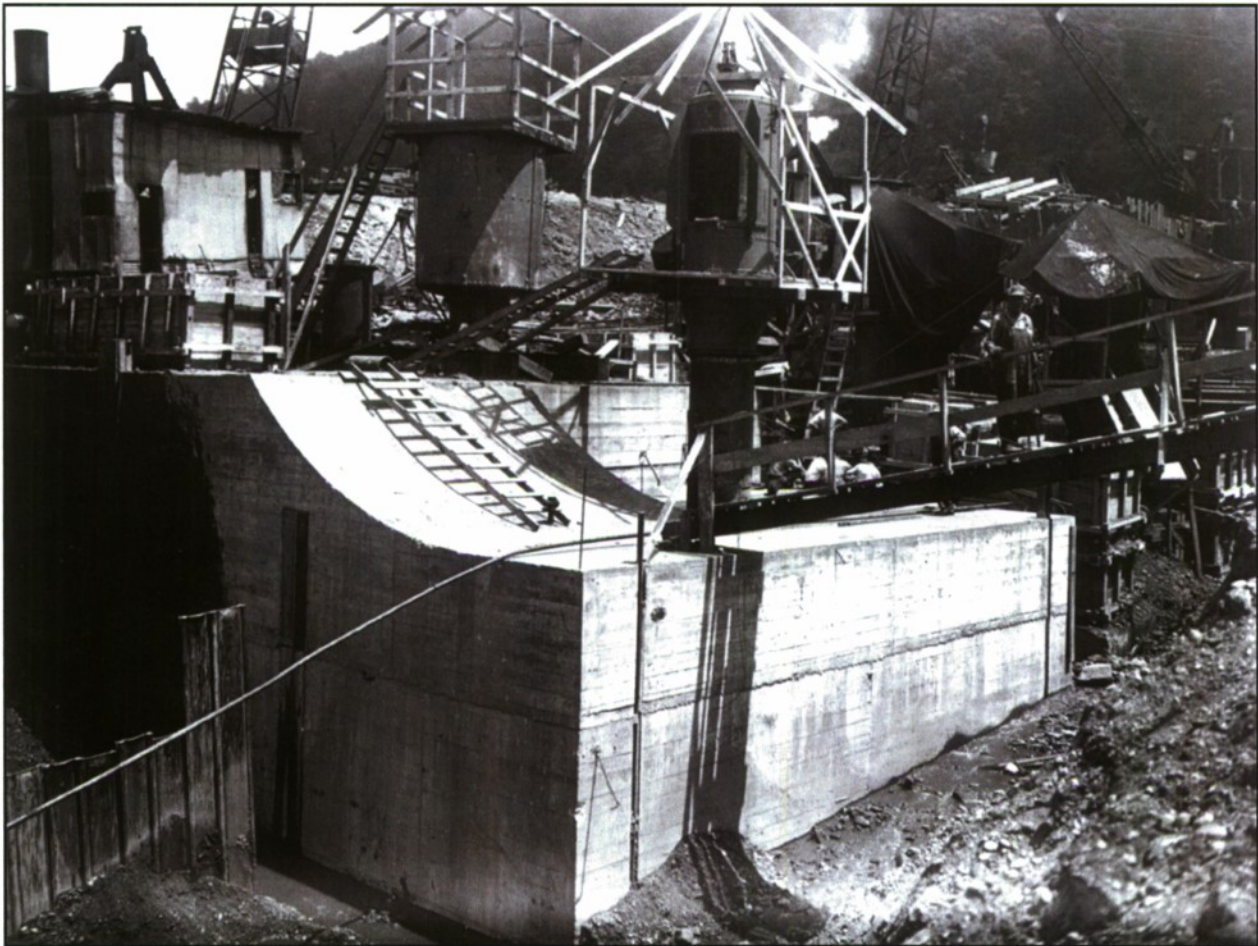


Plate 22. Allegheny River Lock No. 8. Air locks attached to caisson for construction of dam foundations. 25 June 1930. Photo 5552, Folder 2, Allegheny L/D #8 Photographs 1929-1943, Pittsburgh District, USACOE.

water. Workers then descended into the chamber to remove the overburden atop the bedrock and to cut the keyway (Plate 22). Dam No. 8 utilized poured concrete caissons, which were filled with concrete after the completion of the excavation work to become the foundation of the dam.²²⁹

The caissons were used only for keyway excavation and preparation of the dam foundations. Traditional cofferdams were used for the remainder of the work, including construction of the locks. The cofferdams at Lock and Dam No. 4 consisted of traditional timber cribs. The outside faces of the cribs were

lined with wood sheetpiling and protected with berms. The cofferdams at all other construction sites used steel sheet piling (Plate 23). At site Nos. 2, 3, and 9, the cofferdams consisted of 40-foot diameter circular cells (Plate 24), while at Nos. 5, 6, and 7 the Dravo Corporation employed box cofferdams with steel sheet piling, which proved effective in the shallow water conditions that characterized the construction sites. Lock No. 6 was unique in its use of a single-wall steel sheet pile cofferdam, bermed on each side.²³⁰

Dam No. 3, a 1,358-foot pile-founded structure, was constructed inside a series of five



Plate 23. Allegheny River Lock No. 8. Cofferdam construction, view downstream. 11 March 1933. Photo 5420, Folder 1, Allegheny L/D #8 Photographs 1929-1943, Pittsburgh District, USACOE.

cofferdams. When the work in one section was completed the cofferdam was removed, and the work continued within the next section. The erection of the cofferdam in successive sections, extending from the right bank to the previously completed lock, created a complex construction sequence. Each section measured approximately 500 feet in length. As the concrete work within each section was completed, the cofferdam walls were removed, permitting the river to pass through gaps intentionally left in the upper portion of the concrete structure. A bulkhead wall, the end wall of the next section, was built behind the end wall of each cofferdam permitting

removal of the previous section. This system allowed work to progress, at different stages in different cofferdams, reducing construction time and permitting the reuse of material from one cofferdam to the next.²³¹

The cofferdams, begun in 1934, consisted of diaphragm type steel sheet pile cells with arched inner and outer walls and straight connecting partitions, as at the 1913 Troy Lock and Dam. The 50-foot piles in the outer walls were driven to rock, while the 34-foot piles of the inner walls and connecting partitions simply were driven to the top elevation of the outer wall piles. This provided a flat

surface to the top of the cells. Railroad tracks were laid atop the cell to facilitate the handling of material and to provide for a pile-driver carriage. The design of the cofferdam cells did not represent a significant advancement in design, but it is significant to note that these cofferdams predate the diaphragm type structures used at Gallipolis Locks and Dam by about a year, and may have provided Corps engineers with an opportunity to familiarize themselves with the details, and performance under operating conditions, of the diaphragm type cell design.²³²

Kanawha River

In 1930, Congress approved the establishment of a 9-foot channel on the Kanawha River. This required construction of four major improvements to the existing slackwater system. Initial plans called for two high dams,

with movable roller gate crests and twin 56-foot by 360-foot locks, at Marmet and London, West Virginia. In 1932, in keeping with an increasing effort by the Corps to coordinate and link river improvement projects, plans were advanced for construction of a high roller gate dam and twin locks at Winfield, on the Kanawha, and a huge roller gate dam at Gallipolis on the Ohio River, 13.5 miles downstream from the mouth of the Kanawha. The dam at Gallipolis would provide a 9-foot pool up to the proposed site of the Winfield Dam, while also permitting removal of Lock and Dam Nos. 24, 25, and 26 on the Ohio. Together the four projects at Gallipolis, Winfield, Marmet, and London would provide a 9-foot channel for the entire navigable section of the Kanawha.²³³

The improvements on the Ohio River at Gallipolis, constructed between 1933 and 1937,

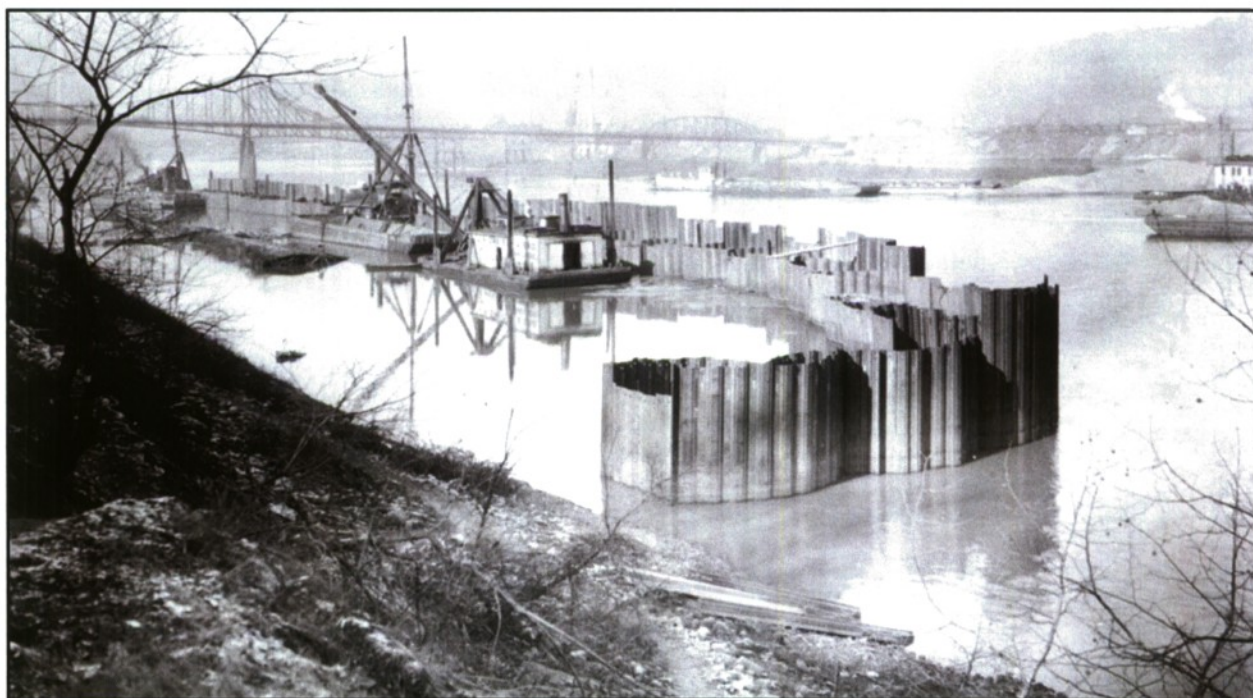


Plate 24. Allegheny River New Lock No. 2. Cofferdam for lock, looking downstream. 28 November 1932. Photo 6821, Folder 1, Allegheny L/D #2 Photographs, 1933-1959, Pittsburgh District, USACOE.



Plate 25. London Locks and Dam, Kanawha River. View downstream of Lock A cofferdam prior to placement of fill, showing wood spreaders and steel tie rods between walls of steel sheet piling. The lower set of tie rods are visible just at the waterline. 28 May 1931. RG 77-RH, Box 47, London L/D Lock and Lock Cofferdam Folder, NARA.

are described above. The three projects on the Kanawha, built between 1932 and 1937, all employed steel sheet pile cofferdams. The locks were constructed within box type cofferdams with steel sheet piling (Plate 25). One of these box type cofferdams failed at the London project in February 1932 (Plate 26). The dams were constructed within circular cell steel sheet pile structures (Figure 34). The cells were connected on both their inner and outer sides by short arcs of sheet piling, and were filled with sand and gravel and paved with concrete, both to protect the fill

from floodwaters and to provide a level working surface (Plate 27). The Dravo Corporation was responsible for the work at all four sites.²³⁴

Persistence of Traditional Technologies: Wilson Dam on the Tennessee River

During the 1920s, the Corps of Engineers routinely began to employ steel sheet piling cofferdams in river improvement projects. Dissemination and adoption of the new tech-

nology proceeded cautiously. Corps engineers and their civilian contractors first substituted steel sheet piling for wooden sheet piling in conventional box type designs. Gradually, as designers and contractors gained familiarity and confidence in the new material, cellular cofferdams, a radically different design, were introduced. By the early 1930s, Corps engineers were employing circular cell and diaphragm cell steel sheet pile cofferdams.

The increasing use of steel sheet pile cofferdams did not mean that traditional designs and materials were abandoned. The continued viability of traditional designs and methods is exemplified by construction of Wilson Dam on the Tennessee River between 1918 and 1925.

In 1916, Congress appropriated \$20 million for the construction of nitrate plants, a critical ingredient in the production of explosives and munitions. The production of nitrates



Plate 26. London Locks and Dam, Kanawha River. Collapse of river arm of Lock A cofferdam. The inner wall of sheet piling has failed and the cofferdam fill is sloughing out into the work area as the outer wall of piling fails. 4 February 1932. RG 77-RH, Box 47, London L/D, Lock and Lock Cofferdam Folder, NARA.



Plate 27. London Locks and Dam, Kanawha River. View of second dam cofferdam. Note the steel pile cofferdam cells and the whirley crane mounted atop the cofferdam. 2 November 1933. RG 77-RH, Box 47, London L/D. Dam and Cofferdam Folder, NARA.

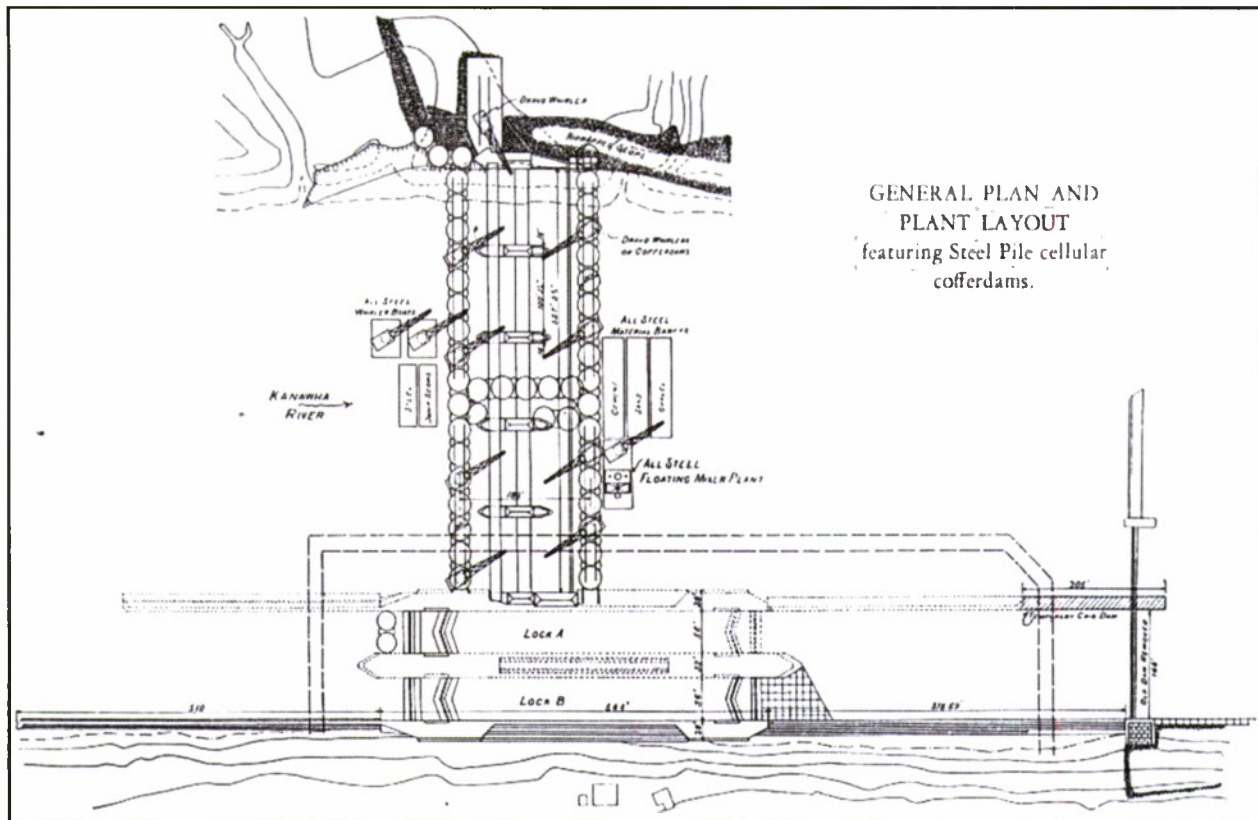


Figure 34. Marmet Lock and Dam, Kanawha River. General plan and construction plant layout showing cellular steel pile cofferdam, 1932-1934. From Dravo Corporation *Locks and Dams* (1947).

required prodigious amounts of electricity. President Woodrow Wilson chose Muscle Shoals on the Tennessee River as the site for a nitrate plant because the shoals offered a favorable location for the generation of abundant, inexpensive hydroelectric power. Two nitrate plants were built in the vicinity of Muscle Shoals by 1918. Wilson Dam, the second dam within the complete project, was authorized in February 1918. The dam was intended to provide electrical power for the production of nitrates or other products needed for the manufacture of munitions during wartime. It was assumed that in peacetime, the nitrates produced by the plants could be used to produce fertilizer and other non-military products.²³⁵

When completed in 1925, Wilson Dam was the largest dam in the world, nearly 1 mile long and 139 feet high, and contained 36 million cubic feet of concrete. The project consisted of three sections: a two-stage navigation lock on the north bank of the river, and the spillway and powerhouse sections to the south. Construction of Wilson Dam required the use of six cofferdams. These all consisted of rock-filled timber cribs, measuring 14 to 16 feet square, with scrap lumber used as sheeting (Plates 28-30). The upstream arms of the cofferdams consisted of a single row of cribs with clay and earth “sealing material” placed against the upstream face. The river and downstream arms consisted of two rows of rock-filled 16-foot wide cribs, placed 16 feet apart, with the space between the rows filled



Plate 28. Wilson Lock and Dam, Tennessee River. View of rock excavation in south end corner of Cofferdam No. 1. Note timber crib cofferdam with rock infill. October 14, 1919. RG77-RH, Box 169, Tennessee River Wilson L/D Cofferdam #1 Folder, NARA.

with earth and clay. The powerhouse cofferdam comprised two rows of 14-foot cribs, with a 20-foot puddle wall between the rows.²³⁶

The Corps of Engineers' decision to use traditional rock-filled crib cofferdams in the construction of what was then the largest masonry dam in the world exemplifies the importance of issues such as the availability of local construction materials, the cost of transportation, and the condition of the river bottom in determining the type of cofferdam employed for any particular project. The relatively remote construction site, which increased transportation costs to the site, the abundant local supplies of inexpensive timber, and the condition of the river bottom permitted the efficient and economical use of crib cofferdams and obviated against the use of more expensive, but technologically sophisticated steel sheet-pile structures. Clearly, decisions regarding the appropriate

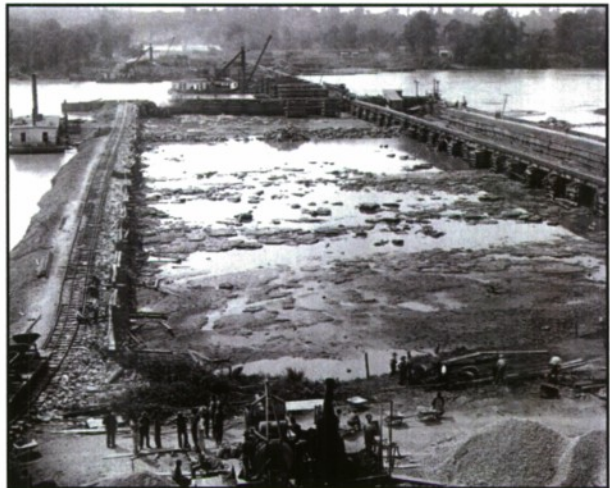


Plate 29. Wilson Lock and Dam, Tennessee River. View of interior of Cofferdam No. 1. Note that the river and upstream (left) arms of the cofferdam are of timber crib construction, while the downstream arm (right) is an Ohio River type box structure. 26 August 1919. RG77-RH, Box 169, Tennessee River Wilson L/D Cofferdam #1 Folder, NARA.

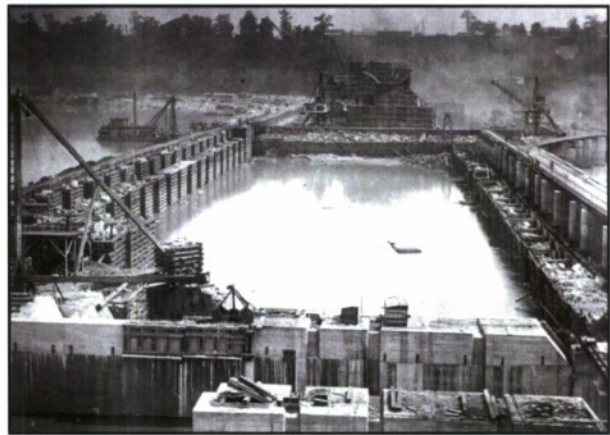


Plate 30. Wilson Lock and Dam, Tennessee River. View of interior of Cofferdam No. 5. Note that the upstream (left) arm of the cofferdam consists of cribs constructed of dimensional lumber, while the river and downstream (right) arms appear to be log cribs. 31 July 1923. RG77-RH, Box 169, Tennessee River Wilson L/D Cofferdam #5 Folder, NARA.

type of cofferdam for a particular construction project were not based solely upon the availability of new technology.

9 Slackwater Navigation on the Upper Mississippi

Prior to 1930, the most significant inland river improvement projects undertaken by the Corp of Engineers involved the canalization of the Ohio River. After 1930, the scene shifted to the upper Mississippi River, where the Corps oversaw the design and construction of a slackwater navigation system that stretched from Minneapolis to St. Louis. The design of the upper Mississippi slackwater system was both shaped by and expanded upon the Corps' Ohio River experience. Cofferdams used upon the upper Mississippi included the full range of design types and technologies previously described. Indeed, the eclectic approach to cofferdam design seen on the upper Mississippi tends to confirm that local conditions drove the selection of the cofferdam design for any particular project. During the 1930s, Corps engineers and their contractors had not settled upon a standardized approach to cofferdam design and construction.

From Open River to Slackwater Navigation

Prior to 1930, the Corps of Engineers managed the upper Mississippi River for open river navigation. In 1882, reservoir dams were constructed at the river's headwaters to provide additional water during dry seasons, but these dams were not located in navigable sections of the river. In 1894, work began on two locks and dams near St. Paul and Minneapolis, a section of the river generally closed to open

river navigation. In 1903, the Keokuk & Hamilton Water Power Company broke from the tradition of open navigation when it planned to construct a dam at the foot of the Des Moines Rapids. The Corps of Engineers endorsed this project in 1902, following a study that determined that although 15 percent of river traffic passed the rapids in open water, rather than through the government lock, the amount of open river traffic was declining, largely because of a decline in the number of packet steamers and lumber rafts. Work began on the project in 1905, and when completed in 1914 it consisted of a lock and non-navigable dam (Plate 31).²³⁷

Despite the precedent set by the Keokuk project, Corps improvements on the Upper Mississippi continued to emphasize open river navigation. The next major project on the river, the Moline Lock, located approximately 123 miles upstream from Keokuk and completed in 1908, included provisions for open river navigation. The Dravo Corporation used an Ohio River type box cofferdam for construction of the lock. The cofferdam was designed so that the river arm cut diagonally across the flow of the river, in water from 8 to 12 feet deep and with a current of 5 miles per hour. Attempts to hold the cofferdam in position with anchors and an anchored spud boat proved unsuccessful, so holes were drilled into the rock river bottom, eyebolts driven into the holes, and wire rope clamped to the eyebolts and the cofferdam.²³⁸



Plate 31. Mississippi River Lock and Dam No. 19. Building last crib of Illinois cofferdam. Dam constructed by the Keokuk & Hamilton Water Power Company and subsequently incorporated into the 9-foot channel project. A timber crib cofferdam. The speed of the water through the gap and the absence of any safety equipment for the workers are striking. 20 July 1912. RG77-RH, Box 85, Mississippi River L/D #19, Cofferdam Folder, NARA.

The Corps did not begin to move away from open river navigation on the upper Mississippi until the late 1920s. The lock and dam constructed at Hastings, Minnesota, between 1928 and 1930 provided for a navigable pass only 100 feet wide, narrower than those provided at the Moline Lock and the 1921-1924 Le Claire Canal at the Rock Island Rapids. The narrow navigable pass forced most river traffic to pass through the lock.²³⁹

The movement for a slackwater navigation system on the Upper Mississippi was promoted during the 1920s as a means of alleviating the farm crisis in the upper Midwest and allaying inequities between railroad and water freight rates that developed after the 1914 completion of the Panama Canal. In the early 1920s, agricultural commodity prices plummeted as European nations resumed production following the end of World War I and as new agricultural producers, such as Australia and Argentina, began to obtain a

larger segment of the international markets. At the same time, per-acre yields for American farmers were increasing, resulting in over production during a period of rising costs. The completion of the Panama Canal lowered shipping rates for farmers in other regions of the United States, but not for farmers in the upper Midwest. Within the region, it was widely held that a reliable, year-round water route to the Gulf of Mexico would result in lower railroad freight rates and economic relief for farmers.²⁴⁰

In 1927, Congress ordered the Corps of Engineers to study the feasibility of creating a 9-foot deep channel on the Upper Mississippi, which would create a uniform channel depth from St. Paul to New Orleans. The Corps initially determined the project economically inadvisable, but following additional surveys, and under considerable political pressure, reported in favor of the project in February 1930. The project was quickly added as an amendment to the 1930 Rivers and Harbors Act.²⁴¹

As originally authorized, the 9-foot channel project called for construction of 26 non-navigable dams and associated locks between St. Paul, Minnesota, and Alton, Illinois (Figure 35). In 1937, Congress authorized a 4.6-mile extension upstream that resulted in the construction of two additional complexes. In 1953, Congress authorized an extension of the project downstream to St. Louis, which resulted in the construction of the Chain of Rocks Canal and Lock No. 27, both completed in 1964. The final project consisted of 29 lock and dam complexes strung along 669 miles of river.²⁴²

Initially, design work for the project was centralized in the Corps' newly created Upper Mississippi Valley Division. William H. McAlpine served as the division's chief engineer. McAlpine previously served as supervisor of construction for the government locks and dams on the lower Ohio. By the end of 1931 designs for the first two complexes, Lock and Dam No. 4 at Alma, Wisconsin, and Lock and Dam No. 15 at the foot of the Rock Island Rapids in the Quad Cities, had been completed. The designs for all individual sites included a gated, non-navigable dam, a 110-foot by 600-foot lock, and, at minimum, provision for an auxiliary lock measuring 100 feet by 269 feet. The dams all had gated spillways, fitted with some combination of roller gates and/or Tainter gates.²⁴³

In the early days of Franklin D. Roosevelt's administration, the project was attacked on environmental grounds, for the flooding and destruction of habitat caused by the dams; on progressive grounds, because it would allegedly lead to the over-industrialization of the region; and on economic recovery grounds, as a subsidized form of competition with tax-paying railroads. Proponents of the project argued that the opposition all stemmed from the railroad companies, who feared competition and, in the depths of the Depression, cited the employment opportunities offered by the project.²⁴⁴

In 1933, the project's prospects to assist economic recovery and provide employment overwhelmed the opposition. The design process was decentralized, with each Corps district along the river assuming responsibility for the complexes located within their

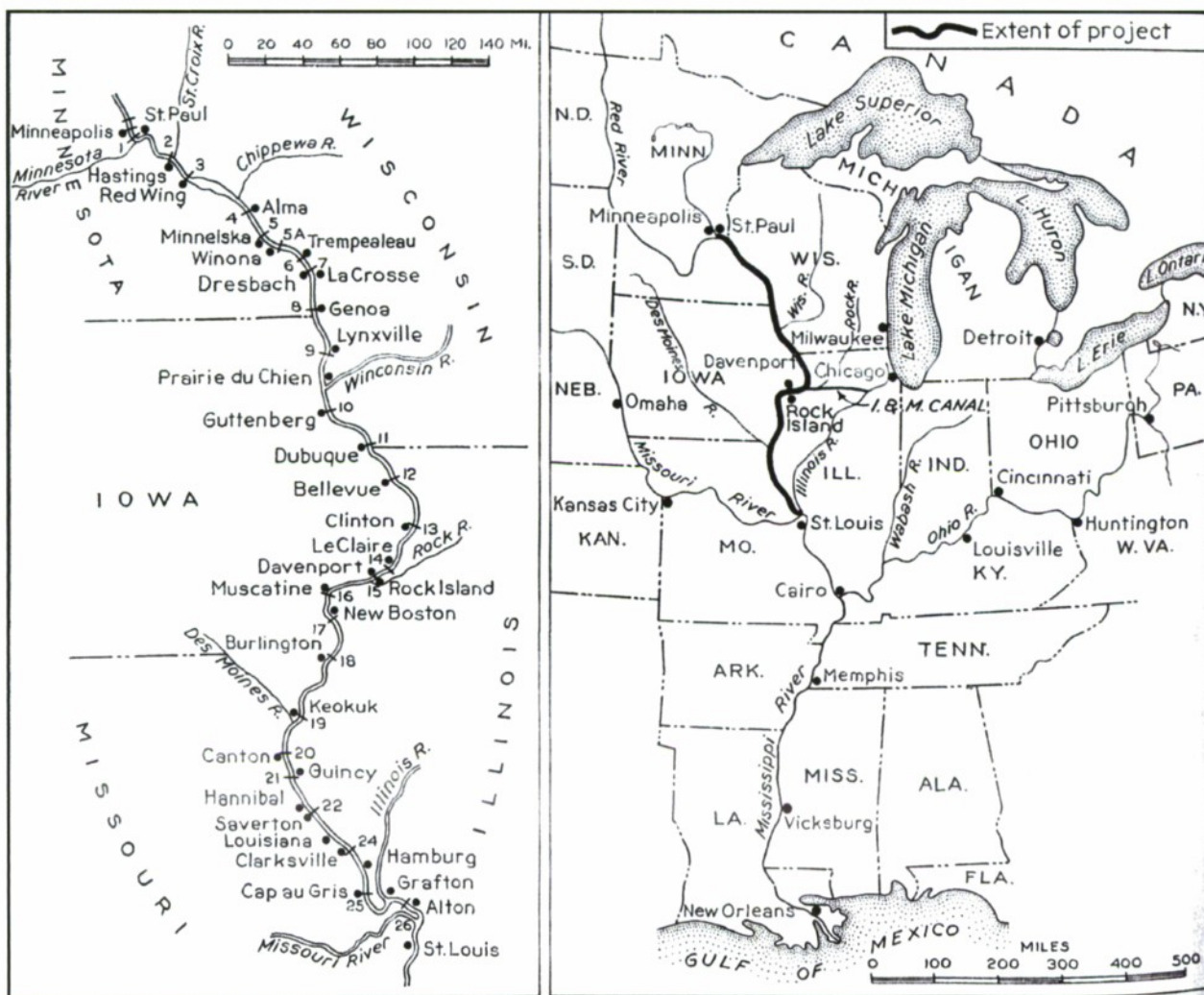


Figure 35. Map of upper Mississippi 9-foot channel project. From Gross and McCormick "The Upper Mississippi River Project" (1941).

boundaries. It also was decided to move forward on many complexes simultaneously, since that approach would employ more workers. These decisions led to an extraordinarily rapid pace of technological innovation on the project. Innovation occurred so rapidly that some structures essentially were out of date when completed.²⁴⁵

Upper Mississippi 9-Foot Channel Project Cofferdams

In general, the contractors for individual locks and dams were responsible for design of

the required cofferdams. The Corps of Engineers incorporated requirements as to the height and stability of the cofferdam into the contract specifications for each project, and required that the contractor's plans be approved by Corps engineers. Details in regards to materials, type, and construction, as well as the final adequacy of the structure, were left to the contractor. Contractors employed the full range of cofferdam design types on the upper Mississippi. Indeed, in 1935, at Lock and Dam No. 3, located about 6 miles upstream from Red Wing, Minnesota, and



Plate 32. Mississippi River Lock and Dam No. 24. Aerial view of steel pile box cofferdam for first portion of the dam. Note interior berms. 7 September 1938. RG77-RH, Box 88, Mississippi River L/D #24, Dam Cofferdam Folder, NARA.

about 40 miles downstream from St. Paul, a simple earthen dike served as the cofferdam for the lock.²⁴⁶

At the onset of the project, wooden Ohio River type box cofferdams were the most commonly used design type. This partially reflected the personal preferences of the project's head engineer, William H. McAlpine, who believed that the difficulty and expense associated with removing and salvaging steel sheetpiles outweighed their advantages. Only in 1933, after design responsibility was decentralized out of the Upper Mississippi Valley Division and McAlpine transferred to the Office of the Chief of Engineers in Washington, D.C., did steel sheet pile cofferdams, of both box and cellular type designs, become widely used on the project. A reduction in the cost of steel sheet piling, combined with its high salvage value, contributed to more widespread use of this material.²⁴⁷

Box type cofferdams generally measured 20 to 30 feet thick, while the individual cells of cellular cofferdams generally measured 25 to 30 feet in diameter. Both designs usually were provided with outside and inside berms to improve stability and provide a longer course of travel for seepage (Plate 32). The government specified the minimum height above low water for each cofferdam, generally the equivalent of a three-year flood. Some contractors chose to build taller cofferdams in order to provide greater protection against floods but, in general, the Mississippi cofferdams were 20 to 30 feet tall, measured from the river bottom to the structure's finish elevation. The cofferdams were, therefore, approximately square in cross section, as tall as they were wide. Penetration of the sheet piles into the river bottom varied considerably, from only a few feet to about 15 feet.²⁴⁸

Some contractors used steel sheet piling for the outside wall and wood piling for the inside wall of box type cofferdams (Plate 33). The steel proved more resistant to abuse from boats, barges, ice, and debris, and could be driven more deeply into sand bottoms, offering additional stability and protection from scour. If the outside wall of the cofferdam proved fairly tight, no advantage was seen in making the inner wall watertight. Ground water gauges that measured the line of saturation within the cofferdam fill indicated that the inner wall had no influence on the saturation line. The only purpose served by the inner line of sheeting was to retain the fill material and provide stability to the structure. For cofferdams founded on rock bottoms, the inner wall of sheeting did somewhat influence the saturation line, depending upon the relative tightness of the sheeting.²⁴⁹

By early 1936, thirty cofferdams, most enclosing lock sites, had been constructed in the Rock Island District, which included Lock and Dam Nos. 10 through 22. Nine of these cofferdams were seated on rock, while the remainder was on sand. Those seated on rock presented no significant engineering challenges in terms of design and maintenance. The principal design requirements issued by the Corps of Engineers called for lateral stability, to resist sliding, and fill material that offered sufficient resistance to the passage of water, reducing leakage to an amount economically handled by pumps. River sand, readily available at each job site, generally was used as fill because the cost of impervious fill, which would eliminate the need for pumping, exceeded the cost of removing a reasonable amount of leakage with pumps.



Plate 33. Mississippi River Lock and Dam No. 4. Detail of lower arm of lock cofferdam before filling. Inside wall of cofferdam constructed with wood piles, wales, and sheet piling. Outside wall of steel sheet piling. The walls are tied together with steel tie rods extending through the piles on the inside wall. Note pile driver rig at left rear driving wood sheet piling. 17 March 1933. RG 77-RH, Box 72, Mississippi River L/D #4, Lock Cofferdam Folder, NARA.

Sand provided both adequate structural stability and an acceptable degree of impermeability.²⁵⁰

Engineers were not greatly concerned with water passing through the cofferdam structure and into the work area, though, as noted, berms were widely employed to lengthen the course of travel for seepage. The major source of water flowing into the work area was percolation of water through the material below the cofferdam. If the sheetpiling could not be driven to an impervious stratum, and in many instances, the depth of the sand and gravel overlaying bedrock approached 100 feet, no depth of penetration was considered sufficient to guarantee against excessive leakage from beneath the cofferdam. Engineers observed that a 20- to 25-foot thick cofferdam built upon impervious material and filled with river sand admitted about 1 gallon of water per minute per foot of length at low river stages. The same cofferdam design

seated on sand admitted 5 to 15 times this amount of water. The material underlying the cofferdam, rather than the design and construction of the structure itself, proved the major factor in determining the amount of expected leakage. Some engineers considered the upward percolation of water into the cofferdam as a rise of ground water, rather than leakage.²⁵¹

Prior to about 1933, virtually all cofferdams were kept free of water by using large surface pumps to discharge water collected in sumps. Water was led to the sumps by surface ditches or by small pumps that removed water from specific areas of the work site. Beginning in 1933, contractors began to use the well-point system to keep the working area free of water (Plate 34). Well points consist of a series of vertical, perforated tubes, driven into the ground that collect subsurface water. The individual tubes are connected to a horizontal header pipe, which is in turn connected to a pump that discharges the collected water. The well point system, in effect, lowers the water table within the work area. A well-point system was more costly than large surface pumps, but it permitted work to be conducted in drier conditions, thus increasing productivity.²⁵²

Cofferdam construction was generally the first major task undertaken at any site, and removal of the cofferdam was among the last tasks completed. Pumping and maintenance of the cofferdam were a continuous, and often



Plate 34. Mississippi River Lock and Dam No. 21. Dewatering the steel pile box type cofferdam for first portion of dam. Note well point system used to lower water table within cofferdam. 21 October 1936. RG77-RH, Box 87, Mississippi River L/D #21, Dam Coffers Folder, NARA.

costly, operation throughout the duration of the work. During high river stages, when the cofferdams were exposed to considerable heads, as well as accelerated currents that increased scour, “a feeling of uneasiness, including extreme watchfulness and care is always present.” These were, after all, temporary structures designed to balance “reasonable safety and cost.”²⁵³

The following sections provide information on the wide array of cofferdam design types, ranging from simple earthen dikes to circular cell steel sheet pile cofferdams, employed on the upper Mississippi. In addition to describing cofferdam designs, these sections also offer some insights into the overriding significance of local conditions in the determination of a viable design and practical construction methods. New York City-based, Spencer White & Prentiss, one of the nation’s preeminent foundation engineering firms, constructed many of these structures.

Ohio River Type Box Cofferdams

As noted above, many of the early upper Mississippi lock and dam projects employed wooden Ohio River type box cofferdams. As on the Ohio, these structures consisted of an articulated framework of wood wales and steel tie rods (Figures 36 and 37). The framework, which generally measured 20 feet wide, was fabricated on a barge and placed into position using a derrick (Plate 35). The framework rested directly on the river bottom. If rock was located close to the river bottom a trench might be dredged to permit the framework to sit directly upon the rock. Wood sheet piling set into the framework also rested directly upon the river bottom.²⁵⁴

This design was not self-supporting, and its stability depended upon protective berms placed against the inside and outside walls of the structure. Great care was taken, particularly during periods of high water, to assure that the river current did not erode the outside berm, which generally was covered with rip rap. Upstream corners were heavily protected with rip rap or dolphins (a group of pilings placed off the corner), the latter also offered a degree of protection against floating ice and debris.²⁵⁵

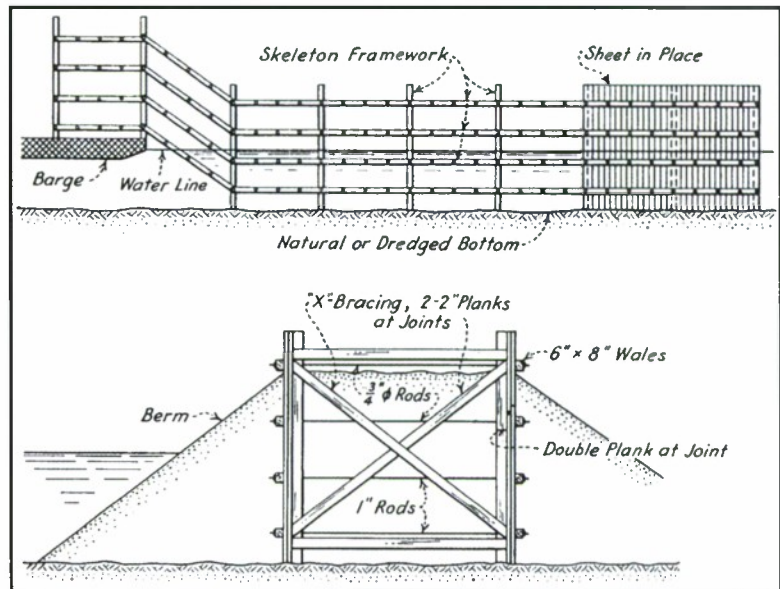


Figure 36. Construction of Ohio River type box cofferdam. From White and Prentis *Cofferdams* (1940).

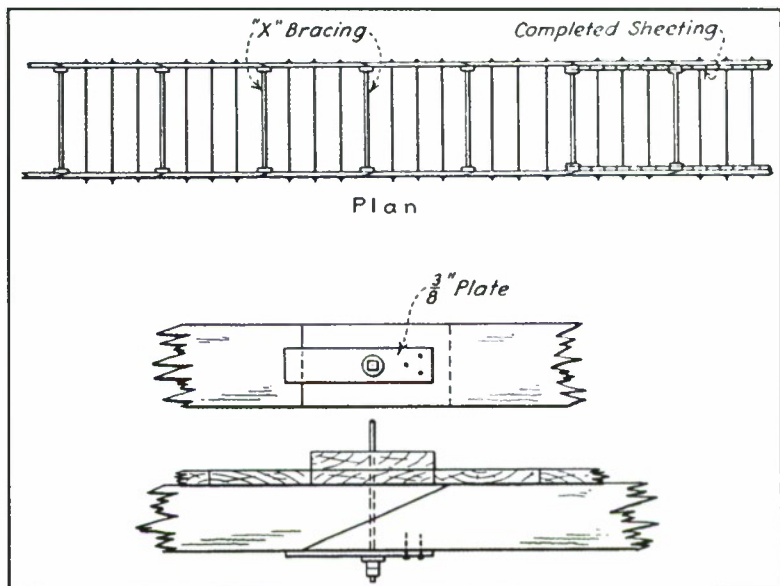


Figure 37. Ohio River type box cofferdam. Detail of articulated joint. From White and Prentis *Cofferdams* (1940).

Double-Wall Wood and Steel Cofferdam – Lock No. 6

Beginning in late 1933, Lock No. 6, at Trempealeau, Wisconsin, 139 miles downstream from Minneapolis, was constructed within a double-wall cofferdam with earth fill. This

design, one of the most common used on the upper Mississippi, consisted of a pile-supported box cofferdam, built in place, filled with sand, and provided with a substantial interior berm. The walls generally consisted of steel sheet piling or a combination of wood and steel sheet piling. At Lock No. 6 steel sheet piling was used for the outer (river) wall, while the inner (land) wall was constructed using wood sheet piling.²⁵⁶

The Lock No. 6 cofferdam measured 25 feet in width and enclosed an area of approximately 8.25 acres (Figure 38). It rested upon an indeterminate depth of sand. The steel sheet piling consisted of Carnegie Arch Web piling measuring between 37 and 45 feet in length. The wood sheet piling was rough 3 inch by 12-inch planks. Both walls were braced during construction with wood piles and wales as falsework, and were permanently tied together with 1.5-inch tie rods.²⁵⁷

Work on the cofferdam began in early December 1933, and by the middle of the month the Mississippi had frozen solid, forcing the contractor to change from water to land construction methods. The ice actually aided the construction process, bracing the framework during construction and permitting all material to be hauled directly to the work site in railroad cars.²⁵⁸

Construction began by driving wooden piles for a light trestle that served as bracing and falsework for

the cofferdam piling. Next, the permanent wales for the inner and outer walls were bolted into place from the ice and temporary sway bracing and pile capping installed. This structure supported a steam-powered caterpillar crane, which was used to drive both the steel and wood sheet piling. As the work progressed, the temporary bracing was removed and moved forward, so that it was continuously reused. The inner wall consisted of a row of wood piles with wales bolted to their outside faces. The wood sheet piling was driven against these wales and a second set of wales placed outside the sheet piling. The steel tie rods passed through this outside row of wales and were secured by nuts. An addi-

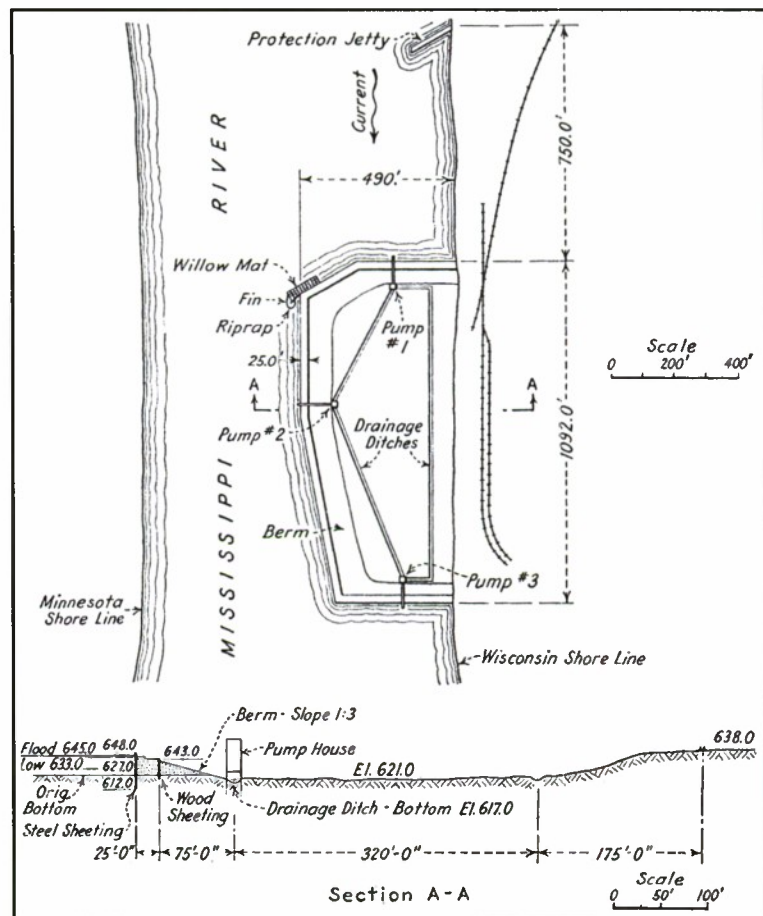


Figure 38. Mississippi River Lock and Dam No. 6. Double-wall cofferdam with earth fill, plan and section. From White and Prentis *Cofferdams* (1940).



Plate 35. Mississippi River Lock and Dam No. 15. Construction of Ohio River type box cofferdam. Framework section completed and ready to be dropped into river. Note the hinged scarf joints that facilitate placement of the framework. 16 March 1932. RG77-RH, Box 81, Mississippi River L/D #15, Cofferdam Folder, NARA.

tional row of wood piles was driven against the outside row of wales and these piles were bolted to both sets of wales and the sheet piling. The outside wall consisted of a row of wood piles with wales bolted to their outside faces. The steel sheet piling was placed against these wales and driven, and a second set of wales placed outside the steel. The steel tie rods passed through this outside row of wales and were secured in place by nuts (Figure 39). The wood sheet piling penetrated the river bottom an average of 5 feet, while the steel was driven to about 15 feet, except at the upstream outboard corner of the cofferdam, where the sheet piles were driven to a penetration of about 25 feet in order to provide a safeguard against erosion.²⁵⁹

Once enough piling had been delivered to assure that driving could progress without delay, the installation of the steel sheet piling began at the upstream shore end of the cofferdam and continued until the outboard upstream corner was completed. The work had to pass this point without delay in order to avoid erosion and scour. If a delay were encountered, erosion might reach a point where the available sheet piling was not long enough, resulting in long and costly construction delays and threatening the completed portion of the cofferdam. A steel sheet pile fin at the upstream outboard corner of the cofferdam directed the main force of the current further into the river, shifting the

eddy that forms at this corner, and which always erodes the river bottom, away from the main cofferdam structure. Willow mats and riprap were placed on the bottom at this corner to further hamper erosion. Additionally, a protection jetty was constructed about 730 feet upstream from the cofferdam. This jetty, a substantial, decked trestle with steel sheet piling on the upstream face, extended about 150 feet into the river and diverted the main current into the middle of the river, preventing it from striking with full force against the upper arm of the cofferdam. Construction of the upstream arm required only a few days. Nevertheless, the bottom eroded 2 to 4 feet each night. With the help of the upstream protection jetty, cofferdam fin, willow mats, and rip rap, the total scour at the upstream corner totaled only 9 feet.²⁶⁰

Model tests conducted on this cofferdam design at the University of Iowa's Hydraulics Laboratory indicated that the inner row of sheet piling contributed little to the hydraulic stability of the cofferdam. Established in 1919, the Hydraulics Laboratory, renamed the Iowa Institute of Hydraulics Research in 1931, conducted model tests throughout the 1930s that proved instrumental in the planning and design of the upper Mississippi locks and dams.²⁶¹

The results of the model tests were confirmed in 1934, when most of the wood sheet piling in the lock cofferdam was removed and used elsewhere on the job site after the spring floods. No increase in the flow of water into the cofferdam was noted after removal of this piling. Nevertheless, engineers determined

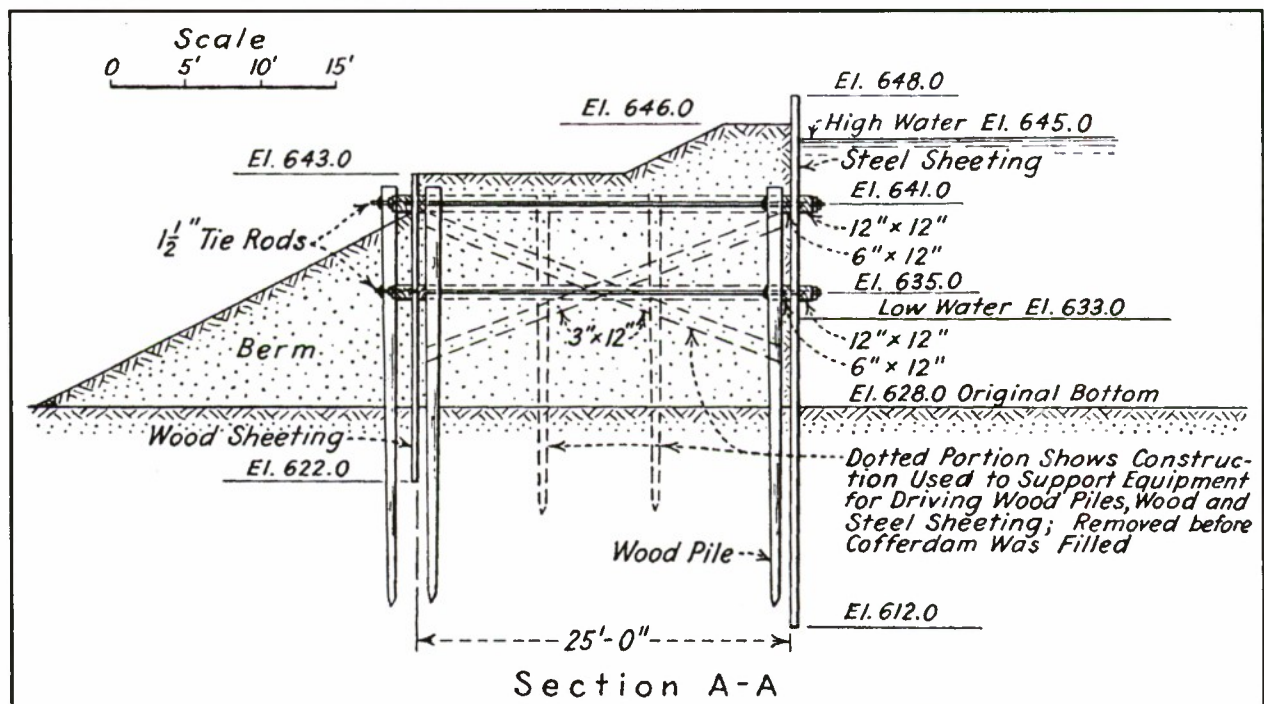


Figure 39. Mississippi River Lock and Dam No. 6. Detail of double-wall cofferdam with earth fill. From White and Prentis *Cofferdams* (1940).

that this inner row of sheet piling was necessary as a point of attachment for the tie rods that supported the outer wall and as protection against erosion of the sand fill in case of overtopping. Consequently, most cofferdams of this design employed both an inner and outer wall of sheet piling.²⁶²

Single-Wall Cofferdam – Dam No. 6

The model tests conducted on the Lock No. 6 cofferdam, and the practical experience gained during construction when the inner wall of wood sheet piling was removed from the structure without adverse results, convinced engineers to omit this inner wall of sheet piling in the two dam cofferdams.²⁶³

The upper and lower arms of the first dam cofferdam measured approximately 600 feet in length, with the outer 225 feet extending into the river beyond the extreme low-water line. The river arm of the structure measured 380 feet. The land arm and those portions of the upper and lower arms above the extreme low-water line consisted of a 10-foot high earthen dike. The remainder of the structure consisted of steel sheet piling supported by a series of wood five-pile bents placed 12 feet on center, perpendicularly to the sheet piling. The wood piles were 35 to 40 feet long, which provided 10 to 15 feet of penetration in water normally 15 to 20 feet deep. Timber wales were spiked to the two

outer piles in each bent to provide guides for driving the 35-foot long sheet piling. Five planks of 3-inch by 12-inch timber were bolted across the inside face of the innermost piles to anchor the sheet piling against the pressure of the sand fill. The inner four piles of each bent also were cross-braced to increase the rigidity of the bent (Figure 40).²⁶⁴

Once the bents were driven and framed, the steel sheet piling was set and driven in batches. During one eight-hour shift, the work crew set as many steel sheet piles as possible, driving one pile out of every 10 or 12 to grade in order to prevent the entire line being blown over by the wind. The next shift completed driving the line. This system permitted about 100 feet of sheet piles to be driven in 16 hours.²⁶⁵

This single-wall cofferdam proved successful, withstanding spring floods that produced a head of 20 feet. Consequently, the same design was used for the second dam cofferdam, which extended from the end of the first cofferdam.

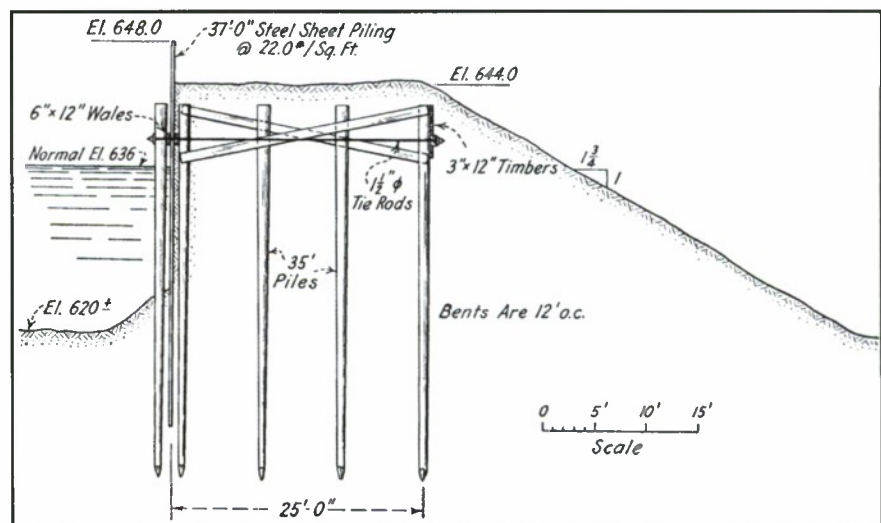


Figure 40. Mississippi River Lock and Dam No. 6. Cross section of single-wall cofferdam. From White and Prentis *Cofferdams* (1940).

ferdam to the river wall of the previously constructed auxiliary lock.

Steel Sheet Pile Cofferdams – Lock and Dam No. 26

Lock and Dam No. 26, the most downstream of the originally authorized improvements on the upper Mississippi, was located at Alton, Illinois, 25 miles north of St. Louis,. At this location, the river measured about 0.5 mile wide and about 30 feet deep, with a current of about 5 miles per hour. The size of the river, volume of water, soil conditions, and cramped site—which included an existing swing span bridge of the Missouri & Illinois Bridge & Belt Railway, greatly complicated the construction process.²⁶⁶

In November 1933, the Corps of Engineers put twin locks No. 26 out for bid. The John Griffiths & Son Company of Chicago submitted the low bid, \$3.2 million, a figure \$350,000 below the government estimate for the work and \$200,000 below the next lowest bid. Griffiths & Son were established large-scale contractors, but had virtually no experience in the highly specialized field of in-water construction. Nevertheless, in January 1934, the Corps accepted their bid and issued the firm a notice to proceed.²⁶⁷

The Corps approved Griffiths & Son's cofferdam design for the Main Lock in mid-January 1934. The design called for an exceptionally heavy and strong structure, largely because of the awkward construction site, which required that two piers of the Missouri & Illinois Bridge & Belt Railway Bridge be incorporated into the lock walls. The presence of the

bridge required that river traffic be passed through the area of the auxiliary lock during construction of the main lock, which, in turn, dictated that the river arm of the main lock cofferdam be placed very near the wall separating the main and auxiliary locks. This prevented placement of a berm on the inside of the main lock cofferdam.²⁶⁸

Griffiths & Son began constructing the cofferdam on February 1, 1934. Plans called for construction of a diaphragm type steel sheet pile cofferdam enclosing 13 acres. The inner and outer walls of each cell were curved, while the connecting walls were straight. Y-connection piles, connected to two structural frames, tied the individual cells together at the panel points. Outside wall piles measured 55 feet in length, while inside wall piles measured 40 feet. Because the riverbed at Alton consisted of at least 80 feet of sand above bedrock, none of the piles were driven to rock.²⁶⁹

Between February and mid-April 1934, work crews erected a pile-supported trestle along the center line of the cofferdam site. Railroad tracks atop the trestle supported a succession of derricks and cranes, which began driving the steel sheet piles for the cofferdam cells in early March, completing this work by the end of April. Serious seepage issues developed when the cofferdam was dewatered. Griffiths & Son addressed this problem by installing an extensive system of wellpoints, which lowered the water surface 1 to 2 feet below grade.²⁷⁰

Griffiths & Son completed the main lock in late September 1935 and began to remove the cofferdam. However, the structure's heavy

construction delayed this work, which, in turn, delayed the start of work on the auxiliary lock cofferdam. Work could not begin on the auxiliary lock cofferdam until the main lock cofferdam was completely removed and the lock opened to river traffic, since the railroad bridge confined traffic to the swing span opening.²⁷¹

Griffiths & Sons' work on the auxiliary lock proved calamitous. Work crews finally began construction of the river arm of the auxiliary lock cofferdam, a diaphragm type cellular steel sheet pile structure like that used for the main lock, in early October 1935. By mid-December, the river and lower arms of the structure were complete. Then, over the objections of the Corps' resident engineer, Griffiths & Son closed the lower arm of the cofferdam in the hope that the river would deposit the 2 to 8 feet of fill required to bring the auxiliary lock site up to grade.²⁷²

On December 19 the temperature fell sharply. The next day ice began to run in the river, and by December 26 the cofferdam was filled with ice. In early January 1936, ice damaged a portion of the river fin, an extension of the cofferdam designed to streamline the flow of the river around the structure and reduce erosion and scour. Efforts to repair the damage proved unsuccessful and, as a stopgap measure, the Corps placed a barge loaded with derrick stone against the fin to protect it from flowing ice. Pile driving on the upper arm of

the cofferdam resumed, and by January 17, when cold and ice again halted the work, all but three cells had been completed (Figure 41).

The cold weather continued unabated, and by the end of February, the entire river was gorged with heavy ice. On the night of February 26, a breakup of ice upstream from the cofferdam damaged the fin on the lock side of the structure. Because the upstream arm was not closed, the height of the water inside the cofferdam was about 1 foot higher than the water outside. Ice jammed the river and nearly overtopped the structure. On the night of February 28, the river fin failed and the steel cells began to collapse like a line of dominos. By March 22, nearly the entire upper and river arms had been lost. Griffiths & Son abandoned the work, leaving the removal of the collapsed cofferdam to the Corps of Engineers.²⁷³

In late April 1936, the Corps placed timber mattresses against the intermediate lock wall to prevent scour and protect the completed main lock. Corps work crews removed the surviving standing cells of the auxiliary lock cofferdam in order to eliminate eddies and other vortices in the current and to facilitate the passage of river traffic. In June, the Corps began very careful borings to determine the precise location and depth of the wreckage. Divers confirmed the results of these borings, and found the collapsed cells laying on their sides beneath 8 to 12 feet of sand.²⁷⁴

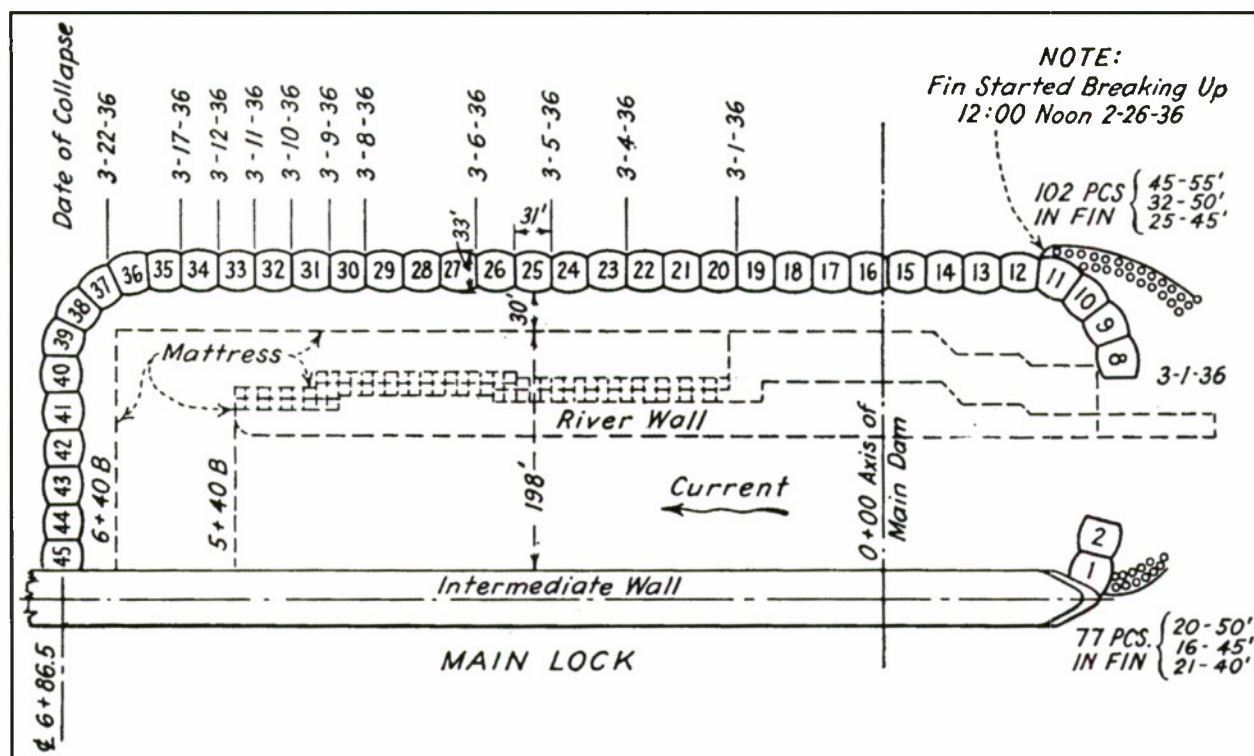


Figure 41. Mississippi River Lock and Dam No. 26. Plan of cofferdam for auxiliary lock. From White and Prentis, *Cofferdams* (1940).

W.F. Goodson, one of the engineers engaged in raising the battleship *Maine* from the bottom of Havana harbor, and then assigned to the Corps' Buffalo District, assisted in the removal effort. Dredges removed the sand from atop the collapsed cells. Divers then attached shackles to the sheet piling, which was hauled free, 10 to 12 sheets at a time, by a pair of 100-ton derricks. The work progressed rapidly, aided by low river levels, and by late September 1936, the Corps had removed most of the wreckage, permitting the dam contractor to begin work on his third cofferdam, which included the site of the auxiliary lock.²⁷⁵

The Engineering Construction Company, of Delaware, a joint venture among George A. Fuller & Company, the Turner Construction Company, and Spencer, White & Prentis, received the notice to proceed on the work for

Dam No. 26 in mid-June 1935. In sharp contrast to Griffiths & Son, then engaged in the construction of the main lock, the Engineering Construction Company designed their entire operation according to generally accepted principles of marine construction. Spencer, White & Prentis recently had completed construction of Lock and Dam No. 6 at Trempealeau, Wisconsin, and were in the midst of constructing Lock No. 3 at Red Wing, Minnesota.²⁷⁶

The Engineering Construction Company employed three cofferdams, starting from the Missouri shore and moving sequentially across the river, to construct Dam No. 26. All three cofferdams consisted of box cofferdams with walls of steel sheet piling. The distance between the rows of sheet piling was generally 30 feet. A tie-rod and wale system con-

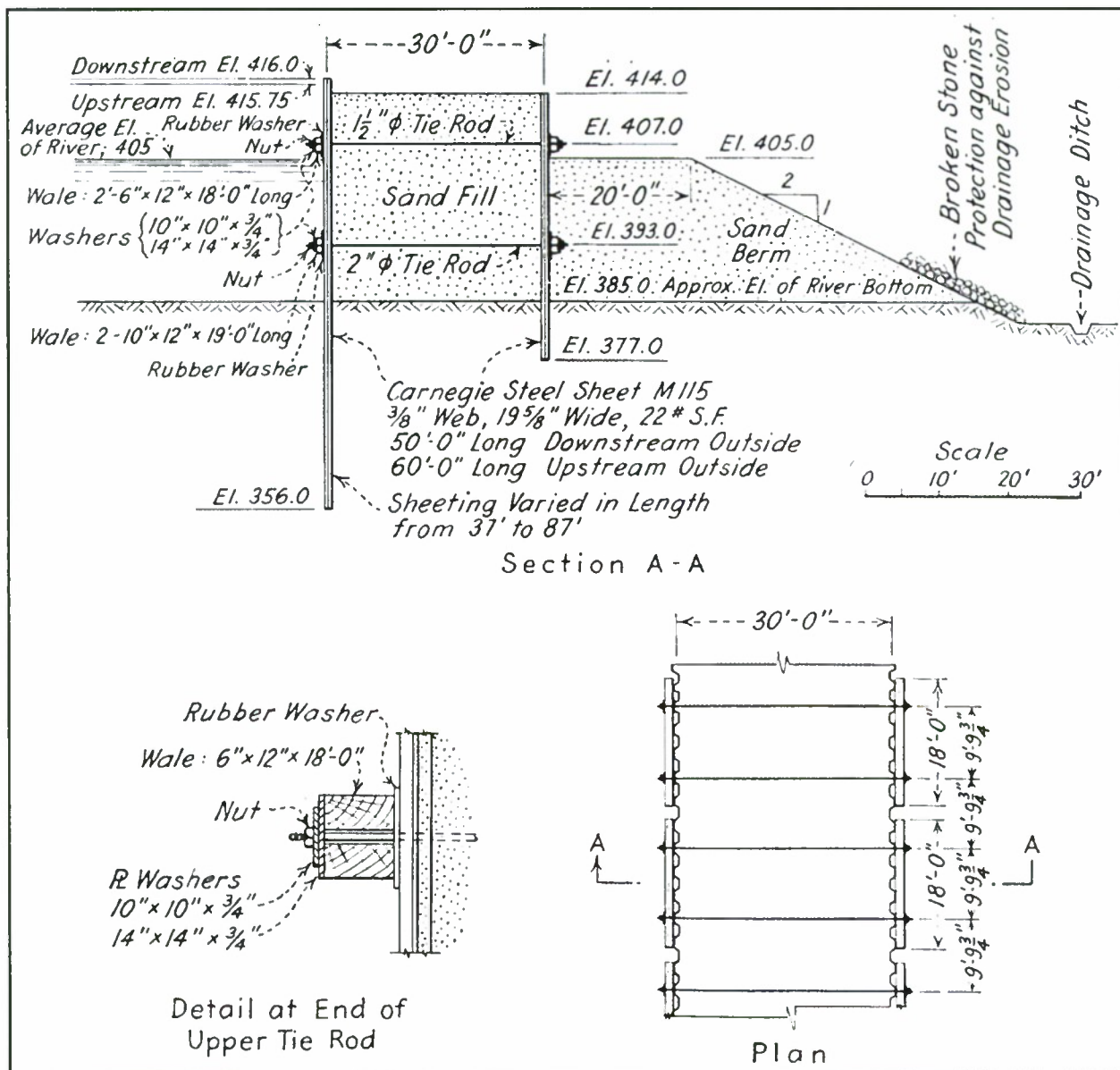


Figure 42. Mississippi River Lock and Dam No. 26. Typical cross section of cofferdam wall. From White and Prentis *Cofferdams* (1940).

nected the two walls of sheeting. Rubber washers, made of old conveyor belting, were placed between the wales and the sheet piling (Figure 42). These prevented water infiltration and loss of sand. The cofferdams required 3,300 tons of steel sheet piling, in lengths ranging from 37 to 87 feet. Approximately 90 percent of the piling was pulled from the cofferdams, reconditioned, and sold, following completion of the work.²⁷⁷

The wooden piles for the cofferdam falsework were driven from a barge. These piles varied in length from 30–80 feet and were driven, on average, to a penetration of 10–15 feet. The framing of the falsework originally consisted of a system of horizontal cross-bracing, but this proved inadequate, and vertical bracing had to be added at each pile bent (Figure 43).²⁷⁸

Revolving steam cranes, fitted with 85-foot booms and mounted on steel barges, placed and set the steel sheet piling. Generally, a section of piling about 50 feet long was set and driven home until the holes for the lower tie rods were just above the water. The tie rods and wales were placed and the sheeting driven to grade. The upper tie rods and wales then were set.²⁷⁹

Dredges filled the cofferdam and constructed the interior berm. Placement of the fill and berm material proceeded evenly, to avoid creating an unbalanced load against the inside wall of sheet piling. As the fill was built up, the temporary trestle between the sheet piling walls was removed for reuse. Berms outside the cofferdam were used in some locations to provide deeper penetration for the sheeting.²⁸⁰ Railroad tracks and access roads were laid atop the upstream and downstream arms of the cofferdams, facilitating the delivery and movement of equipment and construction materials directly from rail cars onto the inside berm by crane.²⁸¹

Work began on Cofferdam No. 1 in mid-June 1935 and pumping began in mid-August (Figure 44). The upstream arm of the cofferdam was begun first, and always was kept ahead of the downstream arm, which was begun two

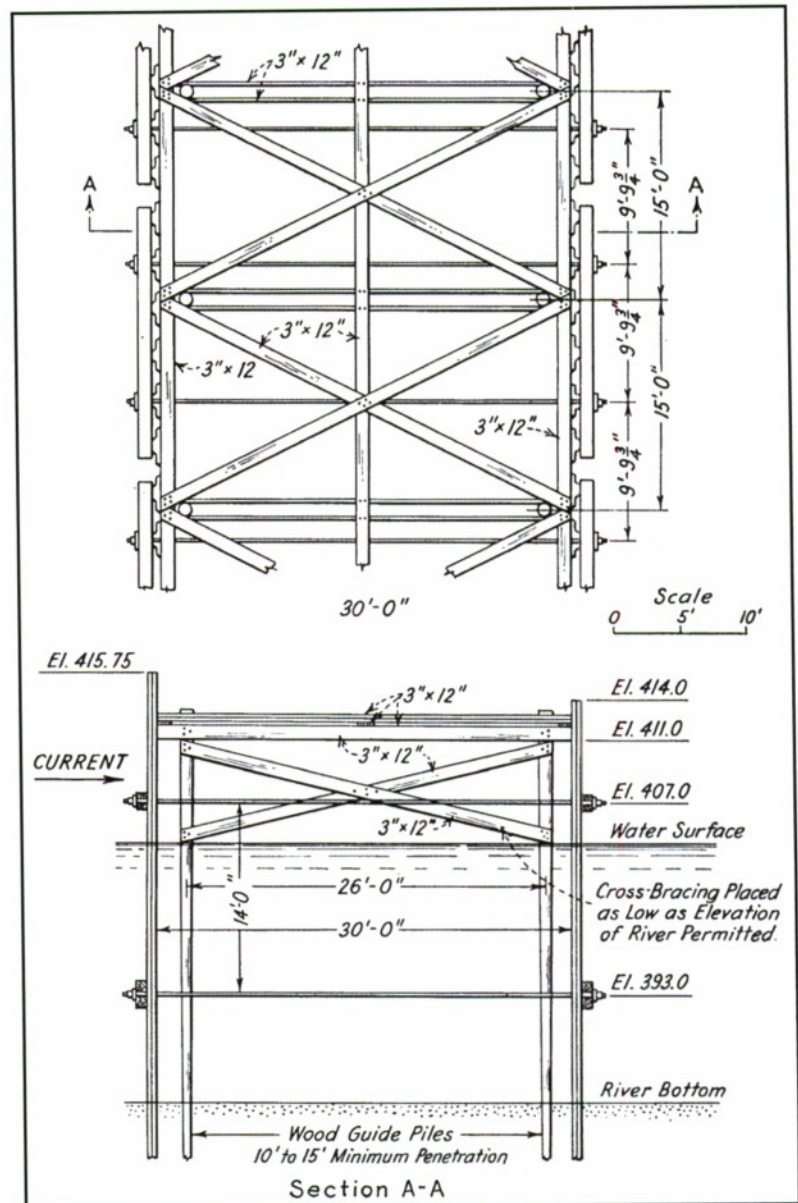
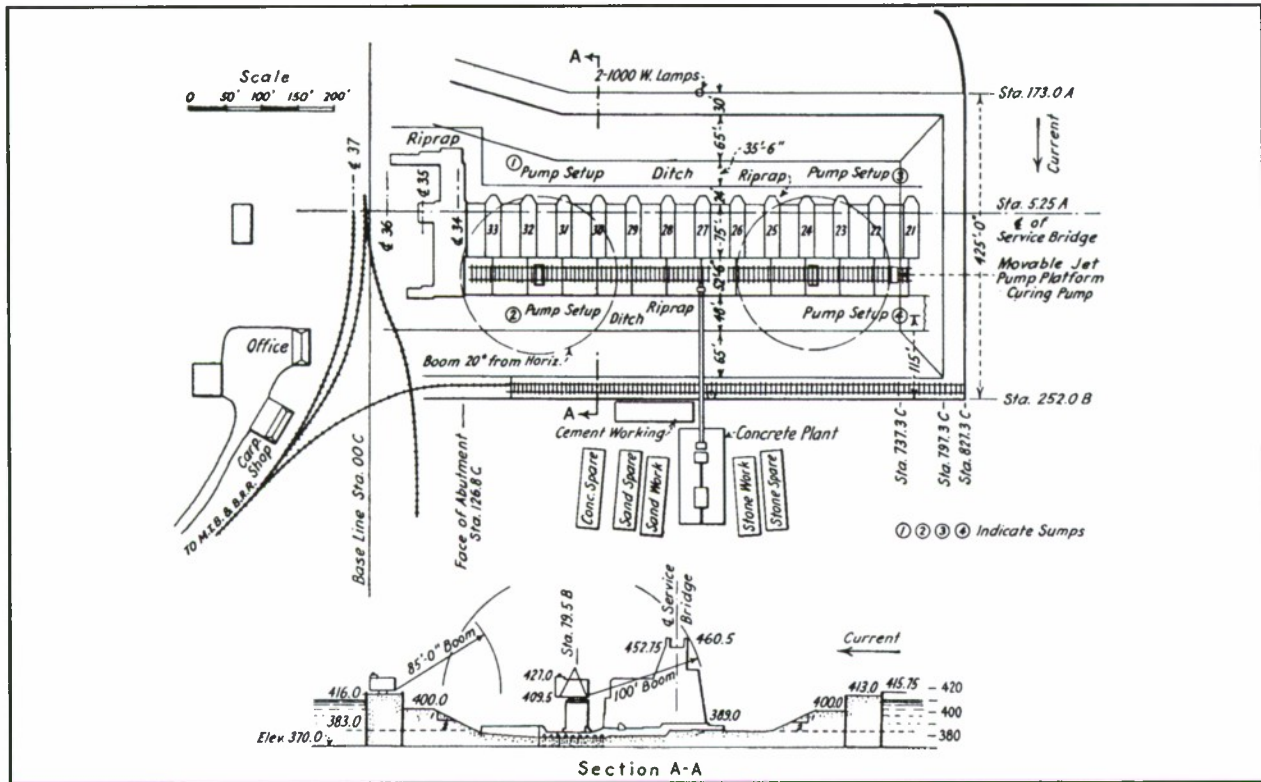


Figure 43. Mississippi River Lock and Dam No. 26. Guide pile and bracing system used for driving steel sheet piling. From White and Prentis *Cofferdams* (1940).

days later. The river arm was started from the downstream end, and the work timed so that it approached its upstream limit at the same time that the upstream arm reached its limit. Just after the upstream corner was completed, scour of the river bottom caused the sheet piling to settle 3 to 4 feet, threatening the entire cofferdam with collapse. The turbulent water prevented construction of the



streamline fin. Dredges pumped material back into the area of scour and yards of riprap were placed. Conditions stabilized after the hole reached a depth of 50 feet. As a result of this unnerving experience, the fins for the other two cofferdams were built in advance of the rest of the structure, making the point of closure near the center of the upstream arm.²⁸²

constructed of timber and wooden piles, and 60-foot long steel sheet piling was driven and bolted to the framework. The fin was guyed to the cofferdam and protected by riprap dumped against the sheet piling. Subsequent soundings indicated that the fin caused scouring to occur at a point away from the cofferdam, where it could do no harm, and led to the deposition of sand and silt along the entire length of the river arm.²⁸³

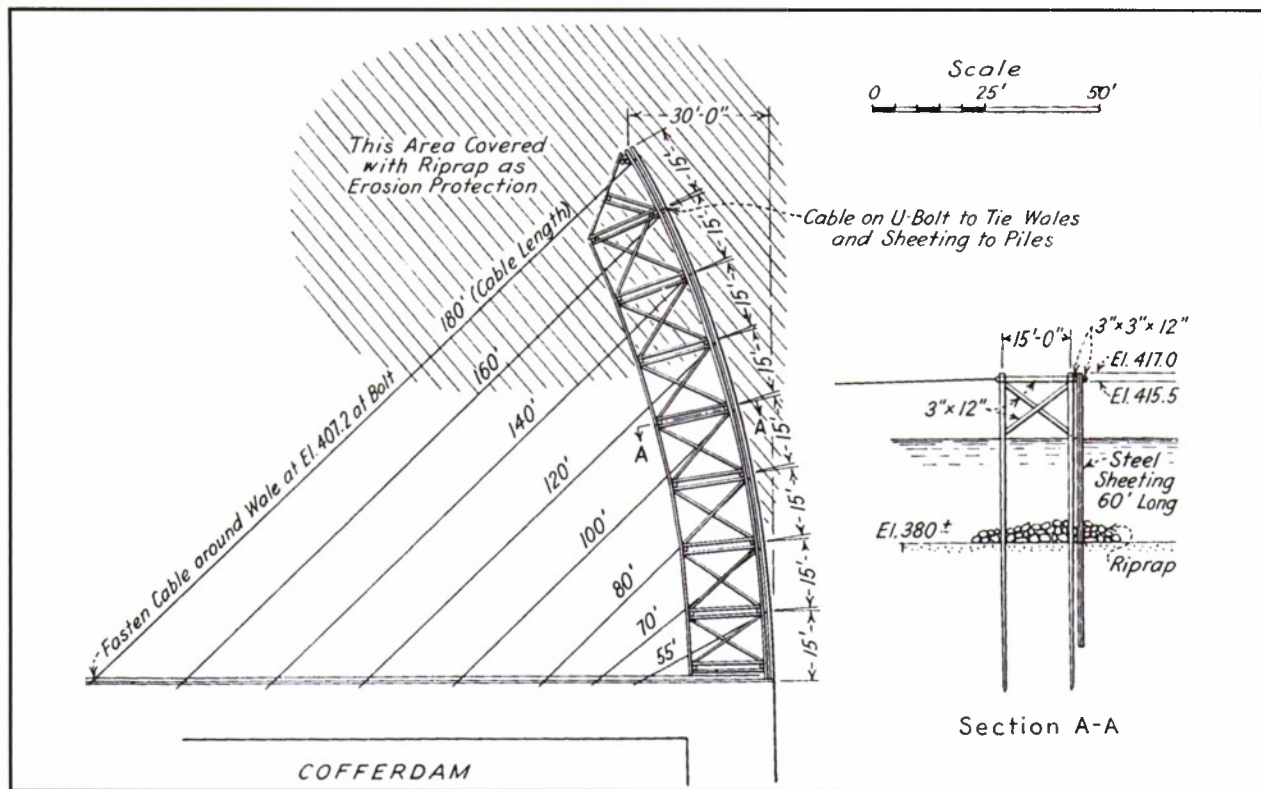


Figure 45. Mississippi River Lock and Dam No. 26. Design of streamline fin, Cofferdam No. 1. From White and Prentis *Cofferdams* (1940).

river, which carried about three-fourths of the river's 90,000 cubic feet per second flow and measured up to 55 feet deep. Experience with the first two dam cofferdams indicated that scour could lower the river bed 15 to 25 feet in a day, meaning that closure of the final gap in the third cofferdam might entail a 70-foot depth of water, unless the effects of scour were reduced. This was accomplished by building up the river bed to as shallow a depth as possible, setting and driving the sheet piling as rapidly as possible, and replacing scoured material by dredge.²⁸⁴

Observation also indicated that the pressure exerted by the river at the point of closure would be considerable, so the falsework guides for the sheet piling were designed with additional cross bracing to resist over-

turning and lateral pressure. The closure section, which measured about 100 feet in length, consisted of 11 wood pile bents spaced 10 feet on centers. Each bent consisted of three 80-foot piles spaced 15 feet on centers. Each bent was rigidly cross braced with timbers bolted to the top 10 feet of the piles. The entire "closure trestle" was braced in the horizontal plane by a latticework of timbers spiked to the top of the trestle. This was designed to make the closure trestle act as a rigid unit, rather than as loosely connected individual bents. Dolphins were placed about 100 feet upstream from the closure trestle and wired to the trestle with 3/4-inch wire rope cable. The entire trestle was positioned directly upstream from the line of the steel sheet piling, where its piles

were less subject to scour than if it had been placed downstream from the point of closure. The steel sheet piling for the closure was driven against the downstream face of the closure trestle. The effects of scour during the closure process were notable, removing nearly 20 feet of material in a period of six hours, thus increasing the depth of water in the closure gap from 25 feet to 43 feet (Figure 46).²⁸⁵

Continued Use of Traditional Designs – Bonneville Dam

Despite the widespread use of steel sheet piling and cellular cofferdam designs on the Upper Mississippi Nine-Foot Channel Project, the Corps of Engineers continued to rely upon traditional designs in certain circumstances. Perhaps nowhere was this better exemplified than at Bonneville Dam on the Columbia River.

Crib cofferdams were a natural development from the simple crib dams used for decades in isolated regions where timber was cheap and the cost of transporting materials to job sites was dear. A timber crib dam consists essentially of a framework of horizontal timbers or logs laid up in alternating courses to form pockets, which are filled with rock and gravel to provide stability against overturning and sliding (Figure 47). The cribs may be faced, generally on the inside of the pockets, with timber sheeting or banked with impervious fill, or both. The timbers were bolted or spiked together.²⁸⁶

By the 1930s, timber cribs, were considered relatively expensive to construct and their use was advised only in situations where difficult construction conditions precluded the use of more economical designs. These conditions included areas of swift current, considerable threat of overtopping by flood, deep water, restricted work space, hard bottoms, and relatively inexpensive timber and expensive steel piling. These conditions prevailed at many dam sites in the far West.²⁸⁷

Conditions on the Columbia River at the Bonneville Dam site favored the use of timber crib cofferdams,. A channel 1,000 feet wide had to be laid bare for construction of a concrete spillway dam measuring 1,250 feet long and 170 feet high. This work had to be done in water ranging from 30 to 50 feet deep, in currents flowing at up to 7 miles per hour, and on a rough and irregular riverbed. Additionally, the cofferdams had to be able to withstand overtopping during the flood season.²⁸⁸

Plans called for dewatering the site in two successive steps. A cofferdam would be built for the south, or Oregon, half of the dam site. After the foundations had been poured for this section of the dam, the river would be turned into the south half of the channel while the north, or Washington, half of the dam site was dewatered (Figure 48).²⁸⁹

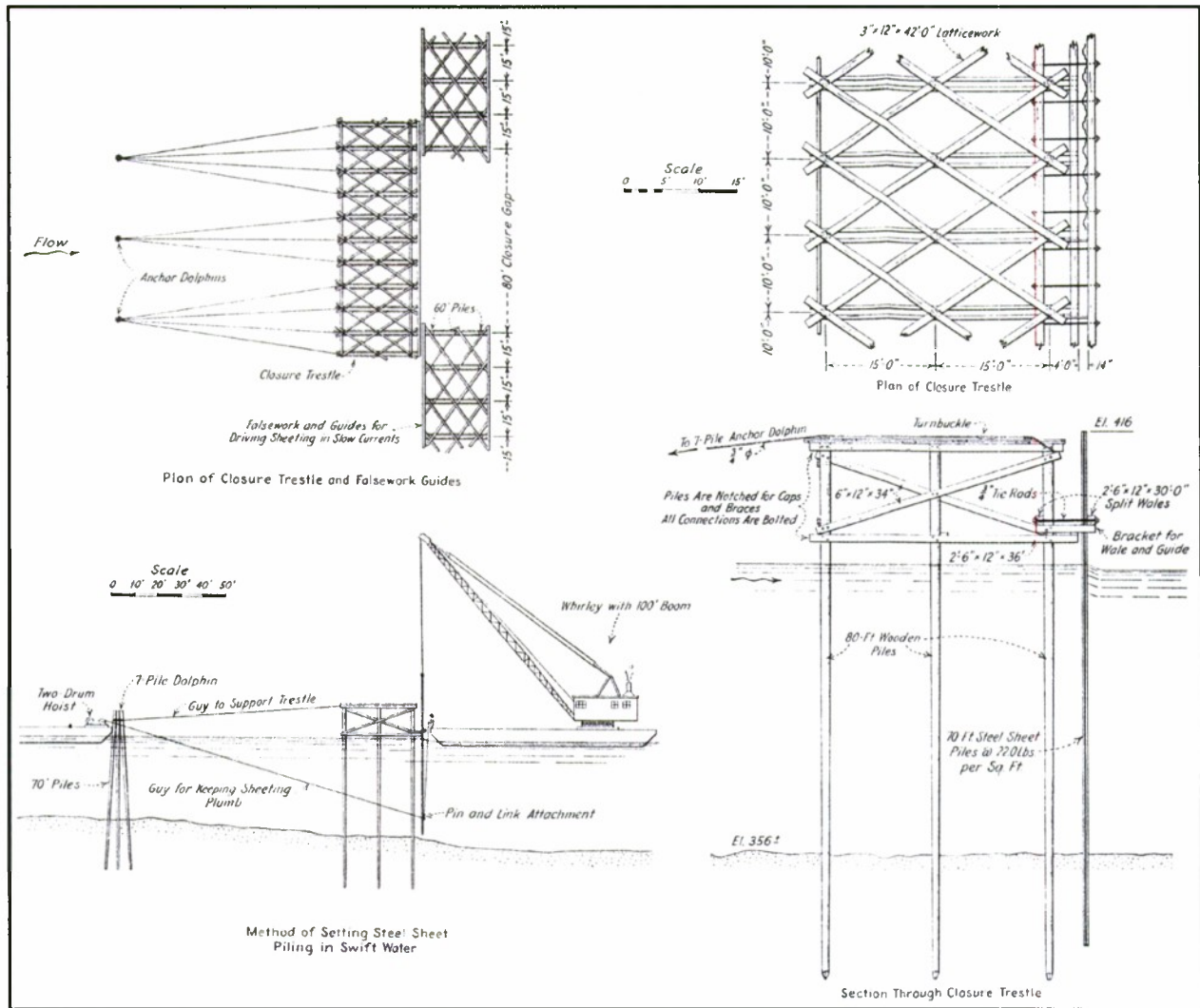


Figure 46. Mississippi River Lock and Dam No. 26. Closure operations and falsework for Cofferdam No. 3. From White and Prentis *Cofferdams* (1940).

Engineers evaluated cofferdam and caisson designs for the project prior to the start of construction in 1934. They determined that reinforced concrete caissons and steel sheet pile cells were more expensive, difficult or impossible to place in the fast-flowing river, and no stronger than timber cribs. Because of the difficulty and risk involved in the cofferdam operation, and because few contractors proved willing to assume this risk, the Corps of Engineers designed the cofferdams and provided the contractor with detailed drawings and specifications for each

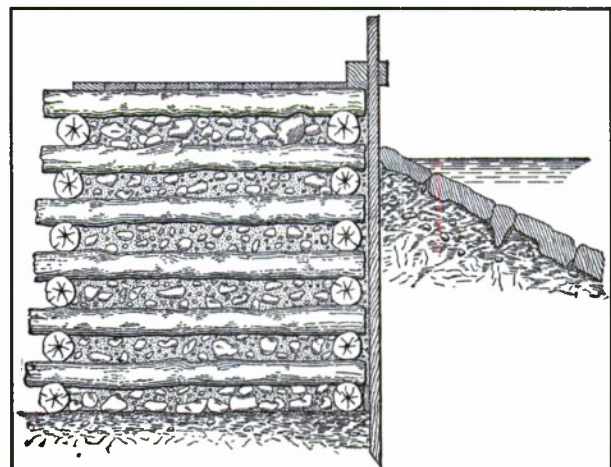


Figure 47. Section of timber crib cofferdam. From Wegmann *The Design and Construction of Dams* (1911).

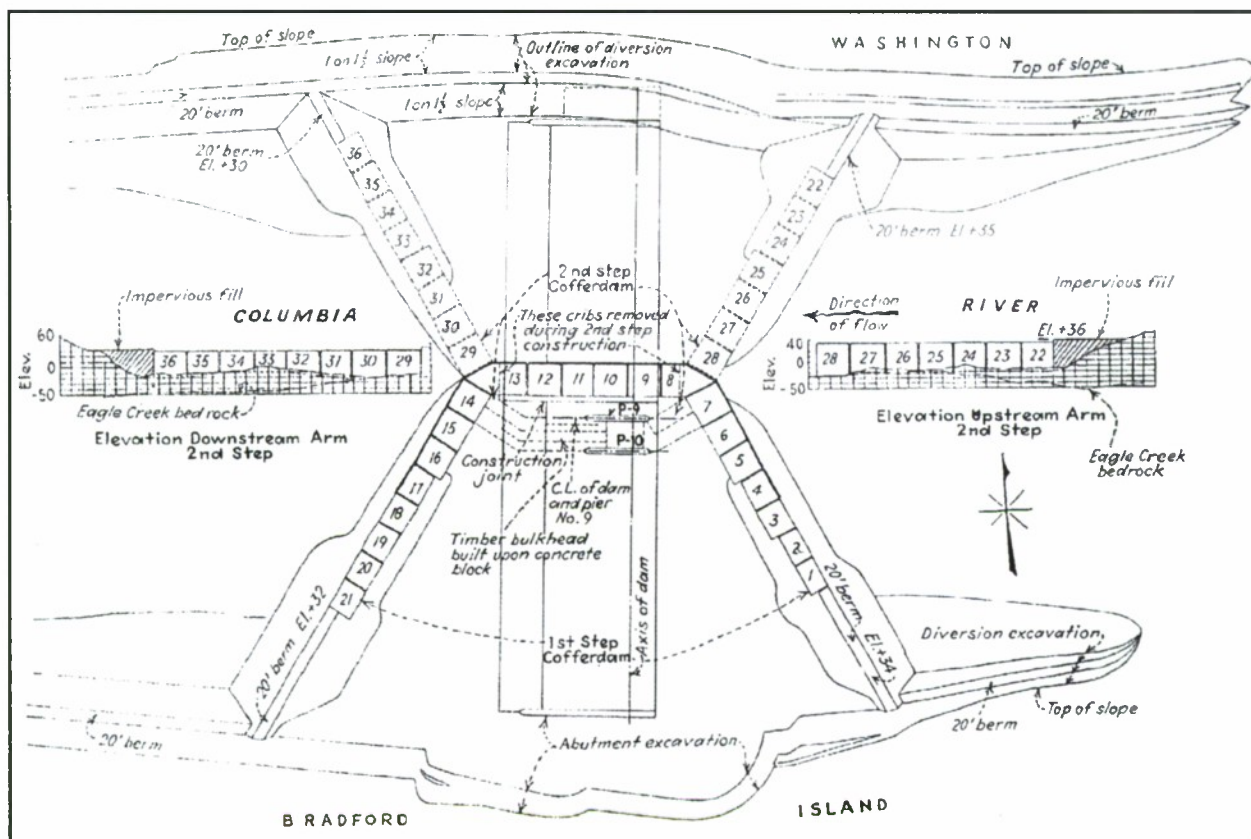


Figure 48. Bonneville Dam, Columbia River site plan with cofferdams. From *Engineering News-Record* (5 September 1935).

crib. Model studies, conducted beginning in March 1934 at the Corps' Bonneville Hydraulics Laboratory, in Linnton, Oregon, provided data on velocities, pressures, and scour conditions, and allowed consultants, contractors' foremen, and others to visualize the job in advance of construction. The contractor was responsible for proper placement and loading of each crib. After completion, inspection, and acceptance of each crib by the government, the government assumed responsibility for its stability when dewatered, or its destruction or loss by flood, ice, or other natural cause.²⁹⁰

The cofferdam consisted of a continuous line of timber cribs, with earth fill at the land ends. The cribs typically measured 60 feet long and varied in width according to their

height. River arm cribs reached a maximum height of 65 feet, while some of the cribs supported by fill were 80 feet tall. The river arm cribs of the south cofferdam sat directly on bedrock. The bottom proved extremely irregular, with a difference in elevation of as much as 15 to 20 feet found beneath a single crib. To avoid dredging and blasting the bottom, the cribs were built to fit the existing bottom conditions. An extensive program of sounding revealed the shape and location of all boulders and ridges. The crib bottoms were constructed to fit the river bottom as accurately as possible, based upon the results of the soundings, with a tolerance of 1 vertical foot and 5 horizontal feet. Many cribs were 5 to 10 feet higher on one side or corner than on the other (Plate 36). The irregular bottoms

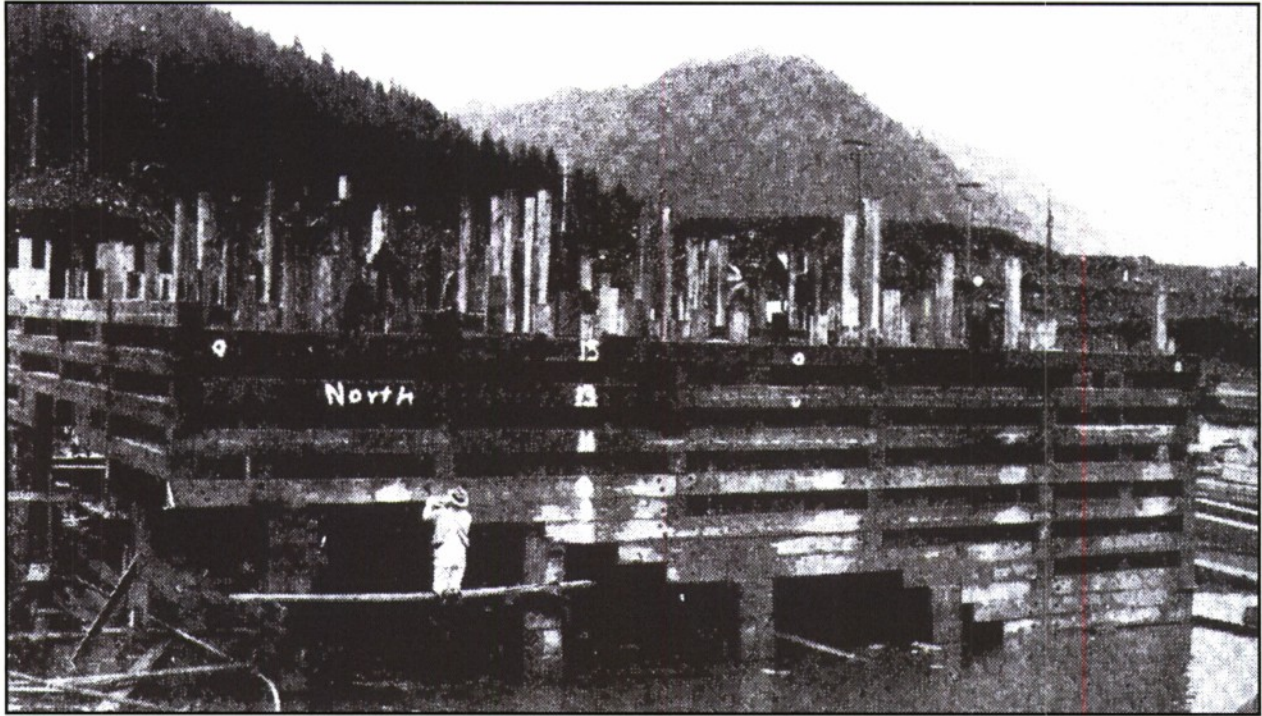


Plate 36. Bonneville Project, Columbia River. Tailoring of bottom of crib to conform to bottom conditions. From White and Prentis, *Cofferdams* (1940).

were formed by bolting in partial courses of timber with intermediate filler blocks.²⁹¹

The cribs for the south cofferdam were built on sloping ways located on the river bank, launched, and moved to their position, where additional courses were added until their height exceeded the depth of the water by a few feet. The cribs were then sunk by dumping boulders and gravel into the weight pockets. The pockets measured 12 feet square, which meant that the cribs were constructed in multiples of 12 feet, based upon their final height. The cribs were constructed using 24-foot and 36-foot long timbers with staggered interior joints. The lower 15 feet of each crib, constructed on the ways, contained the most heavily stressed beams. In this section, vertical timbers were bolted into each exterior pocket corner. Three-inch by 12-inch plank-ing was placed on the water face of all cribs.

The river arm of the south cofferdam was lined outside this sheeting with steel sheet piling driven 2 to 4 feet into the bottom. The cribs were stable when launched, but quickly became unstable as their height increased. Consequently, each crib was fitted with four, 8-foot by 12-foot lined pockets for gravel ballast that served to trim the crib during the process of moving it into position and sinking. The cribs for the south cofferdam were guided into position using a cable system that allowed them to be controlled in the fast flowing river.²⁹²

The cribs for the north cofferdam were built upon a raft that was submerged, as the cribs rose in height, by pumping water into steel buoyancy tanks. This permitted workers to operate from the same work platform throughout the construction process. After

the cribs were maneuvered into their proper location and raised to their final height, they were sunk by dumping gravel and boulders into the weight pockets. Once they reached the bottom, divers were sent down and made soundings to assure that the cribs were firmly seated in their proper position. In one or two instances the divers drilled and blasted the river bottom to procure a firm seat.²⁹³

The south cofferdam was constructed during the low-water season of 1934-1935. It cost about \$1 million and enclosed approximately 8 acres. After sealing and dewatering the cofferdam, nearly 200,000 cubic feet of river fill and rock was removed from the 8-acre construction site. The cofferdam was removed in early 1936 and work began on the north cofferdam.²⁹⁴

In May 1936, a floodflow of 520,000 second-feet overtopped the upstream arm of the north cofferdam, found a channel of escape through the unfinished downstream arm, and generated a head differential of 8 feet between the upper and lower sides of the upstream arm. The overpour swept away 42,000 cubic yards of earthfill and riprap at the shore end of the upstream arm; carried away three nearly completed cribs from the downstream arm, scoured the river bottom, and swept loose material along the Washington shoreline.²⁹⁵

Various methods were employed to close the 130-foot gap. Dumping rock from barges proved slow and difficult. The current had a velocity exceeding 20 feet per second, and in

75 feet of water even the heaviest rocks that could be handled were carried so far downstream before they reached the bottom that their placement could not be controlled to any significant degree. Consequently, a trestle was built starting from a point well upstream of the gap, so that it cut diagonally across the current, taking advantage of shallower water and lower velocities than those found within the gap itself. Enormous quantities of rock were dumped into the gap from rail cars run out along the trestle. Once the gap was closed, the cofferdam was completed and the work proceeded.²⁹⁶

10 Post World War II Cofferdam Design and Construction

By the end of the 1930s, the Corps of Engineers had gained a century of experience in the design and construction of cofferdams. Corps engineers were familiar with a wide variety of cofferdam types and designs, ranging from simple earth dikes to cellular steel sheet pile structures. They were familiar with cofferdams constructed of earth, wood, steel, and various combinations of these materials. They had gained experience constructing cofferdams in a wide variety of conditions, from shallow, slow moving streams to deep, fast rivers, and with bottom conditions ranging from deep layers of mud, silt, and sand, to solid rock. The methods used to design cofferdams had evolved beyond the time-tested rule-of-thumb techniques promulgated by Dennis Hart Mahan to include fairly sophisticated mathematical calculations used to determine the most economical use of materials required to achieve a minimum level of performance under specific conditions.

Construction projects undertaken by other federal agencies during the 1930s provided additional experience with the design and construction of large steel sheet pile cofferdams. In the western United States, the Bureau of Reclamation undertook a number of massive construction projects during the 1930s. The steep canyons that characterized many of these construction sites often prohibited the use of cofferdams and led the Bureau of Reclamation to divert the flow of

rivers through tunnels and channels. However, at Grand Coulee Dam, on the Columbia River in Washington, the Bureau of Reclamation employed steel sheet pile cofferdams of an unprecedented 120 feet in height.²⁹⁷

The Tennessee Valley Authority (TVA), a multipurpose federal development project established by Congress in 1933, constructed a series of large concrete dams in the Tennessee River basin to provide electrical power, navigation, and flood control. By 1945, TVA engineers had constructed 14 cellular steel sheet pile cofferdams and had arguably gained more experience in the design and performance of these structures than their counterparts in the Corps of Engineers.²⁹⁸

The Tennessee Valley Authority's Steel Cofferdams

The TVA designed and built its first steel sheet pile cofferdam at Pickwick Dam, located on the Tennessee River approximately 207 miles upstream from the river's confluence with the Ohio, in 1935. This circular cell cofferdam formed the basis for all subsequent TVA steel sheet pile cellular cofferdams prior to the design of the Kentucky Dam cofferdam in 1939.²⁹⁹

The twelve circular cell cofferdams constructed by the TVA at the Pickwick, Guntersville, Chickamauga, Watts Bar, and Fort

Loudon dams measured between 30 and 55 feet in height. The sheet piling was driven against a specially designed template (first used at Pickwick) that assured accuracy in driving. The TVA chose to use the circular cell, rather than the diaphragm type design after determining that for cofferdams 40 to 50 feet in height the diaphragm type offered no appreciable savings in the amount of required piling. In addition, circular cells offered a distinct advantage in that the fill could be placed within the cell immediately upon completion of pile driving, whereas with the diaphragm type the fill in one cell could not be more than 5 to 10 feet higher than the fill in the adjoining cell without the weight of the fill distorting the diaphragm walls. Circular cells also offered the advantage of being self supporting, so that a failure within an individual cell did not inevitably result in partial or progressive failure of adjoining cells.³⁰⁰

TVA engineers conducted a series of field and laboratory tests in conjunction with the design and construction of their cofferdams that provided them with extensive information on the behavior and performance of these structures. At Pickwick, observations sought to determine the saturation line in the cell fill, using pipes driven vertically into the fill. Additional tests, including the use of strain gauges to determine the stress in the steel sheet piling, tension tests on the interlock strength of piling, and measurements of deflection, were conducted at several other TVA cofferdams.³⁰¹

The Kentucky Dam, located on the Tennessee River just above its confluence with the Ohio,

gave TVA engineers an opportunity to test their practical and theoretical experience. The river at the construction site is 1,600 feet wide at low water and the river bed overburden averaged 50 feet above bedrock. Early calculations suggested that the required cofferdam would be approximately 100 feet tall, rivaling that built for Grand Coulee Dam. Previous TVA cofferdams had been designed in accordance with customary practice in regard to bursting of cells, sliding, and overturning; however, it was determined that vertical shear represented an important consideration in the design of this tall structure. Accordingly, TVA engineers carefully considered the saturation of the fill material within the cells, the interlock tension, and the internal resistance to shear as they designed the structure.³⁰²

Following a thorough investigation to determine the most economical and practical cofferdam arrangement, including construction of a 20-foot diameter test cell, TVA engineers chose a two-stage cofferdam. The upstream and downstream arms consisted of 59-foot diameter circular cells with interior berms. Analysis determined that without the inner berm, an 85-foot diameter cell would have been required to provide proper safety against sliding or vertical shear. The interlock stresses in a cell that large would have proven excessive, so the engineers chose to use a small cell in combination with a berm. At the river arms, the need to construct the cofferdam close to the work site precluded use of an inner berm. Consequently, designers chose to use a cloverleaf cell (Figure 49). The resulting cofferdams measured approximately

2,900 feet long and rose 50 feet above the river bottom, making them among the largest built to that date.³⁰³

Upon completion of the two Kentucky Dam cofferdams, the TVA arguably stood as the most experienced organization in the United States in the design, construction, and evaluation of steel sheet pile cellular cofferdams. TVA structural engineer A.F. Hedman's 1942 *Engineering News-Record* article on the design of the Kentucky Dam cofferdams offered other engineers access to the TVA's design assumptions and calculations and to their analysis of interlock stress and stability. The TVA stood at the forefront of the engineering community in terms of their understanding and application of scientific design theory for cellular cofferdams.³⁰⁴

Design Theory for Cofferdams

Well into the twentieth century, engineers designed wooden cofferdams using rule-of-thumb methods to determine the appropriate width of the structure and the dimensions of the timber wales and other elements. In 1919, Pittsburgh engineer F.R. Sweeny published an article in *Engineering News-Record* that offered a series of mathematical formulas to determine the loads exerted upon timber wales at various points within a cofferdam. Sweeny noted that his equations were "of little practical value to the engineer... [being] too complex for ready calculation" and provided a "very handy diagram" that could

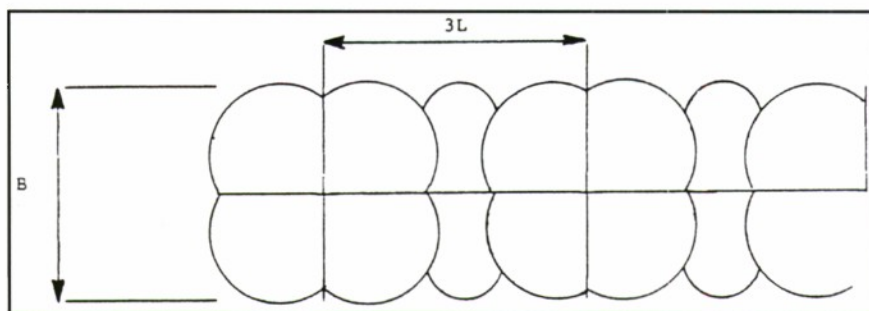


Figure 49. Plan view of a cloverleaf cofferdam. From Rossow and Mosher (1987).

be used to determine the appropriate spacing of wales of various dimensions at various depths and for various spans.³⁰⁵

By the mid-1930s, the increasing use of steel sheet piling led to the design and construction of significantly taller cofferdams. The potential consequences, in terms of cost, construction delays, and threats to workers, associated with the failure of one of these structures were significantly greater than with lower wooden structures. Consequently, engineers sought to determine the theoretical limits of design using steel sheet piling in order to minimize the use of materials while assuring safe operating conditions under a predicted set of conditions.

In 1933 and 1934, Carnegie Steel Company engineer Raymond P. Pennoyer published a series of articles that were the first to try to provide a theoretical basis for the design of steel sheet pile cofferdams. Pennoyer distinguished between rectangular, bulkhead-type structures with parallel walls of sheet piling connected by tie rods, and cellular structures. He subdivided cellular structures into those with circular cells connected by short arcs of sheet piling, and diaphragm cells, with curved outside walls connected by

straight diaphragm walls. The diaphragm cell design required less sheet piling, but the cells had to be filled in stages, keeping the height of the fill in adjoining cells at approximately the same height in order to avoid distortion of the diaphragm walls. Circular cells, in contrast, could be filled, and made stable immediately after completion of each cell.³⁰⁶

Pennoyer sought to establish formulas that would assure a predictable margin of safety against overturning or sliding of a steel cofferdam built upon a rock foundation. In developing these formulas, he assumed that both rectangular and cellular cofferdams obtained most of their stability through their sheer weight, essentially functioning as a gravity structure. Pennoyer also advanced methods for calculating the internal stability of the cells and the tensile stresses in the sheet piling walls.³⁰⁷

Pennoyer's work only addressed cofferdams constructed on rock. In 1940, Lazarus White and Edmund Ashley Prentis, partners in the New York City-based engineering firm Spencer White & Prentis, one of the nation's preeminent foundation engineering firms and contractor for several of the Corps' upper Mississippi River projects, published a monograph on "scientific cofferdam design."³⁰⁸ This volume, based upon the writers' experience on the upper Mississippi and elsewhere, and buttressed by the results of laboratory research and model testing, offered detailed discussions of hydrodynamics, stream erosion, and lateral earth pressures, supported by cases studies of individual projects.

White and Prentis provided the first detailed discussion in engineering literature of the mechanical effects of seepage upon the stability of cofferdams. They protested against the prevailing indifference to the effects of seepage and provided a well-documented argument emphasizing the important role that seepage played in determining the stability of cofferdams built upon sand. They provided formulas for conducting hydraulic analysis of seepage conditions and stressed the importance of understanding the principles of flows through soils. This analysis permitted prediction of the quantity, velocity and direction of seepage flow, as well as seepage pressures. They introduced the "flow net" analysis, which permitted estimations of seepage expected through a permeable dam or under a dam built upon a permeable foundation and tested their theories and analyses using large-scale models, some measuring 16 feet long and 6 feet high. These models proved useful in estimating the inflow or leakage into a cofferdam, information needed to design an effective and adequate pumping system.³⁰⁹

White and Prentis also addressed the issue of erosion or scour, a major concern at construction sites with sand or silt bottoms. Construction of a cofferdam constricts the cross section of a stream, increasing the velocity of the water. The increased velocity is obtained by building up a head of water upstream from the constriction. This head, in addition to increasing the velocity of the water, also produces eddies that cause erosion and can threaten the stability of a cofferdam. The damage depends upon both the character of the stream bed and the velocity of the water.

White and Prentis developed the notion of a streamlined fin, added to the upstream river corner of a cofferdam, to shift the eddies further into the channel and away from the cofferdam. First used at Dam No. 6 on the Mississippi, this design soon became a standard feature for many Mississippi River cofferdams. Model tests conducted at the University of Iowa Hydraulics Laboratory for the Lock and Dam No. 26 project demonstrated the effectiveness of streamlining.³¹⁰

White and Prentis finally addressed “the apparently simple phenomena of lateral earth pressures.” They concluded that the widely used formulas of William John Macquorn Rankine, a renowned nineteenth century Scottish engineer, for the computation of lateral earth pressures, were of little practical use to the designers of cofferdams. Utilizing the science of soil mechanics, they called for an acknowledgement of granular materials as elastic solids, with minute passages in which water circulates in a defined way. This led to an understanding that lateral earth pressure, such as that exerted by the fill within a cofferdam cell against the sheet piling that impounds the earth, was not regular, but varied as the earth settled against the piling.³¹¹

In 1945, Karl Terzaghi published the definitive, to that date, scientific study on cellular cofferdam behavior and design. Terzaghi, an Austrian-born civil engineer and geologist, is considered one of the founders of soil mechanics, a discipline that sought to bring an engineering understanding to soil as a material whose properties could be measured in standardized ways.³¹²

Terzaghi rejected the notion that cellular cofferdams performed like a gravity wall, which had led many engineers to design cofferdams based upon the notion that the width of the structure could be determined by bringing the intersection of two opposing forces—the lateral overturning force and the weight of the contents of the cells—within the middle third of the base. He argued that since cellular cofferdams consists of two very different materials, steel and soil, their properties were much more dynamic than a simple gravity wall and corresponded more closely to those of other composite materials, such as reinforced concrete.³¹³

Terzaghi expanded upon the work of White and Prentis, which was based upon Terzaghi’s own path-breaking work in soil mechanics. As with White and Prentis, he moved beyond Pennoyer’s consideration of cofferdams founded upon rock to address structures built upon sand and clay. He reviewed commonly used design equations and, in several instances, found them to be inadequate because of faulty assumptions regarding the character of the fill in the cells. He noted that widespread use of conservative values for soil constants had assured that the use of these inadequate formulas had yet to lead to catastrophic failures.³¹⁴

Adolph J. Ackerman, Director of Engineering for the Dravo Corporation, and one of the commentators on Terzaghi’s paper, appears to have agreed with these conclusions. Ackerman acknowledged that it was customary to regard cofferdams as gravity walls, and that their design was often based

upon two basic calculations: that the width of the wall be approximately 85–100 percent of the depth of water, and that the stress in the interlocks not exceed a designated acceptable value. Ackerman claimed that these simple calculations had indeed provided safe designs, though considerable “scientific-appearing computation work” was used to make it seem that the structure had been subjected to careful design analysis.³¹⁵

Terzaghi argued, based upon his understanding of soil mechanics, that before a cell overturned or slid on its foundation it was much more likely to fail as a result of shear rupture in the vertical plane of the fill. This conclusion, in consort with his judgment that a cofferdam did not act as a gravity structure, but needed to be evaluated as a composite construction of steel and soil, as well as several other factors, led him to develop a new set of design calculations. These established a factor of safety based upon the ratio of the shear resistance provided by the fill and the transverse sheet pile cell walls to the shear force exerted by the external water pressure.³¹⁶

Several TVA engineers contributed remarks to the discussion of Terzaghi’s paper. They noted Terzaghi’s “valuable and significant” contributions to a rational basis for the design and performance evaluation of cellular cofferdams, but emphasized that the TVA had studied internal shear forces and interlock tensions in advance of Terzaghi. The TVA finally published their own guidelines for cofferdam design and analysis in 1957. While the issue of precedence in the consideration of certain design variables may be open to

debate, it is indisputable that Terzaghi’s conclusions and calculations, often augmented by the TVA’s analysis, provided the basis for a standard approach to cellular cofferdam design that persisted for several decades.³¹⁷

Post World War II Corps of Engineers Cofferdams

During World War II, labor and material shortages halted construction, with the notable exception of the TVA’s Kentucky Dam, on the nation’s inland rivers. After 1945, a new generation of improvements were initiated, some entailed new construction on previously free flowing rivers, while most improved or enlarged facilities originally constructed in the early twentieth century. Cellular steel sheet pile cofferdams, designed based upon Terzaghi’s and the TVA’s analysis and computations, characterized most of these improvements.

The Columbia and Snake Rivers

Prior to World War II, the Corps of Engineers had not played a major role in the development of western rivers for navigation, power generation, flood control, or irrigation. The Department of the Interior’s Bureau of Reclamation took the lead in this portion of the country, with the exception of the Corps’ previously discussed work at Bonneville Dam on the Columbia River. In 1937, President Franklin D. Roosevelt signed the Bonneville Power Act, which created an independent administration within the Interior Department to sell and distribute hydroelectric power produced by Bonneville and Grand Coulee dams, while leaving control of the

dams in the hands of the Corps of Engineers and Bureau of Reclamation. Subsequently, in 1943, Congress authorized a new study of the Columbia River basin, with the intent of identifying potential dam sites. The resulting report, issued in 1948, called for construction of a series of multipurpose dams.³¹⁸

Beginning in 1947, and continuing into the mid-1960s, the Corps designed three dams on the Columbia and four on the lower Snake. Design memorandum issued by the Corps district office presented contractors with the basis for the design and preparation of plans and specifications for cofferdams, as well as all other elements of the projects. The design memorandum included a description of the proposed work and notes on any deviations from the project's general design memorandum necessitated by model studies or other technical investigations completed subsequent to that document. For cofferdams, the design memorandum generally included a discussion of hydraulics; geology and foundation conditions; soils; required instrumentation; and other factors that influenced the design decision. They included a basic description of design parameters, including rough plans, sections, specifications, as well as information on construction sequencing and costs. Cofferdam design memoranda issued for the Columbia and Snake River dams generally called for river arms constructed using circular cells comprised of steel sheet piling. The upper and lower arms of these structures generally were specified to be constructed using earthfill. Virtually every design memorandum

based the design of the cellular portion of the cofferdam upon Terzaghi's 1945 paper and the work of the TVA.³¹⁹

Monongahela River

Terzaghi's theoretical analysis of cofferdams, and the TVA's practical experience, largely addressed construction on undeveloped sites. In contrast, many of the Corps' post-war improvement projects generally required engineers and contractors to work on sites constrained by the presence of existing locks and dams, and to maintain existing river traffic throughout construction. These dictates often required the development of innovative design solutions to address the idiosyncratic site conditions.

These circumstances are well illustrated by the Corps' replacement of outdated locks and dams on the upper Monongahela River. Constructed prior to 1904, Lock and Dam Nos. 10–15 could not handle the larger tows in use in the 1940s. Tows had to be passed through the 56-foot by 182-foot locks in four segments, a task that required more than 90 minutes. The Corps of Engineers proposed to construct new locks, similar in design to those in use on the Ohio, measuring 84 feet by 600 feet. A standard six-barge tow could move through these locks in a single 20-minute passage. Work began on this project in 1948. Most of the cofferdams associated with these improvements consisted of typical circular cell steel sheet pile structures. Upon completion in 1967, Morgantown, Hildebrand, and Opekiska locks and dams had replaced the six former lock and dam complexes on the upper Monongahela.³²⁰

On the lower Monongahela, the Corps constructed new locks at Lock and Dam No. 2, located at Braddock, Pennsylvania, 11.2 miles upstream from the mouth of the river, between 1949 and 1953. In this instance, local conditions required a departure from standard cofferdam practice and resulted in the development of innovative designs and approaches. Poor existing foundations, unstable banks crowded with industrial plants, and the need to accommodate heavy river traffic throughout construction seriously complicated this work. The existing facility, completed in 1906, consisted of twin 56-foot by 360-foot locks. The lock walls were supported on wood piles driven into the gravel river bottom. Plans called for the existing land lock to be enlarged to 110 by 720 feet and a new 56-foot by 360-foot river lock to be constructed further into the stream.³²¹

The Dravo Corporation of Pittsburgh served as contractor for the work, which was undertaken in two stages. The first stage, completed between December 1948 and June 1951, entailed construction of the new river lock while maintaining traffic through the old land lock. During the second stage of construction, traffic would pass through the new river lock while the land lock was enlarged. The first stage of work required removing the existing river wall and a portion of the river lock floor, and building two new lock walls. Once these tasks were completed, the existing middle wall would be removed and the new land lock constructed.³²²

The exact location of the new lock walls was partially determined by the need to maintain river traffic during construction. The new

middle wall had to be located to the river side of the old middle wall so that the land lock could remain in use during construction of the new river lock. This required that the old, pile-founded middle wall be incorporated into the first stage cofferdam. Studies and calculations showed that this wall would be dangerously overloaded if the cofferdam was built high enough to permit operations during high water. The Dravo Corporation solved this dilemma by building a diaphragm-type, steel sheet pile cofferdam down the center line of the new river lock. This cofferdam supported construction cranes and served as the point of attachment for a series of struts used to brace the old middle wall. The struts consisted of 20-inch by 30-inch timbers, each reinforced with two, 12-inch steel beams. The remainder of the first stage cofferdam consisted of a circular cell steel sheet pile structure.³²³

Standard methods for construction of the new middle wall and the section of new river wall adjacent to the existing dam could not be employed because of the danger of undermining the old pile-founded structures. Consequently, these new walls were constructed using either caissons or internally braced cofferdams. The new river wall was constructed upon five reinforced concrete open caissons, sunk approximately 20 feet to bedrock, while the new middle wall was founded on four similar caissons. In the area adjacent to the existing middle wall, the new foundations had to be placed within a 27-foot deep braced sub-cofferdam. The cofferdam employed three sets of bracing, consisting of double 16-inch by 16-inch timbers and 30-inch steel wales. Twelve-inch concrete

blocking at the top of the sub-cofferdam carried the thrust of the existing middle wall through the sub-cofferdam and into the new river wall. Use of open caissons adjacent to the existing lock would have exposed that structure to the threat of undermining as the caissons were sunk.³²⁴

Ohio River Navigation Modernization

In the 1940s, the introduction of diesel-powered towboats permitted the use of tows longer than the standard 600-foot locks on the Ohio, requiring “double locking” barges through each lock in two maneuvers. This hazardous and time-consuming operation caused traffic delays and increased costs for the towing industry. As a result, as early as the 1940s, the Corps began developing initial

plans for modernizing and enlarging the locks and dams on the Ohio. In the years immediately following World War II, barge traffic on the river increased dramatically. At Lock No. 7, for example, the tonnage passing through the lock increased from 6.8 million tons in 1945 to 12.3 million tons in 1951. The existing system simply could not handle the volume of traffic, and modernization of the system became a priority. In 1955, work began on the Ohio River Navigation Modernization Program to replace the existing system of locks and movable dams (Figure 50). The new program incorporated the existing Emsworth, Dashields, Montgomery, and Gallipolis facilities, all of which represented 1920s-1930s enlargements and improvements to earlier facilities. Each of the proposed new high-lift concrete and steel dams

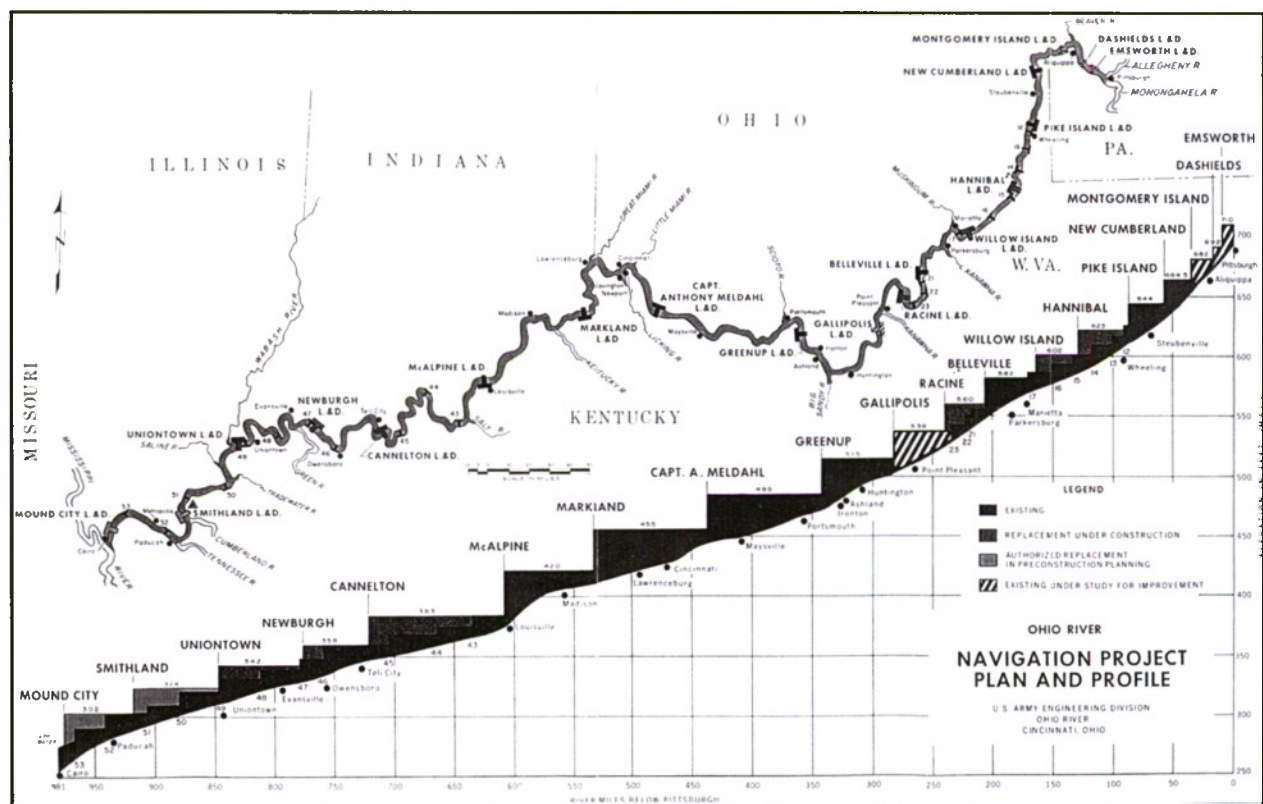


Figure 50. Map and profile of Ohio River navigation modernization (1969).

included two lock chambers, one measuring 600 feet by 110 feet, and the other 1,200 feet by 110 feet. The 1,200-foot chamber could pass a towboat and as many as 15 barges in a single operation. Each of the new non-navigable dams would replace at least two of the old facilities. The new facilities were designed solely to improve navigation, although most included provisions for the future installation of hydroelectric-generating equipment.³²⁵

Design of the new facilities began in the early 1950s. The Corps of Engineers' design memorandum for New Cumberland Locks and Dam, the first of the new facilities, called for a series of circular cell steel sheet pile cofferdams driven to rock, filled with sand and gravel, and capped with concrete. The work had to be staged in sequence across the river in order to maintain traffic and accommodate periods of high water without interrupting the construction. The first stage of work entailed construction of the locks within their own cofferdam, the dam then was constructed within a series of three cofferdams. Most of the Ohio River modernization projects followed this procedure, with cofferdams averaging 63 feet in height.³²⁶

At New Cumberland Locks and Dam, located 2 miles downstream from New Cumberland, West Virginia, the Dravo Corporation began work in 1955. Corps' engineers planned to use 70-foot diameter cells for the first stage cofferdam, but Dravo convinced the Corps to permit the use of 60-foot tall, 54-foot diameter cells, which offered a considerable savings in material. These cells offered a width-to-height ratio of about 0.80 feet, in contrast to

the customary 1.00 feet, the smallest width-to-height ratio attempted to date in a circular cell cofferdam. Dravo Engineering Manager Edwin P. Swatek, Jr. described the structure as "in a sense, a full scale experiment indicating the lower limits for narrow design." According to Swatek, the width proved insufficient. The top of the structure moved inward about 18 inches, significantly more than the normal cell movement of 3 to 6 inches. Swatek argued that the structure should have been built according to customary practice, as wide as it was tall.³²⁷

Despite the fact that the Corps had 80 years of experience building on the Ohio, the modernization program did not proceed without incident. Two cofferdams failed as a result of sliding, but not at the interface between the sheet piles and the rock. At Uniontown Dam, on the lower Ohio, the failure occurred in a thin layer of coal and fire clay located approximately 15 feet below the surface of the rock. Water in this seam lubricated the clay and added uplift pressure. Intersecting faults further weakened the rock strata. The failure occurred when a large slab of rock rotated 70 feet into the cofferdam with four undamaged cells riding on top of it.³²⁸

In 1968, at Cannelton Locks and Dam on the lower Ohio, a sliding failure occurred when the top layers of shale rock broke up as a result of excavation for the dam piers adjacent to the cells. One cell ruptured and five other cells slipped, forcing a work shutdown. The cofferdam consisted of two concentric rings of 60.5-foot diameter circular cells. The combination of the two rings provided a 140-foot head. The sheet piles in the outer ring con-

sisted of spliced piles, while the inner ring piles measured 70 feet in length. Within the inner ring, the contractor, J.A. Jones Construction Company, of Charlotte, North Carolina, removed the bottom sediment and excavated through 20 feet of shale to reach solid rock for the dam's pier foundations at a depth of 160 feet.³²⁹

The shale began to crack as it was being removed from one of the pier foundation holes. Sheet piling was placed in the crevices to brace the excavation, but a cell of the inner cofferdam ring ruptured and the five adjoining cells shifted inwards as much as 12 feet, while the berm behind the cells settled 10 to 12 feet. The contractor flooded the inner cofferdam and dumped 20 to 35 feet of sand in to stabilize the cells. The cofferdam was subsequently modified to include, in effect, a third ring. The sand was left in the hole to anchor the toe of the cells and Z-piles were sunk through the sand, ringing each pier foundation. The sand then was removed within the pier foundation work area, and excavation to bedrock continued.³³⁰

Some of the Ohio River modernization projects employed diaphragm type cofferdams for construction of the locks. As noted previously, diaphragm cells cannot be filled immediately upon completion of pile driving and made self-supporting. A line of diaphragm cells, therefore, requires more time to fill and make the line safe against high water. This precludes the placement of diaphragm cells across the main flow of a stream. However, for cells placed parallel to the flow of the current, diaphragm cells are easier to set and drive than circular cells. The

templates used to drive the piles are easier to place and the cells can be filled using a clam-shell or dragline if fill is first placed over the cross walls to equalize pressure on both sides of the wall.³³¹

At Pike Island Locks, near Wheeling, West Virginia, a high head diaphragm-type cofferdam, without an inside berm, was constructed in 1961. The cofferdam measured 62 feet in height, and rose 19 feet above the normal pool height. In a 1967 article, Edwin P. Swatek, Jr., the former Engineering Manager of the Dravo Corporation, evaluated the structure as performing adequately in terms of stability, shear, and sliding. Swatek noted that "[a]lthough theories have been advanced to support a mathematical solution for the soil stress in a cell, we are still designing the structures largely with experience as our guide. Current fill shear determinations used by some designers require unnecessarily wide cells. The rule of thumb is width approximately equal to height."³³²

11 Contemporary In-River Construction Practice

The conventional methods used to design steel sheet pile cofferdams for the Ohio River modernization program were developed in the 1940s and 1950s largely upon the basis of field and experimental observation. No single method permitted engineers to accurately determine the stresses in the cell fill, so no single method was accepted universally by the engineering community. Four different methods were used to check the factor of internal safety.³³³

The various conventional design methods provided inconsistent answers to the same questions, thereby leaving engineers in a quandary as to which method provided correct answers to issues regarding safety and stability. Many engineers believed, largely based on intuition rather than hard evidence, that conventional design methods produced overly conservative designs. No conventional design method could predict deformations of a cofferdam, none included clear procedures for considering soil-structure effects, and none offered a full consideration of three-dimensional effects upon a structure.³³⁴ Problems with conventional design methods were clearly illuminated during the design and construction of the cofferdams for the replacement of Lock and Dam No. 26 on the upper Mississippi.

Melvin Price Locks and Dam

Melvin Price Locks and Dam, named after Illinois Congressman Charles Melvin Price, is

the first replacement structure in the Upper Mississippi River 9-Foot Channel Project. Located at river mile 200.78, about 17 miles north of Saint Louis, Missouri, Melvin Price Locks and Dam replaced Lock and Dam No. 26, located about 2 miles upstream. The new facility consists of a 1,160-foot long dam fitted with nine massive tainter gates, each measuring 110 feet wide and 42 feet high, and two locks. The main lock measures 1,200 feet by 110 feet; while the auxiliary lock is 600 feet by 110 feet.

Construction began in 1979, with the main lock opening to traffic in 1990. The full structure was completed in 1994. Lock and Dam No. 26, which was demolished in 1990, was plagued with structural issues almost from the date of its completion. Scour holes of particular concern developed below the dam. Some of these holes were deeper than the wood pilings supporting the dam. The scouring of the riverbed led to disintegration of the concrete and a loss of foundation material, which eventually resulted in deflection and settlement of the lock walls and dam piers.

Throughout design and construction, the Corps of Engineers and the various contractors, engaged in an extensive program of computer-assisted design, testing, and evaluation. These sophisticated studies represent one of the first instances of the use of computers in the design and construction of a major river navigation improvement. Com-

puters offered engineers access to much more sophisticated methods of design and analysis than previously available.³³⁵

The first phase of construction began in 1979 and entailed construction of the first stage cofferdam, which enclosed about 25 acres along the Missouri shore and measured approximately 1,500 feet in length and 800 feet in width (Figure 51). The cofferdam consisted of 45 circular steel sheet pile cells, each measuring 64 feet in diameter and 60 feet in height. Construction of the first five gate bays of the main dam began inside this cofferdam in October 1981 and was completed in late 1984. The second stage of the work, begun in August 1984, entailed construction of the main lock and a small section of the dam on either side of the lock. This cofferdam enclosed an area measuring 1,900 feet by 600 feet and consisted of 54 circular cells, those in the Missouri arm measured 60 feet in height,

while those on the river arm measured close to 80 feet tall. The third phase cofferdam enclosed the auxiliary lock and the Illinois end of the dam.³³⁶

The design memorandum for the first stage cofferdam, issued in 1973, called for an extensive program of instrumentation to evaluate the overall performance of the structure because Corps engineers were concerned by the contradictory results produced by analysis of the structure using various conventional methods. Two cells were fitted with earth pressure cells, piezometers, strain gauges, inclinometers, and optical survey markers. The earth pressure cells did not provide credible readings and were considered unreliable. Piezometers installed inside cofferdam cells, on both slopes of the embankment, and at various locations within the work area measured hydraulic head and uplift pressures. Inclinometers determined deflections

in sheet piling and changes within the cofferdam cells in reaction to static and dynamic loads. Alignment surveys were required on a regular basis to monitor movement of the top of the cells, while scour surveys sought to identify the scope and extent of scour.³³⁷

The instrumentation program sought to collect field measurements to determine sheet pile interlock forces at various

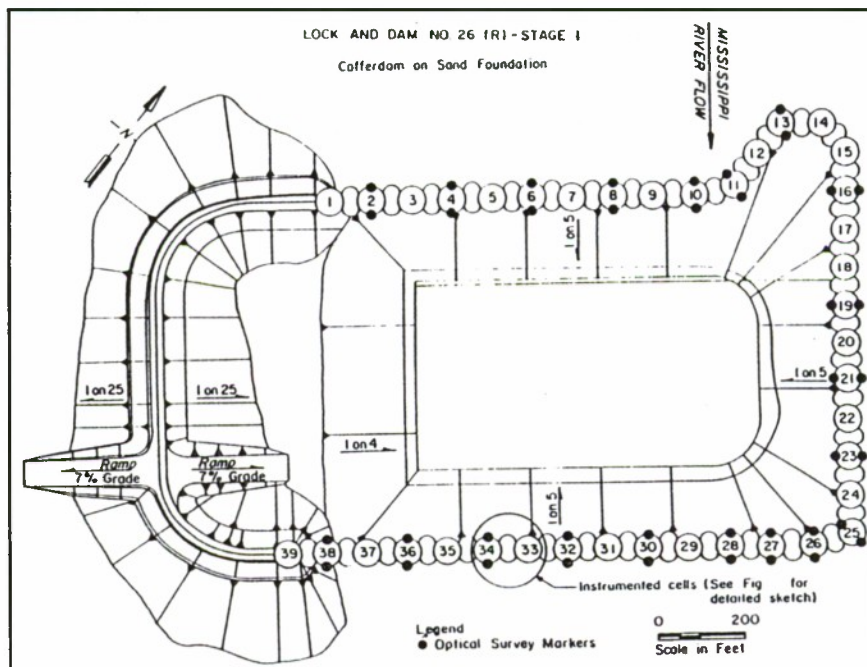


Figure 51. Lock and Dam No. 26(R) (Melvin Price Locks and Dam) Stage 1 cofferdam plan. From Martin and Clough (1990).

levels within the cells, to evaluate the benefits of interior berms, and to assess the overall performance of the structure. Any of the measurements provided by the instrumentation could not be assessed using conventional methods for analyzing cofferdams. This led to development of finite element procedures that could be applied to modeling of the structure, aiding in the interpretation of the instrumentation data and the assessment of the reliability and accuracy of conventional design methods. The use of finite element analysis, a numerical technique for finding approximate solutions of partial differential equations, required development of sophisticated computer programs. The primary challenge in solving partial differential equations is to create a numerically stable equation that reduces errors in the input data and intermediate calculations so that errors do not accumulate and render the output meaningless. Finite element analysis offers a useful method solving partial differential equations over complex domains, such as a cellular cofferdam, that do not behave in a uniform and predictable manner.³³⁸

The Corps' Waterways Experiment Station in Vicksburg, Mississippi, conducted numerous movable bed model studies prior to the issuance of the first stage cofferdam design memorandum. These studies generated valuable data on current velocities and directions, used in the design process to assure that construction of the cofferdam did not generate cross currents capable of complicating and causing difficulties for river traffic. The model tests also provided information on expected locations and patterns of scour that were used to design a cofferdam deflector that would

move the location of maximum scour away from the cofferdam. The tests indicated that a three-stage construction process, beginning on the Missouri side of the river, was practical in terms of flow patterns, velocities, and scour.³³⁹

The second stage cofferdam, placed adjacent to the main navigation channel, generated considerable concern about the influence of the cofferdam upon river navigation. Movable bed model tests conducted at the Waterways Experiment Station demonstrated that the planned construction sequence proved hazardous to navigation and, as a result, to the workers building the cofferdam. The model tests were used to develop a construction sequence that optimized navigation and worker safety.

The original construction plans called for removal of most of the first stage cofferdam prior to starting work on the second stage coffer, thus permitting the river to flow through the gatebays constructed within the first stage coffer and reducing current velocities in the navigation channel. The model tests indicated current velocities low enough to permit construction of portions of the second stage cofferdam prior to removal of the first stage structure, significantly reducing construction time. The model tests also demonstrated that the planned construction sequence created a situation in which current flows would draw tow boats into a temporary 2,000 foot gap in the river arm of the second stage cofferdam. This created a navigation hazard, as well as jeopardizing the safety of the cofferdam workers. A new construction sequence was developed and locations for a

series of navigational markers designed to assist tow boat operators in navigating past the cofferdam were identified.³⁴⁰

Innovations in Design Methods and Behavior Analysis

By the mid-1970s, the design methods of Terzaghi and the TVA had been refined and elaborated. Terzaghi had introduced the concept of designing the fill of a cofferdam cell upon a vertical plane to prevent shear failure, an idea used by TVA engineers during the 1930s, but not published until 1957.³⁴¹ Terzaghi discussed the possibility of slip between the fill and the sheet pile walls, as well as the penetration of the inboard walls into the foundations. In the ensuing years, other engineers expanded upon these types of internal stability failures and published their own design formulae.³⁴²

In 1966, the Office of the Chief of Engineers authorized a Corps-wide survey of cofferdam failures since 1960. The survey, published in 1974, included a detailed analysis of cellular sheet pile cofferdam failures and served as an impetus for additional research and analysis. The Corps determined that the principal sources of failure stemmed from issues related to soil mechanics and foundations, the structural behavior of sheet piles and interlocks, and the fabricated tee and wye pilings used to connect cofferdam cells, environmental conditions, and construction practices. Recommendations and conclusions sought to reduce the number of failures resulting from these causes.³⁴³

Despite the host of technical treatises and the Corps' practical recommendations based upon analysis of past failures, the design of cellular cofferdams remained largely based upon conventional methods that failed to consider the actual process of soil-structure interaction. These methods led to conservative designs, partly because they were unable to provide data on deformation of cells to be expected during construction and filling. These data are important in evaluating the stability of the structure and proved particularly important for cofferdams constructed upon less than optimal foundations. Corps of Engineers designers recognized the need to improve their methods in order to produce more economical structures and to allow for assessment of cofferdam behavior under a wider variety of conditions.³⁴⁴

One method that permitted more complete analysis of cofferdams was the finite element method. This method allows prediction of stress conditions in the cell fill and foundation soils, and the stresses and forces within the sheet pile enclosure. It can consider soil-structure interaction within the parameters of the loading process, and can generate data on the deformations that a cofferdam will experience. The finite element analysis of the first stage cofferdam constructed for Melvin Price Locks and Dam demonstrated the value of this form of analysis and provided accurate data to questions ignored, or only crudely approximated, using earlier methods of analysis. However, the specialized two-dimensional finite element models used by the Corps could not represent the three-dimensional nature of a cellular cofferdam. The potential for catastrophic failure inherent

in the construction of any cofferdam, together with the fact that, since relatively few cellular cofferdams are built, the opportunities to learn from experience and observation are limited, made engineers hesitant to adopt a new design tool, such as finite element analysis.³⁴⁵

In the 1980s, Corps engineers, working with experts from outside the Corps, developed a computer program, CCELL, which used conventional design approaches and criteria to analyze and design cellular sheet pile cofferdams.³⁴⁶ The Corps' experience with cellular sheet pile cofferdams was codified in *Design of Sheet Pile Cellular Structures*, an official Corps' Engineering annual published in 1989. The manual addresses the planning, layout, and construction of cofferdams, with specific chapters devoted to geotechnical considerations, analysis and design, construction, dewatering, and instrumentation. It continues to serve as the Corps' basic manual for the design of cellular sheet pile cofferdams.³⁴⁷

Corps engineers and designers continue to investigate cofferdam design and behavior. In the 1990s, Corps engineers and others developed a three-dimensional finite element analysis for cofferdam modeling, but this method remains largely of academic interest and is not generally employed in the design of cofferdams for specific projects.³⁴⁸

Innovative Design Solutions at the End of the Twentieth Century

Three projects illustrate the Corps of Engineers' continuing commitment to design in-

novation and the adoption and implementation of new technology for in-river construction projects. Issues associated with cost, schedule, and site constraints frequently served as the catalyst for innovation, which seldom, if ever, was adopted solely for the purposes of employing a new technology. These projects all made extensive use of the analytical power afforded by modern computers during the design process. Computers also proved essential in monitoring and analyzing the behavioral and performance data generated by sophisticated instrumentation.

Point Marion Lock

In 1990, work began on a replacement lock chamber at Point Marion Lock and Dam, located on the Monongahela about 75 miles south of Pittsburgh. The dam, rehabilitated in 1959, and the new lock were to replace Lock and Dam No. 8, constructed in 1926. The new lock chamber measured 84 feet by 720 feet, eliminating the traffic bottleneck of the old 56-foot by 360-foot lock chamber. Plans called for the new lock to be constructed landward of the existing lock, which would remain open to traffic during construction. The close proximity of the planned excavation for the new lock to the existing structure led to a decision to utilize the land wall of the existing lock as the river arm of the project cofferdam (Figure 52). This required extensive stabilization of the existing wall, since in some locations the proposed excavations for the new lock were within 8 feet of the existing land wall and extended up to 13 feet below its foundation.³⁴⁹

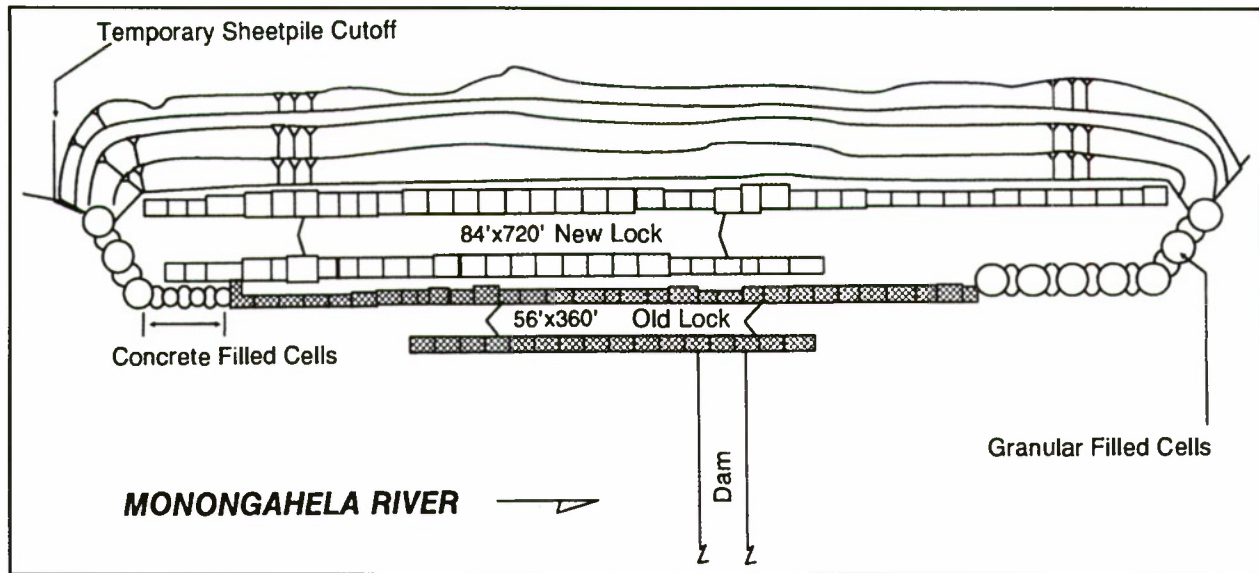


Figure 52. Point Marion Lock. Plan of cofferdam showing location of new and old locks and incorporation of old land wall into cofferdam. From Greene et al. (1993).

Existing walls had been incorporated into cofferdams in the past. In 1915, at Lock and Dam No. 41 at Louisville the Corps used an existing wall of the Louisville & Portland Canal as part of a cofferdam, as described above. In 1961, an attempt to utilize an existing lock landwall as part of a cofferdam at the Tennessee Valley Authority's General Joe Wheeler Lock and Dam had proven disastrous. The lock wall moved about 30 feet into the dewatered excavation, killing two people and suspending navigation on that stretch of the Tennessee River until the lock could be reconstructed. The reported cause of the failure was sliding of the existing lock wall on an undetected weak clay seam in the foundation rock. No stabilization measures or monitoring instrumentation had been used at Wheeler Lock and Dam.³⁵⁰

At Point Marion, nearly 500 large-capacity prestressed rock anchors were installed in three rows to ensure the required stability of the existing land wall (Figure 53). A total of

139 vertical anchors were installed to prevent overturning. Two rows of inclined anchors, a total of 286, were placed to resist sliding of the land wall monoliths along the top of their rock base. Additional anchors were employed to stabilize the cofferdam cells. Excavation proceeded in stages and was closely linked to the installation and stressing of each row of anchors. An array of sensors connected to computers monitored the performance of the cofferdam throughout construction.³⁵¹

In-the Wet Construction: Braddock Dam

In 1997, the Corps of Engineers' Pittsburgh District determined to use an innovative new approach for the construction of Braddock Dam on the Monongahela River. The new structure, designed to replace the 1906 Dam No. 2, would be built using "in-the-wet" construction methods that eliminated the need for cofferdams. In-the-wet construction methods first were used in the construction of immersed tunnels, such as the 3.5-kilometer

Oresund Tunnel between Denmark and Sweden, and offshore oil-rig platforms.³⁵² The Braddock Dam project marked the first use of the technique for an inland river navigation dam in the United States.³⁵³

The concept of in-the-wet construction entails foundation preparation from a floating construction plant and prefabrication of very large floating concrete shells at a separate remote site. Once the foundation preparations and the shells are completed, the shells are towed to the construction site. They either float by themselves or with the aid of external pontoon-like flotation devices. Once at their permanent location, the shells are positioned for attachment to the foundations and are lowered into place by ballasting. Once positioned, the void between the bottom of the shell and the top of the foundation is filled with grout, sand, or other material depending upon the design requirements. The shells then act as permanent forms for fill concrete.³⁵⁴

The design of Braddock Dam was the result of collaboration between the Corps of Engineers Pittsburgh District, the lead design firm of Bergmann Associates, and two subconsultants, Ben C. Gerwick, Inc. (BCG), and D'Appolonia. The private-sector design team evaluated the Corps' initial design concepts for the project and then assisted the Pittsburgh District in development of the final design. BCG, a heavy-construction company with more than 75 years experience in marine

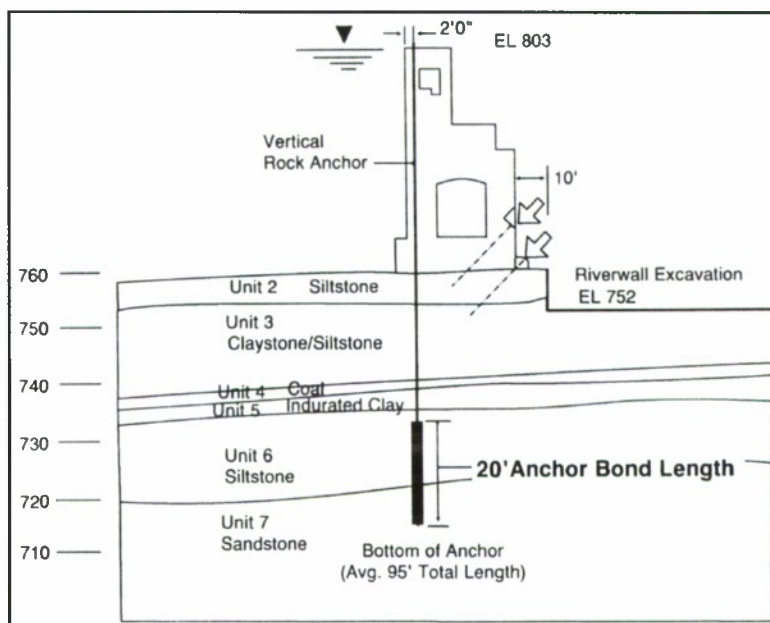


Figure 53. Point Marion Lock. Section of old land wall showing location of rock anchors. From Greene et al. (1993).

projects, undertook the final analysis and design of the two floating dam segments. A joint venture between J.A. Jones Construction Company and Traylor Bros., Inc. undertook the construction. Traylor Bros. had previous experience working with the Corps of Engineers on the Ohio River. The firm was involved in major projects at McAlpine Locks and Dam at Louisville, Kentucky and Dam No. 53 at Mound City, Illinois.³⁵⁵

The new dam's foundation consisted of 89 drilled shafts, each 78 inches in diameter and 30-40 feet long. Each shaft was drilled an additional 15 feet into bedrock, with a 72-inch diameter socket designed to carry the weight of the dam. The foundation for each segment of the dam consisted of six set-down shafts and 77 foundations shafts that transferred the load of the structure to the bedrock. The construction of these shafts was completed, using a floating plant and without the use of cofferdams, by the summer of 2000.³⁵⁶

While work progressed on the dam foundations, the two reinforced concrete shells that comprise the dam were fabricated in a specially constructed two-level casting basin on the Ohio River at Leetsdale, Pennsylvania, about 27 miles downstream from the dam site (Plate 37). Each dam segment consisted of a thin-shelled, hollow, reinforced concrete structure, flat on the sides and bottom, with curved sections of the top that formed the dam's ogee-shaped spillway. Segment 1 measured 333 feet by 104 feet and weighed 11,600 tons, while Segment 2 measured 256 feet by 104 feet and weighed 9,000 tons. The bottom of each segment was recessed to accommodate the set-down and foundation shafts.³⁵⁷

The completed shells were launched individually by flooding the casting basin, and towed to an outfitting pier located 2 miles upstream from the dam site. Upon completion of the outfitting process, the shells were floated to the dam site, positioned, and set down upon the prepared foundations. Once grouted onto the foundations, specially designed underwater concrete was placed within the hollow compartments of the shells to form a solid-mass concrete structure. The remainder of the construction process was completed using the floating plant.³⁵⁸

On July 26, 2001, Braddock Dam Segment No. 1 floated out of its casting basin in Leetsdale and began its trip to the outfitting pier.

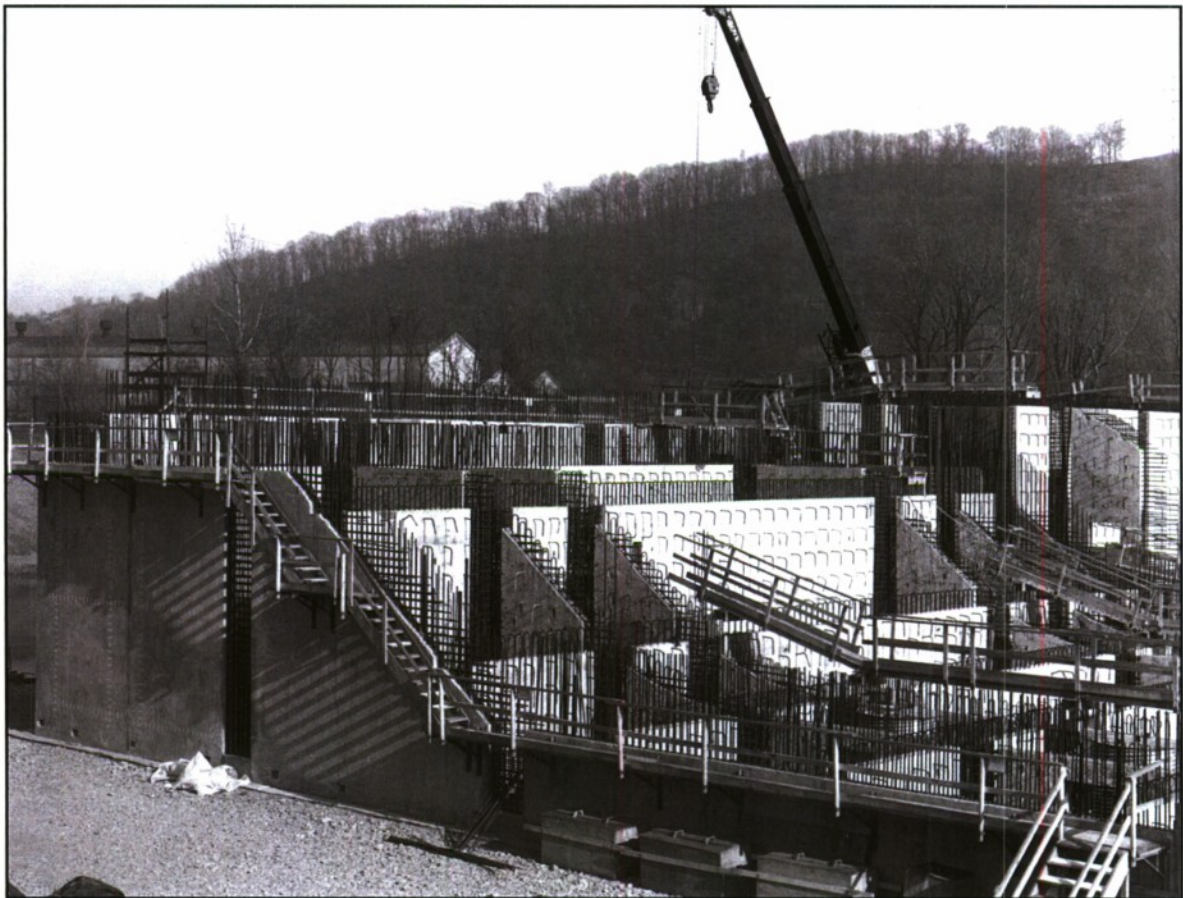


Plate 37. Braddock Dam, Monongahela River. Construction of dam segment in casting basin.

Segment No. 2 followed on February 27, 2002. Enroute the segments had to pass through Dashiels and Emsworth Locks on the Ohio River, nearly filling the lock chambers. After passing through Lock No. 2 on the Monongahela River, the segments were moored at the outfitting pier in Duquesne, where they were prepared for placement onto their foundations.³⁵⁹

On December 5, 2001, Segment No. 1 was transported to the project site, positioned, and sunk onto its prepared foundation (Plate 38). Segment No. 2 was placed on 19 June 2002. Positioning the dam segments, a complex operation requiring extraordinary control, was accomplished using a system of cables, winches, and mooring piles, with assistance from towboats. Once positioned the segments were slowly set down, over an ap-

proximately 48-hour period, upon the prepared foundations by pumping water into compartments built into each segment. After each segment was firmly set down upon its foundation, workers began grouting the segments to the foundations and infilling the segments. The two segments form the lower third of the pier bases and overflow sections of the five-bay gated navigation dam. The balance of the dam was constructed from floating plant above the water. Braddock Dam became fully operational in April 2004.³⁶⁰

The decision to use in-the-wet construction methods at Braddock Dam was not undertaken simply to utilize a new and innovative construction technology. In-the-wet construction allowed work to proceed simultaneously on the dam foundations and the concrete base sections of the structure, accelerating the con-



Plate 38. Braddock Dam, Monongahela River. Positioning Segment No. 1, December 2001.

struction schedule, reducing costs, and eliminating the time and costs required to construct conventional cofferdams and the risks associated with the potential flooding of the cofferdams. The elimination of cofferdams also proved less disruptive to existing river traffic. Construction of the dam segments within the casting basin enabled the Corps and the contractors to more closely monitor and contain any environmental hazards associated with the work, while also permitting a higher quality of construction, in comparison to work performed on the river bed within a cofferdam.³⁶¹

The Work Continues: Olmsted Locks and Dam

Construction began on Olmsted Locks and Dam in 1996 at mile 964.4 of the Ohio River in Pulaski County, Illinois, and Ballard County, Kentucky approximately 2 miles downstream from Lock and Dam No. 53. The project will replace Lock and Dam Nos. 52 and 53,, which were built in 1929 and consist of single 110-foot by 600-foot lock chambers and associated wicket dams, with a single facility consisting of twin 110-foot by 1,200-foot lock chambers and a new navigation dam. The 2,700-foot-long dam will feature five Tainter gates adjacent to locks on the Illinois side, a fixed weir on the Kentucky side, and traditional wicket gates in the middle that will permit open river navigation during high water in the spring.³⁶²

Dam construction for the Olmsted project will be accomplished using in-the-wet methodology, with work done underwater by pumping concrete into precast shells built in the yard, rather than standard in-the-dry construction

requiring the use of cofferdams. The project currently is scheduled for a 2021 completion, depending upon funding. Early construction efforts included preparation of the 1,000-foot by 300-foot yard used to form the precast dam shells and a 1,600-foot skidway with rail and rollers for transporting the shells to the river edge and work areas.

A steel sheet pile cellular cofferdam, consisting of 51 cells, each measuring approximately 64 feet in diameter, was constructed between June 1993 and December 1995 for work on the lock foundations. The cofferdam required more than 8,500, 109-foot long piles, the longest ever produced by Bethlehem Steel. The locks were constructed between December 1995 and November 2001.³⁶³

The complex includes four approach walls, the longest a third of a mile long, to guide tows into the lock chambers. Because the river's height fluctuates, the approach walls occasionally become submerged and muddy. As a result, floating guide walls were designed to reduce maintenance costs. Eleven 375-foot-long segments that comprise the approach walls were built in a graving yard in Paducah, Kentucky, towed to the site, bolted together in the lock chamber, and set in place. Four nose piers, made up of three linked 10-foot diameter pipes filled with concrete and steel were installed at the tip of the approach walls as protection.³⁶⁴

12 Conclusion

Unlike Robert Frost's traveler in the woods, the Corps of Engineers managed to follow two ostensibly contradictory paths in terms of their design and use of cofferdam technology.³⁶⁵ On one hand the Corps displayed a commitment to traditional, tested methods and approaches, while, when conditions or circumstances warranted, the institution adopted and implemented path-breaking new technologies and techniques.

The thread of continuity is perhaps nowhere better exemplified than in the Corps' long reliance upon the basic cofferdam design and analysis published by Dennis Hart Mahan in the 1830s. For nearly three-quarters of a century cofferdams designed by Corps engineers conformed to the basic dictates of Mahan's design. Cofferdams that deviated from Mahan's pile-founded design harkened back to a folk tradition of timber crib dams.

This is not to say that there were no innovations in Corps of Engineers cofferdam design and construction during the nineteenth century. Captain William Turnbull pioneered large scale in-river cofferdam construction in the United States with his work on the Potomac Aqueduct in the early 1830s, prior to the publication of Mahan's work. Indeed, Mahan included details of Turnbull's design solutions for deep cofferdams in later editions of his work.

In the years immediately following the Civil War, Captain P.C. Hains departed from conventional practice and, in consultation with his contractor, Charles G. Case & Company, decided to forego the laborious task of drilling shafts for iron rods into the rock bottom of the Mississippi River at Rock Island Rapids. Hains calculated that the weight of the cofferdam would hold the structure in place and resist sliding and toppling forces. This decision, and its successful implementation, eliminated a time-consuming and expensive element of conventional construction practice, cutting costs and schedules.

Nevertheless, virtually all cofferdams constructed by the Corps prior to the first decade of the twentieth century were fundamentally based upon Mahan's design, which was itself influenced by European, and particularly French, experience, or the vernacular timber crib tradition. These designs remained in use, when site conditions and circumstances warranted, well into the twentieth century. Massive, modern structures such as Wilson and Bonneville dams were erected within cofferdams constructed of timber cribbing.

The Corps has a long tradition of innovation in the design and construction of locks, dams, and other in-water structures. In the decades following the Civil War, Corps engineers built upon French precedents and introduced movable navigation dams to the United States. It is instructive to note, however, that

a vernacular tradition of movable dams in the United States dates to the early nineteenth century, particularly the bear-trap gate designed by Josiah White for the Lehigh Navigation Company.³⁶⁶ Nevertheless, Corps engineers innovated and experimented with Chanoine wicket and needle dams in the last quarter of the nineteenth century introducing these technologically sophisticated structures to the American scene. Likewise, in the 1920s and 1930s, Corps engineers adopted Tainter gates and roller gates, new technologies that improved the performance and operation of movable dams. The innovative efforts of Corps engineers on the Upper Mississippi River's 9-Foot Channel Project in the 1930s occurred so quickly that structures constructed at the onset of the project were, in many regards technologically obsolete by the time the project was completed.

Innovation in the design and construction of cofferdams did not earn the same engineering plaudits or capture the same number of pages in technical journals as the innovation of permanent structures. The temporary nature of cofferdams, designed to survive only during the construction of the permanent works, contributed to their relative obscurity. Nevertheless, Corps engineers pioneered a number of significant improvements in cofferdam design and construction.

On the Ohio River, in the first decade of the twentieth century, Corps engineers and their contractors developed the Ohio River type box cofferdam. The design represented a modification of Mahan's time-tested pile-found design, relying upon a much lighter frame that was not driven to bedrock. The

design took advantage of the bottom conditions that characterized the Ohio, and which did not require deep, pile-founded structures. In addition to developing a lighter design, requiring less material and thereby reducing costs, Corps engineers also created an innovative method of construction, in which the frame of the cofferdam was built on barges and lowered into the river as a continuous frame with hinged joints between sections.

The combination of the design and construction innovations created a cofferdam that used less material and could be more quickly constructed, reducing costs and permitting shorter construction schedules. Given these advantages over the pile-founded Mahan design, the Ohio River type box cofferdam was quickly adopted along the length of the Ohio and its tributaries, as well as upon other inland waterways. The details of the design were published in technical journals and paper, as well as in engineering handbooks, facilitating its dissemination. Corps engineers also carried the details of the design and construction methods with them from duty station to duty station. On the upper Ohio the design became the new status quo, with engineers proving resistant to other design innovations. The success of the design under conditions on the upper Ohio proved so self-evident that new technologies had to demonstrate a clear and considerable competitive advantage in order to be adopted.

Corps engineers in several locations developed steel sheet pile cofferdams for major projects during the first two decades of the twentieth century. Private builders, most notably railroad companies, were the first to use

steel sheet pile cofferdams in the United States, but these projects were relatively small in comparison to those built by the Corps. Beginning with the Black Rock Lock, constructed in 1908 in Buffalo, New York, Corps engineers quickly refined and improved the design of cellular steel sheet pile cofferdams. Major advancements included the circular cells used in the cofferdam associated with the raising of the battleship *Maine* from the bottom of Havana Harbor in 1911, and the diaphragm design developed for the cofferdam constructed in 1913 for Troy Lock and Dam on the Hudson River.

By the onset of World War I, Corps engineers had gained significant experience and expertise with the design of steel sheet pile cofferdams and had demonstrated their advantage, in general, over wooden structures. The new technology met considerable resistance among engineers working on the upper Ohio, where the Ohio River type box cofferdam proved exceptionally well-suited to local conditions. In this region, for this period, continuity held sway over change. Steel sheet pile cofferdams were not used on the upper Ohio until the 1920s, following the retirement of several engineers and the development of new navigation projects that required deeper foundations and more massive excavations than generally were used with the Ohio River type box.

In the 1930s, on the Upper Mississippi River 9-Foot Channel Project, Corps engineers clearly demonstrated both a willingness to rely upon time-tested technologies and to introduce and improve cutting-edge techniques and methods. The 29 lock and dam

complexes constructed for the project between 1933 and 1953 utilized a wide variety of cofferdam designs, including hybrid designs that combined wooden and steel elements. The contrasting patterns of continuity and change within the Corps' designs remained evident on the Mississippi. Steel sheet pile cofferdams became widely adopted only after the departure of head engineer William H. McAlpine, who believed the difficulty and expense associated with their removal outweighed any advantages.

Many of the cofferdams constructed by the Corps on the Upper Mississippi embraced a new, scientific approach to design and performance analysis. Model studies, conducted by university hydrology laboratories and by the Corps' Waterways Experiment Station, were used to test and inform designs. The hybrid designs that employed both wooden and steel sheet piling were, in and of themselves, innovative in their combination of materials and effort to reduce costs by using less expensive and more readily available material where more expensive alternatives were not required to assure the safety of the design.

During the 1930s, while the Corps of Engineers canalized the Upper Mississippi with a series of relatively small, gated dams, other federal agencies, most notably the Tennessee Valley Authority, constructed massive flood control and multiple purpose dams. The size of these projects, the depth of their foundations, and the area to be enclosed and protected during construction, precluded the use of wooden cofferdams. Consequently, while Corps engineers employed an eclectic series

of designs on the Upper Mississippi, based upon the dictates of site conditions, TVA engineers, in particular, became the nation's leading experts on the construction and performance characteristics of steel sheet pile cellular cofferdam structures.

Following World War II, steel sheet pile cellular cofferdams became the dominant design employed by the Corps of Engineers. Corps engineers recognized the depth of experience gained by the TVA during the 1930s and adopted many of that agency's design criteria. Academic and consulting engineers made a considerable effort, in the years immediately following World War II, to develop a rational, mathematically-based performance model for steel sheet pile cellular cofferdams. Corps engineers quickly recognized the value of this work and integrated the results of engineers such as Lazarus White, Edmund Ashley Prentis, and, most significantly, Karl Terzaghi, into their design calculations and contractor specifications.

Despite these efforts to develop a theoretical basis for evaluating the design and performance of steel sheet pile cellular cofferdams, as late as 1967 a veteran designer noted that "we are still designing the structures largely with experience as our guide."³⁶⁷ Sophisticated instrumentation and monitoring programs have been incorporated into many recent cofferdams in order to provide hard data regarding actual performance. These data may then be used to inform the design of future cofferdams. The Corps of Engineers' cofferdams for Melvin Price Locks and Dam on the Mississippi River, begun in 1979, exemplify this use of performance instrumentation.

Computer analysis of the data generated provided engineers with new tools for the analysis of these complex structures that rely upon both soil and steel to achieve their desired goals.

The Corps has assumed a leading role in developing analytical tools for modeling cofferdams. Computer programs employ the methods of finite element analysis to help solve design equations for complex structures such as cofferdams, which do not behave uniformly and predictably. The results of these analytical efforts and practical experience were presented in the Corps' 1989 design manual, *Design of Sheet Pile Cellular Structures*.

At the close of the twentieth century, after nearly 50 years of reliance upon steel sheet pile cellular cofferdams, Corps engineers embraced a new technology for construction of Braddock Dam on the Monongahela River in Pennsylvania. The decision to use in-the-wet construction methods at Braddock Dam was not simply a decision to employ a new, innovative construction technology. In-the-wet construction eliminated the need to construct a cofferdam in a relatively narrow, highly trafficked stream. It also allowed the acceleration of the construction schedule, reduced costs, facilitated both environmental and construction quality monitoring. The new technique offered a suite of advantages over conventional construction methods, given conditions on the Monongahela. The future use of in-the-wet construction, which is planned for a number of projects, will, in part, depend upon a similar coalescence of technical, physical, and traffic conditions.

The twin threads of continuity and innovation in design and construction have characterized the history of the Corps of Engineers' construction efforts on the nation's inland waterways. During the nineteenth century, Corps engineers innovated and perfected the pile-founded design promulgated by Dennis Hart Mahan. During the early twentieth century, a new generation of Corps engineers simultaneously held to traditional designs while, at first tentatively and then enthusiastically, adopting a new technology employing steel sheet piling. By the middle of the twentieth century steel sheet pile cellular cofferdams were as dominant and omnipresent on Corps projects as Mahan's designs had been in the previous century. Steel sheet pile cofferdams now represent a persistent, conventional technology. Innovation of the technology since World War II has largely entailed developing better methods for analyzing and understanding the behavior of these structures. In the last decade of the twentieth century Corps engineers began to embrace a new technology, in-the-wet construction, which may represent another departure from conventional practice. If the past is indeed prologue, one may assume that now conventional steel sheet pile cellular cofferdams will persist, while improvements and refinements in the new technology are developed and introduced by Corps engineers working in the field.

13 Bibliography

- Abbott, Edwin E. "Design for a New Ohio River." *Civil Engineering* 32 (October 1962): 46-49.
- Adams, Lewis M. "New Lock and Dam No. 5, Monongahela River at Brownsville, PA." *Professional Memoirs, Corps of Engineers* 2:6 (April-June 1910): 117-142.
- Albertson, Edwin R. "Cofferdamming Difficulties in a Narrow Tideway." *Engineering News-Record* 118 (20 May 1937): 729-732.
- "An Extensive Cofferdam of Steel Sheet Piling." *Engineering Record* 57 (13 June 1908): 747-748.
- Andrews, D.M. "Dam No. 5, Coosa River: The Problems of Location and Construction." *Professional Memoirs, Corps of Engineers* 8:40 (July-August 1916): 488-503.
- _____. "Foundations on the Coosa and Black Warrior Rivers, Alabama." *Professional Memoirs, Corps of Engineers* 1:4 (October-December 1909): 333-354.
- Arras, J.W. "Locks and Movable Dams of the Ohio River." *Professional Memoirs, Corps of Engineers* 3:12 (October-December 1911): 535-551.
- _____. "The Ohio River." *Proceedings of the Engineers' Society of Western Pennsylvania*. 24 (June 1908): 241-278.
- Bach, Paul E. "Pre-cast Concrete Applications for Navigations Dams and Bridge Piers." Reviewed on-line on January 9, 2009 at <http://www.gerwick.com/conference.asp>
- Bailey Jr., Thomas C.J. "A Determination of Actual Earth Pressure From a Cofferdam Failure." *Engineering News* 56 (16 August 1906): 170.
- Barner, Craig. "Southern Illinois Project: Dam the Ohio River!" *Midwest Construction* (August 2005), http://midwest.construction.com/features/archive/0508_feature1.asp
- Bauknight, Wilfred. "Heavy Industrial Development Dictates Tough Construction Site for Monongahela Locks No. 2." *Civil Engineering* 21 (September 1951): 36-40.
- _____. "New Crest Gate for Dams." *Engineering News-Record* 118 (6 May 1937): 665-666.
- Bell, J. Franklin. "The Emsworth and Davis Island Dams." *The Military Engineer* 15 (September 1923): 405-408.
- _____. "The Monongahela: A Successful River Improvement." *The Military Engineer* 13 (July-August 1921): 305-311.
- Bernstein, Peter L. *Wedding of the Waters: The Erie Canal and the Making of a Great Nation*. New York, W.W. Norton & Company, 2005.
- "Big Cofferdam Built in Turbulent Rapids." *Engineering News-Record* 141 (11 November 1948): 96-99.
- Billington, David P., Donald C. Jackson and Martin V. Melosi. *The History of Large Federal Dams: Planning, Design, and Construction in the Era of Big Dams*. Denver, CO: U.S. Department of the Interior, Bureau of Reclamation, 2005.
- "The Black Rock Lock Cofferdam." *Engineering Record* 59 (3 April 1909): 385-387.
- Black, W.M. "Advances in Waterways Engineering During a Half Century." *Transactions of the American Society of Civil Engineers*. Paper No. 1701 93 (1929) 191-217.

- _____. "Comments on Construction of Lock and Dam at Troy, New York." *Professional Memoirs, Corps of Engineers* 10:53 (September-October 1918): 627-632.
- Bond, P.S. "The Permanent Improvement of the Ohio River – I." *Engineering Record* 58 (26 December 1908): 712-715.
- Bowden, Nicholls W. "Improving Tennessee River Above Chattanooga, Tenn., by Regulation or Open-Channel Method." *Professional Memoirs, Corps of Engineers* 6:30 (November-December 1914): 663-691.
- Bruce, James W. Dwight W. Keller, and James A. Neill. "Modern Facilities for Ohio River Navigation." *Journal of the Waterways and Hydraulics Division, American Society of Civil Engineers* 83 (May 1957): paper 1239.
- Brunot, Felix R. "Improvement of the Ohio River." *Journal of the Franklin Institute* 97 (May 1874): 315-317, 327.
- Buchanan, R. A. "The Diaspora of British Engineering" *Technology and Culture* 27 (1986): 501-524.
- "Building a Hydro-Electric Plant on Saguenay River – III." *Engineering News-Record* 93 (30 October 1924): 702-703.
- "Building Superstructure of Arthur Kill Bridges." *Engineering News-Record* 99 (10 November 1927): 744-748.
- "Building the Rolling-Crest Dam Across Grand River." *Engineering News* 76 (13 July 1916): 60-64.
- Burgess, H. "The Colbert Shoals Canal, Tennessee River, Alabama." *Professional Memoirs, Corps of Engineers* 5:24 (November-December 1913): 613-649.
- _____. "The Colbert Shoals Canal, Tennessee River, Alabama." *Professional Memoirs, Corps of Engineers* 6:25 (January-February 1914): 69-101.
- Burgess, Harry. "The Muscle Shoals Section of the Tennessee River." *Professional Memoirs, Corps of Engineers* 8:37 (January-February 1916): 61-71.
- Burrall, W.H. "Coffer Dams in the Connecticut River." *Van Nostrand's Engineering Magazine* 14 [1882]: 366-369.
- Butler, John S. "Notes on the Construction of Locks B, C, and D, Cumberland River." *Professional Memoirs, Corps of Engineers* 8:39 (May-June 1916): 365-382.
- Cameron, E.G. "Construction Methods on the Welland Ship Canal." *Transactions of the American Society of Civil Engineers*. Paper No. 1850. 98 (1933): 1142-1199.
- "Canalizing the Mississippi for 9-Ft. Navigation." *Engineering News-Record* 112 (1934): 322-324.
- Carroll, Jane Lamm. "Mississippi River Headwaters Reservoirs." Historic American Engineering Record Report MN-6. On file at Print and Photographs Division, Library of Congress.
- Carswell, Charles. "Deep Steel Sheet Pile Cofferdams at Arlington Bridge." *Engineering News-Record* 99 (21 July 1927): 92-93.
- Case, Montgomery B. "George Washington Bridge: Construction of Substructure." *Transactions of the American Society of Civil Engineers*. Paper No. 1822. 97 (1933): 206-221.
- Casey, Hugh J. "Deadman Island Lock and Dam, Ohio River." *The Military Engineer* 21 (September-October 1929): 444-451.
- _____. "Muscle Shoals." *The Kansas Engineer* 10:4 (January 1925): 5-10, 20.
- Chambers, Ralph H. "Intake Tunnel Through New Orleans Levee in Sheetpile Cofferdam." *Engineering News-Record* 92 (3 April 1924): 560-562.

- _____. "Survey of Foundation Construction Methods." *Civil Engineering* 11 (January 1941): 31-34.
- Chase, Clement E. "The Cherry Street Bridge, Toledo, Ohio." *Transactions of the American Society of Civil Engineers*. Paper No. 1362. 80 (1916): 744-764.
- Chittenden, Hiram M. "American Types of Movable Dams and Their Development." *Engineering News* 33 (7 February 1895): 84-86.
- Chivers, Norman M. "The Cofferdam at Lock No. 2, Cape Fear River, North Carolina." *Professional Memoirs, Corps of Engineers* (September-October 1916): 608-621.
- Clark, A.W. "Construction Features of Osage Hydro-Electric Development." *Engineering News-Record* 106 (26 March 1931): 523-528.
- Clay, Floyd M., *A Century on the Mississippi: A History of the Memphis District U.S. Army Corps of Engineers, 1876-1981* (Memphis: U.S. Army Corps of Engineers, 1986).
- "Clay Seam Wrecked Wheeler Lock." *Civil Engineering* 32 (1961): 89-90.
- Clough, G.W. and T. Kuppusamy. "Finite Element Analysis of Lock and Dam 26 Cofferdam." *Journal of the Geotechnical Engineering Division, American Society of Civil Engineers* 111 (1985): 521-544.
- "Coffer Dam and Crib of the Point Pleasant Railroad Bridge, West Virginia." *Engineering News* 13 (14 March 1885).
- "Cofferdamming the Columbia at Rock Island – A Real Construction Battle." *Engineering News-Record* 106 (30 April 1931): 716-719.
- Colburn, R.R. "Sheet-Pile Cofferdams and Test Cell for TVA Projects." *Civil Engineering* 9 (September 1939): 551-553.
- Condit, Carl W. *American Building Art: The Nineteenth Century*. New York: Oxford University Press, 1960.
- _____. *American Building Art: The Twentieth Century*. New York: Oxford University Press, 1961.
- "The Conowingo Development on the Susquehanna River." *Transactions of the American Society of Civil Engineers* 93 (1929): 982-991.
- "Constructing the First Cofferdam [at Grand Coulee]." *Engineering News-Record* 115 (1 August 1935): 148-151.
- "Construction Details of Lock and Dam No. 19, Ohio River," *Engineering News* 71 (29 January 1914): 237-39.
- "Construction of Oklahoma City's New Sewage Plants." *Engineering News-Record* 98 (23 June 1927): 1018-1021.
- "Construction Plan and Plant at the Falls of the Ohio." *Engineering News-Record* 98 (12 May 1927): 762-769.
- "Construction Steps Up at Pickwick, Third TVA Dam." *Engineering News-Record* 116 (16 April 1936): 549-552.
- "Contractors Win River Battle." *Engineering News-Record* 119 (1 July 1937): 13-16.
- Cooper, Hugh L. and Co. "The Water Power Development of the Mississippi River Power Company at Keokuk, Iowa." *Journal of the Western Society of Engineers* 17 (1912).
- Cowdrey, Albert E. *A City for the Nation: The Army Engineers and the Building of Washington, D.C., 1790-1967*. Washington: GPO, 1978.
- Cummings, E.M. "Cellular Cofferdams and Docks." *Proceedings of the American Society of Civil Engineers – Journal of the Waterways and Harbors Division* 83 (September 1957) Paper 1366.

- Daley, E.L. "Canalization of the Upper Mississippi." *Civil Engineering* 6 (1936): 104-108.
- Daley, Edmund L. "The Mastery of the Ohio River." *The Military Engineer* 19 (May 1927): 188-193.
- Davies, H.A. "A Novel Method of Computing Stresses in a Single-Wall Cofferdam." *Cornell Civil Engineer* 33 (November 1924): 31-35.
- "Davis Island Dam on the Ohio River, Pittsburg, Pa." *Scientific American Supplement* 32:813 (1 August 1891): 12983-12984.
- de B. Parsons, H. "Sherman Island Dam and Power-House." *Transactions of the American Society of Civil Engineers*. Paper No. 1573. 88 (1925): 1257-1296.
- "Deep Cofferdam Construction for Bridge Piers, Portland & Rumford Falls R.R." *Engineering News* 37 (27 May 1897): 327.
- "Deep Excavation for Parker Dam." *Engineering News-Record* 119 (25 November 1937): 853-856.
- "Deep Foundations for Lake Champlain Bridge Built with Open Cofferdams." *Engineering News-Record* 103 (21 November 1929): 796-800.
- DiGiacinto, Albert. "Sheetpile Cofferdam for a 30-ft. Head." *Engineering News-Record* 136:11 (21 March 1946): 64-67.
- Dinsmore, Douglas "Historic Resources of the Allegheny River Navigation System, 1739-1948." National Register of Historic Places Multiple Property Documentation Form. Huntingdon, PA: Heberling Associates, 1998.
- Dinsmore, Douglas and Judy A. Heberling. "Allegheny River Navigation System Locks and Dams Nos. 2 through 9: Methodology, Bibliography, and Inventory of Oversize Drawings Located in the National Archives." Huntingdon, PA: Heberling Associates, 1998. Report prepared for U.S. Army Corps of Engineers, Pittsburgh District.
- Dobney, Frederick J. *River Engineers on the Middle Mississippi: A History of the St. Louis District, U.S. Army Corps of Engineers*. Washington: GPO, [1978].
- Dravo Corporation. *A Company of Uncommon Enterprise: The Story of the Dravo Corporation 1891-1966, The First 75 Years*. Pittsburgh, PA: Dravo Corporation, 1974.
- _____. *Locks and Dams*. Bulletin No. 402-C (Pittsburgh, PA: Dravo Corporation, 1947). On file at Historical Society of Western Pennsylvania, Pittsburgh, PA.
- "Failure of Navigable Pass, Dam No. 26, Ohio River." *Professional Memoirs, Corps of Engineers* 5:21 (May-June 1913): 315-329.
- Fatherree, Ben H. *The History of Geotechnical Engineering at the Waterways Experiment Station, 1932-2000*. Vicksburg, MS: U.S. Engineer Research and Development Center, 2006. On file at ERDC Library, Vicksburg, MS.
- _____. *The History of Hydraulic Engineering at the U.S. Army Engineer Waterways Experiment Station*. Vicksburg, MS: U.S. Engineer Research and Development Center, 2004.
- Fetzer, Claude A. and Edwin Paul Swatek, Jr. "Cofferdams." In *Advanced Dam Engineering for Design, Construction, and Rehabilitation*. Robert B. Jansen, ed., 219-238. New York: Van Nostrand Reinhold, 1988.
- Fitch, William K. and Carl B. Jansen. *"Dravo" An Engineering Enterprise Through Teamwork*. New York: The Newcomen Society, 1954.

- "Fixed Dams to Replace Movable Dams on the Upper Ohio." *Engineering News* 77 (22 March 1917): 486-487.
- Fowler, William H. "Circular Cell Cofferdam at Deadman Island Dam." *Engineering News-Record* 104 (9 January 1930): 66-68.
- Franco, John J. *Development of Navigation With Locks and Dams*. Miscellaneous Paper H-76-15 Washington, DC: USACOE, 1976. On file at ERDC Library, Vicksburg, MS.
- Franco, John J. and Thomas J. Pokrefke, Jr. *Smithland Locks and Dam, Ohio River: Hydraulic Model Investigation*. Technical Report HL-83-19. Vicksburg, MS: US Army Engineer Waterways Experiment Station, 1983. On file at ERDC Library, Vicksburg, MS.
- Gifford, L.R. "Steel Sheet piling and Sheet-Piling." *Transactions of the American Society of Civil Engineers*. Paper No. 1115 64 (1909): 440-451.
- Glick, George W. "Skyscraper Foundations in Quicksand Area Built Within Open Cofferdam." *Engineering News-Record* 106 (26 March 1931): 515-519.
- Godfrey, Stuart C. "Progress of Work on the Wilson Dam." *The Military Engineer* 15 (July 1923): 338-339.
- Gordon, Robert B. and Patrick M. Malone. *The Texture of Industry: An Archaeological View of the Industrialization of North America*. New York: Oxford University Press, 1994.
- "Grand Coulee Cofferdam." *Western Construction News* (December 1936): 386.
- Graves, W.J. "Cofferdam for New Locks at St. Mary's Falls Canal, Sault Ste Marie, Mich." *Professional Memoirs, Corps of Engineers* 9:45 (May-June 1917): 265-285.
- Greene, Brian H., John A. Gerlach and Andrew Schaffer. "Geotechnical Design and Instrumentation of an Anchored Cofferdam, Point Marion Lock, Pennsylvania." *Bulletin of the Association of Engineering Geologists* 30:3 (1993): 265-279.
- Gregory, John H., C.B. Hoover, and C.B. Cornell. "The O'Shaughnessy Dam and Reservoir." *Transactions of the American Society of Civil Engineers*. Paper No. 1715. 93 (1929): 1428-1492.
- Gribar, J.C., "Cofferdam Design Problems, Point Marion Lock, Monongahela River, Pennsylvania." *Proceedings of the 1991 Corps of Engineers Structural Conference*. Jacksonville, FL: U.S. Army Corps of Engineers, 1991.
- Griggs, Julian. "Economy of Steel Sheet Piling for Cofferdams." *Engineering Record* 53 (5 May 1906).
- Grimm, C.I. "Cofferdams in Swift Water for Bon-neville Dam." *Engineering News-Record* 115 (5 September 1935): 315-318.
- Gross, Charles P. and H.G. McCormick. "The Upper Mississippi River Project." *The Military Engineer* 33:190 (July-August 1941): 311-317.
- Grover, La Motte. "Well Points on Small Bridge Work." *Engineering News-Record* 118 (10 June 1937): 877-879.
- Hale, John P. "History of the Great Kanawha River Slackwater Improvement," *West Virginia Historical Magazine* 1 (April 1901): 73-74.
- Hall, William M. "Some Notes on the Location and Construction of Locks and Movable Dams on the Ohio River: With Particular Reference to Ohio River Dam No. 18." *Transactions of the American Society of Civil Engineers*. Paper 1510. 86 (1923): 92-179.
- Hammersmith, Jack L. "Raising the Battleship Maine." *Industrial Archaeology* 15 (1980): 318-29.

- Harding, C.R. "Pier Construction for the S.P. Railroad Bridge Across Suisan Bay." *Engineering News-Record* 104 (30 January 1930): 174-180.
- Harper, A.C. "Construction of Concrete Dam in Hudson River at Troy, N.Y., 1916." *Professional Memoirs, Corps of Engineers* 10:52 (July-August 1918): 437-454.
- Harts, William W. "Cumberland River Canalization." *Engineering Record* 61 (16 April 1910): 512-514.
- _____. "Improvement of Inland Rivers." *Professional Memoirs, Corps of Engineers* 1:2 (April-June 1909): 75-107.
- _____. "Improvement of Rivers." *Professional Memoirs, Corps of Engineers* 5:20 (March-April 1913): 139-161.
- Healey, Frank T. "Cofferdam Built in Swift River on Rock and Boulder Bottom." *Engineering News-Record* 92 (14 February 1924): 291-292.
- Hedman, A.F. "Cofferdam Design for Kentucky Dam." *Engineering News-Record* 128 (1 January 1942): 30-34.
- Helmers, N.F. "Cofferdam for 60-Foot Head With One Line of Sheeting." *Engineering News-Record* 115 (4 July 1935): 14-15.
- Hill, Forest. *Roads, Rails and Waterways: The Army Engineers and Early Transportation*. Norman: University of Oklahoma Press, 1957.
- Historic American Engineering Record (HAER). "Bonneville Project." HAER No. OR-11 (1989). On file at the Library of Congress, Prints and Photograph Division, Washington, D.C.
- _____. "Documentation of Braddock Dam." HAER PA-635 (n.d.). Unpublished report on file at U.S. Army Corps of Engineers, Pittsburgh District Office.
- _____. "Gallipolis Lock and Dam." HAER No. WV-58 (1993). On file at the Library of Congress, Prints and Photograph Division, Washington, D.C.
- _____. "Monongahela River Lock and Dam No. 7." HAER No. PA-299 (1994). On file at the Library of Congress, Prints and Photograph Division, Washington, D.C.
- _____. "Ohio Slack Water Dams, Lock & Dam No. 4." HAER No. PA-227A (1992). On file at the Library of Congress, Prints and Photograph Division, Washington, D.C.
- _____. "Ouachita River Lock and Dam No. 8." HAER No. AR-1 (1985). On file at the Library of Congress, Prints and Photograph Division, Washington, D.C.
- _____. "Upper Mississippi River 9-Foot Channel Project: Lock & Dam 26R." HAER No. IL-32 (July 1989). On file at the Library of Congress, Prints and Photograph Division, Washington, D.C.
- _____. "Wilson Dam and Hydroelectric Plant." HAER No. AL-47 (1994). On file at the Library of Congress, Prints and Photograph Division, Washington, D.C.
- A History of the Monongahela Navigation Company by an Original Stockholder*. Pittsburgh, PA: Bakewell & Marthens, 1873.
- Hollingsworth, C.H. "Construction Plant and Methods Employed in Placing the Cofferdam for the New Intake Tower of the St. Louis Water Works." *Engineering and Contracting* (1 April 1914).
- Holway, W. R. "Grand River Crossing – Spavinaw Water-Supply Conduit." *Engineering News-Record* 95 (30 July 1925): 168-171.
- Honans, Fred W. "The Government Dam Across the Rock River at Sterling, Ill." *Engineering News* 62 (5 August 1909): 138-143.

- Humphreys, A.A. Ship Canal Around the Falls of the Ohio River. 40th Congress, 2d Session, House of Representatives, Executive Document No. 181, 1868.
- Hunt, Randell, "Coffer Dams and Floating Caissons." *Engineering and Mining Journal* (19 July 1890): 77-79 and (26 July 1890): 98-100.
- Hunter, Louis C. *Steamboats on the Western Rivers: An Economic and Technological History*. Cambridge, MA: Harvard University Press, 1949.
- "Interlocking Steel Sheet Piles for Bridge Pier Cofferdams." *Engineering Record* 49 (30 April 1904): 557-558.
- "Interlocking Steel Sheeting in Coffer Dam Construction." *Railway Age* (2 May 1902).
- Jackson, Robert W. *Rails Across the Mississippi: A History of the St. Louis Bridge*. Urbana: University of Illinois Press, 2001.
- Jansen, Carl B. "Century of Progress Marks Many Improvements in Construction of Locks and Dams." *Civil Engineering* 18 (10 October 1948): 26-31, 70.
- Jenks, Robert J. "Wrenching Out a Cofferdam." *Engineering News-Record* 120 (12 May 1938): 677-679.
- "Jetty Construction Methods Used to Repair Bon-neville Cofferdam." *Engineering News-Record* 117 (1 October 1936): 461-463.
- Johnson, Leland R. *Addison N. Scott: Kanawha River Canalization, 1875-1901*. Huntington, WV: U.S. Army Corps of Engineers, 1979.
- _____. *The Davis Island Lock and Dam: 1870-1922*. Pittsburgh: U.S. Army Engineer District, 1985.
- _____. *Engineering the Kentucky River: The Commonwealth's Waterway*. Louisville, KY: U.S. Army Corps of Engineers, 1999.
- _____. "Engineering the Ohio" in Robert L. Reid, ed. *Always a River: The Ohio River and the American Experience*. Bloomington, IN: Indiana University Press, 1991.
- _____. *Engineers on the Twin Rivers: A History of the Nashville District Corps of Engineers, United States Army*. Nashville, TN: U.S. Army Corps of Engineers, 1978.
- _____. *The Falls City Engineers: A History of the Louisville District, Corps of Engineers United States Army, 1970-1983*. Louisville: US Army Engineer District, 1975.
- _____. *The Headwaters District: A History of the Pittsburgh District, U.S. Army Corps of Engineers*. Pittsburgh: Pittsburgh District, U.S. Army Corps of Engineers, 1978. (pp. 167-69)
- _____. *Men, Mountains, and Rivers: An Illustrated History of the Huntington District, U.S. Army Corps of Engineers, 1754-1974*. Washington, DC: GPO, 1977.
- _____. "19th Century Engineering: The Muscle Shoals Canal." *The Military Engineer* 63 (July 1971): 260-265.
- _____. *The Ohio River Division, U.S. Army Corps of Engineers: The History of a Central Command*. Cincinnati, OH: U.S. Army Corps of Engineers, 1992.
- _____. "Upriver to Three Forks: The Kentucky River Project, 1835-1917." MS on file at Office of Administrative Services, U.S. Army Engineer District, Louisville, KY.
- Johnson, Leland R. and Charles E. Parrish. *Triumph at the Falls: The Louisville and Portland Canal*. Louisville, KY: USACOE, 2007.
- Jordan, L.J. "Truss-Braced Circular Cofferdam Used in Constructing Intake." *Engineering News-Record* 101 (22 November 1928): 770-771.

- "Kanawha River Improvement and Lock and Dam No. 6," *Engineering News* 16 (20 November 1886): 330-31.
- Keelor, Don P. "Construction of Montgomery Locks, Ohio River." *The Military Engineer* 27 (May-June 1935): 187-190.
- Kemp, Emory. "Gallipolis Locks and Dam." National Register of Historic Places Registration Form (1991). On file at Huntington District, U.S. Army Corps of Engineers, Huntington, WV.
- _____. "Gallipolis Locks and Dam." Historic American Engineering Record. HAER No. WV-58 (1993). On file at Huntington District, U.S. Army Corps of Engineers, Huntington, WV.
- _____. *The Great Kanawha Navigation*. Pittsburgh: University of Pittsburgh Press, 2000.
- Ketchum, E.P. "Removing a Collapsed Cofferdam." *The Military Engineer* 29:165 (May-June 1937): 203-206.
- Kollgaard, Eric B. and Wallace L. Chadwick, eds. *Development of Dam Engineering in the United States*. New York: Pergamon Press, 1988.
- Kreisle, William E. "Development of the Ohio River for Navigation, 1825-1925." Master's thesis. Louisville, KY: University of Louisville, 1971.
- Krysa, A. "Installation of Rock Anchors at Point Marion Lock" in *Proceedings of the Corps of Engineers, ORD/SAD Geotechnical Conference*. Pittsburgh, PA: U.S. Army Corps of Engineers, 1991.
- [Kutz, Charles W.] "Ohio River – An Economic Epic." *The Military Engineer* 21 (November 1929): 509-510.
- _____. "Ohio River Canalization – Its History and Possibilities." *Engineering News-Record* 104 (13 March 1930): 432-441.
- "The Lake Washington Ship Canal, Washington." *Transactions of the American Society of Civil Engineers* 92 (1928): 1012-1015.
- Lamphere, F.E. "Construction Methods on the Ohio and Missouri Rivers." *Proceedings of the American Society of Civil Engineers* 55 (October 1929): 2097-2104.
- "A Large Steel-Pile Cofferdam for a Ship Lock at Buffalo, N.Y." *Engineering News* 60 (8 October 1908): 394-395.
- Larkin, F.J. "Monongahela Magic." *Engineering News-Record* 145 (19 October 1950): 34-35.
- "Last of the Maine: A Fitting Burial at Sea." *Scientific American* 106 (30 March 1912): 288.
- Lee, Donovan H. *Sheet Piling, Cofferdams, and Caissons*. London: Concrete Publications, Ltd., 1945. On file at ERDC Library, Vicksburg, MS.
- Liel, Abbie B. and David P. Billington. "Engineering Innovation at Bonneville Dam." *Technology and Culture* 49 (2008): 727-751.
- "Lock Concreting at Rock Island Dam." *Engineering News-Record* 112 (15 March 1934): 341-345.
- Loveland, P.W. and T.P. Bailey. "Navigation on the Ohio River." *The Military Engineer* 41 (May-June 1949): 171-175.
- Maass, Arthur. *Muddy Waters: The Army Engineers and the Nation's Rivers*. Cambridge, MA: Harvard University Press, 1951.
- McAlpine, W.H. "Roller Gates in Navigation Dams." *The Military Engineer* 26:150 (November-December 1934): 419-423.
- _____. "Elements Affecting Lock Construction on Canalized Rivers Having Fixed Dams." *Professional Memoirs, Corps of Engineers* 3 (October 1911): 587-590.

- McCalla, R.C. "Improvement of the Black Warrior, Warrior and Tombigbee Rivers in Alabama." *Transactions of the American Society of Civil Engineers*. Paper No. 941. 49 (1902): 212-265.
- McCormick, Herbert G. and John W. Dixon. "Mississippi River Cofferdams." *The Military Engineer* 28:158 (March-April 1936): 105-108.
- McDonough, M.J. "Construction of Concrete Lock in Hudson River at Troy, N.Y., 1916, in Charge of Col. W.M. Black, Corps of Engineers." *Professional Memoirs, Corps of Engineers* 10:53 (September-October 1918): 591-626.
- McVarish, Douglas C. "Monongahela River Navigation System: Historical Engineering Evaluation." Report prepared for U.S. Army Corps of Engineers, Pittsburgh District. West Chester, PA: John Milner Associates, 2000.
- Madere, E.L. and Roger B. McWhorter. "Caisson Work at Hales Bar Dam." *Professional Memoirs, Corps of Engineers* 5:19 (January-February 1913): 78-82.
- Mahan, Dennis Hart. *An Elementary Course of Civil Engineering, for the Use of the Cadets of the United States Military Academy*. New York: Wiley & Putnam, 1837.
- Maker, G.W. "Foundation Problems in Enlarging Center Pier of Swing Bridge at Providence." *Engineering News-Record* 99 (8 December 1927): 927-929.
- Martin, James R. III, G. Wayne Clough. *A Study of the Effects of Differential Loadings on Cofferdams*. Technical Report ITL-90-1. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station, 1990. On file at ERDC Library, Vicksburg, MS.
- Martin, William. "Description of Cofferd Dam Used at Davis Island Dam, in the Construction of the Navigable Pass, Season of 1881." *Proceedings of the Engineers' Society of Western Pennsylvania* 1 (1882): 275-279.
- _____. "Davis Island Dam, Ohio River." *Engineering News* 15 (15 May 1886): 306-311.
- Meinig, D.W. *The Shaping of America: A Geographical Perspective on 500 Years of History, Volume 4: Global America, 1915-2000*. New Haven: Yale University Press, 2004.
- Memmm, J.C. "Stresses in Cofferdams and Similar Structures." *Civil Engineering* 4 (December 1934): 639-641.
- Merrill, William E. "Historical Sketch of the Work of the United States in the Improvement of the Ohio River." *Proceedings of the Engineering Club of Philadelphia* 4 (February 1885): 331-338.
- _____. *Improvement of Non-Tidal Rivers*. Washington, DC: Government Printing Office, 1881.
- _____. "Movable Dams." *Engineering News* 5 (28 March 1878): 100-101.
- Merritt, Raymond H. *Creativity, Conflict and Controversy: A History of the St. Paul District, U.S. Army Corps of Engineers*. St. Paul: U.S. Army Corps of Engineers, 1979.
- "Method and Cost of Lock and Dam Construction by the U.S. Government on the Upper White River, Arkansas." *Engineering Contracting* (6 May 1908).
- "Method of Building North Cofferdam Used on Bonneville Main Dam." *Western Construction News* 12 (April 1937): 148-151.
- "Method of Constructing Cofferdam on Shifting Bottom; Ohio River Dam No. 48." *Engineering & Contracting* 39:12 (19 March 1913): 318-320.
- "Methods and Machines Used in Building Montgomery Locks on Ohio River Near Beaver, Pa." *Contractors' and Engineers' Monthly* 28:3 (March 1934): 22-26 +29).

- "Methods of Constructing the Black Rock Harbor Lock; New York State Barge Canal." *Engineering-Contracting* 35 (4 January 1911): 3-5.
- Mills, Gary B. *Of Men & Rivers: The Story of the Vicksburg District*. Vicksburg: U.S. Army Engineer District, Vicksburg, Corps of Engineers, 1978.
- Molloy, Peter. "Nineteenth-Century Hydropower: Design and Construction of Lawrence Dam, 1845-1848." *Winterthur Portfolio* 15 (Winter 1980): 315-343.
- Mosher, Reed L. *Three-Dimensional Finite Element Analysis of Sheet-Pile Cellular Cofferdams*. Technical Report ITL-92-1. Washington, DC: USACOE, 1992. On file at ERDC Library, Vicksburg, MS.
- Mower, H.C. "Locks and Dam No. 17, Black Warrior River, Alabama." *Professional Memoirs, Corps of Engineers* 7:33 (May-June 1915): 307-332.
- Mutel, Cornelia F. *Flowing Through Time: A History of the Iowa Institute for Hydraulic Research*. Iowa City: University of Iowa Press, 1998.
- "New Type of Thin-Wall Cofferdam." *Engineering News-Record* 83 (30 October-6 November 1919): 817-818.
- "New York Piers for 1,000-Foot Ships." *Engineering News-Record* 111 (3 August 1933): 123-126.
- Nichols, Roger L. "Army Contributions to River Transportation, 1818-1825." *Military Affairs* 33 (April 1969): 242-249.
- O'Brien, William Patrick, Mary Yeater Rathbun, Patrick O'Bannon, and Christine Whitacre. *Gateways to Commerce: The U.S. Army Corps of Engineers' 9-Foot Channel Project on the Upper Mississippi River*. Denver, CO: U.S. Department of the Interior, National Park Service, Rocky Mountain Region, 1992.
- Oakes, J[ohn] C. "A Cofferdam on Sand Bottom; Ohio River Dam No. 48." *Engineering News* 69 (10 April 1913): 702-704.
- _____. "Failure of Cofferdam at Lock and Dam No. 48, Ohio River." *Professional Memoirs, Corps of Engineers* 5:23 (September-October 1913): 603-606.
- _____. "Failure of Masonry and Rock Ledge Cofferdam at Louisville and Portland Canal." *Professional Memoirs, Corps of Engineers* 8:37 (January-February 1916): 101-109.
- _____. "Improving the Ohio River below Pittsburgh, Pa." *Professional Memoirs, Corps of Engineers* 9:45 (May-June 1917): 243-264.
- _____. "Ohio River Dam No. 48." *Professional Memoirs, Corps of Engineers* 5:20 (March-April 1914): 177-194.
- _____. "Works at the Falls of the Ohio River, Louisville, Ky." *Professional Memoirs, Corps of Engineers* 6:29 (September-October 1914): 563-603.
- "The Ohio River Dam and Lock No. 37, Near Cincinnati, O." *Engineering News* 61 (4 March 1909): 234-239.
- Ovesen, N. Krebs. *Cellular Cofferdams: Calculation Methods and Model Tests*. Bulletin No. 14. Copenhagen: Danish Geotechnical Institute, 1962. On file at ERDC Library, Vicksburg, MS.
- Oxx, Francis H. "The Ohio River Movable Dams." *The Military Engineer* 27 (January-February 1935): 49-58.
- "Parker Dam Sets a Record for Foundation Depth." *Western Construction News* (March 1938): 96-101.
- Paaswell, George. "Open-Cut Subway, New York City, Built Under Unusual Conditions." *Record* 99:7 (18 August 1927): 269-272.

- Pennoyer, Raymond P. "Design of Steel Sheet-Piling Bulkheads." *Civil Engineering* 3 (November 1933).
- _____. "Gravity Bulkheads and Cellular Cofferdams: Essential Theory of Design When Steel Sheet Piling Is Used." *Civil Engineering* 4 (June 1934): 301-305.
- Pennoyer, Raymond P. and George Hockensmith. "Design of Steel Sheet-Piling Cofferdams." *Civil Engineering* 5 (January 1935): 19-23.
- "Permanent Cofferdams to Be Large Earth-Rock Fills." *Engineering News-Record* 109 (15 December 1932): 709-711.
- "Pier Construction in a 28-Foot Tide." *Engineering News-Record* 112 (15 February 1934): 219-224.
- Pile Buck. *Cellular Cofferdams*. Jupiter, FL: Pile Buck, Inc., 1990. On file at ERDC Library, Vicksburg, MS.
- "Pile Pulling and Re-Use Cuts Cofferdam Costs." *Engineering News-Record* 118 (4 March 1937): 327-328.
- Pitzer, Paul C. *Grand Coulee: Harnessing a Dream*. Pullman: Washington State University Press, 1994.
- Pritchard, John C. "Building Cellular Wall Cofferdam, St. Louis Intake." *Engineering News-Record* 96 (27 May 1926): 862-865.
- _____. "Underwater Pile Driving and Cofferdam Sealing." *Engineering News-Record* 96 (10 June 1926): 930-933.
- "Progressive Cofferdamming for Long Low Dam." *Engineering News-Record* 114 (4 April 1935): 473-477.
- "Proposed Cofferdam for Raising the Battleship 'Maine'." *Engineering News* 52 (8 December 1904): 520-521.
- "Progress in Raising the United States Battleship 'Maine'." *Engineering Record* 63 (20 May 1911).
- Purcell, C.H., Charles E. Andrew, and Glenn B. Woodruff. "Deep Open Caissons for Bay Bridge." *Engineering News-Record* 113 (23 August 1934): 227-233.
- "Raising the United States Battleship 'Maine'." *Engineering Record* 62 (22 October 1910): 452-453.
- Rapp, Robert J., Charles W. Denzel, and Thomas J. Pokrefke. "Unique Utilization of a Physical Model to Develop a Construction Sequence of a Major Cofferdam." *Hydraulics and Hydrology in the Small Computer Age* 2 (1985): 1130-1135. On file at ERDC Library, Vicksburg, MS.
- "Record Cofferdam Beats Slippage." *Engineering News-Record* 180:23 (6 June 1968): 52, 57.
- A Report Upon the Commercial Value and Importance of the Works of the Monongahela Navigation Company, House of Representatives Exec. Doc. No. 112, 49th Cong. 2nd sess. (1887).
- Reuss, Martin. "Andrew A. Humphreys and the Development of Hydraulic Engineering: Politics and Technology in the Army Corps of Engineers, 1850-1950." *Technology and Culture* 26 (January 1985): 1-33.
- _____. *Army Engineers in Memphis District: A Documentary Chronicle*. Memphis, TN: U.S. Army Corps of Engineers, Memphis District, 1982.
- Riegel, Ross M. "Deep Trench Emergency Intake for Pittsburgh Water Works." *Engineering News-Record* (18 April 1929): 638-640.
- Ringers, J.A. "Construction of the New Ijmuiden Lock." *Engineering News-Record* 104 (8 May 1930): 769-772.

- Roberts, S.G. "Canalization of the Upper Mississippi River." *Scientific American* 152 (February 1935): 72-74.
- _____. "Roller Gate Dams for the Kanawha River." *Engineering News-Record* 111 (21 September 1933): 337-342.
- Roberts, Thomas P. "Construction of Cofferdams." *Proceedings of the Engineers' Society of Western Pennsylvania* 21 (July 1905): 305-318.
- _____. "The Monongahela River." *Proceedings of the Engineers' Society of Western Pennsylvania* 24 (May 1908): 193-220.
- Robinson, Michael C. *History of Navigation in the Ohio River Basin*. Alexandria, VA: U.S. Army Corps of Engineers, Water Resources Support Center, 1983.
- "Roller-Gate Dams for Kanawha River." *Engineering News-Record* 111 (21 September 1933): 337-342.
- Rossow, M.P. and R.L. Mosher. "Design of Cellular Cofferdams by the CCELL Computer Program." *Computers and Structures* 42 (1992): 979-988. On file at ERDC Library, Vicksburg, MS.
- Rossow, Mark, Edward Demsky, and Reed Mosher. *Theoretical Manual for Design of Cellular Sheet Pile Structures (Cofferdams and Retaining Structures)*. Technical Report ITL-87-5. Vicksburg, MS: US Army Engineer Waterways Experiment Station, 1987. On file at ERDC Library, Vicksburg, MS.
- Ruff, Charles F. "West Palm Beach Water Co. Builds 20-M.G.D. Purification and Pumping Plant in Ten Months." *Engineering News-Record* 98 (30 June 1927): 1048-1052.
- Ruffner, Ernest H. *The Practice of the Improvement of the Non-Tidal Rivers of the United States*. Quincy, IL: Cadogan & Hatcher, 1885.
- Ryder, Franklin J. *A Century of Service: The Centennial Story of the St. Paul District, Army Corps of Engineers*. St. Paul, MN: U.S. Army Corps of Engineers, 1966.
- Sanderlin, Walter S. *The Great National Project: A History of the Chesapeake and Ohio Canal*. Baltimore, MD: Johns Hopkins Press, 1946.
- Sayers, E.L. and A.C. Polk. "The Lock 12 Development of the Alabama Power Company, Coosa River, Alabama." *Transactions of the American Society of Civil Engineers*. Paper No. 1334. 78 (1915): 1409-1489.
- Schick, H.S. "Field Check on Formulas for Earth Pressure." *Engineering News Record* 88 (15 June 1922): 994-995.
- Schubert, Frederick C. "The Dalles-Celilo Canal." *Professional Memoirs, Corps of Engineers* 5:22 (July August 1913): 375-414.
- Scott, Addison N., "General Notes on the Great Kanawha Improvement, Tripping Bars and Improved Hurters on Chanoine Wicket Dams, Etc." *Transactions of the American Society of Civil Engineers*. Paper No. 708 31 (May 1894): 539-46.
- "Serious Leak Checked in Cofferdam at Grand Coulee." *Engineering News-Record* 118 (22 April 1937): 595-597.
- Shallat, Todd. "Building Waterways, 1802-1861: Science and the United States Army in Early Public Works." *Technology and Culture* 31 (January 1990): 18-50.
- _____. *Structures in the Stream: Water, Science and the Rise of the U.S. Army Corps of Engineers*. Austin: University of Texas Press, 1994.
- Sheriff, Carol. *The Artificial River: The Erie Canal and the Paradox of Progress, 1817-1862*. New York: Hill and Wang, 1996.
- Shriver, Karl H. "Contract Methods and Equipment for a Typical Ohio River Dam," *Engineering News* 73 (29 April 1915): 806-11.

- Sibert, William L. "The Improvement of the Ohio River." *Transactions of the American Society of Civil Engineers*. Paper 1104 63 (1909): 388-425.
- Simmons, M.D. and F.W. Swartz. "Foundation Design of Anchored Walls, Bay Springs Lock Mississippi." *Bulletin of the Association of Engineering Geologists*. 25 (1988): 185-205.
- "Sinking Open Cofferdams Through Glacial Drift." *Engineering News-Record* 114 (3 January 1935): 1-5.
- Skerrett, Robert G. "The Great Cofferdam for the Hudson River Piers." *Scientific American* (1 August 1914).
- Smith, Edwin F. "Building in Navigable and Other Streams." *Proceedings of the Engineering Club of Philadelphia* 7 (August 1888): 7-15.
- Smyser, R.E., Jr. "Chain of Rocks Project Improves Navigation on Mississippi River." *Civil Engineering* 17 (1947): 16-18.
- "Something New. . . Concrete Cofferdam at Bull Shoals." *Construction Methods* 30:4 (April 1948): 86-90.
- Staniford, Charles W. "Unusual Cofferdam for 1,000-Foot Pier, New York City." *Transactions of the American Society of Civil Engineers*. Paper No. 1391. 81 (1917): 498-582.
- Stapleton, Darwin H. "The Transfer of Early Industrial Technologies to America with Especial Reference to the Role of the American Philosophical Society." *Proceedings of the American Philosophical Society* 135:2 (June 1991): 286-298.
- "Steel Cofferdam of Pocket Type Successful for Lock on Cape Fear River." *Engineering Record* 74 (9 September 1916): 325-326.
- "Steel Piling Cofferdams for Bridge Piers." *Engineering Record* 53 (21 April 1906): 505.
- Stewart, C.M. "Construction of New Lock No. 6 Monongahela River," Civil Engineering thesis (Pittsburgh, PA: Carnegie Institute of Technology, 1920).
- Stickle, H[orton] W. "Monongahela River Navigation." *Professional Memoirs, Corps of Engineers* 10 (November 1919): 695-713.
- Styer, W.D. "The Tygart River Reservoir Project." *Civil Engineering* 5 (June 1935): 339-342.
- Suppiger, E.W. "Ohio River Lock and Dam No. 53." *The Military Engineer* 20 (November-December 1928): 512-514.
- Swatek Jr., Edwin Paul "Cellular Cofferdam Design and Practice." *Proceedings of the American Society of Civil Engineers – Journal of the Waterways and Harbors Division* 93 (August 1967): 109-132.
- Sweeny, F.R. "Notes on the Design of a Singlewall Cofferdam." *Engineering News-Record* 82 (10 April 1919): 708-711.
- Taft, Harrison S. "Floating Concrete Caissons (Foreign and Domestic Development)." *Professional Memoirs, Corps of Engineers* 7:32 (March-April 1915): 145-175.
- Telford, R.L. "Deep Cofferdam for Hudson River Bridge." *Engineering News-Record* 101 (16 August 1928): 232-236.
- Tennessee Valley Authority. Divisions of Engineering and Construction. *Steel Sheetpile Cellular Cofferdams on Rock*. Technical Monograph No. 75. Knoxville, TN: Tennessee Valley Authority, 1957. Reprinted in Pile Buck, Inc. *Cellular Cofferdams*. Jupiter, FL: Pile Buck, Inc., 1990. On file at ERDC Library, Vicksburg, MS.
- Terzaghi, Karl. "Does Foundation Technology Really Lag." *Engineering News-Record* 168:7 (1962): 58-59.

- _____. "Soil Mechanics – A New Chapter in Engineering Science." *Journal Institution of Civil Engineers*. London (June 1939).
- _____. "Stability and Stiffness in Cellular Cofferdams." *Transactions of the American Society of Civil Engineers*. Paper No. 2253. 110 (1945): 1083-1202. On file at ERDC Library, Vicksburg, MS.
- "They Made Money on Floods." *Construction Methods and Equipment* 41:8 (August 1959): 80-87.
- Thomas, B.F. "Movable Dams." *Transactions of the American Society of Civil Engineers*. Paper No. 830. 39 (June 1898): 431-572.
- Thomas, B.F. and D.A. Watt. *The Improvement of Rivers: A Treatise on the Methods Employed for Improving Streams for Open Navigation, and for Navigation by Means of Locks and Dams*. 2nd ed. New York: J. Wiley & Sons, 1913.
- Thomas, Henry H. *The Engineering of Large Dams*. 2 vols. New York: John Wiley & Sons, 1976.
- Thomas, T.C. "Box Cofferdams on the Ouachita and Big Sunflower Rivers." *Professional Memoirs, Corps of Engineers* 9:43 (January 1917): 51-71.
- Thomson, E. Burlem. "Methods and Cost of Cofferdam Construction at Oregon City Locks, Willamette River, Oregon." *Professional Memoirs, Corps of Engineers* 10:50 (March-April 1918): 171-191.
- "Three Cableways of 1,510-Ft. Span Place 250,000 Yd. of Concrete in Montgomery Island Locks." *Construction Methods* 16 (July 1934): 26-30.
- "Three Long-Span Cableways Place Concrete on Ohio River Locks." *Engineering News-Record* 113 (25 October 1934): 515-518.
- "Toe of Cofferdam at Hudson Bridge Fails; Three Drown." *Engineering News-Record* 99 (29 December 1927): 1057.
- Trescott, Paul B. "The Louisville and Portland Canal Company, 1825-1874." *Mississippi Valley Historical Review* 44 (1958): 686-708.
- Trippe, H.M. "Foundation for an Ohio River Dam." *The Military Engineer* 16 (May 1924): 242-243.
- Turnbull, William. Reports on the Construction of the Piers of the Aqueduct of the Alexandria Canal Across the Potomac at Georgetown, District of Columbia. (DC: GPO, 1873).
- Tweet, Roald D. *A History of Navigation Improvements on the Rock Island Rapids (The Background of Locks and Dam 15)*. Rock Island, IL: U.S. Army Corps of Engineers, 1980.
- _____. *A History of The Rock Island District Corps of Engineers*. U.S. Army Engineer District, Rock Island, 1975.
- "Unique Construction Methods and Devices Employed at Lock and Dam No. 1, Mississippi River Improvement." *Engineering & Contracting* 39:12 (19 March 1913): 315-318.
- United States. Army. Corps of Engineers. *Design of Sheet Pile Cellular Structures*. Engineer Manual EM 1110-2-2503. Washington, DC: USACOE, 1989. On file at ERDC Library, Vicksburg, MS.
- United States. Army. Corps of Engineers. *Engineering for Prefabricated Construction of Navigation Projects*. Engineer Manual EM-1110-2-2611. Washington, DC: U.S. Army Corps of Engineers, 2004.
- United States. Army. Corps of Engineers. Office of the Chief of Engineers. *An Analysis of Cellular Sheet Pile Cofferdam Failures*. Cincinnati, OH: U.S. Army Corps of Engineers, Ohio River Division, 1974. On file at ERDC Library, Vicksburg, MS.

- United States. Army. Corps of Engineers. Office of the Chief of Engineers. *Annual Report of the Chief of Engineers*. Washington, DC: Government Printing Office. Annual reports reviewed from 1865-1920.
- United States. Army. Corps of Engineers. Office of History. *The U.S. Army Corps of Engineers: A History*. Alexandria, VA: U.S. Army Corps of Engineers, 2007.
- United States. Army. Corps of Engineers. Ohio River Division. *Ohio River Navigation: Past-Present-Future*. Cincinnati, OH: U.S. Army Corps of Engineers, 1979.
- United States. Army. Corps of Engineers. Pittsburgh District. *Navigation on the Monongahela and Allegheny Rivers*. Pittsburgh, PA: U.S. Army Corps of Engineers, 1939.
- United States. Army. Corps of Engineers. Pittsburgh District. *New Cumberland Locks, Ohio River - Design Memorandum No. 12: Lock Walls, Sills, and Cofferdam*. Pittsburgh, PA: U.S. Army Corps of Engineers, 1955.
- United States. Army. Corps of Engineers. St. Louis District. *Lock and Dam No. 26 (Replacement) Upper Mississippi River Basin, Mississippi River - Alton, Illinois, Missouri and Illinois; Design Memorandum No. 7: Cofferdam Phase I*. St. Louis, MO: U.S. Army Engineer District, St. Louis, 1973. On file at ERDC Library, Vicksburg, MS.
- United States. Army. Corps of Engineers. Walla Walla District. *Ice Harbor Lock and Dam, Snake River Project - Design Memorandum No. 12: Second Step Cofferdam*. Walla Walla, WA: U.S. Army Engineer District, Walla Walla, 1958. On file at ERDC Library, Vicksburg, MS.
- _____. *John Day Lock and Dam, Columbia River - Design Memorandum No. 21: Second Step Cofferdam*. Walla Walla, WA: U.S. Army Engineer District, Walla Walla, 1961. On file at ERDC Library, Vicksburg, MS.
- _____. *Little Goose Lock and Dam, Snake River Project - Design Memorandum No. 13: First Step Cofferdams*. Walla Walla, WA: U.S. Army Engineer District, Walla Walla, 1963. On file at ERDC Library, Vicksburg, MS.
- _____. *Lower Monumental Lock and Dam, Snake River Project - Design Memorandum No. 2: First Step Cofferdam*. Walla Walla, WA: U.S. Army Engineer District, Walla Walla, 1960. On file at ERDC Library, Vicksburg, MS.
- _____. *Lower Monumental Lock and Dam, Snake River Project - Design Memorandum No. 20: Second and Third Step Cofferdams*. Walla Walla, WA: U.S. Army Engineer District, Walla Walla, 1962. On file at ERDC Library, Vicksburg, MS.
- United States. Congress. House. Report on the Construction of the Potomac Aqueduct. Report prepared by William Turnbull. 24th Cong., 1st sess., 1838. H. Doc. 459.
- Van Pelt, Sutton. "Building a Lock and Dam on the Illinois River." *Engineering News-Record* 102 (16 May 1929): 778-782.
- Vance, John E. "The Improvement of the Ohio River." *Annals of the American Academy of Political and Social Science* 31 (1908): 139-145.
- _____. "Sketch of Ohio River Improvements." *Ohio Archaeological and Historical Society Publications* 18 (1909): 415-420.
- Verhoeff, Mary. *The Kentucky River Navigation*. Filson Club Publications No. 28. Louisville, KY: John P. Morton & Co., 1917.
- Vitruvius, *The Ten Books on Architecture*. Morris Hicky Morgan, trans. Cambridge, MA: Harvard University Press, 1914.
- Walker, Heber P. "Louisville and Portland Canal." *Indiana Magazine of History* 27 (March 1932): 21-30.

- Warren, Lee. "Cofferdams and Stream Control at Jordan Dam, Alabama." *Engineering News-Record* 106 (14 May 1931): 804-808.
- Watt, D.A. "Steel Sheetpile Cofferdams for Troy Lock and Dam." *Engineering News* 76 (21 September 1916): 533-540.
- Weeks, W.C. and S.C. Godfrey. "Notes on the Construction of the Wilson Dam." *The Military Engineer* 13 (April 1921): 112-116.
- Wegmann, Edward. *The Design and Construction of Dams, Including Masonry, Earth, Rock-fill, Timber, and Steel Structures also the Principal Types of Movable Dams*. 6th ed. New York: John Wiley & Sons, 1911.
- "Well Points Dry Up Wet Excavation for New York Incinerator Plant." *Engineering News-Record* 114 (11 April 1935): 515-516.
- Wellons, Charles M. "Construction and Operation of a Modern River Lock." *National Waterways* 5 (January 1929): 57-58.
- White, E.E. "Mile-Long Cofferdam Withstands 75-ft Head in Chain of Rocks Project." *Civil Engineering* 19 (June 1949): 44-47.
- White, Lazarus and Edmund Astley Prentis. *Cofferdams*. New York: Columbia University Press, 1940.
- Whitford, Noble E. *History of the Canal System of the State of New York Together with Brief Histories of the Canals of the United States and Canada*. Supplement to the Annual Report of the State Engineer and Surveyor of the State of New York For the Fiscal Year Ending September 30, 1905. Albany, NY: Brandow Printing Company, 1906.
- Willingham, William F. *Army Engineers and the Development of Oregon: A History of the Portland District United States Army Corps of Engineers*. Washington: GPO, 1983.
- _____. *Water Power in the "Wilderness": The History of Bonneville Lock and Dam*. rev. ed. Portland, OR: U.S. Army Corps of Engineers, Portland District, 1997.
- Woodworth, R.B. "New Uses for Steel." *Proceedings of the Railway Club of Pittsburgh* (April 1908).
- Yao, Sam X., Dale E. Berner, and Ben C. Gerwick. *Assessments of Underwater Concrete Technologies for In-the-Wet Construction of Navigation Structures*. Technical Report INP-SL-1. Vicksburg, MS: U.S. Army Engineer Research and Development Center, 1999. On file at ERDC Library, Vicksburg, MS.
- Yao, Sam X. and Ben C. Gerwick. *Positioning Systems for Float-In and Lift-In Construction in Inland Waterways*. ERDC/GSL Technical Report TR-02-22. Vicksburg, MS: U.S. Army Engineer Research and Development Center, 2002. On file at ERDC Library, Vicksburg, MS.

Index

A

Ackerman, Adolph J..... 131
 Act to Improve the Navigation of the Ohio and
 Mississippi Rivers 13, 14
 Alabama 8, 9, 26, 57, 64, 65
 Alabama Power Company 65
 Alabama River 64
 Albany District 75
 Alexandria Canal 19, 20
 Alexandria, Virginia 19
 Allegheny River 10, 52, 66, 92
 Dam No. 2 93
 Dam No. 3 95
 Dam No. 4 93
 Dam No. 8 93, 94
 Lock and Dam No. 1 92
 Lock and Dam No. 2 53, 92, 93
 Lock and Dam No. 3 92, 93
 Lock and Dam No. 4 53, 92, 93, 94
 Lock and Dam No. 5 53, 92, 93
 Lock and Dam No. 6 53, 92, 93
 Lock and Dam No. 7 53, 92, 93
 Lock and Dam No. 8 53, 92, 93
 Lock and Dam No. 9 92
 Lock No. 2 53
 Lock No. 3 53
 Lock No. 6 94
 Alton, Illinois 104, 114
*An Elementary Course of Civil Engineering, for the
 Use of the Cadets of the United States Military
 Academy* 16
Annual Reports of the Chief of Engineers 26, 33
 Arkansas 59, 62, 63
 auxiliary lock 51, 104, 114, 115, 120, 138, 139

B

Baltimore & Ohio Southwestern Railroad 69
 barge ... 15, 27, 32, 33, 36, 38, 41, 43, 45, 47, 59, 60, 61,
 63, 93, 107, 109, 115, 118, 126, 133, 135, 149
 battleship *Maine* 72, 116, 150
 bear-trap gates 37, 81, 82, 149
 Beattyville, Kentucky 56
 Beaver River 36, 37
 Bergmann Associates 144
 berm 39, 40, 42, 44, 45, 65, 71, 75, 78, 85, 94, 106, 107,
 109, 110, 114, 119, 128, 137, 140
 Bernard, Simon 11, 32
 Bethlehem Steel 147
 Big Sandy River 54
 Big Sunflower River 60
 Black River 62
 Black Rock Harbor 69
 Black Rock Lock 69, 72, 75, 150
 Black Warrior River 64

Lock and Dam No. 14 64
 Lock and Dam No. 15 64
 Lock Nos. 10-20 64
 Black, William M. 72
 Bonneville Dam 122, 132
 Bonneville Hydraulics Laboratory 124
 Bonneville Power Act 132
 Booth & Flinn Company of Pittsburgh 87
 Boston Mountains 59
 Braddock Dam 143, 144, 145, 146, 151
 Brown's Ferry 9
 Brownsville, Pennsylvania 6, 10, 51
 Buffalo District 72, 116
 Buffalo, New York 5, 59, 69, 150
 Bureau of Reclamation 127, 132, 174

C

Cairo, Illinois 32, 46
 caisson 18, 47, 48, 58, 85, 123
 pneumatic caissons 48, 58, 81
 Calhoun, John C. 11
 Campbell's Chain 27, 29
 canal 4, 5, 6, 7, 9, 11, 12, 30, 32, 41, 47
 Cannelton Locks and Dam 136
 Cape Fear River 76, 82
 Lock No. 2 82
 Carnegie Steel Company 68, 75, 129
 Carrollton, Kentucky 56
 Cass, Lewis 21
 casting basin 145, 147
 Chain of Rocks 104
 Champlain Canal 5
 Chanoine dams 53
 Chanoine wickets 33, 37, 54
 Charleroi, Pennsylvania 91
 Charles G. Case & Company 28, 29, 30, 148
 Chattanooga & Tennessee River Power Company 58
 Chattanooga, Tennessee 57, 58
 Chesapeake & Ohio Canal 19
 Chicago, Burlington & Quincy Railway 68
 Chittenden, Hiram M. 41
 Cincinnati, Ohio 6, 32, 36, 42
 Civil War 6, 7, 15, 26, 33, 50, 53, 148
 Coahoma County Mississippi 60
 coal fleets 33
 cofferdam . 1, 2, 3, 4, 9, 10, 15, 16, 17, 18, 19, 20, 21, 22,
 23, 24, 25, 26, 27, 28, 29, 30, 32, 33, 34, 35, 37, 38,
 39, 40, 41, 42, 43, 44, 45, 46, 47, 50, 51, 52, 53, 54,
 55, 56, 57, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69,
 70, 71, 72, 73, 75, 76, 77, 79, 80, 81, 82, 84, 86, 87,
 89, 90, 91, 93, 94, 95, 96, 98, 100, 102, 105, 106,
 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117,
 118, 119, 120, 122, 123, 124, 125, 126, 127, 128, 129,
 130, 131, 132, 133, 134, 136, 137, 138, 139, 140, 141,
 142, 143, 144, 147, 148, 149, 150, 151

circular cell84, 89, 98, 108, 127, 133, 134, 136
circular steel sheet pile cells 72, 89, 139
cloverleaf cell..... 128
diaphragm or semi-circular cell..... 75, 88
Ohio River type box.... 37, 40, 41, 62, 63, 64, 66, 77,
78, 79, 84, 91, 106, 109
pile-founded 26, 37, 47, 51, 55, 56, 57, 59, 63, 74,
91, 95, 110, 114
steel sheet pile .. 1, 67, 68, 69, 70, 72, 73, 75, 76, 77,
78, 79, 80, 81, 82, 84, 87, 88, 89, 91, 94, 95, 97,
98, 106, 107, 108, 110, 111, 113, 114, 117, 118,
122, 125, 127, 128, 129, 132, 133, 134, 136, 138,
147, 149, 150, 151, 152
timber crib9, 26, 28, 54, 59, 64, 74, 94, 100, 122,
123, 124
Cofferdam..... 1, 2, 3, 16, 26, 58, 68, 102, 109, 127, 129,
132, 148
Colbert's shoals 9
Columbia River 122, 127, 132
computer-assisted design138, 140, 142
concrete 1, 39, 44, 46, 50, 51, 58, 59, 64, 69, 73, 81, 82,
85, 86, 87, 88, 89, 92, 93, 95, 97, 100, 122, 123,
127, 131, 134, 135, 136, 138, 144, 145, 146, 147
Condit, Carl W.3, 174
Coosa and Alabama Rivers 65
 Dam No. 5..... 65
Coosa River..... 64, 65
cribs 2, 28, 42, 54, 56, 59, 65, 93, 94, 100, 122, 124,
125, 126
Cross Lake, Minnesota..... 59
Crozet, Claudius12
Cuivre River 68
Cumberland River 15, 57
 Lock and Dam No. 1 57
 Lock B 57
 Lock D..... 57
 Locks 1-21 57
 Locks A-F..... 57
 Locks C 57
Cumberland, Maryland..... 11, 19

D

dam . 1, 2, 4, 9, 10, 16, 17, 23, 28, 29, 30, 32, 33, 37, 42,
46, 47, 48, 50, 51, 53, 54, 56, 58, 59, 62, 65, 73, 76,
80, 84, 85, 86, 88, 89, 90, 92, 93, 94, 96, 99, 100,
102, 103, 104, 109, 113, 114, 116, 120, 122, 130, 133,
134, 136, 138, 139, 142, 144, 145, 146, 147, 150
Dashields Dam 80, 82, 84, 135, 146
Davenport, Iowa..... 27
Davis Island Lock and Dam .. 33, 35, 36, 37, 50, 52, 53,
82
Deadman Island Locks and Dam..... 80, 82, 84, 85, 86,
87, 89, 92
Des Moines Rapids..... 27, 30, 59, 102
Des Moines 26, 27, 30
design memorandum 133, 136, 139, 140
Design of Sheet Pile Cellular Structures 142, 151
dewatering ... 2, 10, 17, 27, 46, 72, 73, 82, 115, 122, 124,
126, 142, 143
diaphragm..... 75, 82, 88, 89, 95, 98, 114, 115, 128, 129,
134, 137, 150
Dismal Swamp Canal 5

dolphins 109
Dolphins 121
Dravo Corporation ... 47, 53, 64, 80, 81, 84, 88, 89, 92,
94, 97, 102, 131, 134, 136, 137
Duck Creek Chain..... 28, 29

E

earthen dike..... 9, 106, 113
Ecole Polytechnique12
Elk River 9
Ellet, Charles 33
Emsworth Locks and Dam..... 82, 84, 92, 135, 146
Engineering Construction Company 116, 117
Engineers' Society of Western Pennsylvania 34, 79
Engineers' Society of Western Pennsylvania
 Proceedings 34
Erie Canal 5, 7, 174
erosion 39, 44, 111, 113, 115, 130

F

Fairfax, W.M.C. 20
Falls of the Ohio 7, 8, 11, 26, 27, 32, 37, 41, 47, 89
Fernbank, Ohio 42
fill 17, 39, 42, 44, 60, 64, 70, 75, 76, 77, 85, 87, 88, 97,
107, 110, 113, 115, 119, 122, 124, 126, 128, 130, 131,
132, 137, 138, 141, 144
fin 112, 115, 119, 120
finite element procedures 140
Fitzherbert Gregson, Charles Arthur..... 67
floating guide walls 147
flood 2, 6, 9, 10, 30, 43, 45, 75, 81, 90, 106, 113, 114,
122, 124, 127, 132, 150
flow net analysis 130
Foundation & Contracting Company of New York ... 68
foundations 3, 18, 19, 21, 23, 37, 39, 44, 45, 46, 48, 49,
68, 81, 94, 122, 134, 137, 141, 144, 145, 146, 147,
150
France 12, 16, 21, 33
 Neuilly 21
 Orleans 21
Friestadt, Luther P. 68
Fulton, Robert 6, 13

G

Gallatin, Albert 11
Gallipolis Locks and Dam 88, 89, 96, 97, 135
Gay, Edward 32
General Joe Wheeler Lock and Dam 143
General Survey Act..... 11, 13, 14, 27
 April 30, 1824 13
George A. Fuller & Company 116
George W. Jackson, Inc..... 68
Georgetown, D.C. 19
Gerwick, Ben C. 144
Gibbons v. Ogden 13, 14
Gibbons, Thomas 13
Goodson, W.F. 116
Grand Coulee Dam 127, 128
Green River..... 14

grouting 58, 146
 Guild, Jo Conn..... 58

H

Hains, P.C. 27, 28, 148
 Hales Bar Dam 58
 Hastings, Minnesota 103
 Havana, Cuba 72
 headwaters of the Mississippi River 59
 Hedman, A.F. 129
 Henderson, Kentucky.....14
 Herr's Island..... 53, 92
 Holston and French Broad Rivers 57
 Hudson River5, 6, 73, 150
 Hughes, George W. 32
 Huntington District.....80
 Huntington, West Virginia 54
 hydroelectric..... 58, 65, 89, 99, 132, 136

I

ice 2, 28, 42, 81, 82, 107, 109, 110, 115, 124
 Ice6, 115
 inclinometers.....139
 instrumentation 133, 139, 142, 143, 151
 interlocks 67, 68, 70, 75, 128, 132, 141
 in-the-wet construction 143, 147
 Iowa Institute of Hydraulics Research..... 112

J

J.A. Jones Construction Company 137, 144
 Jacobs & Davis 58
 James & Kanawha River Company 53
 Jefferson, Thomas..... 11
 John Griffiths & Son Company..... 114

K

Kanawha River37, 53, 88, 96
 Kearney, James 20
 Kentucky 7, 8, 9, 11, 14, 26, 44, 47, 54, 57, 90, 129, 132, 144, 147
 Kentucky Dam 127, 128, 129
 Kentucky River 56
 Keokuk & Hamilton Water Power Company 102
 Keokuk, Iowa 30
 keyway 93, 94
 Knoxville, Tennessee..... 9, 57

L

Lackawanna Steel Company 68, 70, 72, 76
 Lake Champlain 5
 Lake Erie.....5, 7
 Lake Superior 26
 Larssen, Trygve 67
 lateral earth pressure 130, 131
 Le Claire Canal 103
 Lee, Robert E. 27

Leetsdale, Pennsylvania.....145
 Levisa Fork 54
 Livingston, Robert.....13
 lock... 2, 9, 10, 30, 33, 34, 35, 37, 41, 42, 43, 44, 45, 46, 47, 48, 50, 51, 53, 54, 55, 56, 58, 60, 62, 64, 65, 69, 70, 71, 73, 75, 77, 80, 81, 84, 87, 92, 93, 95, 100, 102, 103, 104, 106, 107, 109, 113, 114, 115, 116, 133, 134, 135, 138, 139, 142, 143, 146, 147, 150
 locks and dams .. 7, 9, 12, 33, 36, 37, 44, 46, 50, 52, 54, 56, 57, 62, 64, 79, 82, 91, 102, 104, 105, 113, 133, 135
 London..... 96, 97
 Long, Stephen H.....14
 Louisa, Kentucky 54
 Louisville & Portland Canal 7, 143
 Louisville, Kentucky. 6, 7, 11, 26, 32, 37, 40, 44, 47, 51, 143, 144

M

MacArthur Brothers Company of Chicago 69
 Macomb, Alexander14
 Mahan, Dennis Hart 16, 26, 34, 65, 127, 148, 152
 Mahan, Frederick A..... 34
 Marietta, Ohio 36, 41
 Marmet and London, West Virginia..... 96
 Martineau, John 20
 McAlpine Locks and Dam 144
 McAlpine, William H.104, 106, 150
 Meigs, Montgomery 27
 Melvin Price Locks and Dam 138, 141, 151
 Memphis, Tennessee..... 6
 Merrill, Wlliam E..... 33
 Merrimack River 5
 Middlesex Canal 5
 Millwood, West Virginia 80
 Minneapolis, Minnesota 102, 110
 Minnesota..... 104, 106, 116
 Mississippi River 6, 26, 28, 32, 50, 59, 60, 62, 64, 102, 130, 131, 138, 148, 149, 150, 151
 Cofferdam No. 1..... 119
 Lock and Dam No. 15 104
 Lock and Dam No. 26 114, 131, 138
 Lock and Dam No. 3..... 106
 Lock and Dam No. 4..... 104
 Lock and Dam No. 6..... 116
 Lock No. 6.....110, 113
 Missouri & Illinois Bridge & Belt Railway..... 114
 Mobile River 64
 model studies 112, 131, 133, 140
 Mohawk River 5
 Moline Chain..... 29
 Moline Lock 102, 103
 Monongahela Navigation Company 10, 50, 51
 Monongahela River 6, 9, 10, 50, 51, 52, 91, 92, 133, 134, 142, 143, 146, 151
 Dam No. 2.....143
 Dam No. 5.....51
 Lock and Dam No. 1.....50, 92
 Lock and Dam No. 2.....134
 Lock and Dam No. 2..... 50
 Lock and Dam No. 3..... 10, 50
 Lock and Dam No. 4.....10, 50, 91

Lock and Dam No. 5.....	10, 50
Lock and Dam No. 6.....	10, 50, 51
Lock and Dam No. 7.....	10, 50, 52
Lock and Dam No. 8	50
Lock and Dam No. 9.....	50
Lock No. 1.....	10
Lock No. 2.....	10
Montgomery Island Locks and Dam	86, 87
Morgantown, Hildebrand, and Opekiska locks and dams	133
Morgantown, West Virginia.....	10, 50
Muscle Shoals	8, 9, 26, 27, 57, 99
Muskingum River	36

N

Nashville, Tennessee.....	15, 57
National Contract Company	44
National Road.....	11, 32
navigable pass	33, 34, 35, 37, 41, 42, 43, 56, 81, 103
needle dam	54
New and Gauley rivers	53
New Cumberland Locks and Dam	136
<i>New Orleans</i>	6, 11, 104
Nickajack Dam	59
non-navigable dam	102, 104, 136
Norfolk & Western Railroad	68

O

Oakes, J.C.	41
Ogden, Aaron.....	13
Ohio River 5, 8, 9, 10, 11, 32, 33, 36, 38, 40, 41, 43, 44, 45, 46, 47, 50, 52, 53, 57, 60, 62, 64, 65, 66, 77, 78, 79, 80, 81, 82, 84, 88, 90, 91, 92, 96, 97, 102, 109, 135, 136, 137, 138, 144, 145, 146, 147, 149, 150	
Lock and Dam 26	88
Lock and Dam No. 18.....	41
Lock and Dam No. 19.....	43, 44
Lock and Dam No. 2.....	37
Lock and Dam No. 23	80
Lock and Dam No. 24	88
Lock and Dam No. 25.....	88
Lock and Dam No. 3.....	37
Lock and Dam No. 31.....	37
Lock and Dam No. 32	47, 81, 82
Lock and Dam No. 37.....	42
Lock and Dam No. 4.....	37, 86
Lock and Dam No. 41.....	47, 51
Lock and Dam No. 48	44
Lock and Dam No. 5.....	37, 86
Lock and Dam No. 52.....	147
Lock and Dam No. 53.....	147
Lock and Dam No. 53.....	46
Lock and Dam No. 6.....	37, 86
Lock and Dam No. 9.....	41, 43, 44
Lock No. 7.....	135
Ohio River Contract Company.....	44
Ohio River Navigation Modernization Program.....	135
Olmsted Locks and Dam	147
Oregon.....	122, 124
Oresund Tunnel.....	144

Ouachita River.....	62
Dam No. 8	63
Lock No. 3.....	63

P

Palmer, Timothy.....	3
Panama Canal.....	103
Parkersburg, West Virginia.....	41, 43
Pennoyer, Raymond P.....	129
Pennsylvania	10, 32, 50, 92, 134, 151
Pennsylvania Railroad	53
Permanent Bridge	3
Philadelphia, Pennsylvania.....	3, 21
Pickwick Dam	127
piezometers	139
Pike Island Locks	137
pile driver	2, 15, 21, 22, 55, 57, 68, 77, 80
piles 2, 14, 17, 20, 21, 22, 23, 24, 25, 28, 29, 32, 34, 38, 42, 44, 45, 46, 47, 51, 55, 56, 59, 60, 61, 65, 68, 69, 70, 72, 73, 75, 77, 79, 84, 93, 96, 107, 110, 113, 114, 115, 118, 120, 121, 134, 136, 137, 141, 146, 147	
Piscataqua River Bridge.....	3
Pittsburgh.....	1, 6, 10, 32, 33, 36, 40, 43, 48, 50, 51, 52, 53, 80, 86, 89, 92, 129, 134, 142, 143
Pittsburgh District.....	144
Point Marion Lock.....	142
Point Pleasant, Ohio.....	53
Potomac Aqueduct	19, 25, 148
Potomac River	11, 19
Powell, Charles F.	53
Prentis, Edmund Ashley	130, 151
<i>Professional Memoirs</i>	66
puddling.....	17, 18, 20, 22, 23, 24, 25, 28, 29, 34, 35
pumps	2, 10, 17, 21, 46, 71, 107, 108

R

railroad	44, 50, 68, 103, 104, 110, 115, 149
Randolph Street Bridge.....	68
Rankine, William John Macquorn	131
Red River	62
Red Wing	106, 116
Ridley, Clarence S.....	76
riprap	39, 42, 46, 49, 112, 119, 120, 126
River and Harbors Act of June 1910.....	36
Roberts, Nathan	19
Roberts, Thomas P.	79, 91
Roberts, W. Milnor.....	10, 32, 79
Rock Island	26, 27, 28, 29, 30, 41, 59, 103, 104, 107, 148
Rock Island Rapids	26
roller gates	88, 96, 104, 149
Roosevelt, Franklin D.	104, 132

S

Sandy Lake Dam.....	59
Santee & Cooper Canal.....	5
saturation	107, 128
Sault Ste. Marie	26
Schuylkill River	3

Scioto River 68
 scour..14, 39, 107, 108, 111, 115, 119, 120, 121, 124, 130,
 139, 140
 Scour 138
 seepage.....18, 44, 46, 75, 106, 107, 115, 130
 Sganzin, Joseph-Marie.....12
 shear128, 132, 137, 141
 sheet piles16, 17, 21, 23, 24, 45, 61, 70, 111, 114
 sheet piling17, 18, 21, 22, 24, 25, 28, 34, 37, 38, 44, 45,
 51, 55, 56, 61, 64, 70, 71, 72, 74, 75, 76, 109, 110,
 112, 113, 116, 119, 120, 121, 128, 129, 130, 131, 139
 steel sheetpiles 106
 Sheet piling29, 34, 55, 63, 137
 slackwater improvements9, 12, 65
 French-style.....12
 slackwater navigation..7, 10, 32, 33, 50, 53, 56, 59, 64,
 91, 92, 96, 102, 103
 snag removal7, 60, 64
 snags6, 11, 15, 32, 53
 soil mechanics 131, 132, 141
 Spencer, White & Prentis..... 109, 116, 130
 St. Louis, Missouri6, 26, 68, 102, 104, 114
 St. Paul, Minnesota 102, 104, 106
 steamboat 6, 11, 13
 Stewart, A.20
 strain gauges.....128, 139
 Swatek, Jr., Edwin P. 136, 137
 Sweeny, F.R. 129
 Sycamore Chains 27

T

Tainter gates 104, 147, 149
 Tennessee8, 9, 26, 57, 58, 98, 99, 127, 128, 143, 150
 Tennessee Electric Power Company..... 58
 Tennessee River 57, 58, 99, 127, 143
 Tennessee Valley Authority 58, 127, 128, 129, 132, 133,
 141, 151
 Terzaghi, Karl 131, 151
 Thayer, Sylvanus12
 Thomas, B.F..... 41, 174
 Thomas, Thomas C..... 66
 tie rods 28, 34, 38, 44, 45, 56, 59, 63, 80, 87, 109, 110,
 111, 113, 118, 129
 Tombigbee River 64
 Lock and Dam No. 1 64
 Lock and Dam No. 2..... 64
 Lock and Dam No. 3..... 64
 Topographical Captain William Turnbull19
 Totten, Joseph G. 11, 32
 Traylor Bros..... 144
 trestle51, 110, 112, 114, 119, 121, 126
 Troy, New York..... 73, 76
 Tug Fork 54
 Turner Construction Company.....116
 two-dimensional finite element models..... 141

U

U.S. Army Corps of Engineers 1, 11, 12
 U.S. Military Academy 12, 66
 West Point 12, 13, 16
 U.S. Steel Corporation 68
 Uniontown Dam136
 University of Iowa Hydraulics Laboratory.....112, 131
 Upper Mississippi 59, 102, 103, 104, 122, 138, 149, 150
 Upper Mississippi 9-Foot Channel Project 105
 Upper Mississippi Valley Division..... 104, 106
 Upper White River 59
 Lock No. 1 59
 Lock No.2..... 59

V

Vicksburg District..... 60, 62, 64, 66
 Vicksburg, Mississippi 60, 140
 Vitruvius, Marcus Pollio1

W

Wakefield sheet piling..... 42
 wales 17, 28, 38, 44, 45, 55, 57, 60, 61, 63, 76, 109, 110,
 113, 117, 118, 129, 134
 War of 1812 4, 5, 6, 11
 Warrior River
 Lock and Dams Nos. 4-9..... 64
 Lock No. 1 64
 Lock No. 2..... 64
 Lock No. 3..... 64
 Washington, D.C.19, 106
 Waterways Experiment Station 140, 150
 Watt, D.A. 41, 174
 well-point system 108
 Weston, William..... 3
 Wheeling, West Virginia11, 32, 137
 White River..... 59
 White, Lazarus..... 130, 151
 Wilmington, North Carolina..... 76
 Wilson Dam98, 99, 100
 Wilson, Woodrow..... 99
 wing dam.....14, 15, 32, 52, 53, 57, 59, 60, 64
 World War I..... 58, 65, 66, 79, 80, 82, 91, 104, 150
 World War II 132, 135, 151, 152
 Wright, Benjamin19

Y

Yazoo River..... 60

Z

Z-piles 137

Notes

- ¹ Vitruvius, *The Ten Books on Architecture*, Morris Hicky Morgan, trans. (Cambridge, MA: Harvard University Press, 1914), 162-164.
- ² Carl B. Jansen, "Century of Progress Marks Many Improvements in Construction of Locks and Dams," *Civil Engineering* 18 (October 10, 1948): 26-31, 70.
- ³ Ibid., 26; B.F. Thomas and D.A. Watt, *The Improvement of Rivers: A Treatise on the Methods Employed for Improving Streams for Open Navigation, and for Navigation by Means of Locks and Dams*, 2nd ed. (New York: J. Wiley & Sons, 1913), 348.
- ⁴ Ibid.
- ⁵ John Seelye, *Beautiful Machine: Rivers and the Republican Plan* (New York: Oxford University Press, 1991), 8-9.
- ⁶ David P. Billington, Donald C. Jackson, and Martin V. Melosi, *The History of Large Federal Dams: Planning, Design, and Construction in the Era of Big Dams* (Denver: U.S. Department of Interior, Bureau of Reclamation, 2005), 1.
- ⁷ Carl W. Condit, *American Building Art: The Nineteenth Century* (New York: Oxford University Press, 1960), 77.
- ⁸ Ibid., 80.
- ⁹ Ibid.; R.A. Buchanan, "The Diaspora of British Engineering," *Technology and Culture* 27 (1986): 506.
- ¹⁰ Condit, *American Building Art: The Nineteenth Century*, 255.
- ¹¹ Ibid., 255-256.
- ¹² Robert B. Gordon and Patrick M. Malone, *The Texture of Industry: An Archaeological View of the Industrialization of North America* (New York: Oxford University Press, 1994), 134.
- ¹³ Ibid.
- ¹⁴ George Rogers Taylor, *The Transportation Revolution: 1815-1860* (New York: Holt, Rinehart & Winston, 1951), 32.
- ¹⁵ Carol Sheriff, *The Artificial River: The Erie Canal and the Paradox of Progress, 1817-1862* (New York: Hill and Wang, 1996); Peter L. Bernstein, *Wedding of the Waters: The Erie Canal and the Making of a Great Nation* (New York, W.W. Norton & Company, 2005).
- ¹⁶ Taylor, *The Transportation Revolution*, 33.
- ¹⁷ Ibid., 33; D.W. Meinig, *The Shaping of America: A Geographical Perspective on 500 Years of History, Volume 2: Continental America, 1800-1867* (New Haven, CT: Yale University Press, 1993), 318-321.
- ¹⁸ Ibid., 33-34; Sheriff, *The Artificial River*, 22-27.
- ¹⁹ Meinig, *The Shaping of America, 1800-1867*, 320-321.
- ²⁰ Taylor, *The Transportation Revolution*, 63-67; Louis C. Hunter, *Steamboats on the Western Rivers: An Economic and Technological History* (Cambridge, MA: Harvard University Press, 1949).
- ²¹ Ibid., 6-27.
- ²² Ibid., 27-43; Taylor, *The Transportation Revolution*, 63-64.
- ²³ Ibid., 65; Hunter, *Steamboats on the Western Rivers*, 181-215.

- ²⁴ Ibid., 181.
- ²⁵ Hunter, *Steamboats on the Western Rivers*, 182.
- ²⁶ Paul B. Trescott, "The Louisville and Portland Canal Company, 1825-1874," *Mississippi Valley Historical Review* 44 (1958): 686-708; Hunter, *Steamboats on the Western Rivers*, 182-186.
- ²⁷ Ibid., 182-186; Ruffner, *Practice of Improvement*, 11; Trescott, "The Louisville and Portland Canal," 686-708; U.S. Army Corps of Engineers, *Annual Report, 1873*, 538-539.
- ²⁸ Hunter, *Steamboats on the Western Rivers*, 186-187.
- ²⁹ Ibid.; Ruffner, *Practice of Improvement*, 12.
- ³⁰ Hunter, *Steamboats on the Western Rivers*, 206.
- ³¹ *A History of the Monongahela Navigation Company by an Original Stockholder* (Pittsburgh, PA: Bakewell & Marthens, 1873), 3-4; Thomas P. Roberts, "The Monongahela River," *Proceedings of the Engineers' Society of Western Pennsylvania* 24 (May 1908): 193-194; H.W. Sickel, "Monongahela River Navigation," *Professional Memoirs, Corps of Engineers* 10 (November 1919): 695.
- ³² *History of the Monongahela Navigation Company by an Original Stockholder*, 5.
- ³³ Ibid., 6-7; Roberts, "The Monongahela River," 200; Leland R. Johnson, *The Headwaters District: A History of the Pittsburgh District, U.S. Army Corps of Engineers* (Pittsburgh, PA: U.S. Army Corps of Engineers, [c. 1978]), 93-95.
- ³⁴ Ibid., 94-97; *A Report Upon the Commercial Value and Importance of the Works of the Monongahela Navigation Company*, House of Representatives Exec. Doc. No. 112, 49th Cong. 2nd sess. (1887), 12-14; *History of the Monongahela Navigation Company by an Original Stockholder*; U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1896* (Washington, DC: Government Printing Office, 1897), 2173; Roberts, "The Monongahela River," 200, 205; Sickel, "Monongahela River Navigation," 696.
- ³⁵ Meinig, *The Shaping of America 1800-1867*, 313-316; Johnson, *The Headwaters District*, 63; U.S. Army Corps of Engineers, Office of History, *The U.S. Army Corps of Engineers: A History* (Alexandria, VA: U.S. Army Corps of Engineers, 2007), 31.
- ³⁶ Ibid., 41.
- ³⁷ Forrest G. Hill, *Roads, Rails and Waterways: The Army Engineers and Early Transportation* (Norman: University of Oklahoma Press, 1957), 9-25; Leland R. Johnson, "Engineering the Ohio," in Robert L. Reid, ed. *Always a River: The Ohio River and the American Experience* (Bloomington: Indiana University Press, 1991), 187.
- ³⁸ Corps of Engineers, *The U.S. Army Corps of Engineers: A History*, 31, 35, 41.
- ³⁹ The history of the origins of the Corps of Engineers is taken from Corps of Engineers, *The U.S. Army Corps of Engineers: A History*, 1-8.
- ⁴⁰ Ibid., 16; Todd Shallat, *Structures in the Stream: Water, Science, and the Rise of the U.S. Army Corps of Engineers* (Austin: University of Texas Press, 1994), 90-94.
- ⁴¹ Ibid., 17-25.
- ⁴² Ibid., 25-39.
- ⁴³ U.S. Army Corps of Engineers, Office of History, *The U.S. Army Corps of Engineers: A History*, 21-22; Shallat, *Structures in the Stream*, 43-44.
- ⁴⁴ Hill, *Roads, Rails and Waterways*, 35
- ⁴⁵ Ibid., 48-49.
- ⁴⁶ *Gibbons v. Ogden*, 22 U.S. 1 (1824).

- ⁴⁷ HR 139, "An Act to Improve the Navigation of the Ohio and Mississippi Rivers," 18th Cong. 1st sess. (1824).
- ⁴⁸ Hunter, *Steamboats on the Western Rivers*, 201; U.S. Army Corps of Engineers, Office of History, *The U.S. Army Corps of Engineers: A History*, 45-46.
- ⁴⁹ Hunter, *Steamboats on the Western Rivers*, 201; Johnson, *Headwaters District*, 66-67; Shallat, *Structures in the Stream*, 101.
- ⁵⁰ Hunter, *Steamboats on the Western Rivers*, 201.
- ⁵¹ Johnson, "Engineering the Ohio," 190-191.
- ⁵² Hunter, *Steamboats on the Western Rivers*, 203-204.
- ⁵³ Shallat, *Structures in the Stream*, 95-96; Dennis Hart Mahan, *An Elementary Course of Civil Engineering, for the Use of the Cadets of the United States Military Academy* (New York: Wiley & Putnam, 1837).
- ⁵⁴ The following description is from Mahan, *An Elementary Course of Civil Engineering*, 67-69.
- ⁵⁵ *Ibid.*, 67.
- ⁵⁶ *Ibid.*, 69.
- ⁵⁷ *Ibid.*, 69-71.
- ⁵⁸ Dennis Hart Mahan, *An Elementary Course of Civil Engineering, for the Use of the Cadets of the United States Military Academy* 6th ed. (New York: Wiley & Halsted, 1857), 128.
- ⁵⁹ *Ibid.*, 128-130.
- ⁶⁰ *Ibid.*, 130.
- ⁶¹ Shallat, *Structures in the Stream*, 137.
- ⁶² Walter S. Sanderlin, *The Great National Project: A History of the Chesapeake and Ohio Canal* (Baltimore, MD: Johns Hopkins Press, 1946); Albert E. Cowdrey, *A City for the Nation: The Army Engineers and the Building of Washington, D.C., 1790-1967* (Washington, DC: GPO, 1978), 14..
- ⁶³ U.S. Congress. House. *Report on the Construction of the Potomac Aqueduct*. Report prepared by William Turnbull. 24th Cong., 1st sess., 1838. H. Doc. 459, 2-3.
- ⁶⁴ *Ibid.*, 3-4.
- ⁶⁵ Martineau had served as an engineer on the Chesapeake & Ohio Canal, and Stewart was a member of that firm's board of directors.
- ⁶⁶ *Ibid.*, 5.
- ⁶⁷ *Ibid.*
- ⁶⁸ *Ibid.*, 5-6.
- ⁶⁹ *Ibid.*, 6-7.
- ⁷⁰ *Ibid.*, 7-8.
- ⁷¹ *Ibid.*, 8.
- ⁷² *Ibid.*, 8-9.
- ⁷³ *Ibid.*, 9.
- ⁷⁴ It is important to note that the mud and sand that lay on the river bottom was not excavated before placement of the puddling. Placing the puddling on top of this material led to serious problems.

- ⁷⁵ Ibid., 9-10.
- ⁷⁶ Ibid., 10.
- ⁷⁷ Ibid., 10-13.
- ⁷⁸ Ibid., 13-18.
- ⁷⁹ Ibid., 18-22.
- ⁸⁰ Mahan, *An Elementary Course of Civil Engineering*, 6th ed., 131.
- ⁸¹ E.H. Ruffner, *The Practice of the Improvement of the Non-Tidal Rivers of the United States* (Quincy, IL: Cadogan & Hatcher, 1885), 11.
- ⁸² U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1869* (Washington, DC: Government Printing Office, 1870), 248.
- ⁸³ Hunter, *Steamboats on the Western Rivers*, 188.
- ⁸⁴ House Executive Document 67, 46th Congress, 2nd session (1879).
- ⁸⁵ Roald Tweet, *A History of Navigation Improvements on the Rock Island Rapids (The Background of Locks and Dam 15)* (Rock Island, IL: U.S. Army Corps of Engineers, 1980), 1-4.
- ⁸⁶ Ibid., 5-6; U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1867* (Washington, DC: Government Printing Office, 1868), 36-37, 283-296; U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1886* (Washington, DC: Government Printing Office, 1887), 1450.
- ⁸⁷ U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1868* (Washington, DC: Government Printing Office, 1869), 421.
- ⁸⁸ Ibid., 437; U.S. Army Corps of Engineers, *Annual Report, 1886*, 1450.
- ⁸⁹ U.S. Army Corps of Engineers, *Annual Report, 1868*, 437.
- ⁹⁰ U.S. Army Corps of Engineers, *Annual Report, 1886*, 1450.
- ⁹¹ U.S. Army Corps of Engineers, *Annual Report, 1868*, 421; U.S. Army Corps of Engineers, *Annual Report, 1869*, 238-248.
- ⁹² U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1870* (Washington, DC: Government Printing Office, 1871), 302, 310.
- ⁹³ U.S. Army Corps of Engineers, *Annual Report, 1886*, 1451-60; Tweet, *History of Navigation Improvements*, 6-8.
- ⁹⁴ U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1880* (Washington, DC: Government Printing Office, 1881), 1534-1535.
- ⁹⁵ Hunter, *Steamboats on the Western Rivers*, 188-189; Tweet, *History of Navigation Improvements*, 1; U.S. Army Corps of Engineers, *Annual Report, 1867*, 36.
- ⁹⁶ U.S. Army Corps of Engineers, *Annual Report*, 53; U.S. Army Corps of Engineers, *Annual Report, 1869*, 45; U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1874* (Washington, DC: Government Printing Office, 1875), 59; U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1876* (Washington, DC: Government Printing Office, 1877), 657-660.
- ⁹⁷ U.S. Army Corps of Engineers, *Annual Report, 1876*, 657-660.
- ⁹⁸ U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1883* (Washington, DC: Government Printing Office, 1884), 239.

- ⁹⁹ P.S. Bond, "The Permanent Improvement of the Ohio River – I." *Engineering Record* 58 (December 26, 1908): 712-715; U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1888* (Washington, DC: Government Printing Office, 1889), 1656-1659.
- ¹⁰⁰ William M. Hall, "Some Notes on the Location and Construction of Locks and Movable Dams on the Ohio River, With Particular Reference to Ohio River Dam No. 18," *Transactions of the American Society of Civil Engineers*, Paper 1510 86 (1923): 107.
- ¹⁰¹ The survey provided cold comfort to Pittsburgh commercial interests seeking improvements to the upper Ohio, since it only addressed the lower Ohio, downstream from Louisville, and the Mississippi.
- ¹⁰² Edmund L. Daley, "The Mastery of the Ohio River." *Military Engineer* 19 (May 1927): 188-189.
- ¹⁰³ Leland R. Johnson, *The Davis Island Lock and Dam 1870-1922* (Pittsburgh, PA: U.S. Army Corps of Engineers, 1985), 8; House Executive Document 492, 60th Congress, 1st session (1907).
- ¹⁰⁴ U.S. Army Corps of Engineers, *Annual Report, 1873*, 499-502, 541; U.S. Army Corps of Engineers, *Annual Report, 1874*, 408; Daly, "Mastery of the Ohio River," 189.
- ¹⁰⁵ *Ibid.*; U.S. Army Corps of Engineers, *Annual Report, 1874*, 400-481; House Executive Document 127, 43rd Congress, 1st session (1873); John L. Vance, "Sketch of Ohio River Improvements," *Ohio Archaeological and Historical Society Publications* 18 (1909): 415-420
- ¹⁰⁶ U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1881* (Washington, DC: Government Printing Office, 1882), 1913; William Martin, "Davis Island Dam, Ohio River." *Engineering News* (May 15, 1886): 306-311; "Davis Island Dam on the Ohio River, Pittsburg, Pa." *Scientific American Supplement*. 32:813 (August 1, 1891): 12983-12984; J. Franklin Bell, "The Emsworth and Davis Island Dams" *Military Engineer* 15 (September 1923): 405-408; Johnson, *The Davis Island Lock and Dam*.
- ¹⁰⁷ *Ibid.*, 45; William Martin, "Description of the Cofferdam Used at Davis Island Dam." *Engineers' Society of Western Pennsylvania Proceedings* 1 (1882): 275-279.
- ¹⁰⁸ *Ibid.*, 275-276.
- ¹⁰⁹ *Ibid.*, 276-279; U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1882* (Washington, DC: Government Printing Office, 1883), 1912-1914; C.W. Kutz, "Ohio River Canalization – Its History and Possibilities." *Engineering News-Record* 104 (March 13, 1930): 433; William L. Sibert, "The Improvement of the Ohio River." *Transactions of the American Society of Civil Engineers*, Paper 1104, 63 (1909): 400-401.
- ¹¹⁰ U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1889* (Washington, DC: Government Printing Office, 1890), 1869-1872; Kutz, "Ohio River Canalization," 432-437; Hall, "Some Notes," 113; Daly, "Mastery of the Ohio," 189-190..
- ¹¹¹ J.W. Arras, "The Ohio River." *Proceedings of the Engineers' Society of Western Pennsylvania*. 24 (June 1908): 242.
- ¹¹² U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1893* (Washington, DC: Government Printing Office, 1894), 2484-2485; U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1896* (Washington, DC: Government Printing Office, 1897), 2100; U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1899* (Washington, DC: Government Printing Office, 1900), 2352-2353; Vance, "Sketch of Ohio River Improvements," 418; Sibert, "Improvement of the Ohio River," 400-401; Edmund L. Daley, "The Mastery of the Ohio River," *Military Engineer* 19 (May 1927): 189.
- ¹¹³ Hall, "Some Notes," 113-114, 155; Arras, *The Ohio River*, 245-263; Francis H. Oxx, "The Ohio River Movable Dams," *The Military Engineer* 27 (January 1935): 49-58; J.W. Arras, "Locks and Movable Dams of the Ohio River." *Professional Memoirs, Corps of Engineers* 3:12 (October-December 1911): 535-551.

- ¹¹⁴ Arras, *The Ohio River*,” 127-128.
- ¹¹⁵ Thomas and Watt, *The Improvement of Rivers*, 359; Jansen, “Century of Progress,” 28.
- ¹¹⁶ Thomas and Watt, *The Improvement of Rivers*, 359; Dravo Corporation, *Locks and Dams*, Bulletin No. 402-C (Pittsburgh, PA: Dravo Corporation, 1947), 6-7.
- ¹¹⁷ *Ibid.*; Dravo Corporation, *Locks and Dams*, 7.
- ¹¹⁸ *Ibid.*, Jansen, “Century of Progress,” 28.
- ¹¹⁹ U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1894* (Washington, DC: Government Printing Office, 1895), 1932.
- ¹²⁰ Karl H. Shriver, “Contract Methods and Equipment for a Typical Ohio River Dam,” *Engineering News* 73 (April 29, 1915): 806-807; Hall, “Some Notes,” J.C. Oakes, “Ohio River Dam No. 48,” *Professional Memoirs, Corps of Engineers* 5:20 (March-April 1913): 179; J.C. Oakes, “A Cofferdam on Sand Bottom; Ohio River Dam No. 48,” *Engineering News* 69 (April 10, 1913): 702-704.
- ¹²¹ Thomas and Watt, *The Improvement of Rivers*.
- ¹²² Hall, “Some Notes,” 115-116.
- ¹²³ “The Ohio River Dam and Lock No. 37, Near Cincinnati, O.” *Engineering News* 61 (March 4, 1909): 234-239.
- ¹²⁴ Hall, “Some Notes,” 116, 119.
- ¹²⁵ Shriver, “Contract Methods and Equipment for a Typical Ohio River Dam,” 806-811; “Construction Details of Lock and Dam No. 19, Ohio River,” *Engineering News* 71 (January 29, 1914): 237-239.
- ¹²⁶ Shriver, “Contract Methods and Equipment for a Typical Ohio River Dam,” 807.
- ¹²⁷ “Construction Details of Lock and Dam No. 19,” 237.
- ¹²⁸ J.C. Oakes, “A Cofferdam on Sand Bottom; Ohio River Dam No. 48,” *Engineering News* 69 (April 10, 1913): 702.
- ¹²⁹ *Ibid.*; J.C. Oakes, “Ohio River Dam No. 48,” *Professional Memoirs, Corps of Engineers* 5:20 (March-April 1914): 177.
- ¹³⁰ *Ibid.*
- ¹³¹ In keeping with Mahan’s recommendation that cofferdams be constructed one-foot thick for every foot of water depth, an engineering rule of thumb that apparently had not changed in 75 years.
- ¹³² Oakes, “A Cofferdam on Sand Bottom, 702-704; Oakes, “Ohio River Dam No. 48,” 182-192.
- ¹³³ Oakes, “A Cofferdam on Sand Bottom, 702-704; Oakes, “Ohio River Dam No. 48,” 182-192; “Method of Constructing Cofferdam on Shifting Bottom; Ohio River Dam No. 48,” *Engineering & Contracting* 39 (March 19, 1913): 318-320.
- ¹³⁴ *Ibid.*, 318; Oakes, “A Cofferdam on Sand Bottom,” 702; Oakes, “Ohio River Dam No. 48,” 182-184.
- ¹³⁵ E.W. Suppiger, “Ohio River Lock and Dam No. 53.” *Military Engineer* 20 (November 1928): 512-513.
- ¹³⁶ Oakes, “Works at the Falls,” 578-579.
- ¹³⁷ *Ibid.*, 583-584; J.C. Oakes, “Failure of Masonry and Rock Ledge Cofferdam at Louisville and Portland Canal,” *Professional Memoirs, Corps of Engineers* 8:37 (January-February 1916): 101-109.
- ¹³⁸ Dravo Corporation, *Locks and Dams*, 18-19; H.M. Trippe, “Foundation for an Ohio River Dam.” *The Military Engineer* 16 (May 1924): 242-243.
- ¹³⁹ *Ibid.*; Dravo Corporation, *Locks and Dams*, 19-20.

- ¹⁴⁰ U.S. Army Corps of Engineers, *Annual Report, 1896*, 2144; Stickle, "Monongahela River Navigation," 696; Roberts, "The Monongahela River," 203, 210-211; J. Franklin Bell, "The Monongahela: A Successful River Improvement," *The Military Engineer* 13 (July-August 1921): 305-306.
- ¹⁴¹ Roberts, "The Monongahela River," 201-202; Stickle, "Monongahela River Navigation," 696; Pittsburgh District, U.S. Army Corps of Engineers, comp. "Navigation on the Monongahela and Allegheny Rivers" (Pittsburgh, PA: U.S. Army Corps of Engineers, 1939), 5.
- ¹⁴² Lewis M. Adams, "New Lock and Dam No. 5, Monongahela River at Brownsville, PA." *Professional Memoirs, Corps of Engineers* 2:6 (April-June 1910): 117-142.
- ¹⁴³ *Ibid.*, 138-139.
- ¹⁴⁴ C.M. Stewart, "Construction of New Lock No. 6 Monongahela River," Civil Engineering thesis (Pittsburgh, PA: Carnegie Institute of Technology, 1920), 3-7. Original thesis lost. Partial photocopy on file at Pittsburgh District, U.S. Army Corps of Engineers; U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1917* (Washington, DC: Government Printing Office, 1918); Dravo Corporation, *Locks and Dams*, 25.
- ¹⁴⁵ Douglas Dinsmore and Judy A. Heberling, "Allegheny River Navigation System Locks and Dams Nos. 2 through 9: Methodology, Bibliography, and Inventory of Oversize Drawings Located in the National Archives" (Huntingdon, PA: Heberling Associates, 1998), 7. Report prepared for U.S. Army Corps of Engineers, Pittsburgh District.
- ¹⁴⁶ Dravo Corporation, *Locks and Dams*, 8.
- ¹⁴⁷ Dinsmore and Heberling, "Allegheny River Navigation System", 7.
- ¹⁴⁸ "Kanawha River Improvement and Lock and Dam No. 6," *Engineering News* 16 (November 20, 1886): 330.
- ¹⁴⁹ *Ibid.*, 330-331; Emory L. Kemp, *The Great Kanawha Navigation* (Pittsburgh, PA: University of Pittsburgh Press, 2000); Thomas and Watt, *The Improvement of Rivers*, 595; Leland R. Johnson, *Men, Mountains, and Rivers: An Illustrated History of the Huntington District, U.S. Army Corps of Engineers, 1754-1974* (Washington, DC: Government Printing Office, 1977), 57, 81-91.
- ¹⁵⁰ Kemp, *The Great Kanawha Navigation*, 62; U.S. Army Corps of Engineers, *Annual Report, 1889*, 1948; U.S. Army Corps of Engineers, *Annual Report, 1894*, 1954-1956; U.S. Army Corps of Engineers, *Annual Report, 1896*, 2252.
- ¹⁵¹ U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1897* (Washington, DC: Government Printing Office, 1898), 2534-2547.
- ¹⁵² *Ibid.*
- ¹⁵³ U.S. Army Corps of Engineers, *Annual Report, 1886*, 283; Billington, Jackson, and Melosi, *The History of Large Federal Dams*, 16.
- ¹⁵⁴ U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1884* (Washington, DC: Government Printing Office, 1885), 1729-1746; House Executive Document 117, 48th Congress, 1st session (1884).
- ¹⁵⁵ U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1890* (Washington, DC: Government Printing Office, 1891), 2265; Leland R. Johnson, *The Falls City Engineers: A History of the Louisville District, Corps of Engineers United States Army, 1970-1983* (Louisville, KY: United States Army Engineer District, 1984), 261, 267.
- ¹⁵⁶ U.S. Army Corps of Engineers, *Annual Report, 1884*, 1663; U.S. Army Corps of Engineers, *Annual Report, 1889*, 1840-1841.
- ¹⁵⁷ John S. Butler, "Notes on the Construction of Locks B, C, and D, Cumberland River," *Professional Memoirs, Corps of Engineers* 8:39 (May-June 1916): 368-369.

- ¹⁵⁸ Ibid., 365-382.
- ¹⁵⁹ U.S. Army Corps of Engineers, *Annual Report, 1876*, 711; W.W. Harts, "Improvement of Inland Rivers." *Professional Memoirs, Corps of Engineers* 1:2 (April-June 1909): 75-107.
- ¹⁶⁰ E.L. Madere, and Roger B. McWhorter, "Caisson Work at Hales Bar Dam." *Professional Memoirs, Corps of Engineers* 5:19 (January-February 1913): 78-82.
- ¹⁶¹ Ibid., 80-82.
- ¹⁶² Jane Lamm Carroll, "Mississippi River Headwaters Reservoirs" Historic American Engineering Record Report MN-6. On file at Print and Photographs Division, Library of Congress.
- ¹⁶³ U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1887* (Washington, DC: Government Printing Office, 1888), 1666-1674.
- ¹⁶⁴ U.S. Army Corps of Engineers, *Annual Report, 1896*, 1833-1834.
- ¹⁶⁵ U.S. Army Corps of Engineers, *Annual Report, 1899*, 365-366.
- ¹⁶⁶ U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1901* (Washington, DC: Government Printing Office, 1902), 2112; U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1904* (Washington, DC: Government Printing Office, 1905), 3753-3754.
- ¹⁶⁷ Ibid., 3754.
- ¹⁶⁸ U.S. Army Corps of Engineers, *Annual Report, 1886*, 234.
- ¹⁶⁹ T.C. Thomas, "Box Cofferdams on the Ouachita and Big Sunflower Rivers," *Professional Memoirs, Corps of Engineers* 9 (January 1917): 54-55.
- ¹⁷⁰ Ibid., 55-57.
- ¹⁷¹ Gary B. Mills, *Of Men & Rivers: The Story of the Vicksburg District* (Vicksburg, MS: U.S. Army Engineer District, Vicksburg, 1978), 92; U.S. Army Corps of Engineers, *Annual Report, 1901*, 346.
- ¹⁷² Historic American Engineering Record (HAER), "Ouachita River Lock and Dam No. 8." HAER No. AR-1 (1985), Photograph 24. On file at the Library of Congress, Prints and Photograph Division, Washington, D.C. Thomas, "Box Cofferdams on the Ouachita and Big Sunflower Rivers," 51.
- ¹⁷³ Ibid., 52.
- ¹⁷⁴ R.C. McCalla, "Improvement of the Black Warrior, Warrior and Tombigbee Rivers in Alabama." *Transactions of the American Society of Civil Engineers*. Paper No. 941. 49 (1902): 212-215; D.M. Andrews, "Foundations on the Coosa and Black Warrior Rivers, Alabama." *Professional Memoirs, Corps of Engineers* 1:4 (October-December 1909): 333-334.
- ¹⁷⁵ McCalla, "Improvement of the Black Warrior, Warrior and Tombigbee Rivers," 214-216.
- ¹⁷⁶ Ibid., 228, 240 242, ,
- ¹⁷⁷ H.C. Mower, "Locks and Dam No. 17, Black Warrior River, Alabama." *Professional Memoirs, Corps of Engineers* 7:33 (May-June 1915): 307-332.
- ¹⁷⁸ Dravo Corporation, *Locks and Dams*, 12.
- ¹⁷⁹ Ruffner, *Practice of Improvement*, 172; D.M. Andrews, "Dam No. 5, Coosa River: The Problems of Location and Construction." *Professional Memoirs, Corps of Engineers* 8:40 (July-August 1916): 488-503; D.M. Andrews, "Foundations on the Coosa and Black Warrior Rivers, Alabama." *Professional Memoirs, Corps of Engineers* 1:4 (October-December 1909): 333-354.
- ¹⁸⁰ Thomas, "Box Cofferdams on the Ouachita and Big Sunflower Rivers."

- ¹⁸¹ J.B. Wheeler, *An Elementary Course of Civil Engineering for the Use of Cadets of the United States Military Academy* (New York: John Wiley & Sons, 1890), 297-300; G.J. Fiebeger, *Civil Engineering: A Text-Book for a Short Course* (New York: John Wiley & Sons, 1906), 433-435.
- ¹⁸² Gifford, L.R. "Steel Sheeting and Sheet-Piling." *Transactions of the American Society of Civil Engineers*. Paper No. 1115 64 (1909): 486-488. "History and Types of Sheet Piling," <http://pz27.pilebuckinternational.com/overview/history.php>.
- ¹⁸³ Ibid.; Gifford, L.R. "Steel Sheeting and Sheet-Piling," 448-449, 488-489.
- ¹⁸⁴ "Interlocking Steel Sheet Piles for Bridge Pier Cofferdams," *Engineering Record* 49 (April 30, 1904): 557-558.
- ¹⁸⁵ "Steel Piling Cofferdams for Bridge Piers," *Engineering Record* (April 21, 1906): 505.
- ¹⁸⁶ "An Extensive Cofferdam of Steel Sheet Piling," *Engineering Record* 57 (June 13, 1908): 747-748; "A Large Steel-Pile Cofferdam for a Ship Lock at Buffalo, N.Y." *Engineering News* 60: (October 8, 1908): 394-395; "The Black Rock Lock Cofferdam," *Engineering Record* 59 (April 3, 1909): 385-387.
- ¹⁸⁷ "An Extensive Cofferdam," 747; "The Black Rock Lock Cofferdam," 385-386.
- ¹⁸⁸ Ibid., 385; "A Large Steel-Pile Cofferdam," 394.
- ¹⁸⁹ "The Black Rock Lock Cofferdam," 386-387; "Methods of Constructing the Black Rock Harbor Lock; New York State Barge Canal." *Engineering-Contracting* 35 (January 4, 1911): 3-5.
- ¹⁹⁰ Ibid., 3.
- ¹⁹¹ Karl Terzaghi, "Stability and Stiffness in Cellular Cofferdams." *Transactions of the American Society of Civil Engineers*. Paper No. 2253. 110 (1945): 1083. On file at ERDC Library, Vicksburg, MS.
- ¹⁹² U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1911* (Washington, DC: Government Printing Office, 1912), 1119-1120, 3042-3048.
- ¹⁹³ "Raising the United States Battleship 'Maine'," *Engineering Record* 62 (October 22, 1910): 452-453.
- ¹⁹⁴ Ibid., 452.
- ¹⁹⁵ U.S. Army Corps of Engineers, *Annual Report, 1911*, 3042-3044.
- ¹⁹⁶ U.S. Army Corps of Engineers, *Annual Report of the Chief of Engineers, 1912* (Washington, DC: Government Printing Office, 1913), 3565-3566.
- ¹⁹⁷ D.A. Watt, "Steel Sheetpile Cofferdams for Troy Lock and Dam," *Engineering News* 76 (September 21, 1916): 533-540.
- ¹⁹⁸ Ibid., 535; Terzaghi, "Stability and Stiffness of Cellular Cofferdams," 1084.
- ¹⁹⁹ Watt, "Steel Sheetpile Cofferdams," 536; W.M. Black, "Comments on Construction of Lock and Dam at Troy, New York," *Professional Memoirs, Corps of Engineers* 10:53 (September-October 1918): 627-632.
- ²⁰⁰ Ibid., 537-540.
- ²⁰¹ "Steel Cofferdam of Pocket Type Successful for Lock on Cape Fear River," *Engineering Record* 74 (September 9, 1916): 325-326; Norman M. Chivers, "The Cofferdam at Lock No. 2, Cape Fear River, North Carolina" *Professional Memoirs, Corps of Engineers* (September-October 1916): 608-621.
- ²⁰² Chivers, "The Cofferdam at Lock No. 2, 618-621.
- ²⁰³ Ibid., 608-611.
- ²⁰⁴ Ibid., 612-614.
- ²⁰⁵ Ibid., 614-615.

- ²⁰⁶ Ibid., 620-621.
- ²⁰⁷ Shriver, "Contract Methods and Equipment for a Typical Ohio River Dam," 806.
- ²⁰⁸ Thomas P. Roberts, "Construction of Cofferdams." *Proceedings of the Engineers' Society of Western Pennsylvania* 21 (July 1905): 305.
- ²⁰⁹ Ibid., 305-306.
- ²¹⁰ Johnson, *Headwaters District*, 101, 126, 167-168.
- ²¹¹ H.S. Schick, "Field Check on Formulas for Earth Pressure," *Engineering News-Record* 88 (15 June 1922): 994-995; Dravo Corporation, *Locks and Dams*, 16.
- ²¹² Ibid., 16-17.
- ²¹³ Ibid.
- ²¹⁴ Ibid., 20-21.
- ²¹⁵ Hugh J. Casey, "Deadman Island Lock and Dam, Ohio River," *The Military Engineer* 22 (September-October 1929): 444; Bell, "The Emsworth and Davis Island Dams," 406; Daly, "Mastery of the Ohio," 190.
- ²¹⁶ William H. Fowler, "Circular Cell Cofferdam at Deadman Island Dam." *Engineering News-Record* (January 9, 1930): 66; Dravo Corporation, *Locks and Dams*, 28.
- ²¹⁷ Ibid., 28-30; Fowler, "Circular Cell Cofferdam, 66-68; Casey, "Deadman Island Lock and Dam," 449-450.
- ²¹⁸ Ibid., 450-451.
- ²¹⁹ Don P. Keelor, "Construction of Montgomery Locks, Ohio River" *Military Engineer* 27 (May 1935): 187.
- ²²⁰ Ibid., 187-188; "Three Cableways of 1,510-Ft. Span Place 250,000 Yd. of Concrete in Montgomery Island Locks." *Construction Methods* 16 (July 1934): 26-28.
- ²²¹ Dravo Corporation, *Locks and Dams*, 43.
- ²²² Ibid., 43.
- ²²³ Ibid., 44-46.
- ²²⁴ "Construction Plan and Plant at the Falls of the Ohio." *Engineering News-Record* 98 (May 12, 1927): 762.
- ²²⁵ Ibid., 762-765.
- ²²⁶ Dravo Corporation, *Locks and Dams*, 32.
- ²²⁷ Pittsburgh District, "Navigation on the Monongahela and Allegheny Rivers," 5; McVarish, "Monongahela River Navigation System," 5;
- ²²⁸ Dinsmore and Judy A. Heberling, "Allegheny River Navigation System," 8.
- ²²⁹ Dinsmore, "Historic Resources of the Allegheny River Navigation System," 69
- ²³⁰ Ibid., 69-70; Dravo Corporation, *Locks and Dams*, 26-27, 31.
- ²³¹ "Progressive Cofferdamming for Long Low Dam," *Engineering News-Record* 114 (April 4, 1935): 474-475.
- ²³² Ibid., 473-474.
- ²³³ Ibid., 34; W.H. McAlpine, "Roller Gates in Navigation Dams," *The Military Engineer* 26:150 (November-December 1934): 419-423; Johnson, *Men Mountains and Rivers*, 137-138.

- ²³⁴ Dravo Corporation, *Locks and Dams*, 36-42.
- ²³⁵ W.C. Weeks and S.C. Godfrey, "Notes on the Construction of the Wilson Dam," *Military Engineer* 13 (April 1921): 112-113; Billington, Jackson, and Melosi, *History of Large Federal Dams*, 111-112.
- ²³⁶ Weeks and Godfrey, "Notes on the Construction of the Wilson Dam," 113-114; Hugh J. Casey "Muscle Shoals," *The Kansas Engineer* 10 (January 1925): 8; Stuart C. Godfrey, "Progress of Work on the Wilson Dam," *Military Engineer* 15 (July 1923): 338-339.
- ²³⁷ William Patrick O'Brien, Mary Yeater Rathbun, Patrick O'Bannon, and Christine Whitacre, *Gateways to Commerce: The U.S. Army Corps of Engineers' 9-Foot Channel Project on the Upper Mississippi River* (Denver, CO: National Park Service, 1992), 37-39.
- ²³⁸ *Ibid.*, 42; Dravo Corporation, *Locks and Dams*, 11.
- ²³⁹ O'Brien, et al., *Gateways to Commerce*, 42.
- ²⁴⁰ *Ibid.*, 14, 21-22; S.G. Roberts, "Canalization of the Upper Mississippi River," *Scientific American* 152 (February 1935): 72-74.
- ²⁴¹ O'Brien, et al., *Gateways to Commerce*, 27-30.
- ²⁴² *Ibid.*, 13-14.
- ²⁴³ *Ibid.*, 48, 65, 109; Charles P. Gross, and H.G. McCormick, "The Upper Mississippi River Project," *The Military Engineer* 33:190 (July-August 1941): 311-317.
- ²⁴⁴ *Ibid.*, 55-56.
- ²⁴⁵ *Ibid.*, 59, 63.
- ²⁴⁶ Lazarus White and Edmund Astley Prentis, *Cofferdams* (New York: Columbia University Press, 1940), 122-134.
- ²⁴⁷ O'Brien, et al., *Gateways to Commerce*, 109; Herbert G. McCormick and John W. Dixon, "Mississippi River Cofferdams," *The Military Engineer* 28:158 (March-April 1936): 106.
- ²⁴⁸ *Ibid.*, 107.
- ²⁴⁹ *Ibid.*, 106.
- ²⁵⁰ *Ibid.*, 105.
- ²⁵¹ *Ibid.*, 105-106.
- ²⁵² *Ibid.*
- ²⁵³ *Ibid.*, 105-108.
- ²⁵⁴ White and Prentis, *Cofferdams*, 150-154.
- ²⁵⁵ *Ibid.*
- ²⁵⁶ *Ibid.*, 158.
- ²⁵⁷ *Ibid.*, 155.
- ²⁵⁸ *Ibid.*, 158.
- ²⁵⁹ *Ibid.*, 158-159.
- ²⁶⁰ *Ibid.*, 157-159.
- ²⁶¹ Cornelia F. Mutel, *Flowing Through Time: A History of the Iowa Institute for Hydraulic Research* (Iowa City: University of Iowa Press, 1998).
- ²⁶² White and Prentis, *Cofferdams*, 155.

- ²⁶³ Ibid., 134.
- ²⁶⁴ Ibid., 134-136
- ²⁶⁵ Ibid., 135-136.
- ²⁶⁶ Ibid., 164.
- ²⁶⁷ O'Brien, et al., *Gateways to Commerce*, 108.
- ²⁶⁸ Ibid., 108, 110; E.P. Ketchum, "Removing a Collapsed Cofferdam," *Military Engineer* 29 (May-June 1937): 203.
- ²⁶⁹ O'Brien, et al., *Gateways to Commerce*, 110-111.
- ²⁷⁰ Ibid., 111.
- ²⁷¹ Ibid., 114; Ketchum, "Removing a Collapsed Cofferdam," 203.
- ²⁷² Ibid.; O'Brien, et al., *Gateways to Commerce*, 115.
- ²⁷³ Ibid., 115-117; Ketchum, "Removing a Collapsed Cofferdam," 203-204; White and Prentis, *Cofferdams*, 166.
- ²⁷⁴ Ibid., 167; Ketchum, "Removing a Collapsed Cofferdam," 204; O'Brien et al., *Gateways to Commerce*, 116-117.
- ²⁷⁵ Ketchum, "Removing a Collapsed Cofferdam," 204-206; O'Brien et al., *Gateways to Commerce*, 117; White and Prentis, *Cofferdams*, 167-168.
- ²⁷⁶ O'Brien, et al., *Gateways to Commerce*, 118-119.
- ²⁷⁷ White and Prentis, *Cofferdams*, 168-169.
- ²⁷⁸ Ibid., 171-172.
- ²⁷⁹ Ibid., 172.
- ²⁸⁰ Ibid., 174.
- ²⁸¹ Ibid.
- ²⁸² Ibid., 170-171.
- ²⁸³ Ibid., 171.
- ²⁸⁴ Ibid., 177-182; O'Brien et al., 121.
- ²⁸⁵ Ibid., 182-185.
- ²⁸⁶ White and Prentis, *Cofferdams*, 210.
- ²⁸⁷ Ibid.
- ²⁸⁸ C.I. Grimm, "Cofferdams in Swift Water for Bonneville Dam," *Engineering News-Record* 115 (September 5, 1935): 315; William F. Willingham, *Water Power in the "Wilderness": The History of Bonneville Lock and Dam*, rev. ed. (Portland, OR: U.S. Army Corps of Engineers, Portland District, 1997); Historic American Engineering Record, "Bonneville Project" HAER No. OR-11 (1989). On file at the Library of Congress, Prints and Photograph Division, Washington, D.C.
- ²⁸⁹ Grimm, "Cofferdams in Swift Water," 315.
- ²⁹⁰ Ibid., 315-316; White and Prentis, *Cofferdams*, 211-215; Abbie B. Liel and David P. Billington, "Engineering Innovation at Bonneville Dam," *Technology and Culture* 49 (2008): 727-751.
- ²⁹¹ Ibid., 218-219; Grimm, "Cofferdams in Swift Water," 316-317.
- ²⁹² Ibid., 317; White and Prentis, *Cofferdams*, 222-224.

- ²⁹³ Ibid., 226-228; Grimm, "Cofferdams in Swift Water," 317.
- ²⁹⁴ Grimm, "Cofferdams in Swift Water," 315.
- ²⁹⁵ "Jetty Construction Methods Used to Repair Bonneville Cofferdam," *Engineering News-Record* 117 (October 1, 1936): 461.
- ²⁹⁶ Ibid., 461-463.
- ²⁹⁷ Paul C. Pitzer, *Grand Coulee: Harnessing a Dream* (Pullman: Washington State University Press, 1994); "Constructing the First Cofferdam," *Engineering News-Record* 115 (August 1, 1935): 148-151; "Serious Leak Checked in Cofferdam at Grand Coulee," *Engineering News-Record* 118 (April 22, 1937): 595-597; "Contractors Win River Battle," *Engineering News-Record* 119 (July, 1 1937): 13-16; Robert J. Jenks, "Wrenching Out a Cofferdam," *Engineering News-Record* 120 (May 12, 1938): 677-679.
- ²⁹⁸ D.W. Meinig, *The Shaping of America: A Geographical Perspective on 500 Years of History*, Volume 4: Global America, 1915-2000 (New Haven: Yale University Press, 2004), 46, 82, 139-143; Terzaghi, "Stability and Stiffness of Cellular Cofferdams," 1136.
- ²⁹⁹ Tennessee Valley Authority, *Steel Sheetpile Cellular Cofferdams on Rock*. Technical Monograph No. 75 (December 1957) in Pile Buck, Inc. *Cellular Cofferdams* (Jupiter, FL: Pile Buck, Inc., 1990), 3-4. On file at ERDC Library, Vicksburg, MS.
- ³⁰⁰ "Construction Steps Up at Pickwick, Third TVA Dam," *Engineering News-Record* 116 (April 16, 1936): 549-552; R.R. Colburn, "Sheet-Pile Cofferdams and Test Cell for TVA Projects," *Civil Engineering* 9 (September 1939): 551-553; Terzaghi, "Stability and Stiffness of Cellular Cofferdams," 1136.
- ³⁰¹ Colburn, "Sheet-Pile Cofferdams and Test Cell for TVA Projects," 551; Terzaghi, "Stability and Stiffness of Cellular Cofferdams," 1133-1134, 1139-1140, 1146-1147.
- ³⁰² A.F. Hedman, "Cofferdam Design for Kentucky Dam," *Engineering News-Record* 128 (January 1, 1942): 30-34; Terzaghi, "Stability and Stiffness of Cellular Cofferdams," 1133, 1136.
- ³⁰³ Hedman, "Cofferdam Design for Kentucky Dam," 50-55.
- ³⁰⁴ Ibid.
- ³⁰⁵ F.R. Sweeny, "Notes on the Design of a Singlewall Cofferdam," *Engineering News-Record* 82 (April 10, 1919): 708-711.
- ³⁰⁶ Raymond P. Pennoyer, "Design of Steel Sheet-Piling Bulkheads." *Civil Engineering* 3 (November 1933); Raymond P. Pennoyer, "Gravity Bulkheads and Cellular Cofferdams: Essential Theory of Design When Steel Sheet Piling Is Used," *Civil Engineering* 4 (June 1934): 301-305.
- ³⁰⁷ Ibid.; N. Krebs Ovesen, *Cellular Cofferdams: Calculation Methods and Model Tests*, Bulletin No. 14 (Copenhagen: Danish Geotechnical Institute, 1962), 7. On file at ERDC Library, Vicksburg, MS.
- ³⁰⁸ White and Prentis, *Cofferdams*.
- ³⁰⁹ Ibid., 3-43; Terzaghi, "Stability and Stiffness of Cellular Cofferdams," 1101.
- ³¹⁰ White and Prentis, *Cofferdams*, 44-61.
- ³¹¹ Ibid., 62-85.
- ³¹² Terzaghi, "Stability and Stiffness of Cellular Cofferdams."
- ³¹³ Ibid., 1086, 1092, 1124.
- ³¹⁴ Ibid., 1099.
- ³¹⁵ Ibid., 1156.
- ³¹⁶ Ibid., 1113-1114, 1156; Ovesen, *Cellular Cofferdams*, p. 7.

- ³¹⁷ Terzaghi, "Stability and Stiffness of Cellular Cofferdams," 1133-1155; Tennessee Valley Authority Divisions of Engineering and Construction, *Steel Sheetpile Cellular Cofferdams on Rock*. Technical Monograph No. 75 (Knoxville, TN: Tennessee Valley Authority, 1957) reprinted in Pile Buck, Inc. *Cellular Cofferdams* (Jupiter, FL: Pile Buck, Inc., 1990). On file at ERDC Library, Vicksburg, MS.
- ³¹⁸ William F. Willingham, *Army Engineers and the Development of Oregon: A History of the Portland District United States Army Corps of Engineers* (Washington: GPO, 1983), 93, 150-151; Billington, Jackson, and Melosi, *The History of Large Federal Dams*, 222-229.
- ³¹⁹ Conclusions based upon review of numerous design memorandum for Columbia and Snake river dams on file at ERDC Library, Vicksburg, MS. These include: Walla Walla District, U.S. Army Corps of Engineers, *Ice Harbor Lock and Dam, Snake River Project - Design Memorandum No. 12: Second Step Cofferdam* (Walla Walla, WA: U.S. Army Corps of Engineers, 1958); Walla Walla District, U.S. Army Corps of Engineers, *Lower Monumental Lock and Dam, Snake River Project - Design Memorandum No. 2: First Step Cofferdam* (Walla Walla, WA: U.S. Army Corps of Engineers, 1960); Walla Walla District, U.S. Army Corps of Engineers, *John Day Lock and Dam, Columbia River - Design Memorandum No. 21: Second Step Cofferdam* (Walla Walla, WA: U.S. Army Corps of Engineers, 1961); Walla Walla District, U.S. Army Corps of Engineers, *Lower Monumental Lock and Dam, Snake River Project - Design Memorandum No. 20: Second and Third Step Cofferdams* (Walla Walla, WA: U.S. Army Corps of Engineers, 1962); Walla Walla District, U.S. Army Corps of Engineers, *Little Goose Lock and Dam, Snake River Project - Design Memorandum No. 13: First Step Cofferdams* (Walla Walla, WA: U.S. Army Corps of Engineers, 1963).
- ³²⁰ McVarish, "Monongahela River Navigation System," 20-21.
- ³²¹ Wilfred Bauknight, "Heavy Industrial Development Dictates Tough Construction Site for Monongahela Locks No. 2." *Civil Engineering* 21 (September 1951): 36; F.J. Larkin, "Monongahela Magic." *Engineering News-Record* 145 (October 19, 1950): 34.
- ³²² Ibid., 34; Bauknight, "Heavy Industrial Development, 36, 40.
- ³²³ Ibid., 38-39; Larkin, "Monongahela Magic," 35; Edwin Paul Swatek Jr., "Cellular Cofferdam Design and Practice," *Proceedings of the American Society of Civil Engineers - Journal of the Waterways and Harbors Division* 93 (August 1967): 124-125..
- ³²⁴ Ibid., Larkin, "Monongahela Magic," 35.
- ³²⁵ James W. Bruce, Dwight W. Keller, and James A. Neill, "Modern Facilities for Ohio River Navigation." *Journal of the Waterways and Hydraulics Division, American Society of Civil Engineers*. Paper 1239. 83 (May 1957): 1-13; Johnson, *The Headwaters District*, 249-252.
- ³²⁶ Pittsburgh District, U.S. Army Corps of Engineers, *New Cumberland Locks, Ohio River - Design Memorandum No. 12: Lock Walls, Sills, and Cofferdam* (Pittsburgh, PA: U.S. Army Corps of Engineers, 1955); Claude A. Fetzer, and Edwin Paul Swatek, Jr., "Cofferdams" In *Advanced Dam Engineering for Design, Construction, and Rehabilitation*, Robert B. Jansen, ed. (New York: Van Nostrand Reinhold, 1988), 219.
- ³²⁷ Swatek, "Cellular Cofferdam Design and Practice," 114-115; "They Made Money on Floods," *Construction Methods and Equipment* 41:8 (August 1959): 80-87.
- ³²⁸ Fetzer, and Edwin Paul Swatek, Jr., "Cofferdams," 232.
- ³²⁹ Ibid., 223; "Record Cofferdam Beats Slippage," *Engineering News-Record* 180:23 (June 6, 1968): 52, 57.
- ³³⁰ Ibid.
- ³³¹ Swatek, "Cellular Cofferdam Design and Practice," 112-114.
- ³³² Ibid., 114.

- 333 Reed L. Mosher, *Three-Dimensional Finite Element Analysis of Sheet-Pile Cellular Cofferdams*, Technical Report ITL-92-1 (Washington, DC: USACOE, 1992), 2. On file at ERDC Library, Vicksburg, MS.
- 334 Ibid.
- 335 Patrick W. O'Bannon, "Upper Mississippi River 9-Foot Channel Project: Lock & Dam 26R, Alton vicinity, Madison County, IL," HAER No. IL-32 (July 1989). On file at the Library of Congress, Prints and Photograph Division, Washington, D.C.
- 336 Ibid.; Martin, James R. III, G. Wayne Clough. *A Study of the Effects of Differential Loadings on Cofferdams*. Technical Report ITL-90-1. Vicksburg, MS: US Army Engineer Waterways Experiment Station, 1990, 20-22. On file at ERDC Library, Vicksburg, MS.
- 337 Ibid., 23; Mosher, *Three-Dimensional Finite Element Analysis*, 3-4; G.W. Clough, and T. Kuppusamy, "Finite Element Analysis of Lock and Dam 26 Cofferdam," *Journal of the Geotechnical Engineering Division, American Society of Civil Engineers* 3 (1985): 521-544; U.S. Army Corps of Engineers. St. Louis District. *Lock and Dam No. 26 (Replacement) Upper Mississippi River Basin, Mississippi River – Alton, Illinois, Missouri and Illinois; Design Memorandum No. 7: Cofferdam Phase I* (St. Louis, MO: U.S. Army Engineer District, St. Louis, 1973), 7-1. On file at ERDC Library, Vicksburg, MS;
- 338 Mosher, *Three-Dimensional Finite Element Analysis*, 3-4.
- 339 U.S. Army Corps of Engineers. St. Louis District. *Lock and Dam No. 26 (Replacement) Design Memorandum No. 7*, 3-3, 3-4.
- 340 Robert J. Rapp, Charles W. Denzel, and Thomas J. Pokrefke, "Unique Utilization of a Physical Model to Develop a Construction Sequence of a Major Cofferdam," *Hydraulics and Hydrology in the Small Computer Age* 2 (1985): 1130-1135. On file at ERDC Library, Vicksburg, MS.
- 341 Terzaghi, "Stability and Stiffness of Cellular Cofferdams;" Tennessee Valley Authority, *Steel Sheetpile Cellular Cofferdams*.
- 342 E.M. Cummings, "Cellular Cofferdams and Docks," *Proceedings of the American Society of Civil Engineers – Journal of the Waterways and Harbors Division* 83 (September 1957) Paper 1366; N. Krebs Ovesen, *Cellular Cofferdams: Calculation Methods and Model Tests*. Bulletin No. 14. (Copenhagen: Danish Geotechnical Institute, 1962). On file at ERDC Library, Vicksburg, MS.
- 343 U.S. Army Corps of Engineers, Office of the Chief of Engineers, *An Analysis of Cellular Sheet Pile Cofferdam Failures* (Cincinnati, OH: U.S. Army Corps of Engineers, Ohio River Division, 1974). On file at ERDC Library, Vicksburg, MS.
- 344 James R. Martin, III and G. Wayne Clough, *A Study of the Effects of Differential Loadings on Cofferdams*, Technical Report ITL-90-1 (Vicksburg, MS: US Army Engineer Waterways Experiment Station, 1990), 6. On file at ERDC Library, Vicksburg, MS.
- 345 Ibid.; M.P. Rossow and R.L. Mosher, "Design of Cellular Cofferdams by the CCELL Computer Program," *Computers and Structures* 42 (1992): 979. On file at ERDC Library, Vicksburg, MS.
- 346 Ibid., 979-988; Mark Rossow, Edward Demsky and Reed Mosher, *Theoretical Manual for Design of Cellular Sheet Pile Structures (Cofferdams and Retaining Structures)*, Technical Report ITL-87-5 (Vicksburg, MS: US Army Engineer Waterways Experiment Station, 1987). On file at ERDC Library, Vicksburg, MS.
- 347 U.S. Army Corps of Engineers, *Design of Sheet Pile Cellular Structures*, Engineer Manual EM 1110-2-2503 (Washington, DC: USACOE, 1989). On file at ERDC Library, Vicksburg, MS.
- 348 Mosher, *Three-Dimensional Finite Element Analysis*.
- 349 Brian H. Greene, John A. Gerlach and Andrew Schaffer, "Geotechnical Design and Instrumentation of an Anchored Cofferdam, Point Marion Lock, Pennsylvania." *Bulletin of the Association of Engineering Geologists* 30:3 (1993): 265-266.