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1 May 2006

US Army Corps
of Engineers®

ENGINEERING AND DESIGN

Hydraulic Design of Navigation Locks

ENGINEER MANUAL

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DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

CECW-CE

Manual
No. 1110-2-1604

1 May 2006

Engineering and Design
HYDRAULIC DESIGN OF NAVIGATION LOCKS

1-1. Purpose. This manual presents the results of research, design studies, and operation experience as guidance for the hydraulic design of navigation locks.

1-2. Applicability. This manual applies to all HQUSACE elements, major subordinate commands, districts, laboratories, and field operating activities having responsibilities for the design of civil works projects.

1-3. General. The guidance is limited to lock types that are considered design options by the U.S. Army Corps of Engineers (CE). Other designs, such as mechanical lifts and water slopes occasionally used in Europe, are discussed in Appendix G, but not in detail since they have not been feasible options for waterways within the United States. Detailed theory, computer programming, and computer codes are not presented; however, sources of these types of information are noted. The site, structure, hydraulic system, and operation of most existing CE lock configurations are summarized. Laboratory and field studies and other information data sources pertinent to these locks are identified. The overall broad scope of materials specifically addresses the following two design circumstances.

a. Existing locks. General information concerning hydraulic factors that tend toward safe, efficient, and reliable lock performance is directed toward repair or rehabilitation of existing locks. Many existing locks are not current state-of-the-art designs; design guidance for obsolete systems is not presented.

b. New locks. Detailed information regarding state-of-the-art hydraulic systems is directed toward new or replacement locks. General information regarding parameters used as the basis for design as well as specific information regarding function, structure, performance, and operation of modern locks is included.

FOR THE COMMANDER:

10 Appendices
(See Table of Contents)

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This manual supersedes EM 1110-2-1604, Hydraulic Design of Navigation Locks, 30 June 1995.

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Chapter 1
Introduction

Section I
General

1-1. Purpose

This manual presents the results of research, design studies, and operation experience as guidance for the hydraulic design of navigation locks.

1-2. Scope

The guidance is limited to lock types that are considered design options by the U.S. Army Corps of Engineers (CE). Other designs, such as mechanical lifts and water slopes occasionally used in Europe, are discussed in Appendix G, but not discussed in detail since they have not been feasible options for waterways within the United States. Detailed theory, computer programming, and computer codes are not presented; however, sources of these types of information are noted. The site, structure, hydraulic system, and operation of most existing CE lock configurations are summarized. Laboratory and field studies and other information data sources pertinent to these locks are identified. The overall broad scope of materials specifically addresses the following two design circumstances.

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1-4. References

Appendix A groups references into three lists: the Required Publications and Related Publications consisting of CE-Sponsored Lock Hydraulic System Study Reports and General Bibliography. Each list is discussed below.

a. HQUSACE Publications. Applicable Corps guidance including Engineering Regulations, Engineering Manuals etc., are listed in numerical order in Appendix A, paragraph A-1. References throughout the manual use the document number.

b. CE-Sponsored Lock Hydraulic System Study Report. These reports are U.S. Army Corps of Engineers sponsored laboratory studies of lock systems administered by the U.S. Army Engineer Research and Development Center (ERDC) (formerly Waterways Experiment Station (WES)), Bonneville

Hydraulics Laboratory (BHL), or St. Paul District (STP). References throughout the manual begin by a number (e.g., item 01, item 02, ..., item 86). Corresponding references are listed chronologically in Appendix A, paragraph A-2.

c. General Bibliography. These references include other general literature relevant to hydraulic design of navigation locks or applicable hydraulic topics. References throughout the manual begin with a letter (first letter of the author's last name) followed by a number (e.g., A1, A2, B1, B2, etc). Corresponding references are listed in alphabetical order by author in Appendix A, paragraph A-3.

1-5. Explanation of Terms

Symbols used throughout this manual are defined in Appendix J and, as far as practical, conform to the American Standard Letter Symbols for Hydraulics (item A4). Symbols are also defined at the first use within the text.

1-6. Technical Data

Plates at the end of the appropriate chapter provide design guidance and details for hydraulic design. Data sources are identified. A summary of existing CE locks including various arrangements of hydraulic features is presented in Appendix B and EP 1105-2-11.

Section II
Technical Coordination

1-7. General

Specific services are available to the designer in subject areas complementary to the hydraulic design. These are not, in general, described in this manual. Centers of expertise addressing environmental topics, hydropower, navigation, etc., may be located by query to HQUSACE.

1-8. Automatic Data Processing (ADP)

The development and management of computer-based capabilities is an ongoing process within the CE. ADP coordinators at HQUSACE, Division, District, and Research offices may be queried with regard to program and equipment status. The WES Automatic Data Processing Center (ADPC) Computer Program Library (WESLIB) provides computer information and services to CE Divisions and Districts. One service is the Conversationally-Oriented Real-Time Programming System (CORPS), which provides a set of proven engineering applications programs that can be accessed on several different computer systems by engineers with little or no computer training. A catalog of WESLIB programs is maintained (updated as needed) and distributed to ADP users throughout the CE. References to programs available to the lock designer are noted in this manual by the CORPS program number.

1-9. WES Capabilities and Services

WES has capabilities and furnishes services in the fields of hydraulic modeling, analysis, design, and prototype testing. Expertise has been developed in the areas of water quality studies, mathematical modeling, and computer programming. Procedures necessary to arrange for WES participation in hydraulic studies of all types are covered in Engineer Regulation (ER) 1110-1-8100. WES also has the responsibility for coordinating the CE hydraulic prototype test program. Assistance during planning and testing is included in this program (ER 1110-2-8150).

1-10. Design Memorandum Presentations

General and feature design memoranda should contain sufficient information to ensure that the reviewer is able to reach an independent conclusion as to the design adequacy. For convenience, the hydraulic information, factors, studies, and logic used to establish such basic features as type of lock intake, manifold system, outlet, valves, etc., should be complete and readily identifiable within the hydraulics presentation. Appurtenant items such as debris barriers and emergency closure procedures should be presented in similar detail. Operating characteristics over the full range of hydrologic, navigation, and other site-specific boundary conditions should be provided.

Section III
Project Function

1-11. General

The function of a lock is to provide safe passage for navigation between two pools not at the same water level. The difference in water level may exist naturally (as in the Panama Canal Locks) or be developed for economic reasons (such as hydropower at Bonneville Lock on the Columbia River or navigation at Bay Springs Lock on the Tennessee-Tombigbee Waterway). Other considerations (economic, environmental, geotechnical, etc.) are constraints to the design process. Site-specific constraints, including those that for practical reasons are beyond the scope of this manual, should be clearly stated in hydraulic presentations.

1-12. Primary Components

All lock designs presented in this manual contain the four primary components given below and shown schematically in Figure 1-1.

a. Upper approach. The canal immediately upstream from the lock is referred to as the upper approach. The guide wall serves to align and to guide a downbound tow into the lock chamber and is usually a prolongation of one wall of the chamber. The guard wall provides a barrier that prevents the tow from entering an area having hazardous currents or potentially damageable or damaging structures. The term guide-and-guard wall may be used when the combination of functions results in deviations from usual guide wall design practice. Guidelines for approach channel design are included in EM 1110-2-1611. Design guidance for upper approach guard walls can be found in item 104.

b. Lock chamber. The downbound traffic is lowered to lower pool and the upbound traffic is raised to upper pool within the lock chamber. The upper and lower gates are movable barriers that can be opened to permit a vessel to enter or exit the chamber. Sills, which extend across the lock chamber at the base of the gates, provide a surface for gate closure and are the structural limits for navigable depth in the lock. Lock wall appurtenances are recessed so that the clear width and the usable width are identical. Conversely, because of clearances provided for gate operation and for longitudinal tow drift, the usable length of the chamber differs from commonly specified nominal lengths, i.e., less than the pintle-to-pintle length shown in Figure 1-1. The difference between upper and lower pool elevations is termed lift.

c. Filling and emptying system. For a lock filling operation, the emptying valves are closed. The filling valves are opened. Flow enters the intake manifolds and exits by means of the culvert-to-chamber manifolds into the lock chamber. For emptying, the filling valves are closed and the emptying valves are opened. Flow enters the culvert-to-chamber manifolds and exits by means of the outlet manifolds. Many

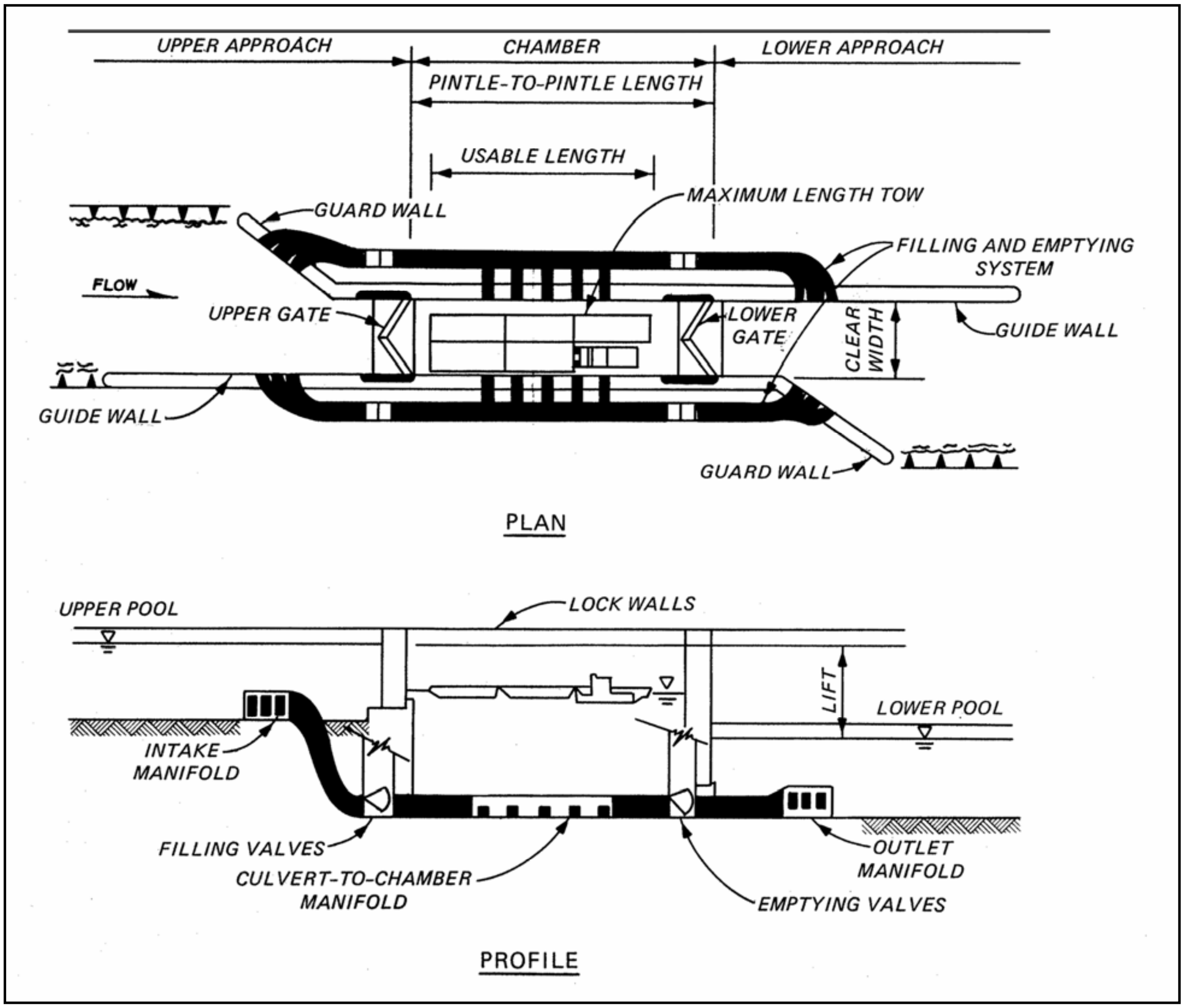


Figure 1-1. Common lock features for a lock with culverts in the sidewall

differences are possible and acceptable between the idealized system shown in Figure 1-1 and an actual design. Intakes and outlets may not be located directly in the approach canals; the number, general shape, and location of the manifolds vary between designs; the filling-and-emptying system may be separated; etc.

d. Lower approach. The canal immediately downstream from the chamber is referred to as the lower approach. Guide, guard, and guide-and-guard walls are used and defined similarly both upstream and downstream from the lock (EM 1110-2-1611).

1-13. Special Needs

Operation and maintenance considerations (as well as more site-specific topics such as environment, relocations, and geotechnical factors) require additions to the schematized navigation lock shown in Figure 1-1. Construction cofferdams, emergency closure devices, surge suppression pools, and impact barriers are examples of more common special needs that are studied during hydraulic design of navigation locks.

1-14. Classification Systems

Two methods are used to classify lock projects.

a. Project classification (*lift*). *etc.*) within the chamber to obtain smooth filling and emptying. In addition, higher lifts require the filling-and-emptying system to be designed such that cavitation, abrasion, flow-induced vibration, and other liabilities associated with high-velocity flow do not occur. A lock project is therefore viewed by lift as being in one of four categories as identified from studies of existing projects (Plate 1-1). The categories are listed in Table 1-1.

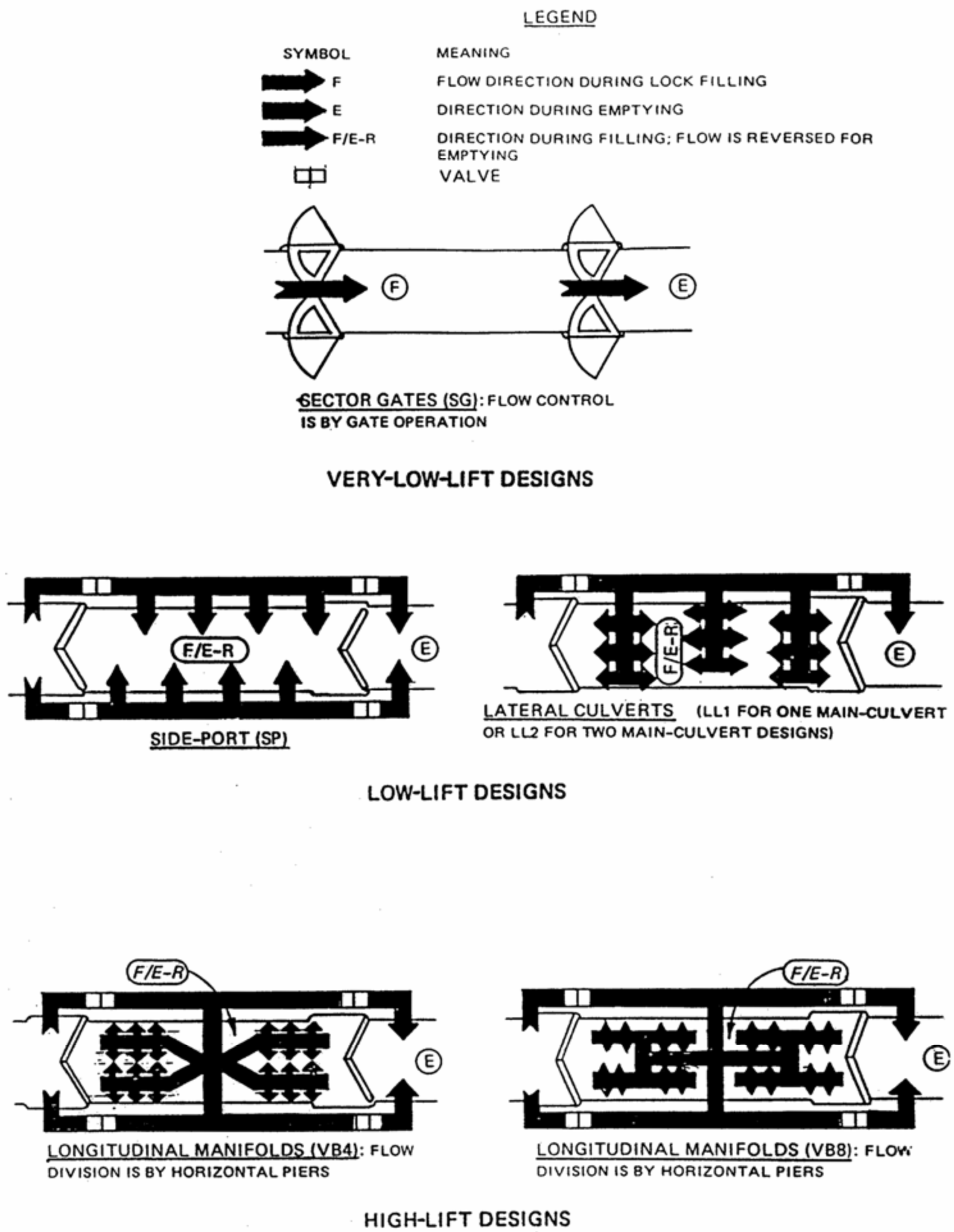
b. Design classification (*filling-and-emptying systems*). Specifications regarding within-chamber manifolds, baffles, and other structural elements are derived from laboratory testing and prototype experience. Small variations in these elements, particularly for high-lift locks, may cause significant surface currents or local turbulence unfavorable to lock operation. Two specific design alternatives are suggested in this manual for each range of project lifts. Schematics of the suggested designs are shown in Figure 1-2 and comments regarding their applicability are included in Table 1-1. Higher lift designs function well at lower lifts; however, increased costs are also associated with higher lift designs.

1-15. CE Lock Operating Experience

A list of most existing CE locks is in Appendix B. Plate 1-1 illustrates the historic trend away from certain designs (i.e., loop culverts and valves-in-gates) reflecting economic or operational liabilities. Substantial experience with sector gate (very-low-lift) and side-port (low-lift) designs is evident. One each of the longitudinal manifold (vertically divided flow by means of horizontal splitters) designs suggested for high-lift projects is in operation. An extensive summary of devices and concepts used in earlier (pre-1940) CE navigation locks and dams is available (item U1).

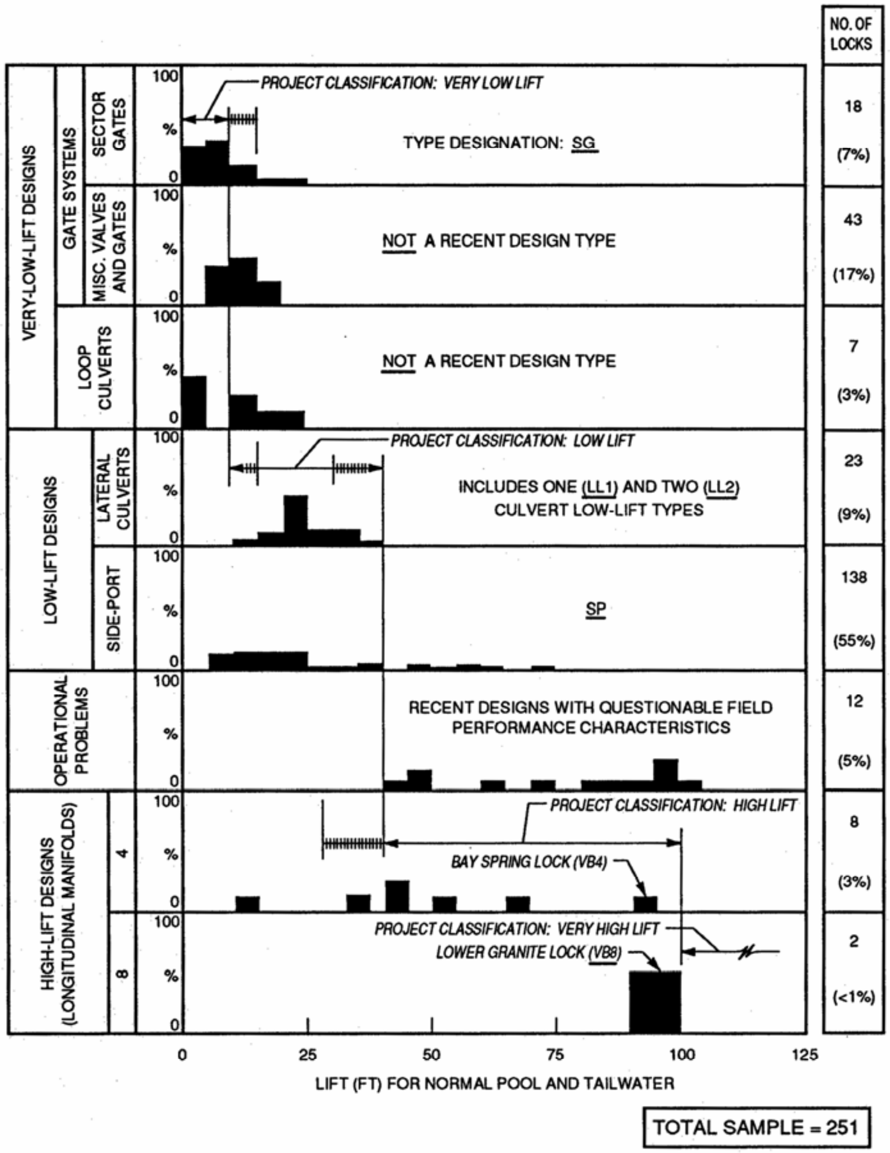
Table 1-1
Classification of Projects by Lifts

Range of Maximum Design Lift (ft to ft)	Project Classification	Percent of Corps Locks	Suitable Design Types
0∀ to 10	Very low lift	25	End filling-and-emptying systems are suitable. Each of the three general types (gate, valve(s)-in-gate, and loop culvert) can normally provide satisfactory chamber conditions. Choice of type is influenced by economic, operational, and layout factors. The sector gate has been used exclusively for CE very-low-lift designs since 1950.
10 to 30/40	Low lift	60	Wall culverts with side ports (side-port systems) are generally best suited for lifts below about 30 ft. The auxiliary system using lateral manifolds is suitable for low-lift projects requiring one culvert lock operation. Simplified high-lift designs have been model-tested for lifts in the 30- to 40-ft range. The In-Chamber Longitudinal Culvert System Design has been modeled for lifts between 20 and 40 ft (items 92, 94, 96, and 103).
30/40 to 100	High lift	15	Longitudinal manifold systems are suitable. Choice of type (4 or 8 manifolds) is influenced by economic and layout factors. Recent designs subdivide the flow by means of horizontal rather than vertical piers.
100 to __ (Undefined)	Very high lift	0	These projects are outside the range of CE lock operational experience (Plate 1-1); the exception in John Day Lock (107-ft lift) on the Columbia River. High-lift designs augmented by analytical and laboratory studies are suggested for preliminary (prior to physical model testing) layout.



Note: Other lateral culvert systems have been used for CE locks (see Appendix B: BL2 is a two-culvert low-lift design and BLC/S and BLC/I are two-culvert high-lift designs). Because of operational limitations, these lateral systems will receive careful review prior to design acceptance.

Figure 1-2. Flow distribution of recommended designs



NOTES:
1. DESIGN DETAILS VARY WITHIN EACH DESIGN TYPE.
2. ORDINATE PERCENTAGES ARE PER DESIGN TYPE.
3. ABSCISSA (LIFT) INCREMENT IS 5 FT.
4. REPORTING PROCEDURE (LIFT AND TYPE) IS IMPRECISE; ALL CE LOCKS ARE NOT INCLUDED.
5. REFER TO EP1105-2-11 AND APPENDIX B FOR PROJECT INFORMATION.
6. |###### INDICATES OVERLAPPING OF DESIGN TYPES.

HISTOGRAMS
CE LOCK OPERATION EXPERIENCE

Plate 1-1

Chapter 2
Project Identification

Section I
Design Management

2-1. General

Lock design is a multidisciplinary activity. Coordination among disciplines is initiated prior to hydraulic design of the filling-and-emptying system and is continued throughout the design process. Capacity and economic studies precede project authorization so that general guidance for *location*, *lockage time*, *lift variations*, *number of chambers*, *design vessel*, *usable length*, and *clear width* is available at the onset of hydraulic feature design. Capacity concerns (items B7, D5, D7, D10, E2, F2, G1, K1, K2, L1, S2, and S5) are dynamic as quality, size, and timeliness of database content and computer software and hardware capabilities change. Two WES studies (items D1 and D2) are examples of computer-based analysis of inland waterway systems. Guidance and assistance for these studies were from the Navigation Support Center (ORLPD-C), U.S. Army Engineer District, Louisville.

2-2. Design Constraints

Table 2-1 lists selected preliminary topics that influence the hydraulic design of locks. These topics, termed constraints herein, are documented prior to design. The source or cause of each constraint and, where appropriate, physical and economic values, are included in the documentation. Design time is reduced when constraints are well-defined and conflicts between constraints are resolved in a timely manner. Site-specific constraints are reviewed and quantified prior to hydraulic design. Environmental issues are often site-specific due to differences in the impacts of climate, water quality, economic development, and many other factors on local ecology. Macrofouling by the nonindigenous zebra mussel (*Dreissena polymorpha*) is an example. Information regarding the effects of zebra mussel infestation is available as technical notes, workshop proceedings, and other databases. These are available from the U.S. Army Engineer Waterways Experiment Station, ATTN: CEWES-ER-A, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199.

2-3. Incremental Effects

Certain factors, such as number of chambers, when incremented are a major change in project concept and are not included in feature design. Other factors, such as operation time, may be varied by the design process to increase benefits but must be economically balanced with the increase in cost. Information regarding relative unit costs of property, operational efficiencies, and structural elements can be used to develop cost-effective projects.

2-4. General Studies

The numerous multidisciplinary studies that precede hydraulic design are beyond the scope of this manual. However, the following sections summarize four study topics that commonly are used to resolve most constraints listed in Table 2-1: navigation system studies concern the interdependency of waterway, vessel, and commodity characteristics; navigation transit time studies concern the problem of expeditiously moving vessels through the project; chamber alternatives studies derive optimum chamber dimensions and number of chambers based on economic and physical factors; and geotechnical and structural studies tend to identify chamber location and type of structure.

Table 2-1
Examples of Constraints Considered During Hydraulic Design of Locks

Scope	Type of Constraint	Scope	Type of Constraint
Authorization	Type (New Design, Rehabilitation, Replacement) Funding Capacity Economics Other Authorization Requirements	Project	Multipurpose Functions Compatibility (Navigation) Compatibility (Flows) Lock Chamber Location Approach Channel Layout
System	Economics/Standardization Number of Parallel Chambers Clear Width Usable Length Lockage Procedures Appurtenant Equipment Emergency Procedures		Hydrologic/Operational Projections Upper Pool (Maximum, Minimum, Design) Lower Pool (Maximum, Minimum, Design) Lock Status During Extreme Flows
	Vessel Characteristics Design Type (Shape, Length, Width, Draft) Vessel Mix		Lock-Structure Design Requirements Geotechnical (Foundations, etc.) Structural (Monolith Design, etc.) Electrical-Mechanical (Power Supply, etc.)
	Hydrology Projected Distribution of Flows Extreme (High and Low) Flows Ice and Debris Management		Archeologic, Historic, and Environmental Requirements
	Navigation Navigation Limits Special Needs		Operational Needs Lockage Procedures Emergency Closure Deicing (Chamber and Equipment) Debris and Ice Control Inspection and Maintenance Safety Other Operational Needs
	Other System Requirements		Construction Closure or Diversion Lock Status
			Property Relocations Acquisitions and Easements
			Other Site-Specific Concerns

Note: This listing of constraints is not exhaustive. A site-specific situation may require any item to be rigid, flexible, minor, or nonexistent. Many constraints require relative-cost studies of alternate workable schemes. The resolution of conflicts between constraints is a major part of lock design management. *Primary Function = Navigation Capacity*

Section II
Navigation System Characteristics

2-5. Information and Data Required

Navigation systems are addressed in the National Waterways Study (item U2) and other transportation-planning reports (item 58, for example). The studies quantify constraints imposed by standardization as well as by the system-wide transportation function. Near-project constraints concerning layout and location are described in EM 1110-2-1611 for shallow-draft waterways and in EM 1110-2-1613 for deep-draft waterways.

2-6. Waterway

The physical characteristics of a waterway such as width, depth, and bend radii limit the types of traffic that can use the channels. The type of traffic, in turn, influences the design of any lock. The Great Lakes connecting channels, the St. Lawrence Seaway, channels in estuaries, and several channels contiguous to the coast are deep enough for vessels drawing 27 to 35 feet (ft). Shallow river channels and canals limit the traffic to shallow-draft tows and pleasure craft: 14 ft, Columbia River, is the maximum design draft for U.S. tows; 9 ft, Ohio River and others, is a more common limit. Overviews of navigation systems are available (items S8 and U2). Reviews of channel development for these systems are also available (EM 1110-2-1611 and items H2 and F4). Examples of published reviews for specific systems are as follows:

a. St. Lawrence Seaway (items B12 and D3).

b. Upper Mississippi (L&D) River (item D8).

c. New York State Barge Canal (item H7).

d. Great Lakes (item M3).

e. Lower Cumberland (item D14).

f. Columbia River (item H3).

g. Mississippi and Gulf Coast (item M11).

h. Welland Canal (item 02).

2-7. Vessels

Decisions regarding depth on the lock sills, size of chambers, guide wall layout, and to some extent the type of filling system are influenced by the types of vessels that will use the waterway. For example, recreational traffic uses locks designed for either shallow-draft (barge) or deep-draft (large ship) traffic, but there are conflicting requirements for locks that are to be used by *both* barge tows and large ships--over 75,000 deadweight tons (dwt). Maximum values of length, width, and draft are of particular concern. Larger tows are of concern in that the extent of breaking and making of tows influences decisions regarding general lock operational procedures as well as tie-up and fleeting area design. Reviews of vessel characteristics are available (items G4, S8, and U2) and are to some extent included in discussions regarding lock sizes (items B6 and D6) and vessel equipment (items D13 and H5). The contrast between barges used for the Ohio River and connecting systems (items C2 and M9) and the Columbia River system (item T1) illustrates the effect of commodity type on the commercial carrier design. Detail from these and similar reviews, because of timeliness, requires verification prior to inclusion in the design process.

2-8. Commodities

The economic studies required for lock authorization use tonnage projections that are developed through economic studies of past, present, and future commodity movements. Most engineering impacts of commodity type are resolved by studies of vessel characteristics (paragraph 2-7); certain concerns, such as the dominance of downbound versus upbound loads or the presence of hazardous or otherwise sensitive cargos, may be site-specific operational concerns.

Section III
Transit Time

2-9. Definition

The annual tonnage that can be passed through a project is influenced by

a. Time required for tows to transit the locks (transit time).

b. Number and size of lock chambers.

c. Average tonnage per tow.

d. Number of days per year that the locks can physically operate.

e. Percentage of time that tows are available for lockage.

f. Cost of delays to tows waiting lockage.

Transit time (*a* above), derived from capacity/economic studies, becomes a specific design objective; chamber option (*b* above), similarly derived, is a design constraint not usually altered by the design process; other factors (*c*-*f* above) are system characteristics. Transit time is defined as the total time required for a tow to move into a lock from a waiting point (arrival point), be raised or lowered, and then proceed out of the lock to a position where it will not interfere with any other tow that needs to transit the lock. Transit time includes

a. Time required for a tow to move from an arrival point to the lock chamber.

b. Time to enter the lock chamber.

c. Time to close the gates.

d. Time to raise or lower the lock surface (fill or empty).

e. Time to open the gates.

f. Time for the tow to exit from the chamber.

g. Time required for the tow to reach a clearance point so that another tow moving in the opposite direction can start toward the lock.

h. Time required for break down, locking through, and reassembling a tow that is too large for the lock chamber.

The objective in the overall planning of a lock project (capacity/economic studies) is to establish a value for transit time commensurate with authorization constraints (paragraph 2-2).

2-10. Evaluation

Two of the seven time components listed in paragraph 2-9 (gate operating time and filling and emptying time) are dependent entirely on design of the lock. Approach time, entry time, exit time, and departure time are dependent on pilot skill and towboat capability and on design of approach channels, guide walls, and lock chambers. For a single lockage at modern locks, operation time constitutes only about 25 to 40 percent of the total transit time. The Performance Monitoring System (EP 1105-2-11) is a CE-maintained database established for the purpose of monitoring parameters relative to the economic analysis of navigation locks. Transit time components are available for many existing locks in this database; guidance regarding access, use, and status of the Performance Monitoring System is available in Pamphlet 84-PM-1.

2-11. Chamber Performance

During hydraulic design, meeting the project capacity economic constraint requires reducing the time, termed operation time, required to fill or empty the chamber to a value equal to or less than the value used for project authorization. The within-chamber navigation constraint on rapid filling is termed chamber performance; acceptable chamber performance is normally studied by means of filling-and-emptying operations in small-scale physical hydraulic models as discussed in Chapter 6. Typical observations are as follows:

a. Surface currents and turbulence. Acceptable performance requires that surface turbulence hazardous to small vessels be identified and to the extent possible eliminated.

b. Drift of free tows. The movement of unmoored vessels (from the traffic mix) must be acceptable to navigation and lock operations and not be hazardous to either vessels or structure.

c. Hawser forces. Mooring line stresses required to restrain the vessel from longitudinal and lateral movement must be acceptable to navigation and to structural design. Specific numerical limiting values have been placed on model hawser stresses. The historic development is based on breaking strength of one used 2.5-inch (in.)-diameter manila hawser: a 10,000-pound (lb) loading has been used as a safe nonbreaking value. Many years of prototype observation and model testing have shown that when a lock is designed not to exceed the hawser stresses given in (1)-(3) below as determined in a model, the prototype mooring conditions will be satisfactory for the design vessel as well as for small craft.

(1) *Barge tows*. For various sizes and numbers of barges in any location in the lock chamber, the hawser stress as extrapolated from a model does not exceed 5 tons (2,000-lb tons).

(2) *Single vessels--ships up to 50,000 tons*. Hawser stress does not exceed 10 tons.

(3) *Single vessels greater than 50,000 tons*. Hawser stress for larger vessels is allowed to exceed 10 tons, since these vessels require more mooring lines than either barge flotillas or the smaller single vessels. Model tests indicate that if a lock-filling system is designed to meet guidance (1) and (2) above, hawser stress (extrapolated from the model) will not exceed approximately 25 tons for vessels up to 170,000 dwt.

Existing chamber feature design is based on this guidance; more severe or alternate requirements may require substantially different concepts in hydraulic feature design.

2-12. Application

Time saved during lockage is economically significant at most projects and becomes more important when growth of traffic begins to cause prolonged queuing delays. Decreased operation time causes reduced total transit time unless surges and currents in the approaches adversely affect entry and exit conditions. By means of model and prototype tests (see Chapter 6) and design studies, filling-and-emptying systems have been developed that achieve operation times near 8 minutes (min). Both severe decreases and severe increases (unless accomplished by using long valve opening times) in operation time require the development of new systems. For existing systems, operation-time benefit, usually presented as a per minute value, is used to evaluate design modifications that may vary operation time between 8 and 10 min for low-lift and 8 and 12 min for high-lift projects.

Section IV
Chamber Alternatives

2-13. General

The number and size of chambers are based primarily on capacity studies with system standardization and economics as major constraints (items B6, D6, and U2). Chamber alternatives are briefly discussed in the following paragraphs; guidance and data relating to navigation facility for both single-chamber and multichamber projects are included in EM 1110-2-1611.

2-14. Number of Parallel Chambers

In the initial development stage of a waterway transportation system, common practice has been to provide one chamber at each project; then, as traffic has increased, additional chambers have been added. For a new project on a developed waterway, where traffic patterns are well-established and continued growth is assured, two or more chambers may be initially justified on an economic basis. A need for continuous operation may lead to double chambers since, in the event of outage of one lock, essential traffic can be handled on a priority basis. In redevelopment of the Ohio River system, a minimum of two locks have been provided at each of 19 locations.

2-15. Chamber Dimensions

Chamber dimensions are influenced by sizes of existing barges and towing equipment; conversely, existing barges and towing equipment have been influenced by sizes of existing chambers. Most of the locks built in the United States since 1950 have usable horizontal dimensions of 84 by 600 ft, 110 by 600 ft, and 110 by 1,200 ft. A number of locks with other sizes have been built: 56 by 400 ft; 75-ft width with lengths varying from 400 to 1,275 ft; 80 by 800 ft; 82 by 450 ft; and 84-ft width with lengths of 400, 720, 800, and 1,200 ft. Recent western locks (along the Columbia and Snake Rivers) have usable dimensions of 86 by 675 ft. Additional lock chamber length is provided for clearance between the tow and the gates so that gate-to-gate chamber length is greater than usable length. Smaller chambers are used on waterways where the traffic is exclusively recreational boats and small craft.

2-16. Chamber Types

The majority of CE lock chambers are for commercial tows with drafts equal to or less than 14 ft, 9 ft being the most common. The design guidance in this manual is derived from studies relating to these chambers. Certain waterways require chambers that are unusual but that provide supplemental operational experience to recent CE lock design, testing, and operational data; these chambers are not evaluated herein. The following listing includes five such chambers.

a. Ship locks. Chambers used by oceangoing ships are included in the listing given in Appendix B. Lower sill submergence values for these locks are given in Table 2-2.

Table 2-2
Lower Sill Submergence Values

Navigation System	Lock Name	Normal Lower Sill Submergence, ft
Gulf Intracoastal Waterway	Inner Harbor	31
Lake Washington Ship Canal	Chittendon (Large)	29
	Chittendon (Small)	16
St. Marys River, South Canal	MacArthur	31
	Poe	32
St. Marys River, North Canal	Davis	23.1
	Sabin	23.1

b. Great Lakes shipping. Commercial vessels are normally individually powered and relatively (for ships) shallow draft. For example, ships with drafts in the range of 16 to 25 ft and sizes from 15,000 to 30,000 dwt are accommodated on the Great Lakes. Lock entry and exit requirements for these types of vessels differ from either barge tow or oceangoing-ship needs (item D3).

c. Deep drafts. Chambers designed for both large tows and deep-draft ships (draft 25 ft or greater) need special entry and exit features. Sills are located sufficiently deep to accommodate squat, trim, and sinkage. Towing winches and other assisting mechanisms are used. Ships greater than 100,000 dwt are assisted into the lock chamber. A side-port design has been studied (item 77) for the New Ship Lock, Mississippi River-Gulf Outlet and the Inner Harbor Navigation Canal replacement lock (item 102). These test results are for a 150- by 1,200-ft lock; maximum normal head = 18.4 ft; vessel draft = 45 ft (ships) and 9 and 12 ft (tows), and for a 110- by 1,200-ft lock: maximum normal head = 19.8 ft; vessel draft = 36 ft (ships) and 9 and 11 ft (tows), respectively. Deep-draft navigation projects are discussed in EM 1110-2-1613.

d. Recreational locks. Locks having usable lengths less than 400 ft are listed in Appendix B and are considered recreational locks herein. Limited small-tow and special commercial vessels also use many of these locks. Small locks (and recreational vessels) are discussed in the National Waterway Study (item U2) and published literature (item G4, for example).

e. Repair facilities. Dry docks (items A5, B8, and K4, for example) and other similar chambers have mechanical and structural elements comparable to lock chambers. Expeditious closure and sealing during unwatering are major design requirements.

Section V
Foundation and Structure Concerns

2-17. Hydraulic Loading

The foundation and structural features establish the stability and durability of the structure. Hydraulic loadings during construction, completion, and operation are a major concern. These loadings, because of magnitude and spatial and temporal variations, are complex and require particularly thorough study and interdisciplinary coordination. For example, static conditions at chamber full as compared to chamber empty are recurring changes in loadings that influence deflections and stability parameters for the foundation, walls, and sills of the chamber. Known extreme conditions, such as exist during inspections, in addition to filling or emptying, cause recurring changes in differential-pressure loading across structural elements. Unusual extreme conditions, such as exist during unusual valve and emergency operation, are also of concern. For high-lift locks, the hydraulic design includes high-velocity flow so that passageways may require, for example, special treatment to avoid surface cavitation and abrasion damage. The need for relief of pore pressure within the foundation or within monolith cracks and joints is dependent on hydraulic conditions. These loadings are discussed in EM 1110-2-2602 and other structural presentations (item U1, volume II, for example).

2-18. Chamber Structure

Concrete lock structures have been generally reliable and desirable based on engineering and economic considerations. On waterways where traffic is not heavy and at locations on waterways where the lift is very low, sheet-pile locks or possibly earth wall locks have sometimes been used.

a. Concrete lock structures. The most common lock structure uses concrete gravity walls founded on either piling or rock (EM 1110-2-2002 and EM 1110-2-2602). Culverts, valve shafts, access passageways, and numerous other special-purpose cavities are contained within the wall. Intakes and outlets may also be formed in the wall although at many locks these are located well outside the actual lock chamber. More unusual concrete lock structures are of the buttress-wall type or have rock walls with anchored concrete facing. For these thin-wall designs, the filling-and-emptying system components are essentially separated from the walls. For the two parallel chambers shown in Figure 2-1, a gravity-wall low-lift design, the intermediate wall serves both chambers. A high-lift lock with concrete gravity walls is shown in Figure 2-2. In Figures 2-3 and 2-4 are high-lift designs with thinner concrete walls anchored to natural rock.

b. Sheet-pile structures. Very-low-lift projects permit structures other than concrete to be considered for design; masonry, earth embankment, and sheet-pile structures have been used. Sheet-pile lock walls are of two basic types: sheet-pile cells and M-Z sheet piling supported laterally by wales and tie rods. Sheet-pile locks are filled and emptied by sector gates or other very-low-lift systems. Gate bay monoliths are normally concrete. The low initial cost for sheet-pile structures is offset by short useful life and high maintenance. Recent use has been at sites where temporary (or emergency) locks were needed. A sheet-pile cellular lock is shown in Figure 2-5. Sheet-pile structures are commonly used for cofferdam functions and are discussed in ER 1110-2-2901 and in published literature (items C7 and S10).

c. Earth embankments. Earth embankments with concrete gate bays are considered for low-use, very-low-lift projects. For example, these locks are included in the Gulf Intracoastal Waterway to prevent saltwater intrusion and to prevent adverse or dangerous currents during abnormal tide conditions. The walls are essentially levees, with riprap protection on the side slopes. Riprap protects the bottom of the

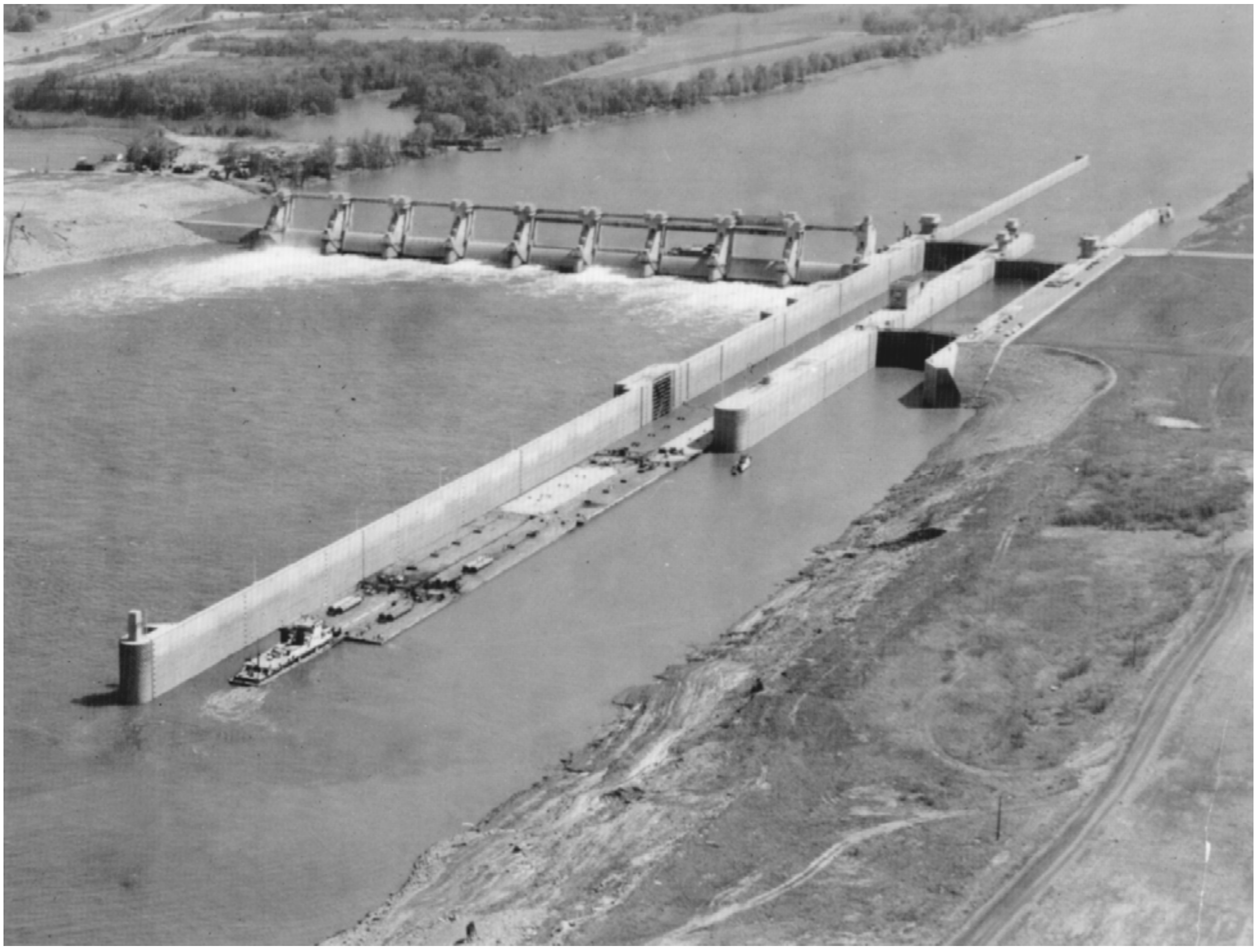


Figure 2-1. Parallel locks with gravity walls. Willow Island Locks, Ohio River, with design lift = 20 ft

channel (the chamber) from scour due to towboat propellers. Tows moor to timber guide walls during lockage. A lock of this type equipped with sector gates is shown in Figure 2-6. Geotechnical guidance concerning embankment (levees, for example) design is applicable.

d. Wall designs for navigation projects are presented in item 98 for tall, flexible anchored tieback walls and in item 99 for tall, stiff tieback walls.

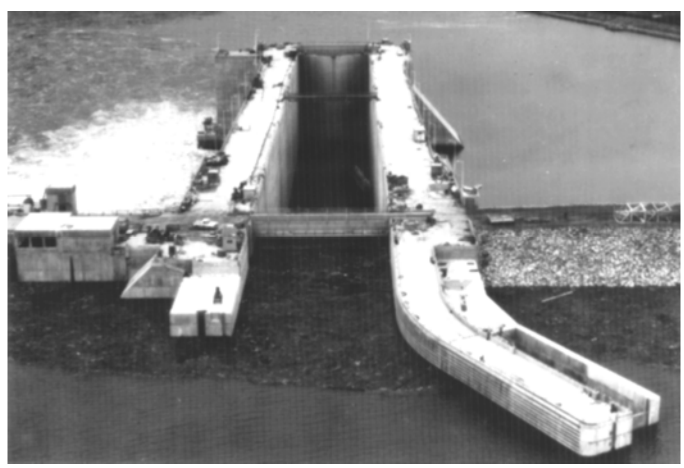


Figure 2-2. Lock with gravity walls. Lower Granite Locks, Snake River, with design lift = 100 ft

2-19. Guide and Guard Walls

Navigation needs (see EM 1110-2-1611 and EM 1110-2-1613) require the proper location and alignment of guide and guard walls and are resolved by means of general river hydraulic models; project purposes in addition to navigation are normally also of concern. These studies, which require

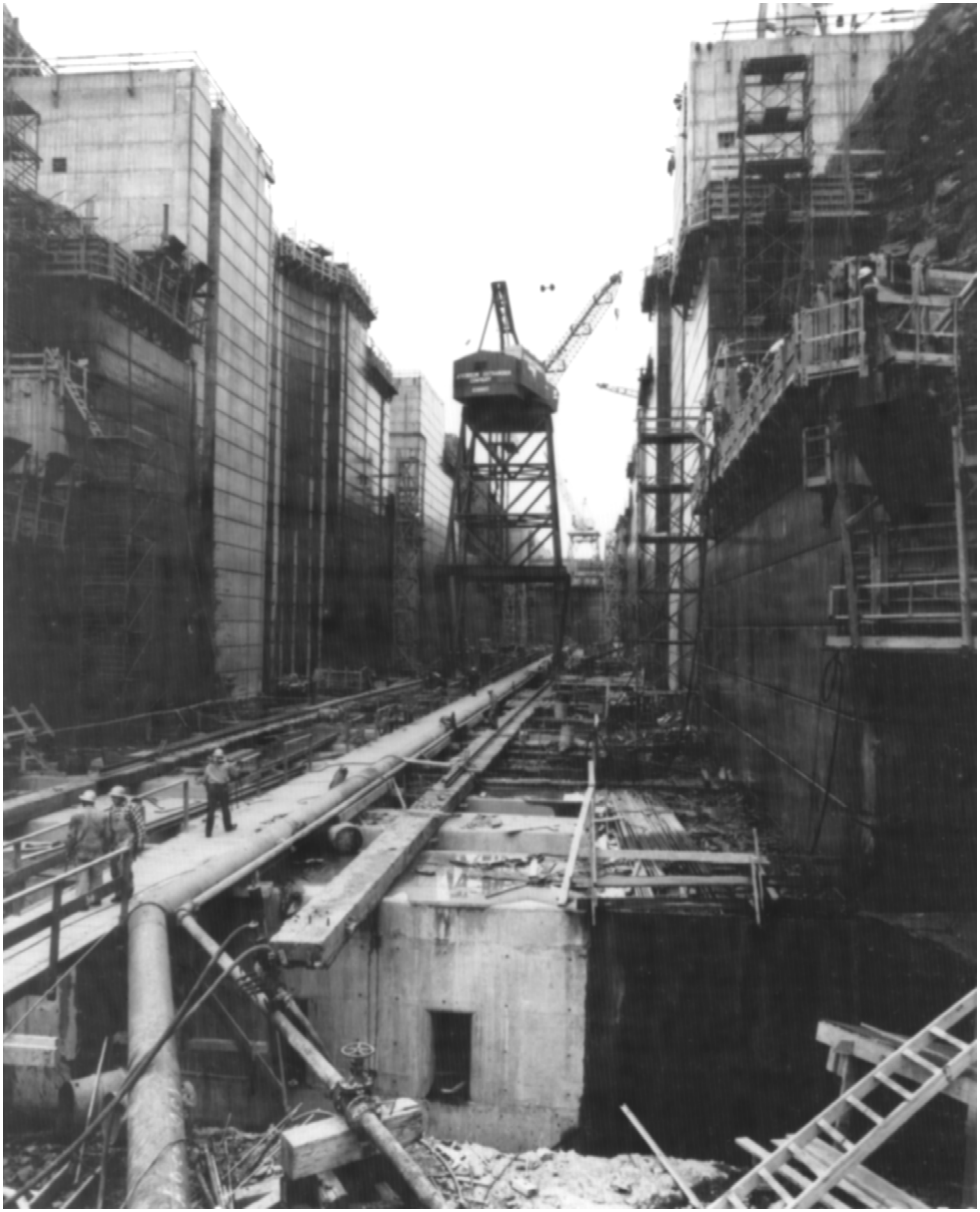


Figure 2-3. Lock with thin walls. The Dalles Lock, Columbia River, with design lift = 88 ft (under construction)

Figure 2-4. Lock with thin walls. Bay Springs Lock, Tennessee-Tombigbee Waterway, with maximum design lift = 92 ft

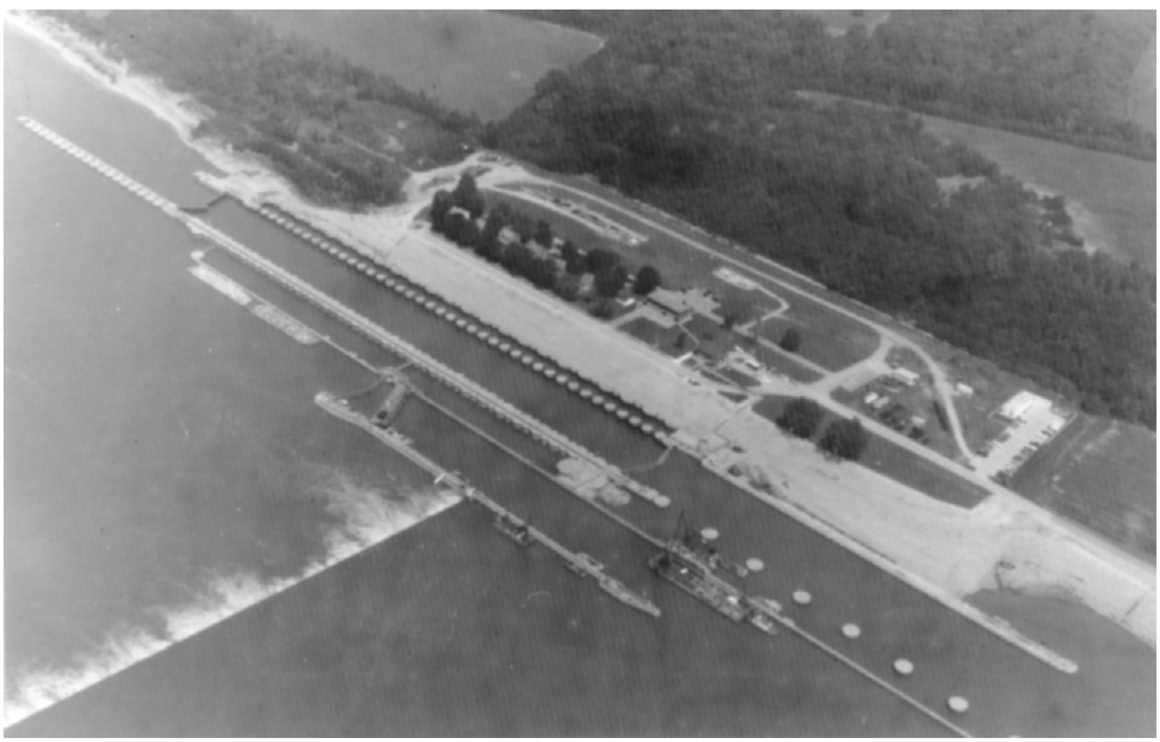


Figure 2-5. Temporary lock with cellular sheet pile. Lock and Dam No. 52, Ohio River, with design lift = 12 ft

Figure 2-6. Earth embankment with concrete gate bays and sector gates. Vermilion Lock, Gulf Intracoastal Waterway, with design lift = 3 ft (under construction, 1984)

preliminary estimates of lockage inflow and outflow hydrographs, also determine the impact on navigation regarding type of wall (i.e., floating, ported, or solid). When navigation needs are resolved, then construction and maintenance economics determine the type of wall actually used at a specific project. Similarly, the heights of guide, guard, and lock walls are influenced by operational as well as navigational needs during high river stages. The following are examples of structural types:

a. Concrete gravity walls.

b. Concrete walls supported by concrete-filled sheet pile cells, or bearing piles driven within granular sheet pile cells.

c. Timber walls supported by pile clusters.

d. Moored floating caisson structures.

Timber structures are normally limited to very-low-lift locks preferably where traffic consists of smaller tows.

2-20. Other Structures

Navigation conditions may require mooring facilities, fleeting areas, and other aides. Examples of structures currently in use are pile dikes (Columbia River, item D11), pile cluster dolphins (item E5), and caissons such as those used for barge docks (item H4). Energy absorption required due to barge impact is a design concern as noted in the reference items; fendering (item R6, for example) structural design guidance is included in EM 1110-2-2703.

Chapter 3
Hydraulic Features

Section I
Filling and Emptying

3-1. Project Type

Hydraulic design addresses all features relating to filling and emptying the lock chamber. Decisions based on specific authorization requirements (constraints, Table 2-1) narrow hydraulic options.

a. Maximum navigation lift. This value determines design type as previously shown in Figure 1-2. For maximum lift near 10 ft, conservative design practice is to use a low-lift rather than a very-low-lift design type. Similarly, for maximum lift near 40 ft, conservative practice is to use a high-lift rather than a low-lift design type. For low-usage locks or for projects with significant variation in lift, economic considerations warrant less conservative design. Lifts greater than 100 ft exceed CE operating experience.

b. Chamber navigation constraints. Project identification studies (Chapter 2) identify four constraints relative to chambering:

(1) Vessel characteristics (types, drafts).

(2) Clear chamber width.

(3) Usable chamber length.

(4) Operation time (economics).

These constraints, compared with existing lock data (Appendix B, EP 1105-2-11, item U2, etc.), establish design status compared to CE operating experience. Model- and prototype-tested geometries (see Appendix C and CORPS computer program database H5300) establish status compared to CE verifiable laboratory and field experience. An overview of operating conditions for five specific CE design types is provided in Table 3-1; traffic is different mixes of commercial tows and recreational vessels.

3-2. Design Type

The following designations for type of lock filling systems are used throughout this EM.

LC = loop culvert(s)
LCSG = loop culvert(s) and sector gate
SG = sector gates
SP = side ports
SPF = side ports with flume
MP = multiport system
BL1 = centered lateral-manifolds; one culvert
BL2 = centered lateral-manifolds; two culverts
BLC = centered lateral-manifolds; high-lift modified
SBLC = split lateral-manifolds
OC = longitudinal centered and ported culvert

HB4 = horizontal flow divider; 4 longitudinal manifolds
HB8 = horizontal flow divider; 8 longitudinal manifolds
VB4 = vertical flow divider; 4 longitudinal manifolds
VB8 = vertical flow divider; 8 longitudinal manifolds

New projects are compared in terms of lift, chamber geometry, and navigation constraints with existing designs listed in Table 3-1; however, site-specific conditions may require a different design. For each lift category, the design type is judged as matching, modified, or new as follows.

a. Very-low-lifts (0-10 ft). For matching *sector gate* (SG) designs, sill and floor elevations and gate operation schedules are from specific model-tested designs (Appendix C). Modified designs to accommodate small chamber-dimension changes (when geometric similarity is essentially retained) can be reliably determined from existing designs. New designs (due to unusual or more stringent navigation constraints, untested end-filling devices, or major changes in chamber dimensions) require laboratory testing and evaluation to determine chamber performance. Low-lift design types (*b* below) are conservative alternatives for very-low-lift projects.

b. Low-lifts (10-30/40 ft). For matching or modified *side-port* (SP) designs, sill and floor elevations and valve schedules are from design criteria (see Appendix D). For two-culvert projects the choice of lateral culverts (BL2) as compared to side ports has been an economic consideration (structural cost, chamber maintenance, and excavation costs are major factors); the side-port system is least-cost for the ongoing Gallipolis new main lock (110 by 1,200 ft, 23-ft normal lift). Unfortunately, existing BL2 designs have unfavorable single-culvert operating characteristics which tend to preclude their use for new projects (paragraph 3-3). For one-culvert projects (auxiliary or alternative locks) a lateral design (BL1) is used. Because of the broad extent of testing and experience with these types of locks, a need for a new design is considered unlikely. However, were a site-specific situation to require more rigid requirements on chamber performance or to require alternate culvert geometries (due to an unusual site-specific constraint, for example) then an alternative design could be justified. The alternate design would probably be similar in concept to the existing high-lift designs and would require extensive laboratory testing and evaluation to determine chamber performance (item 74, for example).

c. High-lifts (30/40-100 ft). For matching balanced flow designs for both four manifolds (HB4) and eight manifolds (HB8), sill and floor elevations and valve schedules are from design criteria (see Appendix E). Matching designs must agree in detail; that is, in addition to chamber dimensions, ports, baffles, sills, etc., are to be sized and shaped according to either HB4 or HB8 existing details. The complete culvert-to-chamber (crossover culvert) system must also match in geometric detail. Any change constitutes a modified design which, as for a new high-lift design, requires laboratory testing and evaluation in terms of chamber performance and of reliability and durability of the total design.

3-3. Lateral Culverts

Concepts similar to the BL2 design have been tested and are in operation at numerous projects. Unlike side-port designs, inconsistency in geometric detail for lateral-culvert designs (note BLC, BL1, BL2, and SBLC in Appendix B, Table B-1) precludes the development of broad design criteria. The following factors have caused lateral culverts (including the BL2 design) to be viewed as less acceptable than side-port systems (for low-lift) or longitudinal systems (for high-lift).

a. Slow valving. Four-minute or greater valve times have been used extensively; rapid operation requires more rapid valving.

Table 3-1
Experience with Recommended Designs (Geometries Constructed Since 1950)

Type	No. of Similar Locks	Chamber Clear Width ft	Usable Length ft
	Very-Low-Lift Designs (Maximum Lift[a] < 10 ft)		
Sector gate (SG)	1	86	600
	1	84	600
	1	75	1,200
	1	75	1,150
	1	75	800
	1	56	800
	1	45	800
	7	30	90
	7	30	90
Temporary (SPF)	2	110	1,200
Total	**23**		
	Low-Lift Designs (Maximum Lift[b] < 30/40 ft)		
Side port (SP)	10	110	1,200
	67	110	600
	10	84	600
	22	56	360
Laterals (BL2)	7	110	1,200
	6	110	600
	2	84	720
Laterals (BL1)	7	110	600
Total	**131**		
	High-Lift Designs (Maximum Lift > 40 ft); Longitudinal Manifolds		
4-manifold (HB4)	2	110	600
8-manifold (HB8)	1[c]	86	675
Total	**3**		

Notes:
[a] Lifts greater than 10 ft are experienced at many of these projects.
[b] Lift experienced during actual operations extends up to about 37 ft; commercial traffic is primarily 9-ft-draft tows.
[c] Lower Granite Lock became operational in 1975; tows up to 14-ft draft use this project.

b. Rigid valve times. The valve time established during testing (*a* above) cannot be reduced without a significant deterioration in chamber performance.

c. Harmonic oscillations. Natural oscillations of the chamber water surface appear (item 71) to be excessively stimulated, leading to large hawser forces.

d. Synchronous valving. Any valving other than two-valve fully synchronized valving causes chamber performance to severely deteriorate in terms of oscillations (*c* above) and free tow movement.

3-4. Features

The design considers each of the following six compatible systems.

a. Intake system. Conditions in the upper approach channel are concurrently resolved by hydraulic design, navigation facility and safety, operations, and other multipurpose or multidiscipline concerns. Guide and guard walls are specific items of major concern to navigation. Intake manifold, trash rack, and transition conduit are hydraulic design features.

b. Filling valve system. Valve design is a hydraulic concern as are the valve well, bulkheads, air vent, and flow-passage designs. Hydraulic loadings required for structural and mechanical detail design are required in addition to flow parameters needed solely for lock filling and emptying.

c. Culvert-to-chamber system. The culvert, manifold(s), ports, and transitions are hydraulic design features. Chamber navigation conditions (expressed as turbulence, hawser stress, and vessel drift) are highly influenced by culvert-to-chamber geometry.

d. Chamber system. Features making up the lock chamber, such as the upper and lower gates and navigation and operation aids, are concurrently resolved by hydraulic design, navigation facility and safety, operations, and other design functions. The lock sill and chamber floor elevations, manifold recesses, and baffles are hydraulic features.

e. Emptying valve system. The listing of features is the same as for the filling valve (see *b* above).

f. Outlet system. Conditions within the lower approach channel are, as for the upper approach, multipurpose and multidiscipline concerns. The transition conduit and outlet manifold and baffles and energy dissipator are hydraulic design features.

The features within each system are modified during design for each site-specific lock. The systems for each basic design type (very-low-lift, low-lift, and high-lift locks) are distinctly different; and within each design type, certain features are varied when necessary to resolve project constraints.

3-5. Recent Designs

Projects of each of the seven design types listed in Table 3-1 have recently been designed. Each of the types and the corresponding feature locations (paragraph 3-4) are shown in Plates 3-1 through 3-8 as summarized in Table 3-2. The vertically split balanced flow system was evaluated for the New Bonneville lock, item 89, for both 4 and 8 manifold systems.

Section II
Appurtenant Concerns

3-6. General

Constraints, such as those listed previously in Table 2-1, result in design features that are resolved concurrently with the design of the basic filling-and-emptying system. Constraints and resulting features vary on a project-to-project basis; specific needs leading to common appurtenant concerns are described in the following paragraphs with design detail for major items included in Chapter 7.

Table 3-2
Design Types and Example Project Locations

Plate No.	Design Type Symbol	Design Type	Project Lock	Key Reference Studies Item, Appendix A
3-1	SG	Sector Gate	Vermilion; Gulf Intracoastal Waterway	20: WES TM 2-309 36: WES TR 2-556
3-3	SP	Side Port	Willow Island Main	51: WES TR 2-678
			Lock; Ohio River	57: WES TR 2-713
3-4	SP	Side Port	Ozark; Arkansas River	61: WES TR 2-743 72: WES MP H-75-7
3-5	BL2	Bottom Lateral (2 culverts)	Belleville Main Lock; Ohio River	46: STP No. 66 43: STP No. 74
3-6	BL1	Bottom Lateral (1 culvert)	Willow Island Auxiliary; Ohio River	17: STP No. 52 23: STP No. 59
3-7	VB4	Vertically Split Balanced Flow (4 Manifolds)	Bay Springs; Tenn-Tombigbee Waterway	78: WES TR H-78-19
3-8	VB8	Vertically Split Balanced Flow (8 manifolds)	Lower Granite; Snake River	79: BHL TR No. 126-1

3-7. Navigation Aids

These devices are recessed into the lock wall, flush-mounted on the wall face, or located on the upper surface of the wall. The objective is to provide assistance to navigation (for all anticipated vessel types) commensurate with clear chamber width and minimum maintenance. Examples are floating mooring bitts, ladders, line hooks, check posts, ring bolts, and staff gages.

3-8. Surge Reduction

Currents and water-surface elevations in the upper and lower approaches to the chamber are major concerns to navigation. For canals and smaller waterways these surge effects, during both filling-and-emptying, are severe constraints to hydraulic design (EM 1110-2-1606). Coordination involving both navigation (EM 1110-2- 1611) and hydraulic studies is needed in order to determine locations of intakes and outlets, alignment and types of guide and guard walls, and geometries of the approach canals such that surge effects are acceptable to navigation. In the event that these effects cannot be resolved at acceptable costs, then the hydraulic filling or emptying operation times may be extended either by valving or by using a less efficient hydraulic system. Alternatives to slowing the systems, such as using storage basins (surge reduction basins) adjacent to intakes or outlets, are noted in Chapter 5.

3-9. Impact Barriers

Protection of the upper or lower gates from collision by navigation vessels is the primary objective. Wood, rubber, and metal fenders and bumpers are used on gates, on key locations along guide and guard walls, and on the exposed surfaces of the recessed gates as inexpensive and repairable energy absorbers. Protective equipment is discussed in EM 1110-2-2602.

3-10. Water Saving

Environmental or economic factors may require design features directed toward minimizing the quantity of water transferred during lockage. The problem is addressed at three stages in project life:

a. Preliminary studies for the selection of number of chambers and chamber sizes may result in including either a small hydraulic lock or a mechanical lift for smaller (normally recreational) vessels.

b. During design, consideration of either adding an extra set of lower gates (to permit fractional chamber operation) or including a water-saving chamber (to permit saving a fraction of the water normally lost during emptying for use during filling) may be warranted. Neither has been feasible for CE locks. Staged-lifts (item 07) normally use less water than single-lift locks at an expense in operating costs and transit time.

c. During operation, lockage procedures directed toward reducing the number of operations required for passing a mix of vessel sizes result in water-savings benefits.

3-11. Dewatering

Maintenance is the primary objective. Scheduled inspections require full and partial dewatering of the lock chamber and most flow passages. Provisions to facilitate pumping for elevations below lower pool should be provided. Closure is during static conditions and is normally accomplished by means of bulkheads. Canal bulkheads above and below the upper and lower, respectively, chamber gates are used to isolate the chamber gates. Culvert bulkheads above and below each valve are used to isolate the culvert valves. Hydraulic design emphasis, particularly for high-lift locks, is to shape and locate the culvert bulkhead slots for minimum disturbance to the flow with no cavitation at the boundary while satisfying sealing and structural requirements during closure.

3-12. Emergency Closure

Risk associated with failure of the upper miter gates may justify the installation of devices for closure of the chamber during free-surface flow directly over the upper sill. Various closure devices are available as described in EM 1110-2-2703 and EM 1110-2-2602. For a highly developed waterway, such as areas along the middle reaches of the Ohio River, significant monetary losses and other hazards could result from unrestricted flow. The three principal sources of loss are:

a. Loss of pool upstream from the lock.

b. Possible flood damage downstream from the lock.

c. Loss to shipping, recreation, and other project purposes on both pools, particularly in the upstream pool.

The high-lift locks and dams along the Columbia and Snake Rivers in Washington and Oregon provide a contrast to the Ohio River emergency situation. These dams create relatively large deep reservoirs that are used to produce hydropower. Free flow through a lock at one of these projects does not constitute a major portion of the total riverflow and the loss of reservoir storage results primarily in a loss of power production.

3-13. Debris Control

Material that drifts along waterways includes sediment, damaged barges, timber, ice floes, etc. Chamber siting and guide and guard wall design (see EM 1110-2-1611) influence the extent to which waterway debris tends to enter the upper approach. These materials are of concern to navigation; valve, gate, and flow passage operation; and general maintenance of chamber and approaches.

Primary hydraulic concerns are:

a. Flow patterns and operational procedures directed toward flushing surface (floating) material over the upper sill, through the lock chamber, and out of the lower approach.

b. Trash bars and trashracks at culvert intakes designed for exclusion of submerged materials from the filling-and-emptying system.

c. Selection and design of the gates (see EM 1110-2-2703) and sills for reliable operation in the presence of both surface and submerged debris and for maintenance removal of unusual materials.

d. Identification of locations along the flow passage boundaries and the chamber floor at which long-term accumulations, physical damage, and other major inspection and maintenance concerns exist.

3-14. Ice Control

Recent interest in year-round navigation has led to specialized studies of winter lockage problems. The interest is directed toward navigation problems in general and includes lock design and maintenance techniques. These are reviewed in Chapter 7 and specific guidance is included in EM 1110-2-1612.

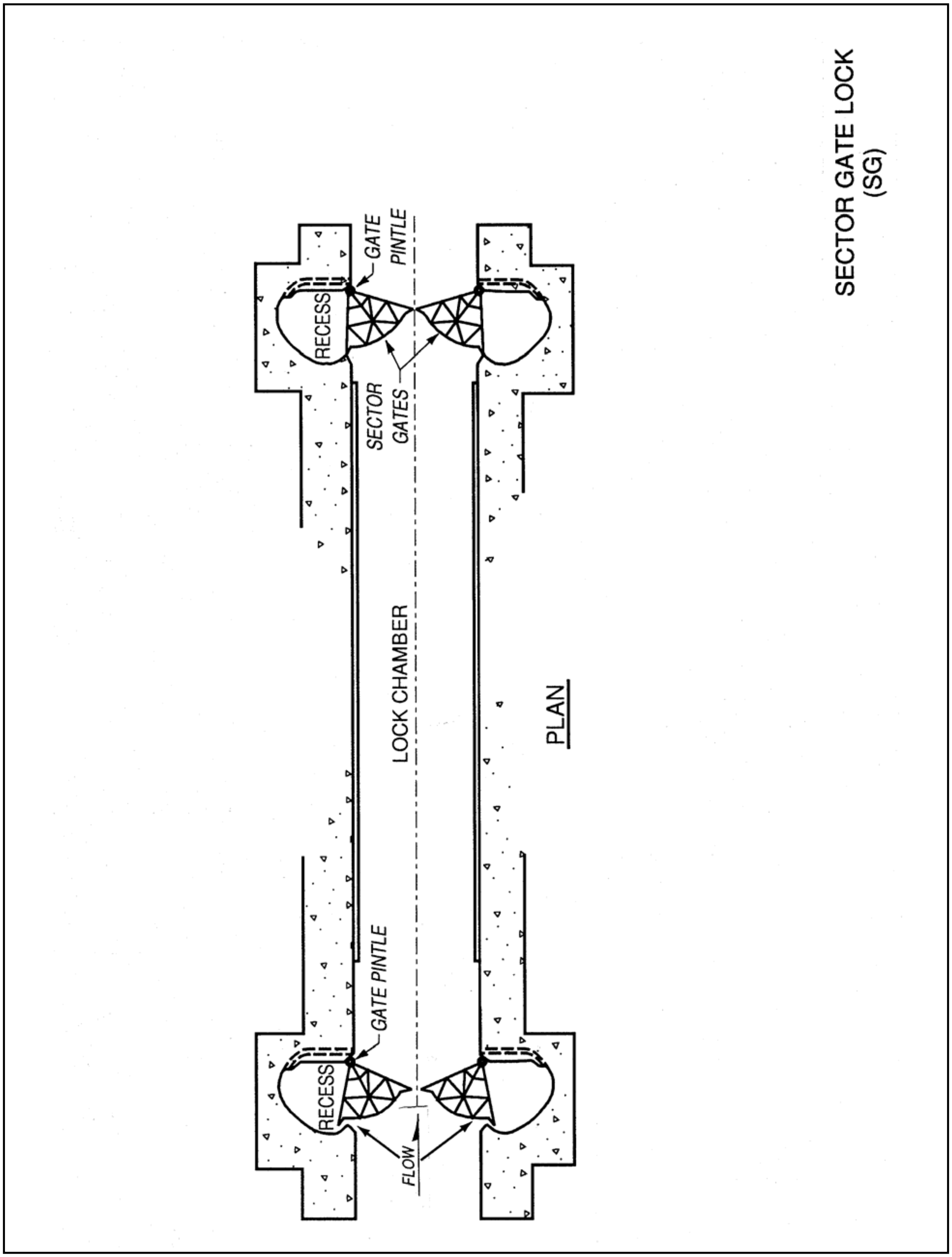

SECTOR GATE LOCK
(SG)
PLAN
LOCK CHAMBER
RECESS
GATE
PINTLE
SECTOR
GATES
RECESS
GATE PINTLE
FLOW

Plate 3-1

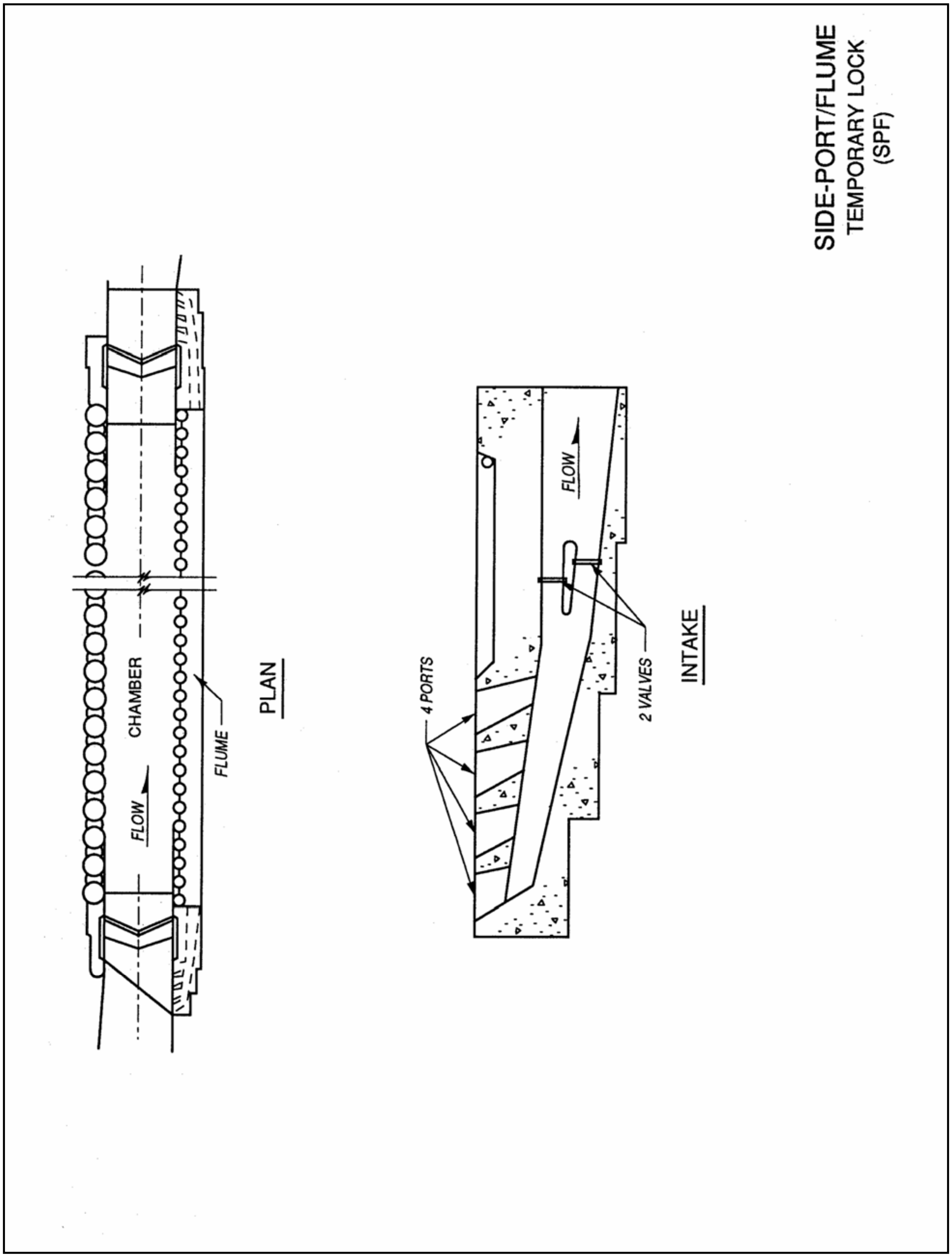
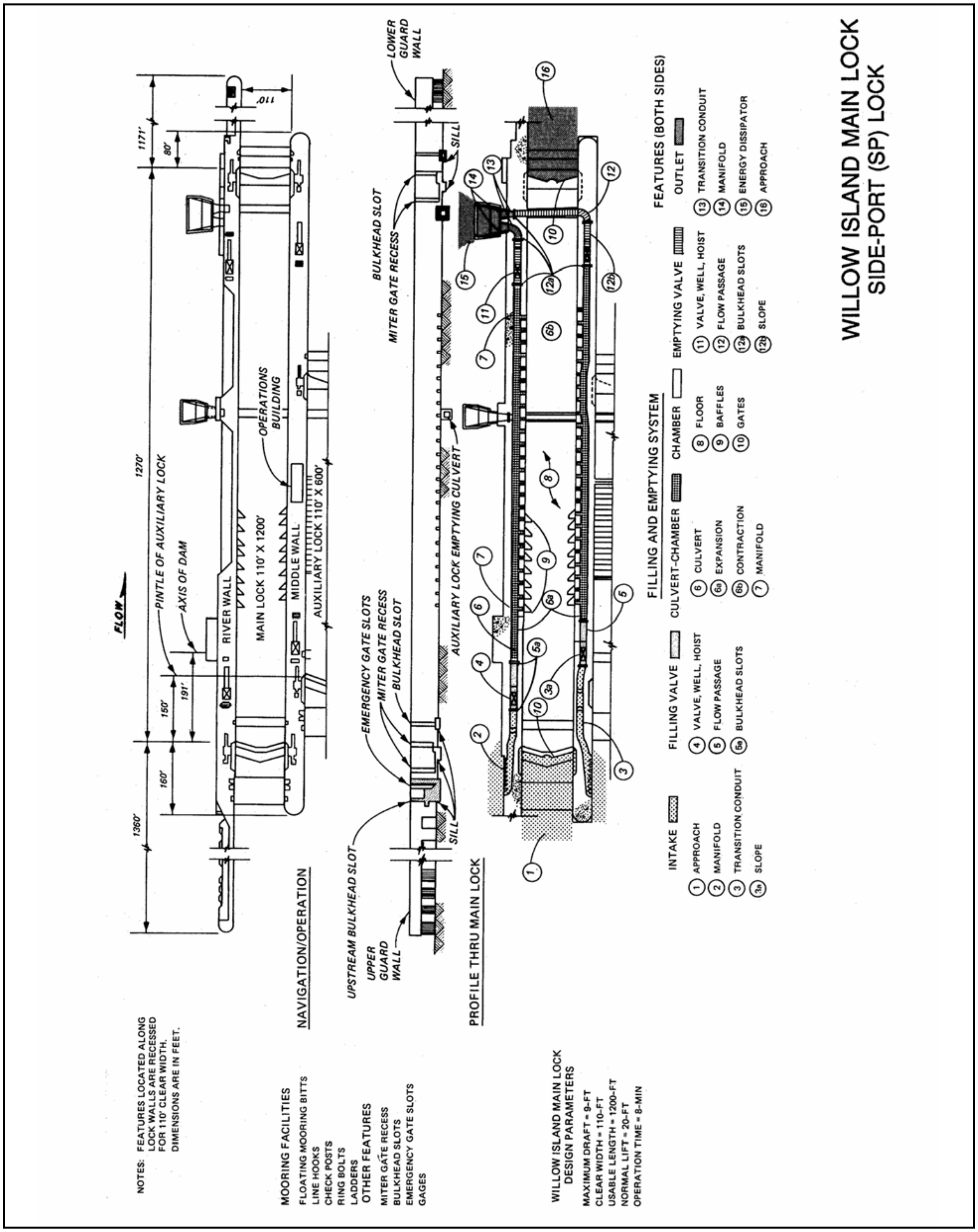

SIDE-PORT/FLUME
TEMPORARY LOCK
(SPF)
CHAMBER
FLOW
FLUME
PLAN
4 PORTS
FLOW
2 VALVES
INTAKE

Plate 3-2


WILLOW ISLAND MAIN LOCK
SIDE-PORT (SP) LOCK
NOTES: FEATURES LOCATED ALONG LOCK WALLS ARE RECESSED FOR 110' CLEAR WIDTH. DIMENSIONS ARE IN FEET.
NAVIGATION/OPERATION
PROFILE THRU MAIN LOCK
FLOW
PINTLE OF AUXILIARY LOCK
AXIS OF DAM
RIVER WALL
MAIN LOCK 110' X 1200'
MIDDLE WALL
AUXILIARY LOCK 110' X 600'
OPERATIONS BUILDING
BULKHEAD SLOT
MITER GATE RECESS
EMERGENCY GATE SLOTS
UPSTREAM BULKHEAD SLOT
UPPER GUARD WALL
LOWER GUARD WALL
SILL
AUXILIARY LOCK EMPTYING CULVERT
1360'
160'
150'
191'
1270'
171'
80'
110'
MOORING FACILITIES
FLOATING MOORING BITTS
LINE HOOKS
CHECK POSTS
RING BOLTS
LADDERS
OTHER FEATURES
MITER GATE RECESS
BULKHEAD SLOTS
EMERGENCY GATE SLOTS
GAGES
WILLOW ISLAND MAIN LOCK DESIGN PARAMETERS
MAXIMUM DRAFT = 9-FT
CLEAR WIDTH = 110-FT
USABLE LENGTH = 1200-FT
NORMAL LIFT = 20-FT
OPERATION TIME = 8-MIN
FILLING AND EMPTYING SYSTEM
INTAKE
1 APPROACH
2 MANIFOLD
3 TRANSITION CONDUIT
3a SLOPE
FILLING VALVE
4 VALVE, WELL, HOIST
5 FLOW PASSAGE
5a BULKHEAD SLOTS
CULVERT-CHAMBER
6 CULVERT
6a EXPANSION
6b CONTRACTION
7 MANIFOLD
CHAMBER
8 FLOOR
9 BAFFLES
10 GATES
EMPTYING VALVE
11 VALVE, WELL, HOIST
12 FLOW PASSAGE
12a BULKHEAD SLOTS
12b SLOPE
OUTLET
13 TRANSITION CONDUIT
14 MANIFOLD
15 ENERGY DISSIPATOR
16 APPROACH
FEATURES (BOTH SIDES)

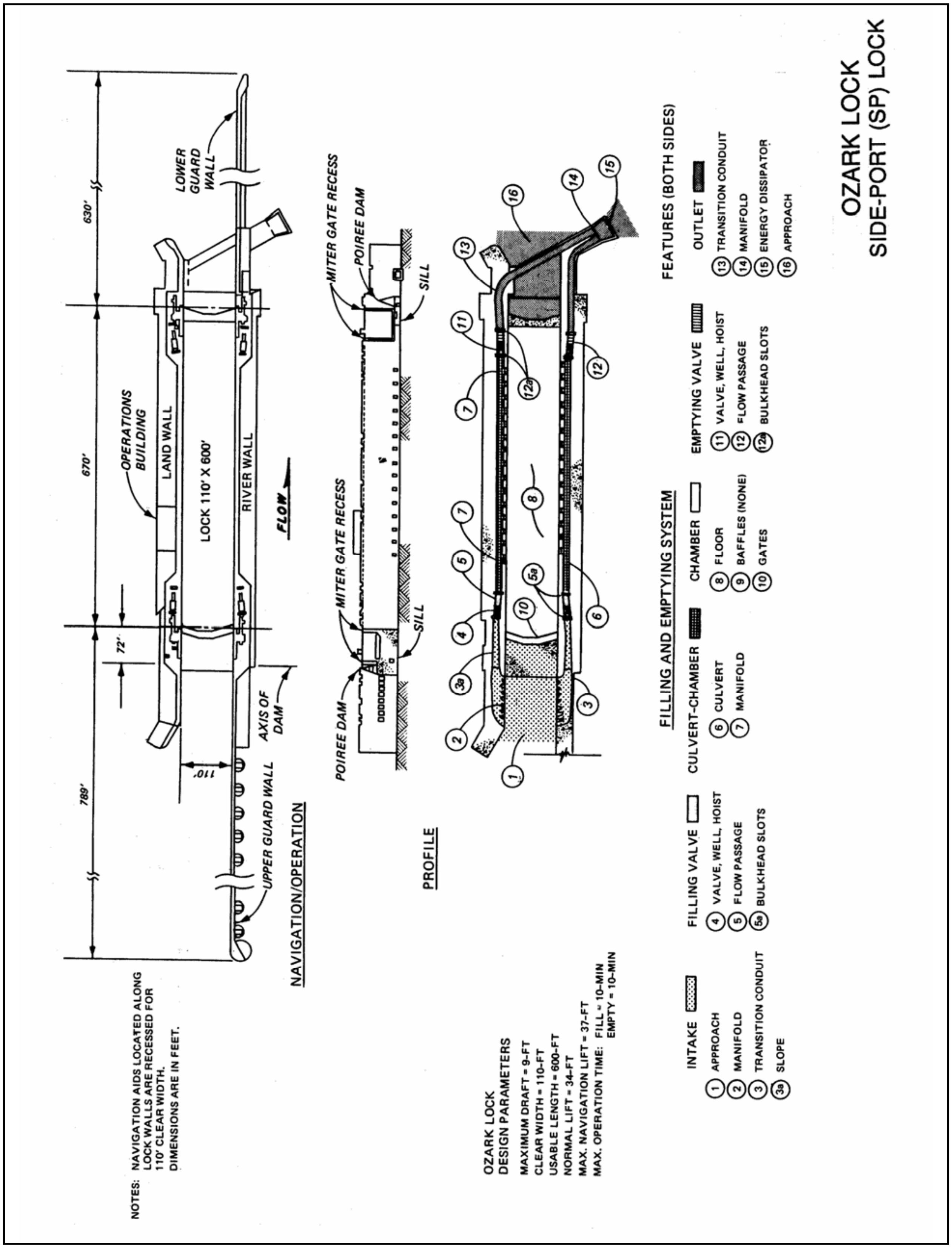
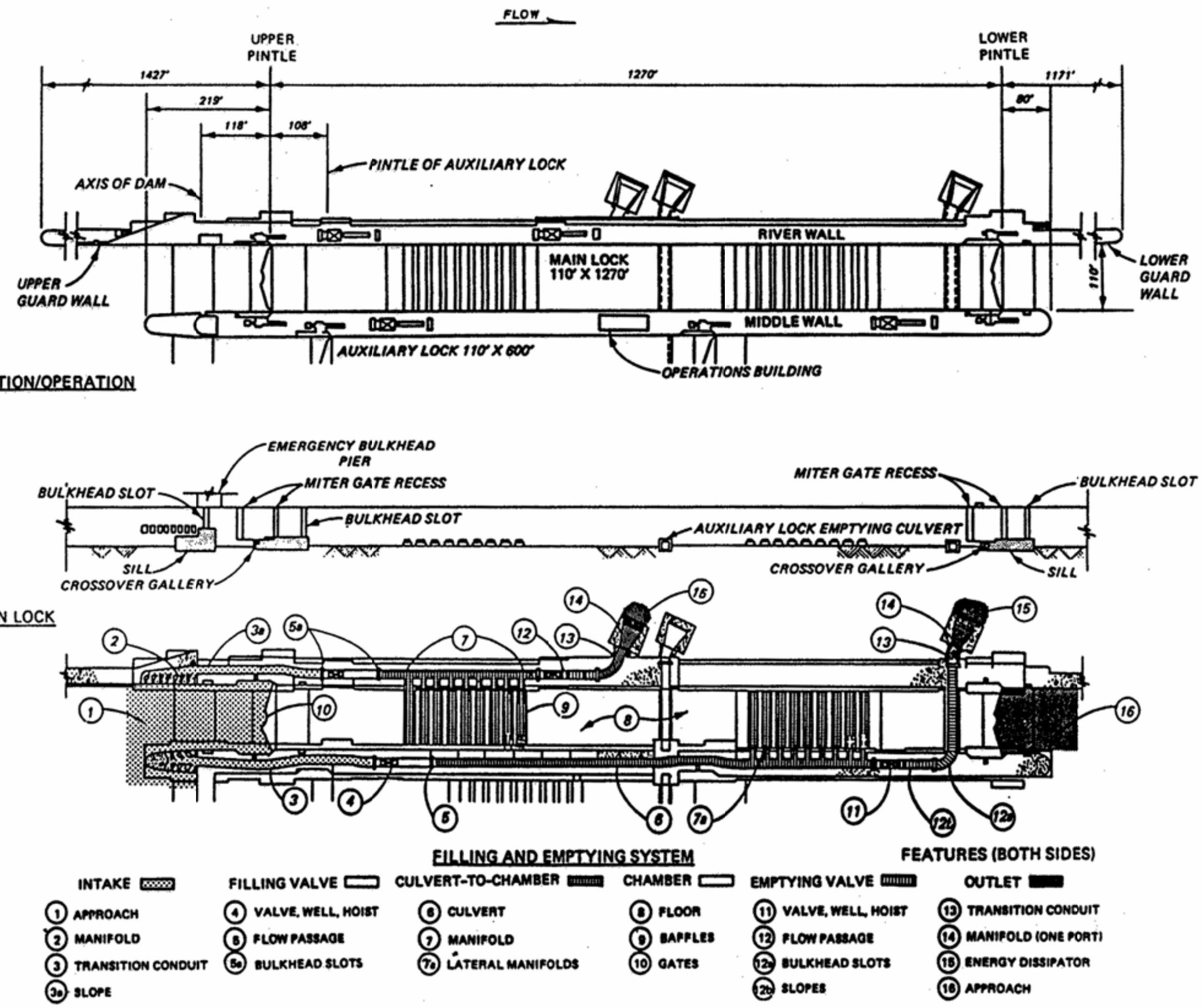

OZARK LOCK
SIDE-PORT (SP) LOCK
NAVIGATION/OPERATION
789'
670'
630'
110'
72'
UPPER GUARD WALL
AXIS OF DAM
OPERATIONS BUILDING
LAND WALL
LOCK 110' X 600'
RIVER WALL
FLOW
LOWER GUARD WALL
PROFILE
POIREE DAM
MITER GATE RECESS
SILL
MITER GATE RECESS
POIREE DAM
SILL
NOTES: NAVIGATION AIDS LOCATED ALONG LOCK WALLS ARE RECESSED FOR 110' CLEAR WIDTH.
DIMENSIONS ARE IN FEET.
OZARK LOCK
DESIGN PARAMETERS
MAXIMUM DRAFT = 9-FT
CLEAR WIDTH = 110-FT
USABLE LENGTH = 600-FT
NORMAL LIFT = 34-FT
MAX. NAVIGATION LIFT = 37-FT
MAX. OPERATION TIME: FILL = 10-MIN
EMPTY = 10-MIN
FILLING AND EMPTYING SYSTEM
INTAKE
1 APPROACH
2 MANIFOLD
3 TRANSITION CONDUIT
3a SLOPE
FILLING VALVE
4 VALVE, WELL, HOIST
5 FLOW PASSAGE
5a BULKHEAD SLOTS
CULVERT-CHAMBER
6 CULVERT
7 MANIFOLD
CHAMBER
8 FLOOR
9 BAFFLES (NONE)
10 GATES
EMPTYING VALVE
11 VALVE, WELL, HOIST
12 FLOW PASSAGE
12a BULKHEAD SLOTS
OUTLET
13 TRANSITION CONDUIT
14 MANIFOLD
15 ENERGY DISSIPATOR
16 APPROACH
FEATURES (BOTH SIDES)

Plate 3-4

NOTES: FEATURES LOCATED ALONG LOCK WALLS ARE RECESSED FOR 110' CLEAR WIDTH.
DIMENSIONS ARE IN FEET.



BELLEVILLE MAIN LOCK
DESIGN PARAMETERS

MAXIMUM DRAFT = 9-FT
CLEAR WIDTH = 110-FT
USABLE LENGTH = 1200-FT
NORMAL LIFT = 22-FT
MAX. NAVIGATION LIFT = 26-FT
OPERATION TIME = 8-MIN

BELLEVILLE MAIN LOCK
BOTTOM LATERALS
(BL2)

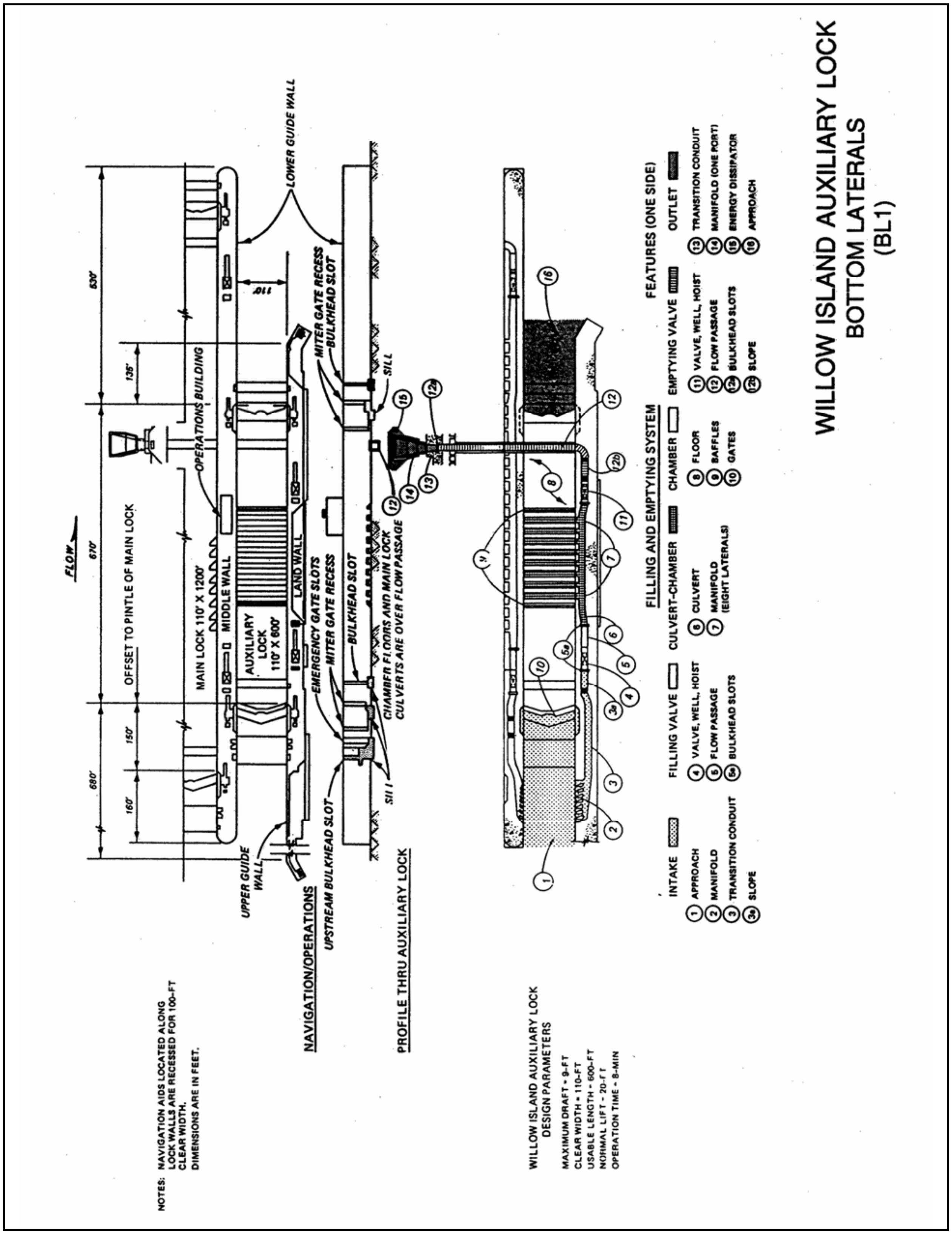
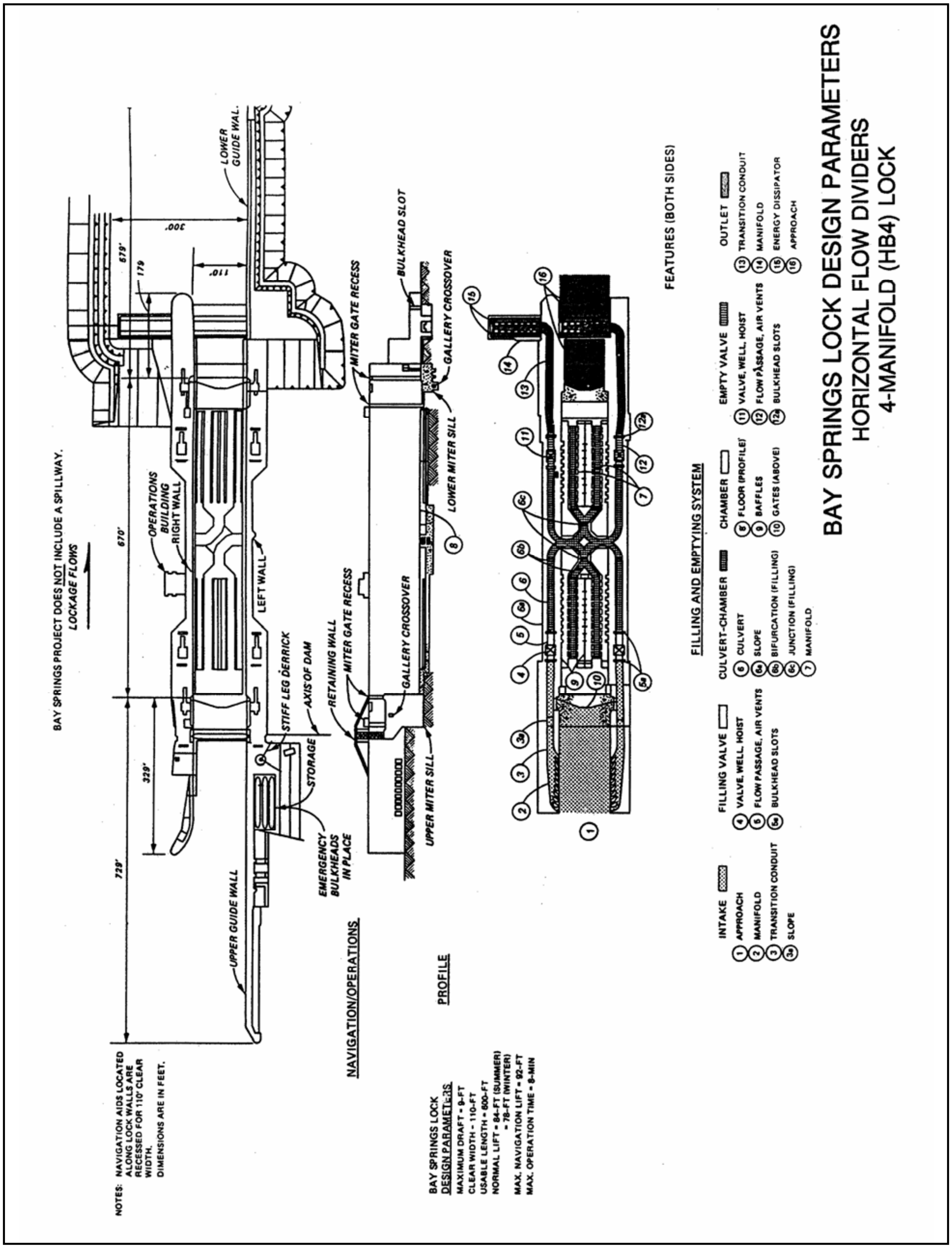

WILLOW ISLAND AUXILIARY LOCK
BOTTOM LATERALS
(BL1)
NOTES: NAVIGATION AIDS LOCATED ALONG LOCK WALLS ARE RECESSED FOR 100-FT CLEAR WIDTH.
DIMENSIONS ARE IN FEET.
NAVIGATION/OPERATIONS
PROFILE THRU AUXILIARY LOCK
WILLOW ISLAND AUXILIARY LOCK
DESIGN PARAMETERS
MAXIMUM DRAFT - 9-FT
CLEAR WIDTH - 110-FT
USABLE LENGTH - 600-FT
NORMAL LIFT - 20-FT
OPERATION TIME - 8-MIN
FLOW
OFFSET TO PINTLE OF MAIN LOCK
MAIN LOCK 110' X 1200'
MIDDLE WALL
AUXILIARY LOCK 110' X 600'
LAND WALL
OPERATIONS BUILDING
UPPER GUIDE WALL
LOWER GUIDE WALL
UPSTREAM BULKHEAD SLOT
EMERGENCY GATE SLOTS
MITER GATE RECESS
BULKHEAD SLOT
CHAMBER FLOORS AND MAIN LOCK CULVERTS ARE OVER FLOW PASSAGE
SILL
680'
160'
150'
670'
135'
530'
110'
FILLING AND EMPTYING SYSTEM
INTAKE
1 APPROACH
2 MANIFOLD
3 TRANSITION CONDUIT
3a SLOPE
FILLING VALVE
4 VALVE, WELL, HOIST
5 FLOW PASSAGE
5a BULKHEAD SLOTS
CULVERT-CHAMBER
6 CULVERT
7 MANIFOLD (EIGHT LATERALS)
CHAMBER
8 FLOOR
9 BAFFLES
10 GATES
EMPTYING VALVE
11 VALVE, WELL, HOIST
12 FLOW PASSAGE
12a BULKHEAD SLOTS
12b SLOPE
OUTLET
13 TRANSITION CONDUIT
14 MANIFOLD (ONE PORT)
15 ENERGY DISSIPATOR
16 APPROACH
FEATURES (ONE SIDE)

Plate 3-6


BAY SPRINGS LOCK DESIGN PARAMETERS
HORIZONTAL FLOW DIVIDERS
4-MANIFOLD (HB4) LOCK
BAY SPRINGS PROJECT DOES NOT INCLUDE A SPILLWAY.
LOCKAGE FLOWS
LOWER GUIDE WALL
300'
110'
579'
179
670'
329'
729'
OPERATIONS BUILDING
RIGHT WALL
LEFT WALL
STIFF LEG DERRICK
AXIS OF DAM
STORAGE
EMERGENCY BULKHEADS IN PLACE
UPPER GUIDE WALL
NAVIGATION/OPERATIONS
BULKHEAD SLOT
GALLERY CROSSOVER
MITER GATE RECESS
LOWER MITER SILL
RETAINING WALL
UPPER MITER SILL
PROFILE
NOTES: NAVIGATION AIDS LOCATED ALONG LOCK WALLS ARE RECESSED FOR 110' CLEAR WIDTH.
DIMENSIONS ARE IN FEET.
BAY SPRINGS LOCK DESIGN PARAMETERS
MAXIMUM DRAFT = 9-FT
CLEAR WIDTH = 110-FT
USABLE LENGTH = 600-FT
NORMAL LIFT = 84-FT (SUMMER) = 78-FT (WINTER)
MAX. NAVIGATION LIFT = 92-FT
MAX. OPERATION TIME = 8-MIN
FEATURES (BOTH SIDES)
FILLING AND EMPTYING SYSTEM
INTAKE
1 APPROACH
2 MANIFOLD
3 TRANSITION CONDUIT
3a SLOPE
FILLING VALVE
4 VALVE, WELL, HOIST
5 FLOW PASSAGE, AIR VENTS
5a BULKHEAD SLOTS
CULVERT-CHAMBER
6 CULVERT
6a SLOPE
6b BIFURCATION (FILLING)
6c JUNCTION (FILLING)
7 MANIFOLD
CHAMBER
8 FLOOR (PROFILE)
9 BAFFLES
10 GATES (ABOVE)
EMPTY VALVE
11 VALVE, WELL, HOIST
12 FLOW PASSAGE, AIR VENTS
12a BULKHEAD SLOTS
OUTLET
13 TRANSITION CONDUIT
14 MANIFOLD
15 ENERGY DISSIPATOR
16 APPROACH

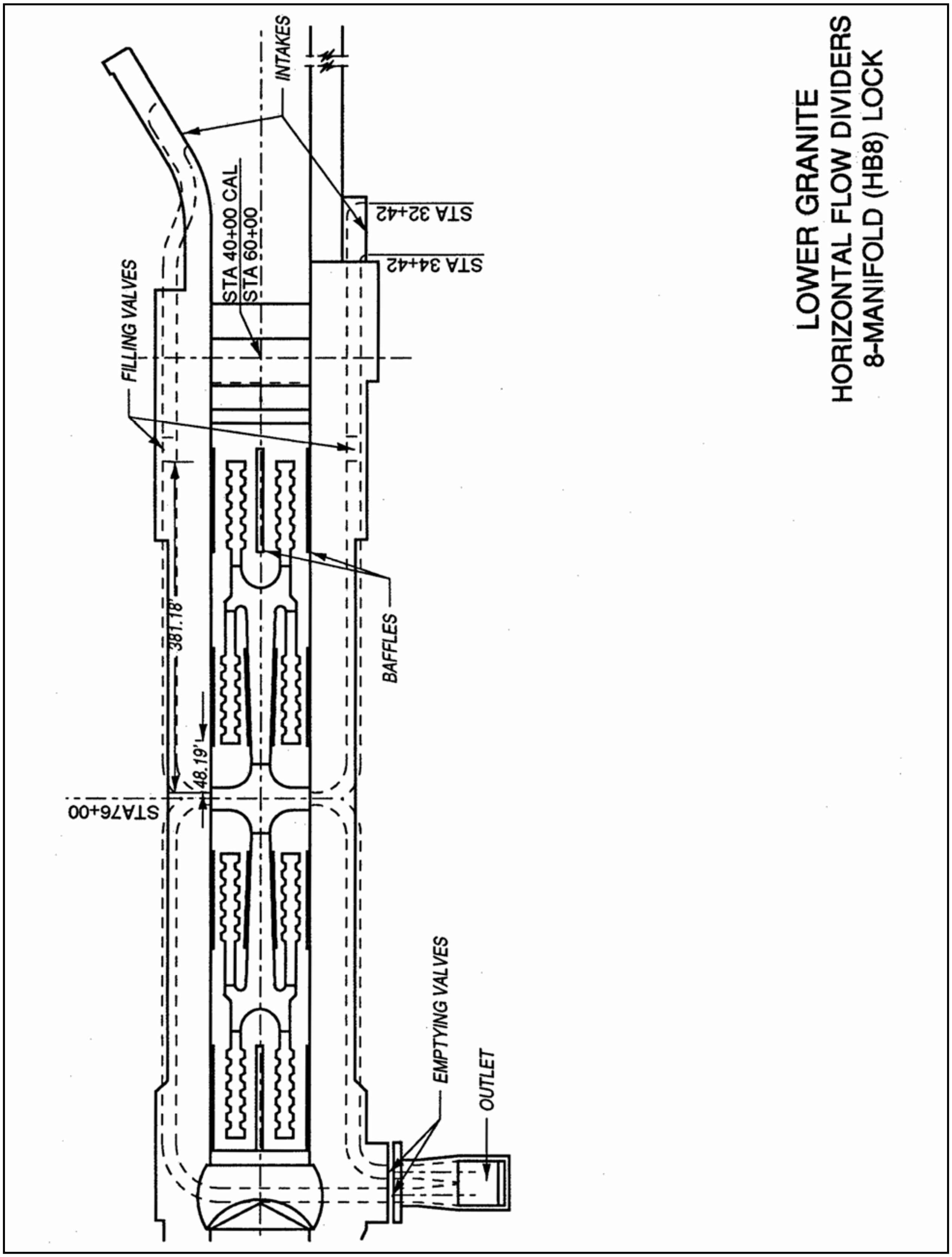

LOWER GRANITE
HORIZONTAL FLOW DIVIDERS
8-MANIFOLD (HB8) LOCK
INTAKES
STA 32+42
STA 34+42
STA 40+00 CAL
STA 60+00
FILLING VALVES
BAFFLES
381.18'
48.19'
STA76+00
EMPTYING VALVES
OUTLET

Plate 3-8

Chapter 4
Filling-and-Emptying Feature Design

Section I
Preliminary Calculations

4-1. General

The following paragraphs identify preliminary calculations required for very-low-lift (SG and SPF), low-lift (SP, BL1, and BL2), and high-lift (HB4 and HB8) designs. See Table 3-2 for design type definitions. For lifts near design-type limits, ranges 5 to 10 ft and 30 to 40 ft, economic cost/capacity studies may require the review of both a lower lift design (normally with lower initial cost) and a higher lift design (normally with greater capacity).

4-2. Sill Spacing Parameters

Preliminary layouts required for navigation, geotechnical, and structural studies require the sill spacing to be estimated early in the design process. Since the usable length is fully committed to navigation, the actual chamber length is usable length plus the gate length plus a safety clearance value.

a. Lower and upper miter gates. The lower miter gate swing (EM 1110-2-2703 and Figure 4-1) requires about 60 ft for 110-ft clear width locks and, similarly, 46 ft for 84-ft widths. Design practice is to provide a spacing of about 10 ft to accommodate obstructions and clearance at the upper sill and clearance at the lower leaf while the leaf is approaching the fully recessed position. Typical dimensions are listed in Table 4-1.

b. Lower and upper sector gates. Requirements are similar to miter gate installations. For example, Vermilion Lock, which has a clear width of 110 ft and usable length of 1,200 ft, has a 1,270-ft spacing between sector gate pintles. Large tows and small vessels near sector gates (Plate 3-1) require secure moorings and slow gate operation in order to prevent drift (items 19, 27, 36, B9, B11, S7). Usable length based on clearance, as in *a* above, is therefore greater than a usable length based on chamber conditions.

c. Lower miter and upper submergible tainter gates. The tainter gate trunnion is located and recessed within the chamber at Lower Granite Lock. Clearance factors at lower pool are the same as found in *a* above; protection for the tainter gate is an additional concern at higher pool levels. Typical dimensions in feet are:

(1) Clear width = 86

(2) Usable length = 675

(3) Lower leaf extension = 52

(4) Lower miter pintle to tainter gate trunnion = 728

(5) Lower miter pintle to sill face = 749 (varies)

(6) Clearance at lower pool = 22

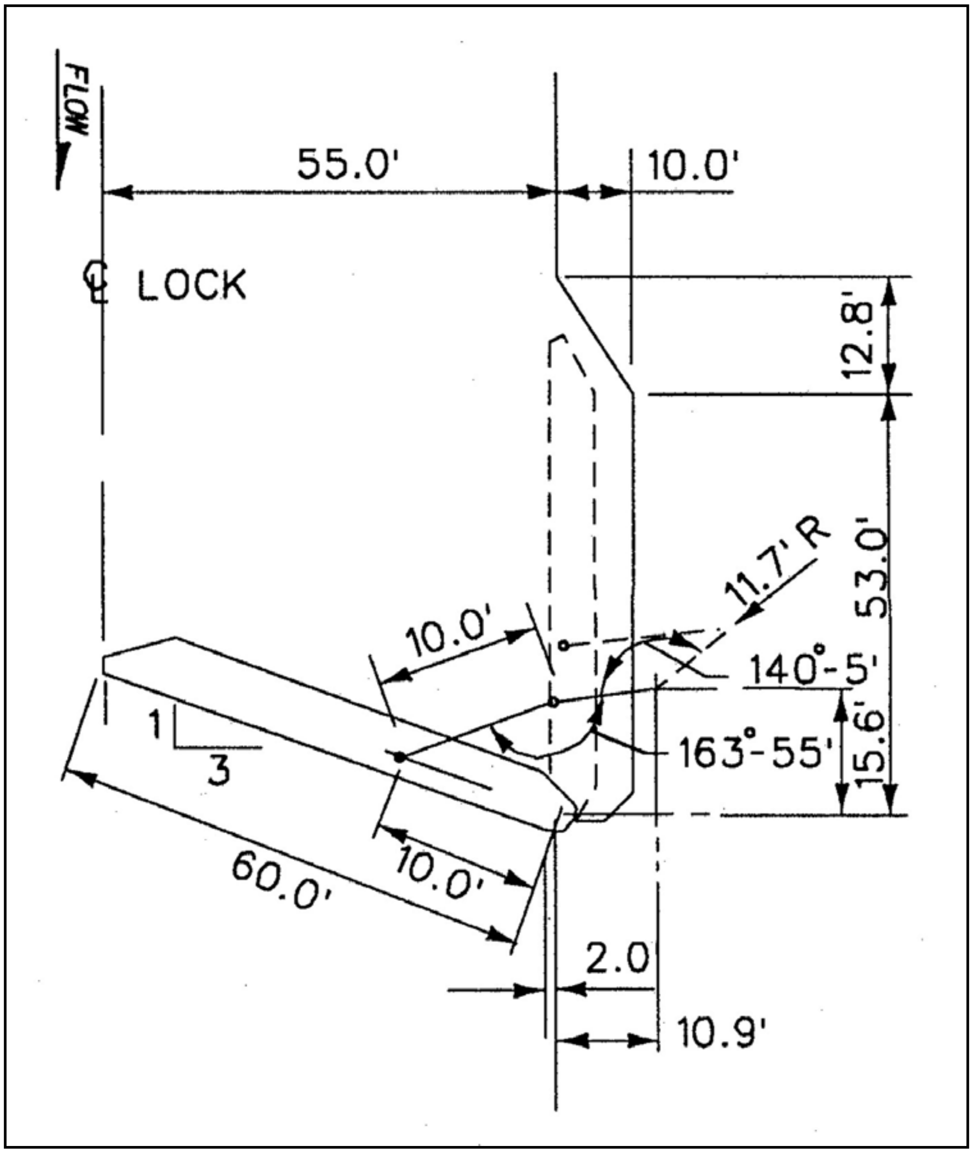


Figure 4-1. Miter gate leaf and recess. Dimensions are those used in WES model test (item 49, WES TR 2-651). Four types of strut arm linkages are reported in EM 1110-2-2703: Ohio River (above), Modified Ohio River, Panama Canal, and Directly Connected. The choice is influenced by type of drive (electrical or hydraulic) and by chamber width

Table 4-1
Miter Gate Dimensions, Feet

Clear Width	110	110	84
Usable Length	1,200	600	600
Leaf Extension	60	60	46
Clearance	10	10	9
Pintle-to-Pintle	1,270	670	655

Spillway tainter gate structural details are suggested as appropriate for tainter gates on lock sills (EM 1110-2-2703).

d. Other gates. Navigation inconvenience at lower pool (rising single-leaf vertical lift gates) and clearance for opening at upper pool (submergible or rising single- or double-leaf vertical lift gates) preclude a significant reduction in sill spacing by using narrower gates. Gate designs are discussed briefly in Appendix B and detailed in EM 1110-2-2703. Lock chambers using gates other than miter gates are unusual in CE design practice.

4-3. Sill Spacing

For preliminary layouts, sill spacing is based on usable length and miter gate or sector gate leaf extension; approximately 10 ft is added to provide a combined sill and gate clearance. Final gate selection considers structural, mechanical, and economic factors in addition to hydraulics and may result in an alternate gate and a small change in sill location.

4-4. Location of Intake Structures

The chamber inflow hydrograph (flow rate, Q, as a function of time, t) is finalized during hydraulic feature design; however, estimates of flow are required before these details are known. Intake structures are located so that lockage flows are a minimum liability to navigation and also satisfy other site-specific constraints. Navigation conditions are often determined by means of small-scale hydraulics models (see EM 1110-2-1611 and item F4, for example) which require preliminary estimates of lock inflow rate.

4-5. Lock Filling

Corps program H5320 or other expedient calculations (item R1 or item 103, for example) are used to provide Q as a function of t for the lift and geometry of the new lock. Should operation time (T, Chapter 5) be greater than authorized, then system size is increased; additional costs as compared to the existing lock are anticipated. Should operation time be less than authorized, then system size may be decreased. Idealized hydrographs, as shown in Figure 4-2, may also be used to establish preliminary estimates of lock inflow. The volume of inflow, using a discharge Q as a function of time t, is set equal to the change in lock chamber water volume. The following guidelines identify rapid filling times (small T values) for existing designs.

a. Very-low-lift designs. For SG locks, the gate opening rate and pattern are adjusted in the prototype to accommodate various lift, vessel, and approach conditions. For SPF locks, valve pattern and port openings are adjusted in the prototype for the same reasons. Operation times near 10 min (items B9, P2) are the minimum achievable for acceptable chamber performance. For small SG chambers with recreational traffic, lower lifts, and adequate submergence, an operation time nearer 5 min may be appropriate.

b. Low-lift designs. For SP locks, acceptable chamber performance is obtained during hydraulic feature design for a specific filling time and specific commercial traffic (9-ft-draft tows) because of tested relationships between lift, chamber dimensions, submergence, port dimensions, baffles, and valving. An 8-min operation time is a common goal for lifts near midrange, 25 ft. Predesign estimates of SP operation time for an 84-by 600-ft chamber and 4-min valving are shown in Figure 4-3. Neither BL2 nor BL1 designs have as comprehensive a set of operation time versus submergence data as do side-port systems. For these systems, a filling time T of 8 min and a valve time t_v of 4 min are suggested for preliminary inflow estimates for the entire low-lift range.

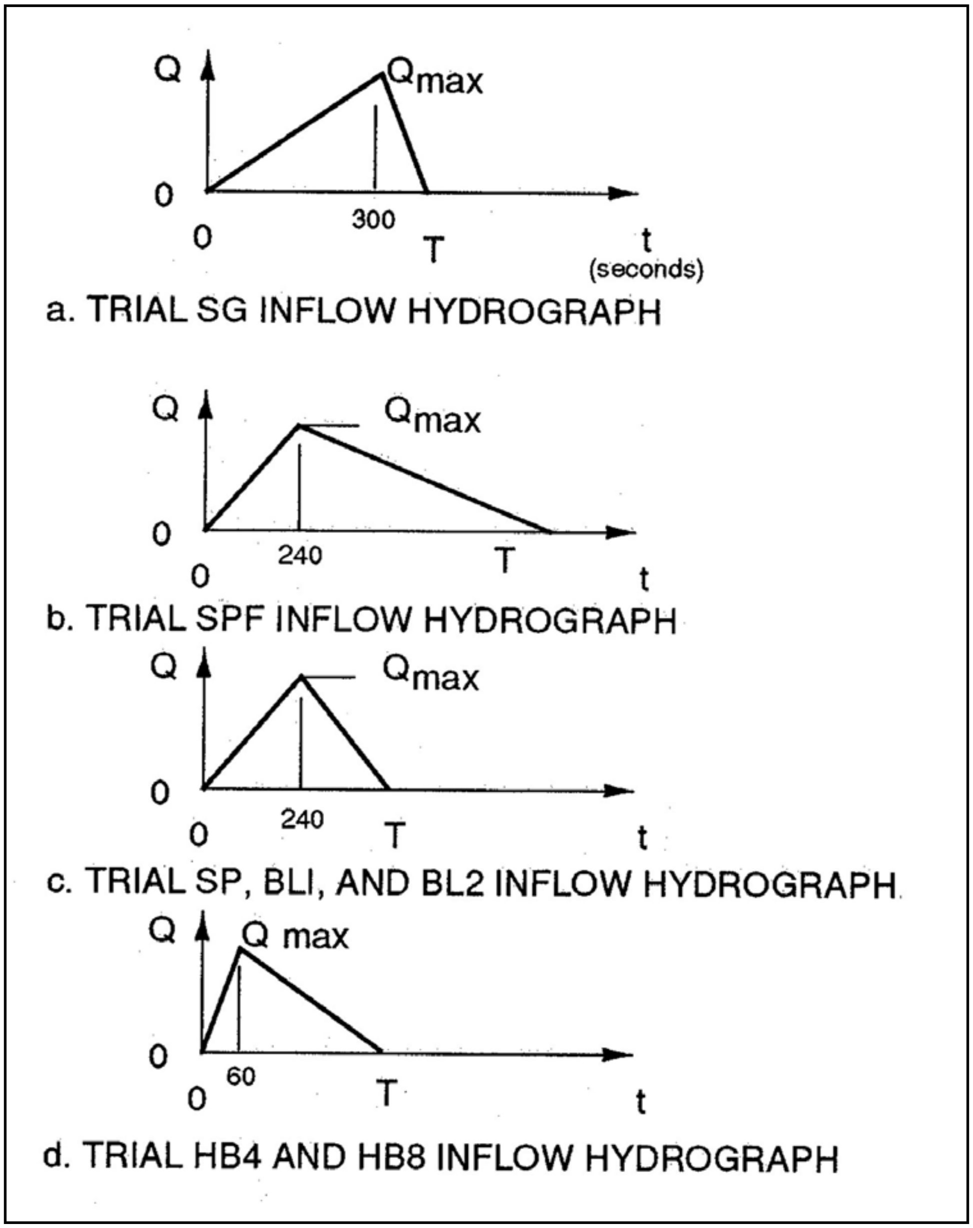


Figure 4-2. Idealized lock filling hydrographs for preliminary estimates of lock inflow

c. High-lift designs. HB4 and HB8 chamber details are variable during design only with extensive laboratory testing regarding chamber performance. Both systems are designed for rapid valving (t_v = 1 min) and rapid filling. Prototype filling times for these systems are estimated in Figure 4-3 for lifts ranging from 40 to 100 ft. Making these systems slower, except by valving, or faster requires significant changes of chamber features.

4-6. Chamber Depth

Chamber depth D_c (Figure 4-4) for design purposes is the depth of water in the lock during navigation lockage conditions. The minimum depth corresponds to the minimum tailwater elevation and the maximum

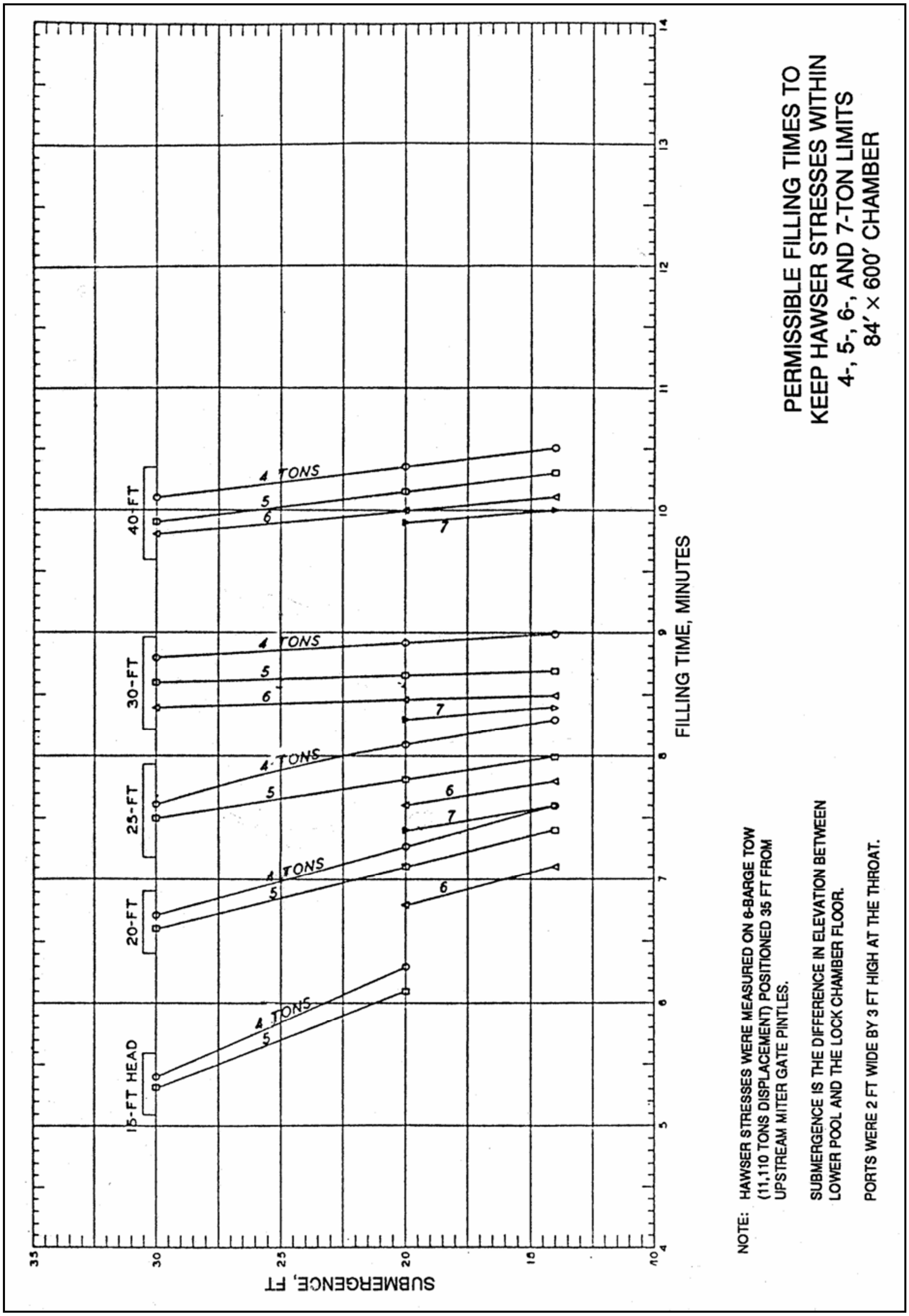


Figure 4-3. Filling time test data. Side-port data are from model tests; the prototype will operate about 10 percent faster

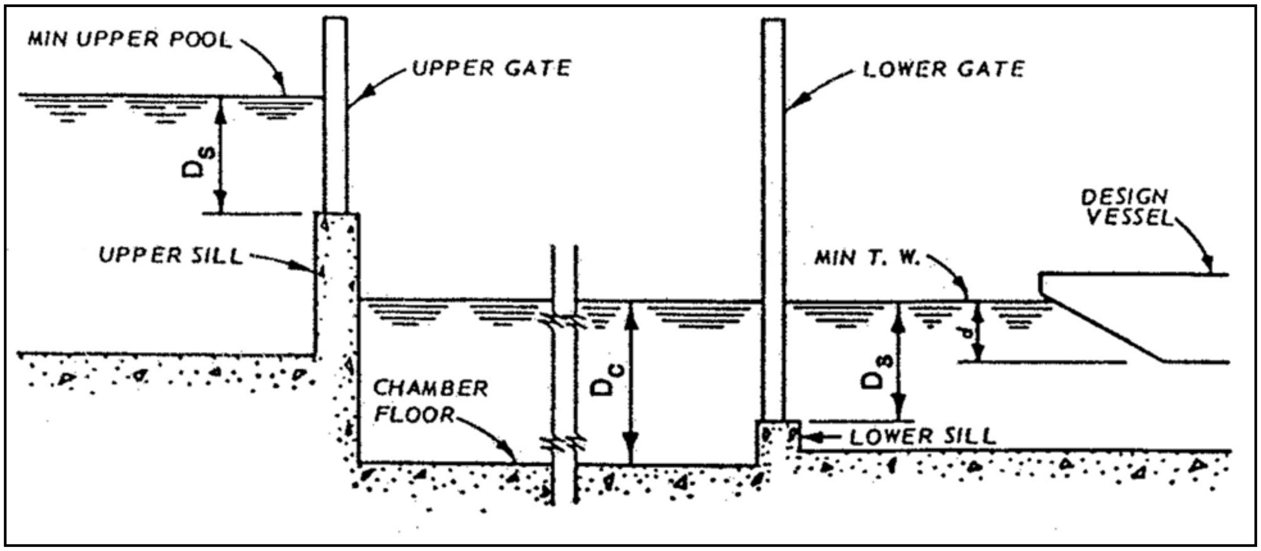


Figure 4-4. Sill elevations

depth to the maximum upper pool elevation for which lockage is planned. The choice of the chamber floor elevation must include safety and economic considerations. The time of entry and the filling/emptying time are decreased while the cost of the structure is increased as the chamber depth is increased. Safety is improved as the chamber depth is increased. The minimum chamber depth must have a filling time that is slow enough not to violate the 5-ton hawser stress guidance. Figure 4-3 is an example. It may be that the sill depth requirements (paragraph 4-7) will limit the minimum chamber depth. An economic analysis using the incremental delays in lock transits for increments of tailwater/headwater durations versus the incremental structural cost of providing various chamber depths is employed to optimize the benefit to cost ratio. Project experience is listed in Table 4-2 and discussed in the following paragraphs. Submergence is defined as the difference in elevation between lower pool and chamber floor. Cushion is defined as the elevation difference between vessel keel and chamber floor for zero velocity conditions.

a. Very-low-lift designs (0-10 ft). These locks have been constructed with chamber floor at navigation channel bed elevation. The submergence has therefore been established by upstream and downstream channel conditions rather than chamber performance.

b. Low-lift designs (10-30/40 ft). The minimum submergence for optimum filling/emptying time for side-port locks is the tow draft plus one-half the side-port spacing (item 72). For a 9-ft-draft tow in a 110-ft-wide lock, the optimum minimum submergence is 14 + 9 = 23 ft. When excavation costs associated with deep submergence are significant, then the lateral BL2 system has been used. Using 16-ft submergence plus 7-ft lateral-culvert total height = 23 ft as criterion, then for lifts less than about 25 ft, BL2 is not an economical alternative to SP systems. For lifts above 25 ft, the BL2 design has been used instead of the SP design provided reduced excavation represents a major economic factor as compared to the expense of lateral culverts and risk during single or nonsynchronous culvert operation is operationally acceptable. The high-lift HB4 type of design is expected to be an effective alternative to BL2 designs, although use in 1,200-ft chambers has yet to be studied. The auxiliary lock, BL1, is normally set so that submergence is equal to that of the main lock.

Table 4-2
Submergence Values

Project (see Appendix B)								Traffic	
Design Type	Name	Data[a]	Length ft	Width ft	Lift ft	Type	Draft ft	Submergence[b] ft	Cushion[c] ft
				Very-Low-Lift Projects					
SG	Vermilion	D	110	1,200	5	Tow	9	15 [12]	6 [3]
						Rec.	12	15 [12]	3 [0]
SG	W. G. Stone	D	86	640		Tow	9	15	6
						Tow	14	15	1
SG	Algiers	M	75	800	8	Tow	9	13.5	4.5
SG	S-61	D	30	120	Rec.	NV[d]	7.5	NV[d]	
SPF	L&D 52	D	110	1,200	12	Tow	9	12.0	3
				Low-Lift Designs					
SP	Willows Is. Main	D	110	1,200	20	Tow	9	25	16
SP	Ozark	D	110	600	34	Tow	9	27	18
BL2	Belleville Main	D	110	1,200	22	Tow	9	28	19
BL2	Markland	M	110	1,200	3	Tow	9	16.5	7.5
BL2	Greenup	M	110	1,200	30	Tow	9	16	7
BL1	Willow Is. Aux.	D	110	600	20	Tow	9	25	16
				High-Lift Designs					
VB4	Bay Springs	M	110	600	92	Tow	9	15	6
VB8	Lower Granite	M	86	675	105	Tow	9	17	8

Notes:
[a] M = model tested for satisfactory chamber performance; D = design normal values. Listing includes projects shown in Plates 3-1 through 3-8.
[b] Submergence is lower pool elevation minus chamber floor elevation; values in brackets are minimums.
[c] Cushion is submergence minus draft; values in brackets are minimums.
[d] NV = no value available; submergence ranges from 7.5 to 9 ft for Kissimmee River Locks.

c. High-lift designs (30/40-100 ft). Submergence values are as shown in Table 4-2 for the listed lifts. The extreme excavation measured from lower pool to the lowest invert in the crossover area is 34 ft for HB4 design and 41 ft for HB8 design. The HB8 design with modified crossover culverts has been model-tested for a 69.5-ft lift, 14-ft-draft tows, 5-ft cushion, and 86-ft by 675-ft chamber with no evidence of unsatisfactory performance. The VB4 designs, which have similar manifolds but modified crossovers as compared to HB4, have been model-tested for lifts ranging from 30 to 100 ft for a range of lifts and chamber sizes; prototype experience (see Appendix B) is available with these designs. The HB4 design (modified) was considered for a 130-ft lift, 84- by 600-ft chamber; however, the project was terminated for economic rather than operational reasons.

4-7. Sill Elevation

Sill depth D_s (Figure 4-4) for design purposes is the depth of water over the sill during navigation lockage conditions. The minimum depth corresponds to the minimum tailwater elevation for the lower sill and to the minimum upper pool elevation for the upper sill. The effects of lock sill and chamber depths on transit time for shallow draft navigation are discussed in item 95.

4-8. Sill Elevation Guidance

The choice of sill depth must include safety and economic considerations. As the sill depth is either the same or less than the chamber depth, it becomes the governing factor for safety and tow entrance time. A sill depth less than 1.5 times the tow draft (1.5d), except for very-low-lift (0-10 ft) locks, should not be considered due to safety reasons (item K3). A normal entrance speed of approximately 3 mph requires a sill depth of 2d to avoid excessive squat and loss of vessel speed control. When gate operating clearance above the floor to allow for some accumulation of trash is necessary, either a 2- or 3-ft height of sill above the floor or a floor recess is provided. Since there is very little difference in the cost of the sill versus the cost of the gate, the sill elevation should be kept as low as possible for ease of tow entry and exit and for safety reasons due to the possibility of grounding caused by squat and/or ice accumulation. The upper sill depth should be equal to or greater than the lower sill depth. Consideration can be given to a much greater depth if a need to pass emergency traffic during a loss of pool situation or other exigency is projected. Table 4-3 provides examples of sill depths at some existing projects. EP 1105-2-11 and augmenting database (see Appendix A) provide a complete listing of Corps locks. The influence of the sill depths due to tailwater and upper pool elevation durations at various levels is part of the economic analysis called for in paragraph 4-6.

Table 4-3
Existing Sill Elevations

Lock	Design Type	D_c ft	Upper D_s ft	Lower D_s ft
Vermilion	SG	15	S	S
Lock 52	SPF	12	15.4	11
Willow Is. Main	SP	25^r	35, 18^b	15
Ozark	SP	27^r	18^n, 16^m	17^n, 14^m
Belleville Main	BL2	28^r	37, 20^b	15
Willow Is. Aux	BL1	25^r	35, 18^b	15
Bay Springs	HB4	15	21^n, 15^m	15
Lower Granite	HB8	17	21^n	15^m

Note: S = same as chamber floor; r = rock floor; b = initial; n = normal; m = minimum; values are for normal pools unless otherwise noted.

4-9. Location of Outlet Structures

Constraints are so that lockage flows (emptying) are a minimum liability to navigation and satisfy other site-specific concerns and so that satisfactory chamber performance is retained. For sector gates the outflow point is the lower gates, and discharge is directly into the lower approach channel. For culvert systems the outflow is either into the approach channel (by means of bottom or side manifolds) or, when possible, into the main river remote from the approach, or by a division of flow between main river and approach canal. Three specific preliminary information needs are as follows.

a. Navigation. Discharge hydrographs are required for studies (EM 1110-2-1611) of navigability in the lower approach. Control during emptying is at the outlet ports which, in design, can be modified to increase peak flows (decrease operation time). For preliminary calculation the outflow hydrograph is made identical to the inflow hydrograph (Figure 4-2) although a 10 to 20 percent decrease for peak flow during emptying is not uncommon.

b. Channel stability. Discharge hydrographs are required; the estimates (*a* above) are used for preliminary studies of bed and bank stability. Structures for energy dissipation and stone for bed and bank protection are often required.

c. Stages. For remote outlets, the differential between stage at the outlet location and stage in the lower approach channel affects lower gate operation. Values are required for the navigable range of hydrologic conditions at the project.

4-10. Typical Outlet Locations

The outlet structure types in Table 4-4 are from Plates 3-1 to 3-8.

Table 4-4
Outlet Structure Types

Project (Typical)	Outlet Structure Type
Vermilion	Sector gate
Lock 52	Channel side; one multiported structure
Willow Is. Main	Remote; one with two ports
Ozark	Remote; one with two ports
Belleville Main	Remote; two with one port
Willow Is. Aux.	Remote; one structure with one port
Bay Springs	Channel bed; two multiported structures
Lower Granite	Remote; one structure with two ports

Section II
Very-Low-Lift Designs

4-11. General

Relatively small static and dynamic hydraulic loadings occur for locks with very low lifts (water-surface differential $H < 10$ ft). In addition, constraints with regard to chamber performance (filling time and hawser stress) are normally sufficiently flexible so that adjustments to the field operating procedure, rather than design information, are used to optimize chamber performance. These adjustments are:

a. Sector gate (SG) locks. To obtain satisfactory chamber performance, the gate opening rate, pattern, and duration are finalized in the prototype.

b. Side-port-and-flume (SPF) locks. The number and sizing of open ports are chosen during prototype operation.

Model and prototype hydraulic measurements are unavailable for the SPF locks; these design layouts are patterned after low-lift SP systems. Model data (items 19, 20, and 36) are available for SG locks. More rigid constraints or unusual geometric concerns (see item 13, for example) commonly require physical hydraulic model testing (items B9, B11, S7). Overstressing of SG operating machinery during reverse heads (laboratory studies, item 65; prototype studies, item 66) resulted in gate framing and lip designs presented in EM 1110-2-2703 that have not been rated for lock filling and emptying.

4-12. Sector Gate Design Concept

The gate and recess, shown in Plate 3-1 with EM 1110-2-2703, are geometrically formed so that the minimum dimension between recess lip and recess boundary equals the clear opening at the lock center line. Flow is distributed across the width of the chamber since the recesses, in addition to the center-line opening, are flow passages.

4-13. Hydraulic Evaluation

Sector gate lock studies include four fundamental evaluations:

a. Operation time. Longer filling and emptying times are expected for projects requiring larger chamber water-surface areas or having higher lifts. The size and shape of the flow passages through the gate recesses affect the rate of flow into and out of the chamber as well as affecting the mooring conditions immediately downstream from the gate. The primary means of altering the operation time for a specific sector gate design is by optimizing the rate and extent of gate opening. The values in Table 4-5 apply to constant rate gate opening tests for the Sacramento Barge Canal Lock; see item 36 for a wider range of test conditions.

b. Chamber mooring conditions. Velocities and turbulence near the upper gate during filling and lower gate during emptying are unfavorable as mooring conditions. For example, a usable chamber length of about 540 ft, rather than 640 ft, based on gate location is suggested (item 36) for the Sacramento Barge Canal Lock. An alternate solution is slow gate operation.

c. Hydraulic loadings. The forces required to open and close the sector gate under normal and reverse flows are sensitive to gate lip shape. Loadings are presented in EM 1110-2-2703 (from items 36 and 65). The more recent results (item 65) are for sector gates operating under reverse heads and provide guidance on gate lip detail. Loadings for a 110-ft-wide sector gate are provided in item 102.

d. Flow rate. The chamber water-surface elevation is evaluated by simultaneously numerically integrating flow rate Q and elevation z relationships:

$$Q = c b_g h^{3/2} \tag{4-1}$$

$$Q = A_L \frac{dz}{dt} \tag{4-2}$$

where

c = a coefficient that is assumed constant for free-flow conditions, but under submerged conditions gradually decreases with increased submergence (see Figure 4-5)

b_g = effective gate opening which includes the center-line opening and the gaps through the recesses

h = upper pool water-surface height above the upper sill

z = chamber water-surface height above the upper sill

Table 4-5
Constant Rate Gate Opening Tests (Sacramento Barge Canal, Item 36)

Stage[a] ft	Lift ft	Gate Opening Rate deg/min	Filling Time T min	Emptying Time T min	Maximum Gate Opening Filling deg	Emptying deg
34.5	21	0.33	13.7	20.1	4.6	6.7
		0.66	9.4	13.7	6.2	9.0
29.5	12	0.33	12.5	15.1	4.1	5.0
		0.66	8.8	10.7	5.8	7.1
		1.00	7.2	8.8	7.2	8.8
22.5	6	0.33	12.6	14.3	4.2	4.7
		0.66	8.1	10.1	5.4	6.7
		1.00	7.2	7.8	7.2	7.8

Note:
[a] Stage is referenced to upper gate sill.

A_L = lock chamber water-surface area

dz/dt = rate of change of the chamber water-surface elevation

Filling is initiated with the upper gates closed and the lock chamber at lower pool level. An example of a calculation for Algiers Lock, item 20, is shown in Figure 4-5. For filling with continuously submerged flow ($z/h > 0.7$), Equation 4-2 in conjunction with the orifice equation is probably more reliable than the above procedure. The flow rate is expressed as

$$Q = cb_g h\sqrt{2g(h-z)} \qquad (4\text{-}3)$$

in which the coefficient c is about 0.55 (item S7). Concepts associated with wave action in the chamber and inaccuracies associated with flow calculations for sector gate locks are discussed elsewhere (items S7 and R1, for example). Model and prototype experience, with provision for field adjustment of the sector gate opening pattern, is an essential part of the hydraulic design of sector gate locks.

4-14. Side-port Flume (SPF) Designs

Prototype study data are available from the U.S. Army Engineer District, Louisville. These data include valve operation schedules and operation times for lifts experienced at Locks 52 and 53 (temporary locks). Qualitative information regarding port sizing, flume and chamber performance, and operational experience are also available. These locks have not been model-tested, so generalized design data are not available.

Section III
Culvert-to-Chamber Systems

4-15. General

The arrangement and sizing of the chamber ports affect chamber performance (hawser stresses, for example) as well as operation time. The flow through the culvert-to-chamber system is bidirectional; that is, the ports are discharge orifices during filling and intakes during emptying. These requirements have resulted in

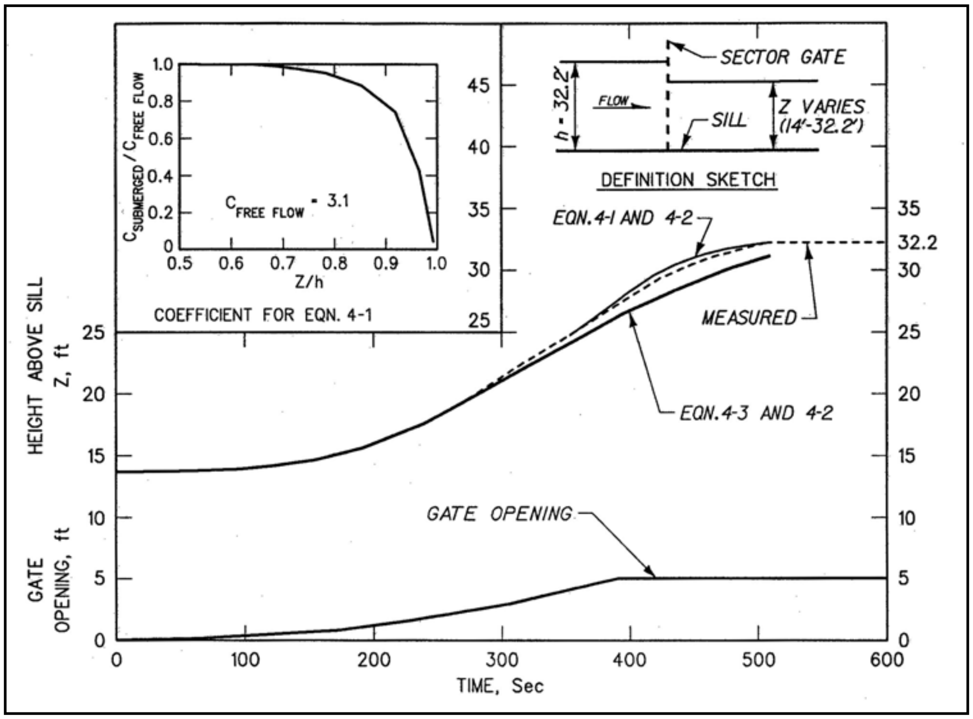


Figure 4-5. Example of Sector Gate Filling (Algiers Lock, Item 20)

a small set of effective designs (SP, BL1, BL2, HB4, and HB8) that are suited to a reasonably broad range of design constraints. Guidance for the hydraulic design of side-port locks, which have been tested for a very broad range of constraints, is presented in Appendix D. Guidance for the In-chamber Longitudinal Culvert System is provided in Appendix H. Guidance for extension of 600-ft-long locks to 1,200-ft-long locks is provided in Appendix I.

4-16. Chamber Port Arrangements

The layout of lateral (BL1 and BL2) design is based on model tests conducted for Greenup and Markland Locks (item 43). Small variations in locating and sizing the lateral manifolds have been adopted for design and have performed acceptably in the field. The location of the SP manifolds relative to chamber length follows specific guidelines outlined in Appendix D. The location of the longitudinal manifolds (HB4 and HB8) is invariant; i.e., all chamber details are required to be identical to Bay Springs Lock, HB4, or Lower Granite Lock, HB8. These detail dimensions are available in two model test reports (item 78 for HB4 and item 79 for HB8) and in project construction drawings. Deviations from these details require site-specific hydraulic model studies.

4-17. Flow Passage Areas

The discharge orifice areas (chamber ports for filling and outlet ports for emptying) are primary elements for meeting operation time criteria. The most rapid systems are ones in which these areas are maximized while energy losses within the culverts and manifolds (and valving times) are minimized. Flow passage areas for five lock designs are listed in Table 4-6.

Table 4-6
Flow Passage Areas

		Description (Size = Width H Height, ft H ft)					
Location	Item	Ozark	Willow Island	Belleville	Willow Island	Bay Springs	Lower Granite
Chamber Ports	Type	SP	BL2	BL2	BL1	VB4	VB8
	Number,[a] N_1	14	24	18	18	24	12
	Size (Face)[b]	3.25 × 3.50	3.69 × 4.70	1.83 × 2.08	1.83 × 2.08	1.5 × 3.5	1.25 × 3.46
	Size (Throat)	2.54 × 3.50	2.75 × 4.07	NA[c]	NA	NA	NA
Chamber Manifolds	Number,[d] N_2	1	1	9	8	2	4
	Shape	Box	Box	Stepped	Stepped	Box	Box
Culvert	Size (Maximum)	12 × 12	16 × 18	8 × 5	8 × 5	14 × 9	14 × 9
	Size	12 × 12	16 × 18	15 × 16	14 × 16	14 × 14	12 × 22
Outlet Ports	Number,[d] N_3	1	1	1	1	16	1
	Shape	Basin	Basin	Basin	Basin	Stepped	Basin
	Size	17 × 12	20 × 16	19 × 16	20 × 16	3 × 6	12 × 14
Operation	Evaluation	Area Ratios					
Filling	2) 1	0.78	0.65	NA	NA	NA	NA
	3) N_1 × 1; 3) N_1 × 2	0.90; 1.16	0.69; 1.07	0.58	0.58	1.00	1.16
Filling	4) N_2 × 3	1.00	1.00	0.67	0.70	0.78	1.10
	4) N_1 × N_2 × 1	0.90	0.69	0.39	0.41	0.78	1.27
Emptying	N_1 × N_2 × 1) N_3 × 5	0.78	1.30	2.04	1.72	0.88	1.24
	4) N_3 × 5	0.71	0.90	0.79	0.70	0.68	1.57

Notes:
[a] Per manifold.
[b] Excludes 0.5- to 1.5-ft radius surface contour.
[c] Not applicable.
[d] Per culvert.

a. Filling. Systems that contract from main culvert to chamber (HB8 at Lower Granite) adapt to requirements for rapid filling by using relatively large culverts with minimum losses attributable to culvert features. Energy dissipation is primarily by baffling within the chamber. Systems that expand from main culvert to chamber (BL1, BL2, HB4) adapt to requirements for rapid filling by using relatively large ports with significant energy dissipation occurring within the culverts as well as within the manifold sections. For example, in the Barkley Lock prototype BL2 design (16 ports per lateral, 8 laterals per culvert) the loss is about three times greater than for a streamlined system (item 71). Similarly, for the Greenup system (18 ports per lateral, 11 laterals per culvert) the loss is nearly six times greater (item 59).

b. Emptying. Chamber ports are inefficient as intakes. Efficient systems that contract from chamber to outlet (VB8 at Lower Granite) are designed for longer emptying than filling times and for energy dissipation concentrated downstream from the outlet. Expanding systems (SP at Ozark and VB4 at Bay Springs) tend toward more rapid emptying, although relatively greater losses are caused by chamber ports and manifolds.

Deep submergence for water-surface elevations near upper pool reduces the possibility of cavitation within the chamber ports and manifolds during emptying.

4-18. Chamber Ports, Baffles, and Manifolds

Ports for SP systems are discussed in Appendix D. Port and manifold geometries, as used in BL1 and BL2 systems, are shown in Plate 4-1. For lateral systems, ports within a manifold are equally spaced on each wall and equally sized (2.08 ft high by 1.83 ft wide is common); the number of ports per manifold and the number of manifolds vary between designs. The manifold roof is horizontal, whereas the interior sidewalls are stepped as shown. Port extensions are used when flow alignment, particularly from the upstream ports, during filling is of concern. Baffling is provided at adjacent manifold walls by offsetting ports between manifolds. Ports are chamfered with regard to outflow (filling) and inflow (emptying). Ports for high-lift designs (HB4 and HB8) experience high velocities and are chamfered for flow in either direction as shown in Plate 4-1. Tee baffle walls and baffles located on lock and culvert walls are required. The ratios of total port area to manifold areas are 1.000 and 0.865 for HB4 and HB8, respectively. These values near unity, similar to SP systems, are required for efficiency for bidirectional operation. Values substantially greater, 1.7 for the Greenup system shown in Plate 4-1, are efficient with regard to emptying (i.e., as an intake) but relatively inefficient for filling.

Section IV
Outlet Systems

4-19. General

Discharge outlet systems are the orifice controls for the emptying operation. The dominant chamber performance constraint is operation time as affected by outlet sizing. The dominant downstream approach channel constraint is navigation facility as affected by discharge hydrographs and outlet location (paragraph 4-9). The following distinctions regard sizing:

a. Expanding systems. The outlet port area is made greater than the chamber port area normally for the purpose of decreasing operation time. Concurrently, greater energy losses occur within the system (i.e., the chamber ports are not efficient as intakes) so that outflow velocities are also decreased. Both effects are favorable for low-lift locks. For high-lift locks, low local pressures and high pressure fluctuations are associated with expanding high-velocity systems.

b. Contracting systems. The outlet port area is made equal to or less than the chamber port area. The common purposes are to raise the hydraulic grade line within the system and to reduce discharge rates within the approach channel at the expense of increased operation time. Contracting systems are best suited for high-lift designs and are rarely appropriate for low lifts.

4-20. Design Types

Outlet design variations occur because of options regarding location. General types are outlined in Plate 4-2 as follows:

a. Manifolds in approach channel floor. One or several manifolds from each emptying culvert extend across the approach channel. The Bay Springs design results in uniform transverse flow distribution near the lock. The new Bonneville design requires the channel expansion (as tested for the Dalles lock, item 52) to be initiated near the manifolds in order to attain a uniform flow within the approach channel. The new

Bonneville system contracts (discharge port area to chamber port area ratio equals 0.83) whereas the Bay Springs system expands (ratio equals 1.14, item 78). The St. Anthony Falls Lower Lock is an example of large expansion and uses four lateral manifolds branching from one discharge culvert (item 44). The flow conditions in the lower approach for the new Kentucky Lock manifold were evaluated numerically (item 91) to help assess the impact to navigation during lock operations.

b. Manifolds in guide and guard wall. Two such expanding systems are shown in Plate 4-2. The Trinity River model test manifold discharges directly into the lock approach (item 74). The New Cumberland Main Lock discharge is subdivided by the main lock into river, main approach, and auxiliary approach components (item 21). The Trinity River system requires baffles at each port. These types of approach-channel manifolds are low cost and are well-suited for low-lift projects when higher velocities and turbulence in the approach near the lock are acceptable (as contrasted with remote outlets, *c* and *d* below). An outlet similar to the Trinity River system was evaluated for the Red River Locks, item 88, to help flush sediment away from the lower miter gates. Prototype tests were performed for the existing Kentucky Lock manifold (item 93) which discharges into the lower approach to determine hawser forces on tows moored in this area. A manifold and stilling basin design were developed for the landside outlet diffuser model tested for the J. T. Myers Lock extension project (item 107).

c. Basins. Normally and when economically feasible, the most favorable outlet location as regards navigation is in the main river remote from the lock approach. Basins used for these outlets are as shown in Plate 4-2. The Greenup Lock type basin is relatively deeply submerged (item 43) so that energy dissipation within the flow exterior to the basin is acceptable. The Jackson Lock type is designed (item 32) as a stilling basin; test data pertain to designs without and with various spacings of baffle blocks and end sill. Lower Granite (high-lift) uses a Greenup-type basin with a contraction (discharge port area to chamber port area ratio equals 0.80). Ozark Lock (low-lift) uses a Jackson Lock unbaffled basin with an expansion (ratio equals 1.29).

d. Other types. The outlet may be placed (usually remotely) so that other outlet structures as used elsewhere (outlet works for example) suit a site-specific design. The structure must:

(1) Provide conditions (particularly with regard to navigation) in the lower approach that are satisfactory.

(2) Have expansion or contraction conditions between chamber manifolds and outlet that are acceptable with regard to chamber performance.

(3) Provide a capability for reliably handling structural and hydraulic needs (particularly large intermittent discharges) during lock chamber emptying.

Section V
Intakes

4-21. General

Intake flows are essentially unidirectional. The design pertains to filling only and seeks to accomplish the following objectives.

a. Navigation and sedimentation. The location and orientation are such that adverse effects on navigation and channel sedimentation are avoided (see constraints, Chapter 2).

b. Debris and ice. The elimination of debris from the culvert normally requires trashracks at the intakes. These are placed on the wall face (common) or immediately within the wall structure (Lower Granite, item 79). The reduction of clogging at the intakes and sediment transport into the culverts is of obvious benefit in terms of lock maintenance (see paragraph 3-13). Trashracks must be secured for small reverse loadings that occur during lock chamber overfill.

c. Velocities. The intake is designed as a highly convergent streamlined manifold having the concurrent objectives of equal flow distribution through the ports and small energy loss. Small energy loss contributes to efficient lock filling and, for two-culvert systems, enables equal culvert flows to be attained with substantially different intake configurations. Low velocities through the trashbars place less stress (and reduce the possibility of flow-induced vibration) on the exposed structural elements. Existing rack structures are generally conservative for peak velocities less than 4 feet per second (fps); higher velocities may require special attention (EM 1110-2-1602; EM 1110-2-2602).

d. Vorticity. The formation of large vortices at lock intakes is considered highly undesirable because of hazard to small vessels, imbalance between culvert flows, and damage to trashrack. The elimination of vortex action for a specific filling pattern requires studies (see Chapter 5, Section VIII) of the following items:

(1) *Local geometry and flow constraints*. Geologic and structural features, such as the shape and orientation of guide and guard walls, may introduce vorticity into the intake flow. Similarly, adjacent spillway or river flows may result in vortex formation under a particular format of overall project operation. An intake located outside the approach channel so that navigation is not affected by vorticity over the intake structure is advantageous at many projects.

(2) *Structure type*. Generally, for small submergence, intakes are long and shallow with numerous ports (8-12 are not uncommon); a uniform distribution of flows over the length of the structure tends to reduce vortex formation. Short and high intakes (four ports at Lower Granite) may function satisfactorily when deeply submerged.

(3) *Submergence*. Deeply submerged intakes (see EM 1110-2-1602) are generally less prone to vorticity than these with shallow submergence. Extrapolating submergence effects based solely on changing upper pool levels as compared to changing intake elevation (with fixed pool level) is questionable because of local geometry.

(4) *Operation*. Vorticity intensifies as the valve is opened and persists during and sometimes beyond the lock-filling period. Operational situations, particularly valve opening times and maximum flow values, are important.

4-22. Design Types

Examples of intake structures are shown in Plate 4-3 with layout parameters listed in Table 4-7. These and other intakes have been studied (physical hydraulic models) and adopted for site-specific application.

Table 4-7
Examples of Model-Tested Intake Layouts[a]

Lock	Lift ft	Q cfs	No. of Ports	Port Height ft	Port Width ft	Manifold Length ft	Pier Thickness ft	Submergence ft
Holt	63.6	7,000	1	31	18	18	NA	46.5
Lower Granite	105.0	13,600	4	30	8	47	5	58.0
Greenup	32	7,000	8	12b	8	99	5	14.0
Bay Springs	84	9,100	10	14	7	115	5	48.0
Dardanelle	54	6,000	13	13	7	151	5	24.0
Barkley	57	4,400	2 × 4	13	7.5	66	12	29.0
Dardanelle	54	6,000	2 × 7	13	7	79	5	24.0

Note:
[a] Dimensions exclude rounding at the wall face.
[b] 4-ft-high sill, culvert at intake 18 ft wide by 16 ft high.

Section VI
Filling-and-Emptying Valve Systems

4-23. General

Recent lock designs use reverse tainter valves for flow control. Alternate valve types provide less desirable hydraulic, structural, operational, or economic conditions. The normal tainter valve (skinplate upstream) has been replaced for lock design by the reverse tainter valve (skinplate downstream) because of the ease of regulating air demand for the latter design. The normal valve is not precluded from lock design (particularly as an emptying valve); however, current practice is to use the reverse tainter valve for emptying as well as filling. Comprehensive design guidance presented in EM 1110-2-1610 provides details regarding valve types, loadings, losses, etc.; this discussion is limited to an overview of the valves as they relate to the overall filling-and-emptying arrangement. The following paragraphs deal exclusively with reverse tainter valves.

4-24. Valve Sizing

By using streamlined contractions upstream and gradual expansions downstream, the valves can be sized substantially smaller than the main culvert section. Section area changes commonly are accomplished by a change in culvert roof elevation rather than offsetting the culvert walls. Large valves (e.g., 18 ft high by 16 ft wide) are designed for the *new* Gallipolis low-lift lock. The extreme contraction-and-expansion design is at the Lower Granite high-lift lock, which, for a 22-ft-high by 12-ft-wide main culvert, uses 14-ft-high by 12-ft-wide filling-and-emptying valves. The advantage of small valves is lower cost particularly, because of the greater loading, at high-lift projects. Higher velocities and lower pressures at the valve location occur for small valve designs during valve full open conditions.

4-25. Valve Siting

Structural, operational, and economic considerations for valve siting must satisfy the following hydraulics topics.

a. Position along the culvert. The filling valve, downstream from the intake manifold, and the emptying valve, upstream from the outlet, are separated from the culvert-to-chamber system by a streamlined transition conduit. The fundamental requirement is that the distribution of flow into and out of the culvert-to-chamber system is not unbalanced due to nonuniformity in the adjacent main conduit flow. Current guidance requires a distance of 6.5 culvert heights (as measured at the filling valve) between the filling valve and the culvert-to-chamber system (EM 1110-2-1610).

b. Elevation. The hydraulic consideration is pressure downstream from the valves that contributes to air entrainment and cavitation. Entrained air, particularly for low-lift locks, may accumulate in the culverts as a pressurized air mass with the potential for bursting through the water surface and through vents and wells. Well-mixed air is more common for high velocities associated with high-lift locks and, when excessive, causes a frothy condition at the outflow water surface. Guidance on air entrainment is included in EM 1110-2-1610. Cavitation, particularly at high-lift locks, may cause surficial damage to culvert walls, valve seals, and other exposed valve components. A condition in which cavitation causes pressure shock waves to occur in the flow downstream from the valve is resolved during design by either air venting the low-pressure region below the valve so that air rather than vapor pockets occur; setting the valve at a low elevation so that vapor pressures do not occur; or using a less efficient system also so that vapor pressures do not occur. Guidance for avoiding cavitation is included in EM 1110-2-1610.

Section VII
Culvert Layouts

4-26. General

The culvert geometry includes bends, contractions, expansions, junctions, bifurcations, etc., as required to resolve the plan and profile layout of the intake, valves, culvert-to-chamber, and outlet systems. Recent designs use rectangular culverts. The aspect ratios (height to width) near 1.0 are common although values as extreme as 1.6 and 0.6 have occasionally been used. Ratios at the valve location (18:16, 14:12, 12:12, etc.) are always near unity for valve structure and economy reasons. Hydraulic design parameters, such as those included in EM 1110-2-1602, are equally applicable to lock culverts provided allowance is made for the normally short spacing between components and the unsteady nature of lock flows. Published compilations (item M9, for example) and studies (item M5, for example) provide useful hydraulics guidance.

4-27. Contracting and Expanding Systems

System sizing (intake, filling valve, culvert-to-chamber, emptying valve, and outlet) establishes the extent of section area and shape changes within the culvert. These changes (examples are illustrated in Plates 3-3 and 3-4, SP systems; Plates 3-5 and 3-6, BL1 and BL2 systems; Plates 3-7 and 3-8, HB4 and HB8 systems) are particularly susceptible to separation at boundaries introducing energy loss, turbulence, and, particularly for high-lift locks, cavitation effects into the flow. To avoid these problems, expansions are normally gradual (roof expansions 1V:6H to 1V:10H are common) and contractions are streamlined. The flare of each SP port sidewall, for example, is about 3 degrees for filling; rounding at port intakes and outlets has ranged from about 0.5 to 2.0 ft.

4-28. Other Transitions

Numerous transitions have been used and tested for lock designs. Hydraulic model and prototype studies (see Appendix C) are sources of information regarding application or previous use in lock design. EM 1110-2-1602, other hydraulics design manuals, and published references (item M9, for example) provide useful guidance for hydraulic design.

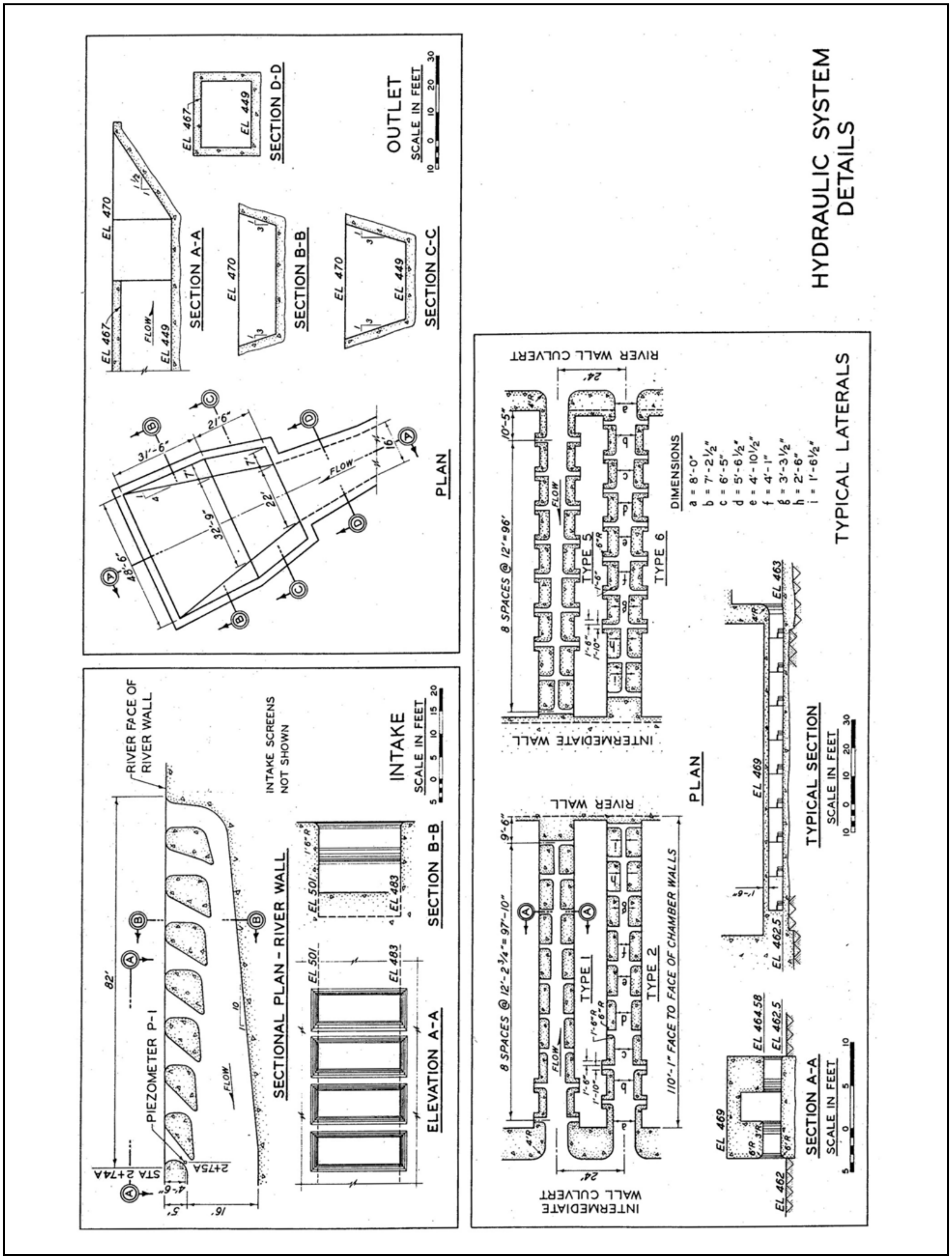
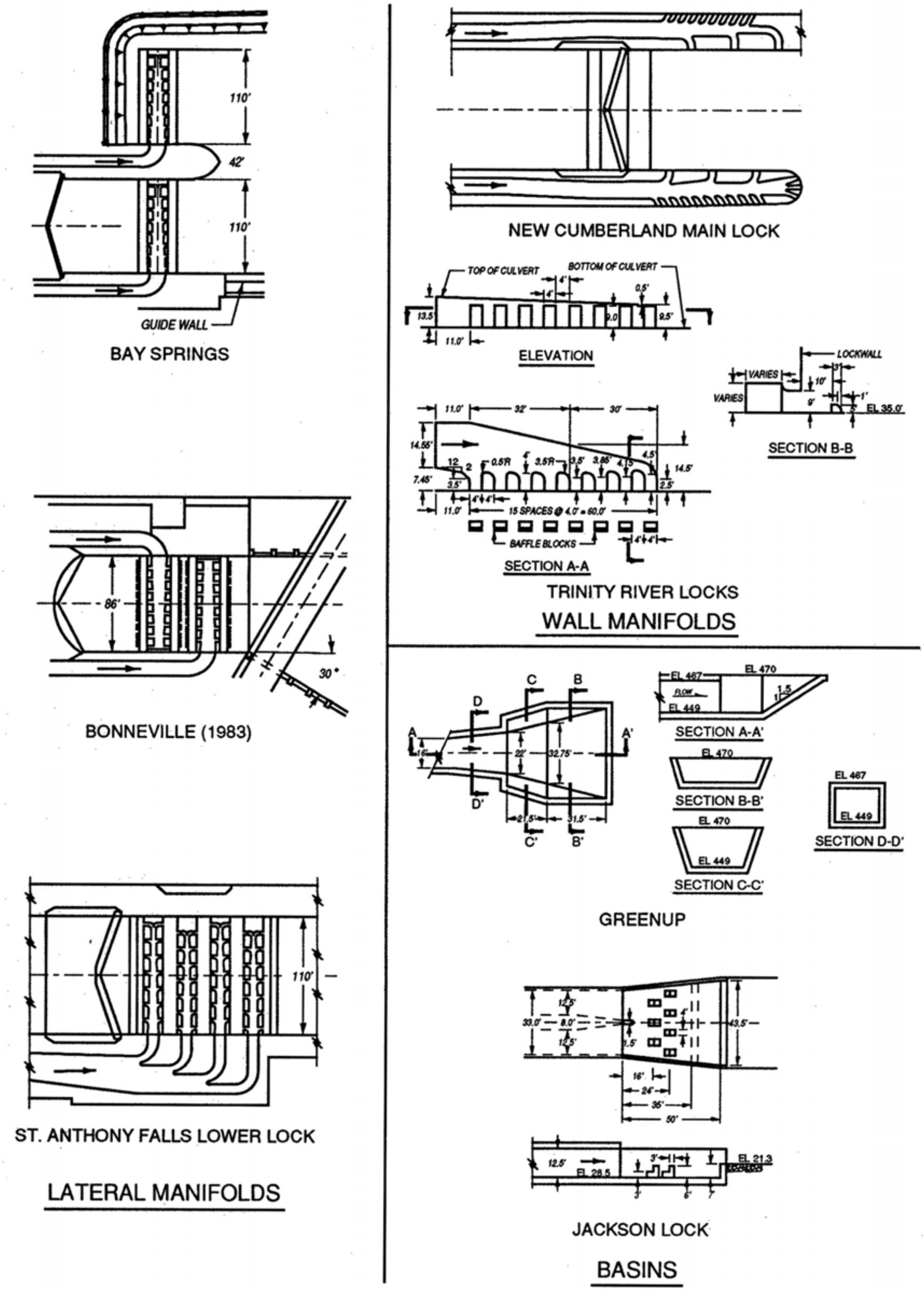
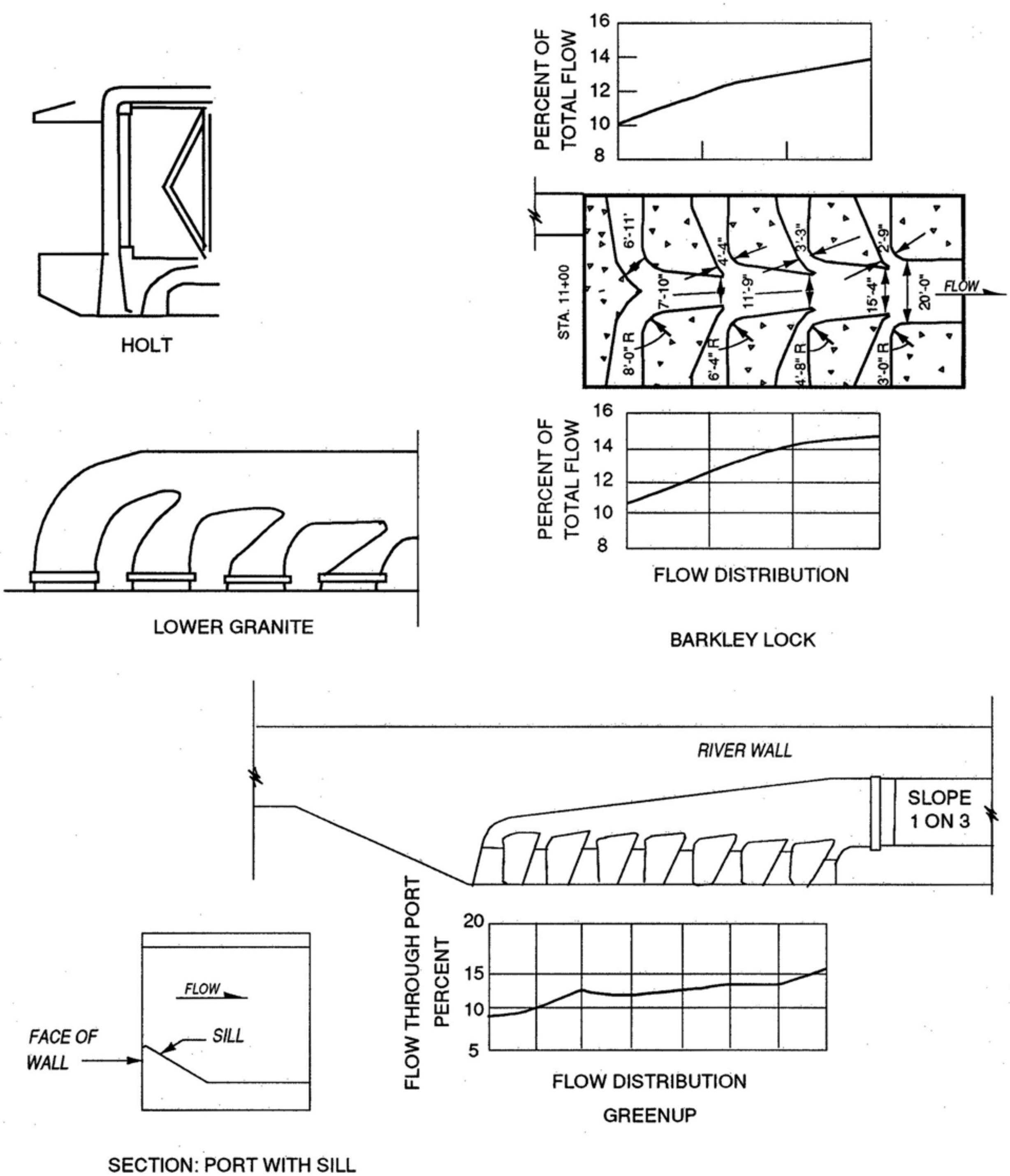

HYDRAULIC SYSTEM DETAILS
PLAN
SECTION A-A
SECTION B-B
SECTION C-C
SECTION D-D
OUTLET
SCALE IN FEET
SECTIONAL PLAN - RIVER WALL
ELEVATION A-A
INTAKE
INTAKE SCREENS NOT SHOWN
RIVER FACE OF RIVER WALL
PIEZOMETER P-1
TYPICAL LATERALS
TYPICAL SECTION
DIMENSIONS
a = 8'-0"
b = 7'-2 1/2"
c = 6'-5"
d = 5'-6 1/2"
e = 4'-10 1/2"
f = 4'-1"
g = 3'-3 1/2"
h = 2'-6"
i = 1'-6 1/2"
RIVER WALL CULVERT
INTERMEDIATE WALL CULVERT
INTERMEDIATE WALL
RIVER WALL
TYPE 1
TYPE 2
TYPE 5
TYPE 6
8 SPACES @ 12'-2 3/4" = 97'-10"
8 SPACES @ 12' = 96'
110'-1" FACE TO FACE OF CHAMBER WALLS

Plate 4-1



OUTLET TYPES


HOLT
PERCENT OF TOTAL FLOW
16
14
12
10
8
6'-11'
4'-4"
3'-3"
2'-9"
STA. 11+00
7'-10"
11'-9"
15'-4"
20'-0"
FLOW
8'-0" R
6'-4" R
4'-8" R
3'-0" R
PERCENT OF TOTAL FLOW
16
14
12
10
8
FLOW DISTRIBUTION
LOWER GRANITE
BARKLEY LOCK
RIVER WALL
SLOPE
1 ON 3
FLOW THROUGH PORT PERCENT
20
15
10
5
FLOW DISTRIBUTION
GREENUP
FLOW
FACE OF WALL
SILL
SECTION: PORT WITH SILL

Chapter 5
Special Hydraulic Study Topics

Section I
Introduction

5-1. Baseline Analysis

The hydraulic analyses of lock filling and lock emptying require an unsteady flow formulation that includes the decreasing head caused by the rise or fall of the chamber water surface. The objective is to determine, as a function of time, three basic quantities:

a. Chamber water-surface elevation.

b. Flow rate exiting (filling) or entering (emptying) each of the chamber manifolds.

c. Hydraulic grade line from the reservoir intakes to the lock chamber (filling) or from the lock chamber to the outlets (emptying). The grade lines include valve wells and other attached flow passages.

5-2. Baseline Constraints

Conditions normally imposed on the analysis are chamber, approach, and system geometries and hydraulic characteristics; initial upper, lower, and chamber water-surface elevations; valve geometry, opening pattern, and hydraulic characteristics; type of valving (commonly two synchronous valves or single valve); and type of operation (filling, emptying, or steady flow). Nonroutine conditions, such as instantaneous valving and bulkhead failures, may also require consideration during hydraulic design. The analysis, excluding mathematical considerations, varies in precision from lock to lock due to the following factors.

a. Stubby culverts. Lock culverts are short and contain elements (manifolds, valves, bends, transitions, etc.) in proximity. Published hydraulic coefficients as tested for individual elements are in error when directly applied to the composite system. Best results are obtained when culvert system coefficients are derived from a geometrically similar model or prototype.

b. Unusual shapes. The intake, chamber, and outlet manifolds, particularly, are function specific. Published data for nonlock manifolds are useful in concept but rarely in detail for the shapes used for lock design. Other unusual shapes and combinations of elements are not uncommon. Useful data, when available for these unusual geometries, generally come from previous lock hydraulic model or prototype tests.

c. Flow acceleration. Analysis, based on incompressible unsteady flow, is similar to established procedures (surge tank design, for example). However, specific information regarding the significance of wells, branches, junctions, ports, etc., is very limited. These information gaps are resolved, to the extent possible during design, by comparison with solutions for similar locks.

5-3. Analysis Results

The baseline analysis (paragraph 5-1) provides the basic quantities required as input for the design of individual flow passage elements. Conventional hydraulic practice applies to the design details.

Section II
Steady Flow in Lock Culverts

5-4. Discharge

For constant valve opening and fixed pool levels, the flow rate is given by an orifice discharge equation:

$$Q = CA\sqrt{2gH} \tag{5-1}$$

in which

Q =discharge per culvert, cubic feet per second (cfs)

C = discharge coefficient (referenced to area A)

A = reference cross-sectional orifice area, square feet (ft)

g = gravitational acceleration, 32.2 ft/second (sec)^2

H = difference in pool levels (head), ft. The difference is upper pool to chamber for filling and chamber to lower pool for emptying

The value of C, a measure of the efficiency of the design, depends on:

a. Reference area. The accepted practice is to use the cross-sectional area A_c at the culvert immediately downstream of the valve as the reference area A in Equation 5-1. Consequently, systems having small valves (relative to total efflux area) in culverts with streamlined contractions and expansions have large C values; systems with large valves having essentially the same Q and H relationship erroneously appear less efficient because of low C values.

b. Exit port geometry. Streamlining the efflux ports tends to increase efficiency (i.e., increasing Q for unchanged H corresponding to a larger C value). Similarly, increasing the total port area A_p tends to increase efficiency. However, observations indicate that when A_p exceeds about 1.1 times the manifold section area, no additional increase of Q is attained.

c. Energy loss. Head losses occur throughout the flow passage. Systems with streamlined transitions, smooth and short culverts, few boundary changes, and efficient manifolds have high C values.

5-5. Energy Loss Coefficient

The overall energy loss coefficient k_t is defined and compared to the discharge coefficient C (Equation 5-1) as:

$$k_t = \frac{H}{V^2/2g} = \frac{1}{C^2} \tag{5-2}$$

where

$V = Q/A_c$ = mean velocity at the reference section, fps. A range in C values from 0.5 to 0.9 corresponds to k_t values from 4 to 1.2; this range includes nearly all existing CE lock designs for either filling or emptying.

5-6. Individual Losses

The sum of individual loss contributions, boundary losses plus losses due to numerous form changes, as calculated using published friction and form loss coefficient values exceeds losses observed for lock filling-and-emptying systems. This difference is attributed to having stubby culverts (i.e., inadequate spacing so that established flow is not reached between identifiable boundary changes). Such summations are avoided in analysis by using model and prototype test data reduced to the form shown schematically in Figure 5-1.

5-7. Reynolds Number

Higher flow rates occur in prototype lock culverts than are predicted from model observations. This difference is attributed to a decrease in loss coefficient values corresponding to the much larger Reynolds number R for prototype flows. Reynold's number is defined as

$$R = VD_h / \upsilon \qquad (5\text{-}3)$$

where

D_h = hydraulic diameter; $D_h = A_c/P_c$ where P_c, ft, is the culvert perimeter at the reference section

υ = kinematic viscosity (for example, υ = 1.05 H 10^{-5} ft^2/sec for water at 70 EF and atmospheric pressure)

For a 1:25-scale model (common size, see Chapter 6) the difference in Reynolds number is 125-fold due to geometry alone. The Darcy-Weisbach friction factor is defined as

$$f = \frac{D_h}{L}\frac{H_L}{V^2/2g} \qquad (5\text{-}4)$$

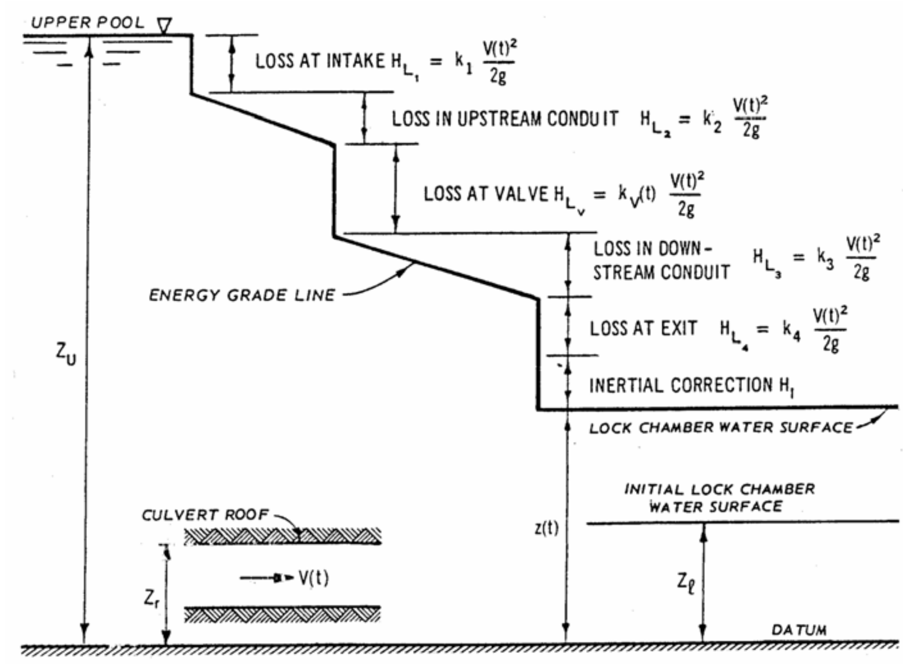
where

H_L = energy loss, in ft, over a length L in ft, of uniform conduit. For smooth boundaries, the reduction in f from a peak model R (say 10^5) to a peak prototype R (say 1.25×10^7) is from 0.018 to 0.008.

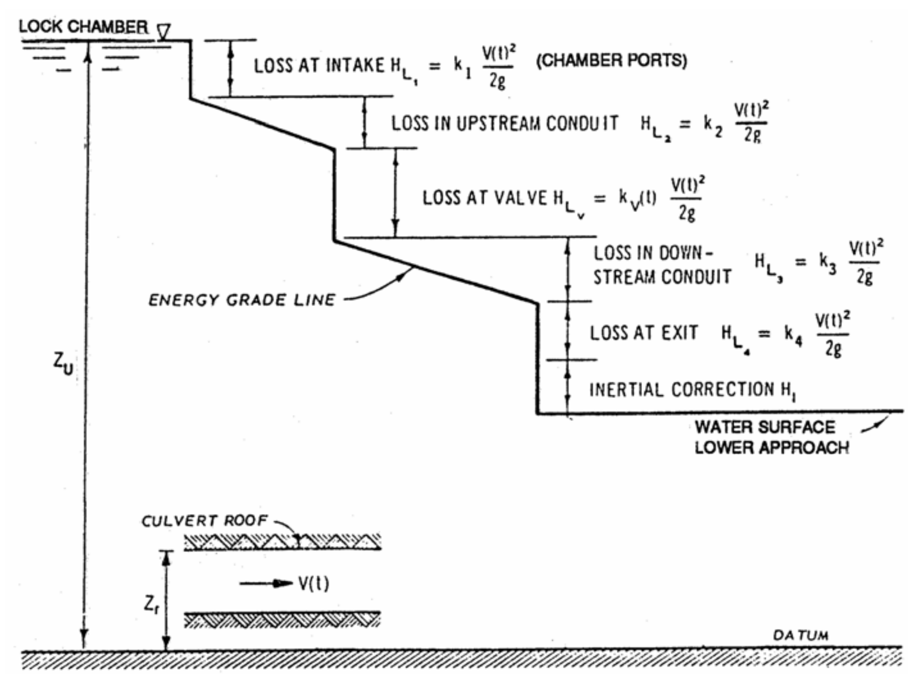
5-8. Energy-Loss Coefficient Values

This illustration uses Lower Granite Lock model test data reduced to the form shown in Figure 5-1 as listed in Tables 5-1, filling, and 5-2, emptying. Data are for two valves fully opened and steady flow.

a. Inflow (filling). Typically, the intake is a highly efficient combining-flow manifold, and the point of measurement (Table 5-1) is upstream of the region within which the velocity profile is restructured to culvert flow. Consequently the k_1 value is low, ranging from near 0.05 to about 0.15. Higher values may occur with a small total port area, trashrack blockage, or inefficient approach conditions.



a. Filling (valve full open)



b. Emptying (valve full open)

Figure 5-1. Hydraulic grade line determination. The schematics show common measurement locations and coefficients determinable from most model and prototype experimental studies. Steady flow conditions apply. Symbols are defined in Appendix J.

Table 5-1
Filling Culvert Loss Coefficient Example; Two Valves Full Open With Steady Flow (Lower Granite Lock, Item 79: BHL, TR No. 126-1, Table J)

Symbol[a]	Location	Coefficient with Reference Area = 168 ft.^{2}
k_1	Intake	0.08
k_2	US culvert	0.25
$k_{v,100}$	Valve	0.045
k_3	DS culvert	0.07
k_4	Chamber	1.19

Notes:
[a] Notation is described in Figure 5-1*a*.
[b] k_t = 0.08 + 0.25 + 0.045 + 0.07 + 1.19 = 1.635

Table 5-2
Emptying Culvert Loss Coefficient Example; Two Valves Full Open With Steady Flow (Lower Granite Lock Item 79: BHL TR No. 126-1, Table M)

Symbol[a]	Location	Coefficient with Reference Area = 168 ft.^{2}
k_1	Chamber	1.40
k_2	US culvert	0.24
$k_{v,100}$	Valve	0.045
k_3	DS culvert	0.16
k_4	Outlet	0.79

Notes:
[a] Notation is described in Figure 5-1*b*.
[b] k_t = 1.40 + 0.24 + 0.045 + 0.16 + 0.79 = 2.635

b. Upstream culvert (filling). This segment of a filling culvert is commonly convergent; vertical and horizontal bends and other changes in form and alignment vary significantly between projects. The k_2 value, 0.25 in Table 5-1, includes losses incurred at the intake as well as boundary and form effects on the flow within the culvert upstream from the filling valve.

c. Valve (filling). Valve loss coefficients, as determined from experimental data for valves in long culverts, are used (see Section IV). For valves located in a nonexpanding culvert the $k_{v,100}$ value is 0.045 as shown in Tables 5-1 and 5-2.

d. Downstream culvert (filling). This segment is commonly of constant section although variations occur (for example, Lower Granite is highly divergent). The determination as to whether the expansion affects valve loss (i.e., nearer to the valve than at Lower Granite) is described in Section IV. A low value, k_3 equals 0.07 in Table 5-1, is common particularly when effects of the more complex geometrical features are included in the chamber outlet loss.

e. Efflux (filling). The chamber manifold ports are orifice-type controls during filling. The value of k_4 decreases toward a minimum expected value of about 1.2 as the total port-to-manifold section area ratio increases to unity. Further increase in port area tends to cause little or no decrease in exit loss coefficient values. The value k_4 equals 1.19 in Table 5-1 includes effects due to the long and complex crossover geometry combined with a ratio equal to 0.84. More efficient filling (and emptying) would be expected with a ratio nearer to unity.

f. Overall loss (filling). Using reference-area values from Table 5-1, the filling loss, k_t = 1.64, corresponds to a discharge coefficient value, $C = \sqrt{1/k_t} = 78$. Typically C filling values range from about 0.5 for inefficient systems, to 0.90 for highly efficient systems, although choice of reference area (valve sizing) can distort these values in a misleading manner.

g. Inflow (emptying). The chamber manifolds are inefficient intake devices (manifold loss coefficient k_m equal to 0.84 in Table 5-2), and when a complex culvert arrangement such as that at Lower Granite is included, a high k_1 value for emptying occurs.

h. Upstream culvert (emptying). The emptying culvert is commonly of constant section although variations occur (for example, Lower Granite is highly convergent). The k_2 value, 0.24 in Table 5-2, includes losses incurred upstream as well as boundary and form effects on the flow within the indicated culvert length.

i. Valve (emptying). Refer to *c* above.

j. Downstream culvert (emptying). This segment is commonly of constant section although variations occur. The losses occurring within this segment at Lower Granite are considered negligible; k_3 equals 0.16 in Table 5-2.

k. Efflux (emptying). The outlets are orifice-type control during emptying; a value of k_4 near unity is expected for an efflux-area-to-reference ratio of one. The low value, 0.79 in Table 5-2, depicts to an unknown extent a larger effective efflux area (due to sidewall flare in the basin).

l. Overall loss (emptying). From Table 5-2, the emptying loss k_t equals 2.64, corresponding to a discharge coefficient C of 0.62. Typically, emptying C values are similar in range to filling values. Distortions due to choice of reference area also occur and, for the same lock, a lower emptying than filling C value is not uncommon.

Section III
Lock Filling and Emptying

5-9. General Features

a. Filling. During a filling run, as sketched in Figure 5-2(a), valve movement is initiated at time t equals zero. The initial differential head H is the difference in elevation between the upper and lower pools (i.e., $H = Z_U - Z$). The rate of rise, dz/dt, of the lock water surface increases to a maximum at time t_m after which it decreases continuously, reaching zero at time t_f. The valve is fully open at time t_v. The operation time (or filling time) is designated as T. The inertia of the water in the filling system causes the lock water surface to rise the distance d_f, termed the overtravel (or overfill) above upper pool, which occurs at time t_f.

b. Emptying. Parameters describing an emptying run (Figure 5-2(b)) are analogous to those of a filling run. For example, during emptying, the water surface tends to lower the distance d_e termed overtravel (or overempty) below lower pool, which occurs at time t_e.

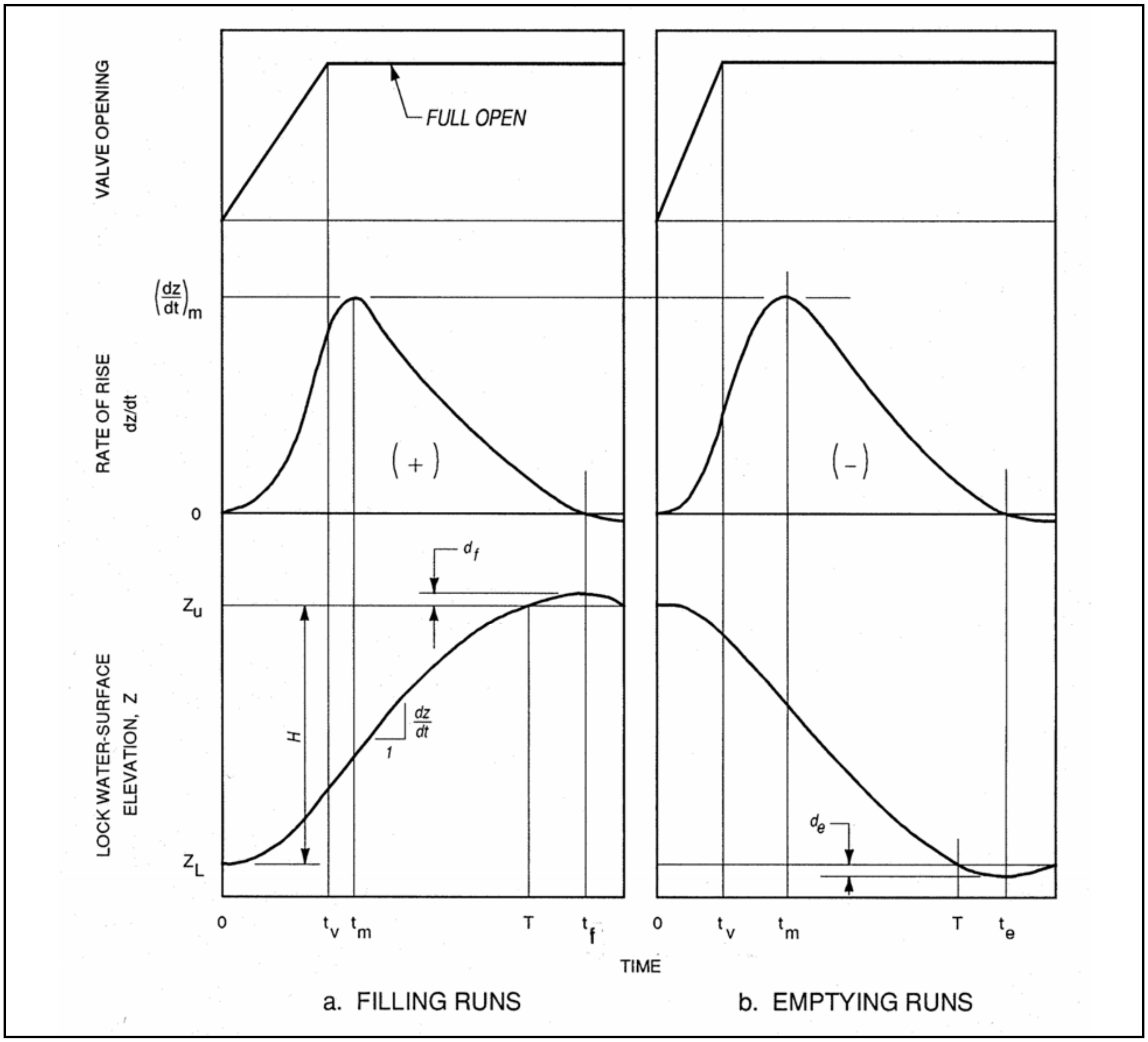


Figure 5-2. Lock filling and emptying (definition sketch)

5-10. Valve Operation

As noted in Figure 5-2, the valve hoist and linkage mechanism normally result in a nonlinear relationship between relative valve opening (b/B) and opening time (t/t_v) where b is the vertical gate opening, B is culvert height, t is time, and t_v is the valve operating time period. The pattern sag varies depending on the valve and linkage geometry and on the operating mechanism. The sag, when t/t_v is equal to 0.5, varies between 0.4 (large sag) and 0.1 (small sag). The following are variations in valve operation (applicable to either filling or emptying):

a. Normal two-valve (synchronous). Flow is through two culverts; the valves' operating mechanisms are identical and mechanically and electrically synchronized so that identical valve patterns are obtained. This is the type of valving preferred for normal lock operation.

b. Single valve. Filling or emptying with one valve (in a two-valve system) may be required for emergency or operation and maintenance reasons. Satisfactory chamber performance using one-valve operation is needed although longer operation times are usually acceptable.

c. Nonsynchronous valves. For this two-valve operation, either or both start time and opening rate differ between valves. This is not general design practice. However, prototype mechanisms and operating procedures contain many examples of designs deteriorated from synchronous into some form of nonsynchronous valving.

d. Stepped valves. The valves are opened to a particular value (commonly about one-fourth open), maintained in that position for some delay time period, then opened to full open. Stepped valving is not usually a design choice. However, certain postconstruction requirements for raising culvert pressures or reducing chamber oscillations have been resolved by means of stepped valves.

e. Special valve patterns. Smoothed (but essentially stepped) patterns are obtained using cams in the valve hoist mechanism for purposes similar to stepped valving. Variable-speed valve operations are capable with automated control, and model tests of the McAlpine Lock Addition (item 96) showed that this type of operation could speed up the safe filling time versus the normal two-valve synchronous operation. The IHNC lock model (item 102) demonstrated that since the sector gates were used due to large reverse head conditions in conjunction with the side port filling and emptying system, these two systems could be operated together during a filling operation to reduce the safe filling time.

f. Overtravel control. The extent of overtravel (d_f or d_e in Figure 5-2) is reduced by initiating valve closure prior to the normal lock operating time. Valve closure for many existing locks is initiated automatically using a differential water-surface-level sensor.

g. Valve opening time. Rapid valve times (near 1 min) are an existing design goal. The slow valving (8 min or greater) that is used at certain locks should be unnecessary for new lock designs.

Lock valve operations have been investigated as a means to lower the upper pool in an emergency situation for Lock 1 on the Upper Mississippi River (item 97). Valve operations were also investigated for the Whitten (formerly Bay Springs) Lock (item 100) to determine if these operations were contributing to culvert damage.

5-11. Lock Coefficient

The continuity relationship between culvert flow and chamber rate-of-rise when combined with steady-flow discharge coefficient (Equation 5-1) is the basis for the traditional empirical lock design equation (item P4). The solution is modified to include effects due to flow acceleration and valve opening pattern

$$T - Kt_v = \frac{2\,A_L\left[(H + d_f)^{1/2} - d_f^{1/2}\right]}{nA_cC_L\sqrt{2g}} \qquad (5\text{-}5)$$

where

T = lock filling time, sec

K = overall valve coefficient (not a loss coefficient)

t_v = valve opening time, sec

A_L = chamber surface area, ft^2

H = initial head (i.e., lift), ft

d_f = overtravel, ft

n = number of valves used, 1 or 2

A = culvert area at the valves, ft^2

C_L = overall lock coefficient

g = acceleration of gravity, 32.2 ft/sec^2

Equation 5-5 is adequate for preliminary study purposes only. A full hydraulic analysis requires numerical completed simulation of the system.

5-12. Operation Time Estimates

Equation 5-5 provides an acceptable estimate of lock operation time subject to the following observations.

a. The valve coefficient K is normally set equal to 0.5, but a variation from 0.4 to 0.6 occurs in practice. Equation 5-5 is therefore more reliable for rapid (instantaneous for model tests) valving.

b. The lock coefficient C_L for existing locks ranges from about 0.45 (relatively slow operation) to about 0.90 (rapid operation). However, since reference area A_c varies due to culvert roof expansions between otherwise similar locks, comparisons based solely on C_L may be misleading. The discharge coefficient C differs from C_L due to factors (Reynolds number, flow acceleration, valve pattern, etc.) not adequately incorporated into Equation 5-5.

c. The overtravel d_f is normally unknown (ranging from near 1 ft for short inefficient culverts to greater than 4 ft for long efficient systems). The relative insensitivity of filling time to overtravel value causes rough estimates to be within acceptable accuracy.

5-13. Basis For Numerical Simulations

The extent of hydraulic detail required in design calculations varies. Higher velocity systems (high lifts) require more detailed grade line elevation and velocity histograms so that energy losses, local velocities and pressures, air entrainment characteristics, surface and form cavitation potential, etc., can be evaluated. These evaluations should use references such as Hydraulic Design Criteria (HDC), EM 1110-2-1602, and other closed conduit flow guidance documents to supplement the hydraulic calculations described in *a* - *e* below.

a. The following summary of equations is an intermediate approach relating to lock filling which applies to emptying provided appropriate sign changes are included. “The overall head loss in the system is assumed to be made up of the five components listed below. Figure 5-3 shows an example of how the pressure gradient and the lock water surface (an indicator of overall head losses) vary with filling time.”

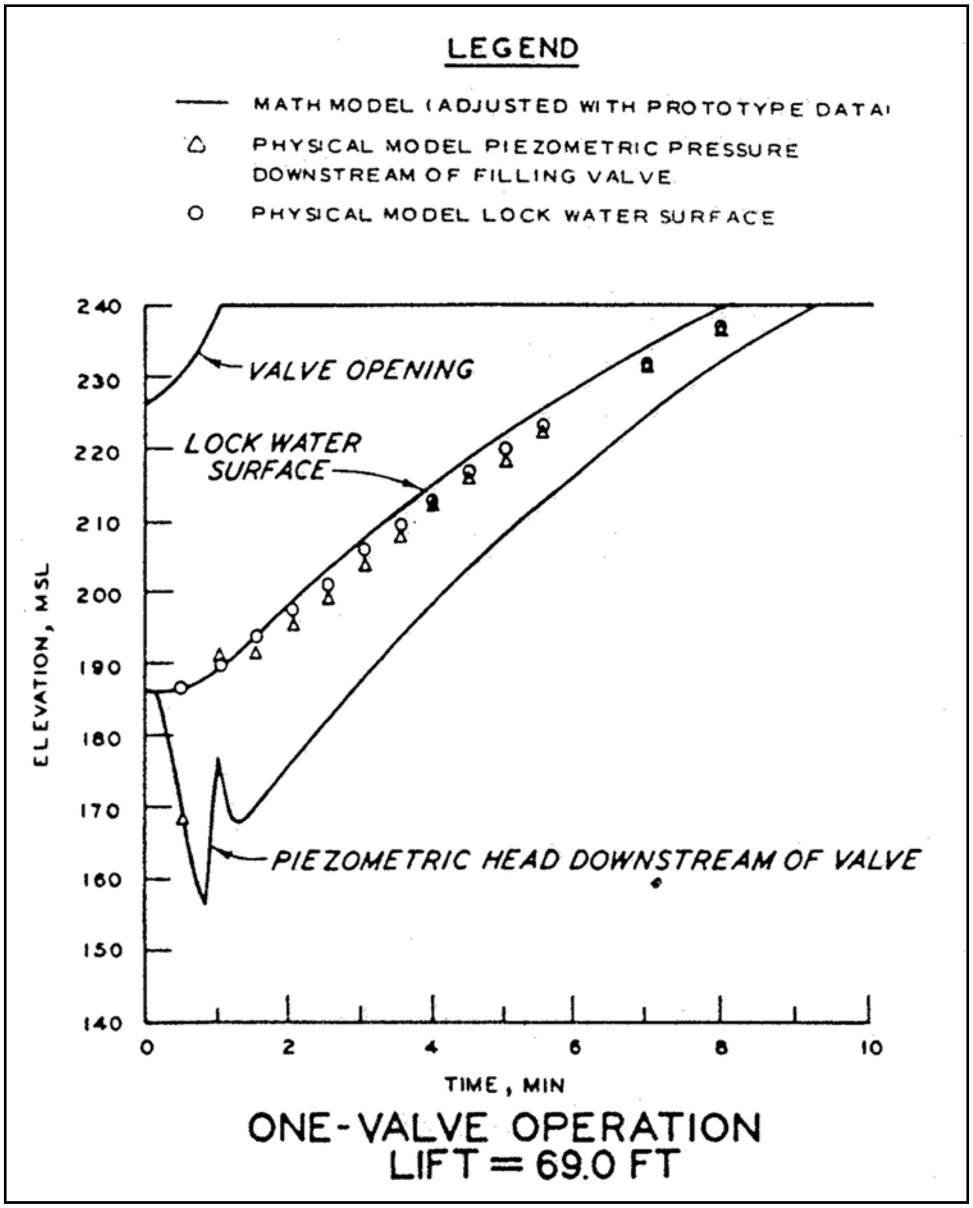


Figure 5-3. Schematic of the lock chamber (filling)

(1) Intake

$$H_{LI} = k_1 \frac{V^2}{2g} \qquad (5\text{-}6)$$

(2) Upstream conduit

$$H_L 2 = \frac{k_2 V^2}{2g} \qquad (5\text{-}7)$$

(3) Valve and valve well

$$H_{Lv} = \frac{k_v V^2}{2g} \tag{5-8}$$

(4) Downstream conduit

$$H_L 3 = \frac{k_3 V^2}{2g} \tag{5-9}$$

(5) Outlet

$$H_L 4 = \frac{k_4 V^2}{2g} \tag{5-10}$$

The overall loss H_{Lt} is

$$H_{Lt} = (k_1 + k_2 + k_v + k_3 + k_4)\frac{V^2}{2g} \tag{5-11}$$

or

$$H_{Lt} = \frac{k_t V^2}{2g} \tag{5-12}$$

Coefficients k_1, k_v, and k_4 are taken to be essentially form-dependent; coefficients k_2 and k_3 are not only affected by form but also by Reynolds number and relative roughness. However, in view of the Astubby@ conduits and the dominance of form effects in a lock system, the conduit coefficients k_2 and k_3 can reasonably be assumed constant for either model or prototype, bearing in mind that significant differences may exist between the model and the prototype values.

b. Since the flow is incompressible, the inertial effect is treated as a lumped quantity, that is

$$H_m = \frac{L_m}{g}\frac{dV}{dt} \tag{5-13}$$

where

H_m = overall inertial effect

L_m = inertial length coefficient

$$L_m = A_c \sum_{i=1}^{m} \frac{L_i \alpha_i}{A_i} \tag{5-14}$$

for a conduit made up of m sections of lengths L_i, areas A_i, and flow ratios α_i (i.e., $\alpha_i = Q_i/Q$ where Q_i is the flow through the i^{th} section).

c. The water-surface differential, $Z_U - z$ in Figure 5-2, is the sum of the inertial effect (Equation 5-13) and the energy losses (Equation 5-5) or

$$\frac{k_t V^2}{2g} = (Z_U - z) - \frac{L_m}{g}\frac{dV}{dt} \tag{5-15}$$

d. Continuity applies to the culvert flow (nA_cV) and the rate-of-rise, $A_L\ dz/dt$, of the lock chamber water surface

$$V = \frac{A_L}{nA_c}\frac{dz}{dt} \tag{5-16}$$

and

$$\frac{dV}{dt} = \frac{A_L}{nA_c}\frac{d^2z}{dt^2} \tag{5-17}$$

e. Integration of Equation 5-15 (with k_t = constant and for reasonably high lifts)

$$\frac{dV}{dt} = \frac{-gnA_c}{k_t A_L} \tag{5-18}$$

$$k_t = \frac{-g\,\dfrac{nA_c^{\,2}}{A_L}}{\dfrac{d^2z}{dt^2}} \tag{5-19}$$

f. Similarly, for overtravel,

$$d_f = \frac{L_m\, nA_c}{k_t A_L} \tag{5-20}$$

or

$$L_m = \frac{d_f\, k_t\, A_L}{nA_c} \tag{5-21}$$

Since the possible measurement error for d_f is always large, Equation 5-21 is not an appropriate means of evaluating L_m.

5-14. Mathematical Aids

a. Computer programs are available for most of the complex problems associated with lock operation. The four programs listed in Table 5-3 are applicable.

b. Database contents, H5300, are outlined in Appendix C. Computer input and output examples, H5310 and H5320, are included in Appendix F.

Table 5-3
CORPS Computer Programs for Lock Operation

Program	Brief Title	Description
H5300	Database-Lock Studies	Reports (86) are being arranged in a database so that description (251 items) and measurement types can be printed. Database is being filled.
H5310	Surge in Canals	Surge characteristics (idealized as presented in EM 1110-2-1606) are evaluated. Program is fully operational.
H5320	Symmetrical Systems	Hydraulic characteristics (idealized as described in Item H2 are evaluated. Program is fully operational.
H5322	Symmetrical Systems (R2)	H5320 revised to accommodate distributed flow acceleration and hydraulic friction and roof expansions. Program is operational off CORPS.

Section IV
Culvert Features

5-15. Goals

The importance of providing efficient hydraulic shapes for entrances, bends, expansions, contractions, etc., cannot be overemphasized. This is particularly important for components of hydraulic systems for locks with high lifts. Many existing locks have been designed without proper regard to efficient and smooth filling operations. However, modernization of obsolete projects introduces opportunities to design faster and more efficient system. In order to reduce the time required for lockage and still maintain safe operating conditions, the filling system is designed to provide equal distribution of flow into and out of chamber ports, to reduce surging and vortex action, and to provide culverts that are as hydraulically efficient as possible. The degree of refinement in the design of various units of the hydraulic system must be balanced by construction costs.

5-16. Improved Performance

Reduced operation time is achieved by streamlining the shape of the culverts and ports to reduce energy loss. Energy losses are reduced by having hydraulically smooth flow passages and rounded entrance corners on ports and conduits. Other aspects of improved performance also exist but are more difficult to evaluate. For example, proper distribution of the flow between manifold ports facilitates the dispersion and dissipation of jets issuing into the lock chamber or lower lock approach. In high-lift locks, streamlining for the elimination of excessive localized negative pressures and cavitation becomes increasingly important. Streamlining of the intake ports effects better flow distribution and reduces vortex action of the intake.

5-17. Evaluation

Although general criteria for the type and degree of streamlining that should be used for a given condition is not available, numerous examples can be found in model and prototype studies (Appendix C) that can be used for comparison. Corners should be sufficiently rounded to prevent separation of the flow from the boundaries. The angle of divergence in venturi-shaped ports should be small to avoid separation at the boundary.

Section V
Valve Hydraulic Characteristics

5-18. Design Concerns

Valve characteristics are provided in EM 1110-2-1610. Items of particular concern for reverse tainter valves as addressed in EM 1110-2-1610 are

a. Valve hoist loads.

b. Valve siting (including submergence and air venting alternatives).

c. Cavitation parameter evaluation.

d. Valve shape and structural description.

e. Valve lip details.

f. Valve loss coefficients.

g. Culvert roof pressure downstream from valves.

5-19. Valves With Expansions Downstream

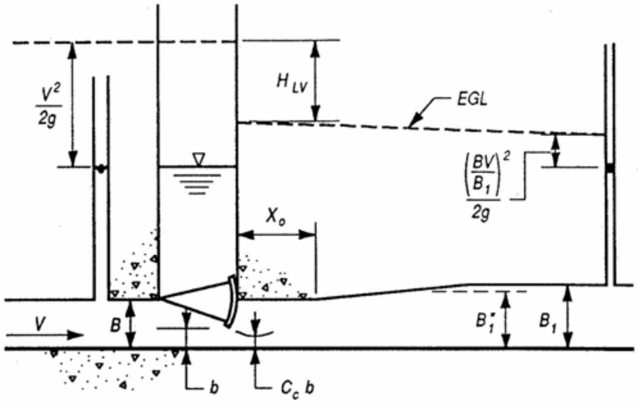
a. Recent concerns (item 83) with the change in energy loss due to a roof expansion immediately downstream from the valve are summarized in Plates 5-1 through 5-3. The roof expands from a value B (Figure 5-4) to a value B_1. The valve loss coefficient is equivalent to an abrupt expansion from a maximum jet contraction, $C_c b$ to an intermediate roof elevation B_1^*. The energy loss is greater with the expansion than with a horizontal roof. When the roof expansion begins more than 4.5 B downstream from the valve, the valve and expansion are treated as separate form loss items.

b. For equal flow rates the pressure drop coefficient defined in Figure 5-5 is not measurably influenced by downstream expansion.

Section VI
Low Pressure Effects

5-20. General Concerns

Subatmospheric pressure permits air to enter the flow (see Section VII). The abrupt release of air into the chamber or valve wells can cause unsatisfactory lock operation. Vapor pressure, which is the extreme lower limit of subatmospheric pressure, is a major concern for high-lift locks. A separation zone (sharp bends, abrupt expansions, joints, etc.) will develop local cavitation for sufficiently high velocities and sufficiently low approach pressures. Incipient cavitation criteria are available for surface finishes, control devices, and flow passage variations (see HDC and items B1, B2, B3, B10, C1, M10, N1, and R7). Criteria based on data from alternate hydraulic structures, such as outlet works, are applicable to locks provided approach velocities and pressures are correctly evaluated.



ENERGY LOSS

VALVE LOSS COEFFICIENT:

$$k_v = \frac{H_{LV}}{V^2/2g}$$

PRESSURE DROP COEFFICIENT:

$$E = \frac{\Delta h}{V^2/2g}$$

AND

$$E = (B/C_c b)^2 - 1.0$$

TERMINOLOGY

b = VALVE OPENING (FT)
B = CULVERT HEIGHT (FT) AT VALVE
B_1 = CULVERT HEIGHT (FT) DOWNSTREAM
B_1^* = EFFECTIVE CULVERT HEIGHT (FT) DOWNSTREAM
C_c = CONTRACTION COEFFICIENT
E = PRESSURE-DROP COEFFICIENT
EGL = ENERGY GRADE LINE; GRADIENT AND ELEVATION BASED ON DOWNSTREAM CONDITIONS
g = ACCELERATION DUE TO GRAVITY (32.2 FT/SEC^2)
h_R = MINIMUM PIEZOMETRIC HEAD (FT) ON CULVERT ROOF REFERENCED TO DATUM AT THE CONTRACTED JET
h_v = VELOCITY HEAD (FT); $h_v = V^2/2g$ AND IS NOT SHOWN
h_{vp} = VAPOR PRESSURE (NOT SHOWN; h_{vp} = -33.5 FT FOR WATER AT 50 °F)
Δh = DIFFERENCE IN PIEZOMETRIC HEAD (FT)
H_{LV} = ENERGY LOSS (FT) ATTRIBUTED TO LOCAL GEOMETRY, VALVE, AND ROOF EXPANSION (FT)
HGL = HYDRAULIC GRADE LINE: PIEZOMETERS ALONG CENTER LINE OF CULVERT ROOF
k_v = VALVE LOSS COEFFICIENT
P_R = MINIMUM PRESSURE (FT) ALONG THE CULVERT ROOF
Q = FLOW RATE (CFS); STEADY FLOW
V = VELOCITY (FT/SEC); $V = Q/BW$
W = CULVERT WIDTH (FT); W IS CONSTANT AND IS NOT SHOWN
X_o = EXPANSION OFFSET DISTANCE (FT)
σ = CAVITATION PARAMETER

Figure 5-4. Valve loss coefficient (definition sketch)

5-21. Reverse Tainter Valves

EM 1110-2-1610 addresses cavitation near reverse tainter valves at high-lift locks. Criteria for the assessment of cavitation potential is presented in Plate 5-4.

Section VII
Air Inflow and Outflow Devices

5-22. High-Lift Lock Air Vents

Valves for high-lift locks are commonly vented to preclude cavitation damage. Air vent design is presented in EM 1110-2-1610, EM 1110-2-1602, and HDC charts. Because of the potential adverse impact of air flow on chamber performance in the prototype lock and concerns regarding the minimum acceptable pressure below the operating valve, design practice is generally to oversize the air vent and establish a satisfactory orifice or air-valve setting to limit air flow. The orifice sizing or valve setting is established by observation in the prototype.

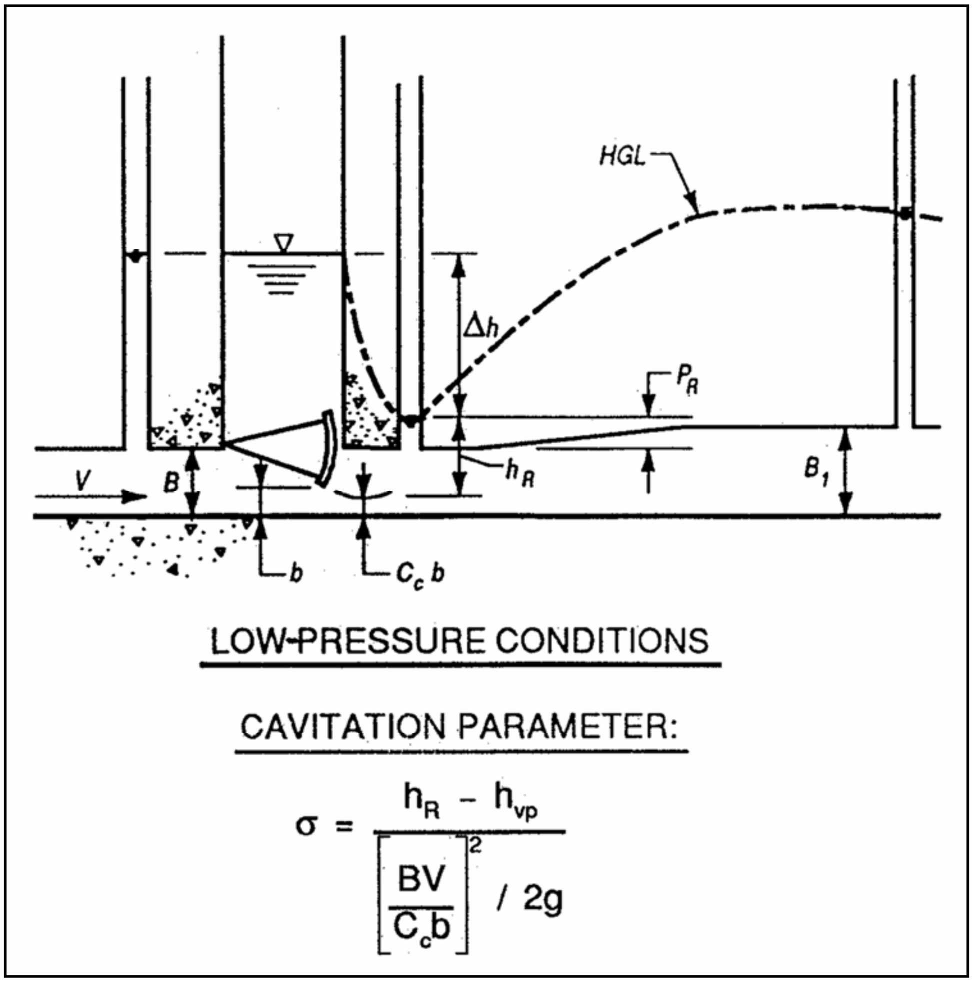


Figure 5-5. Definition sketch. Calculation of pressure at the culvert roof immediately downstream from the filling valve

5-23. Low-Lift Lock Air Vents

Older low-lift locks with high culverts and normal tainter valves have required air release vents between valve and chamber. Occurrences in which large disruptive air bubbles entered these low-lift chambers have been noted. For high-velocity flows (high lifts) the air entering the chamber tends to be frothy and not disruptive to lock performance. For any design (or modification) requiring air outflow vents, the rising pressure gradient along a manifold culvert (items M5 and M10) and air flow characteristics (item F1) are of concern.

Section VIII
Vorticity at Intakes

5-24. General

An intake manifold will operate at its maximum efficiency only when the approach flow is free of turbulence and vortexes. Vortex formation lowers the efficiency of the manifold by diminishing the effective area of the openings and by introducing a component of velocity perpendicular to the direction of flow. Basic design procedures that will ensure vortex-free approach flow are not known, but model tests on intake manifolds have indicated methods of improving approach flow conditions. In model tests on intake manifolds located in the top of the upper sill, with the series of ports parallel to the upstream gate, vortex action was reduced by decreasing the distance between the manifold and the upper gate; increasing the space between ports; increasing the port area at the sill face; and increasing the port submergence. Vortexes are less likely to occur during the accelerating flow of the valve opening period than in decelerating or steady flow. Vorticity is highly affected by local structures and channel geometries. Although precise scaling rules have not been established for these types of vortices, general guidance is to consider a surface swirl as acceptable whereas a depression (> 1/8 in. in the model) becomes questionable.

5-25. Evaluation

A larger entrance reduces intake losses, reduces the tendency to draw air into the intake, and reduces the chance of drift or ice damaging the racks by impact. By using several small intake openings instead of one large one, the flow is spread over a wide area; hence, the tendency for the formation of vortices and the suction of air into the culvert is further reduced. Enlargement of the intake and locating the top of the intake well below the minimum upper pool level ensures that the pressure gradient will be above the roof of the intake making it difficult to draw air into the culvert. The use of several small intake openings is also better structurally when the openings are located in a lock wall. Trashracks can also be kept to a reasonable size by the use of several small openings. When the intakes are located near to the upper pool level where floating drift or ice can easily reach them, the gross intake velocity is usually limited to 8 or 10 fps to avoid damage to the racks by impact.

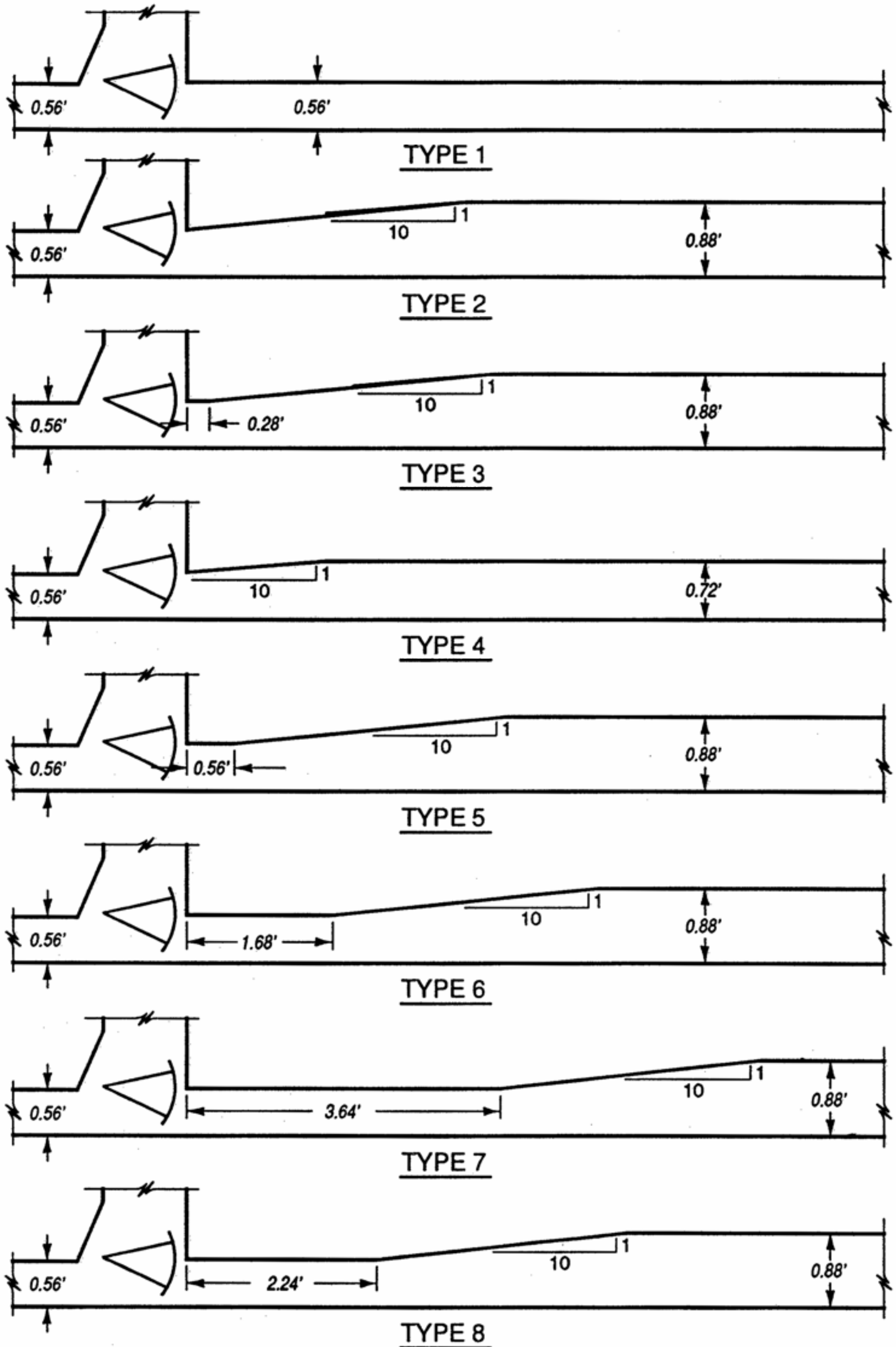
Section IX
Energy Dissipation at Outlets

5-26. Conditions

Unfavorable navigation conditions, such as excessive turbulence and unusual velocity patterns, are the major problems to be considered when designing a discharge manifold in the lower approach. Scour near the outlet structure is an additional concern whenever the outlet is near an unprotected channel boundary. The discharge manifold is usually kept as short as possible to minimize cost. The cushion depth remains essentially the same throughout the locking operation.

5-27. Options

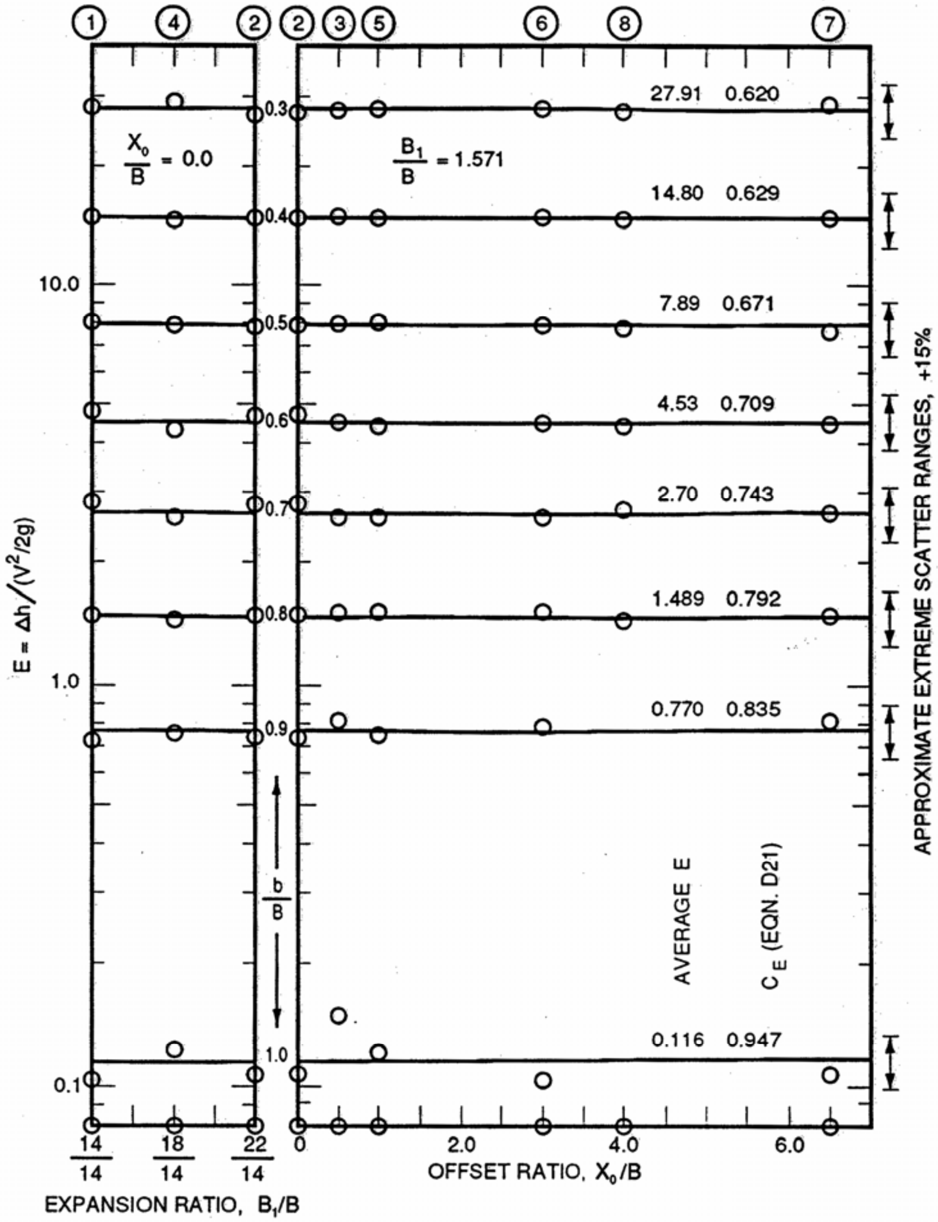
As discussed in paragraphs 4-19 and 4-20, discharge manifolds may empty all or part of the flow into the lower approach or into the river outside of the lower approach walls. When the total flow is discharged into the lower approach, the expansion in port area may have to be quite large to obtain low outlet velocities. The outlet location is normally not a factor (other than with regard to overfill and overempty) in chamber performance.



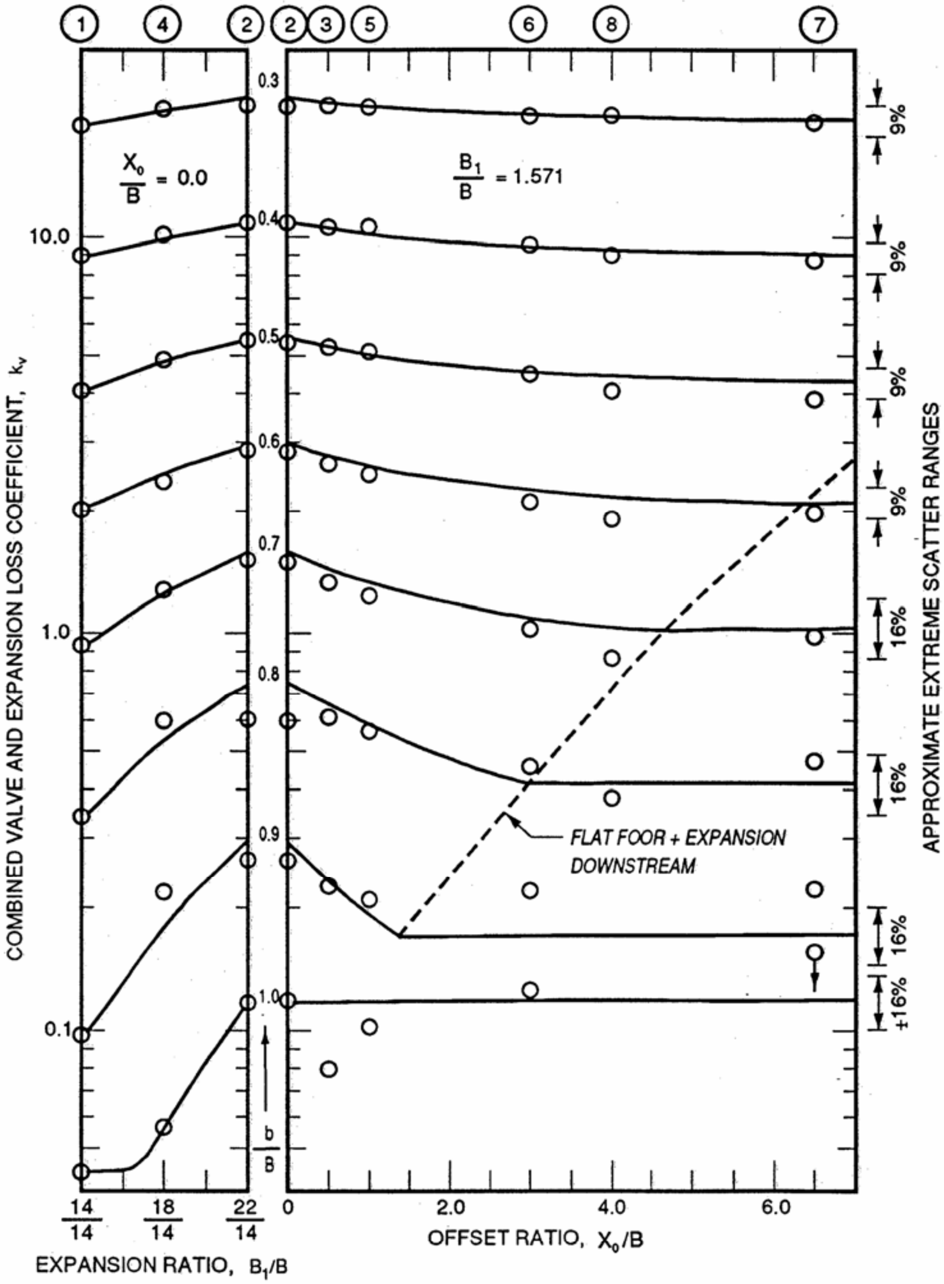
FROM ITEM 83

TYPE OF CULVERT ROOF EXPANSIONS USED IN LABORATORY STUDY

Plate 5-1



PRESSURE DROP COEFFICIENTS



FROM ITEM 83

VALVE-AND-EXPANSION
LOSS COEFFICIENT

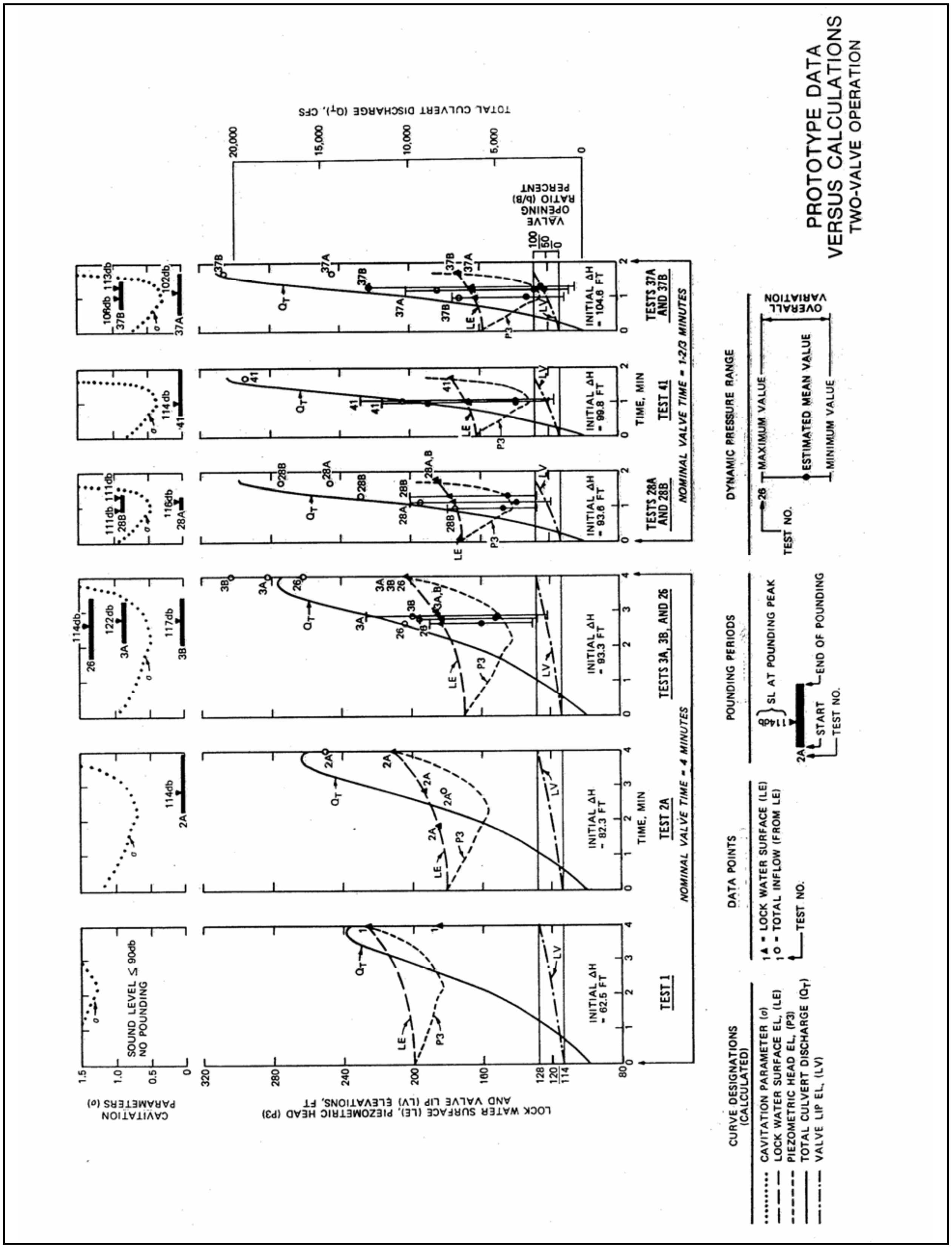

PROTOTYPE DATA
VERSUS CALCULATIONS
TWO-VALVE OPERATION
TOTAL CULVERT DISCHARGE (Q_T), CFS
VALVE OPENING RATIO (b/B) PERCENT
CAVITATION PARAMETERS (σ)
LOCK WATER SURFACE (LE), PIEZOMETRIC HEAD (P3) AND VALVE LIP (LV) ELEVATIONS, FT
SOUND LEVEL ≤ 90db NO POUNDING
INITIAL ΔH = 62.5 FT
TEST 1
INITIAL ΔH = 82.3 FT
TIME, MIN
TEST 2A
NOMINAL VALVE TIME = 4 MINUTES
INITIAL ΔH = 93.3 FT
TESTS 3A, 3B, AND 26
INITIAL ΔH = 93.6 FT
TESTS 28A AND 28B
INITIAL ΔH = 99.8 FT
TIME, MIN
TEST 41
INITIAL ΔH = 104.6 FT
TESTS 37A AND 37B
NOMINAL VALVE TIME = 1-2/3 MINUTES
CURVE DESIGNATIONS (CALCULATED)
CAVITATION PARAMETER (σ)
LOCK WATER SURFACE EL, (LE)
PIEZOMETRIC HEAD EL, (P3)
TOTAL CULVERT DISCHARGE (Q_T)
VALVE LIP EL, (LV)
DATA POINTS
1▲ = LOCK WATER SURFACE (LE)
1○ = TOTAL INFLOW (FROM LE)
TEST NO.
POUNDING PERIODS
SL AT POUNDING PEAK
START
TEST NO.
END OF POUNDING
DYNAMIC PRESSURE RANGE
TEST NO.
MAXIMUM VALUE
ESTIMATED MEAN VALUE
MINIMUM VALUE
OVERALL VARIATION

Plate 5-4

Chapter 6
Hydraulic Model Studies

Section I
Introduction

6-1. General

Laboratory studies have significantly improved the efficiency of lock filling-and-emptying systems. They have reduced lockage times and mitigated many conditions that have been hazardous to both traffic and structures. Prototype studies have verified and added to the data obtained from these model studies.

6-2. Purpose of Model Study

Data for the design of a filling-and-emptying system for a low-lift lock are available. However, if the filling-and-emptying system under consideration varies from conventional types, a thorough study using a hydraulic model may be necessary. A lock with a lift of 40 ft or more generally departs from conventional designs, and normally cannot be confidently patterned after other designs. Even though problems are not apparent, a model study usually brings to light corrections or improvements in design that result in smoother and faster operation and effects savings in construction and maintenance costs. Flow conditions in locks with lifts of 100 ft or more, require model studies and other specialized laboratory studies during early stages of the design process.

6-3. Scales

The most satisfactory scale ratios have been found to range from about 3:100 to 6:100. These scale ratios permit visual observations of turbulence and other flow conditions and permit the use of usual types of laboratory instruments for making measurements of pressures, velocities, discharges, and linear dimensions. A 1:25 scale predominates for recent lock studies.

6-4. Model and Prototype Similarities

Models must be geometrically and, to the extent possible, dynamically similar to the prototype. The common dimensional relationships applied to lock models are listed in Table 6-1.

Table 6-1
Model and Prototype Dimensional Relationships

Quantity	Dimension	Symbol	Scale Relationship
Scale relationship	L_m/L_p	r	____
Length	ft	L	r
Head, lift	ft	h, H	r
Area	ft^2	A	r^2
Volume	ft^3	L^3	r^3
Velocity	ft/sec	V, v	$r^{0.5}$
Time	min or sec	t	$r^{0.5}$
Discharge	cfs	Q	$r^{2.5}$
Force	lb	F	r^3

6-5. Model Construction

Construction materials used for lock models include metal, concrete, plastics, and wood. Transparent plastics are used for sections of conduit where observations of the interior flow conditions are desired and for forming curved surfaces such as entrances, bends, or dividing vanes. Where duplicate parts are required, such as lock chamber ports, lateral entrances, floor laterals, etc., it has been found that accurate reproductions can be made in concrete by the use of wooden forms. Swelling or contraction, which are objectionable features of wood, is not experienced with concrete. Materials for the various parts of the model structure should be selected on the basis of their resistance to dimensional change, particularly those sections and surfaces that are exposed to flow or changing volumes of water. The new Bonneville Lock Model is shown in Figure 6-1.

6-6. Instrumentation

Because of the variable flow conditions in a lock model and because these conditions change quite rapidly, it is essential to have an automatic method for recording most phenomena. Electronic transrecorders, digitizers, etc., have been developed that record and process automatically the following types of data:

a. Elevation of upper pool level (initial value, drawdown, etc.).

b. Elevation of lower pool level (initial value, swell, etc.).

c. Movement of culvert filling (or emptying) valve.

d. Elevation of water surface at required locations in the lock chamber.

e. Pressures at various points in the hydraulic system by means of piezometers, particularly among curved surfaces; at turns, contractions, and expansions; along the culverts; and at the control valves.

f. Longitudinal and transverse forces acting on vessels in the lock chamber (see Figure 6-2).

g. Rate of flow of water into the lock chamber (normally obtained from item *d* above).

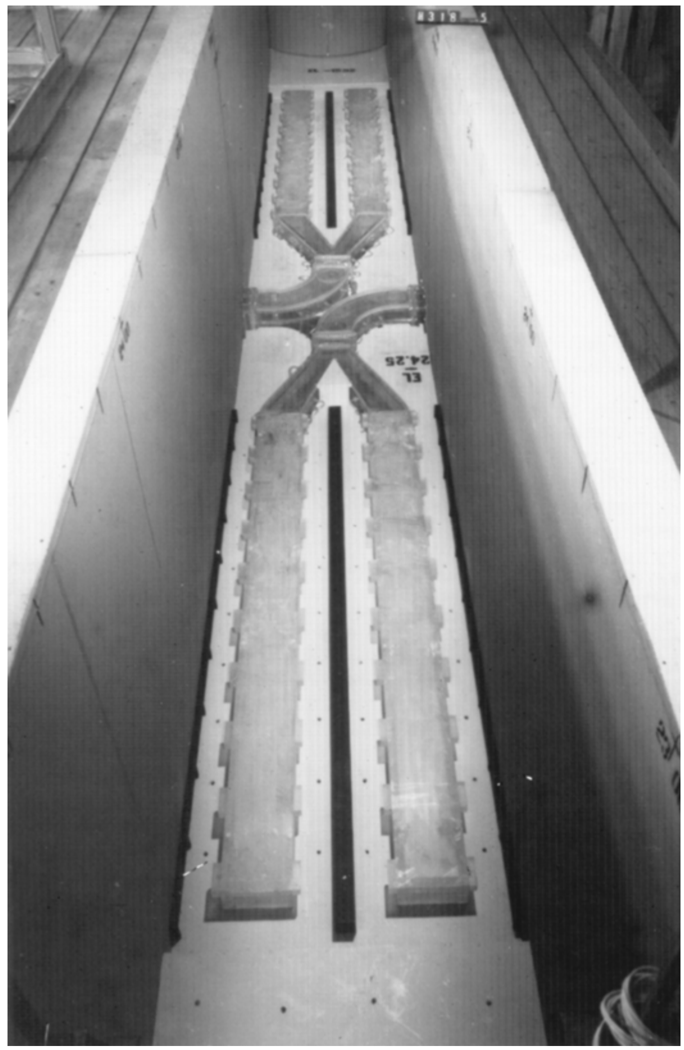


Figure 6-1. Hydraulic model of New Bonneville Lock. The following materials are generally used: chamber, marine grade plywood; culverts, manifolds, valve wells, Plexiglas; valves, bronze plate

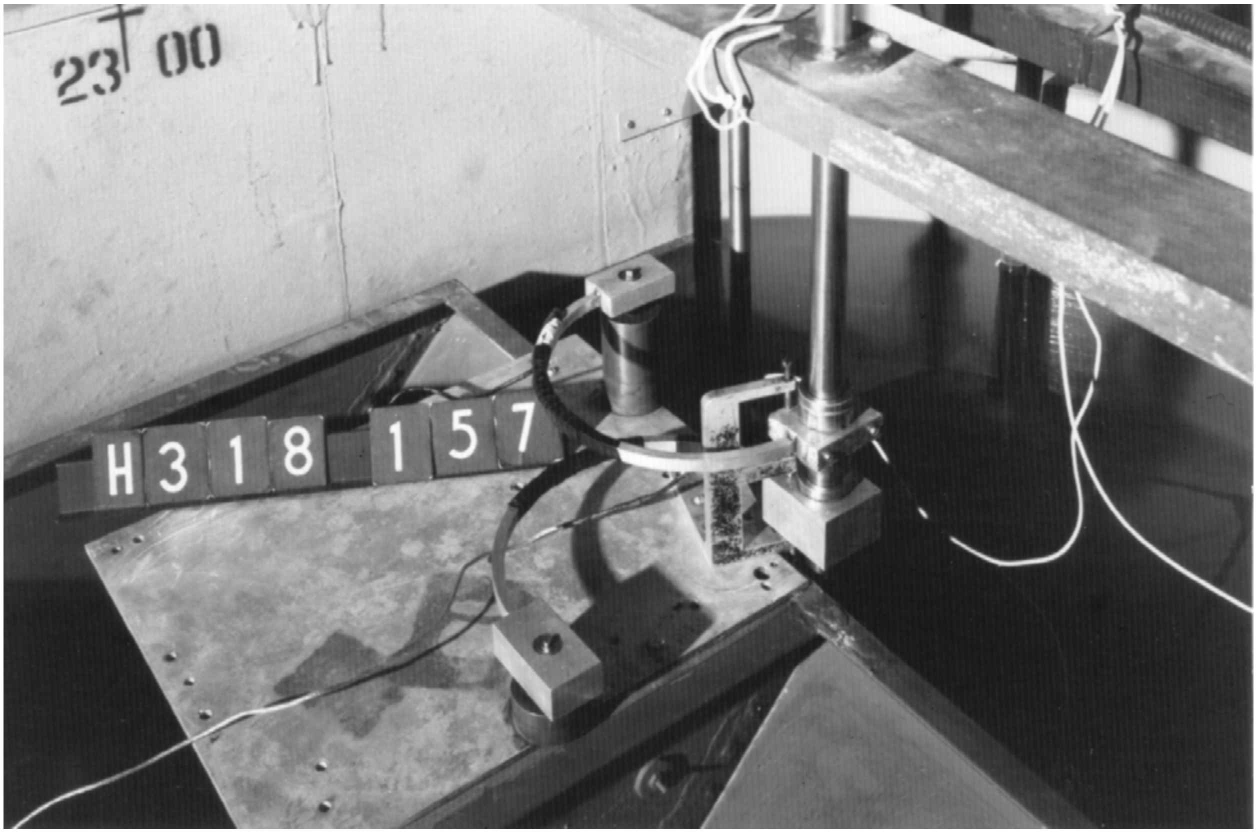


Figure 6-2. Hawser force measuring devices

h. Time synchronization to within about 2 sec (prototype scale); normally to about 0.4 sec, model scale (1:25 model).

i. An event signal that can be operated manually to indicate occurrence of special events such as the taking of photographs during an operation, etc.

6-7. Pressure Measurements

Piezometers recording pressures may be connected by flexible tubing to transparent glass or plastic tubes mounted on a manometer panel board rather than automatically read. These pressures can be read visually on the individual manometers or photographed as a group for later reading and interpretation. Only the latter method is feasible in a regular test where flow conditions are continually changing. Some lag in the readings occurs depending upon the diameter and length of the connecting tubing as well as on the rate of actual pressure change. Steady-flow tests are frequently made to permit more accurate observation of flow and head loss conditions in the system. Flow distribution in manifolds is usually determined using a pitot tube or other small flow-metering device under steady-flow conditions. Where rapid pressure fluctuations occur and cavitation or excessive negative pressures are suspected, the region in question should be investigated by means of surface-mounted electronic pressure cells. Areas of this nature may exist on the downstream face of control valves, culvert surfaces below valves, entrances to inlets, and at gate or bulkhead slots. An example measurement is shown in Figure 6-3.

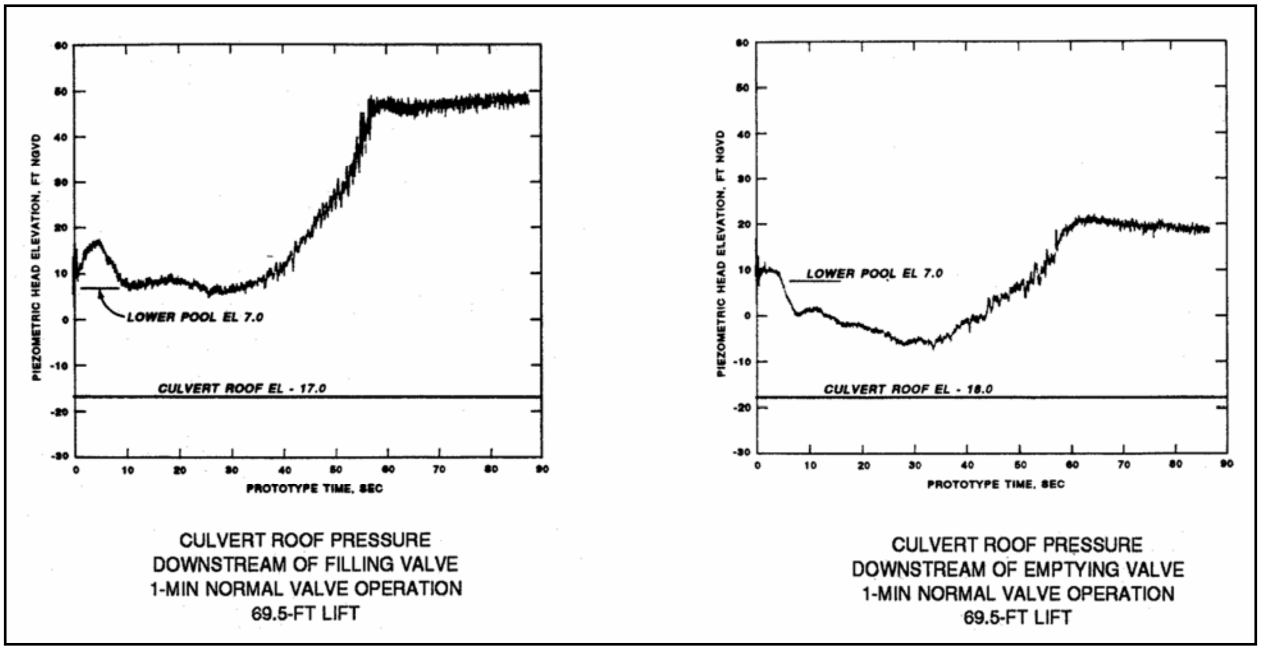


Figure 6-3. Dynamic pressure measurements

Section II
Prototype Expectations

6-8. General

A prototype lock filling-and-emptying system is normally more efficient than predicted by its model (paragraph 6-3). The difference in efficiency is acceptable as far as most of the modeled quantities are concerned (hawser forces, for example) and can be accommodated empirically for others (filling time and overtravel, specifically). However, in circumstances in which knowledge of extreme pressures within the culverts in the prototype is important, additional corrections to the predictions from the model are required. These corrections are particularly important for high-lift locks in which questions regarding cavitation (resulting from extremely low pressures) are of concern. More recent prototype data for locks can be found in items 87, 90, and 97.

6-9. Revisions to Scaled Values

Adjustments to model-based coefficients for prototype application are based on one of the following three general approaches.

a. Filling-and-emptying times. General guidance is that the operation time with rapid valving should be reduced from the model values by about 10 percent for small locks (600 ft or less) with short culverts; about 15 percent for small locks with longer, more complex culvert systems; and about 20 percent for small locks (Lower Granite, for example) or large locks having extremely long culvert systems. Although these values are approximate, the resulting C_L value is a reasonable estimate of discharge coefficient C, which in turn provides a reasonable basis for evaluating a prototype k_t value (see Chapter 5).

b. Similar (model and prototype) locks. A lock as similar as possible to the design lock and for which either operation time or culvert pressure data are available (model and prototype) provides a comparison such as in *a* above, or for pressure values, direct evaluation of prototype loss coefficient values.

c. Reynolds number corrections. Boundary friction differences, assuming smooth boundaries in both model and prototype, explain about one-half of the efficiency change with regard to operation time for certain locks (Lower Granite, for example). The remaining change is due to undeterminable variations in form coefficients or the Reynolds number difference. Sensitivity analysis (systematic variations in individual form coefficients) permits extreme conditions to be accounted for in design.

Section III
CE-Sponsored Hydraulic Model and Prototype Studies

6-10. Database

The database, H5300, contents are summarized in Appendix C. The database is being filled to ultimately include the 86 reports and 251 features studied by WES, Bonneville Hydraulics Laboratory, and the St. Paul District as described in Appendix C.

Chapter 7
Other Hydraulic Design Features

7-1. Scope

Hydraulics design features not directly related to the hydraulic filling-and-emptying system are discussed in the following sections.

Section I
Surge Reduction

7-2. Solutions

Surge reduction is accomplished by:

a. Slower filling-and-emptying systems or longer valving. This results in lower surges at the expense of long operation time.

b. Surge basins to suppress the rapid drawdown (filling) or upwelling (emptying) during the normally brief period of rapid change in discharge rate.

c. Hydraulic surge control methods as a means of removing or adding water to a small canal located between two locks. Additional volume is needed during filling of the lower lock; removal is needed during emptying upstream.

d. Staged lifts to reduce peak flow rates (as in *a* above) at substantial increase in operation time.

e. Broad approach channels to lower surges; i.e., canalized systems are more susceptible to surge effects than are broad river systems.

7-3. Computational Aids

Surge reduction is discussed in EM 1110-2-1606. Surge height calculations as presented in EM 1110-2-1606 are computer accessible in the CORPS program library (H5310). An example input/output is presented in Appendix F. For long canals or more complex geometries, study aids such as more comprehensive analytical (computer-based) solutions or physical model studies are needed.

Section II
Impact Barriers

7-4. Purpose

The purpose of a barrier is to provide an energy-absorbing device for barge tows to prevent damage to the gates in the event of a collision. Four such devices have been considered for use to protect lower miter gates. They are wire rope fenders, steel collision barriers, concrete collision barriers, and rope system impact barriers. The rope system impact barrier has been studied for use upstream of upper miter gates (the other three types appear less suitable for upstream use). These barriers are discussed in EM 1110-2-2602.

Section III
Water Saving

7-5. Water Supply

During periods of low water on canalized waterways, a sufficient supply of water is required to maintain all navigation pools at or above planned normal pool elevations. The following factors affect pool elevation:

a. Available hydrologic water supply.

b. Leakage, seepage, and multipurpose (hydroelectric plant, for example) consumption.

c. Water requirements for lockages.

d. Pumpage or diversion, and return flow (where applicable).

e. Evaporation.

The water supply must be equal to or exceed the algebraic sum of the other factors in order to maintain the navigation pools. The water supply may consist of the natural flow of the stream, the supply furnished by storage reservoirs, or a combination of the two. A thorough investigation should be made for all items when any doubt exists as to the adequacy of the water supply.

7-6. Design Needs

Low-flow lock operation is an overall project concern that places site-specific conditions on hydraulic design. Such factors as operational procedures, canal surges and approach conditions, valve siting, etc., designed for normal conditions may not be suited for low flows.

Section IV
Dewatering

7-7. Concerns

Hydraulic concerns during dewatering include the following:

a. Bulkhead locations.

b. Pumping facilities.

c. Outflow conditions.

7-8. Coordination

Dewatering exerts an extreme static loading on structural elements and requires specific considerations during lock structural detail design (see EM 1110-2-2703 and EM 1110-2-2602). Structures used for emergency closure are normally suitable for dewatering (item B5).

Section V
Emergency Closure

7-9. General Emergency Situations

Emergency situations occur at navigation locks when a lock gate becomes inoperative in an open or partially open position while a head differential exists between the chamber and upper or lower pool. Although the cause may be mechanical failure, the more frequent cause is a navigation error that holds the gate partially open. Although no universally accepted definition of *emergency closure* exists, the required action is generally understood to be that a closure structure must be rapidly placed in flowing water under head differential.

7-10. Consequences of Pool Loss

The main consequences of upper pool loss *downstream* of the project are due to the flood wave. Hazardous navigation conditions and rapid flooding of riverfront property are extreme possibilities. A less severe flood wave will commonly interfere with the operation of private and commercial boat docks. *Upstream* impacts of pool loss include the following:

a. Economic and safety problems occur at commercial and recreational boat terminals. Long periods of navigation suspension have a severe adverse impact on the economy of an entire region. The primary loss on major navigating systems is loss of navigation channel.

b. In many areas, small riverfront communities depend on the maintenance of normal pool for water supply. Loss of pool during low-flow periods causes inconvenience and, possibly, health and fire hazards.

c. Rapid loss of pool and resulting drawdown causes bank instability. This problem is especially severe where important structures, highways, or railroads are located in the reach of instability.

d. A navigation project that includes hydropower loses some or all of its power-generating capability in case of upper pool loss.

e. Upstream pool loss causes a severe and adverse impact on fish and wildlife.

f. Upstream pool loss affects other site-specific factors particularly during extremely low upper pools.

7-11. Preliminary Studies

In the design of most modern navigation lock and dam structures, emergency closures have been provided.

7-12. Types of Closure Systems

A broad range of structures are in place as emergency closure devices at existing CE locks. Operational and economic considerations, rather than purely function, limit the choices for new designs. Structural details are available in EM 1110-2-2703 and in other references (item B5, for example). Examples of the more common closure devices are as follows:

a. Bulkheads.

(1) The most common type of emergency closure for locks and spillway gate bays is a bulkhead consisting of one or more sections and commonly constructed of welded, high-strength steel. A watertight skin plate is generally provided on the upstream side. Top and bottom seals, side seals, and roller assemblies complete the structure. The roller assemblies bear on bearing plates constructed in pier or lock wall recesses. The vertical height of the structure may vary from 3 to 12 ft depending on design constraints of a specific project. Several individual units are usually required for complete lock or dam closure.

(2) Most designs do not permit water flowing over and under the bulkhead units during lowering. Stacking units may be required for successful placement. Some bulkheads are equipped with an overflow plate attached to the top truss. The purpose of such design is to utilize bulkheads for flushing ice and debris, when necessary. If bulkheads are designed for placement in flowing water, hydraulic model studies of previously untested situations are needed.

(3) The units are either stored at the locks or retained in dogged position over the dam. In the former case, an overhead gantry crane is used to transport the individual units to the lock. The first unit is dogged over the bay or the lock and the next unit is moved from storage, latched to the first one, and then the assembly is lowered and dogged a second time. Additional bulkhead units are latched to the assembly until closure is achieved.

(4) Another method of placement uses a stiff-leg derrick positioned at the lock. The derrick raises and places individual units in bulkhead recesses. Additional units are added until closure is achieved. During lowering, the assembly is held in place by a stop log carriage.

b. Vertical lift gates.

(1) Emergency lift gates are either the single-leaf or the double-leaf type (see EM 1110-2-2703). The cost of the gate, storage arrangements, and hoist mechanisms for either type vary according to river stage and project (closure) lift. Economic studies are ultimately used to choose between single- or double-leaf gates. Double-leaf vertical lift gates have been constructed at several navigation locks on the Ohio River navigation system; other navigation systems use single-leaf vertical lift gates. In either system the gates are stored in submerged position under the lock emergency sill upstream of the upper miter gates. The double-leaf construction permits the utilization of locks as floodways when the river stage prohibits navigation. An emergency-closure single-leaf gate is illustrated in Plate 7-1.

(2) For the double-leaf type of design used in the Ohio River navigation system, only the downstream leaf is designed to permit closure in flowing water. However, the vertical height of one leaf is sufficient to effect closure under unbalanced head (flowing water) up to normal pool level. Should closure be required for stages above normal pool, then both leaves can be raised, since upstream and downstream heads are balanced. The operation of double-leaf-type emergency closure is shown in EM 1110-2-2703. For the single-leaf emergency gate, provisions must be made in the design to allow closure.

c. Upstream emergency dam. A type of emergency closure designed and constructed by the U.S. Army Engineer District, Nashville, for several locks on the Cumberland River navigation system is an emergency dam. This consists of several wickets that remain submerged on the floor of the emergency sill during normal locking operation, but they are raised into position during emergency conditions. Each wicket is raised individually by means of a chain hoist, sheaves, and a winch located on the top of the lock wall. When wicket No. 1 is in the lowered position, the landward hoist chain fits into a recess in the lock wall. As the first wicket is raised, it also raises the attached hoist chain of the next wicket. After locking the first wicket in position, the sheave is passed over to the riverward side and the second wicket is raised, which also raises the hoist chain for the third wicket. The operation continues in this manner until all wickets are raised. Similar closures have been constructed and operated on other navigation systems. In the original design, the wickets were constructed with flat skin plate; however, hydraulic model testing includes a curved skin plate.

d. Other systems.

(1) Stop logs, commonly consisting of wooden beams, can be placed in recesses upstream of spillway gates or lock miter gates using a hoisting mechanism. However, in general, operating heads on the dam usually must be reduced before placement. Since this arrangement would result in partial or total loss of pool, they cannot be considered a true emergency closure. Bulkheads, described in *a* above, are sometimes designated as stop logs. An older type of emergency closure is used for the auxiliary lock at McAlpine Lock and Dam on the Ohio River system. This type of closure includes a separate horizontal beam placed across the top of the lock walls with a derrick. Closure panels are vertically placed between the beam and the concrete sill to complete the closure operation.

(2) Submergible tainter gates are another alternate for emergency closure. Under normal operating conditions, the gates rest in a recess built in the emergency sill, upstream of the upper miter gates. During emergency closure, the gates are lifted to position by cables. Provisions must be made to clean the gate recess periodically to free it of accumulated silt and debris.

7-13. Design Loadings

An overview of design loadings (EM 1110-2-2703) is as follows.

a. Hydrodynamic forces result from the water flowing under the emergency closures. On emergency bulkheads, these forces can result in hydraulic uplift or downpull depending on the design. In order to lower bulkheads in flowing water, the uplift force must be less than the submerged weight of the bulkhead. Knowledge of the magnitude of hydraulic downpull is important for the design of the hoisting machinery. Overflow and underflow on emergency bulkheads are undesirable from the standpoint of hydrodynamic forces and should not be used. Hydraulic model studies are sometimes required to determine forces for a particular design.

b. The weight of the bulkhead is to be determined in the usual manner considering the structural elements and members of the closure. The majority of the bulkheads are of structural steel, but aluminum bulkheads have been used. The submerged weight is important in considering the ability to lower the closure structure in flowing water.

c. Frictional forces develop along the side support of closure structures. The magnitude of these forces depends on the type of bearings and side seals as well as on other loadings (*a* and *b* above, for example). Reference is made to EM 1110-2-2703 for details.

d. Some types of emergency closure systems, notably vertical lift gates, can be used in a dual role serving also as lock gates. Barge impact loads are considered for these designs. Reference is made to EM 1110-2-2703 for the magnitude of such loads.

e. Ice forces are considered, depending on the climatic condition at the location of the closure (see Section VI).

Section VI
Ice Control at Locks

7-14. Types of Ice

Ice in and around locks has always been a nuisance. Most lock operators have worked through the winter season using pike poles and steam to combat ice. Some locks, especially in more severe climates, simply close. However, recent interest in year-round navigation has led to closer identification of winter lock-operating problems and development of potential solutions to these problems. Three kinds of ice create problems for navigation: sheet ice, brash ice, and frazil ice. Sheet ice is a continuous cover of more or less equal thickness. Brash ice is an accumulation of ice fragments up to above 6 ft in the longest dimension that can pack to depths greater than the normal ice thickness. Frazil ice is an accumulation of small plates and spicules formed in turbulent water that often adheres to trashracks, gates, intakes, and other structures in the water. EM 1110-2-1612 gives additional background information and details of ice control measures.

7-15. Ice Problems

Ice problems at navigation locks are caused primarily by brash ice floating downstream or being pushed ahead of downbound traffic. The floating pieces of ice hinder gate opening and closing, stick to lock walls creating problems with vessel passage, and stick to lock gates causing operational problems. Large quantities of ice pushed ahead of a downbound ship can interfere with lock operation because a separate lock cycle solely for ice is often required by long ships using short locks. If ice could be prevented from entering the locks, most of these problems would not occur.

7-16. Air Screen

a. An air screen can keep ice from entering a lock. When large volumes of compressed air are released at depth across a channel, a high upstream and downstream surface water velocity is created that precludes the passage of ice or debris. This type of installation is called an air screen, and an application at Sault Ste. Marie has demonstrated its effectiveness. Air screens should be located between the upstream ends of the guide wall and guard wall; when placed closer to the lock, any ice pushed into the lock approach has nowhere to go and will accumulate. This same principle has been used successfully either as a single, point-source bubbler or as a line bubbler to keep ice out of miter gate recesses, allowing them to open fully.

b. An air screen was installed at the upper approach to the Poe Lock on the downstream, vertical face of an emergency stop log gate sill. The sill is located about 200 ft upstream of the lock gates. The riser line was installed in the stop log recess in the wall. The width of the lock at this point is 110 ft and the height from the top of the sill to the top of the lock wall is 39.2 ft. The manifold line was installed at a depth of 34.5 ft in December 1977 and was preassembled into four sections: two sections 27.75 ft long and two sections 24.5 ft long. Union connections joined the sections. The riser was assembled in one 38.5-ft section. The sections were light in weight; two to three people were able to move them by hand. All equipment for a hardhat diver and the preassembled pipes were placed on a 100-ft barge that served as the working platform. The barge was positioned above the sill, and sections were lowered on ropes to the diver below who made the union connections and strapped the line to the concrete sill. One flexible hose coupling, from the diffuser to the riser, was also made underwater. The above-water installation process consisted of simply connecting a 50-ft flexible hose from the top of the riser line to a rented compressor. A 10,000-gallon fuel tank was placed beside the compressor to supply fuel.

c. The air screen was put into operation on 12 January 1978 when ice started to cause problems with lock operations. It was continuously available for service until 30 April 1978, except for a 5-day repair period in late March. By 1 May ice no longer caused problems requiring the air screen, and the rented compressor was returned. During the 104 days of operation, the total running time on the compressor was 754 hr. Total fuel consumption of No. 1 fuel oil was about 7,750 gallons. The air screen has demonstrated that it can hold back ice pushed ahead of downbound traffic. With ships in the 70-ft beam class, the ice was held back until the bow entered the air stream. The stream was not as effective with the wider 105-ft beam ships. Once the bow passes the nose pier about 130 ft upstream of the screen, the approach is just a little over 110 ft wide; so most of the ice remaining in the track is pushed into the lock. The problem might be solved by relocating the air screen upstream of the nose pier area and by providing some area for the ice to be pushed outside the vessel track. The merits of the air screen cited by lock operating personnel, besides the reduction in vessel lockage time, were savings in wear and tear on the lock gate and operating mechanisms and savings in time and effort required to remove ice collar buildup on the lock walls.

7-17. Lock Wall De-icing

Ice buildup on lock walls occurs throughout the winter and presents no problems until it covers mooring bits or becomes so thick that the lock is effectively too narrow to admit vessels. If the lock is normally kept at low pool elevation, the lock walls cool to ambient temperature and upon filling are coated with a glaze of ice. Since this ice coat can continue to build (like dipping a candle) locks are normally kept nearly full during winter operations. When entering ships push ice into the lock, especially downbound, ice is often crushed against and adheres to the lock wall, exacerbating the problem. On rivers the standardization of barge width and the barges' square bows minimize this difficulty, but other locks such as those in the Great Lakes connecting channels can have severe problems.

a. Ice cutting saw. The U.S. Army Cold Regions Research and Engineering Laboratory designed and assembled a mechanical cutting system to remove the ice collars. The device consists of two parts: the cutting system and the drive and propulsion unit. The drive and propulsion unit is a 65-horsepower, four-wheel-drive tractor, originally manufactured as a trencher (the tractor can be purchased without the trencher attachment). The drive line for the trencher was modified to accommodate the cutting system by extending the drive shaft and attaching a drive sprocket to its end. While in the cutting mode, the engine powers the shaft and sprocket directly and the drive wheels indirectly through a separate hydraulic drive system so cutting power and propulsion power can be independently controlled. The cutting system is one used in the coal industry. It consists of a rugged bar and chain with cutting bits attached. The bar is 9.5 in. wide to the chain guide, 1.5 in. thick, and 15.9 ft long and is attached to the drive shaft housing. Movement of the bar is hydraulically controlled. Different kerf and bar thicknesses have been used, but earlier tests showed that a narrow logging saw was too flexible. The bar is grooved to accommodate the sprocket-driven chain and cutting bits and has a roller nose tip to reduce friction and wear. Chain tension is controlled by a high-pressure hydraulic cylinder capable of exerting 1,800 lb/ft at 10,000 lb/square inch (sq in.). The bar and chain hang about 30 in. past the side of the tractor and the drive wheels.

b. Operation of the ice cutting saw. When a problem ice collar has built up, the esplanade along the lock wall is cleared of snow. The tractor is then positioned with the right wheels close to the curbing along the wall so that there is about 1.5 in. of clearance between the wall and the bar and chain. A spacer on the wall side of the bar prevents the cutters from damaging the wall. A guide marker located off the right front wheel is positioned and set so the driver can maintain the proper position by keeping the marker and the reference point (top of curb) aligned. Looked at from the driver's point of view, the chain rotates clockwise with the tension cutting side on top of the bar. To start a slot for the bar, the underside of the saw is used until the tip cuts completely through the collar. The slot is cut with the tractor stationary. Once a slot is cut through, the bar is placed in a forward position about 70 deg from the horizontal. Full throttle operation in third gear produces a chain speed of 380 ft per min, although chain speeds of up to 510 ft per min are possible in fourth gear. A traverse speed of over 10 ft per min can be maintained while cutting ice collars 6 to 8 ft deep by operating the transmission in third gear at full throttle.

c. Copolymer coating. A chemical coating that reduces the adhesive force between the coated surface and the ice can also help solve icing problems, although the ideal material would prevent ice formation altogether. The coating that was developed does not prevent ice formation, but makes removal of ice from coated surfaces much easier. The basic material is a long chain copolymer compound made up of polycarbonates and polysiloxanes. The copolymer coating should not be applied to a concrete surface unless it is certain that the concrete behind the coating can resist frost action in a critically saturated condition. Proper application guidance for surface coatings to concrete can be found in EM 1110-2-2002.

d. Heating lock walls. Intermittent heating of the lock wall to release ice is probably the best solution. One lock has been retrofitted with electric heat tape installed in saw cuts; however, this is a time-consuming and expensive operation. Before new construction or rehabilitation of locks, options for lock wall heating should be investigated.

7-18. Lock Gate and Valve De-icing

The operating machinery for filling and emptying valves has been reported to have icing problems, but little is known beyond the verbal reports from specific lockmasters. Thought should be given to minimizing direct exposure to the atmosphere. Lock gates, especially the lower gate, should be insulated on their downstream side to minimize ice buildup on the upstream side that would make full opening of the lock impossible. On most existing gates, the downstream side of the gate is open, and while passing through the lock, ships push ice between the supports of the gate. To minimize this problem, gates should have a cover skin on the downstream side extending some 3 ft above and 6 ft below pool operating levels.

7-19. Considerations for Rehabilitation and New Construction

Whenever lock rehabilitation or new construction is considered, a number of ice-related concepts should be evaluated. Air screen and lock wall de-icing schemes have been covered in earlier paragraphs. The location of the filling intake should be situated so that filling currents do not pull ice into the lock approach. An ice and debris bypass should be considered whenever the approach channel is longer than a few hundred feet. Gate design should include insulation and a double skin to prevent ice from adding too much weight. Lastly, consideration should be given to a modified filling system that would add water to the upper end of the lock only. This would shorten the time required to flush the lock clear of ice and could be used as an emergency method of getting a disabled or burning vessel out of the locks.

Section VII
Repair and Rehabilitation

7-20. Purpose and Scope

Major rehabilitation includes work that is non-recurring in nature and is intended to either increase the reliability of deteriorated features or increase efficiency, or shall not consist of routine or deferred maintenance, which will continue to be considered in the U.S. Army Corps of Engineers Operation and Maintenance General budget appropriations.

7-21. Reliability Improvement

a. Rehabilitation for reliability is major project feature restoration consisting of structural work on a feature of the lock which is intended to improve reliability the result of which will be a deferral of capital expenditures to replace the structure.

b. Rehabilitation is considered as an alternative when it can significantly extend the physical life of the feature and can be economically justified by benefit-cost analysis. The benefit-cost analysis is a product of a risk analysis which combines probability of unsatisfactory performance with consequences. The work will extend over at least two full construction seasons and will require a specified threshold cost to be exceeded. This amount is specified in the annual Major Rehabilitation Guidance Memorandum. Additional guidance for the major rehabilitation program and the associated reliability analysis is found in ETL 1110-2-532.

7-22. Efficiency Improvement

Rehabilitation for efficiency improvement is intended to enhance operational efficiency of major project components and increase outputs beyond their original project design. Threshold limits on a component that does not exhibit reliability problems is also specified in the annual Major Rehabilitation Guidance Memorandum. Efficiency items include the following:

a. Modern machinery.

b. Modern electrical equipment.

c. Remote controls.

d. Television surveillance system.

e. Floating mooring bits.

f. Tow haulage units.

g. Lock wall extensions.

h. Emergency closure system.

i. Lock gate impact barrier.

j. Improved filling system.

7-23. Threshold Amounts

The threshold amounts listed for the reliability and efficiency improvement categories are adjusted annually according to the Administration's economic assumption published each year as guidance in the Annual Program and Budget Request for Civil Works Activities Corps of Engineers.

7-24. Typical Study Items

The following are common items to consider for major navigation dam rehabilitation projects:

a. Dam stability.

(1) Replace upstream and downstream scour protection.

(2) Install tendons through structure into foundation.

b. Navigation improvement.

(1) Move lock guide/guard walls.

(2) Change approaches.

(3) Change approach currents with training structures.

c. Ice and debris control. Install the following:

(1) Lock wall de-icer.

(2) Lock gate de-icer.

(3) Control booms.

(4) Air screens.

d. Replacement in kind.

(1) Resurface concrete surfaces.

(2) Repair or replace gates.

(3) Fix gate anchorages.

(4) Replace imbedded metal.

Section VIII
Environmental Concerns

7-25. Effect of Lock

The massive character of a navigation lock suggests that environmental evaluations (normally nonhydraulic effects) are required for project construction as well as operation. Navigation locks affect the local economy both in the short term, by construction activities, and in the long term, by the presence of navigation traffic. Visual changes are the major aesthetic effects of navigation lock projects.

7-26. Water Quality

Concerns experienced at other types of hydraulics structure/s are uncommon. Even valve design, which may cause a small change in water quality during the time the valve is vented and significant air entrainment occurs, has not been a significant environmental concern, because of intermittent lockages. Very few studies of change in water quality due to lock operation (see item R8, for example) are available; these studies in general do not show a meaningful deterioration in water quality and very limited possibilities for enhancement.

7-27. Recreational Craft

For projects where recreational craft appear in considerable quantities, the introduction of separate handling facilities is considered particularly when the period of peak recreational demand corresponds to the period of peak commodity movement. Separate facilities (such as a canvas sling or steel tank to lift the craft, a separate small lock, an inclined plane moving lock) are discussed briefly in Appendix G.

7-28. Facility Alternatives

Several alternatives for providing separate facilities for recreational craft for the Upper Mississippi River have been considered. These included the following:

a. A 110-ft by 360-ft auxiliary chamber.

b. A 110-ft by 400-ft auxiliary chamber.

c. A mobile floating lock.

d. A small-scale steel lock.

e. A differential railway lift.

f. A steel tank on inclined rails.

g. A steel tank lift crane.

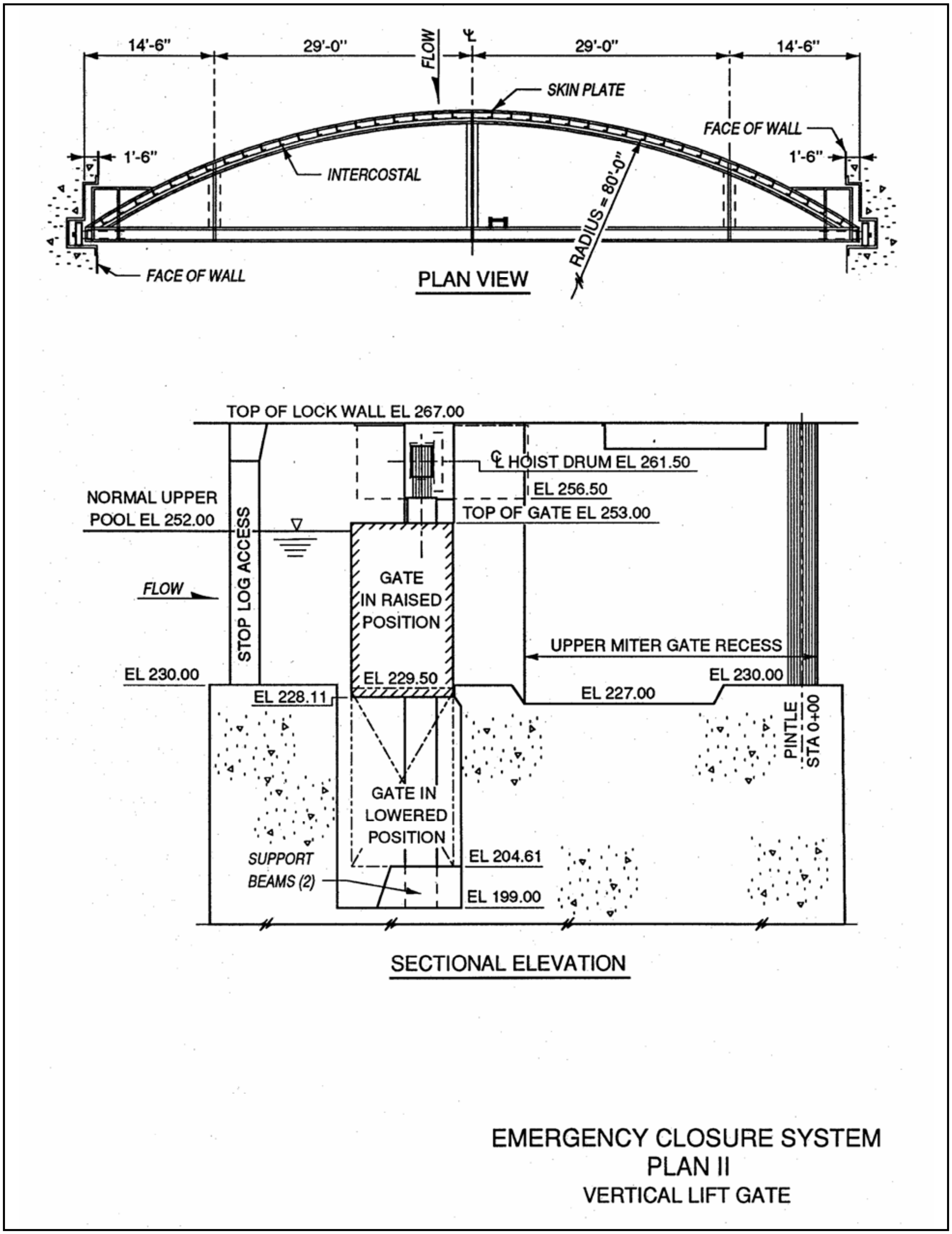
h. A mobile boat carrier.

i. An inclined channel lift.

j. An inclined plane lift.

7-29. Second Lock Chamber

Twenty of the Upper Mississippi River locks have partial provisions for a second lock chamber, 100 ft by 360 ft. These provisions include an upper gate sill, upper portion of the river wall, and recesses in the intermediate wall for the lower miter gate and gate machinery. Completion of this lock chamber would involve damming and dewatering the chamber area; removing accumulated debris and scour protection measures; constructing the river wall and chamber floor; removing and rehabilitating the upper miter gate; and installing gates, valves, operating machinery, and appurtenances.


14'-6"
29'-0"
FLOW
℄
29'-0"
14'-6"
SKIN PLATE
FACE OF WALL
1'-6"
1'-6"
INTERCOSTAL
RADIUS = 80'-0"
FACE OF WALL
PLAN VIEW
TOP OF LOCK WALL EL 267.00
℄ HOIST DRUM EL 261.50
EL 256.50
TOP OF GATE EL 253.00
NORMAL UPPER POOL EL 252.00
STOP LOG ACCESS
FLOW
GATE IN RAISED POSITION
UPPER MITER GATE RECESS
EL 230.00
EL 229.50
EL 230.00
EL 228.11
EL 227.00
PINTLE
STA 0+00
GATE IN LOWERED POSITION
SUPPORT BEAMS (2)
EL 204.61
EL 199.00
SECTIONAL ELEVATION
EMERGENCY CLOSURE SYSTEM
PLAN II
VERTICAL LIFT GATE