8. NAVIGATION LOCKS

8.1 General Considerations

Lock Location. In canalized waterways, the navigation lock is usually located near one bank at the end of the dam so that:

a. Spillway length is maximized.
b. Adverse effects of spillway currents on river traffic is minimized.
c. Pilots can approach the lock by traveling along the protected area near the shore.

In canals, the lock often occupies essentially the entire canal width and acts as the dam. Typical layouts for locks are shown in Figure 8.1, and a general layout of a low-lift navigation lock and dam is shown in Figure 8.2.

In general, where two locks are provided (twin locks of equal size or a main lock and smaller auxiliary lock), it was customary to place the locks side by side, with a common center wall, as shown in Figure 8.1. However, at the new Melvin Price Locks on the Mississippi River, replacement for Lock and Dam 26, the two locks (a 1200-ft main lock and 600-ft auxiliary lock) are separated by a 350-ft spillway section with two gate bays, Figure 8.3 The 350 ft separation extends from the inside face of the land lock to the inside face of the river lock and was provided for more efficient use of the lock and higher traffic capacity. The separation distance was based on operation studies and recommendations from towboat pilots for the minimum distance between locks with two tows passing, one tow approaching the locks and a second tow departing.

Pilots must have a clear view of the lock entrances because momentum of a tow when it is slowing down is difficult to control due to inertia and low power. Minimum sight distance in a lock approach of one mile is usually sufficient for safe operation, permitting tows to align with the lock before reducing speed. Model studies are conducted of tow operation in lock approaches to investigate potential operation problems, and the views of rivers pilots are taken into consideration.

The exact location of a lock depends on such factors as:

a. Configuration of the river reach.
b. Shape of the channel cross section.
c. Hydraulic conditions at the site.
d. Bank elevation and stability.
e. Foundation conditions.

Straight reaches of river are more desirable sites for navigation locks and dams than bends because they are easier to navigate. However, straight reaches of alluvial rivers often tend to be unstable, and adequate depth in the downstream lock approach may be hard to maintain.

Adverse cross currents from spillway discharges also may present problems to traffic in the lock approaches. A pair of locks located on the deep side of a bend, Figure 8.4, may block so much streamflow that spillway operation results in undesirable currents in the upper lock approach. The upstream guide wall, as well as the lock itself, can adversely affect flow conditions. Cross currents in crossings may also interfere with tows approaching a lock.

<u>Cofferdams for Construction</u>. Navigation structures are usually constructed in a series of stages so that river flows can be passed during construction and in some cases, such as during construction of replacement for Lock and Dam 26 on the Mississippi, tows can continue to use the river during construction. Consideration must be given to potential problems with cofferdams during the construction period when evaluating alternative sites for locks and dams and also when evaluating alternative schemes for cofferdams at a particular site, including:

a. The number of cofferdam stages and the extent of each stage. Typical cofferdam layouts are shown in Figure 8.5a. Twin 1200-ft locks at the Smithland project on the lower Ohio River (replacement for Locks and Dams 50 and 51) are shown under construction in a cofferdam in Figure 8.5b.

b. Passing navigation traffic through the construction reach while cofferdams are in place if there is commercial navigation on the river prior to project construction.

c. Seepage into the dewatered area inside the cofferdam and related pumping requirements.

d. Frequency of flow at which the cofferdam would be overtopped and flooded.

e. Difficulties associated with passing high flood flows through the construction area while the cofferdams are in place, including estimated scour with different cofferdam configurations.

f. Cost of alternative cofferdams schemes, including the cost of dewatering, cleanup, and repair associated with overtopping of the cofferdam.

The three-stage cofferdam scheme for construction of the replacement locks and dam for Lock and Dam 26 on the Mississippi River is shown in Figure 8.6. Construction began from the west bank of the Mississippi River, with the Stage I cofferdam which enclosed 6.5 spillway bays. The Stage II cofferdam enclosed the 1200-ft lock riverward lock and two half gate bays (one-half gate bay on each side of the lock), and the Stage III cofferdam enclosed 1.5 gate bays and the 600-ft landward lock.

For construction of Dardanelle Lock and Dam on the Arkansas River, 3-stage and a 4-stage cofferdam schemes were considered. The 4-stage plan, Figure 8.7, used larger diameter cells and required less sheet piling than the 3-stage plan. It was cheaper to construct and, therefore, was selected.

Navigation projects can sometimes be constructed off-channel, as was done for locks and dams on the Red River where 36 cutoffs were constructed to realign the channel for navigation. (The 280-mile navigable reach was shortened 50 miles, or 18 percent.) Locks and dams were constructed on the alignment of cutoffs that were part of the overall plan for stabilization and rectification of the future navigable channel. After completion of the locks and dams in the dry, connecting channels were excavated to the river, the old river channel was closed off at the upstream end, and the river was diverted to the new alignment through the cutoff, Figure 8.8.

Access to Construction Site. Ease of access to the project site affects project costs for construction and also for operation and maintenance after project completion. For projects in remote areas, the cost of constructing access roads may be a large part of total project costs. Availability of waterborne and overland transportation systems and power facilities all affect project costs.

Availability of Construction Materials. The availability of construction materials of sufficient quality and in sufficient quantities for project construction within economic distance of the construction site must be investigated in the planning process. When materials such as coarse and fine aggregate and protection stone are not available locally, they must be brought to the site at higher cost.

8.2 Lock Design Criteria

Lock Size and Number of Locks. Consideration of the types of navigation equipment projected to use the canalized waterway, type and volume of projected traffic, and economic studies including project costs and estimated navigation benefits all influence:

a. Lock chamber size.
b. Optimum filling time (whether or not a fast filling and emptying is needed).
c. Whether or not one or two locks are required at each dam.

In some cases, the size of tow that can be physically accommodated at critical channel points along a canalized river may limit the size of tow using a lock and size of lock chamber. Standard usable lock dimensions in the United States are given in Table 2.

Table 2. Usable Lock Dimensions (feet)

Width	Length
84	400
	600
	720
	800
	1200
110	600
	800
	1200

Where a single lock is used, traffic will be interrupted when the lock is closed for maintenance or repair; however, this may not be a major problem if traffic is highly seasonal and maintenance can be scheduled in the off-season. Two locks increase reliability of the system. If one lock is out of service (due to an accident or for maintenance) some traffic can continue to use the one operable lock.

If economic studies do not justify construction of two locks initially, it may be desirable to include some works (such as the upstream lock gates) in initial construction to minimize costs of adding a second lock in the future.

Lock Lift. Lift is one of the first and most important design criteria to be established in planning a canalization project. Maximum lock lift is the vertical distance from the upper pool normal water surface elevation above the lock to the low-water surface elevation below lock; it is the range of water surface levels in the lock chamber Figure 8.9. The lock lift and upper pool elevation must provide adequate and safe depth for navigation over all obstructions throughout the pool and over the lower gate sill of the next lock upstream. The cost for one high-lift lock may be less than the combined cost of two low-lift locks of equal total lift, but the design is usually more complex.

Lift is the major factor governing the type of filling and emptying system used for a particular lock, and locks are generally classified by lift as follows:

Low-lift lock	Less than 30-ft lift
Intermediate-lift lock	30- to 60-ft lift
High-lift lock	More than 60-ft lift

All new high-lift locks in the United States are based on either Lower Granite or Bay Springs manifold systems, Figures 8.19 and 8.39.

8.3 Lock Types

Locks are of various types, and the design used at a particular site is usually determined by foundation conditions and costs. If there are no unusual foundation conditions, gravity locks are usually the most economical type to design, construct, and maintain due to simplicity of design, the relatively small amount of skilled labor required for construction, and low maintenance costs of the thick sections. Reinforced concrete lock wall design is used for walls at gate bays and approach walls and is similar to design of reinforced concrete retaining walls. Gravity walls are reinforced at thin areas, and the dry-dock lock is a reinforced-concrete structure. Approach walls, abutments, the area around culverts, filling and emptying laterals, and other parts of most modern locks are of reinforced concrete.

Gravity mass concrete locks can be designed for soil, rock, or pile foundations and have few structural limitations as to height or lift. Base width of walls must be sufficient to prevent overturning and sliding and overstressing the foundation. Top and intermediate widths of walls must provide a section to withstand the wall stresses and provide space for filling and emptying systems, anchorages for gates, operating equipment, temporary closure structures, and other machinery. Disadvantages of gravity structures include loads that may be heavy with respect to supporting capacity of the foundation materials and the possibility of unequal settlement of adjacent or opposite monoliths that may result in misalignment or damage of movable structures and operating machinery.

One of the newer innovative designs used on the Kanawha River places the filling and emptying culverts in the lock chamber floor and uses roller-compacted concrete for lock chamber walls between the gate monoliths. This is discussed further in Section 11.

Dry-dock type reinforced concrete locks are used where foundation conditions preclude use of a gravity design and where the use of a pile foundation is not practicable. The lock consists of relatively thin lock walls constructed integrally with a thick floor slab, designed to act together as a monolith, each being heavily reinforced to distribute loads. The dry-dock type lock can be unwatered for inspection and repair without fear of a blow-out and loss of foundation material; however; adequate provision must be made to offset the buoyancy effect of the structure.

Steel sheet piling locks are a combination of sheet piling with one or more other types of construction. For temporary locks and waterways that do not warrant costly construction, steel-sheet piling can be used for the walls between gate bays and for the approach walls. The piling is driven in a straight line, and any offsets along the face of the wall can be eliminated by using timber fenders bolted to the piling at levels where the tows usually rub against lock walls. Locks of this type have a relatively short useful life of about 15 to 25 years.

Combination-type locks combine several types of construction in one design. Where a considerable amount of sound rock must be excavated, a layer of reinforced concrete may be constructed adjacent to the vertical face of the rock to form the lower portion of the lock walls. The concrete is anchored to the rock by steel dowels grouted into drilled holes. The upper portion of the walls is of gravity design.

For low-lift projects and in canals, levees may form part of the lock walls between gate bays. Walls of concrete or sheet piling can be constructed to a height to accommodate navigation a large percent of the time, but the gate bays, gates, and levees should be built to above the maximum stage at which lockage is provided. When the walls between the gate bays are overtopped, the levees and gate bays would maintain the pool elevation.

8.4 Lock Depth and Lock Floor

Locks fill and empty through a system of intakes and culverts upstream of the upper lock gate in the lock walls or upper gate sill; culverts in the lock walls; ports in lock chamber walls or on the lock floor; and emptying systems downstream of the lower lock gate.

It is desirable that lock filling time be as short as possible to minimize delay and cost to tow operators. However, there is some turbulence associated with the filling operation, and the lock must be deep enough to provide a "cushion" of water over the filling ports to dampen turbulence so that tows are not damaged and stresses in the hawsers (lines securing tows to the lock walls) are within acceptable limits.

Depth provided in the lock chamber and over the lock gate sills depends on the type and size of vessels and tows using the lock. Lock depth is the usual dimension governing overall lock design, and is usually determined by design requirements for the filling system. The sill elevation may govern the lock floor elevation in some cases because the floor should be at least 2 ft below the sill for operation and maintenance. For a side port system, the required cushion depth over the ports usually controls. For bottom lateral and longitudinal culvert systems, the top elevation of the bottom culverts may control, as they should be no higher than the top sill elevation.

Where foundation materials are erodible, such as sand and gravel, the concrete lock floor is usually subject to downward pressures when water in the lock is at upper pool level and to upward pressures when it is at lower pool elevation or when the lock is unwatered. Accordingly, the lock floor must be designed to withstand uplift due to hydrostatic head or relief wells must be provided. On alluvial streams, a line of steel sheet piling is sometimes driven around the perimeter of a lock under the walls and sills to stabilize the foundation material and prevent movement of material out from under the lock walls.

For locks excavated in rock, a concrete floor may not be necessary if the culverts and ports are located in the lock walls.

8.5 Lock Gates and Sills

Lock gates operate on sills, as shown schematically in Figure 8.9. Miter, roller, sector, tainter, and vertical lift gates are used as lock service gates, and each type has special characteristics that make it the most suitable for any given site. Design of the gate sill varies with the type of lock gate used, and deeper depths over the sill increases locking efficiency.

Miter gates are the most widely used type of lock gate on inland waterways in the United States and are the only gates that cannot be operated (opened and closed) with a differential head upstream and downstream of the gate. Other gate types can be used as both lock service gates and for filling or emptying the lock and can be opened or closed to any position and held at that position. Miter gates and miter gate operating machinery are designed to be under complete control of the gate operator during opening and closing operations, to remain completely closed when in the closed position, and to remain completely open and in the gate recesses when open.

Lock gates are designed for a static hydraulic load and for a temporary hydraulic load which may either add to or decrease the static head and, in extreme conditions, may produce a reverse head. Reverse loads almost always occur as a result of temporary conditions and are of very short duration, except at tidal locks. Most frequently, reverse heads result from temporary lock overfilling or overemptying due to the momentum of water moving in the culverts, and this is generally the most serious temporary loading condition. Loading conditions are as follows:

a. The maximum static hydraulic load on the upstream gate is the load due to difference in water surface elevation of the maximum upper pool and the gate sill elevation.

b. The maximum static head on the downstream gate is the difference in elevation between the maximum upper pool and the minimum lower pool.

c. Temporary hydraulic loads on gates can be caused by wind waves, seiches, surges, waves from propeller wash, ship waves, and tidal action.

d. Temporary head reversal can cause miter gates to be briefly forced open slightly and then slam shut, possibly damaging the gates.

Davis (1989) suggests the following guidance for evaluating temporary hydraulic loads:

a. Use a temporary hydraulic load of 2.5 ft for durations greater than 30 sec for direct or temporary reverse heads no greater than 2.5 ft. This is a minimum value and applies to structural design of all gates, gate leaves, and operating machinery except miter gate operating machinery.

b. Use a temporary hydraulic load of 1.5 ft for durations exceeding 30 sec as the minimum value for design of miter gate operating machinery.

c. Do not use miter gates where a temporary reverse loading significantly greater than 2.5 ft can occur for more than 30 sec.

d. Because overfilling and overemptying can occur on every lock operation, gate operating procedures should be designed to reduce potential reverse heads to nondamaging values, as by starting closure of the filling valves before the lock chamber is full. Automatic controls can be designed so the valves will be about 95 percent closed when the lock chamber is full.

Lock gate sill elevations are set with relation to normal water surface elevation in the adjacent pool, and gate sill elevation controls the draft of tows that can use a lock. For hinged-pool operation, the upper sill must be low enough to provide adequate depth when the pool is hinged. Because of the difference in pool levels and lock lift, the upper gate sill elevation is always higher than the downstream, and the downstream gates are always much higher than the upstream gates, Figure 8.9. For example, Bay Springs Lock on the Tennessee-Tombigbee Waterway has an 84-ft lift, and the upper gate sill is 75 ft above the look floor elevation, Figure 8.10, while the lower gate sill is at the same elevation as the floor.

Greater additional depth is provided over the downstream sill than over the upstream sill because a tow that fills the width of the lock chamber will squat several feet on entering the lock and may strike and damage the sill unless sufficient clearance is provided. Sill elevations are determined by taking into consideration future development of navigation carriers and possible degradation downstream of the lock. To provide greater clearance at the time of construction usually does not increase initial project costs materially, but to provide it later might require temporary closure of the waterway to traffic and costs could be excessive.

As a tow enters a lock, the water displaced by the tow flows out of the lock chamber between the bottom of the tow and the lock sill, and considerable space is required between the bottom of the barges and the sill. When the last water displaced runs out, there is a sudden drop in resistance to the tow's entry into the lock, and if the tow is not at a dead stop, inertia will carry it forward into the upper sill or into the upper lock gates. Towboat captains are aware of this phenomenon and keep their entrance velocities within safe limits. Operation is easiest, safest, and least time consuming with greater sill and lock chamber depths. Safety considerations are worked out with engineering and experienced operating personnel and in consultation with members of the towing industry.

Under-tow clearance for optimum filling time, would be a 23-ft lock chamber depth, or a depth/draft ratio of 2.5. All Corps of Engineers 110-ft locks constructed since 1970 have a sill depth to draft ratio of at least 1.7 (that is, 6 feet of under-tow clearance for a 9-ft channel) or greater. Ideally, depth over the sill of twice the tow design draft (18-ft depth over the sill for a 9-ft channel) should be available 95 percent of the time, and minimum clearance of 1.7 times the draft should be available 100 percent of the time. Most locks have 1 or 2 ft less depth over the sill than in the lock chamber. In cold climates, such as along the Upper Mississippi River, ice accumulates on the bottom of barges; six to eight ft of ice accumulation is not uncommon. The downstream sill should not be more than 3 ft above the chamber floor as there is not much difference between the cost of one foot of sill height and one foot of lock gate height and greater clearance over the sill increases safety.

All gate sills must resist lateral forces, consisting of both earth and hydrostatic pressure, from the bottom of the gates to the sill foundation. Often ports for culvert filling and emptying systems and crossovers for various utilities are located in the gate sills.

Miter Gates. Miter gates consist of two gate leaves, each rotating on a vertical axis in a recess in the face of the lock walls. When open, they are recessed in the lock walls and are flush with the face of the wall, Figure 8.11. When closed, the stainless steel mitered edges of the two leaves meet at the center line of the lock, and the gates are angled slightly upstream with respect to the lock walls so that upstream water pressure contributes to keeping the gates tightly closed and minimizing leakage. The steel gates have a girder framework covered by a skinplate on one or both sides. They are designed with sufficient rigidity so that they do not twist or become warped when rotated through the water.

Tainter Gates. Tainter gate sills are of two types with respect to loading. One, which merely provides a sealing surface for the gate and a top surface to fit spillway characteristics, is used only for narrow lock chambers where the entire gate load is transferred to the lock walls through the end trunnions as at St. Anthony Falls, Figure 8.12. The second type is used for wide lock chambers where end and intermediate trunnion arms transfer their loads to trunnion castings anchored to buttresses attached to the sill. The sills are generally higher than the lock floor area where the gates swing open so that any debris on the floor of the lock will not interfere with gate operation, Figure 8.9.

Sector Gates. Sector gates, shown in Figure 8.13, are used as lock gates where reversal of head occurs for significant periods of time, for example at a location affected by tidal action where the downstream water level is sometimes higher and sometimes lower than the upper pool. Sector gate sills are primarily to form sealing surfaces for the gates when closed and sometimes to provide rolling tracks to carry a portion of the dead weight of the gates.

Lift Gates. Lift gate sills provide a sealing surface and act as a spillway weir.

Emergency Closure Sills. Emergency closure sills provide a sealing surface for such structures as emergency gates, bulkheads, and so on that are provided to stop flow through the lock chamber if the service gates become inoperative and to close off the lock chamber to permit unwatering for periodic inspection and repair. Emergency closure sills are often outside the intake and discharge ports of the filling and emptying system so that the ports and filling and emptying system can be unwatered for inspection and repair. Bulkhead sills do not resist any part of the bulkhead lateral load, and the sill is designed only to support the weight of the bulkheads and hydrostatic pressures below the bottom bulkhead unit. The bulkhead-type closure provides a positive seal in flowing water without requiring the assistance of a diver at the top of the sill during installation. Emergency closure facilities are discussed further at the end of this section.

8.6 Lock Walls

Lock walls are designated by location and purpose. For a single lock, walls are designated as either land river wall. For two locks side by side, the dividing wall is designated as the intermediate or middle wall. Wall designations by purpose, shown in Figure 8.9, are:

a. Lock chamber walls.
b. Upper gate bay walls.
c. Lower gate bay walls.
d. Culvert intake walls.
e. Culvert discharge walls.
f. Upper and lower approach walls (guide walls and guard walls).

Lock walls always resist part of the gate thrust, and provision must be made to absorb these loads in the walls as well as to provide sufficient space for operating machinery.

The height of lock walls above pool elevation depends on the stage and flow at which navigation ceases, the importance of the waterway, and the value of uninterrupted transportation during high stages as well as on characteristics of the waterway, type of dam, type of lock, balance between initial construction cost and maintenance cost, and other factors. On major waterways, walls are set at sufficient height so that traffic is interrupted only by infrequent flood flows because if published traffic schedules cannot be maintained by shippers during most of the year, or if schedules are subject to numerous interruptions because locks are out of service, projected use of the waterway may never develop.

During the 1993 flood on the Upper Mississippi River, locks were out of service for a total of 77 days (three different closures); seven locks were under water. Costs to repair damage to the navigation locks and dams was estimated at $4 to $5 million dollars. Overall traffic on the Upper Mississippi decreased 30 to 35 percent for 1993, and daily losses to shippers was estimated at $700,000 a day during lock closure.

To protect tows from currents and winds at high river stages, lock walls should be set at least 2 or 3 ft above the stage corresponding to the maximum navigable flow. On the Arkansas River system, it was expected that the river would be navigable for flows up to the 10-yr recurrence interval flood. Velocities for larger floods were expected to be too high for safe and efficient operation of tows. Therefore, the top of lock walls was set at the higher of 10 ft above pool level or 2 ft above the 10-yr recurrence interval flood. Access roads to the locks and dams also were set at the same elevation. The 10-yr recurrence interval flood is also the limit of navigation on the Red River Waterway (140,000-145,000 cfs at Lock and Dam 2 and 120,000 cfs at the head of navigation at Shreveport).

It is usually desirable to set the top of lock walls at as high an elevation as economics of the project permit. Top elevations have been set such that the longest period of traffic interruption during the largest flood of record would not exceed 10 to 15 days. Unless the top of the walls is above flood stage, operating equipment on the walls must be removed each time the walls are likely to be overtopped, and cleanup is necessary after the water has subsided.

<u>Lock Chamber Walls</u>. Lock chamber walls are located between the upper and lower gate bays and enclose the lock chamber. The top width of the land wall is generally 6 to 10 ft, and wall thickness at lower elevations are governed by size of conduits and openings for operating facilities and by stability requirements.

Design of the river wall is limited by its location adjacent to the spillway. Spillway releases flow along the river face of the river wall, and that wall may be designed with uniform batter to provide smooth flow conditions. When the river bed is of erodible material, special protective measures (such as sheet piling or heavy stone protection) along the wall are required to prevent scour from undermining the wall. The river wall is primarily subject to hydrostatic loading, as with the water surface in the lock chamber at upper pool level and lower pool level in the river below the dam, or with the lock chamber unwatered for repair or inspection and lower pool level in the river below the dam.

In the case of two locks side by side, the intermediate wall has a constant top width, the same as required for the gate bay walls. Both faces of the intermediate wall (which form the sides of the two lock chambers) must have continuous straight surfaces for the tows to rub against as they pass through the lock and to provide smooth vertical surfaces for mooring during lockage. Thus, the upper portion of an intermediate wall cannot be narrowed for economy of construction.

<u>Upper and Lower Gate-Bay Walls</u>. These walls house the gate recesses, gate anchorages, gate machinery, and sometimes culvert valves and culvert bulkheads. The top of gate-bay walls must be sufficiently wide to:

a. House the operating mechanism.
b. Provide space for gate anchorages.
c. Enclose the valves.
d. Allow the gates to recess flush with the face of the wall for miter and sector gates.
e. Provide sufficient concrete between the culverts and gate recesses for stability.

<u>Culvert-intake Walls</u>. These walls extend immediately beyond the upper gate bays and provide space for the intake ports for the filling system. They are wide at the top to support:

a. Bulkhead-handling machinery when temporary closure structures are used.

b. Provide bulkhead recesses.
c. House floating-gage wells and other equipment.

Culvert-discharge Walls. These walls extend from the downstream end of the lower gate bay monoliths to the approach walls. They are usually lower than the lock chamber walls because they are below the lower gates and are subjected only to lower pool or high-water stages below the dam. They house the culvert-discharge manifold and diffuser system. When bulkheads are placed downstream from the discharge ports, the loads resisted by the culvert-discharge walls are similar to those on the lock walls during unwatered conditions.

Approach (Guard and Guide) Walls. Approach walls are extensions of the lock chamber walls at both ends of a lock and are required for all locks with barge traffic because tows have poor control and maneuverability when entering and leaving locks at low speed. Approach walls reduce hazards for tows entering and leaving the lock and reduce damage to both tows and lock facilities. They speed up lockages by offering a wider target for tows heading into a lock and provide temporary mooring space for tows with more barges than can be locked through in a single lockage or for tows queued for passing through the lock. Optimum alignment, length, and design of approach walls should be investigated in a general model study.

At locks used by both large ships and shallow draft tows, long guide walls can be an obstruction to the ships which cannot enter a lock under their own power, but must be moved into and out of the lock chamber by tugs or towing engines on lock walls (as at the Panama Canal locks).

One approach wall, the guide wall, is usually longer than the other, the guard wall. The guide wall serves to guide tows into the lock, and tows can put out lines to check posts on the wall to correct alignment for entering the lock. In the United States, many barges are 35 by 110 ft and are locked through three abreast (105 ft total width) in a 110-ft wide lock chamber, leaving little clearance along the lock walls. Guide walls are usually straight-line extensions of the lock chamber walls; however, where guide walls serve as mooring areas, the mooring reach of wall should be flared away from the approach or offset from it.

The shorter guard wall is designed to improve lock entrance and exit conditions for tows and to prevent tows from drifting into areas with hazardous currents and turbulence.

Guide walls can be located on either side of the lock approach, depending on site and current conditions, but are usually located along the landside. However, where cross currents exist in the upper approach because of spillway or powerplant operation or in the lower approach where a slow eddy often forms as the spillway or powerplant discharge widens out downstream of the lock, it is desirable to locate the guide wall on the river side and the shorter guard wall on the land side.

The usable length of the guide wall is usually equal to the length of the lock chamber; however, if the approach is well protected from wind and there are no adverse currents, a shorter length may be satisfactory. If conditions in the upper portion of the downstream approach are hazardous due to turbulence or high velocities, the usuable length of the lower guide should be measured from the point where velocities are less than 6 ft/sec or where excessive turbulence ends (Davis, 1989). Where banks are rock and tows cannot nose safely into the bank to queue for passage through the lock, it may be desirable to lengthen the guide wall to provide mooring space for more than one tow. In this case, the use of mooring piles should be considered, rather than longer walls, to reduce costs.

Approach walls (guard and guide walls) must be able to absorb impact and withstand abrasion from moving tows; however, local damage or failure of an approach wall when hit by a tow is not a serious matter because the lock can continue in operation while repairs are made. Various types of construction have been used for approach walls, each having advantages at particular sites:

a. Guard walls are either solid or are provided with openings (ports), depending on flow patterns and velocities at the specific site. For locks in reservoirs, the upstream approach walls may be slotted to avoid flow concentration, cross-currents, and high velocities at the upstream end of the walls.

b. Gravity walls have been used for approach walls on rock, soil, and pile foundations, but are expensive and rigid and require cofferdam protection during construction. In the United States most locks on rivers have concrete gravity walls. If rock is excavated to provide project depth in the lock approach, the wall can be placed on top of sound rock and the vertical rock face below the wall lined with concrete.

c. Reinforced concrete continuous walls are sometimes used, but they are expensive. Cofferdam protection is required during construction, and the thin sections are not as resistant to impact as are walls of other types.

d. Floating concrete guide walls have been used in the upstream approach at some locks in reservoirs where depths are large or foundation conditions are difficult.

e. Sheet pile construction (cantilevered or tied-back steel) can be used for landside approach walls where backfill extends to the top of the wall and where the approach channel is earth. The wall is set back from the face of the lock walls an amount equal to the thickness of timber fenders bolted to the piling. Construction cost is low, but such a wall can be severely damaged by impact of tows. Steel sheet piling in double rows, connected by diaphragms or tie rods and filled with earth can be used to form a continuous wall, and the top of the wall can be capped with concrete.

f. Cellular steel sheet piling filled with sand can be capped with concrete and supported by bearing piles. Reinforced concrete beams can be used between the cells to form a continuous rubbing surface for tows.

g. Isolated guide or mooring facilities, such as concrete piers, sheet pile cells, and timber-pile clumps equipped with tie-up equipment, may be used at the ends of approach walls to absorb much of the impact from a tow out of control and to serve as mooring points for tows waiting to lock through.

8.7 Lock Filling and Emptying Systems

The type of filling and emptying system used for a particular lock depends on the lift, tonnage capacity required, importance of the waterway, and construction costs. Lift is the most important factor. For low-lift locks (lifts less than 30 ft), a wall culvert-side port system can be used, but an intermediate-lift lock requires a more elaborate design, such as bottom lateral manifolds. For high-lift locks, it is usually desirable to use a bottom longitudinal manifold system that splits the flow vertically in the main wall culvert by means of a horizontal diaphragm and produces equal division of flow to four branch manifolds in the floor of each half of the lock chamber.

Design of modern locks in the United States, including design of filling and emptying systems, has been based on model studies, primarily by the Corps of Engineers and the Tennessee Valley Authority.

To minimize lockage time, lock filling and emptying systems should fill the lock chamber in the shortest practicable time without disturbances that would endanger vessels or the lock itself, particularly lock gates. Filling time is a function of lock lift. In the United States locks with miter gates with lifts of 30 ft or less have filling times of 6 to 8 minutes, and locks with lifts of 30 to 60 ft fill in 8 minutes. For higher lift locks (60 to 100 ft), filling time is greater than 10 minutes.

There are several different basic schemes for lock filling and emptying systems and numerous modifications of the basic designs for specific site conditions, as described later in this section.

Hawser Stresses. Two types of disturbances in lock chambers related to lock filling and emptying operations can be hazardous to tows being locked through:

a. Local turbulence generated by water entering or leaving the lock chamber and the lower lock approach.
b. Surging in the lock chamber as it is filled or emptied.

Tows and vessels in lock chambers are moored to the lock walls by hawser lines. Turbulence related to filling and emptying operations may damage small craft or individual barges in a lock, but surging is the more dangerous because it can cause an entire tow to break loose from the hawsers in the lock chamber and damage the lock, lock gates, or the tow itself. Stress in the hawsers is primarily a function of gross tonnage of the tow and slope of the water surface in the lock.

In the hydraulic design of locks, both longitudinal and transverse hawser stresses are measured in hydraulic models, but tows in a model are more closely restrained than in the prototype and there is more strain in the lines in the prototype than in the model. Thus, prototype stresses are normally less than measured in models, Figure 8.14. Measurements of hawser stresses in models and prototypes have been compared for many years, and it has been concluded that if prototype stresses measured in models do not exceed the following criteria a lock will be safe for barge tows and other vessels:

a. For various numbers and sizes of barges in a lock chamber, hawser stress should not exceed 5 tons and turbulence must not be hazardous for barges and small craft. The 5-ton value is the result of consensus reached in the late 1960s by tow operators and owners, lock operators, and laboratory and design engineers.

b. For single vessels up to 50,000 tons in a lock chamber, hawser stresses should not exceed ten tons.

c. For single vessels larger than 50,000 tons, hawser stresses are allowed to exceed ten tons since such vessels are restrained with more lines than tows or smaller vessels.

Summary data of permissible filling and emptying times for a 1200- by 110-ft lock to keep hawser stress within 4-, 5-, 6-, and 7-ton limits (for lock lifts of 20, 30, and 40 ft) are shown in Figures 8.15 and 8.16, respectively (Davis, 1989).

Filling and Emptying Over, Between, or Around Lock Gates. A tainter gate on the upper lock sill, Figure 8.13, can be used to supplement lock filling by other systems. As the tainter gate is lowered beneath the sill, water flows over the gate and into the lock chamber. However, filling is normally accomplished by a special filling system consisting of:

a. Intake ports upstream of the gate sill (or in the gate sill).
b. Wall culverts.
c. Laterals or ports in the lock chamber.

At St. Anthony Falls locks on the Upper Mississippi River, tainter gates at the locks serve primarily as a supplementary spillway at flood stages and to pass ice and debris through the lock.

Sector gates, Figure 8.13, are used as lock gates where reversal of head of significant duration occurs, for example at a location affected by tidal action where the downstream water surface is sometimes higher and sometimes lower than the upstream pool. As the sector gates swing apart, water flows into or out of the lock through the opening between the gates, and the lock chamber must be sufficiently long so that tows in the lock can be safely moored beyond the region of local turbulent inflow. Some sector gates have been designed to also admit water around the gates through the wall recesses.

Sector gates can be used with heads up to about 20 ft, and reversal of head rarely occurs at locks with normal lifts greater than 20 ft. Although sector gates are designed to operate at the estimated maximum lift, such conditions are usually of short duration and relatively infrequent; normal lifts are usually much less. Sector gates are used only when required, because other types of gate are usually more economical to construct and other types of filling systems provide more satisfactory operation.

Filling and Emptying by Valves in Gates or through Short Culverts. Early locks in the eastern United States used valves located in the lock service gates or short culverts through the river wall (each controlled by a separate valve). However, modern designs use stub or loop culvert systems around the service gate, Figure 8.17a. In this design, short culverts in the service gate monoliths carry water from the upper pool, around the gate, and discharge it into the lock chamber immediately downstream of the gate. Such systems are most economical where a lock is excavated in rock and walls are too thin to accommodate wall culverts. Systems of this type are also used to empty a lock, Figure 8.32a.

Filling and Emptying through Wall Culverts and Ports or Laterals.

- **Early conventional wall culvert and port systems.** The following systems were widely used for early locks on the Ohio, Tennessee, and Upper Mississippi Rivers and have performed well for low lifts:

a. Wall intakes in the upper approach walls.
b. Longitudinal culverts in the lock walls.
c. Wall filling and emptying ports throughout the length of the lock chamber.
d. Wall discharge system downstream of the lower lock gates.

At some locks incremental valve openings have been used to reduce turbulence in the lock chamber when filling and in the lower lock approach when emptying. Ten of the 11 locks initially constructed by the Tennessee Valley Authority (TVA) with conventional systems have comparatively high lifts of 39 to 80 ft, and at some locks the valve operating time is lengthened by holding the valve in a partly open position for various periods, depending on the size of tow being locked through. Turbulence and transverse and longitudinal currents occur to varying degree at locks on the Upper Mississippi River constructed in the 1930s, and valve opening times are lengthened to improve navigation conditions.

- **Modern systems.** In an effort to lessen problems experienced with turbulence and currents using the conventional culvert and port design, more complex systems were developed to provide faster and safe filler and emptying operations. Modern systems for locks of low and medium lift are generally of two types, and which system is used at a particular site is influenced by foundation materials and traffic and is ultimately determined by economics.

a. Systems filling and emptying the lock chamber through ports along the base of the lock walls (side wall port locks or side port locks), Figure 8.18a. This is the most common type of lock on the inland waterway system in the United States and can be used for lifts from 5 to 30 or 40 ft depending on lock chamber size, but generally is not suitable for higher lifts.

b. Systems filling and emptying the lock chamber through laterals and ports or longitudinal culverts and ports recessed in the floor of the lock chamber, Figures 8.18b and 8.19.

These systems take water from the upper pool through an intake manifold into wall culverts that supply water to ports in the lock chamber. The lock is usually emptied through the same system of ports and culverts and through a discharge manifold that discharges water either into the lower lock approach or riverward of the river wall of the lock.

Systems filling and emptying the lock through ports along the base of the lock walls operate satisfactorily with moderate filling times, with the time required for filling dependent on the lift and size of the lock chamber.

Filling and emptying systems recessed in the lock floor (laterals with ports for low-lift locks, Figure 8.18b, or longitudinal culverts with ports for high-lift locks, Figure 8.19) are designed for fast filling times; however, they require deeper excavation than is required for locks with ports along the lock walls. If the excavation is in rock, the additional cost may be hard to justify. If traffic can be served safely by a lock with moderate filling time, such a design is the cheapest and best solution. However, if projected traffic requires so many lockages that a fast-filling system or a second lock would be required, use of a more complex fast-filling design is usually the cheapest and best solution.

Davis (1989) presented data relating lock volume to average filling inflow, Figure 8.20. These curves can be used to obtain a preliminary estimate of lock filling filling time.

- **Intake manifolds**. Intake manifolds consist of a series of ports opening into a larger area that transitions downstream into a smaller rectangular cross section at the culvert control valve, Figure 8.21. The use of multiple ports spreads the incoming flow over a larger area than if a single large port were used, and this reduces the formation of vortices and entrainment of air into the wall culverts.

Intake manifolds are usually located in approach walls, but in some cases are in the upper gate sill, as shown in Figure 8.21, to pass drift and ice through the lock or to provide supplementary discharge capacity. Intake manifolds are streamlined and are designed for flow in one direction only, and intake velocities are usually limited to about 8 to 10 ft/sec. All ports are the same size at the wall face, but have different throat dimensions. The height/width ratio of ports at the wall face is usually in the order of from 2:1 to 4:1. The total port area at the wall face is about 2.5 to 3.5 times larger than the culvert cross-sectional area to reduce intake velocities and thus:

a. Reduce intake losses.

b. Minimize the formation of vortices that draw air into the system and create turbulence in the lock chamber when the air is discharged through the ports.

c. Minimize damage to trash racks on the intake ports.

The throat area of each port in the intake manifold is decreased successively in a downstream direction to obtain equal flow distribution through all ports. The head loss coefficient for the intake manifold is a function of the ratio of total port throat area (ΣA_p) to culvert area (A_c) and decreases as the ratio increases, Figure 8.22. A value in the order of 1.8 is desirable; values ranging from 1.5 to 2.0 have been used successfully (Davis, 1989). Comparison of model and prototype data shown on Figure 8.22 indicates that further increase in the ratio of $\Sigma A_p/A_c$ beyond a value of about 2 has minimal effect on the head loss coefficient. Head loss through the intake manifold can range from 0.16 to $0.4\ V_c^2$ where V_c is culvert velocity.

Much shorter culvert intake walls are required if intake manifold ports can be located on both faces of the walls (Siamese intakes), as for Barkley Lock, Figure 8.17b.

The top of intake ports should be located well below the minimum upper pool level to ensure positive pressure in the system. Davis (1989) suggests that minimum submergence below the minimum upper pool level be set equal to the velocity head at the throat of the most downstream intake port.

Trash racks are used on the face of intake ports, Figure 8.23, to prevent debris and ice from being drawn into the system. When floating drift or ice is present, it is important that intake velocities be limited to 8 to 10 ft/sec to avoid impact damage to the trash racks. Slots are provided in the lock walls for the installation of bulkheads for unwatering the intake area for inspection and repair.

Vortex action and entrainment of air at intake ports in gate sills can:

a. Reduce efficiency of the filling system.
b. Present hazards to operating personnel and small craft.
c. Produce dangerous conditions in the lock chamber when large blocks of air are expelled through the filling ports.
d. Result in damage to trash racks by debris caught in the vortex.

In general, vortex action has been found to be greater in the prototype than in models. Model studies and prototype experience have shown that intakes in the upper gate sill are more susceptible to vortex action than are intakes in the lock walls. At sill intakes there are concentrations of high velocity in the approach and in the port entrances because the width of flow is restricted to that of the lock sill; the closed angle of miter gates affects uniformity of the approach flow; and discontinuities at miter gate recesses can induce eddies leading to the formation of vortices.

In model studies of intake manifolds located on the top of gate sills parallel to the upstream gates, as at the St. Anthony Falls Lower Lock, Figure 8.21c vortex action was reduced or eliminated by:

a. Decreasing the distance between the intake manifold and upper lock gates.
b. Increasing the spacing between intake ports.
c. Increasing the intake port area at the sill face.
d. Increasing submergence of the intake.

To reduce vortex problems at both wall and sill intakes, Davis (1989) recommends avoidance of the following conditions:

a. Unequal distribution of flow in the intake ports.
b. Openings in the guide or guard walls that induce diagonal currents.
c. Breaks in alignment of the approach walls.

Small vortices carry little or no air into the culverts and have essentially no effect on lock chamber turbulence; however, large vortices can produce considerable turbulence. Vortices are difficult to avoid in high-lift locks for shallow-draft traffic where the depth above the upper sill is shallow and the approach floor is at about the elevation of the upper sill.

There are no design criteria that will ensure that lock approaches will be free of vortex problems, but the problems will be minimized if flow conditions are symmetrical, velocities are minimized, and maximum submergence is provided. Where a problem is anticipated, it should be investigated in a hydraulic model.

One of the more recent model studies to investigate potential vorticity at a lock intake was a study at the Waterways Experiment Station of conditions at replacement locks at the old Gallipolis Locks and Dam on the Ohio River (Davidson, 1987). The two new locks (110- by 1200-ft and 110- by 600-ft) are located in a short excavated channel across the inside of a bend. Two alternative intake designs were considered, Figure 8.24. Intake designs were tested on a 1:25 scale model that reproduced 2500 ft of the Ohio River beginning 188 ft upstream of the existing lock guide wall. Model studies indicated vortex problems would occur with both intake schemes as originally designed. However, modifications developed in the model eliminated vortex formation for both designs.

Alternative I, Figure 8.24a, involved filling the locks from the river through three long culverts. In testing, it was observed that flow conditions were unsatisfactory and that the following contributed to the formation of severe air-entraining vortices at the intake structure:

a. Flow entering the intake was unsymmetrical.
b. Layout of the original approach walls caused water to swirl around the abutments.
c. There was insufficient submergence for the design.

Modifying the position of the approach wall to Position 2, Figure 8.25a, decreased the severity of the vortices; however vorticies still occurred. Various other modification were studied. The invert of the intake was lowered 15 ft, and flow entering the intake was made more symmetrical by relocating the approach walls and placing a dike upstream of the existing lock guide walls. A vortex suppressor plate 15.4 ft thick was placed at the same elevation as the intake conduit roof and extended 17 ft upstream to the trash rack, Figure 8-25b. With these modifications, all air entraining vortices were eliminated.

Alternative II, Figure 8.24b, involved filling the locks from the river through a short excavated channel supplying water to two intake manifolds in the guide wall and a third manifold in an intake tower. The original design of the intake tower had a sharp corner at the upstream front face, and a severe vortex developed at that point; however, no vortices formed at the manifolds in the guide wall. Several modifications of the intake tower were tested. A design adding a straight vertical wall with a quarter of an ellipse immediately upstream of the intake tower, Figure 8.25c, eliminated air-entraining vortices for this alternative.

- **Control valves.** Control valve in lock culverts are usually tainter gates in a "reverse" position, that is, with the trunnions on the upstream side and skinplate and sill on the downstream side, as shown schematically in Figure 8.26. With two exceptions, all locks built in the United States since 1940 have reverse tainter control valves. Positioning the valves in this manner prevents air entrainment in the low pressure area downstream of the valve, thus minimizing turbulence and high hawser stresses associated with release of air from the filling system into the lock chamber. Air entrainment becomes a more severe problem as lock lift increases.

Lock filling criteria is based on not exceeding permissible hawser forces of 5 tons. Hawser stress is related to turbulence which, in turn, is related to the depth of water (cushion) in the lock chamber and over the filling ports. The cushion provided has a major impact on project costs, and the depth normally is not greater than needed for bottom clearance (in the order of a few feet) because of cost. Depending on specific site conditions, such as depth to sound rock, it is sometimes economical to provide greater cushion.

Recommended prototype valve opening time to limit hawser forces to five tons for lock chambers of various sizes, based on model studies and reported by Murphy (1975), are shown in Figures 8.27 and 8.28.

- **Wall culverts**: Culverts in lock walls convey water from the intake manifold to the filling and emptying system, and to the outlet system. Downstream from the intake manifold, the culvert transitions to a rectangular or square section at the filling valve, with a culvert height to width ratio of from about 1.0 to 1.15. In wall culvert side-port systems, the culverts are usually of uniform size from the filling valve to the emptying valve. Any culvert expansions should be gradual, about 1 on 10, to minimize head loss and turbulence.

The horizontal location of a culvert in the lock wall, the distance from the culvert to the face of the lock wall, fixes the length of wall ports. This distance is sometimes determined by structural requirements. As a minimum, a port length of about 8 ft is desirable. In side-port systems, the elevation of wall culverts is established by submergence requirements for the ports and pressure conditions at the valves. In bottom filling systems, minimum depth in the lock chamber must also be considered. In high-lift locks with bottom longitudinal systems, valves are placed low to control pressures and air intake, and the valves and wall culverts must be almost as low as the bottom manifold system.

To unwater valves for maintenance, bulkhead slots are usually placed in culverts upstream and downstream of the valve. To minimize cavitation damage, the downstream slot is located downstream of the vena contracta when the valve is 50 to 70 percent open; locating the slot a distance of three times the culvert height downstream will usually place it out of the area most susceptible to cavitation. The upstream bulkhead slot is located at least two times the culvert height upstream of the upstream edge of the valve shaft. For high-lift locks, steel plate culvert liners are used on all surfaces of the culvert downstream from the valve. Model tests indicate that the area most subject to cavitation damage is usually 2.0 to 2.5 times the culvert height downstream from the bottom seal line of the reverse tainter valve, and the liner extends downstream past this area.

- **Wall-port systems**. Wall ports to fill and empty a lock chamber are designed for flow in both directions. They are streamlined, with rounded entrances and exits, and are flared to the lock face to reduce exit velocities when filling. The design shown in Figure 8.29 is considered the best of many designs tested. The ports occupy 50 to 60 percent of the lock length and are located in the center portion of the lock chamber to minimize surging during filling. Ports in one wall are staggered with respect to ports in the opposite wall so that the jets from one wall do not collide with jets from the opposite wall, but pass each other and there is good distribution of energy with little turbulence.

As the filling jet exits the port, it flares upward at about 7 degrees; thus flaring about 14 ft when it reaches the opposite wall of a 110-ft lock. If wall ports are staggered and set on 28-ft centers in a 110-ft lock (at 20-ft spacing in an 84-ft lock), this expansion takes place between jets issuing on the opposite wall, minimizing turbulence. Culverts and valves should be sized to carry the jets to the far side of the lock chamber, but port outflow should not be sufficient to cause a welling up of water on the far side of the lock.. Locks narrower than 110 feet have side ports set on lesser spacing and lesser discharge from the wall ports to avoid upwelling on the far side.

Wall ports should be of sufficient size so that the jets do not completely diffuse before reaching the opposite wall or boils will occur at the surface, thus increasing hawser stresses. For higher lock lifts, the ports may be directed down toward the base of the opposite wall to reduce turbulence. Model studies for Arkansas River locks indicated that triangular recesses, Figure 8.30, in front of the upstream one-third of the ports would reduce upstream longitudinal hawser stresses during filling.

For shallow-draft locks, the bottom of wall ports should be set at the elevation of the bottom of the wall culvert and at, or slightly below, the level of the lock floor.

The total port throat area in one wall should be about 95 percent of the wall culvert area. A smaller ratio would increase filling time, and a larger ratio would result in less favorable hydraulic conditions in the lock chamber. Port face area varies with lock chamber size, as recommended by Davis (1989):

a. 10 to 11 sq ft for a 1200- by 110-ft lock.
b. 9 to 10 sq ft for a 600- by 110-ft lock.
c. 6 to 7 sq ft for a 600- by 84-ft lock.

- **TVA multiport system.** In 1959 the TVA used a somewhat different filling and emptying system in design of three new locks with lifts of from 42 to 60 ft on relative high rock foundations. The multiport system, Figure 8.31, required less excavation and was more economical than the culvert-lateral-port system.

- **Lock chamber lateral diffusers.** A lock chamber lateral diffuser is a filling and emptying system of small culverts (laterals) across the lock chamber with ports in the laterals. The laterals are recessed in a trench in the lock floor so that the jets mix and dissipate most of the energy below the main body of water and tows in the lock chamber, minimizing hawser stresses. A typical installation is shown in Figure 8.18b. They are more expensive than wall port systems, but may be economically justified at some locks serving heavy traffic on the basis of reduction in lock filling and emptying times.

Lock chamber lateral diffusers are similar to discharge diffusers, but differ in that they are designed for flow in both directions, that is for both filling and emptying operations. They are located in the middle third of the chamber for a 600-ft lock, as for the Greenup auxiliary lock, Figure 8.18b. For a long lock, for example the 1200-ft Greenup main lock, Figure 8.18b, the diffusers are split into two systems to keep hawser forces within acceptable limits and one group of laterals is located approximately the middle third of the upstream half of the chamber and the other in the middle third of the downstream half of the chamber.

- **Lock emptying systems.** Lock emptying systems are designed to discharge and distribute outflow from lock emptying so as not to cause turbulence or currents that would endanger craft in the lower lock approach. Outlet systems usually discharge either to the lower lock approach (between the lower guard and guide walls) through wall port manifolds or laterals, or on the river side of the lock, Figure 8.32. The emptying culvert is widened downstream of the emptying valve to reduce exit velocities and head loss, and the discharge system is designed for flow in one direction only.

Where locks empty into the lower approach, a system of laterals across the lock usually is used to minimize turbulence. The single culvert discharge laterals for St. Anthony Falls Lower Lock, Mississippi River, is shown in Figure 8.33. The flow area (cross section) of the laterals is decreased in the downstream direction (across the lock) at successive ports for uniform discharge through the ports. The outside walls of the laterals are parallel, and ports in adjacent laterals are staggered so that jets issuing from the ports are offset and do not collide and can diffuse laterally before reaching the opposite wall.

The emptying system for the Snell Lock, St. Lawrence Seaway, Figure 8.32b, has discharge culverts in both walls and extensions on all ports to direct the jets perpendicularly across the trenches and produce a better flow distribution in the lower approach.

Wall discharge manifolds have been designed to empty completely or partially into the lower lock approach, as for the McArthur Lock, St. Mary's River, Figure 8.32a, and the New Cumberland Main Lock, Ohio River, Figure 8.34. The New Cumberland emptying system was designed to divert two-thirds of the discharge outside the lock approach. Ports discharging into the lock approach are staggered to minimize interference by opposing jets.

Davis (1989) reports that turbulence experienced at these three prototype locks is greatest for the St. Anthony Falls Lower Lock, less for the New Cumberland Lock, and least for Snell Lock. However, cushion depths over the outlets varies significantly for these locks, being 22.2 ft at St. Anthony Falls, 24 ft at New Cumberland, and 48 ft at Snell.

Discharge into the lower lock approach during emptying can create currents that adversely affect upbound tows. When the emptying manifold is placed riverward of the lock, the emptying operation generally has no effect on tows approaching the lock. The emptying system for Greenup Locks, Ohio River, Figure 8.32c, is typical of systems that divert the entire outflow riverward of the lock. Stilling basins are usually included in such outlets to reduce turbulence. With such designs, the lower lock entrance is completely free of disturbances during emptying operation and the entire length of the guide wall can be used for mooring tows. However, outlets such as for Greenup Auxiliary Lock may cause a problem with miter gate operation at moderate flows when the stage in the lock approach is lower than at the outlet (and in the lock chamber) causing a head differential at the gates. Miter gates normally require equal water levels on both side of the gates for opening.

Another outlet design, used for some of the Arkansas River locks, includes a system of baffles, Figure 8.35. Such designs are suitable for low-lift locks at some locations.

A recent example of an emptying system discharging on the riverward side of the lock is the Olmsted project now (1995) under construction on the Ohio River 16.6 miles upstream from the junction of the Ohio and Mississippi Rivers. The Olmsted project, with two 110- by 1200-ft locks and a design lift of 21 feet, will replace two existing locks Locks and Dams 52 and 53, having lower lifts. Tailwater at the site is not affected by a downstream navigation structure. Open-river conditions prevail downstream, and tailwater is influenced by Mississippi River stages. The emptying systems are unique in that discharge culverts from the land wall, the middle wall, and the river wall all empty into a common outlet structure in the river, and culverts from the land wall and middle wall pass under the floor of the river lock (Stockstill, 1992). The outlet is located 25 ft riverward of the river lock in the vicinity of the lower gate monolith. The 14- by 18-ft culverts drop 21 ft vertically over a 76-ft length in the lock walls and then turn 90° to the outlet, Figure 8.36.

Bottom Longitudinal Filling and Emptying Systems. For higher-lift locks, the bottom longitudinal filling and emptying system, with longitudinal culverts with ports recessed in the floor of the lock chamber, has become widely used, as for Lower Granite Lock on the Snake River, with a 32-ft lift, Figure 8.19. These systems are complex in design, but model studies indicate they are superior to other systems for medium- and high-lift locks because of low turbulence in the lock chamber and low hawser stresses, with less chance of damage to tows or to the lock itself. In the bottom longitudinal system, flow in the wall culverts passes into a "crossover" culvert across the lock at the center of the lock chamber, as for Dardanelle Lock on the Arkansas River, with a 54-ft lift, Figure 8.37. A splitter wall in the crossover culvert distributes flow equally to two longitudinal floor culverts with ports, one in the upstream half of the lock chamber and the other in the downstream half of the lock chamber.

The bottom longitudinal filling and emptying system for Dardanelle Lock on the Arkansas River, a "side-by-side" system, Figure 8.37, is representative of such systems designed in the 1960s. The design was later refined and modified, particularly for locks of higher lift and 1200-ft length. Murphy (1980) recommended that the side-by-side design not be used for lifts in excess of 60 ft based on experience with the Bankhead Lock on the Black Warrior River with a 69-ft lift, Figure 8.38.

Model tests indicated that the side-by-side system designed for Dardanelle Lock could fill the lock in 8.4 minutes with a maximum longitudinal hawser stress of about 5.2 tons with normal 2-minute valve operation. Model studies also indicated that baffles along the walls and between the longitudinal culverts, Figure 8.37b, would reduce bottom water movement toward the ends of the the lock chamber, reducing individual boils and turbulence so that conditions would be satisfactory in the lock chamber with normal operation.

Examples of the "over-and-under" bottom longitudinal filling and emptying system are shown in Figures 8.38 and 8.39. At both locks flow from the crossover culvert is directed to combining culverts upstream and downstream of the crossover culvert. At Lower Granite Lock on the Snake River (lift 105 ft), there are four floor culverts in each half of the lock chamber, while Bay Springs Lock on the Tennessee-Tombigbee Waterway (lift 84 ft) has two culverts in each half, Figure 8.39. The Bay Springs system under construction (looking upstream) is shown in Figure 8.40. The floor culverts are 14 ft wide and 9 ft high, each with 12 pair of ports 1.5 ft wide and 3.5 ft high, spaced 15 ft on centers, with a port/culvert area ratio of 1.0. With this design and a 1-minute valve operating time, the lock filled in the model in 9.9 minutes with longitudinal hawser stress of about 7 tons and transverse hawser stress of about 6.5 tons. The lock emptied in about 11.7 minutes.

- **Culvert area ratios**. Murphy (1980) suggested that a relatively constant cross-sectional area be maintained from the wall culverts through the crossover culverts and the combining culvert. He further suggested that initial studies of filling time and cost be primarily concerned with culvert size in this area and that filling valve size be determined later.

- **Longitudinal floor distribution culverts**. Murphy (1980) noted that in the 670-ft Bankhead and Bay Springs locks two distribution culverts in each half of the lock chamber were adequate, but that general tests of a 1200-ft lock indicated four were required in each half. He suggested that the number needed probably depends on lift and culvert size as well as on the length/width ratio of the lock chamber.

- **Port manifolds**. Murphy (1980) recommended that:

a. Port manifolds extend over at least 50 percent of the length of the chamber.

b. If two culverts are used in each half, manifolds be centered on the one- and three-quarter points of the chamber, with each manifold extending over at least 25 percent of the total length of lock.

c. If four culverts are used in each half, manifolds be centered on the one-, three-, five-, and seven-eights points of the chamber, with each manifold extending over at least 12.5 percent of the total lock chamber length.

- **Ports**. Ports tested in model studies have ranged in size from 4.2 to 6.28 sq ft, and Murphy (1980) favors a port similar to that used at Bay Springs (3.5 ft high, 1.5 ft wide, 5.25 sq ft total area) because those ports gave good distribution of turbulence in the lock chamber and are large enough to allow access for inspection and maintenance. He noted that, while in a sidewall port system the total cross-sectional area of ports should be about 95 percent of the culvert area, with the relatively short distribution culverts in this system a port-to-distribution culvert area ratio of 1.0 is preferable and that all available space should be used for the port manifold. He suggested there should be a relationship between trench size and port size, with lift also a factor, so that a large portion of the kinetic energy of jets from the ports is dissipated in turbulence in the trenches along the distribution culverts. Baffles are needed on the walls of the trenches and between the distribution culverts to prevent upwelling of jets from the ports.

- **Operation.** Due to differences in friction factors between model and prototype, prototype locks with bottom longitudinal culvert filling and emptying systems can be expected to fill about 16 percent faster than indicated by a 1:25-scale model (Murphy, 1980).

8.8 Closure Facilities for Locks.

All Corps of Engineers locks have facilities that can be set in place in still water for maintenance of the lock chamber and lock gates. However, few locks have the capability to make closures in flowing water under emergency conditions.

Navigation locks are vulnerable to accidents that result in damage and failure of lock gates so that the pool is drained down through the lock to the top of the upper gate sill. In the United States, accidents with tows ramming miter gates occur from time to time. In a typical case, a tow entering a lock rams and knocks out the closed gates at the far end of the lock chamber before gates behind the tow can be closed. (In one instance, a vessel out of control knocked out the gates at both ends of a lock.)

When miter gates are damaged and cannot be closed, uncontrolled flow through the lock chamber can result in significant losses. The extent of such losses depends principally on development upsteam and downstream of the lock. In a highly developed area, such as along the middle reach of the Ohio River, monetary losses and other hazards can result from:

a. Loss of the upstream pool.
b. Flood damage downstream from the lock.
c. Losses to shipping using both pools, particularly in the upstream pool.

Loss of the upstream pool storage can result in loss of municipal and domestic water supply if the water surface falls below the elevation of the water supply intakes, loss of condenser water for power plants, and losses and damage to tows and vessels that are beached on the channel bottom. Unrestricted flow through a lock may cause a sudden rise in downstream pool level, causing small craft and barges to break their moorings and drift uncontrolled into the channel, sometimes lodging against the spillway of the next dam downstream. A sudden and unexpected rapid increase in river stage can result in greater flood damage to equipment and installations than would occur with a normal slower river rise.

- **Maintenance closures.** Maintenance and operation costs should be considered in selecting the type of closure facilities for a particular lock. At a high-lift lock with a high upstream gate sill, a submergible vertical-lift gate or tainter gate at the downstream edge of the upper gate sill is generally the best solution. However, use of use of such gates at a low-lift lock could result in high maintenance costs because of sediment accumulation on the gate and the need for periodic costly sediment removal. Emergency closure structures can also be used for routine maintenance work that requires dewatering.

Maintenance closure facilities at most Arkansas River locks consist of a center post that is set in a recess in the lock sill with 55-ft long stoplogs on both sides extending over to the lock walls.

- **Emergency closures.** Various types of emergency closure structures have been used successfully. All have advantages and disadvantages, depending on local conditions:

a. Submergible vertical-lift and submergible tainter gates can be operated quickly under flowing water conditions. They can be used at locks with sufficient lift to allow the gates to be submerged downstream from the upper gate sill and above the lock floor.

b. Stop logs can be placed with a crane and hoist or with an overhead locomotive crane, the only difference in the installations being in the equipment used for placement. A crane and hoist can be used under any condition, and stop logs are the least costly type of emergency closure. An overhead locomotive crane has been used for placement of stop logs at some of the newer Ohio River locks; the overhead bridge on the gated spillway piers continues over the upstream end of the lock, and the same crane used to operate the spillway gates is used to place the stop logs in recesses in the lock walls. The operating bridge for the locomotive crane must be high enough to provide the vertical overhead clearance at the lock required for navigation (55 ft above the 2 percent duration flow on the Ohio River), and this may involve added costs for raising the spillway piers.

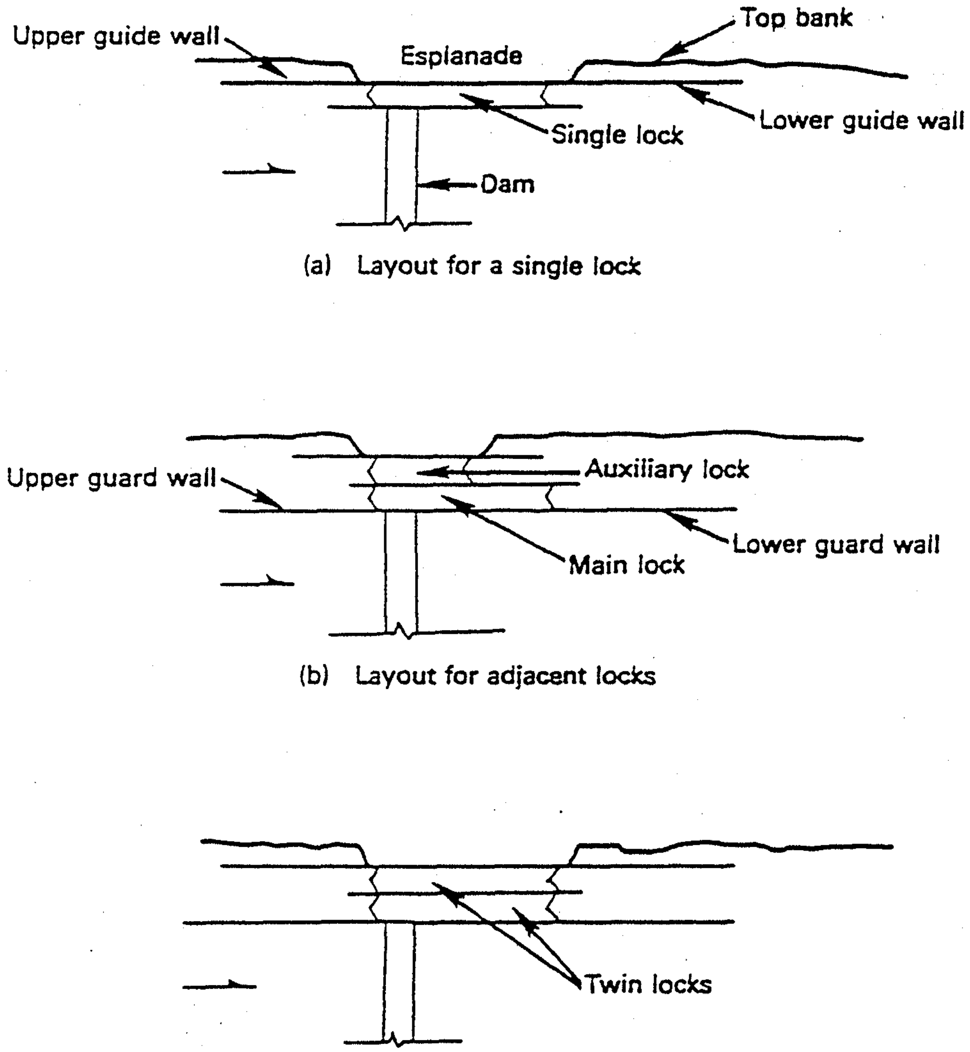
Stop logs placed with a derrick or crane have several advantages in addition to not requiring an overhead structure, including: reliability; no permanently submerged structures to maintain; and little maintenance required for the stop logs, hoists, and derrick or crane. Difficulties are that installing stop logs requires considerable time and space is needed for storage of the stop logs near the upstream end of the lock.

Stops logs cannot be placed individually in flowing water; water flowing over and under an individual stop log produces vortex trails that cause eratic movement, and the stop log jams in the wall recesses. Accordingly, the first stop log is placed in the recesses above the flowing water and held there temporarily; additional stop logs are added one by one, and the entire unit is lowered into the water incrementally, as each stop log is added.

c. Sector gates can be closed in flowing water in a few minutes and require no special equipment, personnel, or mobilization. However, they are large structures and require considerable space, have a very high first cost, require maintenance, and may have a problem with differential settlement if the lock is wide.

d. Overhead vertical lift gates require a high structure across the lock and are unsuitable where high clearance is required for navigation.

Emergency closure sills are discussed earlier in this section. Closure facilities, including all appurtenant equipment (cranes, hoists, trucks, and auxiliary power source), should be readily available and should be inspected periodically to ensure they are operable. Such facilities should be designed to close off uncontrolled flow as quickly as possible, depending on site specific conditions. At some locations (e.g. the Ohio River) uncontrolled flow should be stopped in 2 to 3 hours. The time factor may not be as critical at other, less-developed, locations.



(a) Layout for a single lock

(b) Layout for adjacent locks

(c) Layout for twin locks

Figure 8.1 Typical lock layouts.

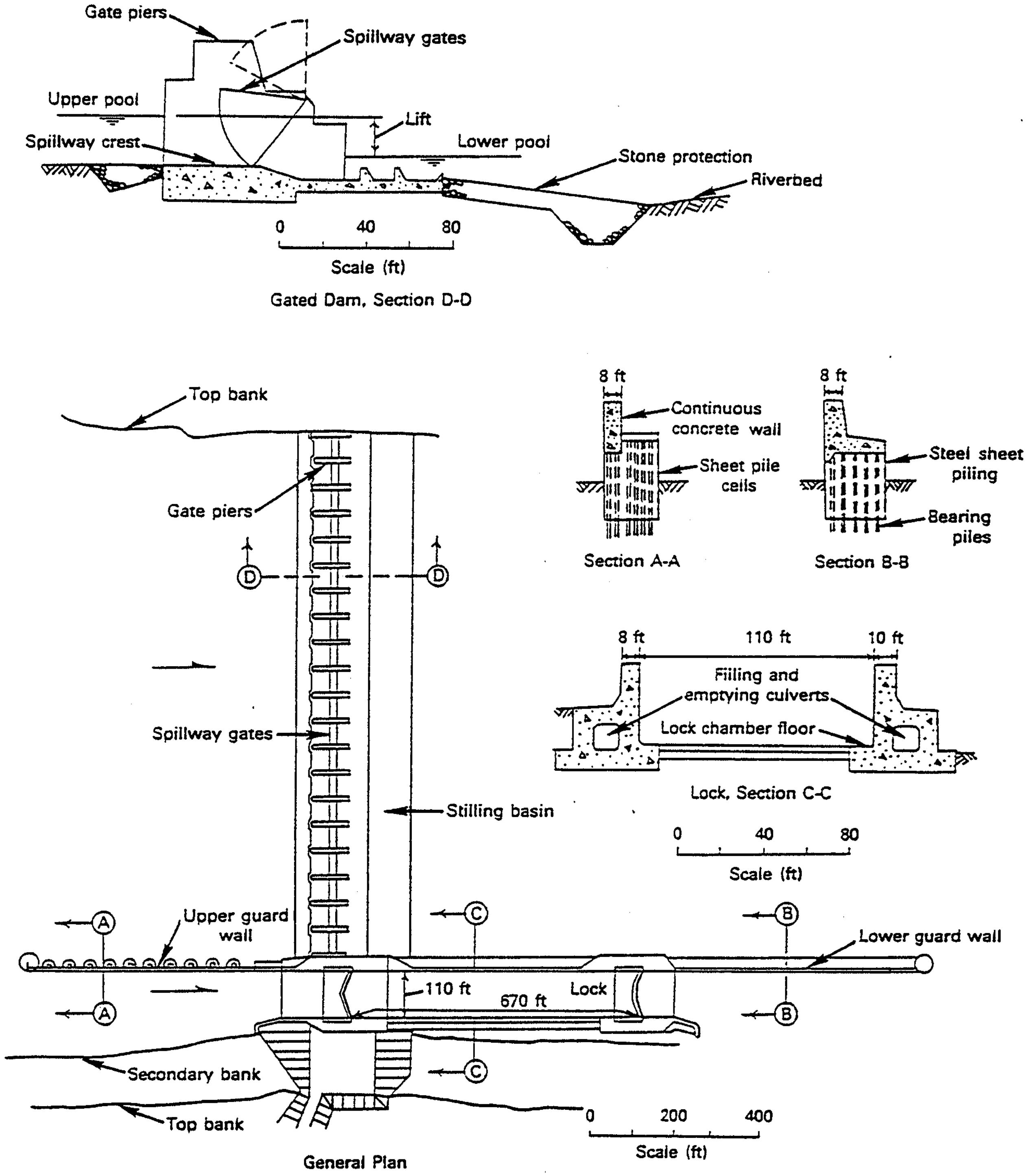


Figure 8.2 Typical low-lift navigation lock and dam (Ables and Boyd, 1966).

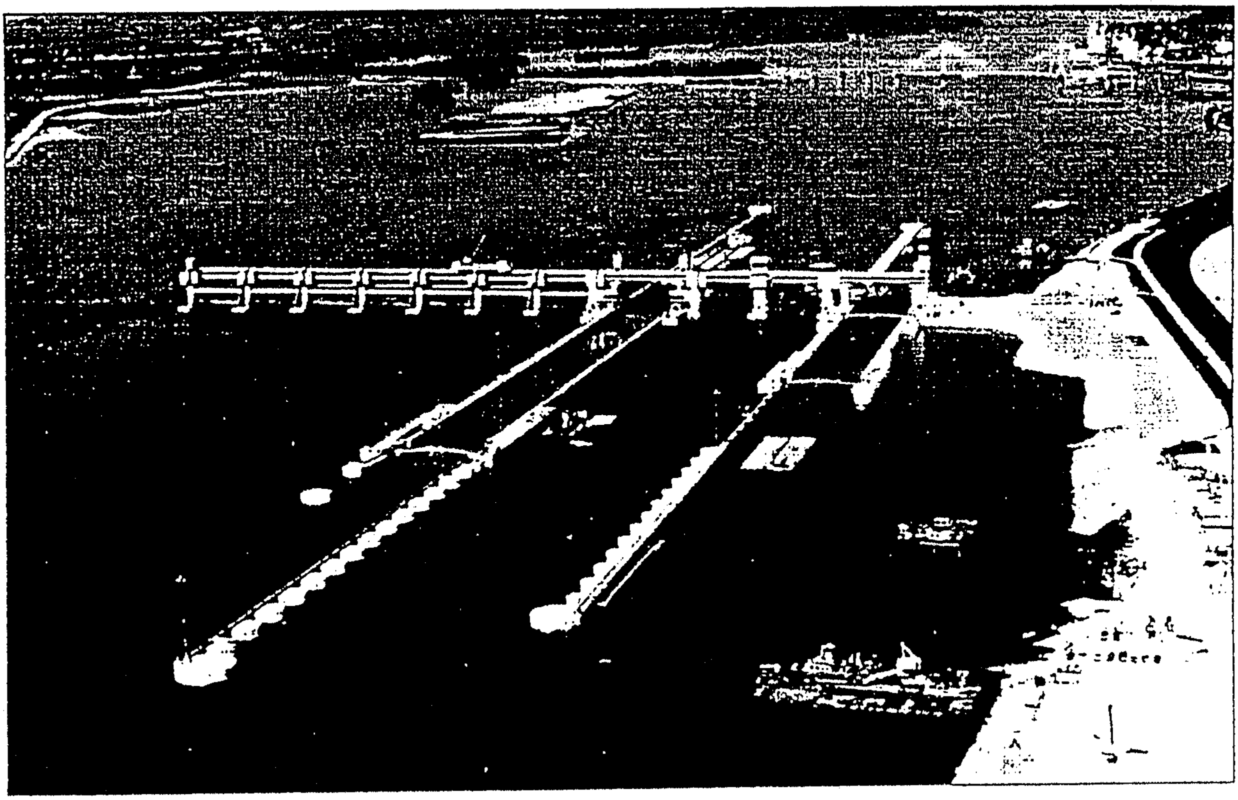


Figure 8.3. Melvin Price Locks and Dam, Mississippi River (Replacement for Lock and Dam 26).

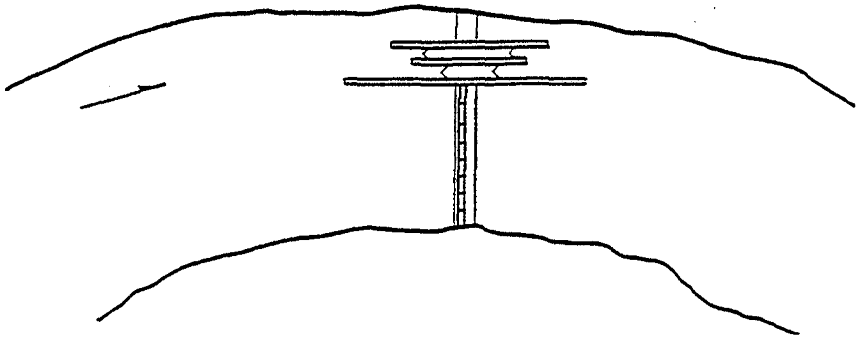


Figure 8.4. Lock in deep part of bend.

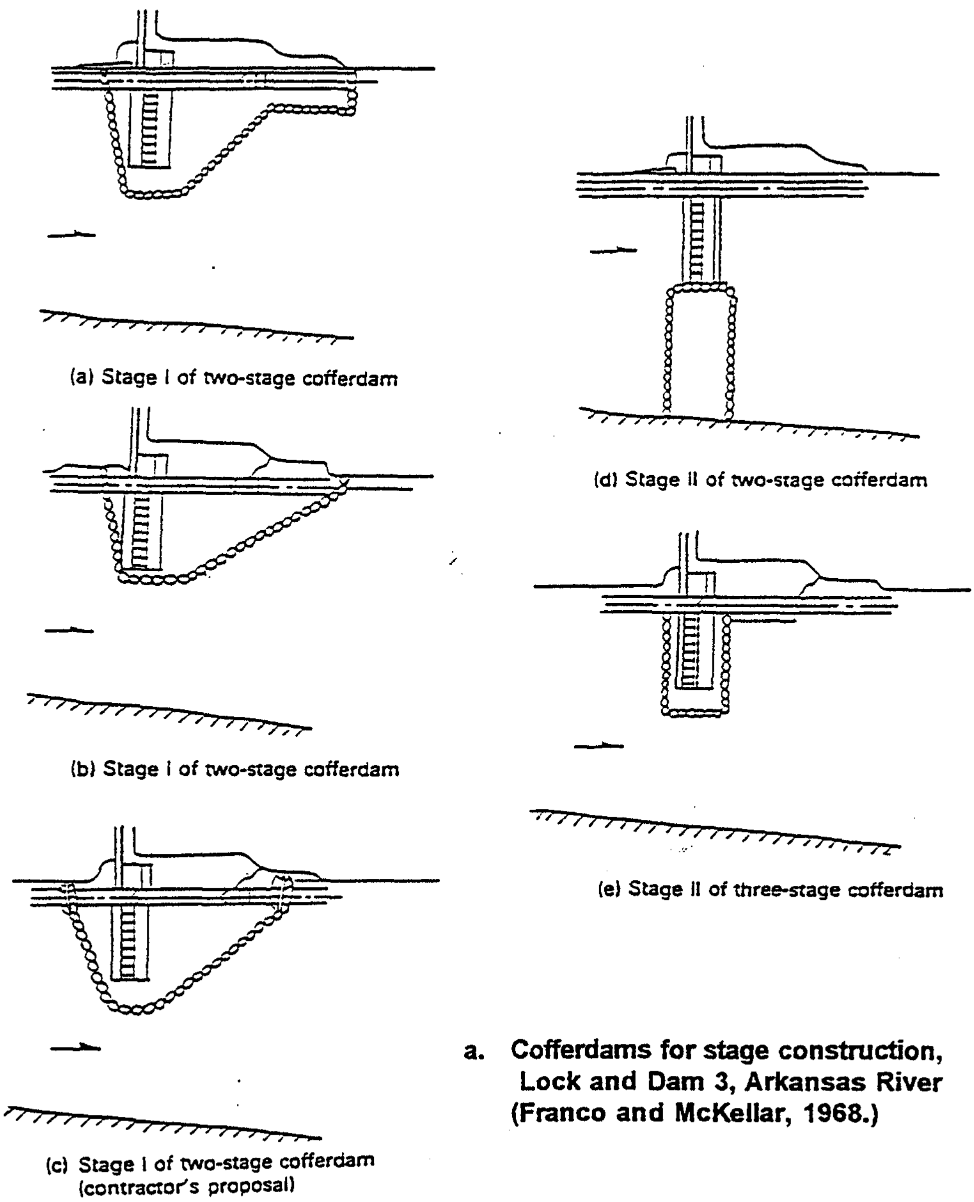
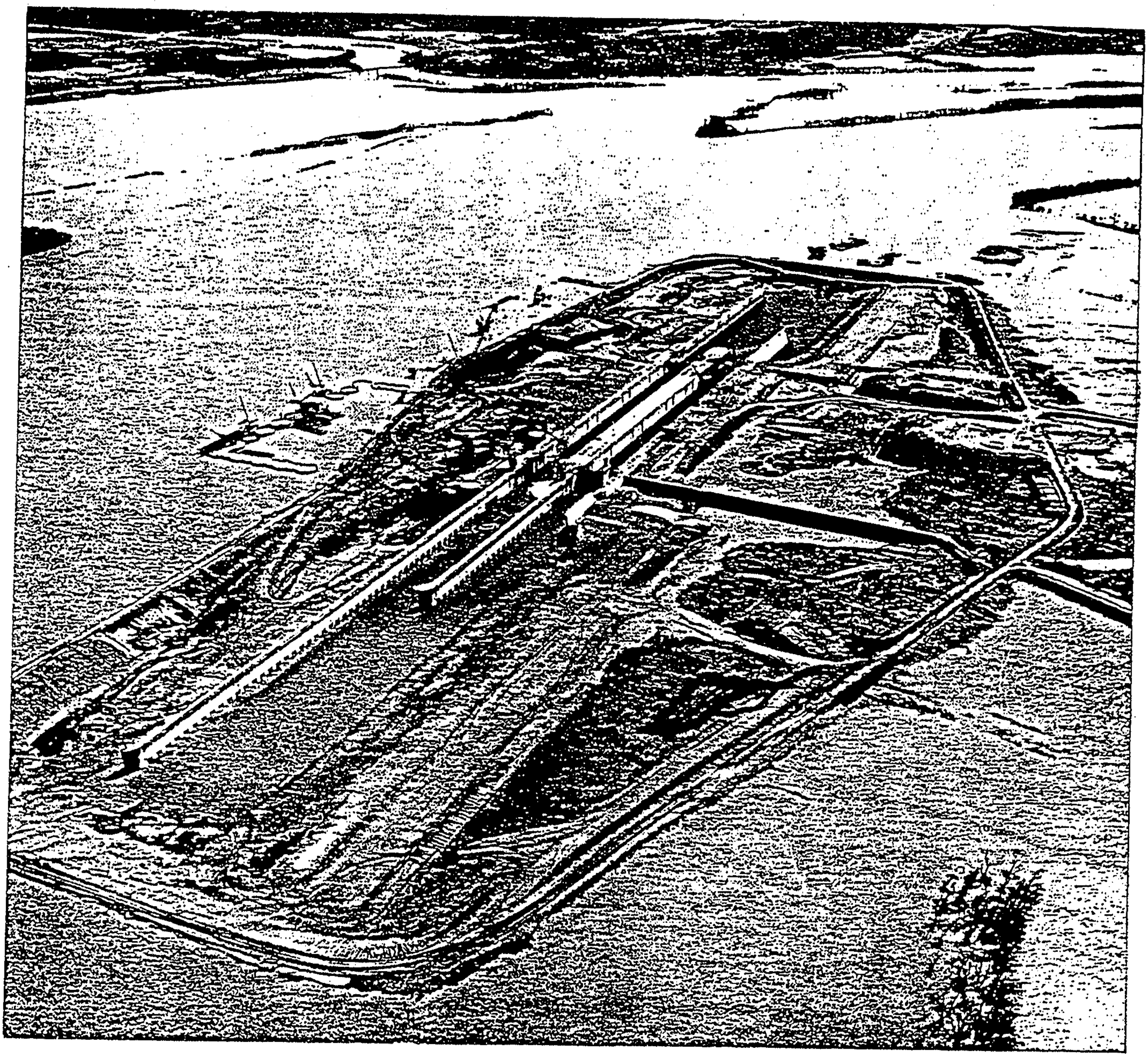


Figure 8.5. Cofferdams for stage construction.



b. Twin 1200-ft locks under construction, Ohio River, Smithland, KY.

Figure 8.5. Cofferdams for stage construction.

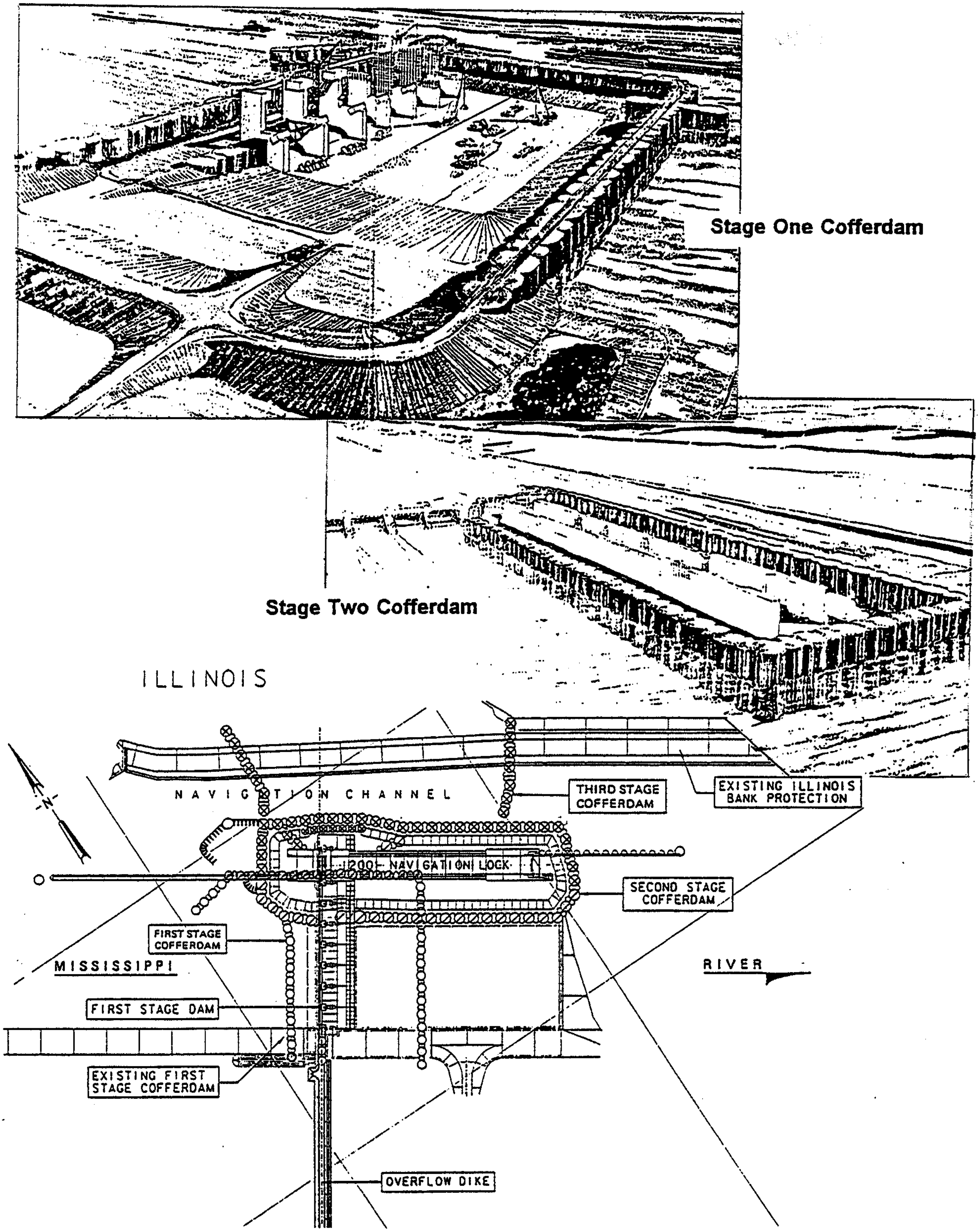


Figure 8.6. Three-stage cofferdam scheme, Replacement for Lock and Dam 26, Mississippi River.

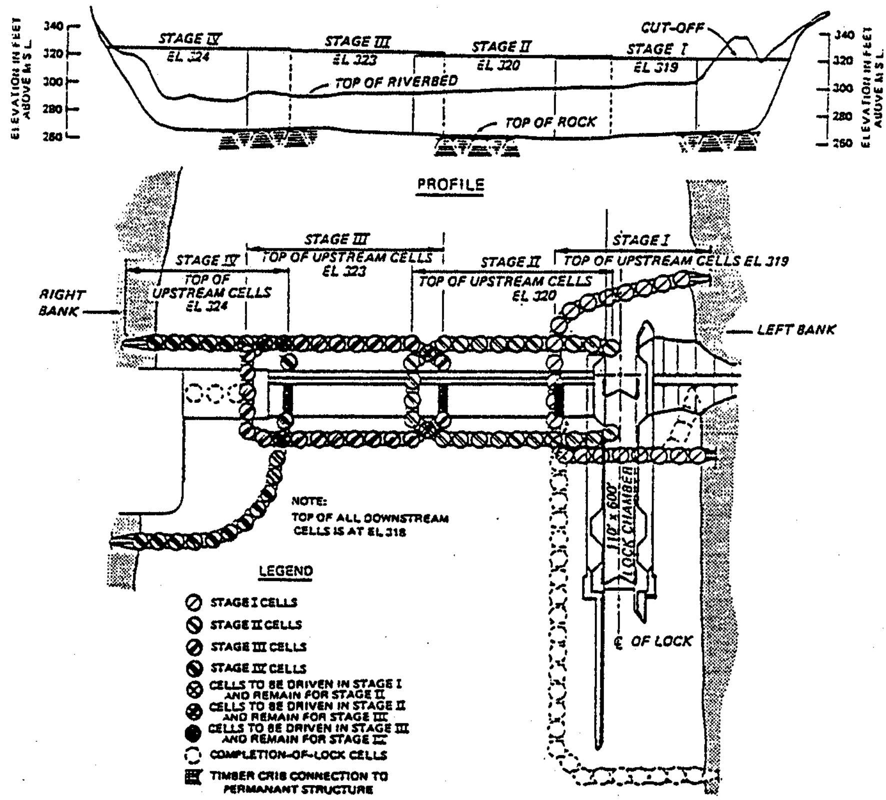
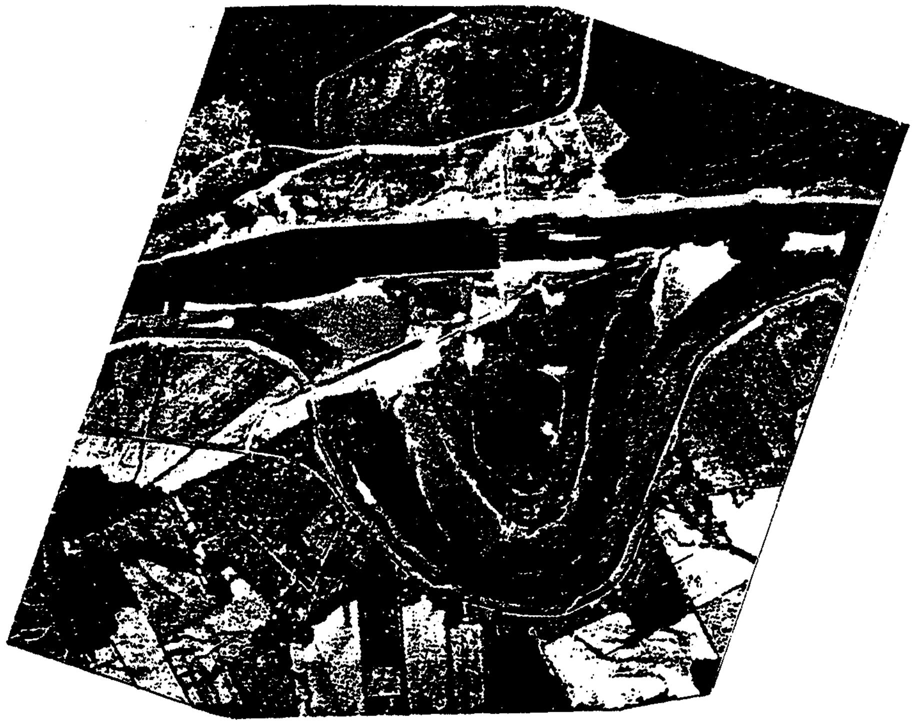


Figure 8.7. Four-stage diversion plan, Dardanelle Lock and Dam, Arkansas River.



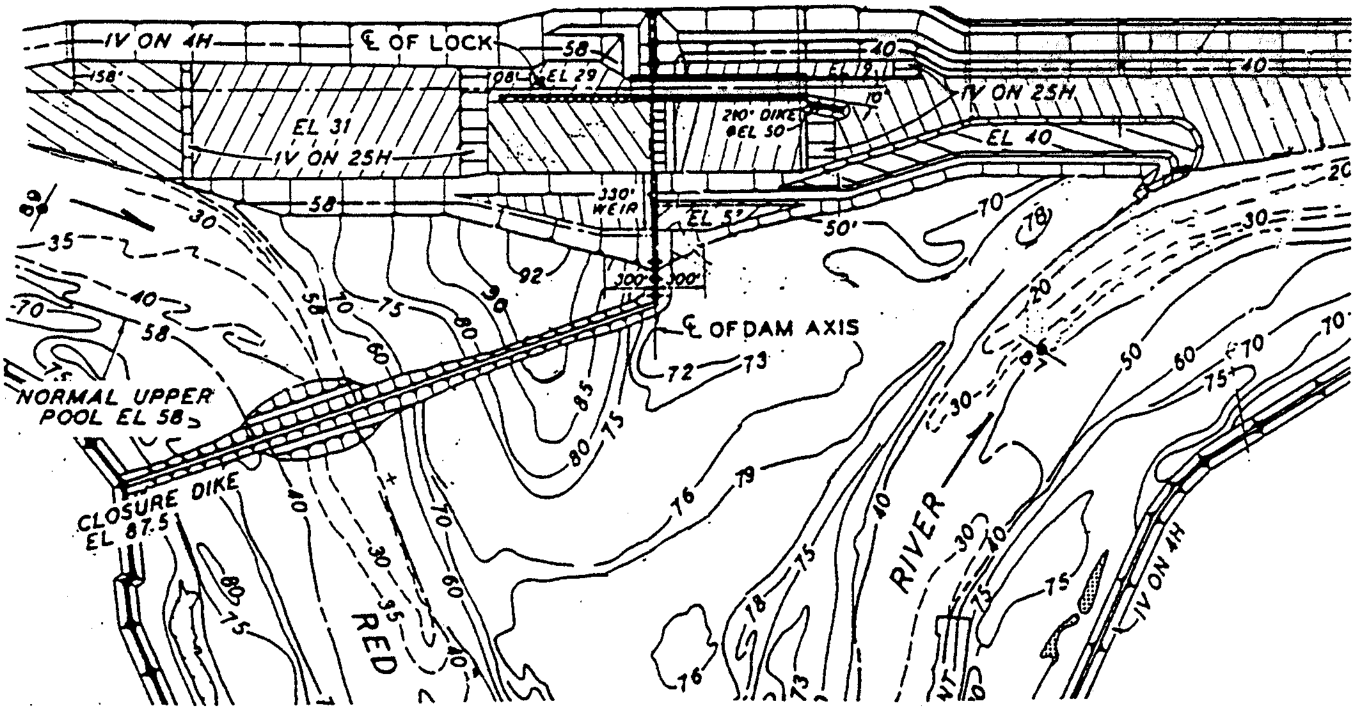


Figure 8.8. Red River Locks and Dams constructed in dry in cutoffs on rectified river alignment.

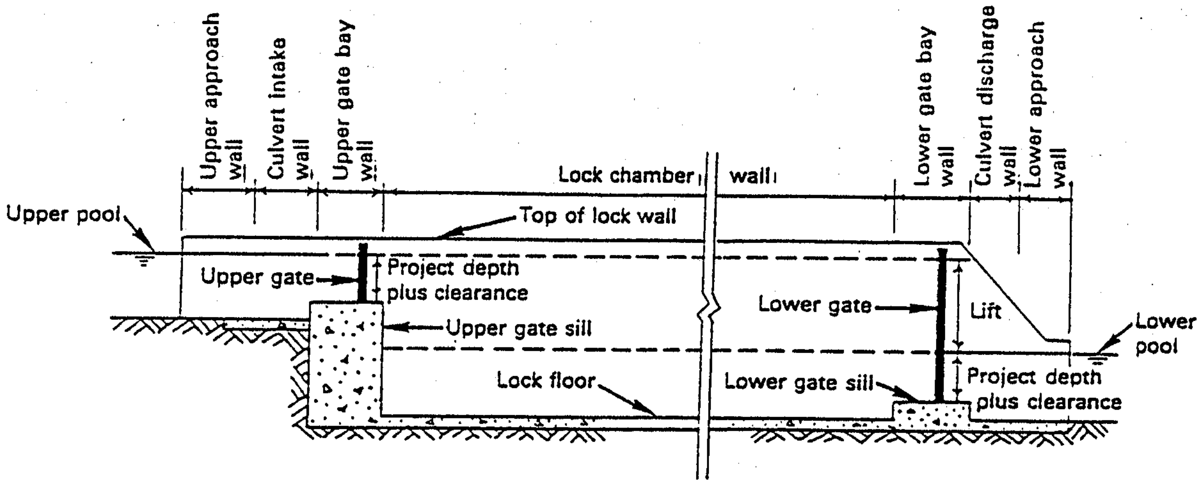


Figure 8.9. Lock walls, gates, and sills.

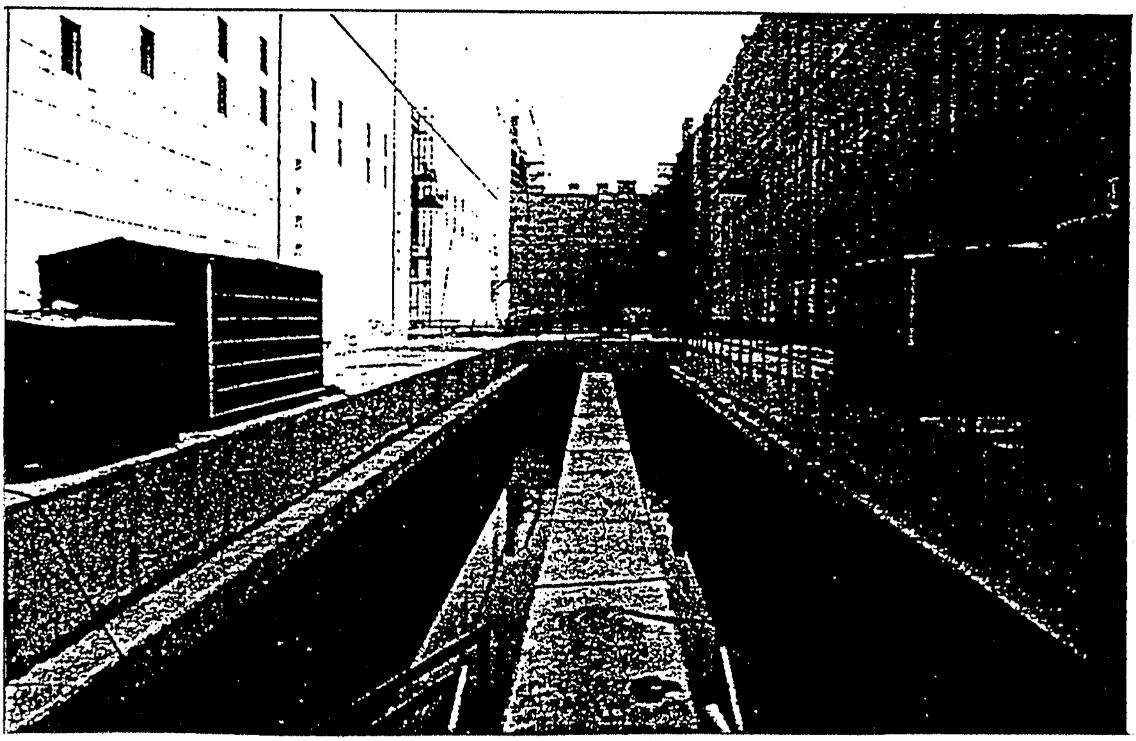
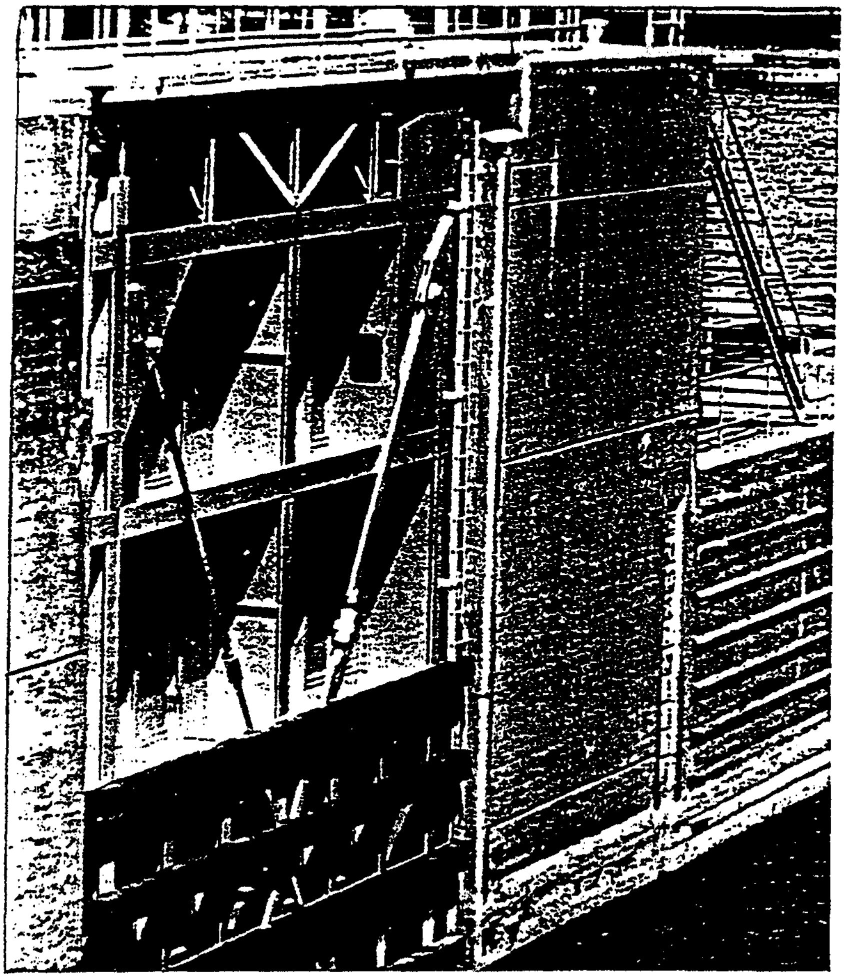


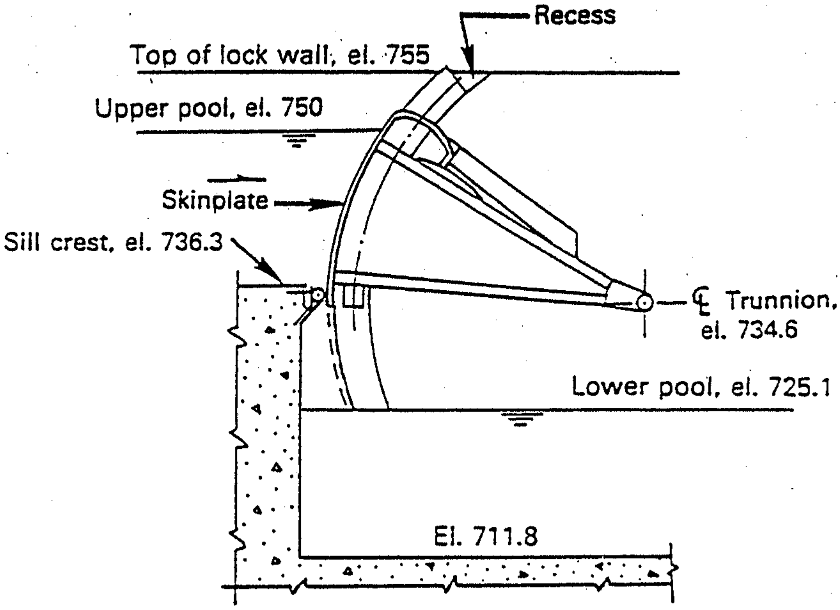
Figure 8.10. Bay Springs Lock chamber during construction, looking at upstream gate sill, Tennessee-Tombigbee Waterway. (U.S. Army, Corps of Engineers, Nashville District.)

(a) Lower lock gate partially open (view from inside lock chamber)



(b) Lower gate fully open and recessed in lock wall

Figure 8.11. Lock miter gates, Lower St. Anthony Falls Lock and Dam, Upper Mississippi River.



(a) Detail (after Nelson and Johnson, 1964)

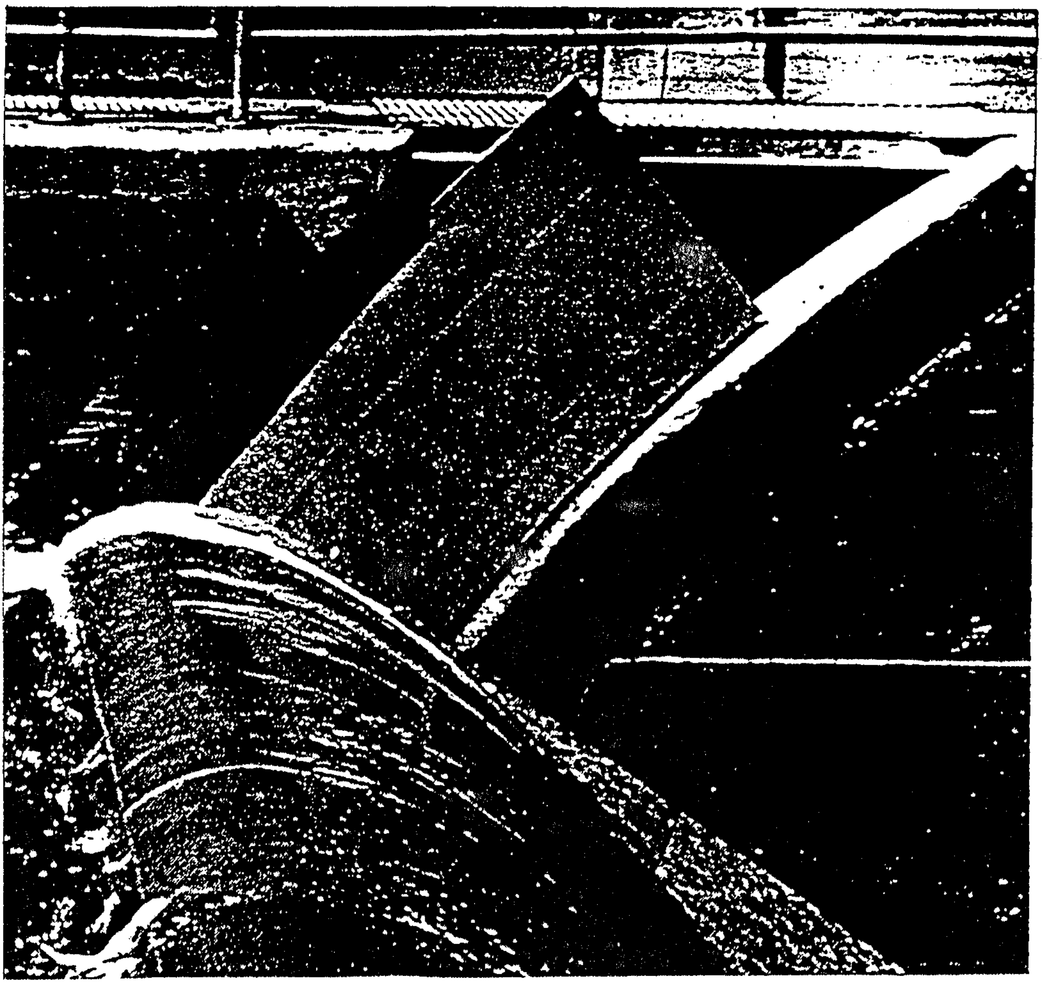
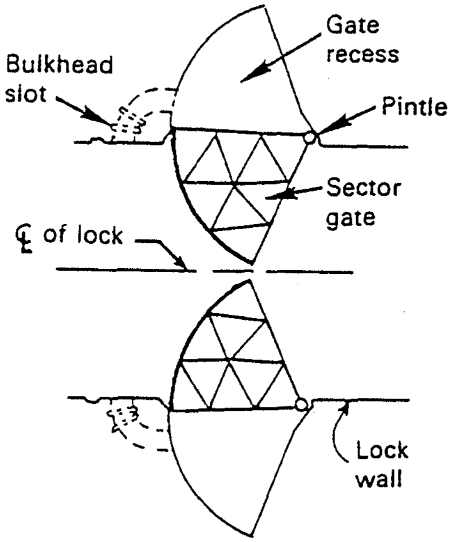
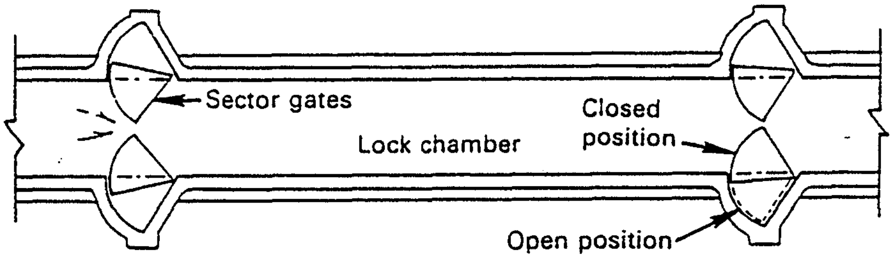


Figure 8.12. Submergible tainter gate (56 ft. long), Lower St. Anthony Falls Lock, Upper Mississippi River.



(b) Sector gates, O'Brien Lock,
Calumet-Sag Project, Illinois
(after Nelson and Johnson, 1964)



(a) Plan

Figure 8.13. Sector gates.

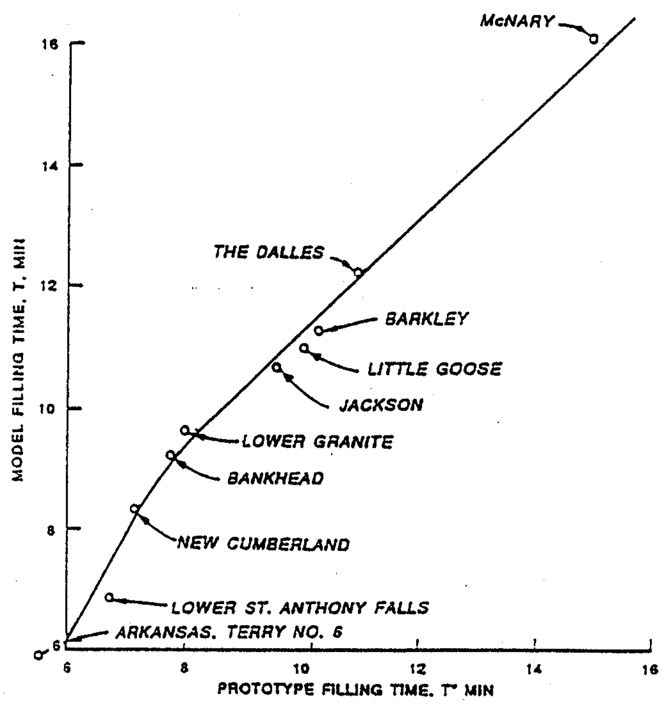


Figure 8.14. Prototype vs model filling time.

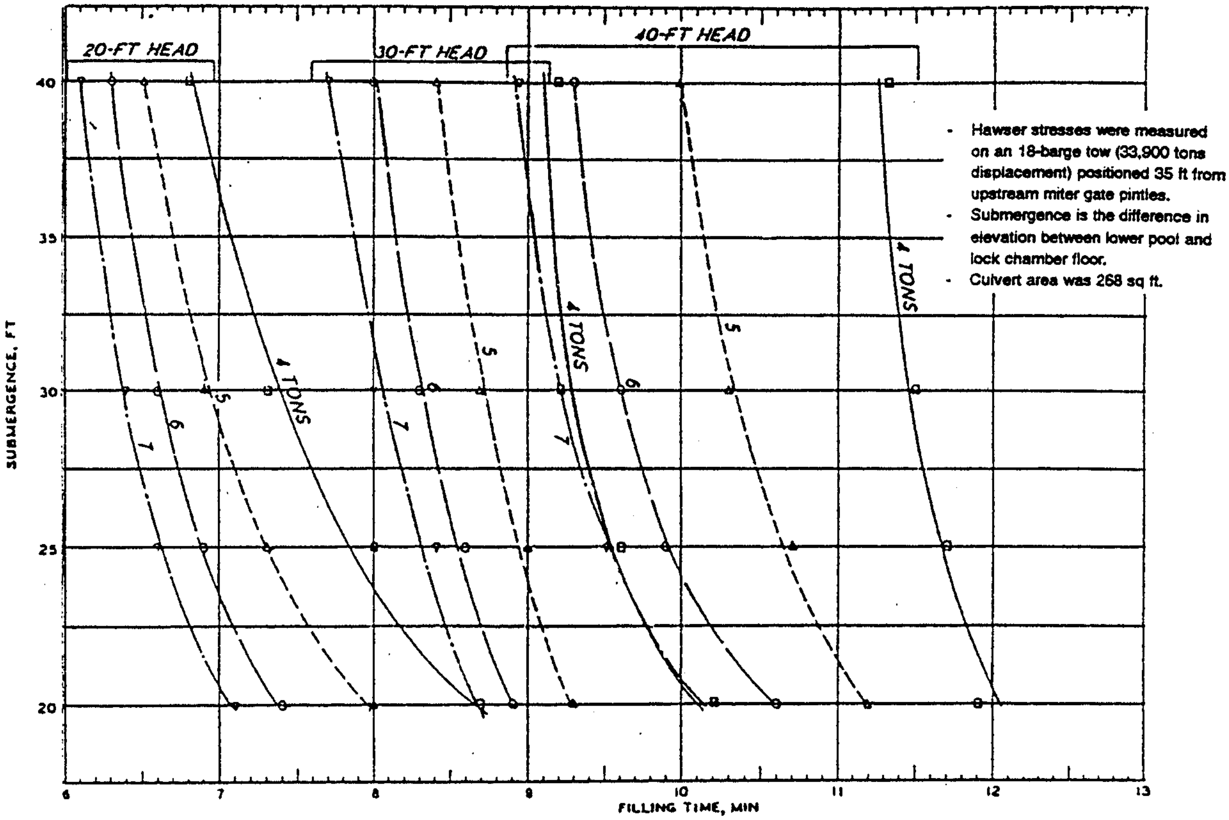


Figure 8.15. Permissible filling time to keep hawser stresses within 4-, 5-, 6-, and 7-ton limits, 110- by 1200-ft lock.

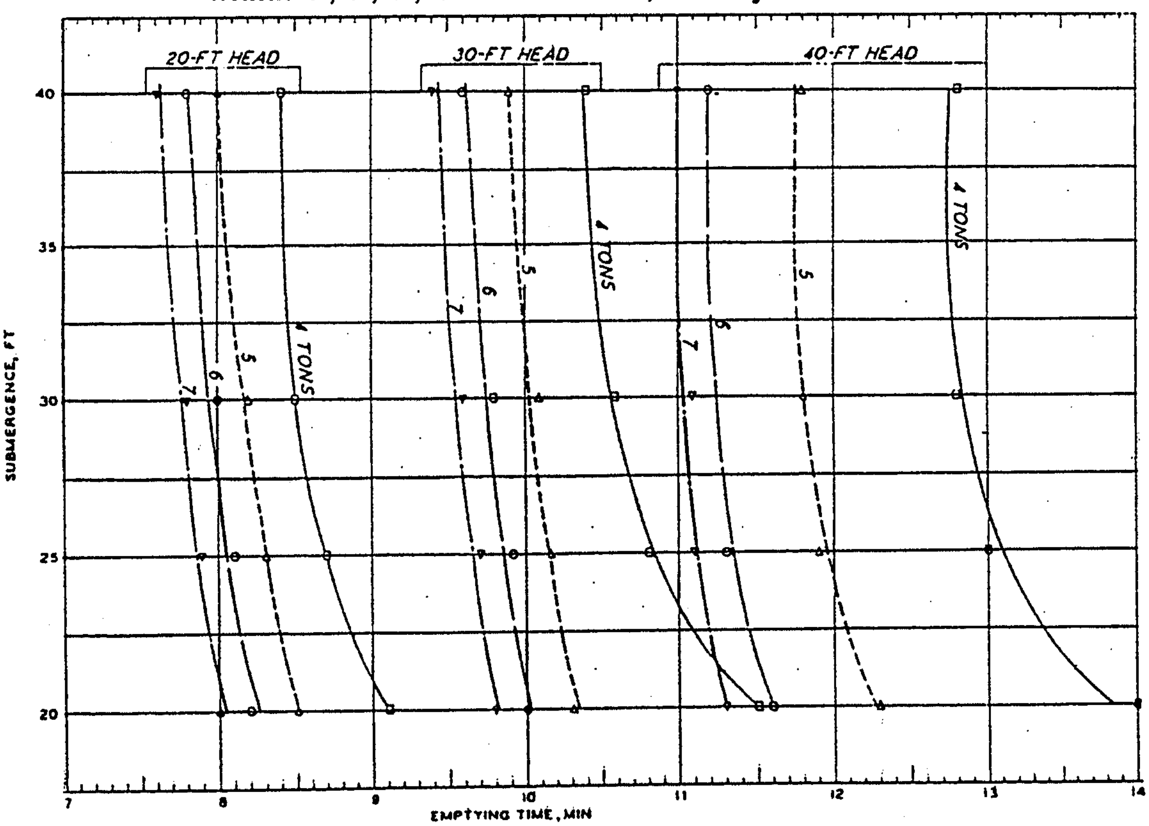
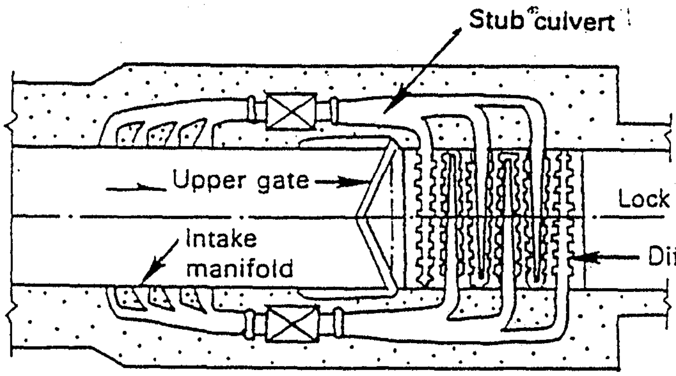
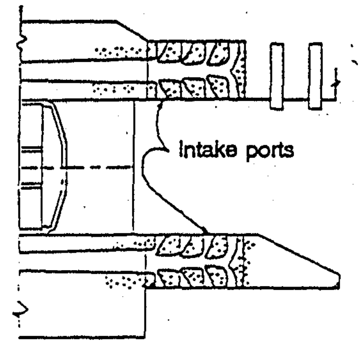


Figure 8.16. Permissible emptying times to keep hawser stresses within 4-, 5-, 6-, and 7-ton limits, 110- by 1200-ft lock.

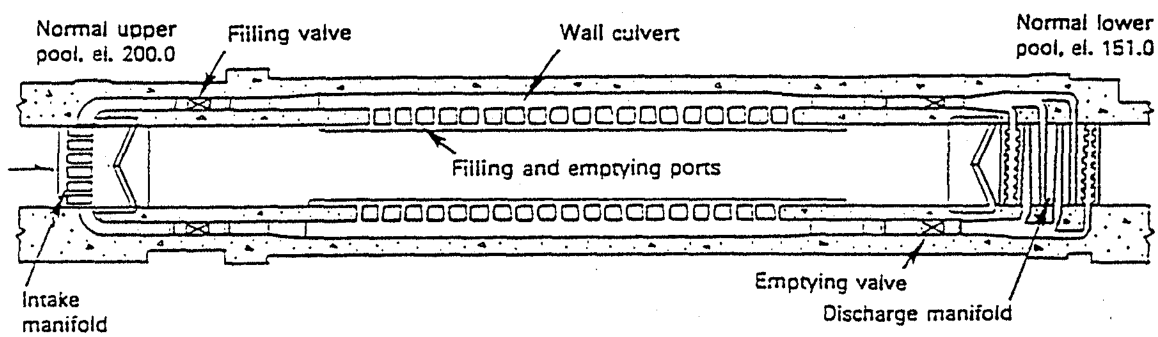


a. **Stub culvert system with diffuser. (Nelson and Johnson, 1964).**

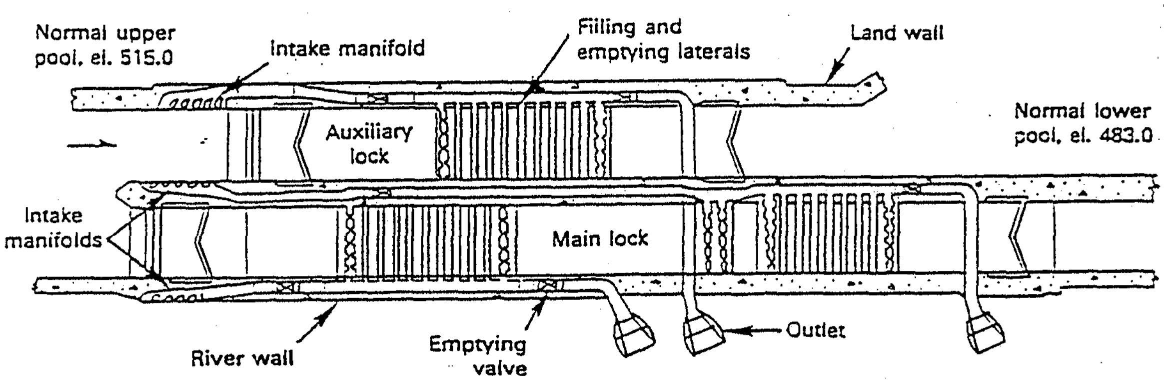


b. **Siamese system, Barkley Lock. (U.S. Army, Corps of Engineers).**

Figure 8.17. Typical lock Filling systems.



a. **Snell Lock, St. Lawrence Seaway (lift 49 ft).**



b. **Greenup Locks, Ohio River (lift 32 ft).**

Figure 8.18. Typical low-lift lock filling and emptying systems. (Nelson and Johnson, 1964).

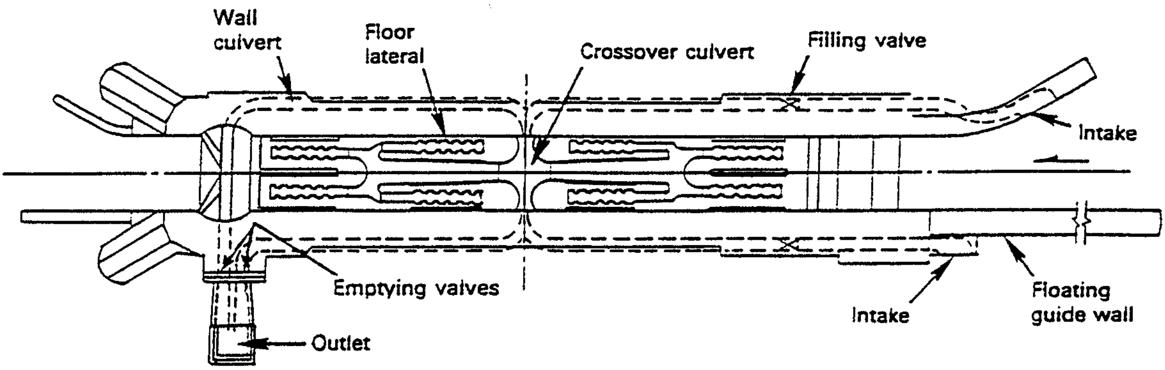
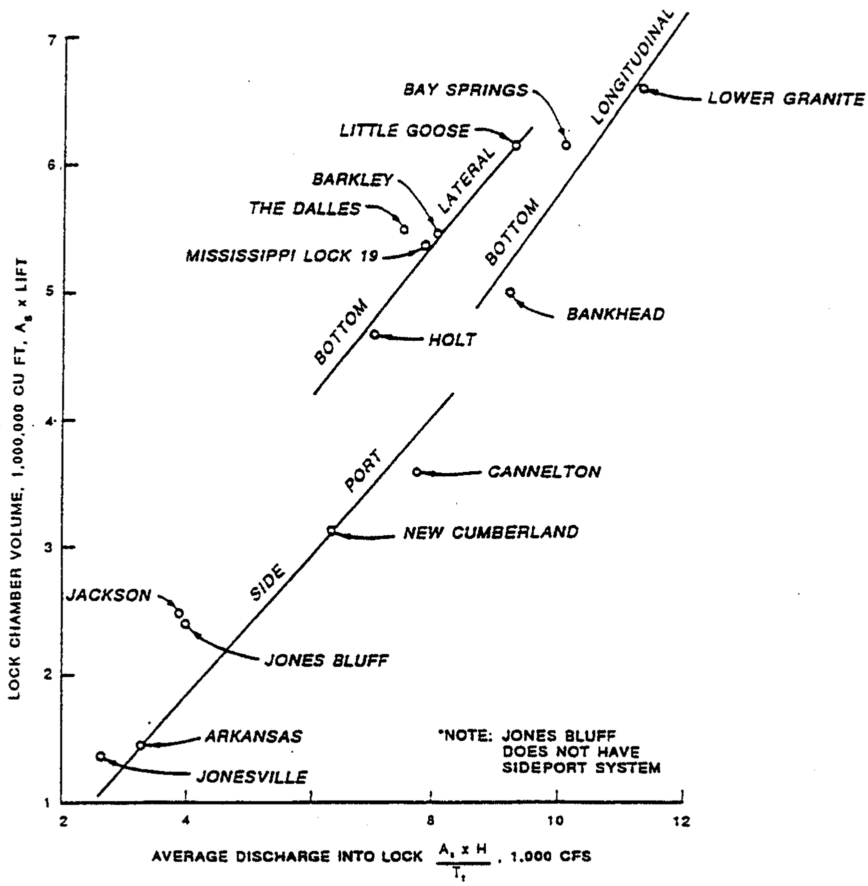
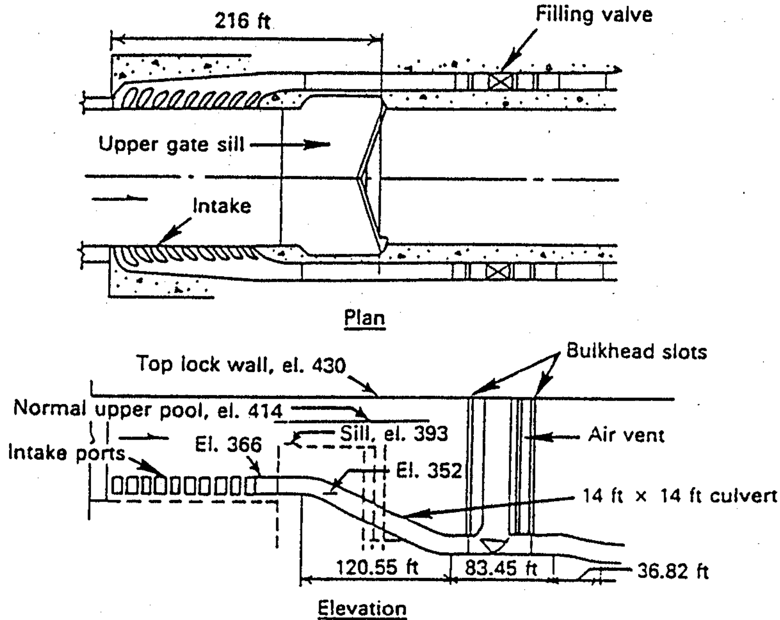


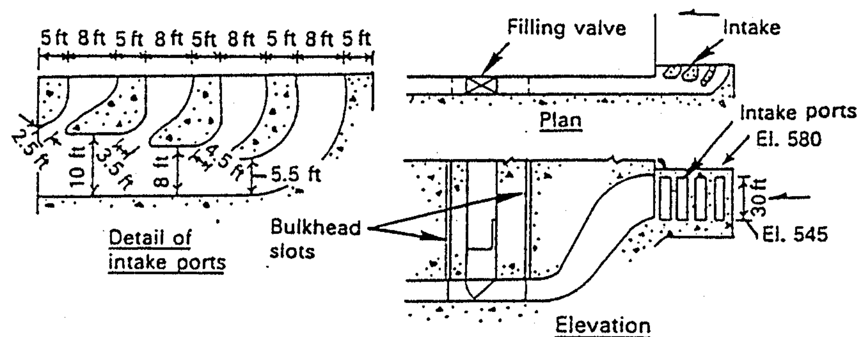
Figure 8.19. Lower Granite Lock, Snake River. (Murphy, 1980).



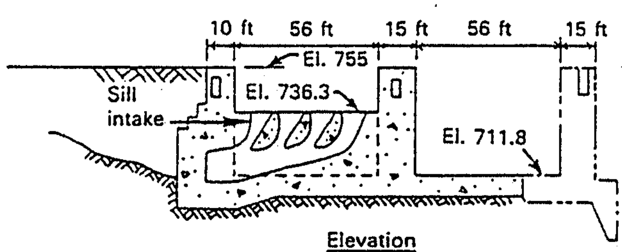
8.20. Lock volume vs average discharge (model filling time). (Davis, 1989).



a. **Bay Springs Lock, Tennessee-Tombigbee Waterway.**

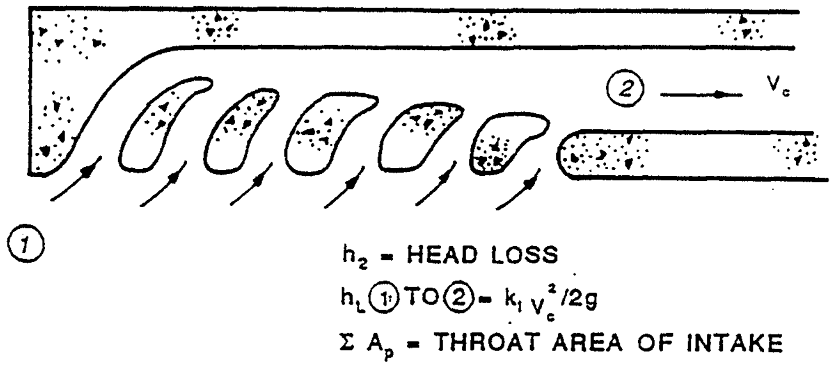


b. **Ice Harbor Lock, Snake River.**



c. **St. Anthony Falls Lower Lock, Upper Mississippi River.**

Figure 8.21. Typical intake manifolds (U.S. Army, Corps of Engineers).



Sectional plan.

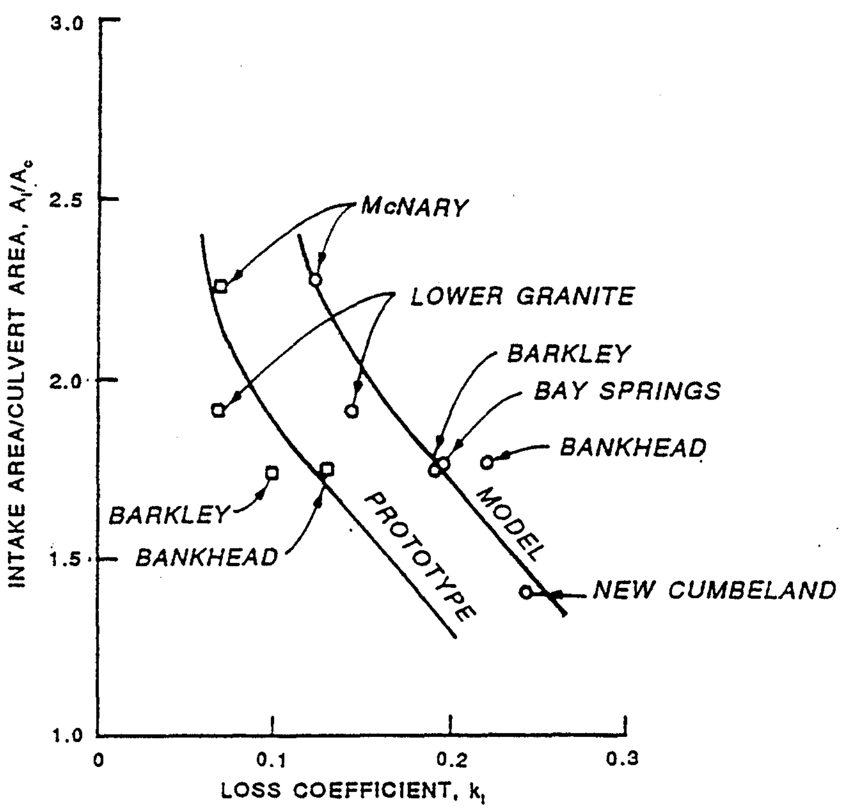


Figure 8.22. Intake head loss coefficient (Davis, 1989).

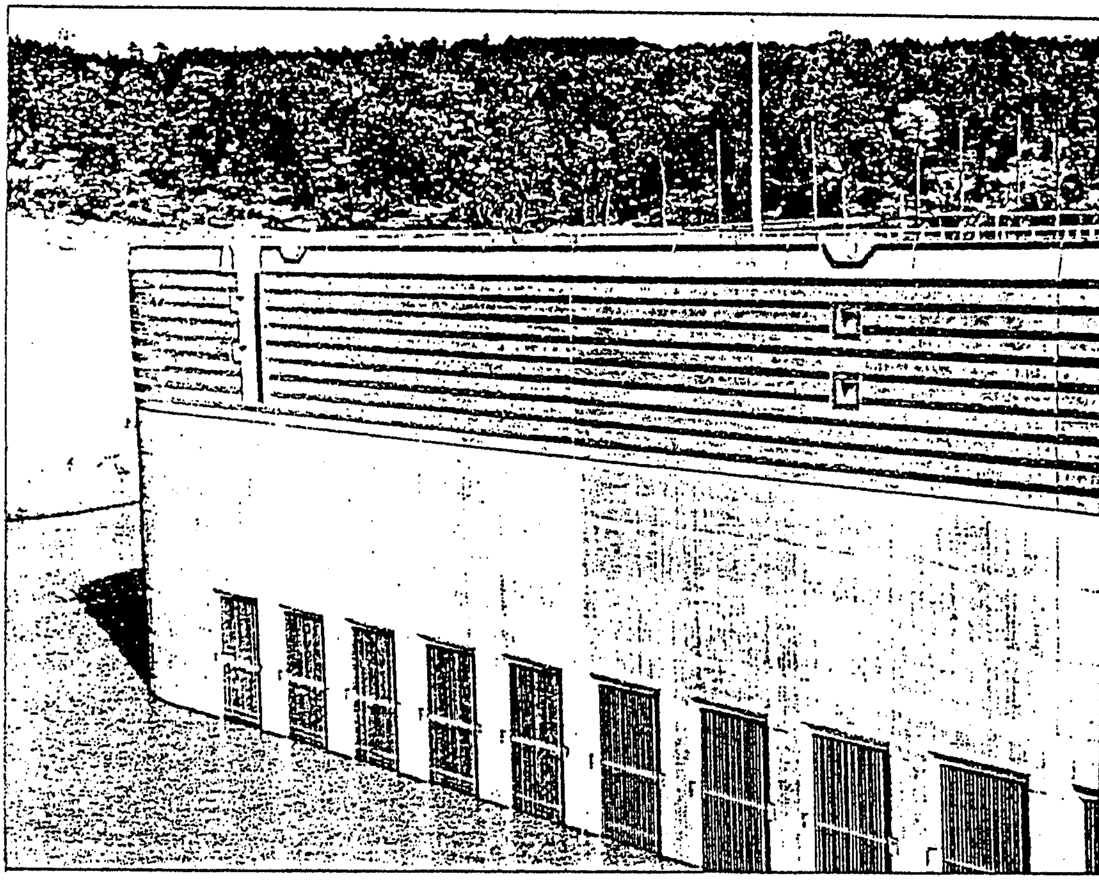
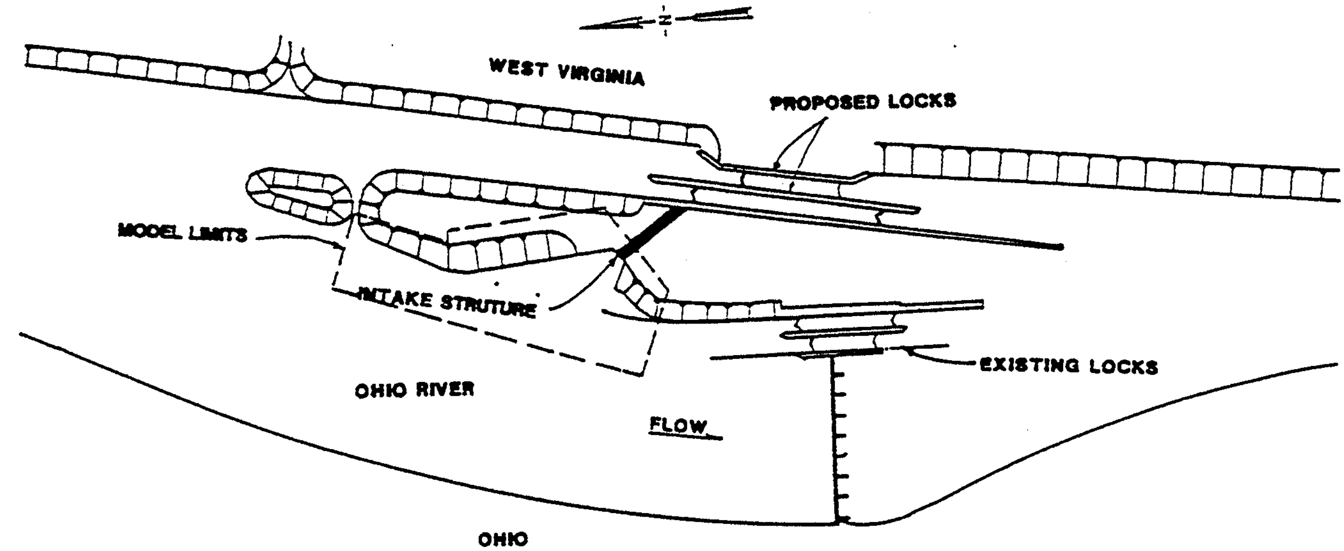
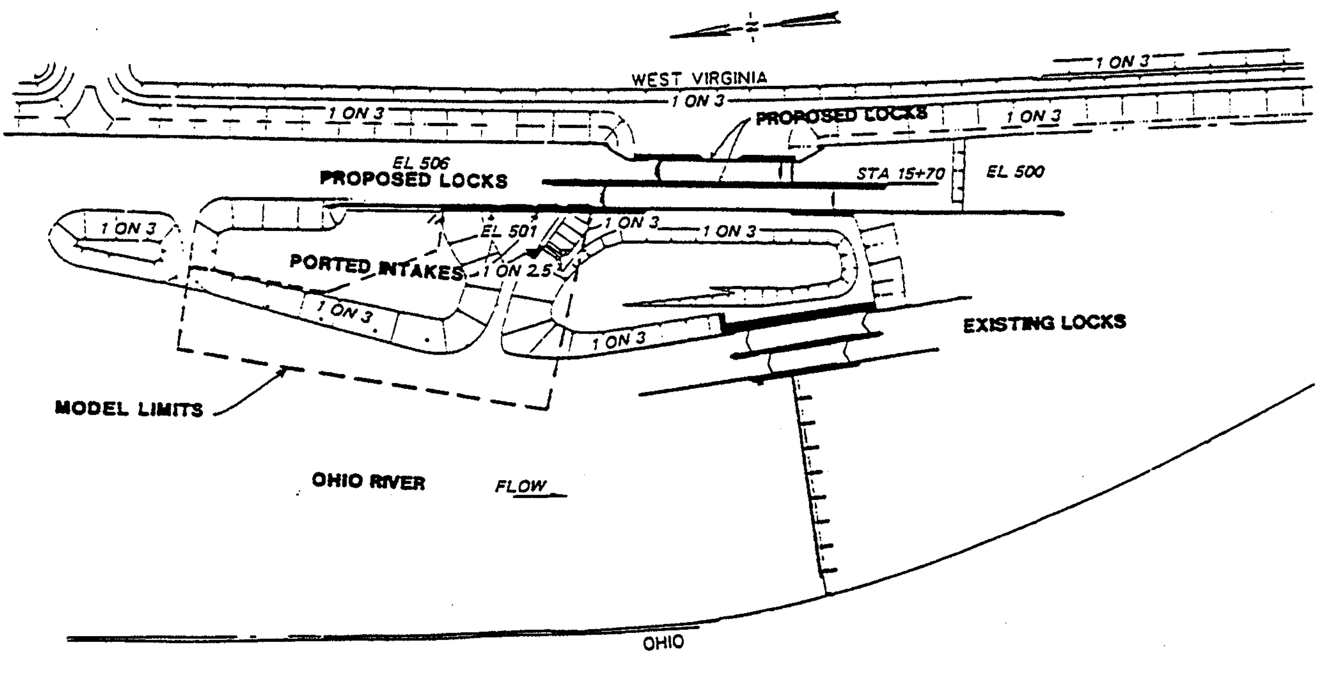


Figure 8.23. Intake ports with trash racks in place during construction, Dardanelle Lock, Arkansas River.

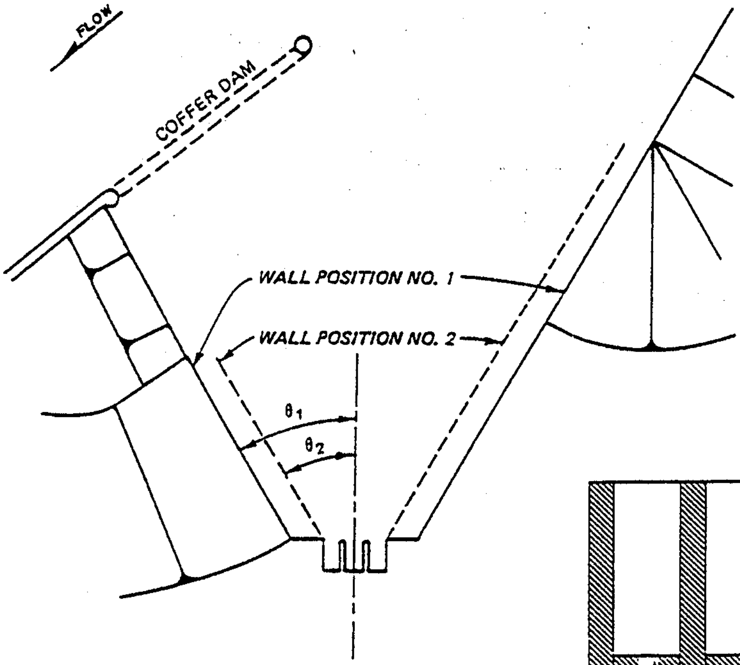


a. Alternative I.

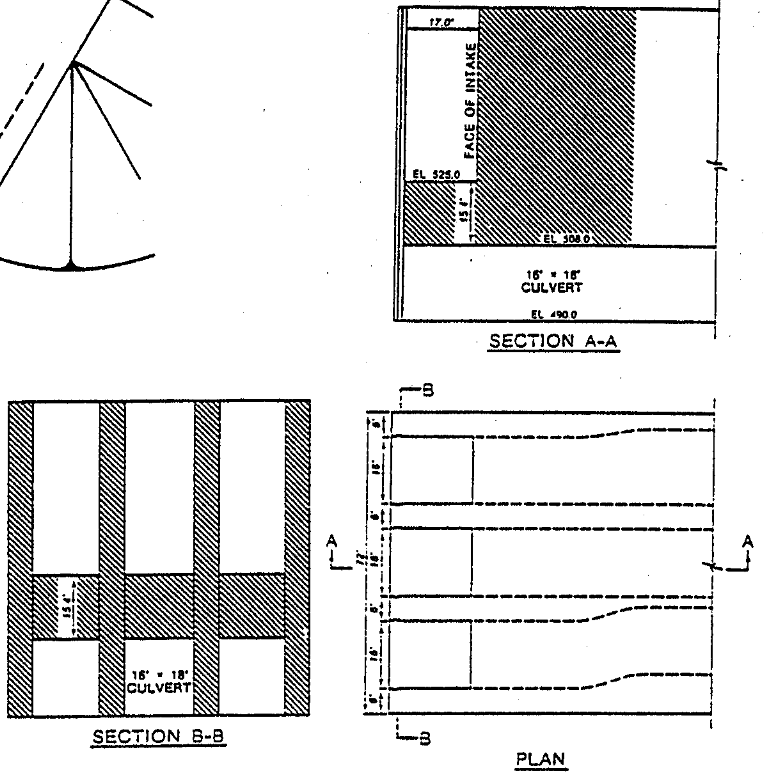


b. Alternative II.

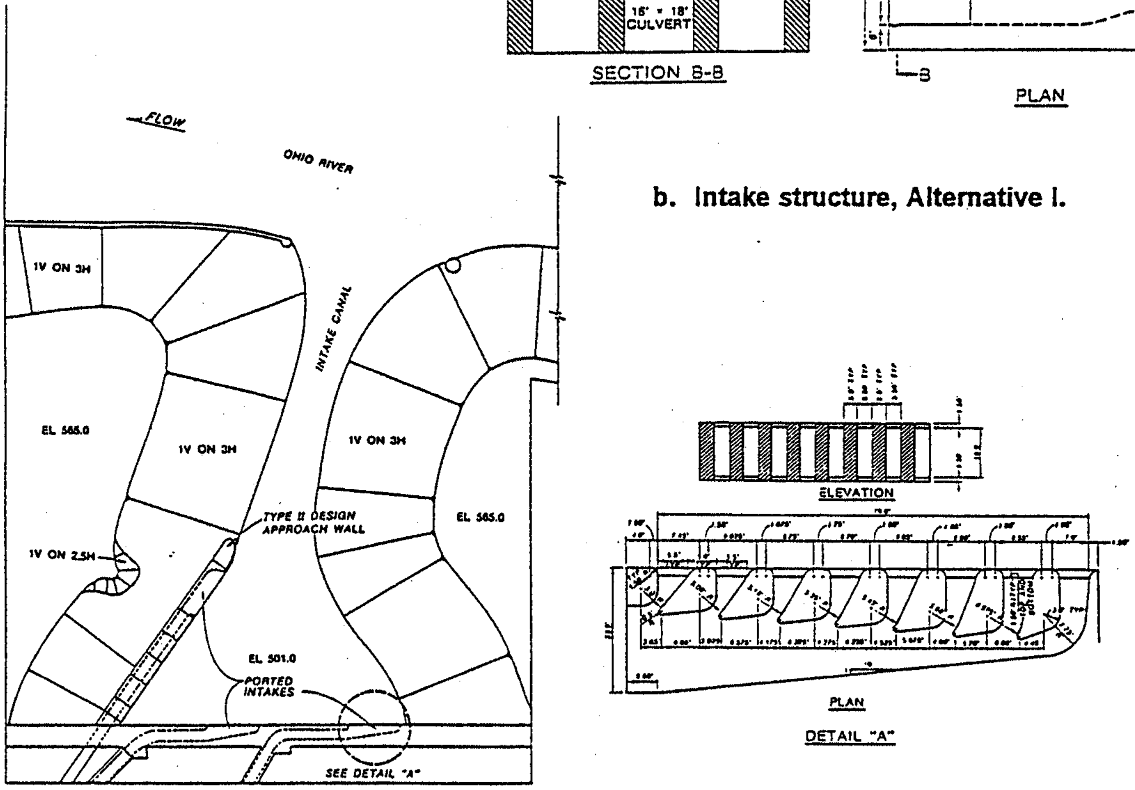
Figure 8.24. Alternative filling schemes, Gallipolis Locks and Dam, Ohio River (Davidson, 1987).



a. Intake approach, Alternative I.



b. Intake structure, Alternative I.



c. Alternative II, Intake canal and manifold.

Figure 8.25. Intakes for alternative filling schemes, Gallipolis Locks and Dam, Ohio River (Davidson, 1987).

V_c = Mean Velocity in Culvert at Valve

V_{vc} = Mean Velocity in Vena Contracta

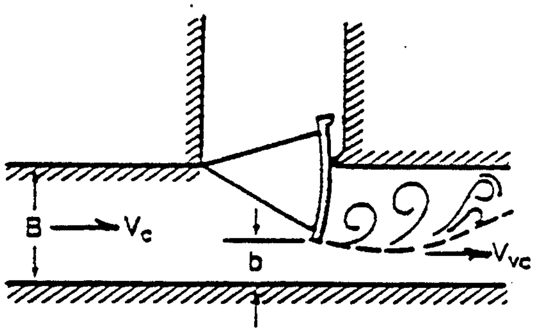


Figure 8.26. Culvert control valve ("reverse" tainter gate).

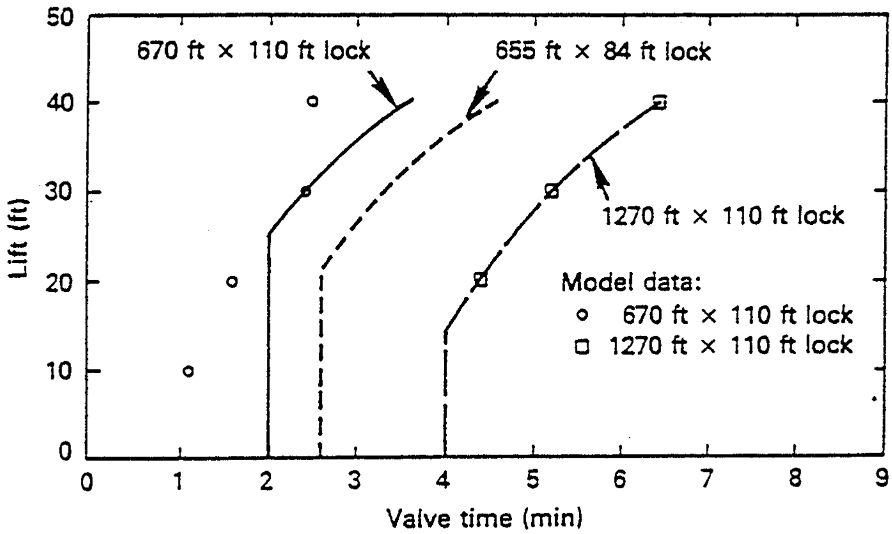


Figure 8.27. Recommended prototype valve opening times for filling (Murphy, 1975).

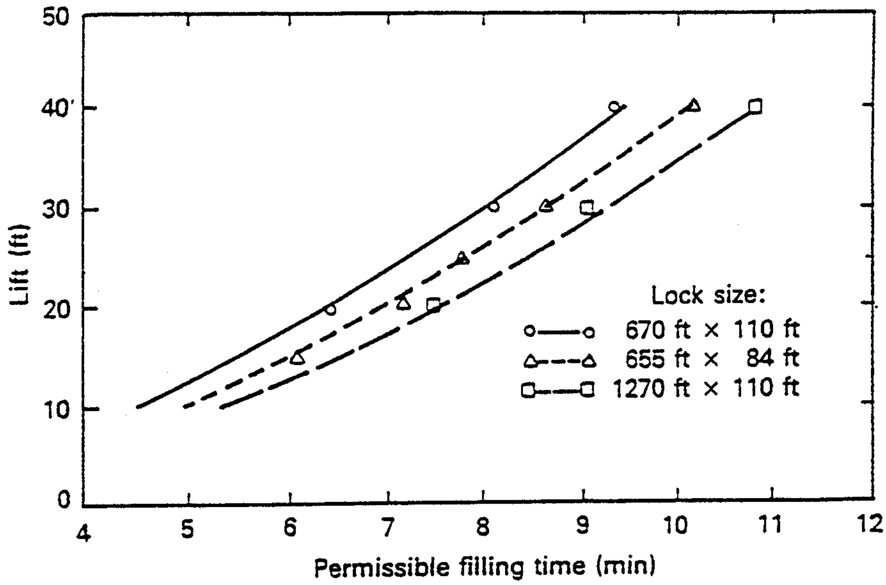


Figure 8.28. Permissible filling times (model) (Murphy, 1975).

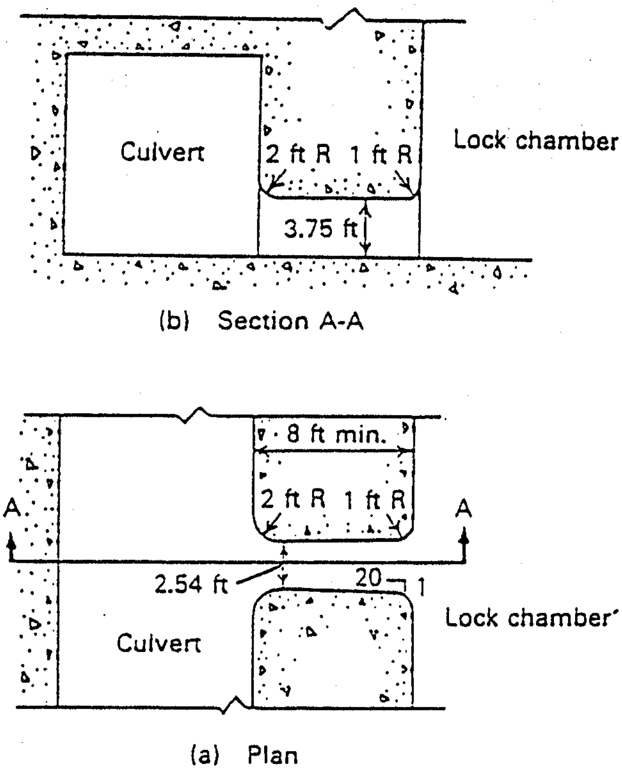


Figure 8.29. Ports for 110-ft-wide lock. (Murphy, 1975).

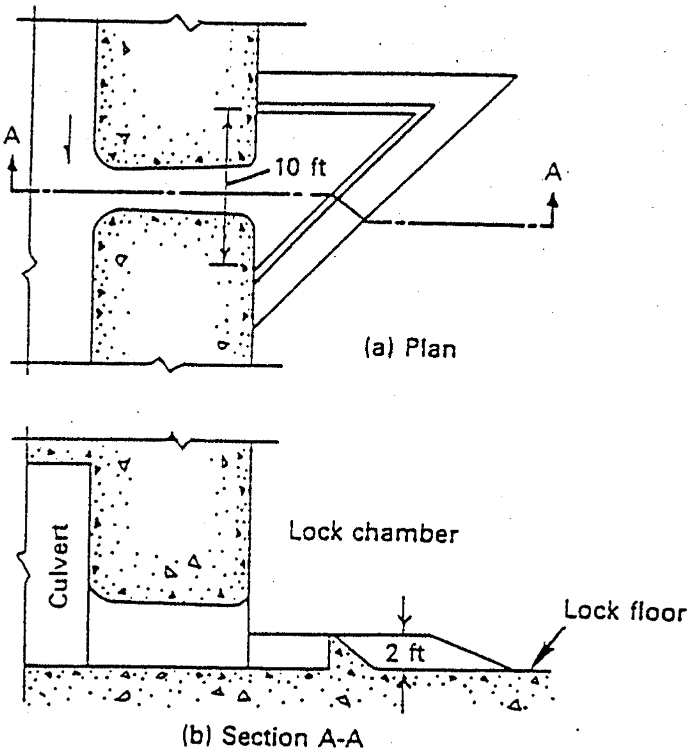


Figure 8.30. Port deflector for 110-ft-wide lock. (Murphy, 1975).

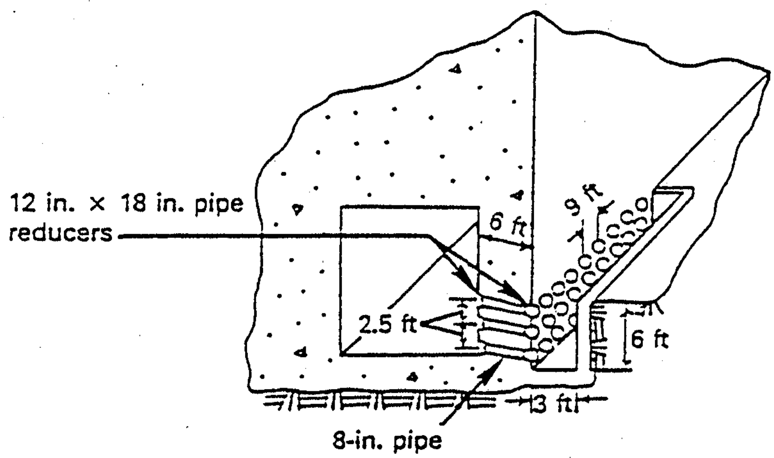
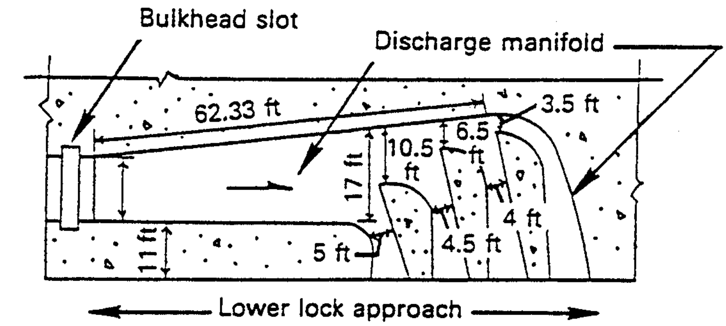
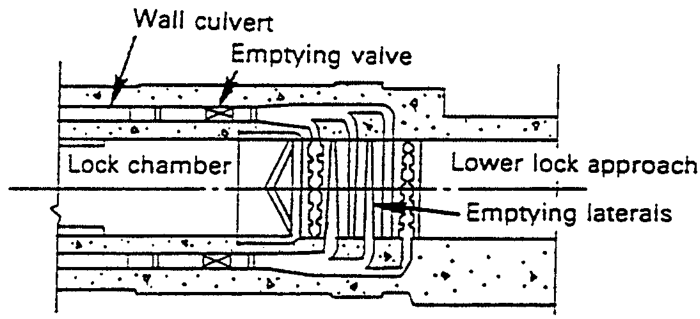


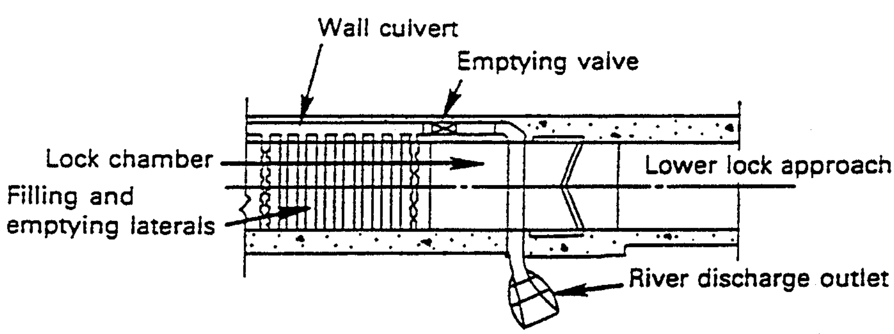
Figure 8.31. TVA multiport system (Elder et al., 1964).



a. McArthur Lock, St. Mary's River (Corps of Engineers, 1956).



b. Snell Lock, St. Lawrence Seaway (Nelson and Johnson, 1964).



c. Greenup Lock, Ohio River (Nelson and Johnson, 1964).

Figure 8.32. Typical lock emptying systems.

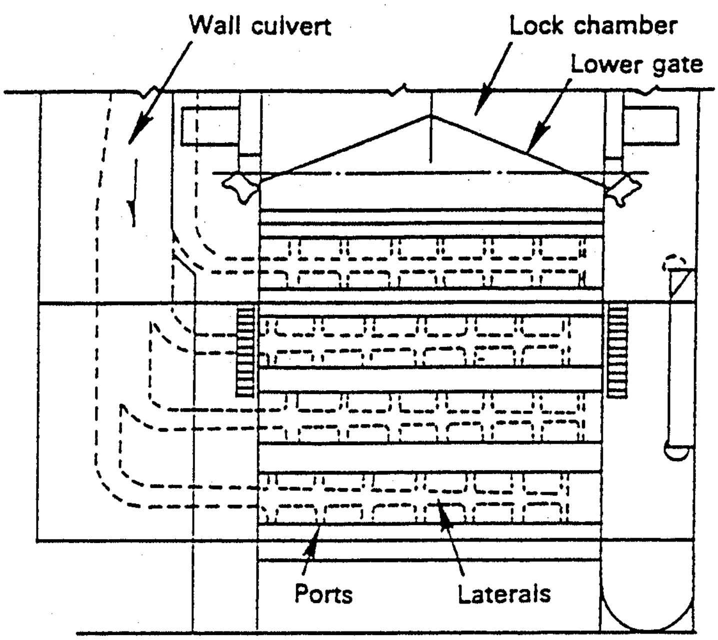


Figure 8.33. Discharge diffuser, St. Anthony Falls Lower Lock, Mississippi River. (U.S. Army, Corps of Engineers, 1956).

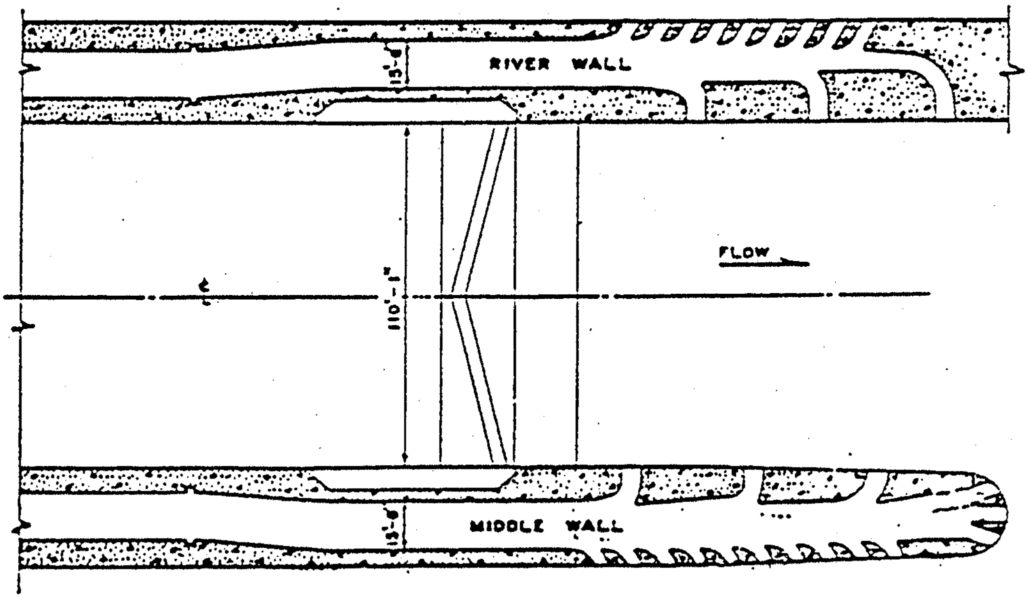
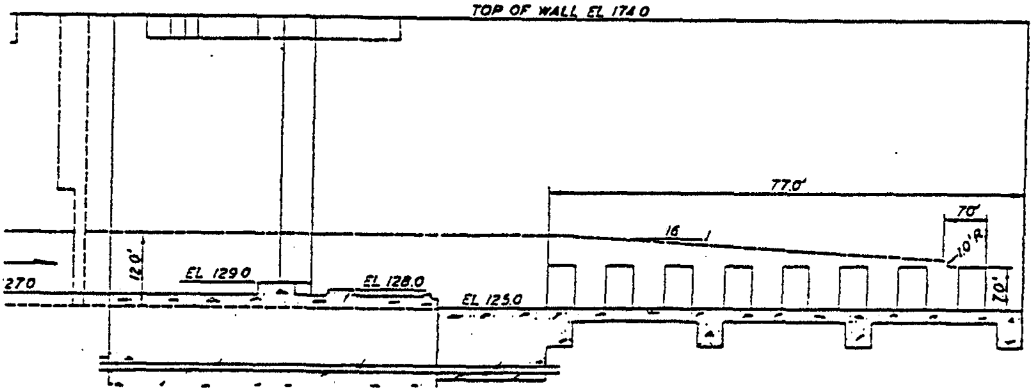
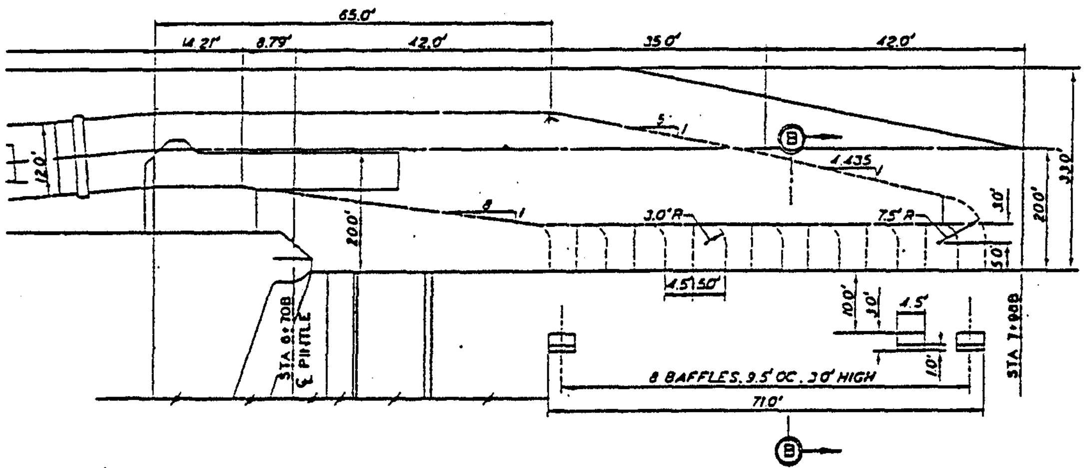


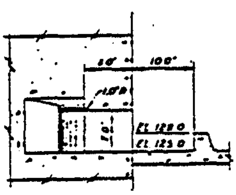
Figure 8.34. Discharge manifolds, New Cumberland Lock, Ohio River (Davis, 1989).



b. Plan

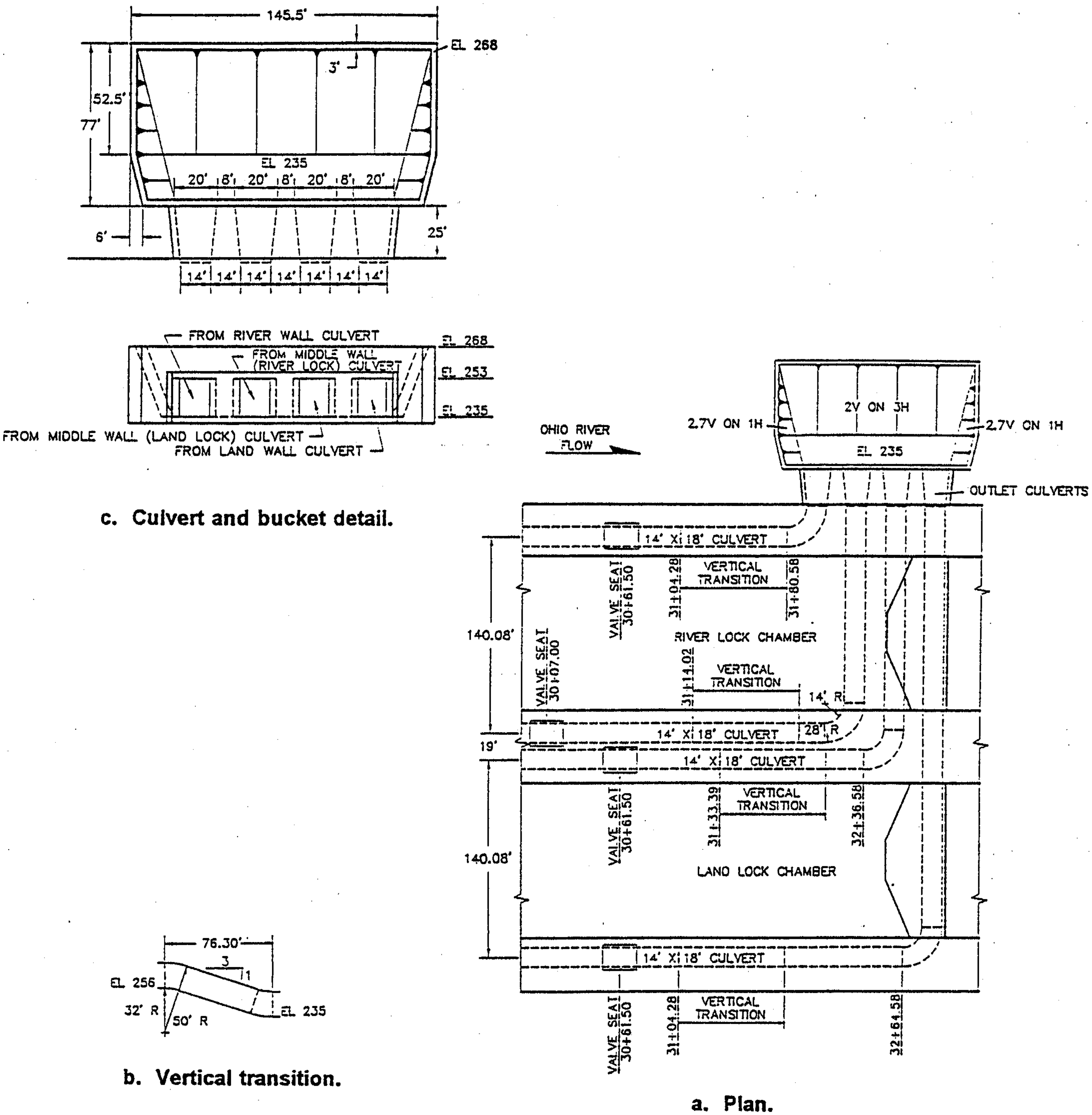


a. Section



b. Section B-B

Figure 8.35. Discharge manifold with baffles, Arkansas River (Davis, 1989).

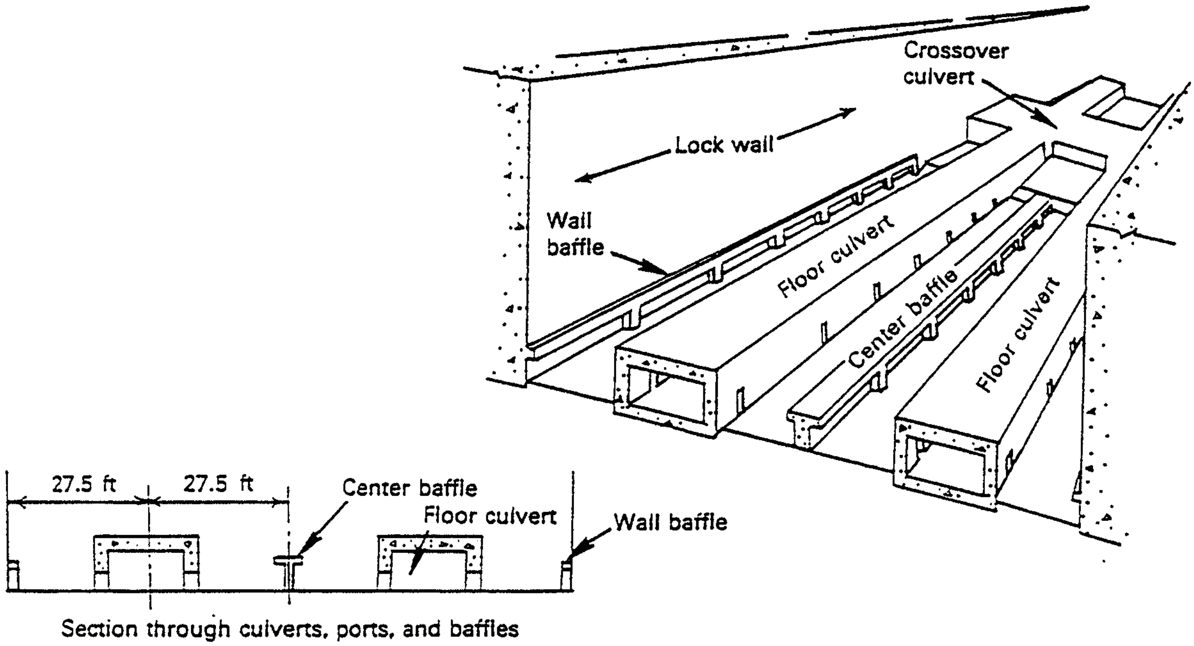


c. Culvert and bucket detail.

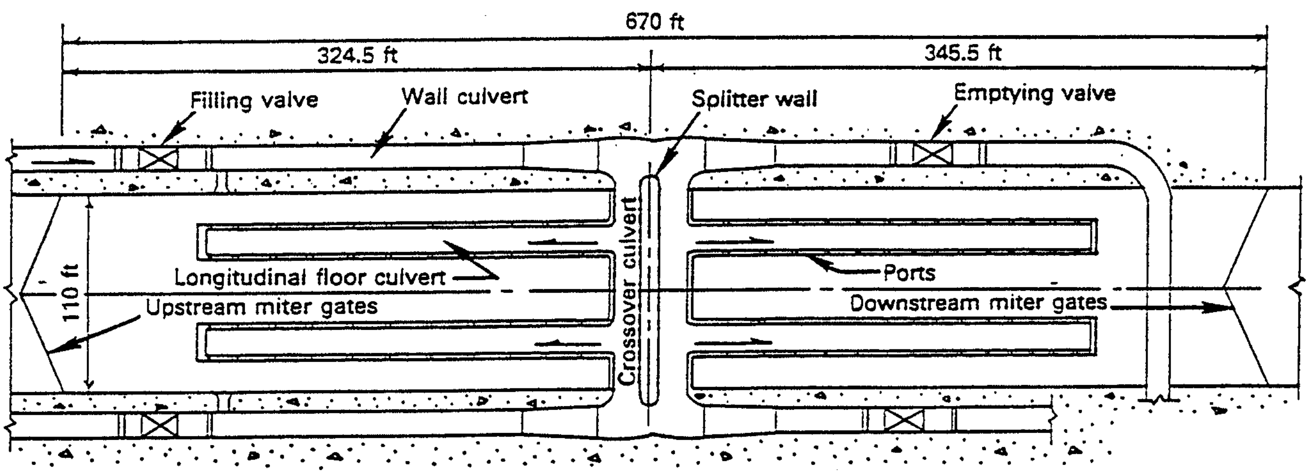
b. Vertical transition.

a. Plan.

Figure 8.36. Outlet system, Olmsted Locks, Ohio River (Stockstill, 1992).



b. Culverts, ports, and baffles.



a. Plan.

Figure 8.37. Bottom longitudinal "side-by-side" filling and emptying system, Dardanelle Lock, Arkansas River. (Ables and Boyd, 1969.)

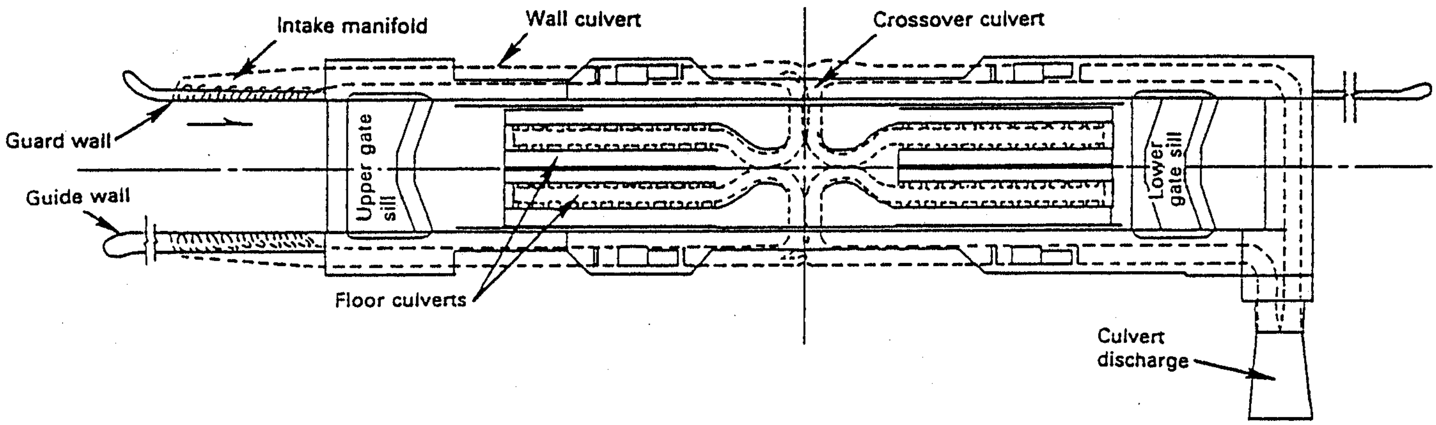


Figure 8.38. Bottom longitudinal "over-and-under" filling and emptying system, Bankhead Lock, 69-ft lift, Black Warrior River, Alabama (Murphy, 1980).

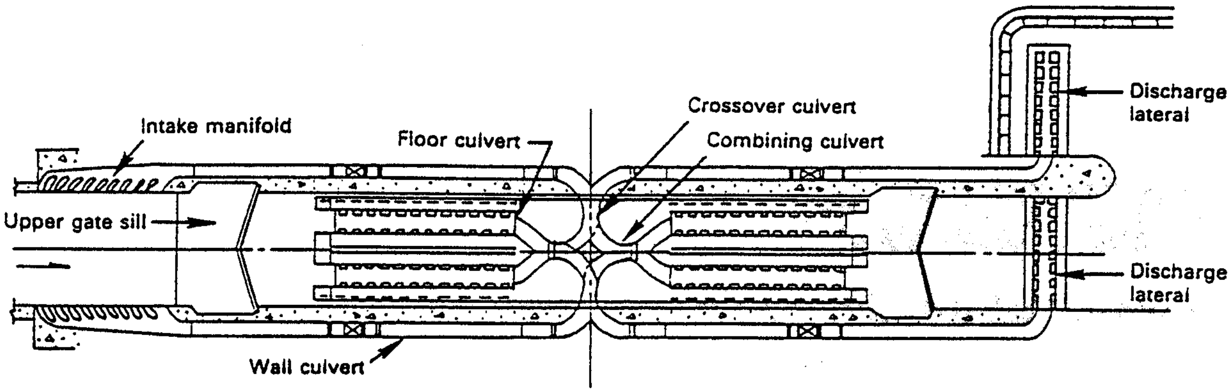


Figure 8.39. Bottom longitudinal "over-and-under" filling and emptying system, Bay Springs Lock, 84-ft lift, Tennessee-Tombigbee Waterway. (Ables, 1978).

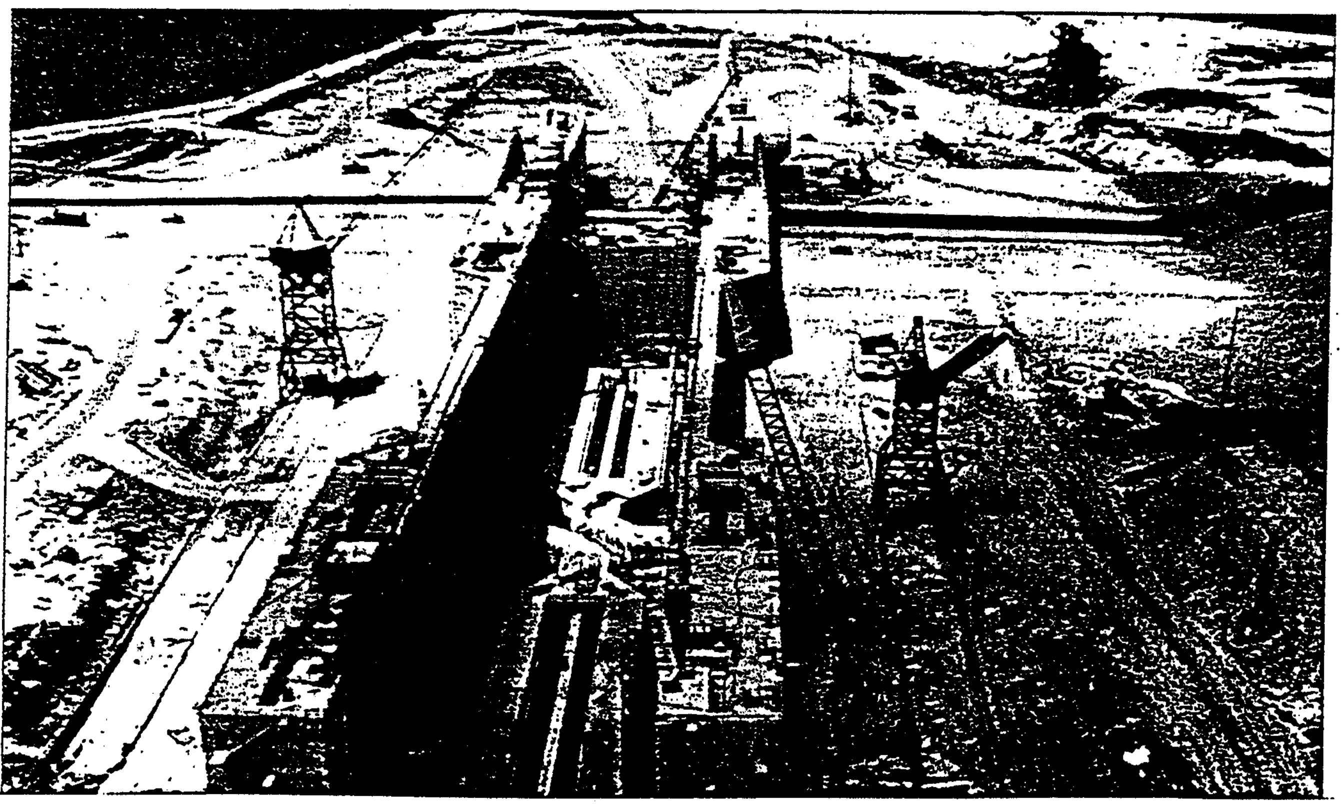


Figure 8.40. Bay Springs Lock under construction, Tennessee-Tombigbee Waterway (U.S. Army, Corps of Engineers, Nashville District).