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Innovations for Navigation Projects Research Program

Innovative Lock Design

Report 1
Case Study, New McAlpine Lock Filling and Emptying System, Ohio River, Kentucky

Hydraulic Model Investigation

by Richard Stockstill

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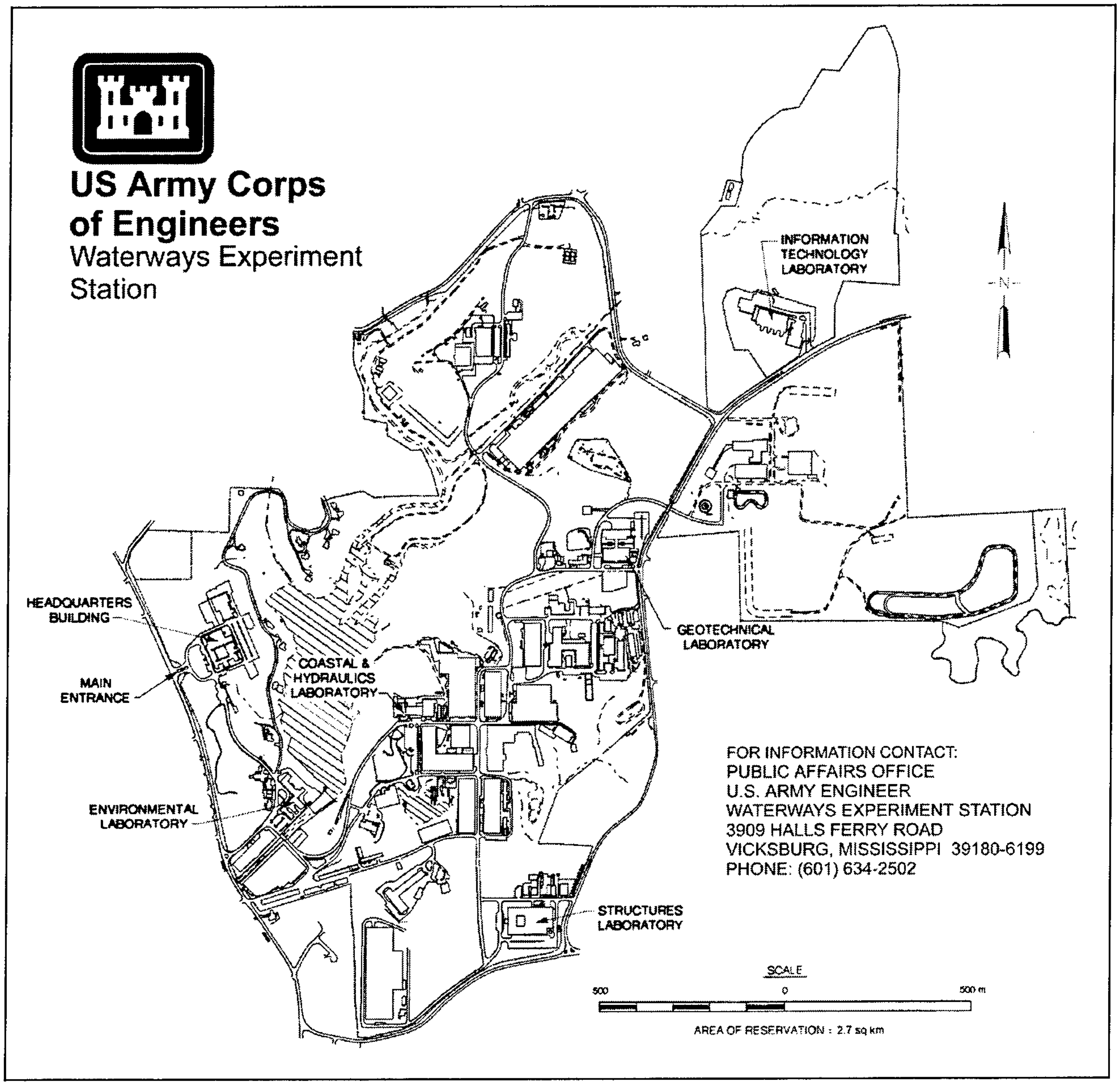

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Contents

Preface

The model investigation reported herein was performed for the U.S. Army Engineer District, Louisville, as part of an innovative lock design partnership with the Huntington, Pittsburgh, and St. Louis Districts. This study, which was one of four physical model investigations for the partnership, was authorized by the Huntington District on 1 September 1994.

This work was conducted in the Coastal and Hydraulics Laboratory (CHL) of the U.S. Army Engineer Waterways Experiment Station (WES) during the period of September 1994 to July 1996 under the direction of Dr. J. R. Houston, Director, CHL; Mr. Charles C. Calhoun, Jr., Assistant Director, CHL; and Dr. P. G. Combs, Chief, Rivers and Structures Division, CHL.

The experimental program was led by Mr. J. E. Myrick under the supervision of Mr. J. F. George, Chief, Fisheries Structural Hydrodynamics Branch, in cooperation with Dr. R. L. Stockstill, who subsequently analyzed the model results. Dr. Stockstill worked under the supervision of Mr. B. P. Fletcher (retired), Chief, Spillways and Channels Branch. Model construction was completed by Messrs. M. A. Simmons and J. A. Lyons of the Model Shop, Department of Public Works (DPW), WES, and the ported manifolds were constructed by Mr. J. Schultz, DPW. Data acquisition and remote-control equipment were installed and maintained by Mr. S. W. Guy, Information Technology Laboratory (ITL), WES. Data acquisition software was developed by Dr. B. W. McCleave, ITL. The report was written by Dr. Stockstill and was peer reviewed by Dr. J. E. Hite, Jr., Leader, Locks and Conduits Group.

During the course of the model study, representatives of the partnering Districts (Louisville, Huntington, Pittsburgh, and St. Louis) and representatives of the navigation industry visited WES to observe model operation, review experiment results, and participate in design discussions.

The McAlpine Lock model study was the first to investigate the appropriateness of an in-chamber longitudinal culvert filling-and-emptying system. Therefore, the results of this study formed the basis for investigations within the "In-Chamber Longitudinal Culvert Design for Lock Filling and Emptying Systems" work unit (Work Unit 33140) of the

Innovation for Navigation Projects research program. Publication of this report was sponsored by the Innovation for Navigation Projects research program managed by Mr. W. F. McCleese, WES.

At the time of publication of this report, Commander of WES was COL Robin R. Cababa, EN.

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
miles (U.S. nautical)	1.852	kilometers
tons (force)	8,896.443	newtons

1 Introduction

Background

Many U.S. Army Corps of Engineers (USACE) Districts are facing the challenge of reducing congestion at their projects to accommodate increases in tow traffic. The Louisville, Huntington, Pittsburgh, and St. Louis Districts formed an Innovative Lock Design team, pooled their resources, and initiated a study with the U.S. Army Engineer Waterways Experiment Station (WES) to find innovative ways to reduce construction and operation and maintenance costs of navigation structures. This team agreed that lock wall construction costs could be greatly reduced if lock filling and emptying culverts were placed inside the lock chamber rather than in the lock walls. This new filling-and-emptying system was named the in-chamber longitudinal culvert filling-and-emptying system (ILCS). Navigation improvements planned for the McAlpine Locks and Dam project provided a desirable site to investigate the ILCS.

The Prototype

The existing McAlpine Locks and Dam project is located on the Kentucky side of the Ohio River at Louisville, Kentucky, generally extending from mile 608 to mile 604[1] (Figure 1). The project consists of a gated spillway, a fixed weir, a powerhouse, one 110-ft by 600-ft auxiliary lock, one 56-ft by 360-ft lock (nonoperational), and one 110-ft by 1200-ft main lock. The existing main lock is operating at capacity and an additional 1200-ft-long by 110-ft-wide lock is necessary to satisfy future capacity projections. The new lock will replace the existing 600-ft lock with the upstream pintles (cross stream axis of the miter gates) located at the same station as those of the existing 1200-ft lock. The normal upper pool

[1] A table of factors for converting non-SI units of measurement to SI units is found on page vii.

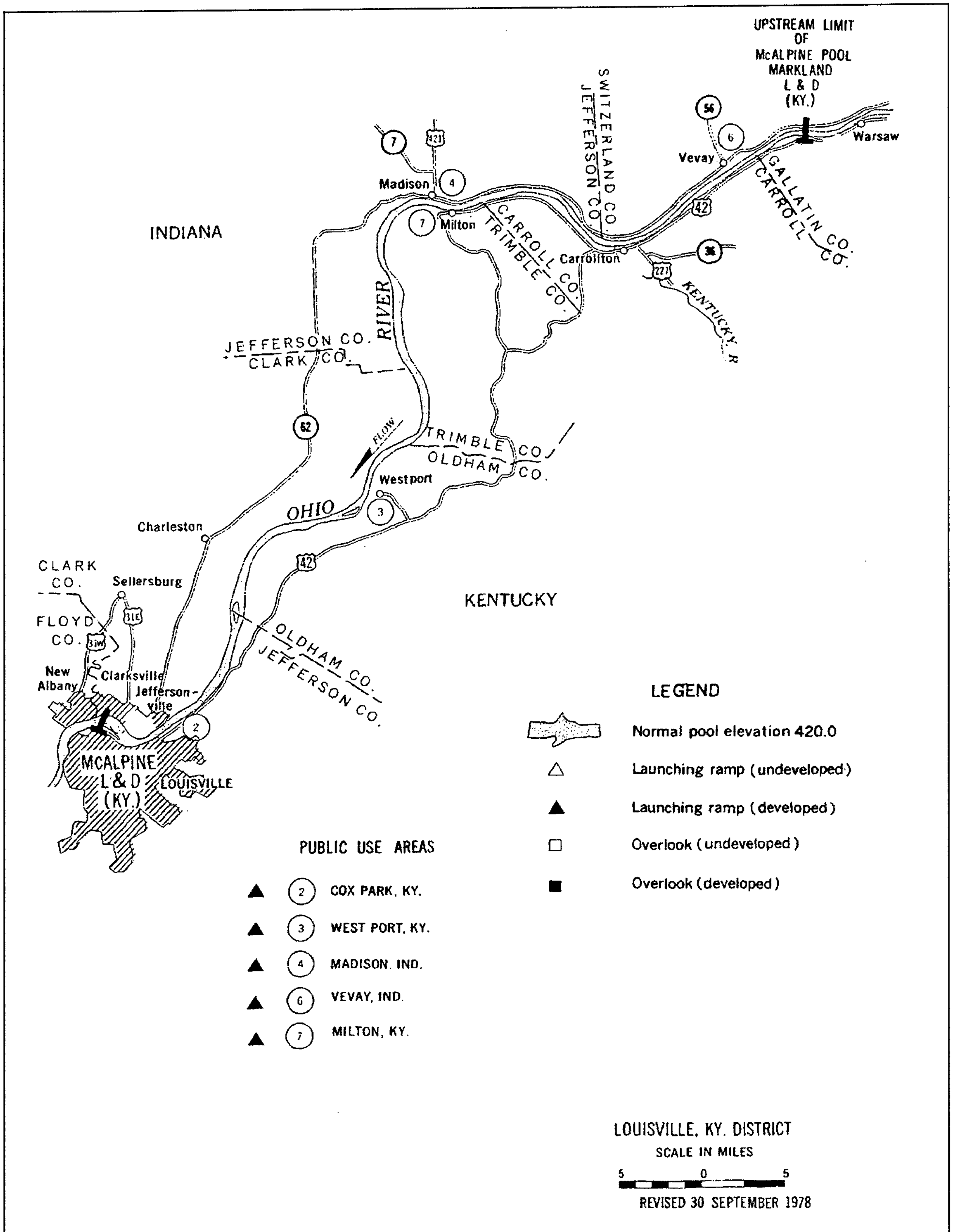

Figure 1. Location map

elevation[1] for the McAlpine project is 420.0 and the normal lower pool elevation is 383.0 resulting in a lift of 37 ft.

Originally, a split-lateral filling-and-emptying system similar to the existing 1200-ft lock was proposed for the new lock. The split-lateral design, which is used on several medium-lift locks on the Ohio River (e.g. St. Anthony Falls Hydraulic Laboratory (1962)) has culverts located in the lock walls with lateral manifolds constructed in the lock floor.

The system discussed in this report features a through-the-sill intake and discharge outlet with a longitudinal in-chamber filling-and-emptying system. One proposed lock discharge plan used an interlaced lateral system located downstream of the lower miter gate pintle. Another alternative being investigated for the discharge system was a landside channel, which discharges downstream of the lower approach guide wall. A final decision on the discharge system was to be made after all alternatives were evaluated.

Purpose and Scope

The fundamental questions to be answered by the Innovative Lock Design studies were whether the intakes and outlets could be placed through the sills and whether the culverts could be placed between the lock walls. Separate studies at WES addressed the question of flow conditions, and in particular, vortex tendencies at the intake approach during filling.[2,3]

This New McAlpine Lock study's principal objective was to develop an innovative hydraulic filling-and-emptying system design for the navigation lock that was efficient, yet less costly than standard systems, while ensuring safe conditions during lock operations.

Specifically, the study was to determine:

a. Filling and emptying times for various valve speeds at the design lift of 37 ft.

b. Flow conditions and motion characteristics of unmoored barges in the lock chamber during filling and emptying operations.

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1 All elevations (el) cited herein are in feet referred to the Ohio River Datum.

2 USACEWES. 18 May 1995. Memorandum for Commander, U.S. Army Engineer District, Louisville, Subject: Data Report, Model Study of McAlpine Intake.

3 USACEWES. 24 October 1995. Memorandum for Commander, U.S. Army Engineer District, Louisville, Subject: Data Report, Model Study of McAlpine Intake.

c. Hawser forces exerted on barges moored in the lock chamber.

d. Pressures in the culverts.

A laboratory model was used to evaluate the ILCS. Model studies of lock filling-and-emptying systems designed for barge train traffic have targeted maximum hawser forces of 5 tons as a design objective. System design and operation are optimized such that a full tow at design draft produces hawser forces of 5 tons or less during lock operations at the design pool conditions. This limiting maximum hawser force guidance is provided in paragraph 8-6 of Engineer Manual (EM) 1110-2-2602 "Planning and Design of Navigation Locks," paragraph E-2 of EM 1110-2-1604 "Hydraulic Design of Navigation Locks," and also in the discussion of permissible filling times in paragraph D-15 of EM 1110-2-1604. Davis (1989) summarizes the findings of physical model studies as follows:

> In working with models to determine hawser stresses, it must be noted that when a hawser stress of only 5 tons is achieved in a model it does not necessarily follow that the hawser stress on the prototype lock will be no greater than the value measured in the model. On a performance basis it has been found that when the model hawser stress is no greater than 5 tons, the prototype lock will perform very well and no surging or severe turbulence will occur.

2 Physical Model

Description

The 1:25-scale model reproduced 275 ft of the upstream approach, the entire filling-and-emptying system, including portions of the upper guide and guard walls, intakes, valves, culverts, lock chamber, outlets, portions of the lower guide and guard walls, and about 550 ft of the downstream approach. The approach areas and the lock chamber were constructed of plywood; the intakes, culverts, and discharge outlets were constructed of plastic. The eight rotating-disc valves were constructed of sheet metal. Six sheet-metal barges, each simulating a length of 195 ft and a width of 35 ft, were loaded with weights to achieve the desired 9-ft draft. Photographs of the model are provided in Figures 2 and 3.

Appurtenances and Instrumentation

Water was supplied to the model through a circulating system. Both the headbay and tailbay contained skimming weirs that maintained essentially constant upper and lower pools during filling and emptying operations. Vertical adjustments of the skimming weirs permitted simulation of any desired upper and lower pool elevations. Dye and confetti were used to study subsurface and surface current directions. Pressure cells were used to measure instantaneous pressures in the culvert just downstream of the filling valves and to record water surface elevation in the lock chamber. These pressure cells, located within the chamber, measured the water-surface variations in time at the upstream end, center, and downstream end. Histories of the end-to-end water-surface differential were also recorded during operations.

Culvert valve movement was controlled by servo-driven linear actuators that were regulated by the output from a personal computer. Programming of the personal computer resulted in varied output, such that the desired valve schedule could be reproduced.

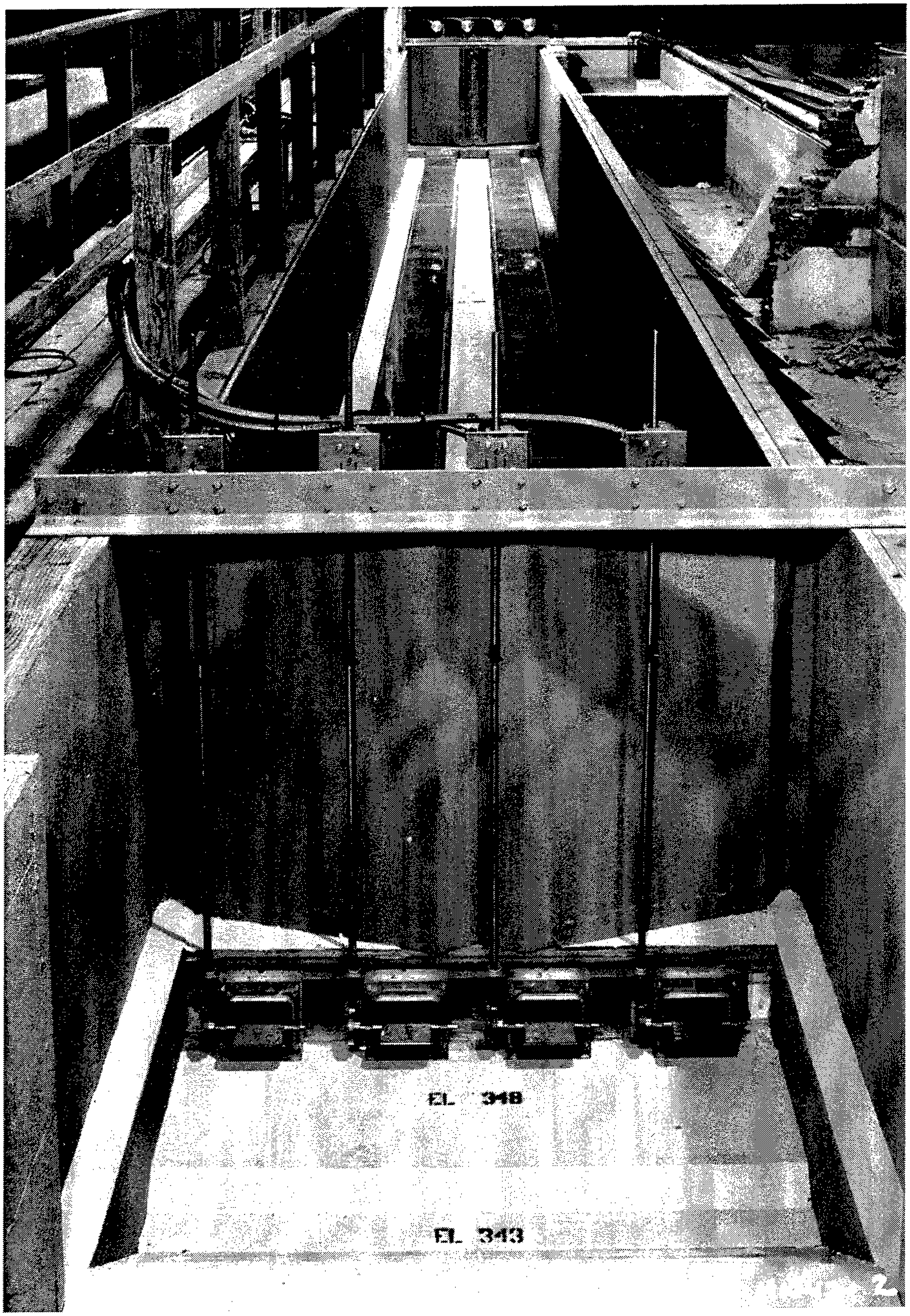


Figure 2. Dry bed view of Type 1 (original) design looking downstream

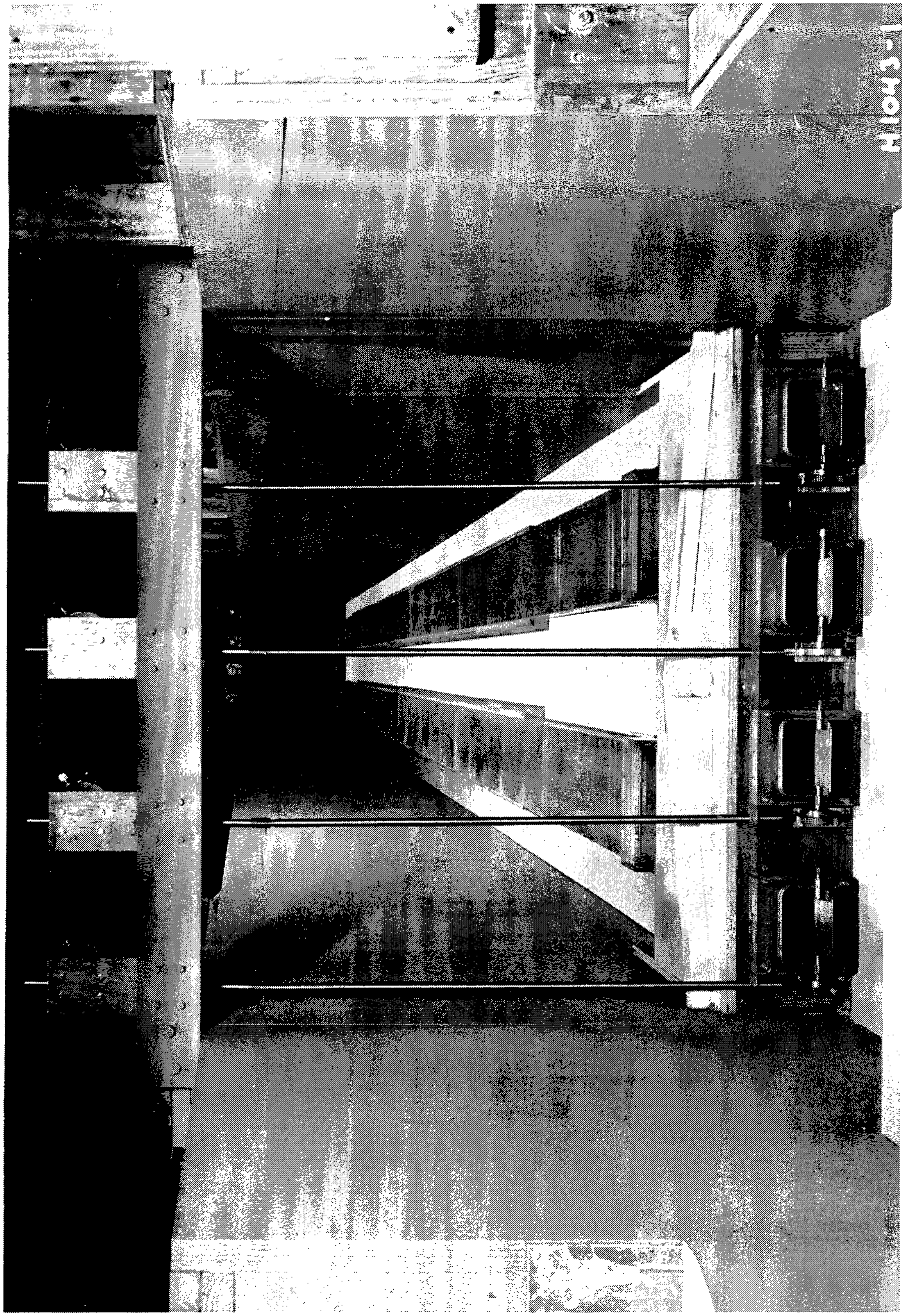


Figure 3. Dry bed view of Type 1 (original) design looking upsteam

A hawser-pull (force links) device used for measuring the longitudinal and transverse forces acting on a tow in the lock chamber during filling and emptying operations is shown in Figure 4. Three such devices were used: one measured longitudinal forces and the other two measured transverse forces on the downstream and upstream ends of the tow, respectively. These links were machined from aluminum and had SR-4 strain gauges cemented to the inner and outer edges. When the device was mounted on the tow, one end of the link was pin-connected to the tow, while the other end was engaged to a fixed vertical rod. While connected to the tow, the link was free to move up and down with changes in the water-surface elevation in the lock. Any horizontal motion of the tow caused the links to deform and vary the signal, which was recorded with a personal computer using an analog-to-digital converter. The links were calibrated by inducing deflection with known weights. All data obtained from the pressure cells (measured instantaneous pressures) and the strain gauges (measured hawser forces) were recorded digitally with a personal computer.

Pressures throughout the systems were measured with piezometers (open-air manometers). Pressures obtained in this manner are considered average pressures because of the reduction in frequency response resulting from the use of nylon tubing.

Similitude Considerations

Kinematic similitude

Kinematic similarity is an appropriate method of modeling free-surface flows in which the viscous stresses are negligible. Kinematic similitude requires that the ratio of inertial forces (pV^2L^2) to gravitational forces (pgL^3) in the model are equal to those of the prototype. Here, p is the fluid density, V is the fluid velocity, L is a characteristic length, and g is the acceleration due to gravity. This ratio is generally expressed as the Froude number N_F

$$N_F = \frac{V}{\sqrt{gL}} \tag{1}$$

where L, the characteristic length, is usually taken as the flow depth in open-channel flow.

The Froude number can be viewed in terms of the flow characteristics. Because a surface disturbance travels at celerity of a gravity wave, $(gh)^{1/2}$, where h is the flow depth, it is seen that the Froude number describes the ratio of advection speed to the gravity wave celerity.

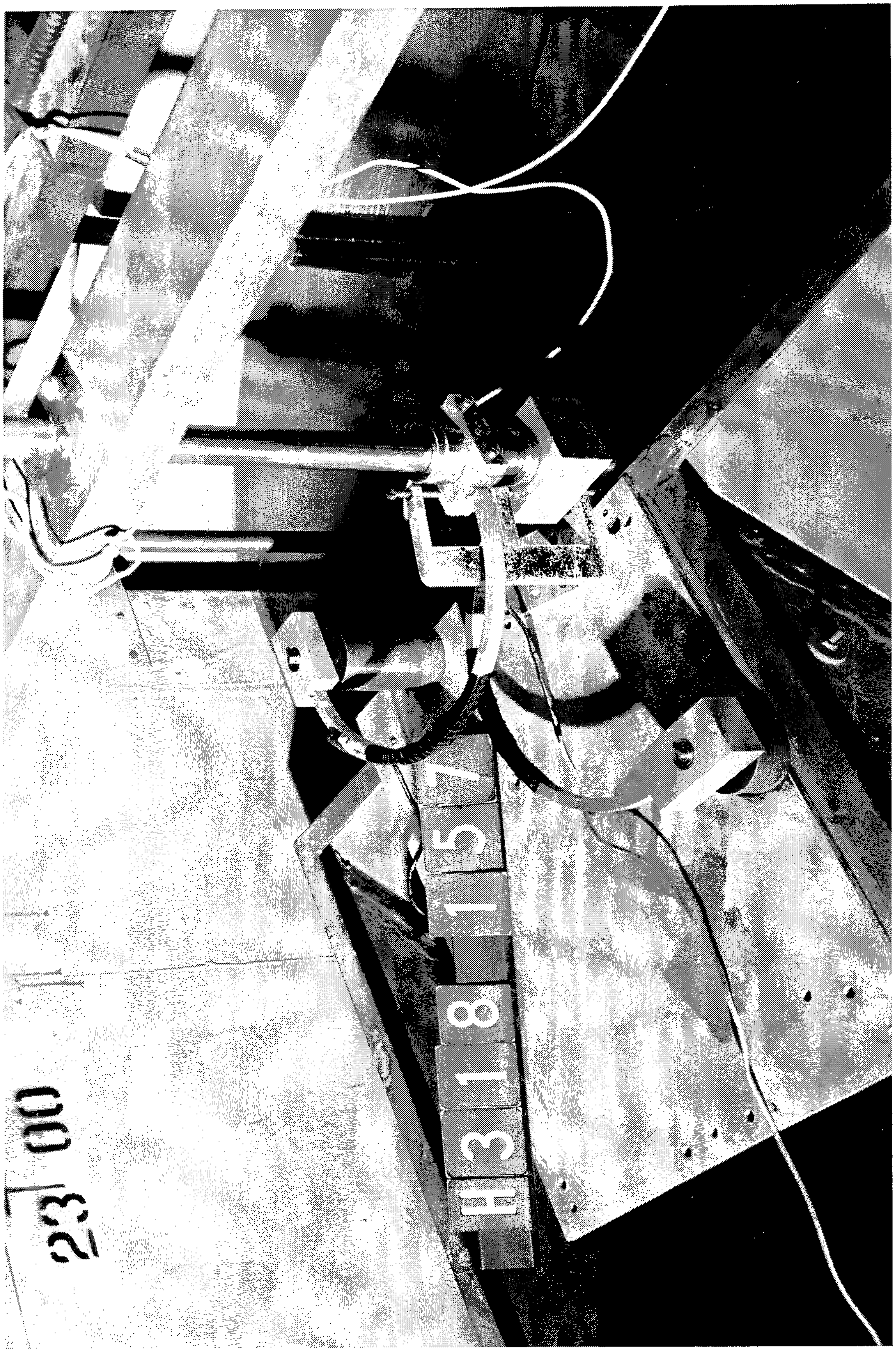


Figure 4. Hawser-pull (force links) measuring device

Evaluation of lock chamber performance primarily concerns modeling of hawser forces on moored barges during filling and emptying operations. These hawser forces are generated primarily by slopes in the lock chamber water surface. The tow's bow-to-stern water-surface differentials are the result of long period seiches in the lock chamber. Seiching is gravity waves traveling in the longitudinal direction from the upper miter gates to the lower miter gates. Equating Froude numbers in the model and prototype is an appropriate means of modeling the lock chamber.

Dynamic similitude

Modeling of forces is a significant purpose of the laboratory investigation. Appropriate scaling of viscous forces requires that the model be dynamically similar to the prototype. Dynamic similarity is accomplished when the ratios of the inertia forces to viscous forces (μVL) of the model and prototype are equal. Here, μ is the fluid viscosity. This ratio of inertia to viscous forces is usually expressed as the Reynolds number

$$N_R = \frac{VL}{\nu} \tag{2}$$

where ν is the kinematic viscosity of the fluid ($\nu = \mu / p$) and the pipe diameter is usually chosen as the characteristic length L in pressure flow analysis.

Similitude for lock models

Complete similitude in a laboratory model is attained when geometric, kinematic, and dynamic similitude are satisfied. Physical models of hydraulic structures with both internal flow (pressure flow) and external flow (free surface) typically are scaled using kinematic (Froudian) similitude at a large enough scale so that the viscous effects in the scaled model can be neglected. More than 50 model and 10 prototype studies of lock filling-and-emptying systems have been investigated (Pickett and Neilson 1988). The majority of these physical model studies used a scale of 1 to 25 (model-to-prototype). Lock model velocities scaled using kinematic similitude (model Froude number equal to prototype Froude number) in a 1:25-scale model have maximum Reynolds numbers at peak discharges on the order of 10^5, yet the corresponding prototype values are on the order of 10^7.

Boundary friction losses in lock culverts are empirically described using the "smooth-pipe" curve of the Darcy-Weisbach friction factor where the head loss is expressed as

$$H_f = f \frac{L}{D} \frac{V^2}{2g} \tag{3}$$

where H_f is the head loss due to boundary friction, f is the Darcy-Weisbach friction factor, L is the culvert length, and D is the culvert diameter. The Darcy-Weisbach friction factor for turbulent flow in smooth pipes is given in an implicit form as (Vennard and Street 1982)

$$\frac{1}{\sqrt{f}} = 2.0 \log \left(N_R \sqrt{f} \right) - 0.8 \tag{4}$$

Because f decreases with increasing N_R , the model is hydraulically "too rough." The scaled friction losses in the model will be larger than those experienced by the prototype structure. Consequently, the scaled velocities (and discharges) in the model will be less and the scaled pressures within the culverts will be higher than those of the prototype. Low pressures were not a particular concern with the McAlpine design; however, the lower discharges would in turn result in longer filling and emptying times in the model than the prototype will experience. Prototype filling and emptying times for similar designs will be less than those measured in a 1:25-scale lock model.

Modeling of lock filling-and-emptying systems is not entirely quantitative. The system is composed of pressure flow conduits and open-channel components. Further complicating matters, the flow is unsteady. Discharges (therefore, N_F and N_R) vary from no flow at the beginning of an operation to peak flows within a few minutes and then return to no flow at the end of the cycle. Fortunately, though, engineers now have about 50 years of experience in conducting large-scale models and subsequently studying the corresponding prototype perfomance. This study used a 1:25-scale Froudian model in which the viscous differences were small and could be estimated based on previously reported model-to-prototype comparisons. If the model and prototype Froude numbers are equal, the relations between the dimensions and hydraulic quantities are as shown in Table 1.

These relations were used to transfer model data to prototype equivalents, and vice versa.

Experimental Procedures

The various elements of the lock system were evaluated on the basis of data obtained during typical filling-and-emptying operations. Performance was based primarily on hawser forces on tows in lockage, movement of unmoored (free) tows in the lock chamber, roughness of the water surface,

Table 1
Relationships Between Dimensions and Hydraulic Quantities

Characteristic	Dimension[1]	Scale Relation Model:Prototype
Length	$L_r = L$	1:25
Pressure	$P_r = L_r$	1:25
Area	$A_r = L_r^2$	1:625
Velocity	$V_r = L_r^{1/2}$	1:5
Discharge	$Q_r = L_r^{5/2}$	1:3, 125
Time	$T_r = L_r^{1/2}$	1:5
Force	$F_r = L_r^3$	1:15,625

[1] Dimensions are in terms of length.

pressures, and time required for filling and emptying. Energy loss coefficients were quantified using fixed-head (steady-flow) conditions with the culvert valve and/or miter gates fully opened or closed.

3 Model Experiments and Results

The primary elements of the new McAlpine system consist of four 12-ft by 12-ft intakes at the upper miter sill face transitioning to two 16-ft by 18-ft culverts located on the lock floor between the lock walls, rotating disk valves of the same size as the intakes, about 32 pairs (actual number varied with design) of 3.5-ft by 1.25-ft ports located in each culvert and four 12-ft by 12-ft outlets positioned at the downstream face of the lower miter sill where the flow is controlled by rotating disk valves. Significant construction cost savings can be realized by placing the intakes and outlets through the miter gate sills and locating the culverts between the lock walls.

Type 1 Design

Numerous designs having various port arrangements were evaluated, beginning with the type 1 design, which had 33 pairs of ports (a sum of port area-to-culvert area ratio of 1.0) centered about the midlength of the lock (Plate 1). The ports in opposite culverts were staggered; therefore, the jet impact distance was the distance between the culverts. Port spacing was selected such that jet interaction between opposite manifolds would not produce bulking of the water surface. The appropriate port spacing was computed based on the idealized description of a submerged two-dimensional momentum jet following the method proposed by Albertson et al. (1950) and later extended by Fisher et al. (1979). The jet boundary was taken as that distance from the jet center line where the jet velocity was negligible (0.01 fps). This boundary set the jet's effective width. The port spacing of 12 ft was set equal to the jet's effective width at the largest impact distance. This impact distance, mentioned previously, was the distance between the manifold culverts (29.42 ft, Plate 1).

Experiments were conducted to observe free tow movement in the lock chamber using an 18-barge tow arrangement initially positioned in the chamber, as shown in Plate 2. Each barge simulated a length of 195 ft, a width of 35 ft, and a draft of 9 ft. Tow movement provides a good indication of how uniform the flow distribution is in the lock chamber during a fill operation.

Free tow drift patterns with the type 1 design are shown in Plate 3. An unmoored 18-barge tow rapidly moved toward the upstream miter gate and struck the gate early in the filling cycle with a 2-min valve and a 37-ft lift. This large acceleration of the tow would result in unacceptable hawser forces and therefore modifications to the manifold arrangement were needed before hawser forces could be measured.

Type 2 Design

The type 2 manifold arrangement was constructed in an attempt to improve the filling-and-emptying system and reduce tow movement during filling. The type 2 manifold arrangement consisted of 2 sets of 16 pairs of ports (sum of port area-to-culvert area ratio of 0.97), each centered about the one third points of the lock length (Plate 4). Free tow drift patterns with this manifold arrangement indicated improved performance; however, this arrangement also produced rapid tow movement and striking of the upstream miter gate.

The manifold jets were examined more closely by setting steady flow through the model. This steady state was accomplished by opening the downstream miter gates, closing the emptying valves, and opening the filling valves. Jets issuing from the manifold ports were aligned in the longitudinal direction rather than in the lateral direction. The short port throat lengths (3 ft) were not long enough to train the jets in the direction perpendicular to the longitudinal manifolds. This resulted in a flow concentration approximately eight port spacings downstream of the first port. This flow concentration produced excessive bulking of the water surface and nonsymmetrical distribution of flow during filling, and caused the rapid tow movement observed in the free tow tests.

Type 3 Design

The type 2 design was modified to include port extensions on the outside of the culverts (type 3 design). These port extensions were located on the downstream face of the ports and were 9 ft in length (perpendicular to the culvert). They were placed on the center-line side of each culvert, as shown in Plate 5. The type 3 arrangement significantly reduced bulking of the water surface during filling; however, this arrangement produced rapid free tow movement and striking of the upstream miter gate.

Type 4 Design

Additional modifications to the filling-and-emptying system included the incorporation of port extensions on the remaining ports, which were located between each culvert, and the lock walls (type 4 design, Plate 6). The type 4 arrangement resulted in slower movement of free tows and although this arrangement resulted in the tow hitting the downstream miter gate, documentation of hawser forces was deemed necessary to quantify this design's performance. Hawser forces during filling and emptying operations with the type 4 design and a 37-ft lift were measured. Maximum hawser forces of 20 tons were generated with a 2-min normal valve operation. As expected, longer valve times produced smaller hawser forces and longer lock operation times. However, even an 8-min valve time produced maximum hawser forces of about 8 tons.

Type 5 Design

The large longitudinal hawser forces measured during filling with the type 4 manifold arrangement were attributed to unbalanced flow between the upstream and downstream end of the chamber. More flow was discharged from the upstream end of the manifold. The type 4 manifold arrangement was modified by shifting ports farther downstream along the manifolds (type 5 design, Plate 7) in an attempt to more evenly distribute the flow along the length of the lock chamber.

Free tows with the type 5 design (Plate 8) drifted slower than in any previous design, yet the tow did move downstream and hit the lower miter gate. Longitudinal and transverse hawser forces were measured with the type 5 arrangement during filling and emptying operations. The maximum longitudinal hawser forces during filling were excessive (10 tons with a 4-min valve), although these forces were less than those measured with the type 4 arrangement. During filling, the maximum longitudinal hawser forces were in the downstream direction. These results suggested that with the type 5 arrangement, more flow discharged from the upstream end of the manifold than from the downstream end during filling.

Type 6-8 Designs

Various port arrangements within the filling and emptying culverts were examined (types 6-8, Plates 9-11). These various designs differed as to the total number of port pairs along the manifold and the arrangement of port extensions. The type 6 design had 32 pairs of ports, with port extensions on the upstreammost 31 pairs of ports, the type 7 design had 33 pairs of ports each having a port extension, and the type 8 design had

33 pairs of ports with port extensions on the upstreammost 31 pairs of ports.

Experiments with the type 6-8 designs included the measurement of transverse and longitudinal hawser forces during filling and emptying operations using 2-, 4-, and 8-min valve times. Maximum longitudinal hawser forces during filling ranged from about 19 tons using a 2-min valve time to 7 tons with an 8-min valve time. Plates 12 and 13 are graphs of these hawser forces and those measured with the type 5 design as a function of filling and emptying times. Although these designs did improve the hydraulic conditions within the chamber, the maximum hawser forces were excessive.

Type 9 and 10 Designs

The type 9 and 10 designs were developed to balance the manifold discharge at the upper and lower ends. The port locations of these designs were unsymmetrical. More ports were placed in the downstream port group. These arrangements were an attempt to force more flow in the lower end of the chamber during filling operations, especially during the early portion of the fill cycle. The type 9 design, shown in Plate 14, had 32 pairs of ports with port extensions on the most upstream 30 pairs or ports. The type 10 design had 34 pairs of ports with port extensions on each of the 31 most upstream ports (Plate 15).

The type 9 design performed better than the type 10 design. A 4-min filling valve with the type 9 design resulted in maximum hawser forces of about 9 tons and a lock filling time of about 10.5 min.

Type 11-13 Designs

Additional modifications were made to the filling-and-emptying system (type 11-13 designs, Plates 16-18) in an attempt to reduce the maximum hawser forces during lock operations. The type 11 design consisted of the type 5 manifold arrangement with 9-ft port extensions located only on the upstream set of 16 ports and with baffles located on the lock walls adjacent to the ported sections of the manifold (Plate 16). The type 12 design, shown in Plate 16, was similar to the type 11 design, but without the wall baffles. The type 13 design used the type 5 manifold arrangement with 9-ft port extensions on the upstream port group and 5-ft extensions on the downstream group of ports (Plate 18).

Maximum hawser forces for each of these designs and those measured with the type 9 design are presented in Plates 19 and 20 for comparison. The best design of this group was the type 11 design filling-and-emptying system shown in Plate 16. The type 11 design filling-and-emptying system produced maximum longitudinal hawser forces during filling, ranging from 13.5 tons using a 2-min valve time to 2.5 tons using an 8-min valve time. A 5-min valve schedule resulted in maximum longitudinal and transverse hawser forces during filling of 4.5 and 3.6 tons, respectively. These maximum hawser forces are significantly lower than those obtained with previous designs with the design lift of 37 ft and are less than the recommended maximum force of 5 tons.

Type 14 Design

The sensitivity of the system's performance to the length of the port extensions developed in prior designs was evaluated because shorter port extensions would be less costly to construct. The 9-ft port extensions used with the type 11 design filling-and-emptying system were replaced with 5-ft port extensions. This design (type 14, Plate 21) resulted in increased maximum hawser forces during filling operations. These experimental results indicate that the system performance was sensitive to the port extension length and that the 9-ft length was appropriate.

Type 15 Design

The wall baffle of the type 11 design was modified in an effort to reduce maximum transverse hawser forces during filling. Vertical baffles were added to the horizontal baffle and this was designated the type 15 design (Plate 22). These vertical members provided additional energy dissipation of the manifold jets at the lock chamber floor and inhibited jet upwelling. The vertical baffles reduced the maximum transverse hawser forces but increased longitudinal hawser forces during filling as compared to the type 11 design.

Type 16 Design

The next configuration designed to reduce transverse hawser forces included T baffles placed along the lock center line between the ported stations (type 16 design, Plate 23). The addition of the T baffles did not significantly change the longitudinal hawser forces. However, these baffles actually increased the transverse hawser forces during filling. Therefore, future modifications excluded the use of T baffles. Types 14-16 design hawser force results are summarized in Plates 24 and 25.

Type 17 (Recommended) Design

Representatives of the Louisville District requested examination of the type 11 design having a modified lock chamber floor (raised to el 367). This configuration (type 17 design, Plate 26) was evaluated to determine if only the areas in the vicinity of the ports needed to be excavated to the port elevation of 360.5. This design would reduce excavation costs during project construction. The type 17 design filling-and-emptying system produced maximum longitudinal hawser forces during filling ranging from 13.8 tons using a 2-min valve time to 2.5 tons using an 8-min valve time. A 5-min filling valve resulted in maximum hawser forces of 4.5 tons and a lock filling time of about 10.7 min. These maximum hawser forces are acceptable and are very similar to those produced by the type 11 design in which the entire lock chamber floor was at el 360.5.

Instantaneous pressures were measured with pressure cells mounted on the roof of the culvert downstream of a filling valve (sta 19+96, Plate 27). The pressure just downstream of the filling valves can become excessively low in conjunction with the high velocities occurring during partial gate openings; however, experimental results showed the design provides positive head during filling operations. Time-histories of the pressure just downstream of the filling valves for typical filling operations with 2-, 4-, 5-, and 8-min valve times are presented in Plates 28-31. These pressure data should be useful in determining maximum loading for the bulkhead slot cap design for the filling valves.

Additional pressures occurring during steady flow were measured at various locations throughout the system using piezometers as shown in the piezometer layout on Plate 27. These measurements were used to quantify loss coefficients for various components of the system. Energy loss through each component is expressed as

$$H_{L_i} = K_i \frac{V^2}{2g} \tag{5}$$

where K_i is the loss coefficient for component i, and V is the culvert velocity which is one fourth of the total discharge divided by a culvert area of 12 ft by 12 ft. The total head loss through the system is

$$H_L = \sum H_{L_i} = \sum K_i \frac{V^2}{2g} \tag{6}$$

The lock coefficient is defined as

$$C_L = \frac{V}{\sqrt{2gH_L}} \tag{7}$$

Equating the headloss H_L in each expression shows the relation between the lock coefficient and loss coefficient.

$$K = C_L^{-2} \quad \text{or} \quad C_L = K^{-0.5} \tag{8}$$

where K is the sum of each K_i.

The total energy loss coefficient for the filling system K was determined to be 2.1. Distribution of this sum by lock filling components is illustrated in Table 2. The corresponding overall lock coefficient C_L for filling was determined to be 0.69.

Table 2
Distribution of Energy Loss Coefficient

Component	Loss Coefficient, K_i
Intakes, valves, and junction	0.7
Culvert upstream of manifold	0.2
Manifold	1.2

For the design lift of 37 ft, the type 17 design with a 5-min valve operating time filled the lock chamber in 10.7 min and emptied in 11.7 min. Due to differences in friction losses as discussed previously in the "Similitude Considerations" section of this report, the prototype can be expected to fill and empty faster than the model. Based on previous model experiments and prototype investigations and considering the geometry of this design, the prototype should fill and empty about 10 percent faster than model results indicate. This will give prototype fill and empty times of 9.6 min and 10.5 min, respectively. Hawser forces were 5 tons or less using a 5-min valve schedule; therefore, use of a 5-min valve schedule is recommended. A time-history of results during a typical lock filling operation are presented in Plate 32 and graphs of maximum hawser forces versus operation time for the type 17 design are provided in Plates 33 and 34.

Flow conditions in the lock chamber during filling with the type 17 design are acceptable and an unmoored tow rises almost vertically (Plate 35). Unmoored tows during lock filling and emptying should not occur in locks, but this performance provides a good indication of how uniform the flow distribution is in the lock chamber during a fill operation. Surface currents within the lock chamber during filling are illustrated with confetti in Figure 5.

a. As filling started

Figure 5. Surface currents in lock chamber during filling operations with type 17 (recommended) design; 4-min valve time; time exposure 15 sec (Sheet 1 of 6)

b. 2 min after filling started

Figure 5. (Sheet 2 of 6)

c. 4 min after filling started

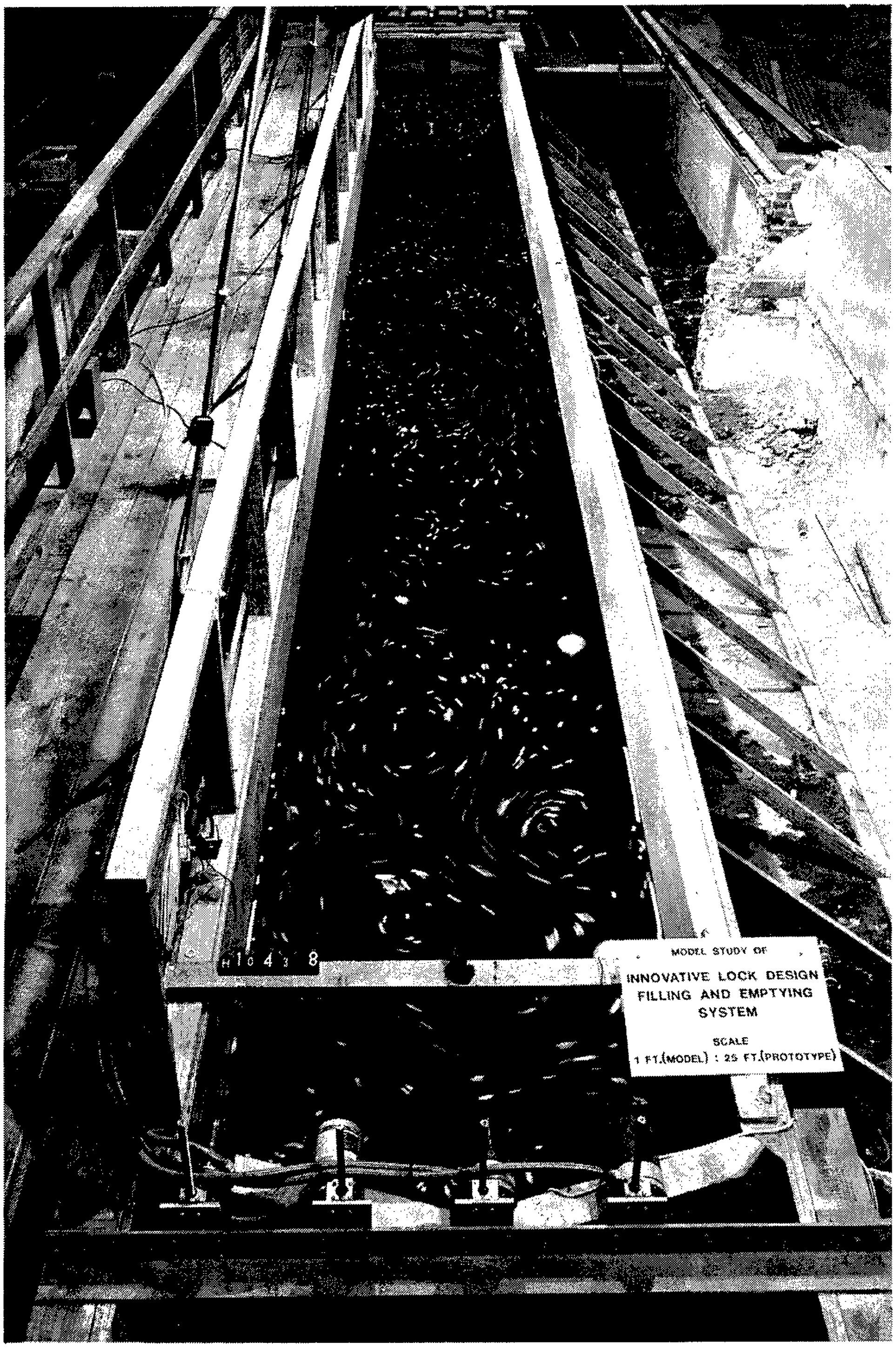
Figure 5. (Sheet 3 of 6)

d. 6 min after filling started

Figure 5. (Sheet 4 of 6)

e. 8 min after filling started

Figure 5. (Sheet 5 of 6)



f. 10 min after filling started

Figure 5. (Sheet 6 of 6)

4 Summary and Conclusions

The optimum filling and emptying system developed (type 17 design, Plate 26) includes 2 sets of 16 pairs of ports (1.25 ft by 3.50 ft) per culvert (sum of port area-to-culvert area ratio of 0.97) with each set centered at the one third points of the lock chamber, 9-ft port extensions located only on the upstream set of 16 ports, and horizontal baffles located on the lock walls. The port extensions serve two purposes. They train the jets in a direction normal to the longitudinal manifold and they reduce the effective area of the ports on which they are added. The short throat length provided by the culvert walls (3 ft) is not long enough to train the jets toward the transverse direction. This results in flow concentrations approximately eight port spacings downstream of the first port. This flow concentration produces excessive bulking of the water surface and nonsymmetrical distribution of flow during filling. Reduction of the effective port areas on the upstream ports is beneficial during the early portion of the fill cycle in which inertial effects result in flow issuing from the upstream ports before the downstream ports. This uneven port flow distribution results in large hawser forces early in the filling operation. This problem is common in sidewall port systems and is remedied using triangular baffles at several of the upstream ports (Ables and Boyd 1966a, 1966b).

Baffling is used to dissipate energy of the jets issuing from the manifold ports during filling. The wall baffles help diffuse the jets at the lock chamber floor and distribute the flow along the lock chamber. This minimizes upwelling at the water surface, which can produce unsafe conditions for vessels within the lock chamber.

Model experiments indicate that only the areas in the vicinity of the ports need to be excavated to the port invert elevation. Similar findings are reported in Stockstill and George (1996). The chamber floor of the remaining area can be excavated to the elevation of the culvert roof. Significant cost savings may be realized in this reduction of lock chamber excavation volume.

This laboratory investigation has demonstrated that construction of the filling and emptying culverts on the lock floor between the lock walls is a viable design. These findings are based on one design and should be applied with caution to other sites having different chamber or culvert sizes.

The following general conclusions drawn from this study can serve as a basis on design guidance for the ILCS:

a. The port-to-culvert area ratio should be about 0.97.

b. The port spacing in each manifold should be staggered.

c. Two groups of ports should be centered about the one third points of the lock length.

d. Port extensions on the upstream group of ports decreased the flow rate issuing from this group (especially early in the filling cycle), thereby making the distribution of flow along the length of the chamber more uniform.

e. Port extensions also train the jets issuing from these ports in a direction normal to the longitudinal culvert.

f. Wall baffles are beneficial because they diffuse the port jets at the lock chamber floor.

g. Only the areas in the vicinity of the ports need to be excavated to the port invert elevation.

Model experiments of lock systems having different dimensions will be invaluable to securing appropriate design guidance incorporating innovative features; in particular, the ILCS.

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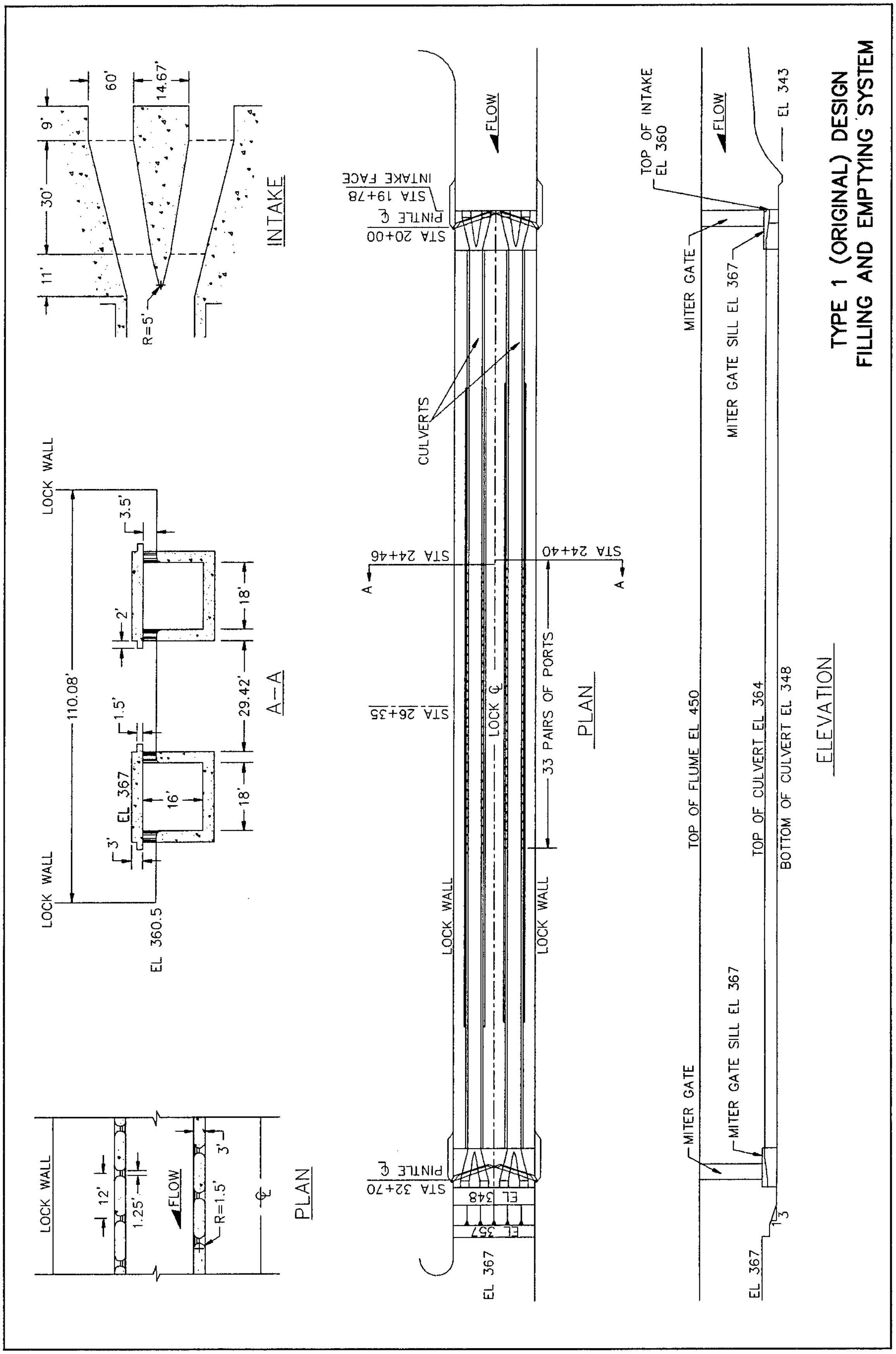
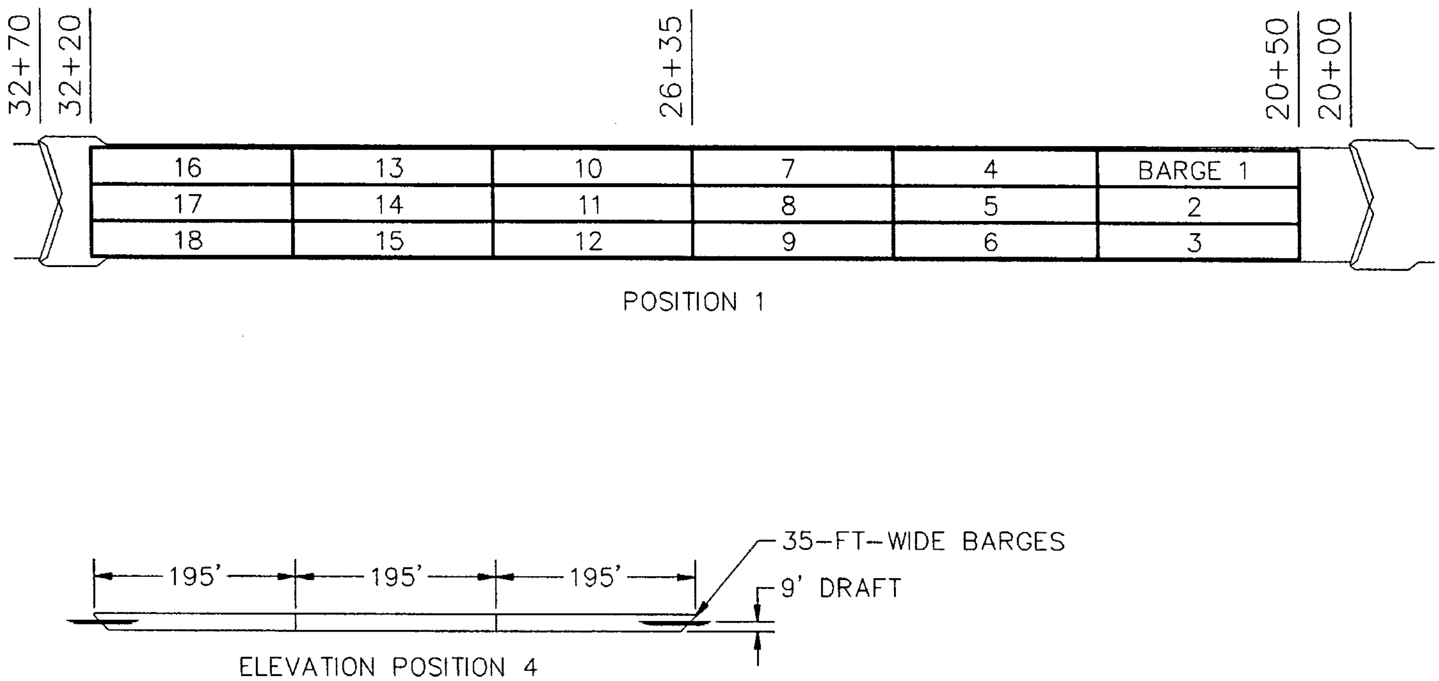
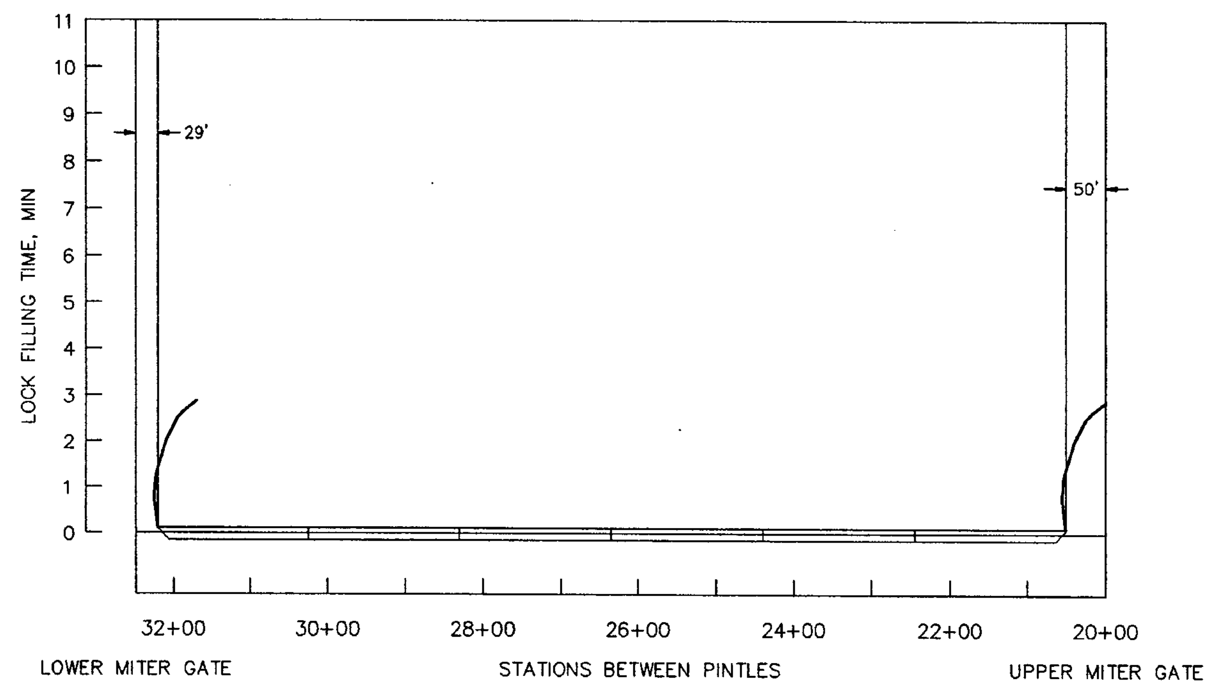


TYPE 1 (ORIGINAL) DESIGN
FILLING AND EMPTYING SYSTEM

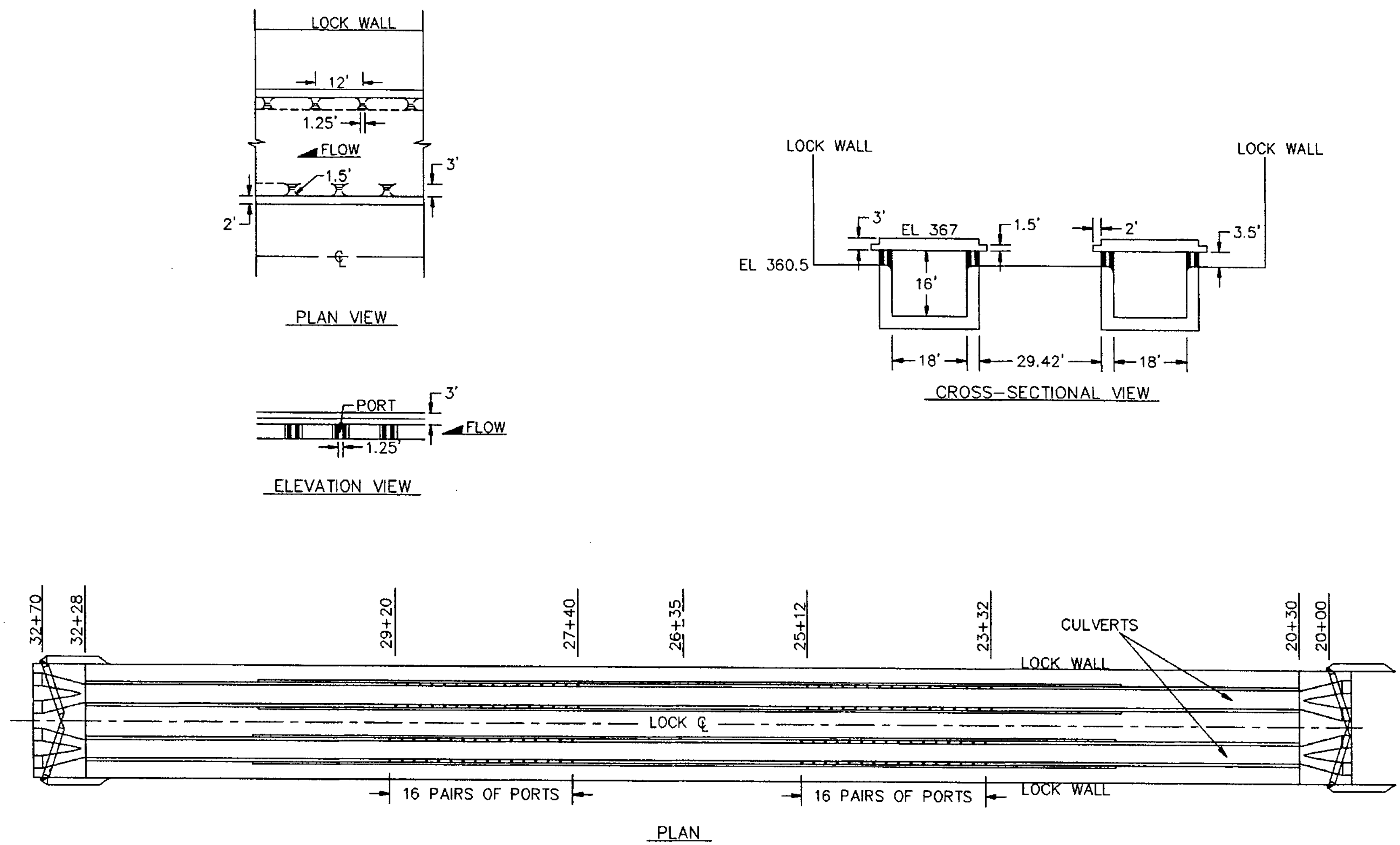


BARGE POSITION AND DETAILS



18–BARGE TOW

TYPICAL FREE TOW MOVEMENT
DURING FILLING OPERATIONS
TYPE 1 DESIGN
2–MIN VALVE OPERATION
U.P. EL 420.0, L.P. EL 383.0



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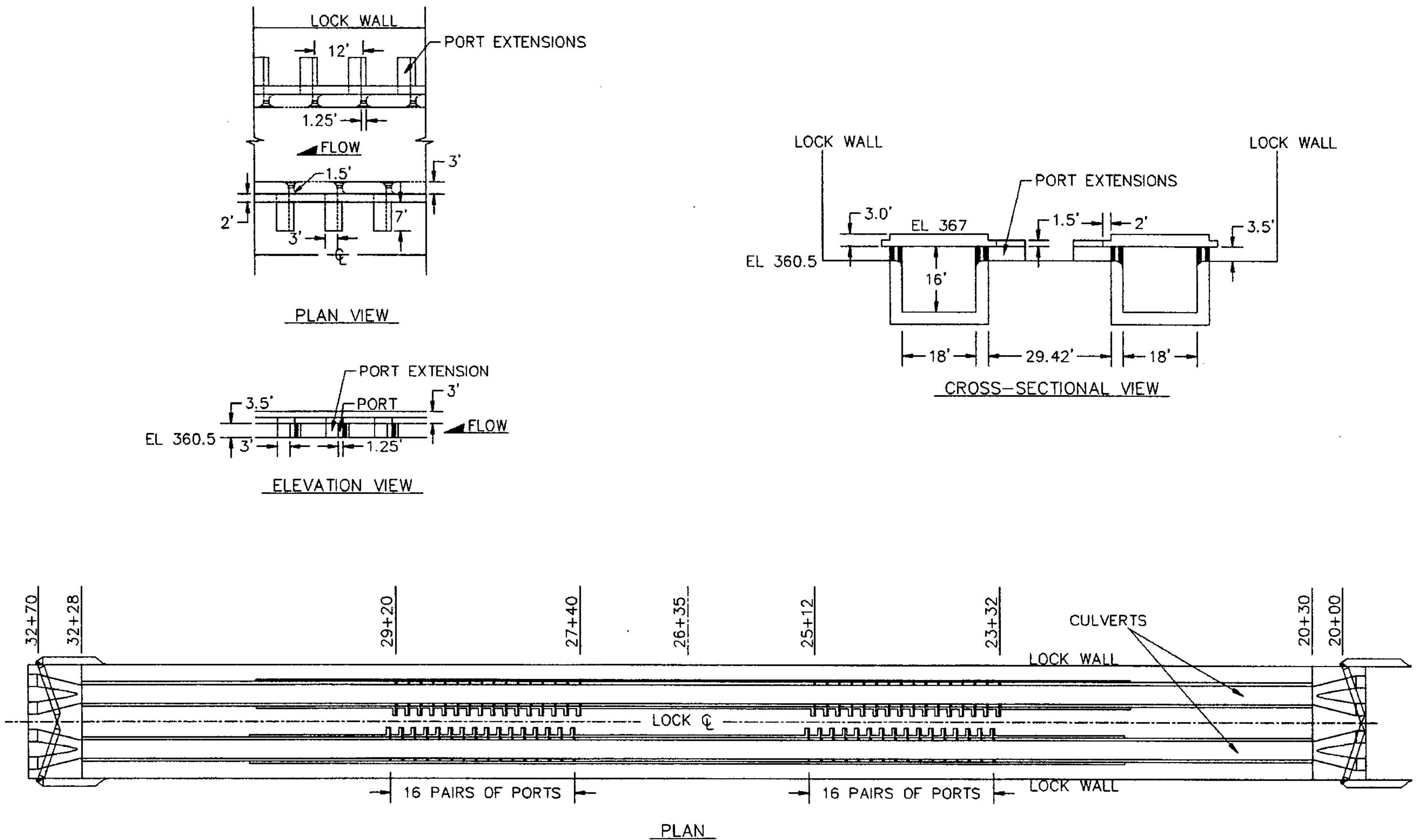

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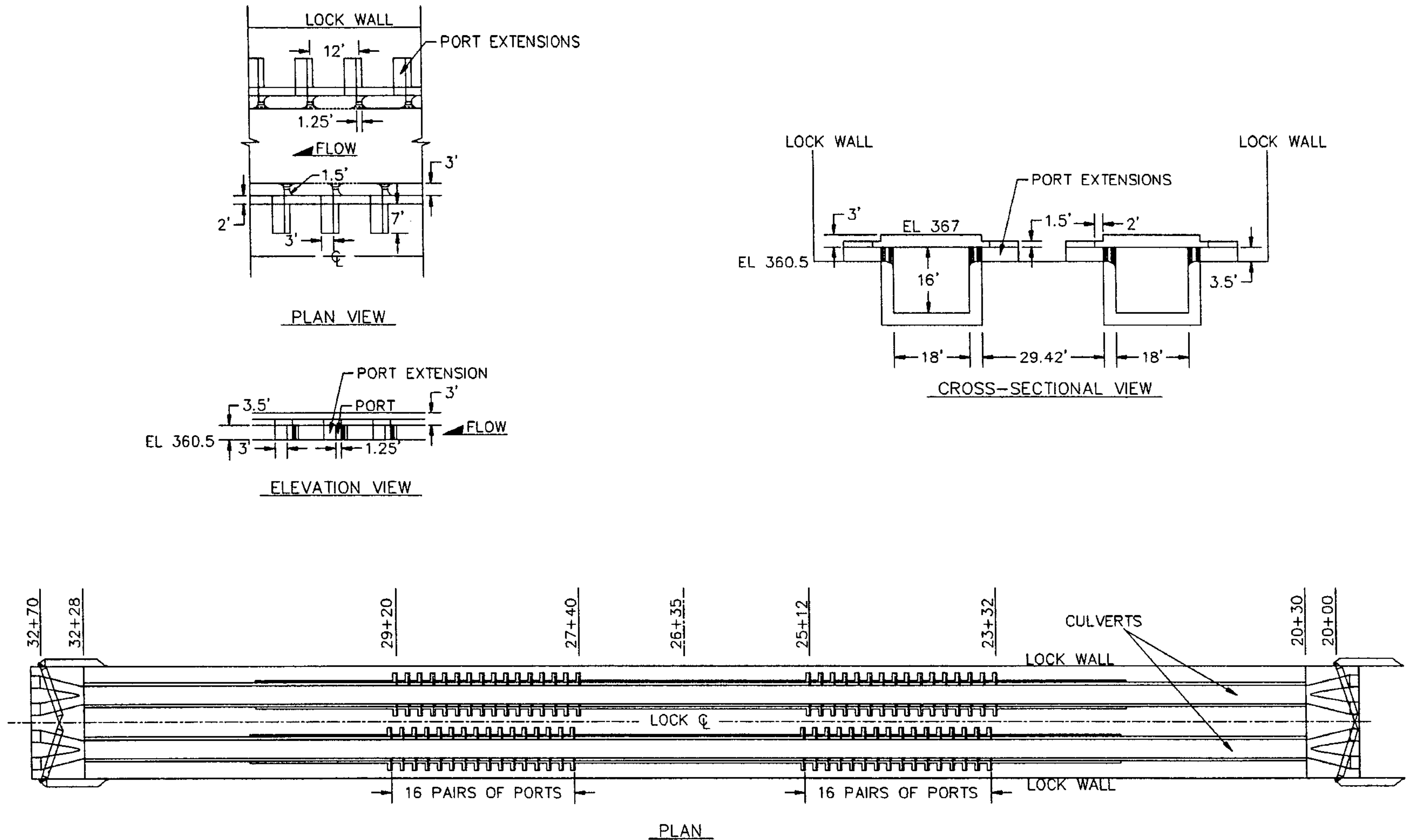

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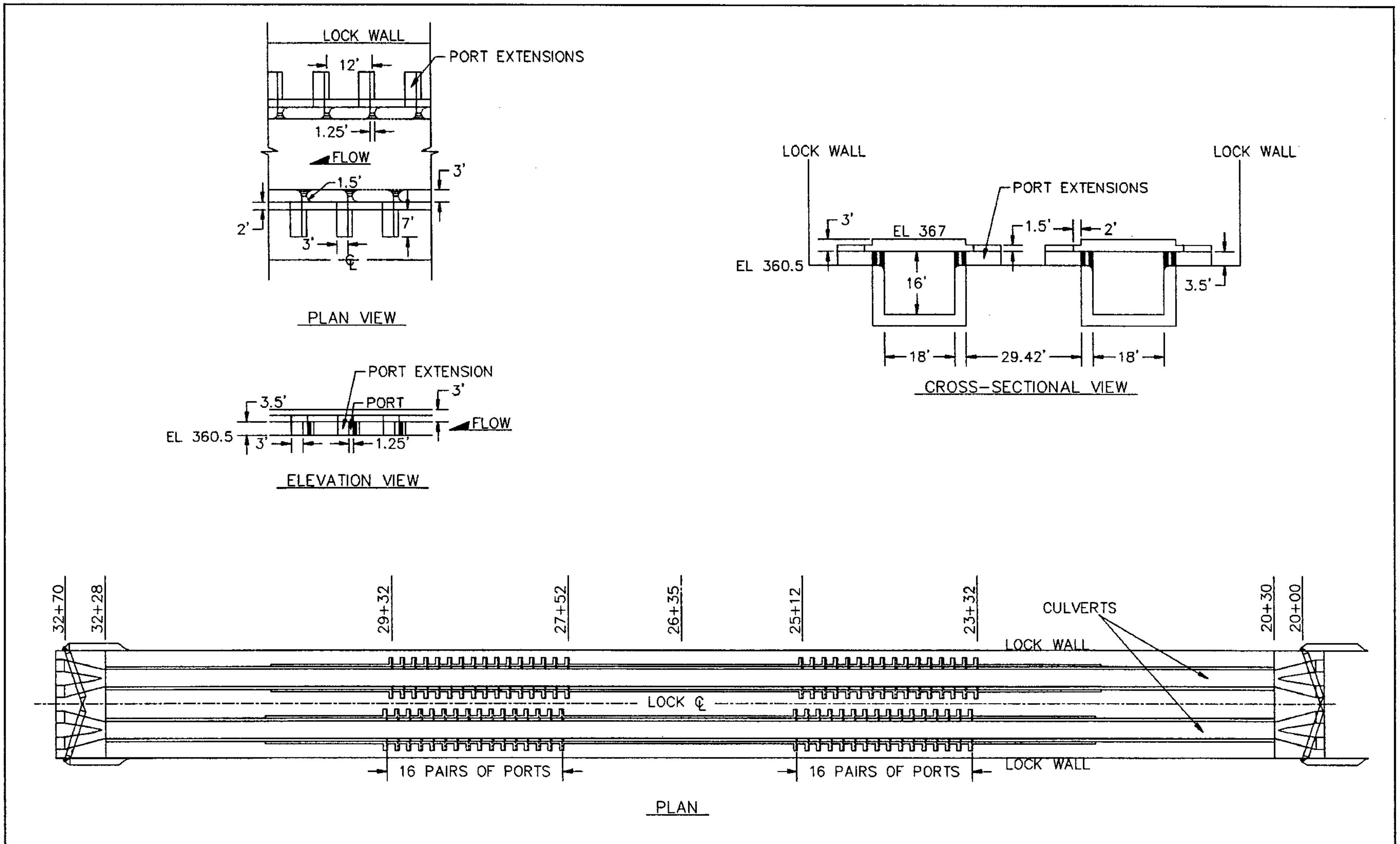

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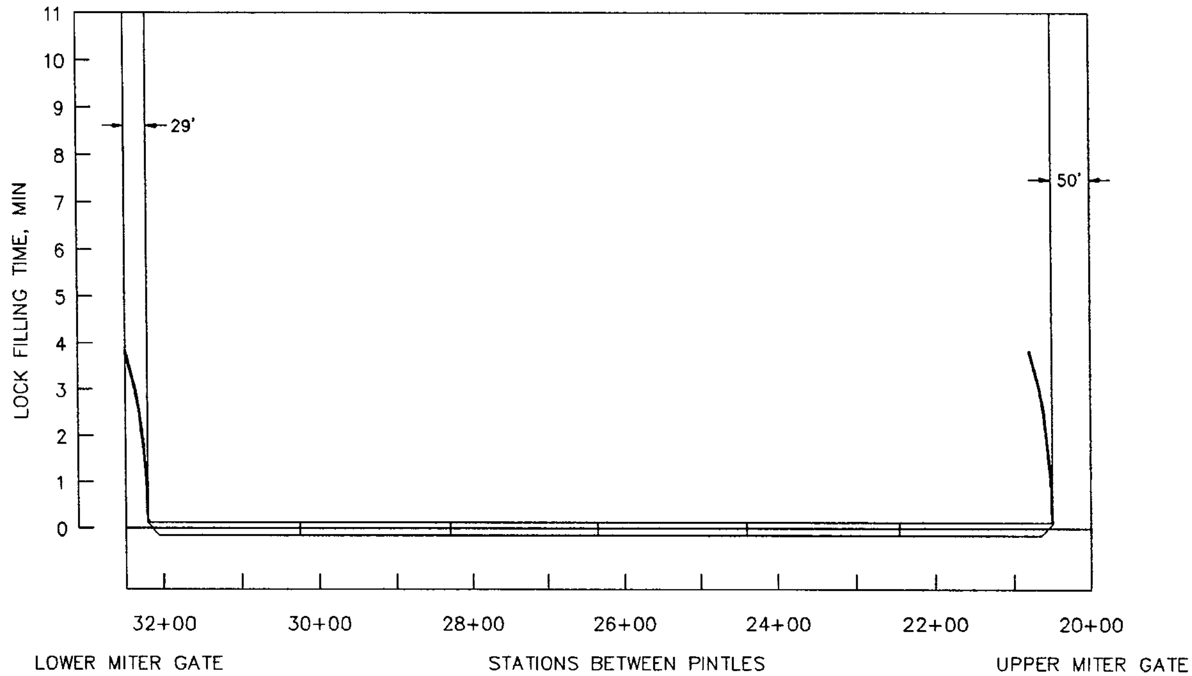
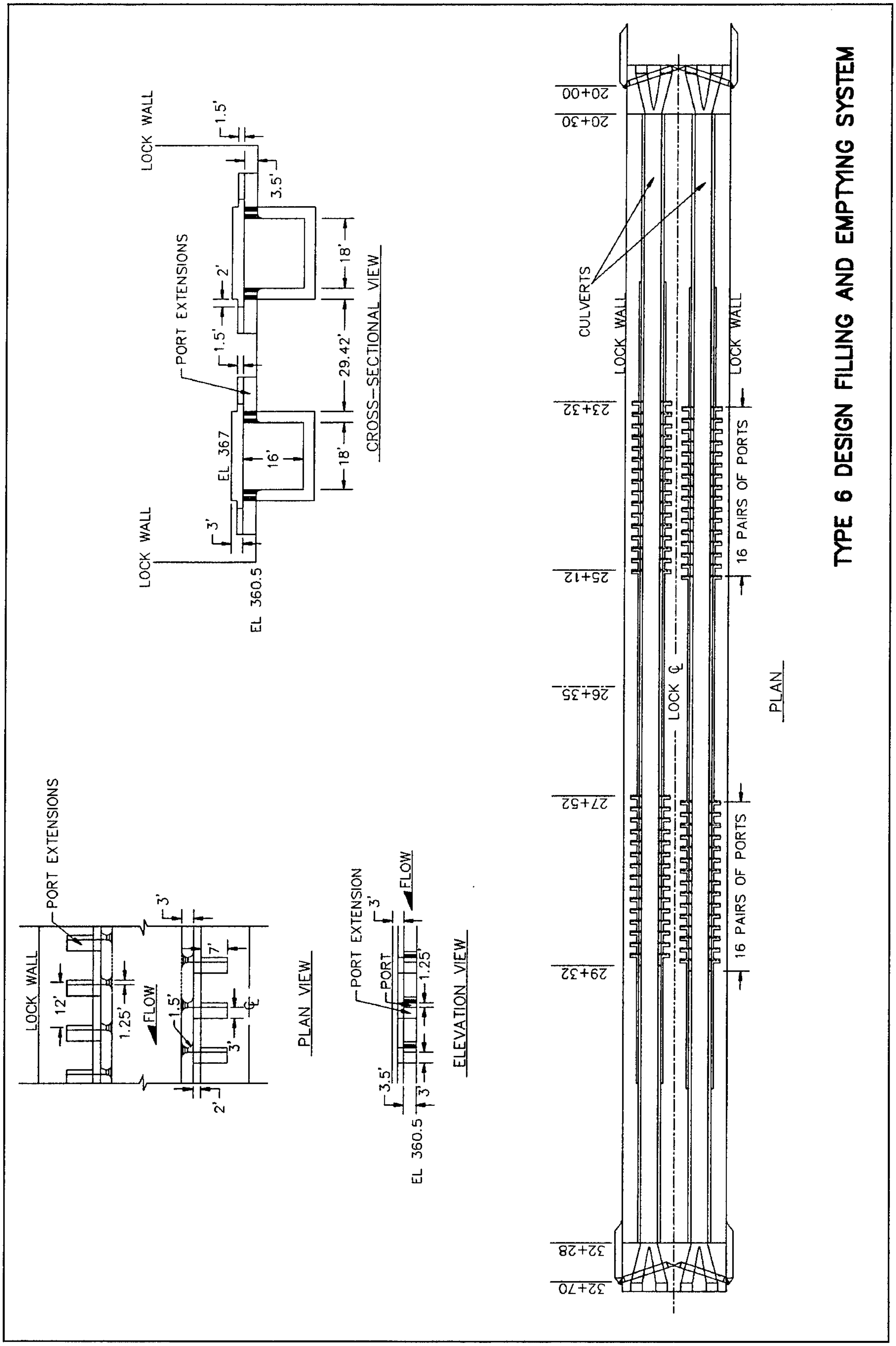


18-BARGE TOW

TYPICAL FREE TOW MOVEMENT
DURING FILLING OPERATIONS
TYPE 5 DESIGN
4-MIN VALVE OPERATION
U.P. EL 420.0, L.P. EL 383.0



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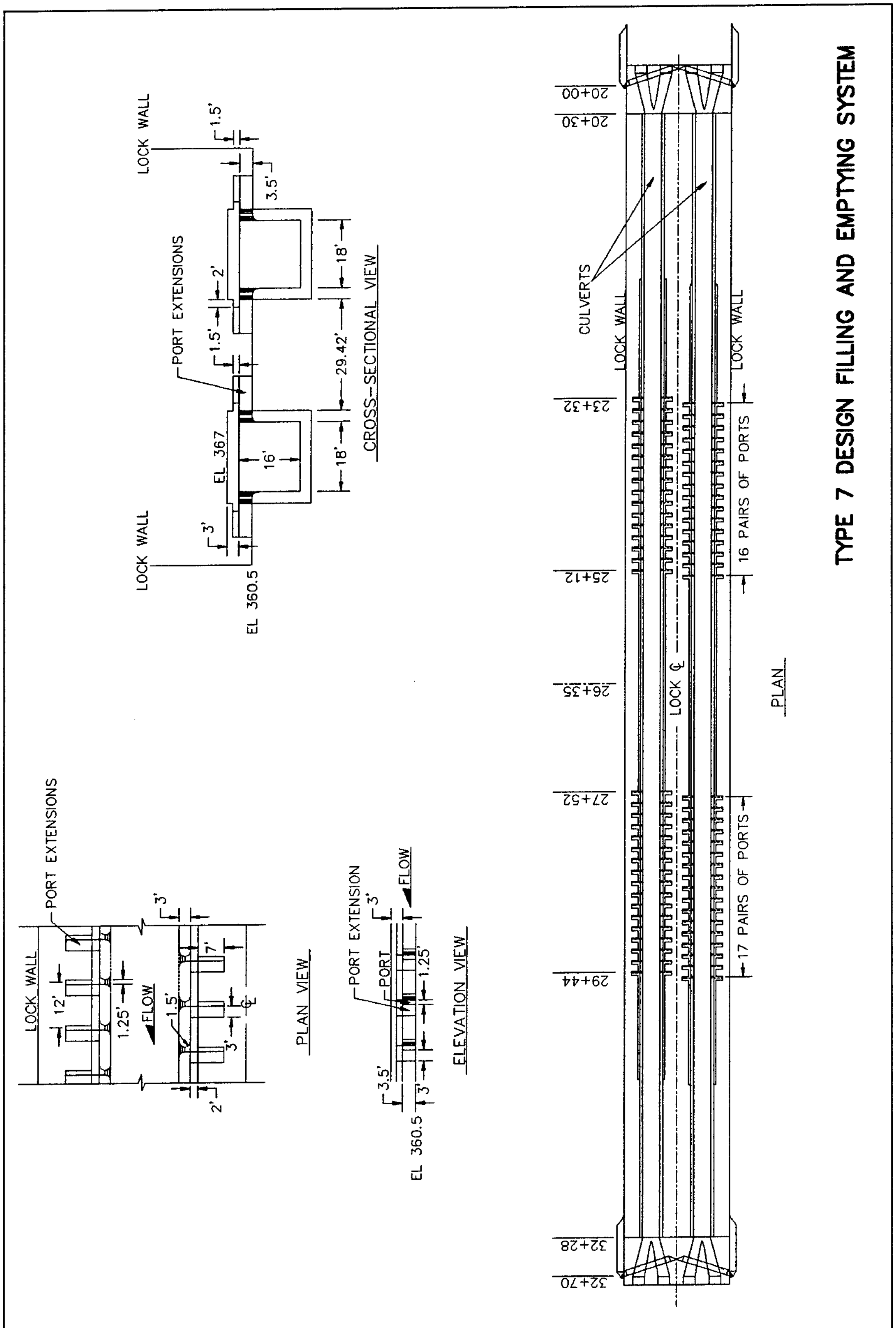
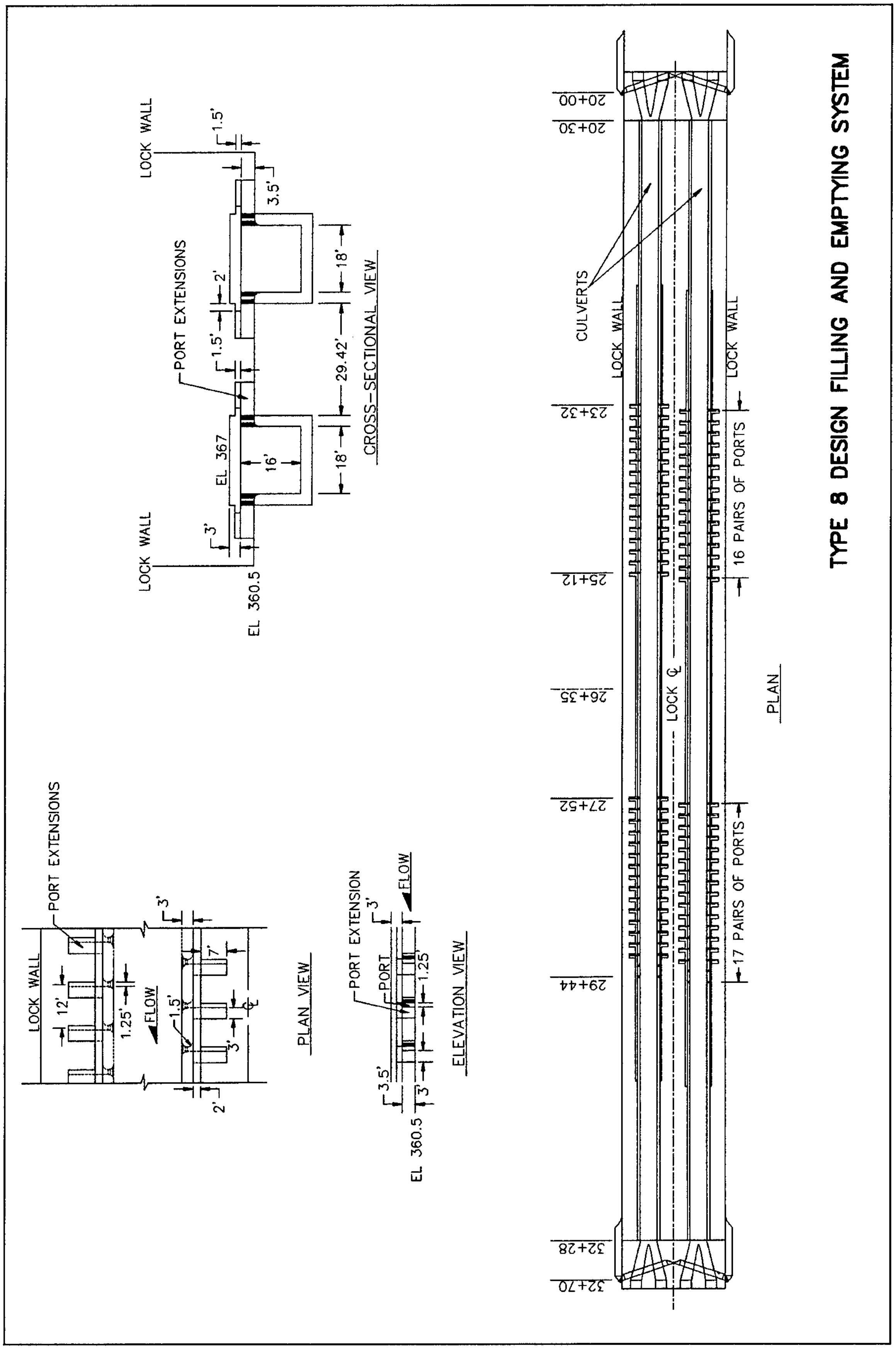


TYPE 7 DESIGN FILLING AND EMPTYING SYSTEM

Plate 10



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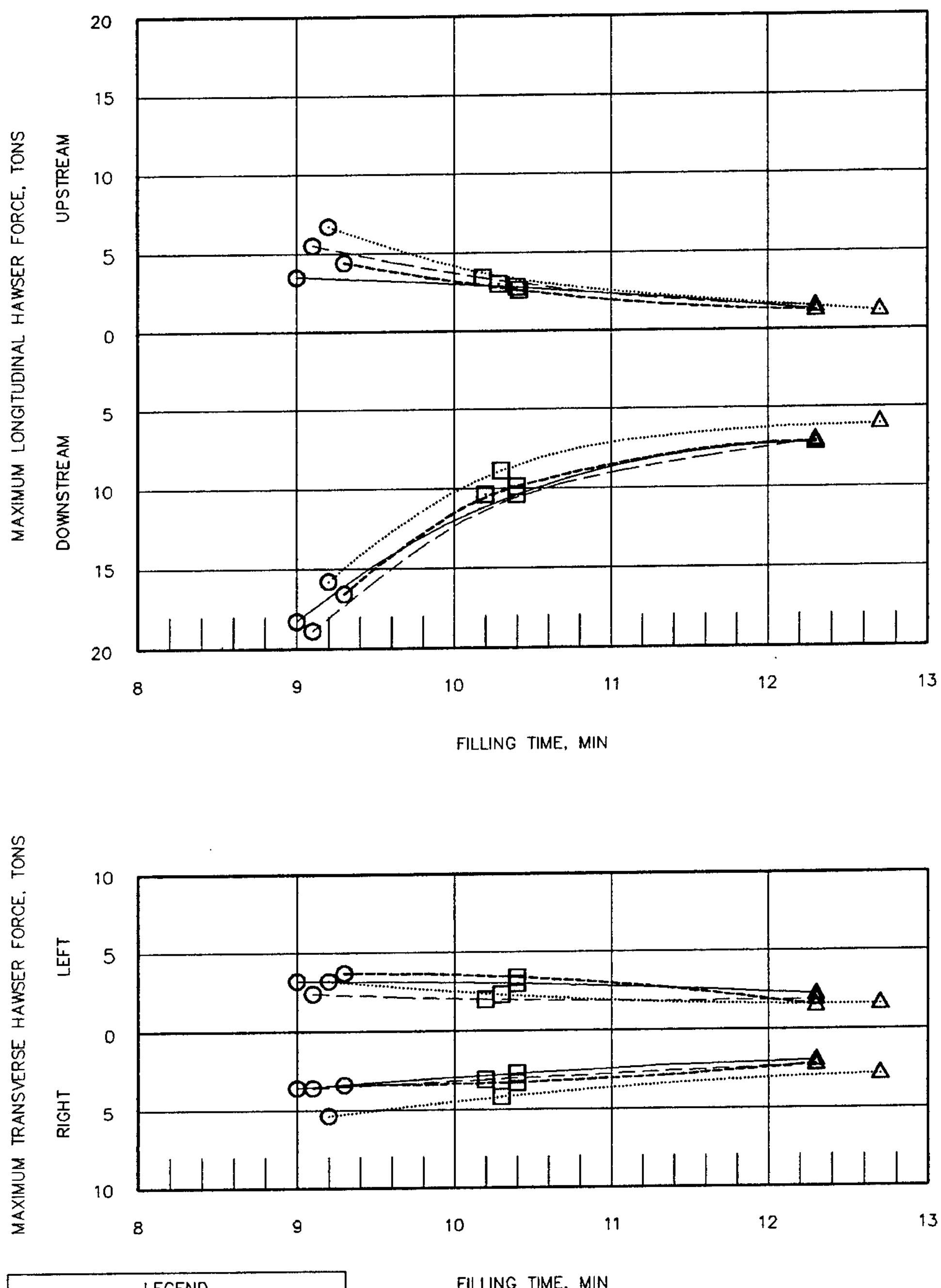

LEGEND	
SYMBOL	VALVE SCHEDULE, MIN
O	2
⊡	4
Δ	8
LINE TYPE	DESIGN TYPE
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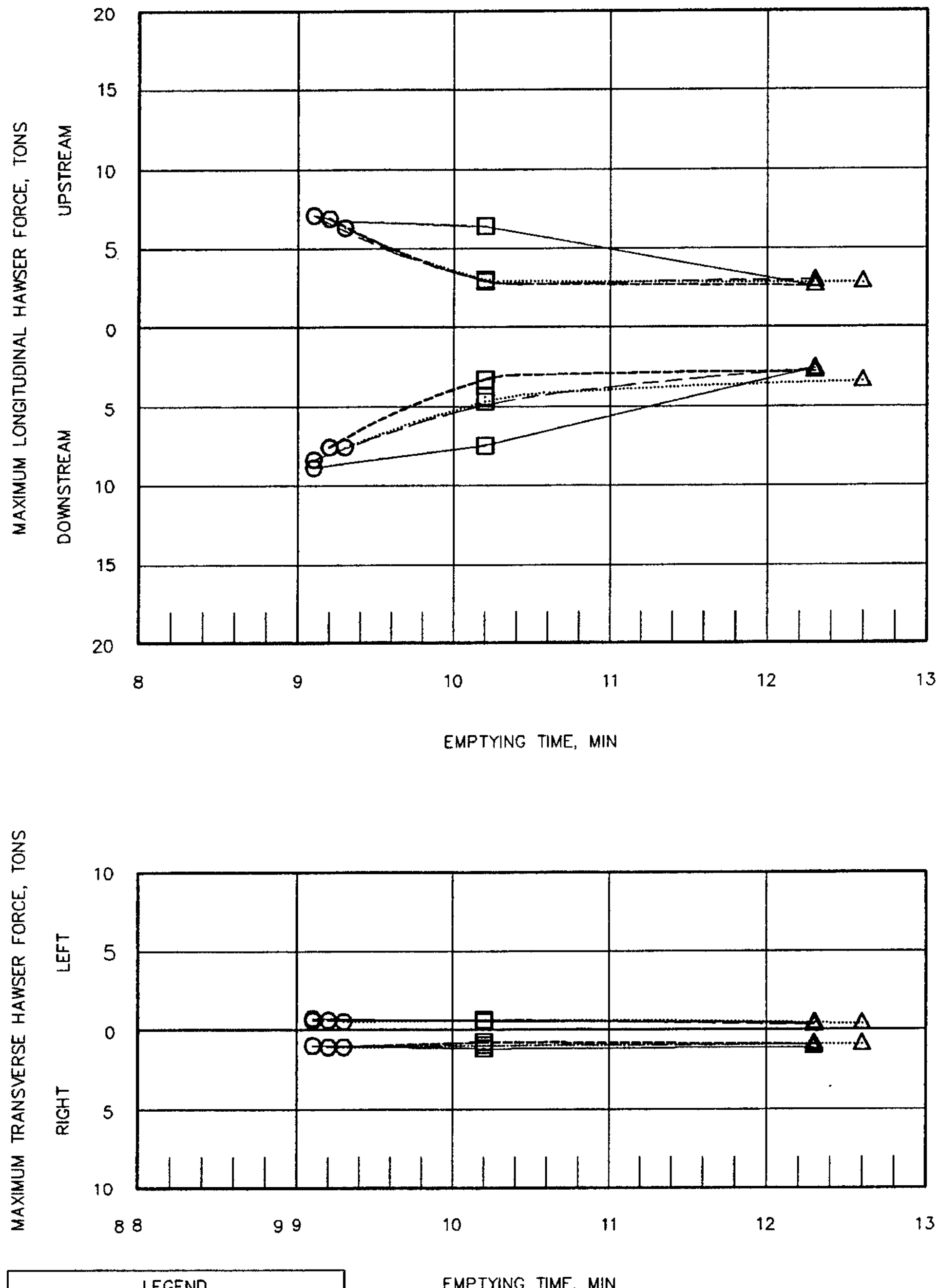
....	8

HAWSER FORCES
DURING FILLING
TYPES 5 – 8 DESIGN



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SYMBOL	VALVE SCHEDULE, MIN
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△	8
LINE TYPE	DESIGN TYPE
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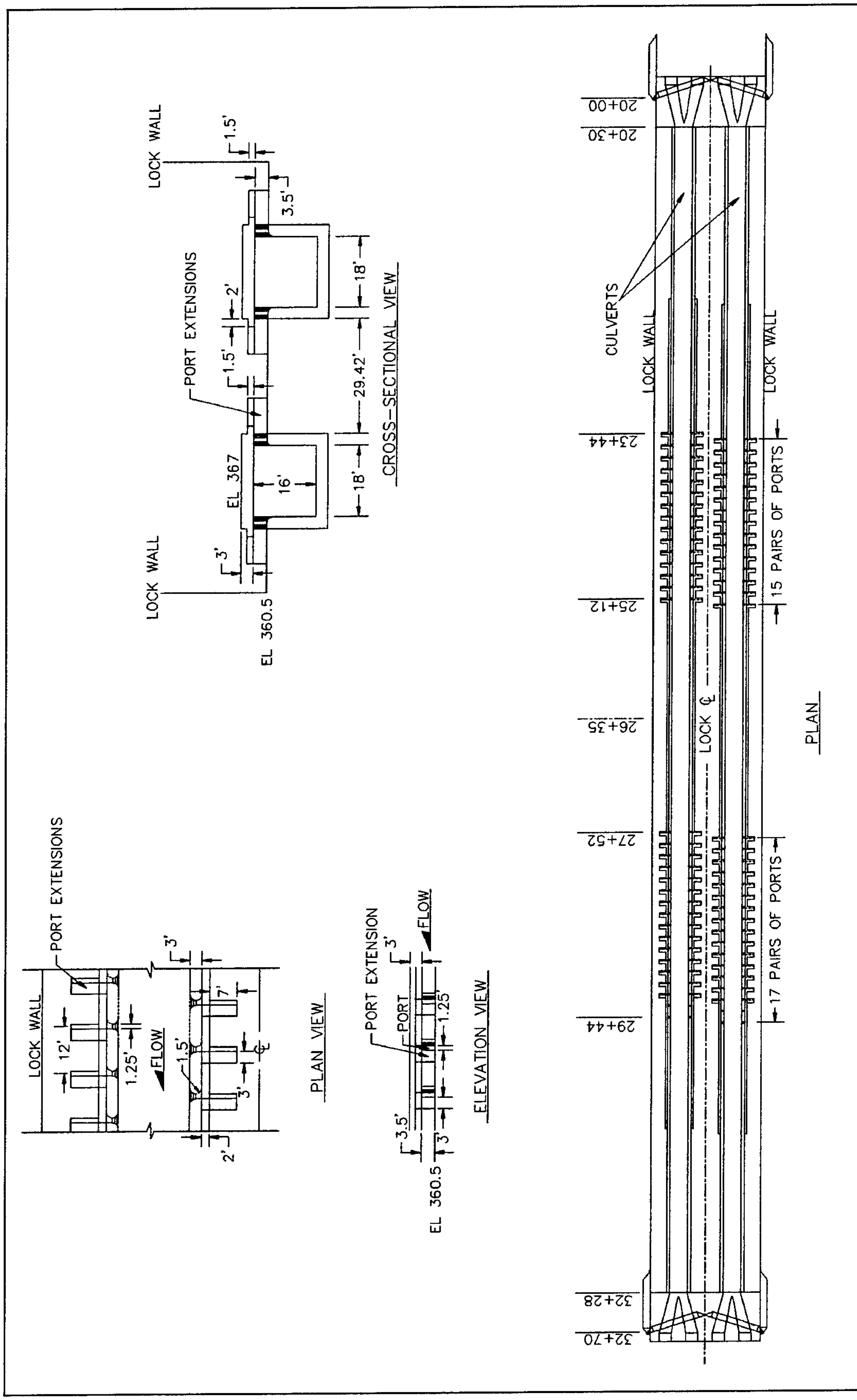
HAWSER FORCES
DURING EMPTYING
TYPES 5 – 8 DESIGN



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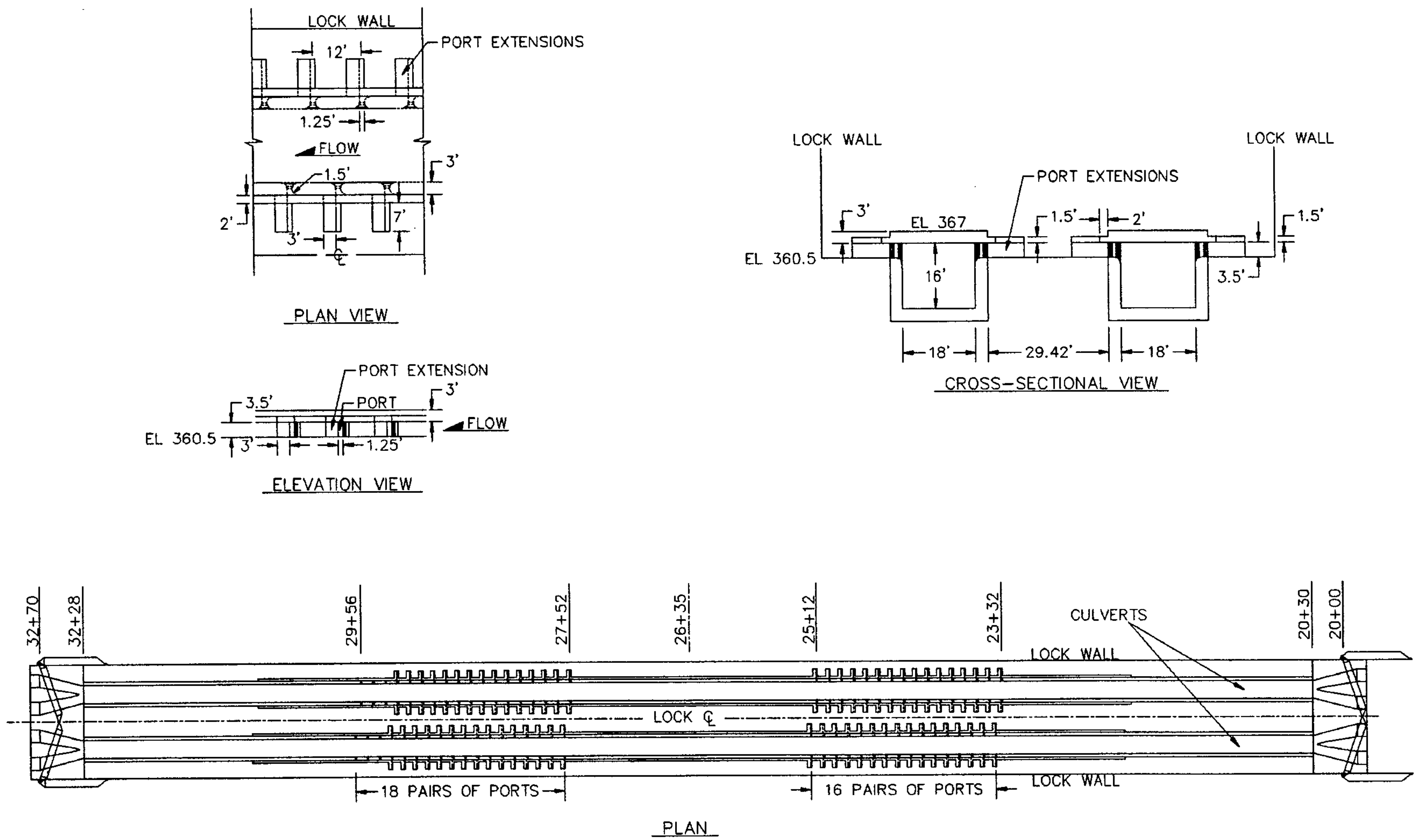

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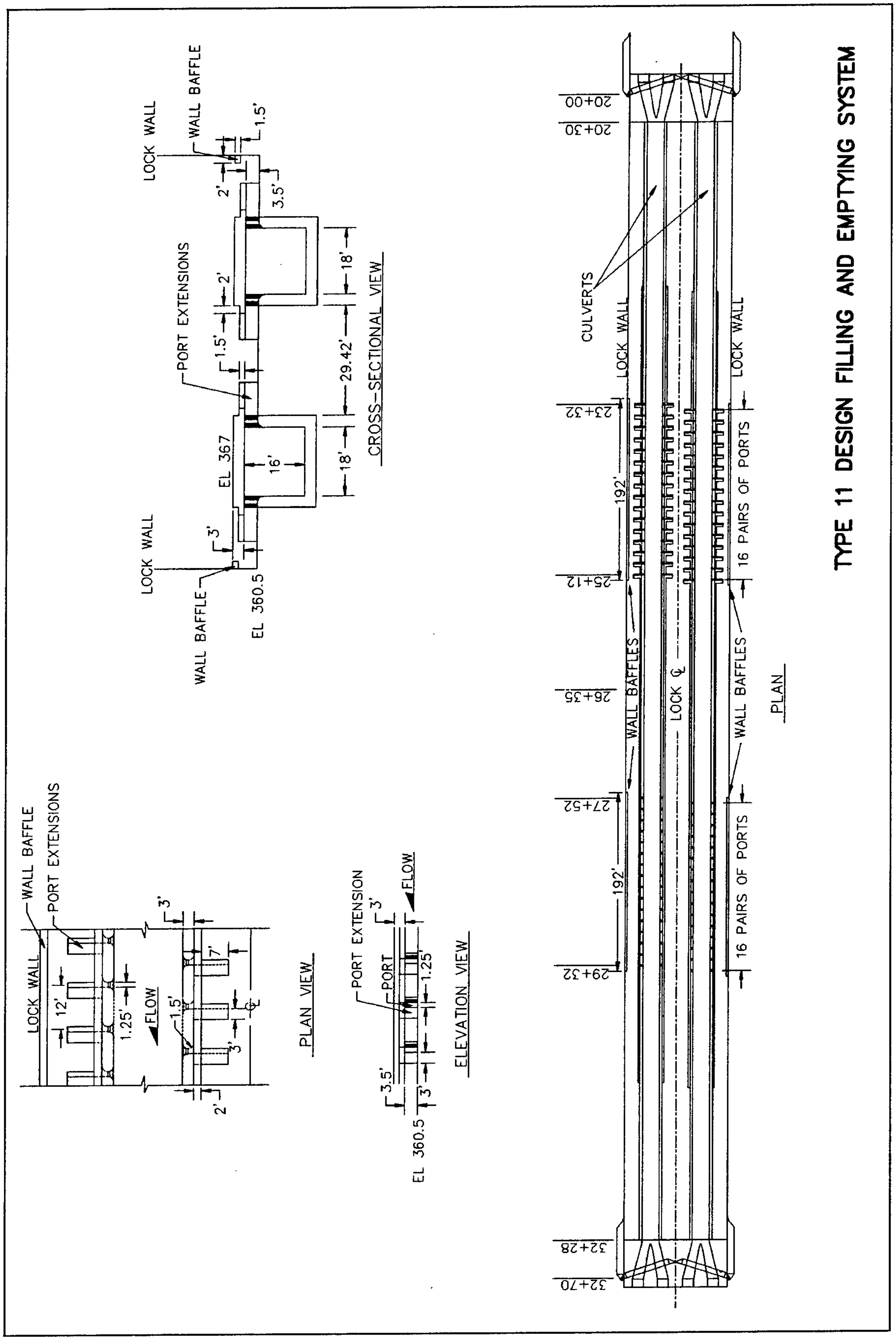
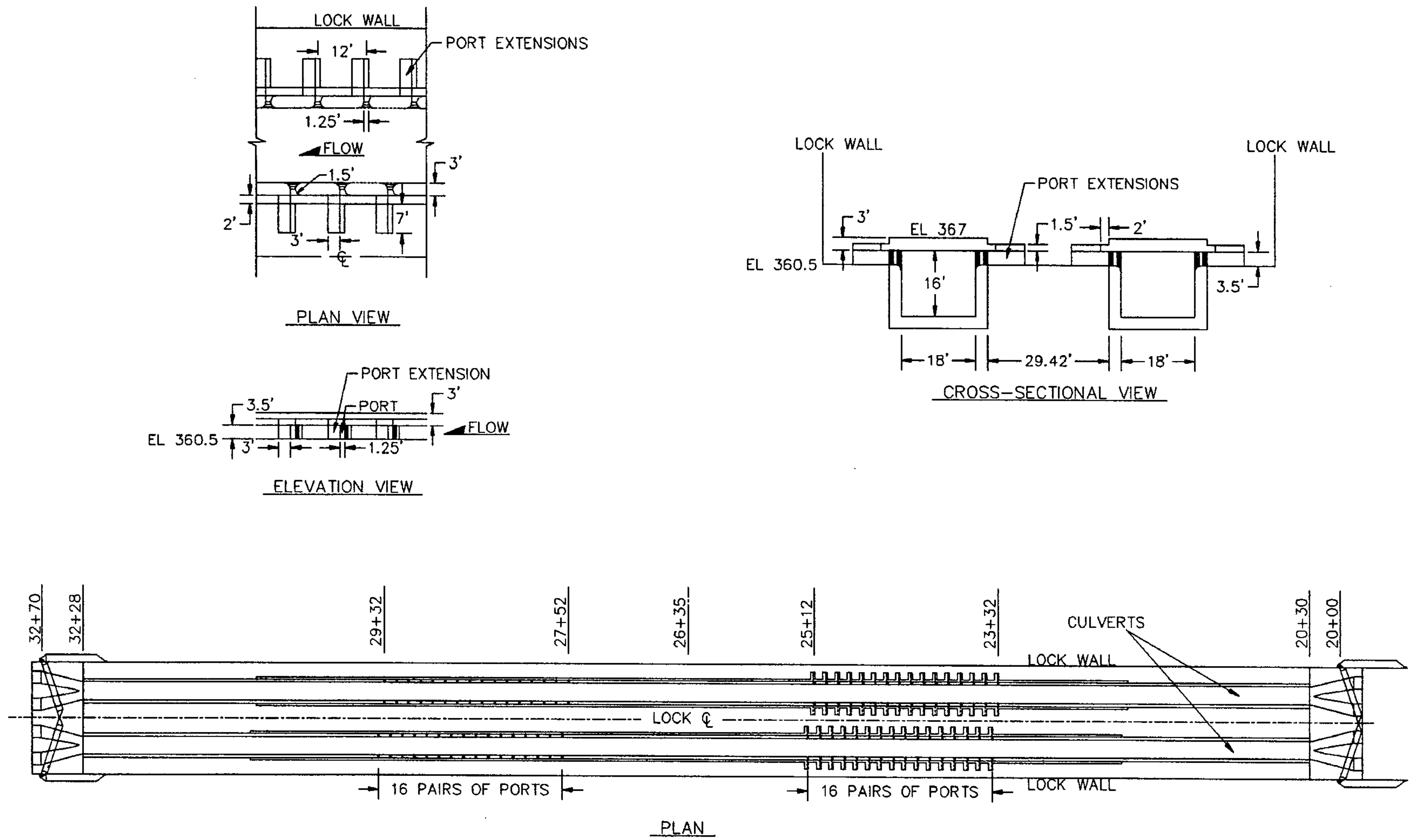


TYPE 11 DESIGN FILLING AND EMPTYING SYSTEM

Plate 16



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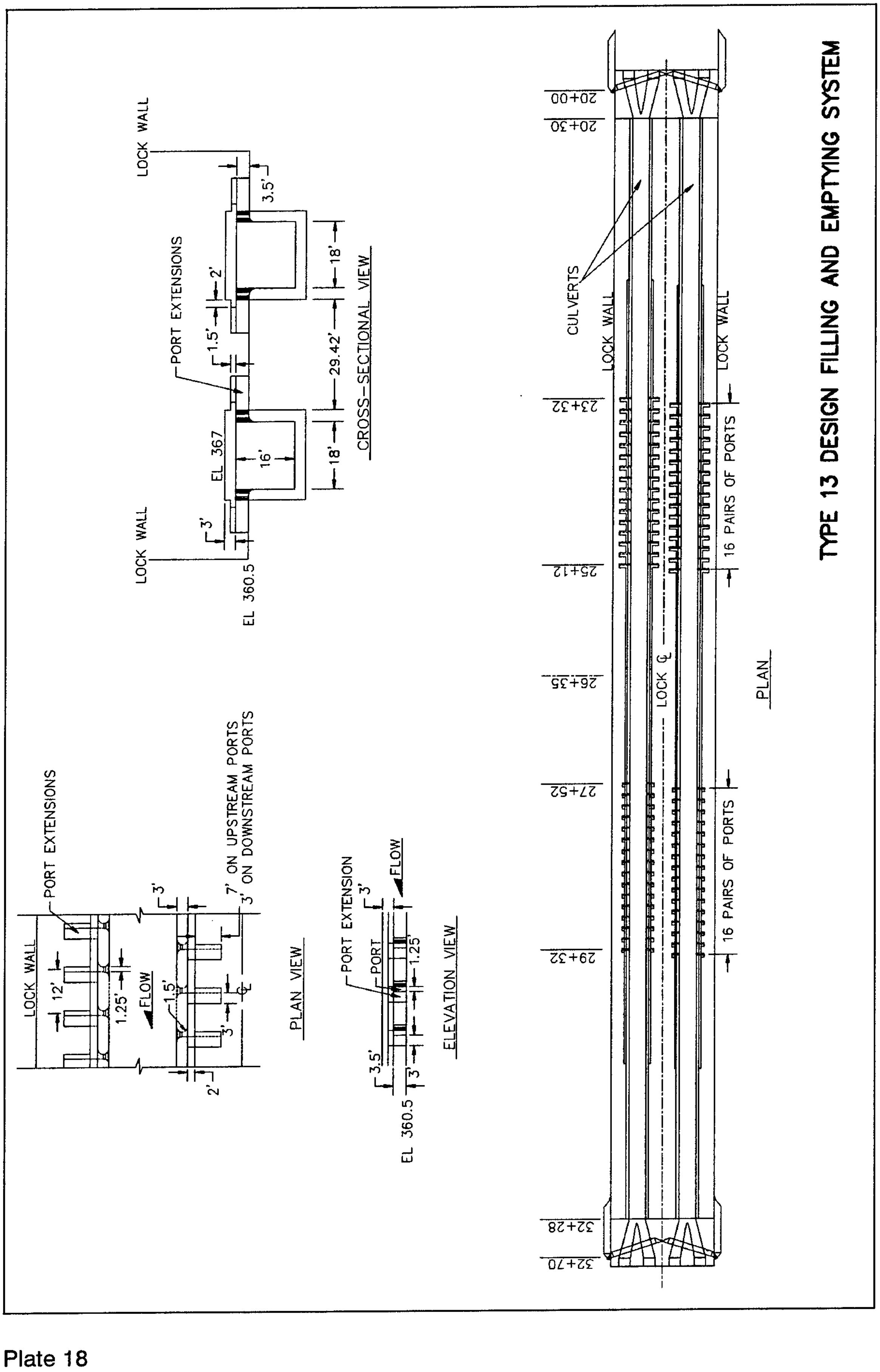

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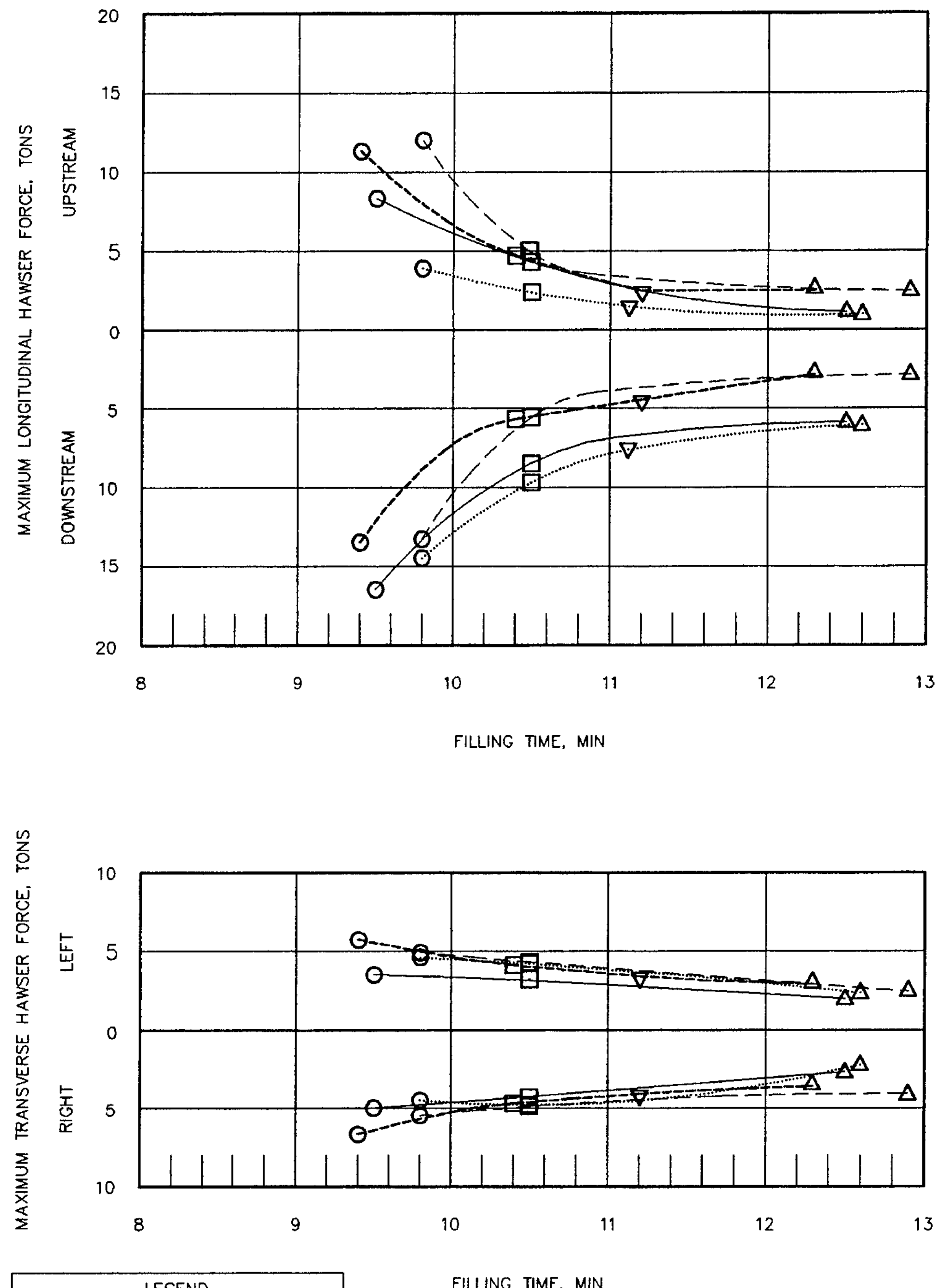

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⊡	4
▽	5
△	8
LINE TYPE	DESIGN TYPE
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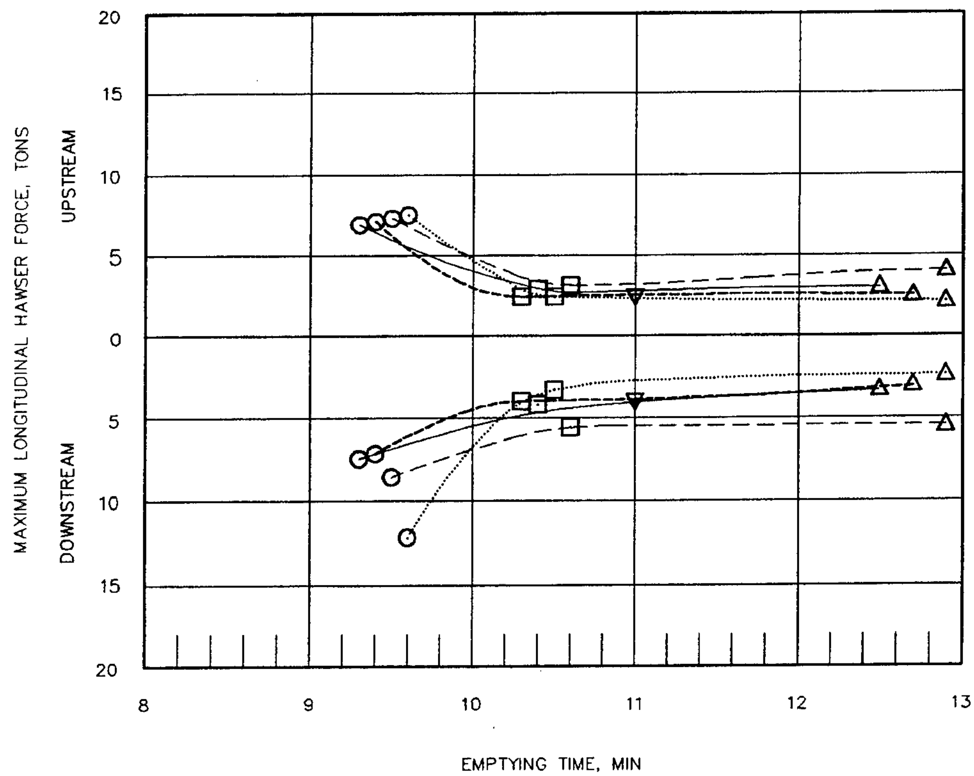
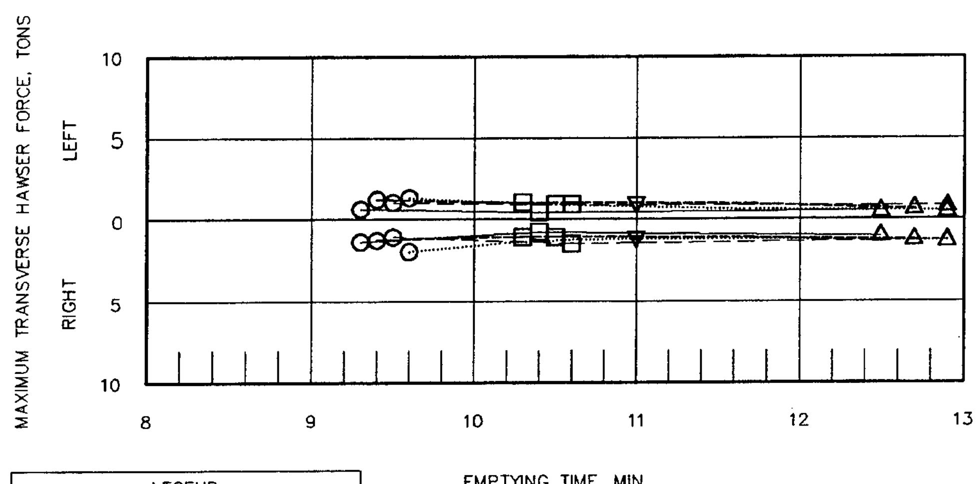
··········	13

HAWSER FORCES DURING FILLING

TYPE 9 AND TYPES 11–13 DESIGNS





LEGEND	
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LINE TYPE	DESIGN TYPE
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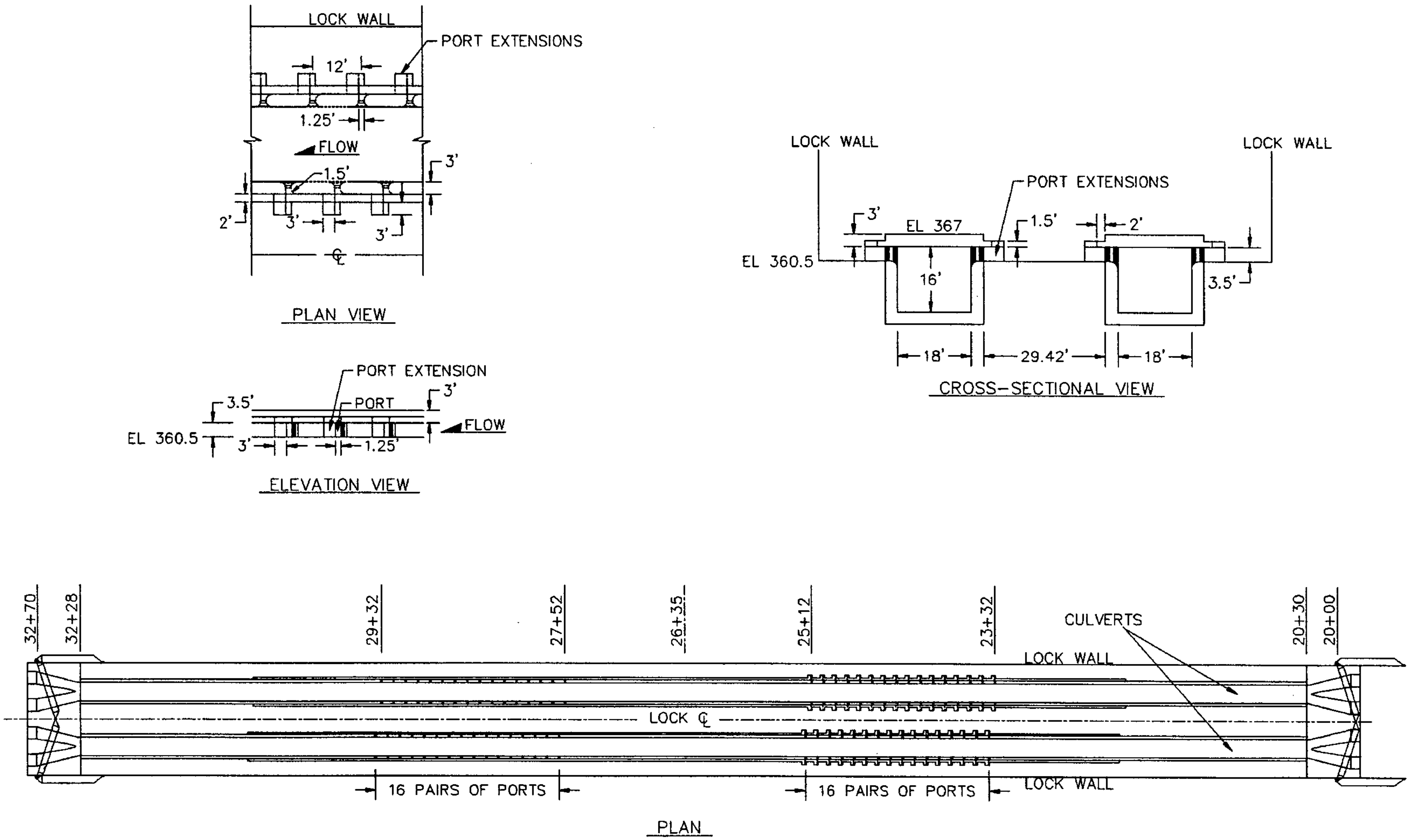
HAWSER FORCES
DURING EMPTYING
TYPE 9 AND
TYPES 11–13 DESIGNS



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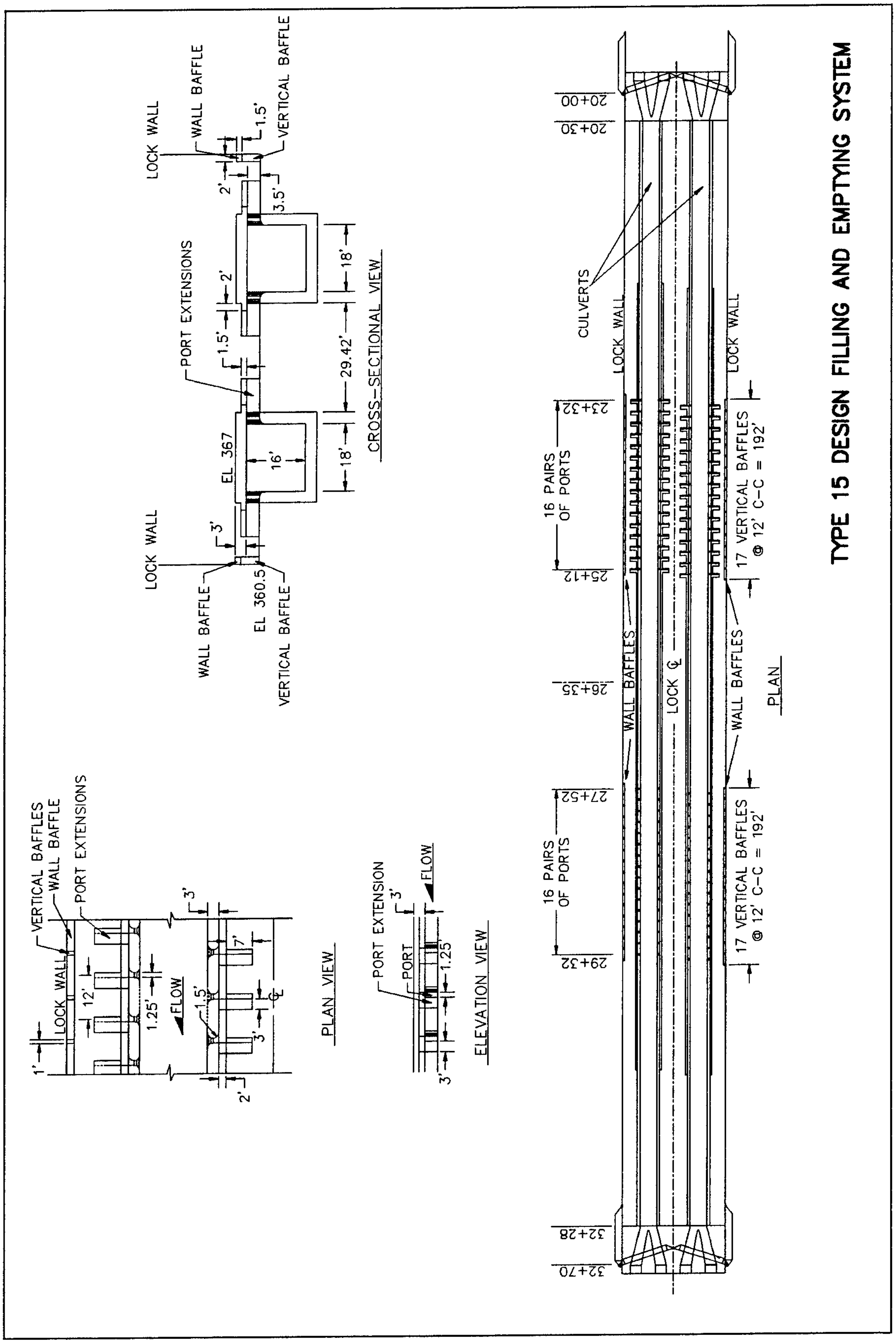

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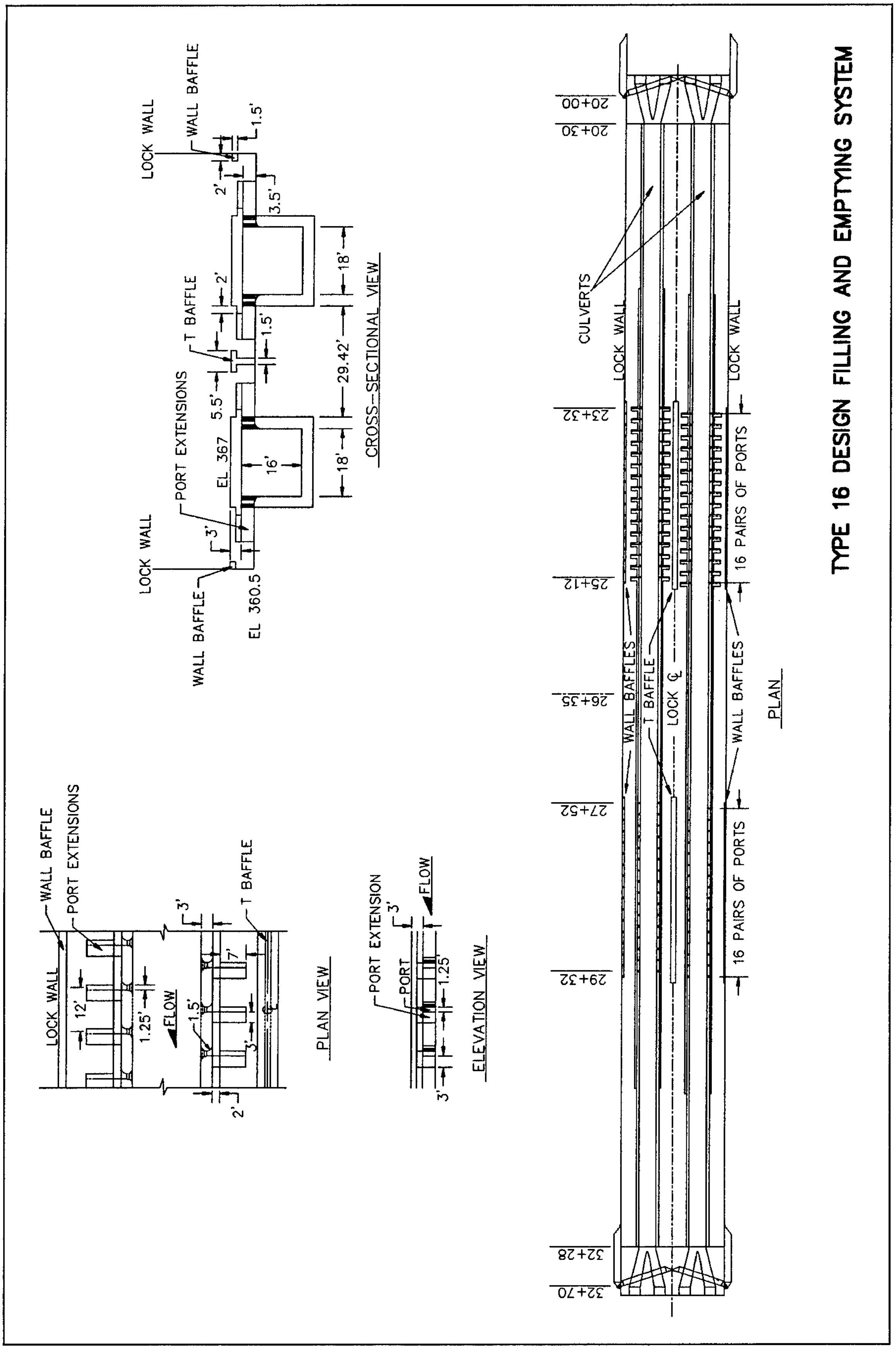
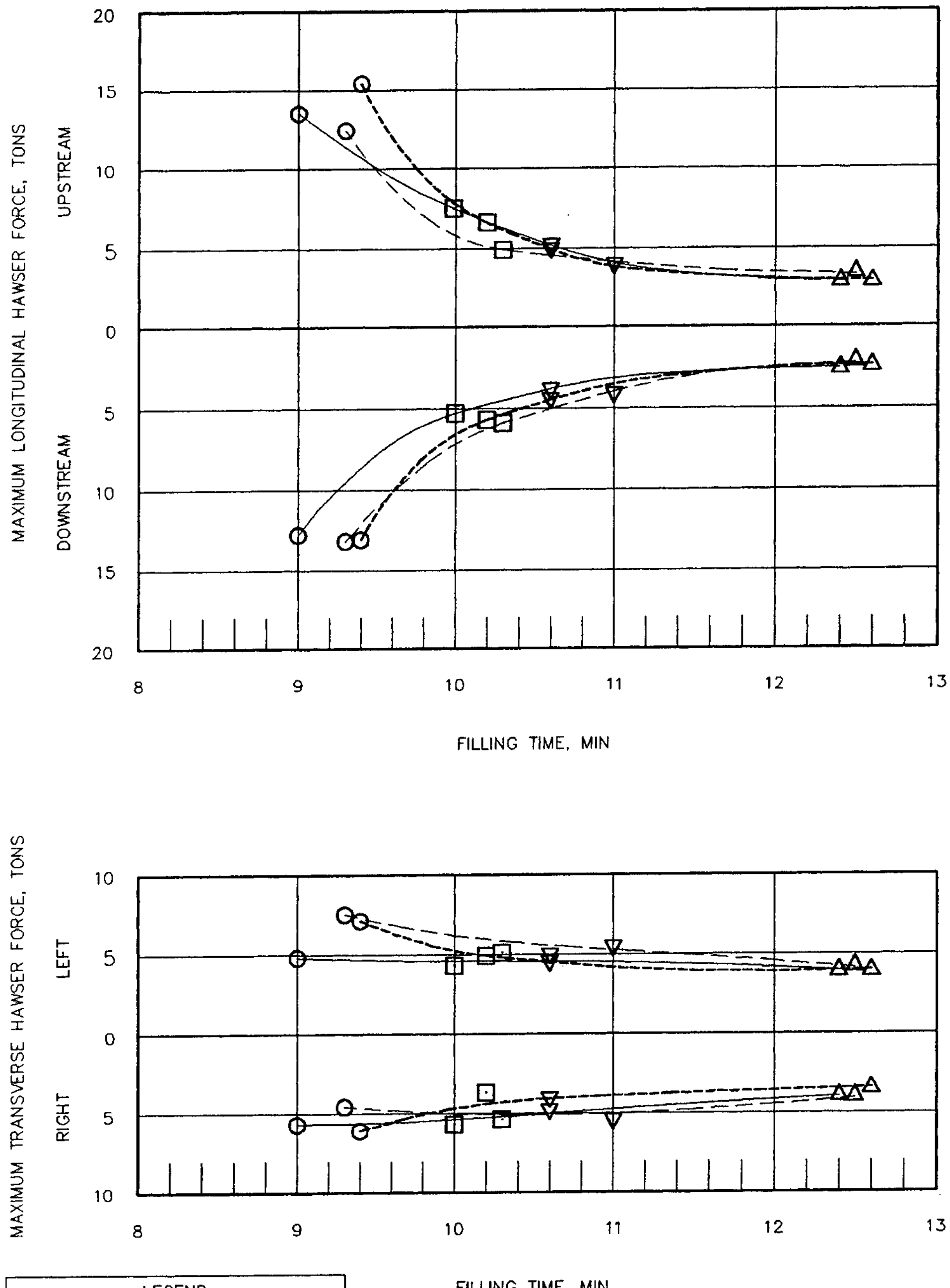

TYPE 16 DESIGN FILLING AND EMPTYING SYSTEM
LOCK WALL
WALL BAFFLE
PORT EXTENSIONS
T BAFFLE
FLOW
12'
1.25'
1.5'
3'
7'
2'
PLAN VIEW
PORT EXTENSION
PORT
1.25
ELEVATION VIEW
EL 367
EL 360.5
16'
18'
29.42'
5.5'
3.5'
CROSS-SECTIONAL VIEW
CULVERTS
WALL BAFFLES
LOCK ℄
16 PAIRS OF PORTS
20+00
20+30
23+32
25+12
26+35
27+52
29+32
32+28
32+70
PLAN



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□	4
▽	5
△	8
LINE TYPE	DESIGN TYPE
———	14
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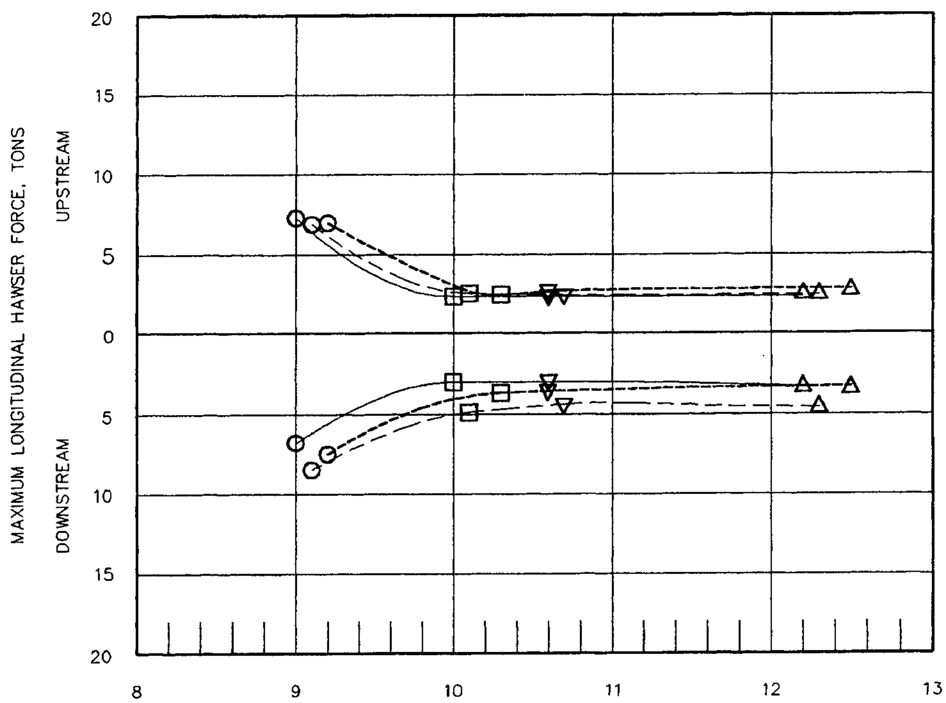
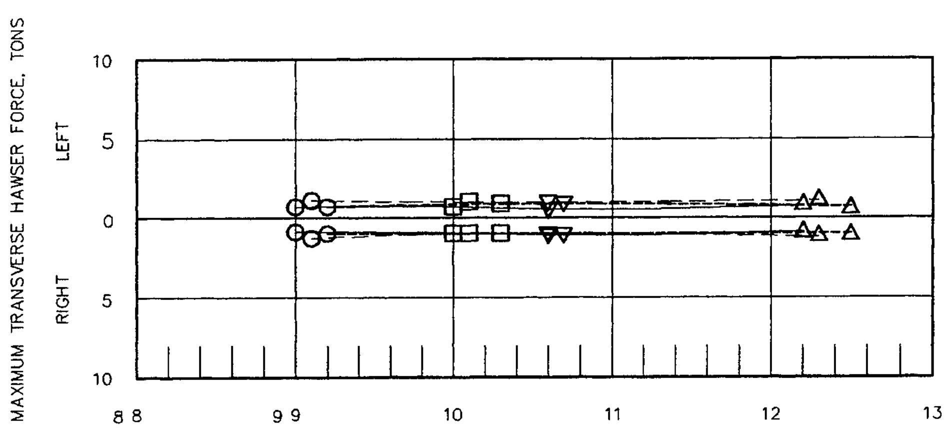
— — —	16

HAWSER FORCES
DURING FILLING
TYPES 14 – 16 DESIGN





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LINE TYPE	DESIGN TYPE
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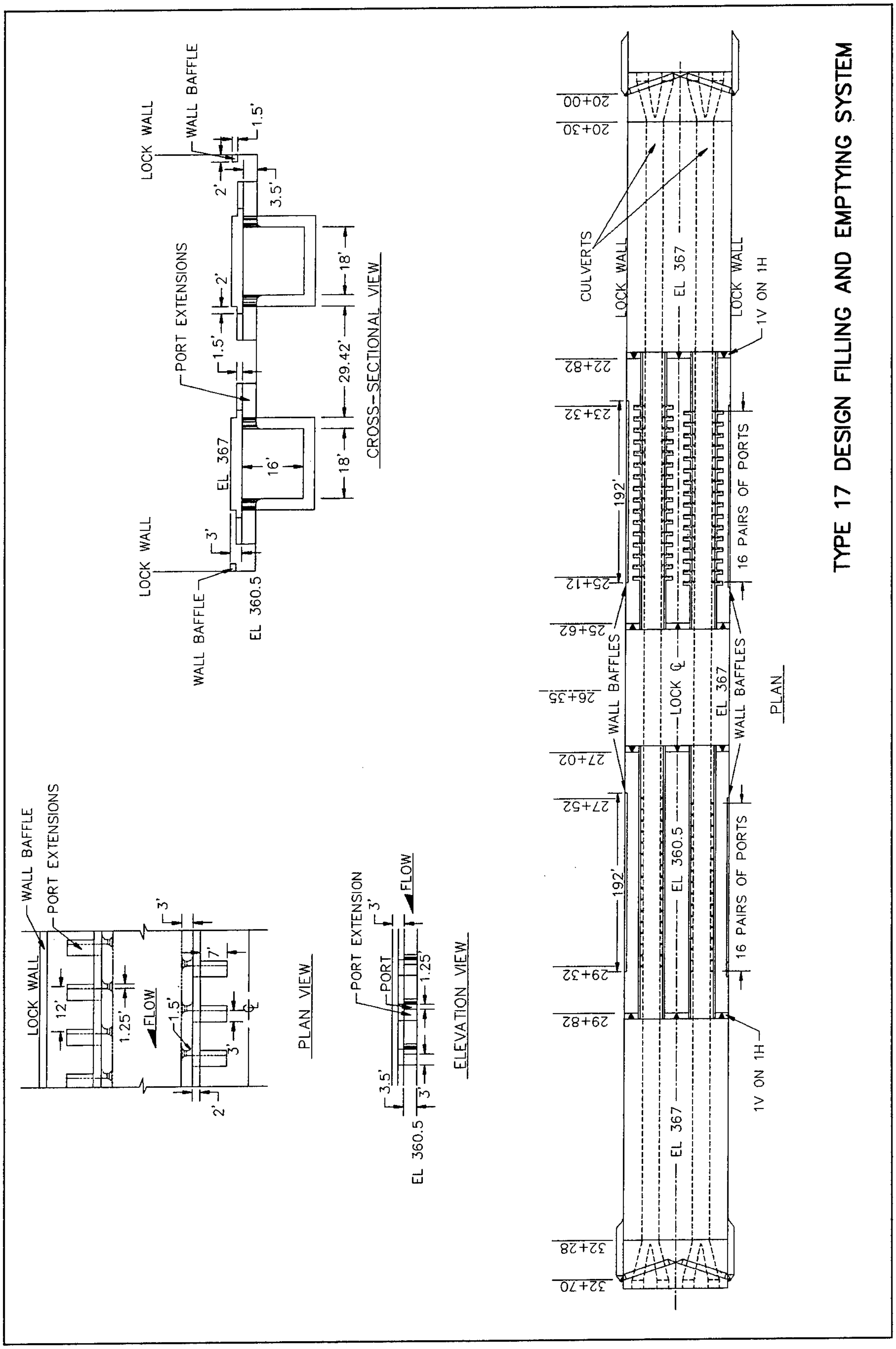
HAWSER FORCES
DURING EMPTYING
TYPES 14 – 16 DESIGN



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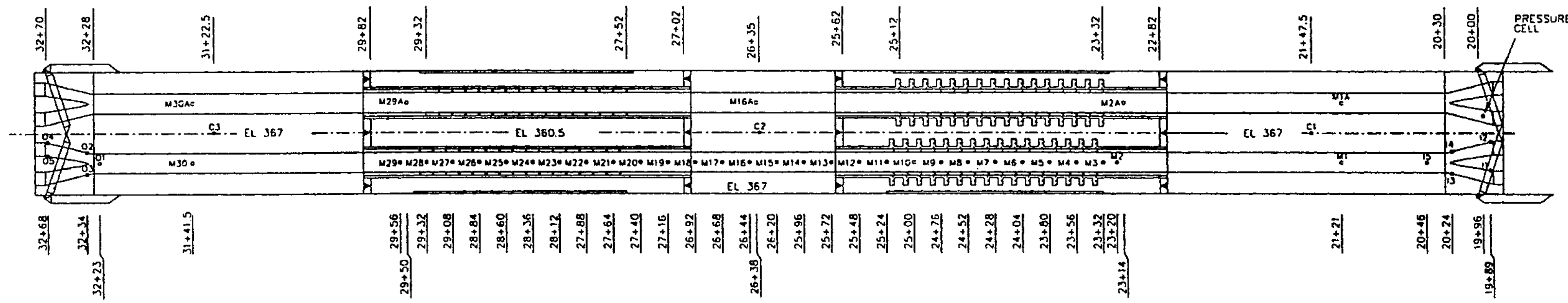
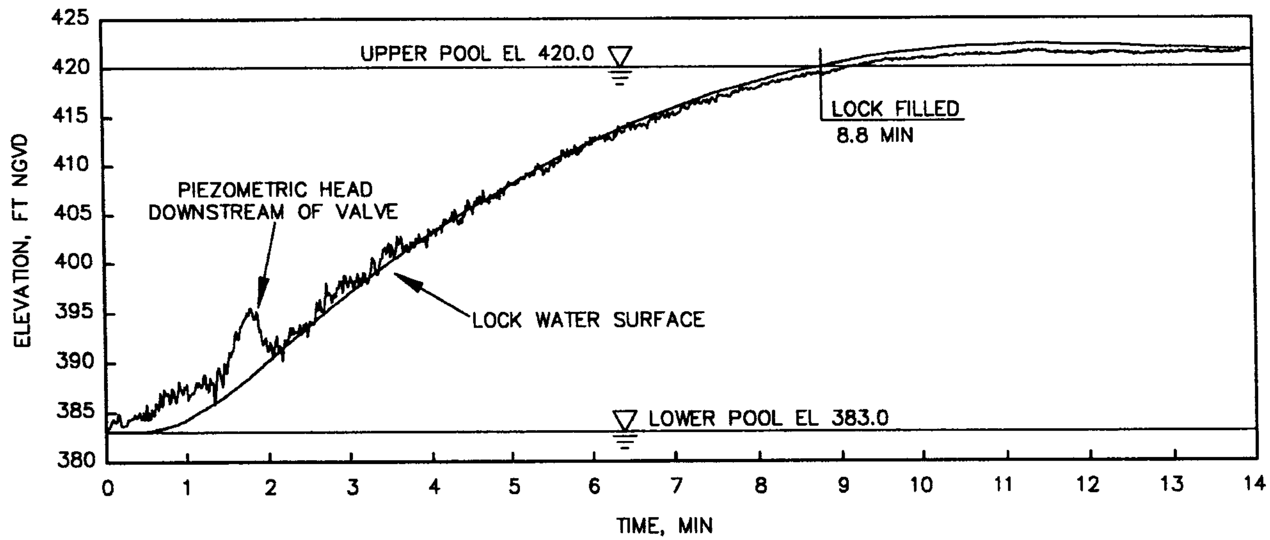
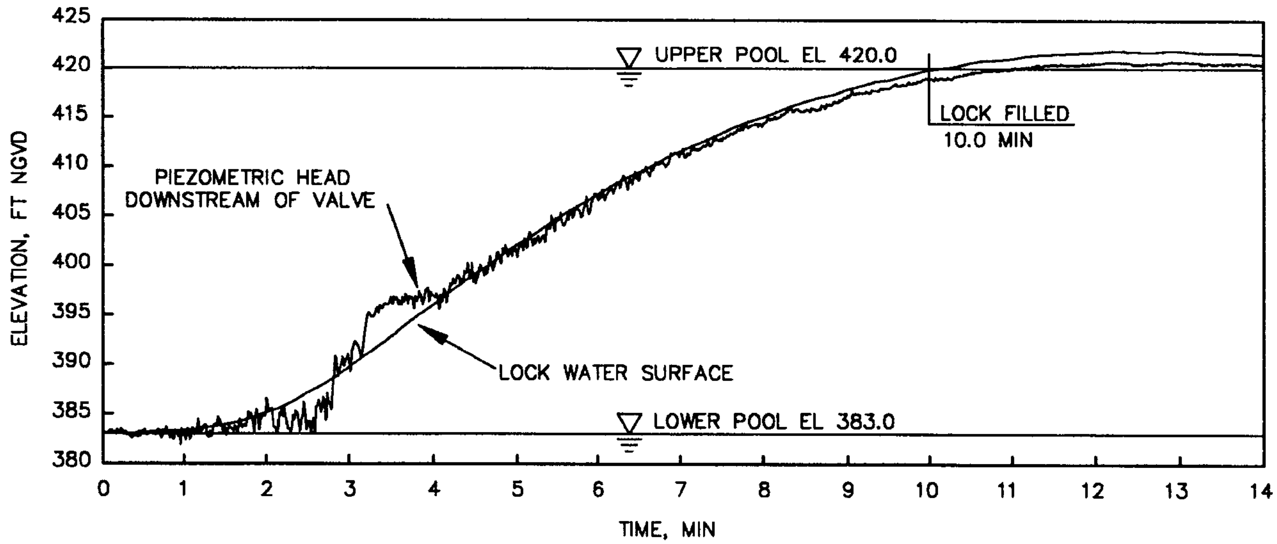


PLAN

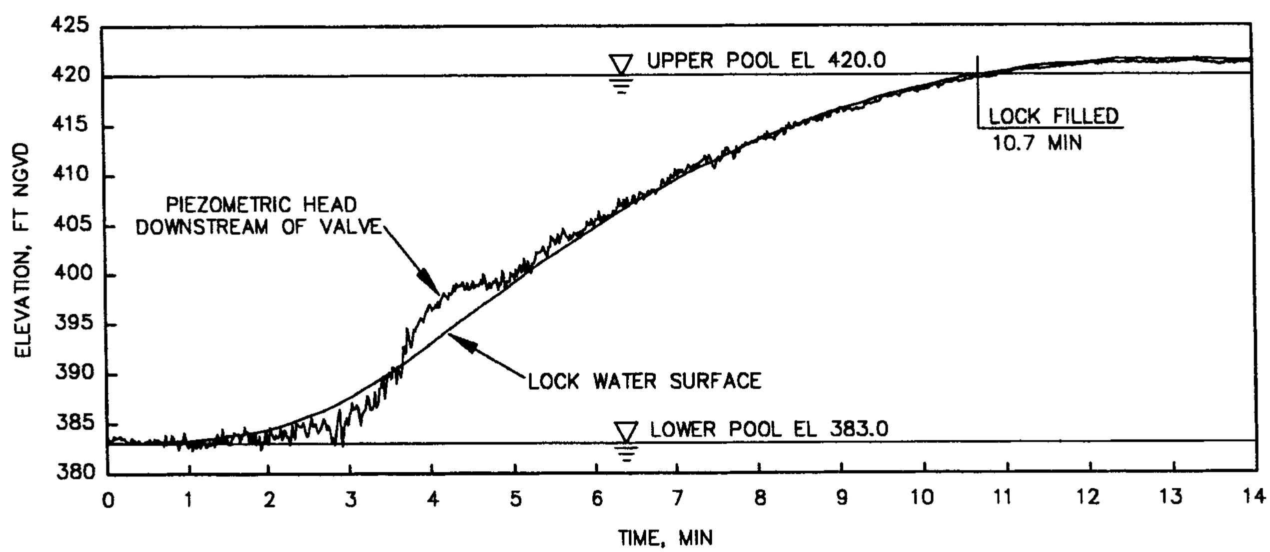
PIEZOMETER LOCATIONS
TYPE 17 DESIGN FILLING AND EMPTYING SYSTEM



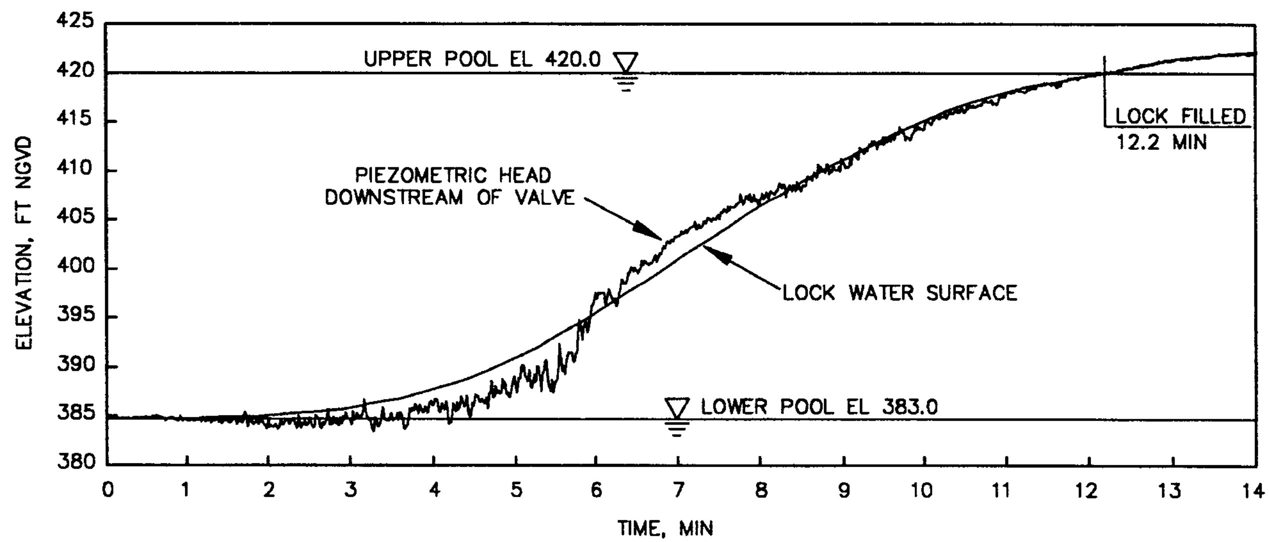
CULVERT PRESSURES DURING FILLING
TYPE 17 DESIGN
2–MIN NORMAL FILL



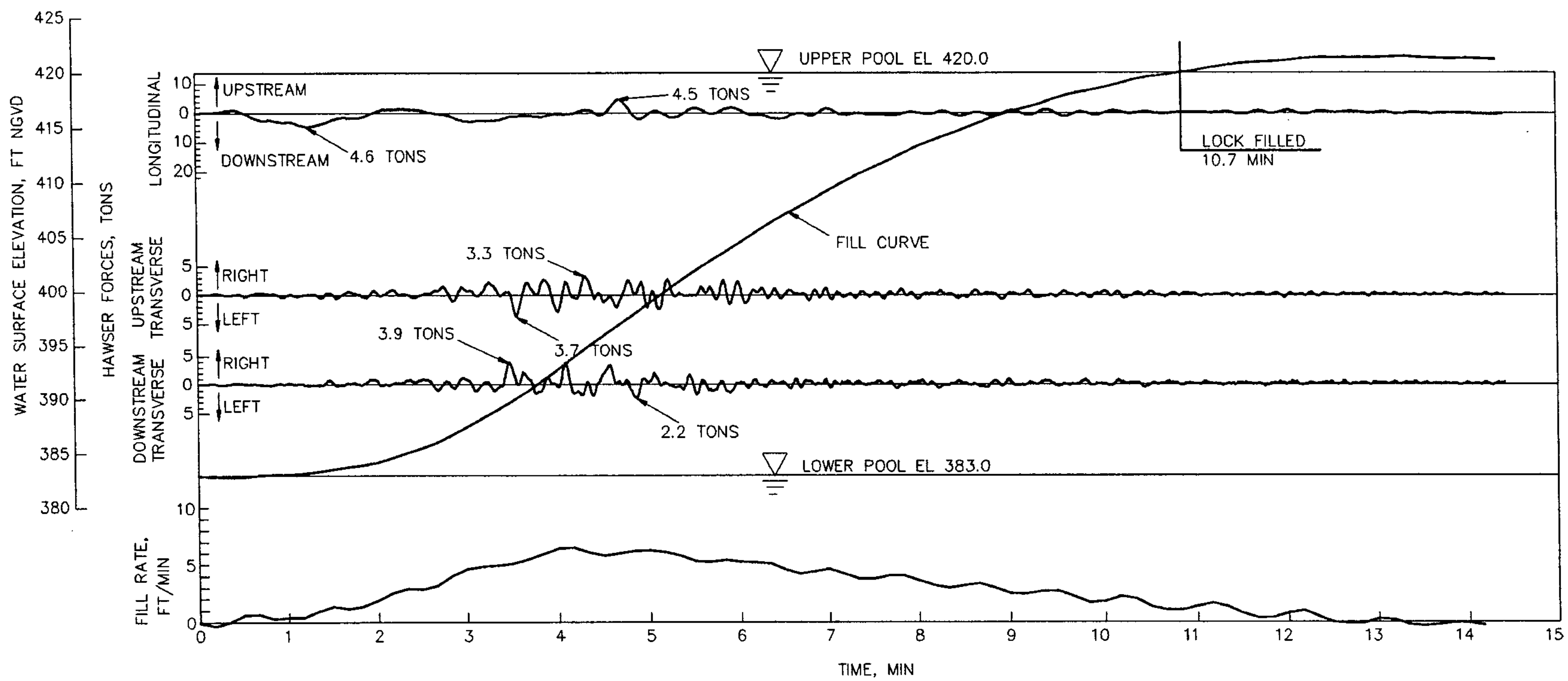
CULVERT PRESSURES DURING FILLING
TYPE 17 DESIGN
4–MIN NORMAL VALVE



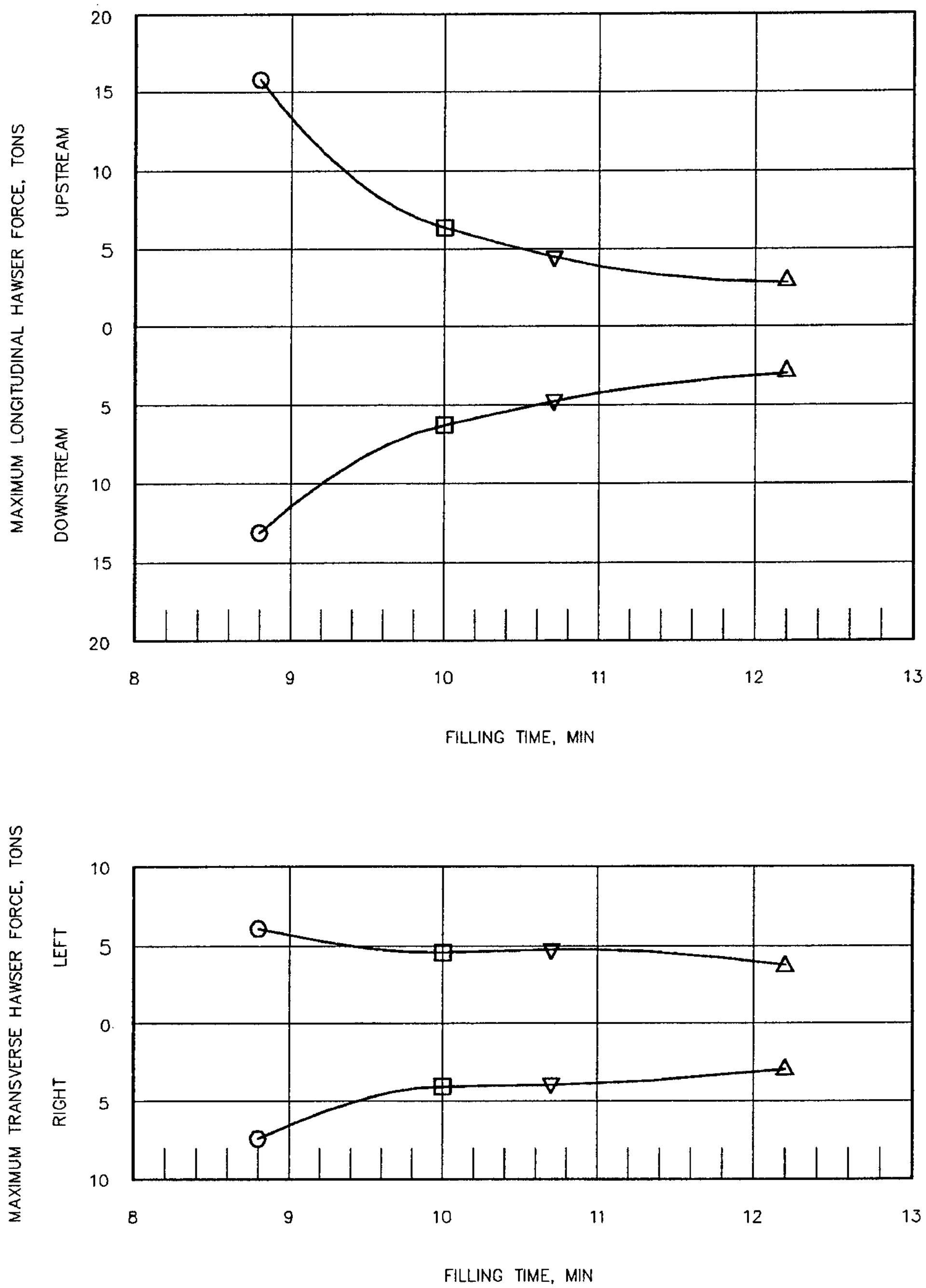
CULVERT PRESSURES DURING FILLING
TYPE 17 DESIGN
5–MIN NORMAL VALVE



CULVERT PRESSURES DURING FILLING
TYPE 17 DESIGN
8–MIN NORMAL VALVE



FILLING CHARACTERISTICS
TYPE 17 DESIGN
5-MIN NORMAL VALVE



LEGEND	
SYMBOL	VALVE SCHEDULE, MIN
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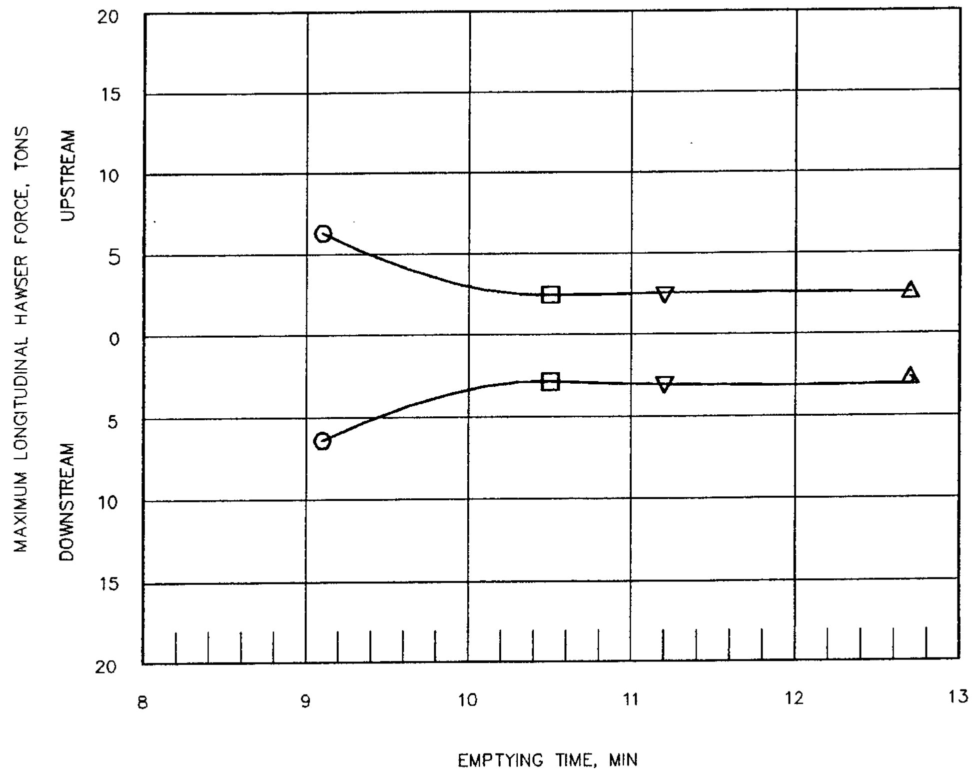
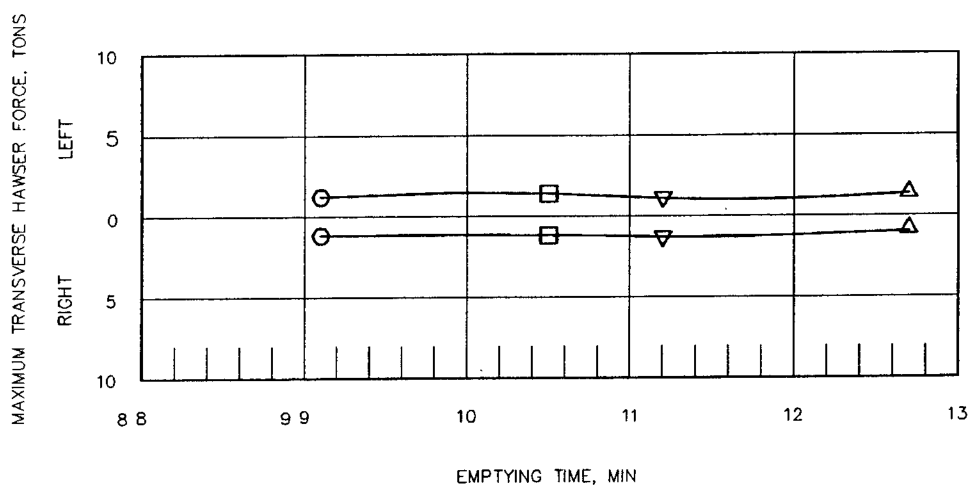
□	4
▽	5
△	8

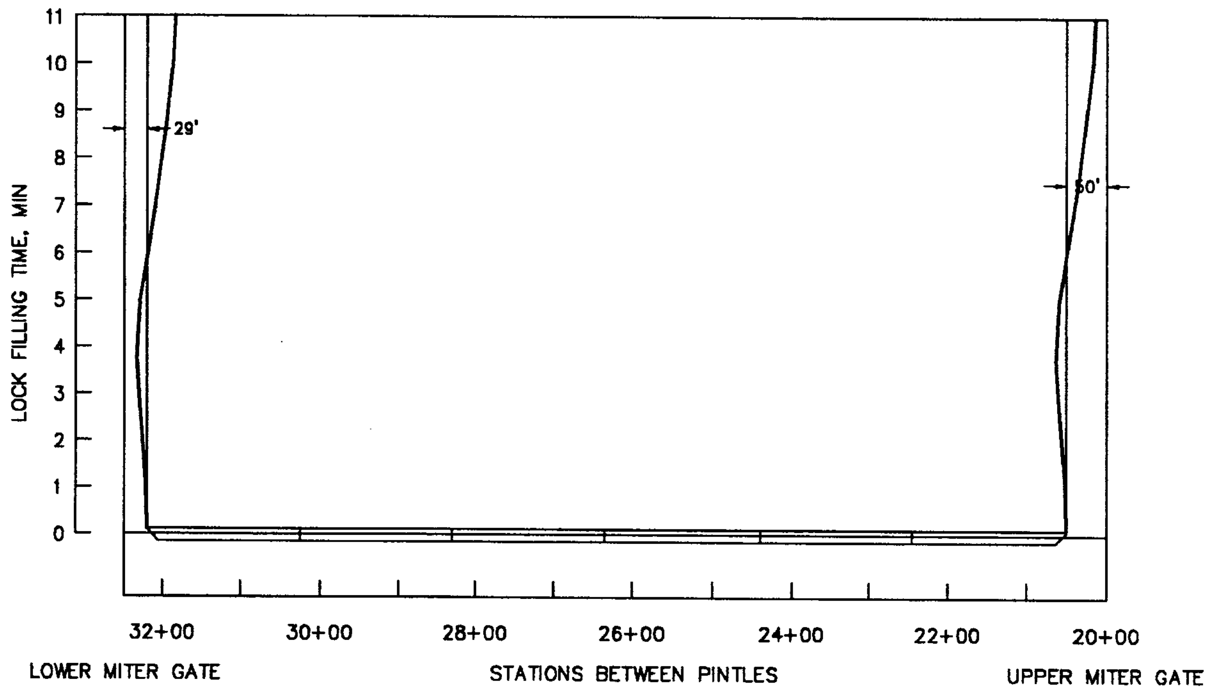
HAWSER FORCES
DURING FILLING
TYPE 17 DESIGN





LEGEND	
SYMBOL	VALVE SCHEDULE, MIN
O	2
⊡	4
∇	5
Δ	8

HAWSER FORCES
DURING EMPTYING
TYPE 17 DESIGN



18–BARGE TOW

TYPICAL FREE TOW MOVEMENT
DURING FILLING OPERATIONS
TYPE 17 DESIGN
4–MIN VALVE OPERATION
U.P. EL 420.0, L.P. EL 383.0

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13. ABSTRACT ***(Maximum 200 words)***

Navigation improvements planned for the Mcalpine Lock and Dam project on the Ohio River provided the prototype for the laboratory model used in this study. The model was used to evaluate the in-chamber longitudinal culvert filling-and-emptying system (ILCS). In the ILCS, lock filling and emptying culverts are placed inside the lock chamber rather than in the lock walls, resulting in significant savings in lock wall construction. The ILCS also features a through-the-sill intake and discharge outlet with a longitudinal in-chamber filling-and-emptying system. Various discharge systems for the ILCS were evaluated. Construction of the filling and emptying culverts on the lock floor between the lock walls was found to be a viable design.

14. SUBJECT TERMS
In-chamber longitudinal culvert filling-and-emptying system (ILCS)
Lock design
Lock filling and emptying culverts
McAlpine Locks and Dam project
Ohio River

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