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Hydraulic Design of Lock Culvert Valves

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
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Manual
No. 1110-2-1610

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Engineering And Design
HYDRAULIC DESIGN OF LOCK CULVERT VALVES

Purpose. The purpose of this manual is to present hydraulic design data on control valves for navigation lock filling and emptying systems.

Applicability. This manual applies to all field operating agencies concerned with Civil Works design, construction, and operational maintenance.

Distribution Statement. Approved for public release; distribution is unlimited.

General. This manual is a guide in the design of control valves for navigation lock filling and emptying systems.

FOR THE COMMANDER:

KIRK E.GIBBS
COL, EN
Chief of Staff

*This memorandum supersedes EM 1110-2-1610, dated 10 July 1989.

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TABLE OF CONTENTS

CHAPTER 1

Introduction

1-1. Purpose. The purpose of this manual is to present data accrued from experience and research that may be useful to U.S. Army Corps of Engineers (USACE) hydraulic designers concerned with the design of control valves for navigation lock filling and emptying systems. Primarily, the objective is to consider the hydrodynamic forces that enter into the design of valves. However, the interrelationship of structural features, operational procedures, and hydraulic performance will be discussed when pertinent to an understanding of the problems involved. Consideration will be given only to valves used to control flow in relatively long culverts. Valves in tubes with a length less than about 5 diameters, such as might be installed in or around the lock service gates, present a somewhat different type of design problem than those installed in longer culverts, and since they are rarely used in any but very low-lift modern locks, they will be omitted from the discussion. Service gates which in themselves either constitute the primary filling system or are used as auxiliary devices, such as sector gates, bascule gates, etc., also will not be treated in this manual.

1-2. Applicability. The provisions of this manual are applicable to USACE Divisions and Districts concerned with civil works design, construction, and operational maintenance.

1-3. Distribution Statement. Approved for public release; distribution is unlimited.

1-4. References. References pertaining to this manual are listed in Appendix A. Additional reference materials pertaining to the subject matter addressed in this manual are also included in Appendix A.

1-5. Typical Filling and Emptying System. The most common type of filling and emptying system used in modern locks is the sidewall port system, which has a longitudinal culvert in each lock wall extending from the upper pool to the lower pool, with a streamlined intake at the upstream end and a diffusion device at the downstream end (Figure 1-1). Flow is distributed from the longitudinal culverts in and out of the lock chamber by short ports or secondary culverts in the floor of the lock chamber. Two valves are required in each longitudinal culvert, one between the intake and the lock chamber manifold to release flow in the filling operation, and the other between the chamber manifold and the discharge diffuser to empty the lock chamber.

1-6. Types of Lock Valves.

a. In 1930 the American Society of Civil Engineers published a manual on lock culvert valves which described valves at 12 projects (American Society of Civil Engineers 1930). At these 12 projects, seven types of valves were used, namely stoney gate, cylindrical, wagon body, butterfly, spool, slide gate, and tainter. Early lock systems, which were all low-lift projects (heads of 30 ft or less), almost exclusively used vertical-lift (e.g. stoney valve and wagon valve) and tainter (radial gate) valve designs. However, since about 1930, tainter valves (an adaptation of the tainter gate developed by Jeremiah B. Tainter and patented by him in 1885 for control of flows over spillway crests) have been used almost exclusively in hydraulic systems of major locks in North America. Among the first locks in which tainter valves were used are Lock No. 2 on the Mississippi River, completed in 1930, and the Welland Ship Canal Locks in Canada, completed in 1933. The valves in these and several other installations were oriented in the manner of the conventional tainter gate, that is, with the trunnions downstream of the skin plate causing the convex surface of the skin plate to face the flow and seal along the upstream end of the valve well. When the Pickwick Lock on the Tennessee River was being designed for a lift of 65 ft, model tests showed that during the opening period the piezometric grade line immediately downstream of the valve skin plate dropped below the top of the culvert; this caused large volumes of air to be drawn down the valve well and into the culvert. The air formed large pockets in the model culvert which restricted the flow until sufficient pressure was developed to expel the air through the ports or into the downstream bulkhead recess. Air expelled through the ports erupted at the water surface in the lock chamber with considerable violence, causing disturbances that would be hazardous to small craft.

b. This manual provides information on three valve designs commonly used to control culvert flow: vertical-lift valves, conventional tainter valves, and reverse tainter valves. Brief descriptions of advantages and disadvantages of the vertical-lift and conventional tainter valves are provided. However, this manual focuses on the hydraulic design of reverse tainter valves since this is the type valve that has been incorporated in almost all modern lock designs.

(1) Vertical-lift valve.

(a) A vertical-lift valve installation is illustrated on Figure 1-2. Vertical-lift valves can be grouped by the way in which they are guided during operation. Valves designed to slide within their slots are commonly referred to as stoney valves. Wheeled vertical-lift valves are often called wagon valves.

(b) Even with all the previous hydraulic model studies and numerical model developments, the determination of downpull forces on vertical-lift valves (Figure 1-3) is still a topic of research. Hydraulic model studies remain the most reliable means of obtaining hoist loads and vibration tendencies on high-head valves. The shape of the lip (lip angle, corner rounding, and the end plate) is critical to vertical-lift valve performance (Naudascher and Rockwell 1994) and it plays an important role in the resulting hoist loads (Aydin et al. 2006). Lip geometries producing unstable flow cause pressure fluctuations on the gate bottom and vortex shedding causes intermittent pressure spikes. These unstable pressures on the gate bottom produce hoist load reversals, which might not be noticeable in the hoisting mechanism, but may induce fatigue. This is why a large portion of the literature associated with vertical-lift valves is concerned with gate vibrations (e.g. Bhargava and Narashimhan 1989 and Thang and Naudascher 1986). High-velocity flow is more likely to induce vibrations, especially since vertical-lift valves are susceptible to pressure fluctuations. Therefore, extreme care must be given to the design of high-lift locks, particularly concerning small valve openings.

(c) Another consideration is that vertical-lift valves require gate slots. The discontinuity in culvert sidewalls produced by gate slots can cause cavitation, especially in high-lift locks. Engineering Manual 1110-2-1602 (Headquarters, U.S. Army Corps of Engineers 1980) provides vertical-lift gate slot design details. EM 1110-2-1602 also gives incipient cavitation coefficients needed to determine the likelihood of cavitation formation.

(d) Locks designed after 1960 have rarely included vertical-lift valves, so there is little experience with the relative high frequency of operations. Construction of a new lock having a chamber of 110 ft by 800 ft was recently completed at Marmet Locks and Dam, Kanawha River. The new Marmet Lock, which has a design lift of 24.0 ft, has vertical-lift valves to control the filling and emptying flow. The valves at this project will be monitored to assess their performance over time. New locks having 1200-ft chambers are in the planning and design stage for Lock and Dam No. 22 and Lock and Dam No. 25 on the Upper Mississippi River (Hite and Maynord 2006). Vertical-lift valves are being considered to accommodate the limited space provided by the existing lock and dam.

(2). Conventional tainter valve.

(a) Early lock designs for United States waterways used conventional tainter valves to control the filling and emptying system's culvert flow. Conventional orientation is similar to spillway tainter gates (radial gates) in that the arms are in compression. A sketch of a tainter valve placed in a culvert in the conventional position is shown in Figure 1-4. The hydraulic performance of tainter valves used to control conduit flow is described in EM 1110-2-1602 (Headquarters, U.S. Army Corps of Engineers 1980). The initial condition for a conventional tainter valve used for filling is tailwater in the well, whereas the upper pool is initially in the well of a reverse tainter filling valve. The water-surface elevation in the valve well corresponds to the pressure on the downstream side of the valve. If the pressure head downstream of the valve reaches elevations lower than the culvert roof, large volumes of air can be drawn into the culvert. During filling operations, these air pockets can produce violent bursts as they are discharged into the lock chamber. These rough conditions can be hazardous to personnel working the tow and those on the deck near the chamber. Air can also become trapped in the culvert and move back upstream as the lock fills. Once this moving pocket of air reaches the bulkhead slot or valve well, it is released and can exit upward quite violently. In some reported cases air blew off the bulkhead grates.

(b) The conventional tainter valve configuration may reduce differential pressures on the valve well walls, which was the case at the Lower Monumental Lock emptying valve location. The Lower Monumental Lock model study (Perkins and Theus 1975) investigated the hydraulic conditions when a conventional valve was used for emptying. The emptying conduit at the valve well was downstream of the chamber, and a thin wall between the valve well and the chamber was subjected to pressure differences due to the emptying valve well water-surface elevation and tailwater differential. Changing to a conventional tainter valve configuration maintained a valve well water-surface elevation near that of the tailwater rather than the high water surface maintained with a reverse tainter valve. Air entrainment through the valve well, which would produce slug flow, was not a problem because the lock outlet was immediately downstream of the valve. This valve configuration was not adopted at the Lower Monumental Lock, but this study shows conditions in which conventional positioning may be advantageous.

(3). Reverse tainter valve.

(a) A tainter valve mounted in the reversed position is shown in Figures 1-5 and 1-6. By reversing the tainter valves, that is, placing the trunnions upstream of the skin plate with the convex surface of the skin plate facing downstream and sealing against the downstream end of the valve well, air was prevented from entering the culvert at the valve recess.

(b) Over the years, several studies have been directed toward developing lock culvert valve hydraulic design guidance. Remediation studies were conducted for Lock 19, Mississippi River, in 1957-1958 (U.S. Army Engineer Waterways Experiment Station 1961a) after prototype operation found that the valves experienced load pulsations. Later (1960-1962), a physical model study was conducted for the development of the Holt Lock culvert valve (Murphy and Ables 1965). The Holt Lock, Warrior River, study evaluated several reverse tainter valves including a series of tests on a double-skin plate configuration in support of Columbia/Snake River project developments. The design for this double-skin plate valve was copied from the McNary Lock, Columbia River. George (1984) conducted a physical model study of a reverse tainter valve for the proposed Walter Bouldin Lock, Coosa River Waterway. The Walter Bouldin Lock was designed to be the highest lift lock in North America at 130 ft. Although Walter Bouldin Lock was never constructed, the model study provides hoist load data for very high heads.

(c) Reverse tainter valves have been used on practically all major locks constructed by the USACE since 1940 (Davis 1989). Therefore, this type of valve will be used in examples in this manual. The reverse tainter valve certainly has proved very satisfactory, it probably will be desirable at most new projects, and its continued use is advocated. However, the designer should consider other types of valves. For instance, if submergence is such that air definitely will not be drawn down the valve well and into the culvert, the use of a tainter valve in the normal position may prove desirable. With the valve in the normal position, loads and load variations on the valve hoist caused by flowing water will be negligible (Murphy 1942). One structural advantage is that the trunnion anchorage is simpler than that of a reverse tainter valve. Further, depending upon whether the position of the valve in the lock wall is upstream or downstream from the lock gate, use of the normal position for the tainter valve may prevent large differentials between the water in the valve well and the lock chamber or lower pool. Also, vertical-lift gates which are used extensively in outlet conduits should be suitable as lock culvert valves. The vertical-lift valve would not require the large recess that is necessary with a tainter valve. With one spare gate at an installation, maintenance could be performed without taking the culvert out of service as is necessary with the tainter valve. However, the vertical-lift valve's rollers, wheels, or sliding surfaces might require considerably more servicing than do the elements of the tainter valve. If a vertical-lift valve is considered, certain procedures given in this manual could be used in design; but it is suggested that model tests be conducted to develop an optimum bottom shape for the gate and to determine valve hoist loads.

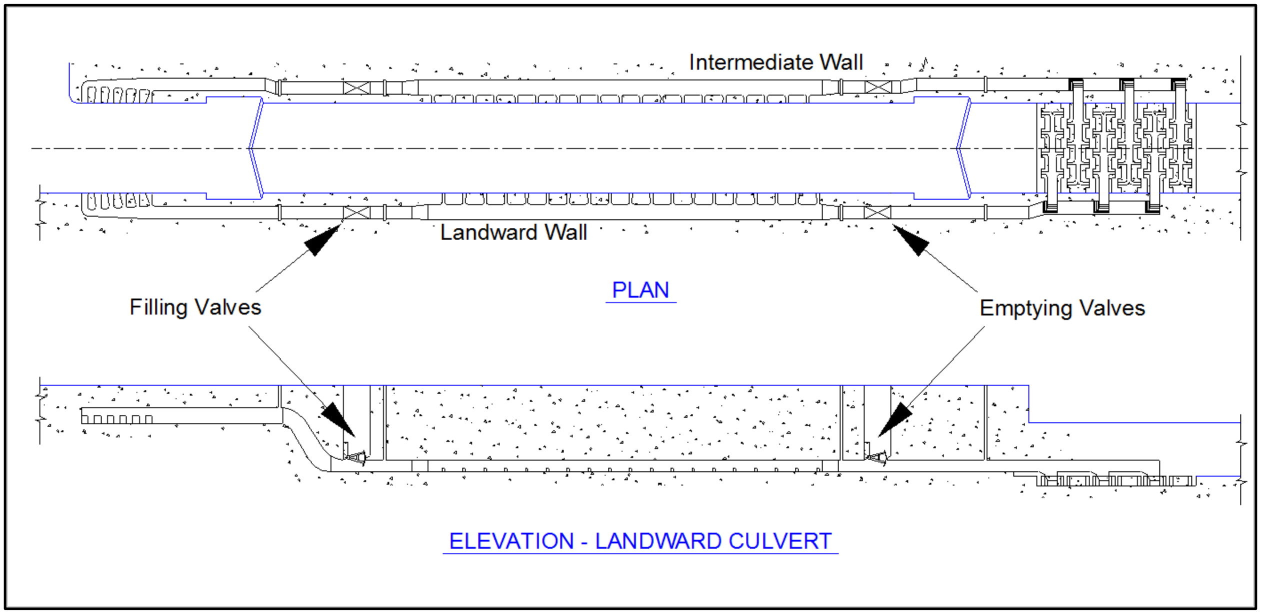


Figure 1-1. Sidewall port filling and emptying system with reverse tainter valves.

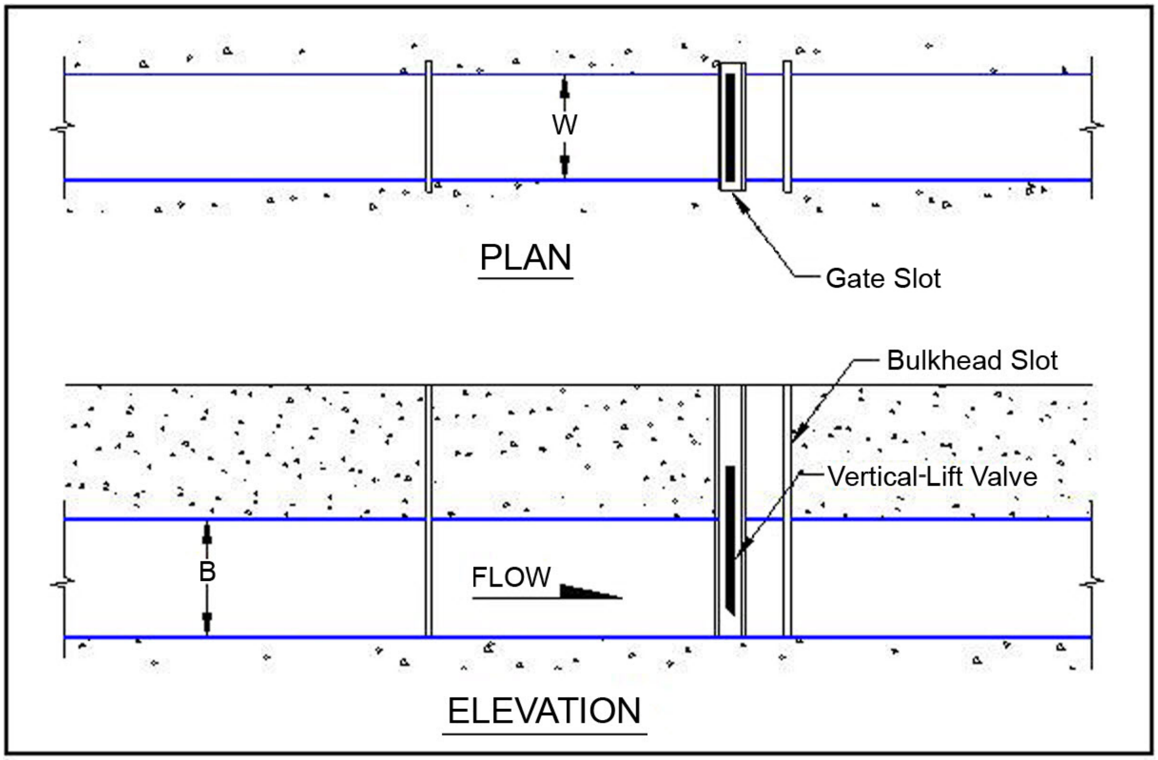


Figure 1-2. Vertical-lift valve installation.

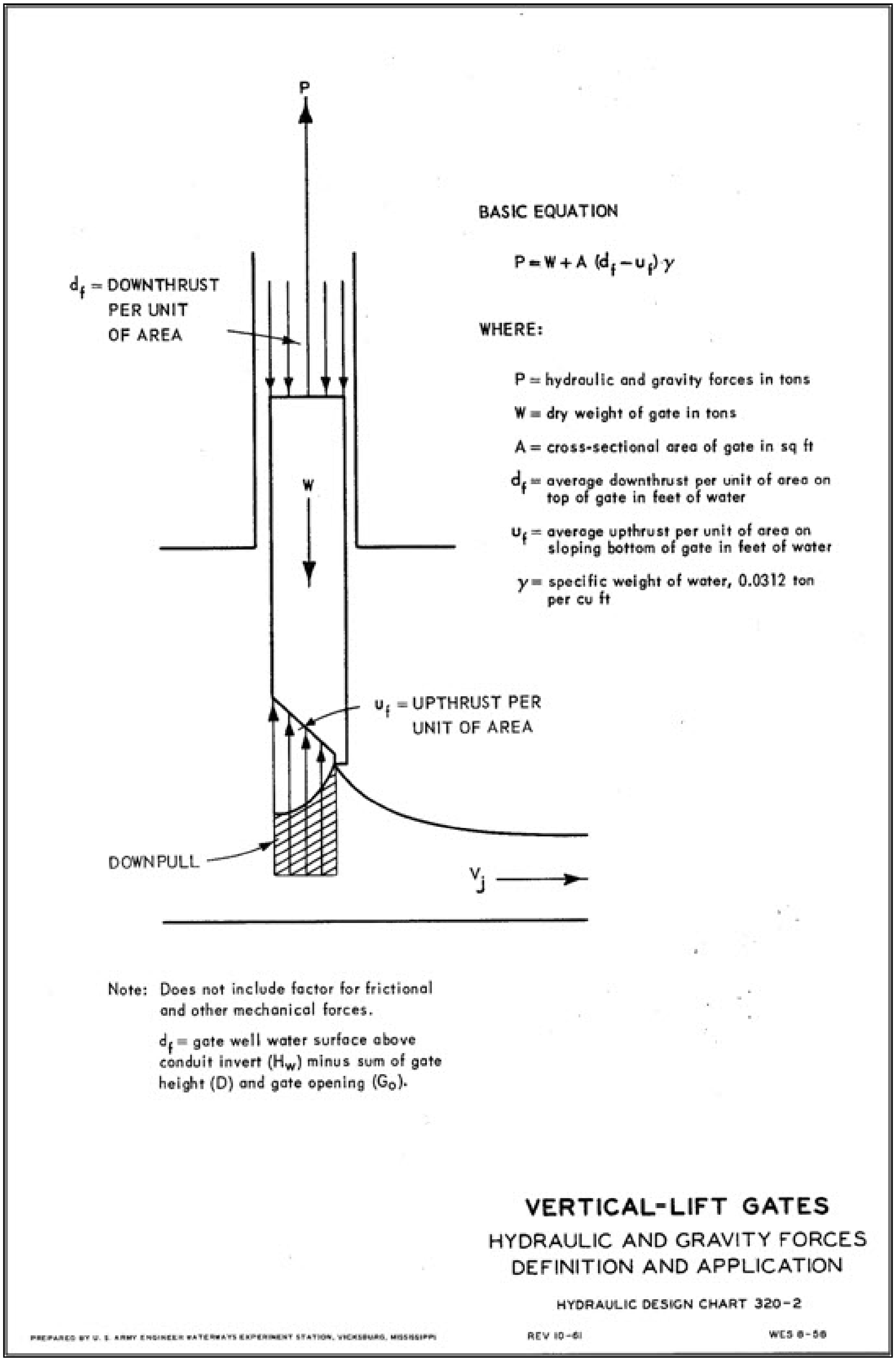


Figure 1-3. Hydraulic and gravity forces on vertical-lift valves.

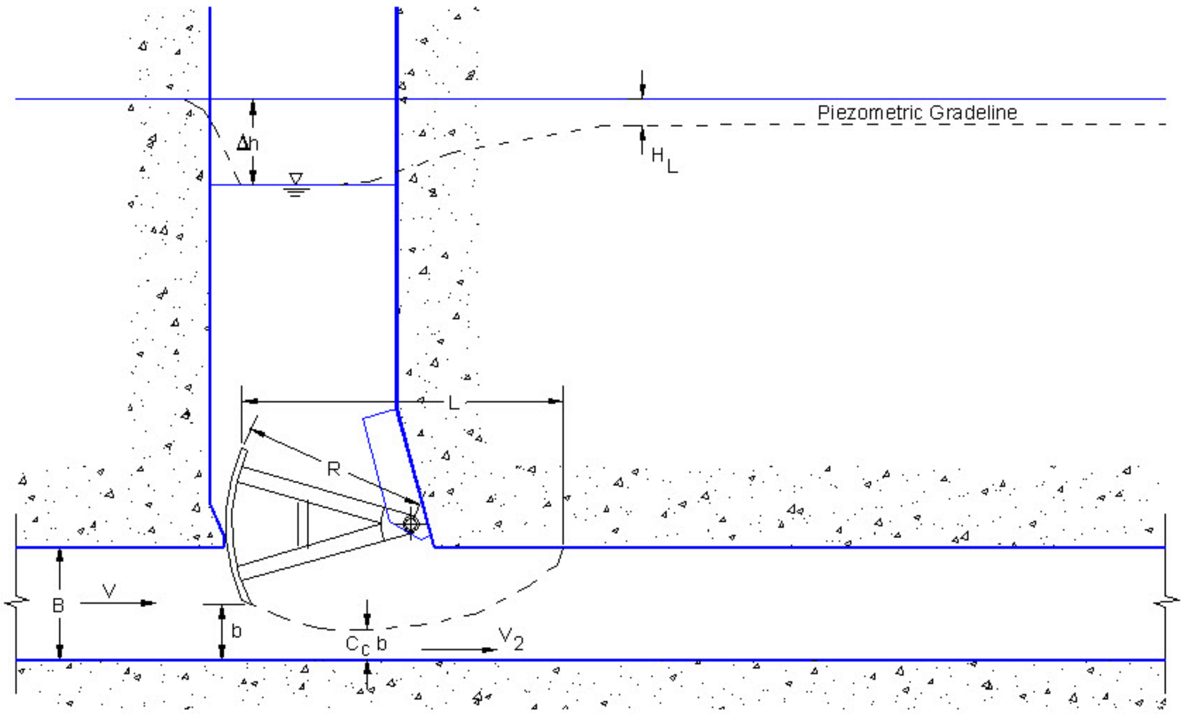


Figure 1-4. Conventional tainter valve installation.

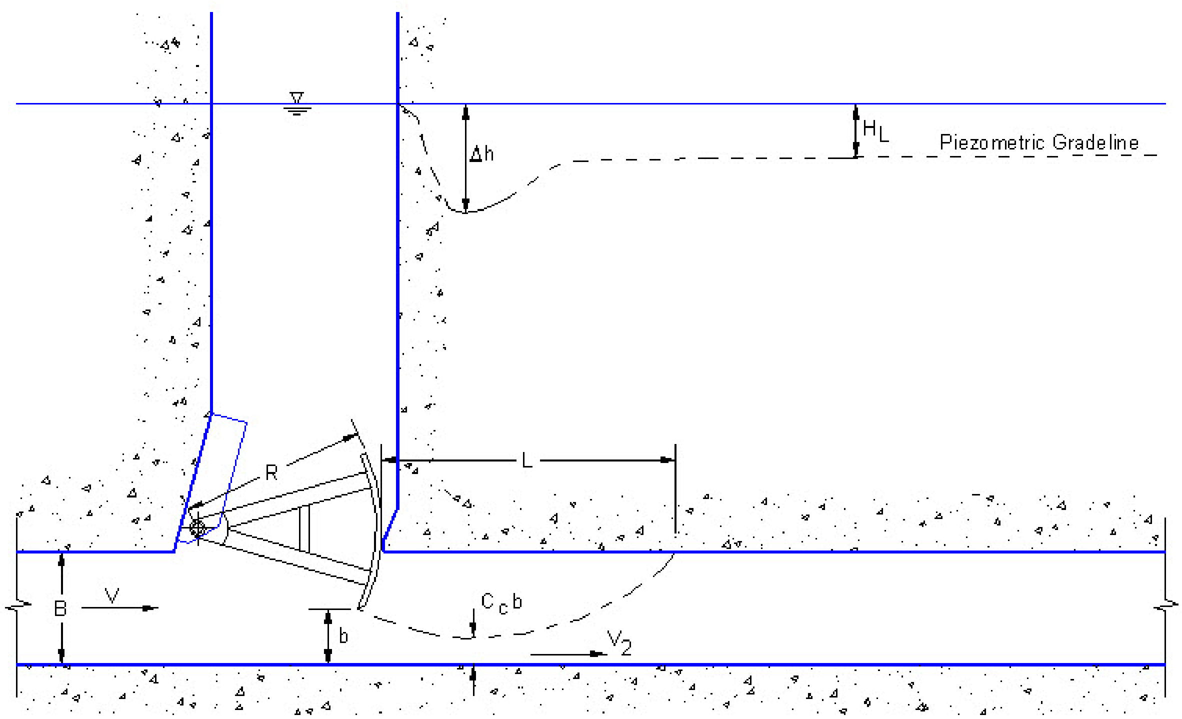


Figure 1-5. Reverse tainter valve installation.

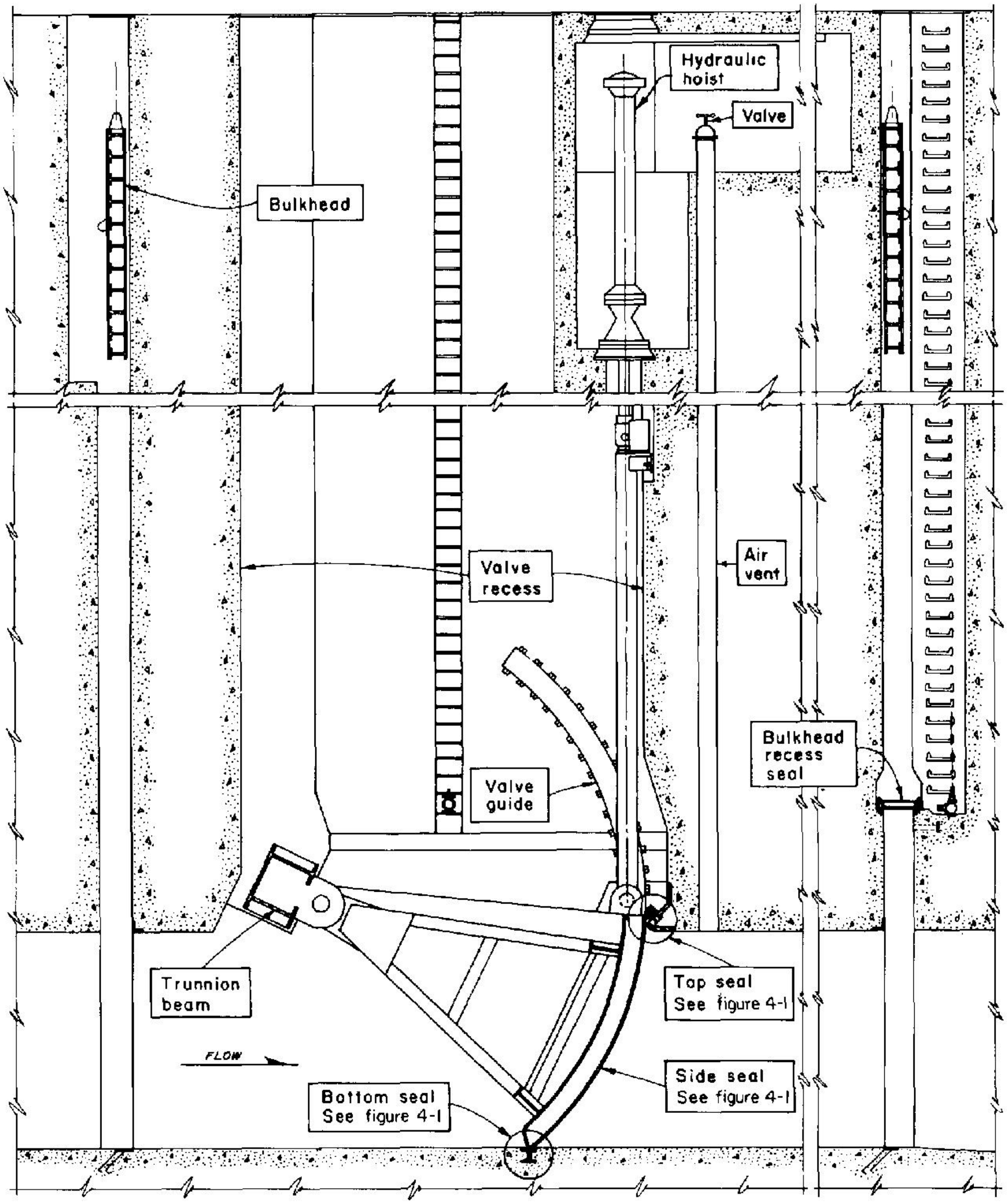


Figure 1-6. Elevation view of typical reverse tainter valve machinery hoist.

CHAPTER 2

Air in Culvert Systems

2-1. Experience with Air in Culvert System.

a. At several old locks (notably Ohio River Lock No. 41, old Wilson Locks on the Tennessee River, and Mississippi River Lock No. 1) portions of the roofs of the culverts between the filling and emptying valves were at elevations higher than the lower pool. This resulted in air seeping into the culvert system and forming pockets along the roof when the chamber water surface was at lower pool level. In the filling operation, the air pockets were compressed and forced along the culvert until expelled through an available exit (valve well, bulkhead recess, or ports into the lock chamber). The air emerged with such explosive force that it endangered personnel on the lock walls, created disturbances in the chamber which were hazardous to small craft, and increased hawser forces on moored tows. Conditions at these locks were mitigated somewhat by installation of blow-off vents, but it was concluded that all air should be sealed from the filling system.

b. When the 92-ft-lift McNary Lock was constructed on the Columbia River six 12-inch-diameter air vents, two in the culvert roof and two in the upper portion of each sidewall, were installed immediately downstream of each valve. During initial operation of the lock, the air vents at the filling valves were capped. Pounding noises, resembling thunder or cannon shots, seemed to come from the bulkhead slots on the downstream sides of the filling valves when the valves were partially open. It was found that opening one of the 12-inch-diameter air vents in the roof of the culvert at each valve virtually eliminated these noises (U.S. Army Engineer Waterways Experiment Station 1960). Consequently, the lock has been operated with one air vent open at each valve. Air is drawn through the vent into the culvert system during the valve opening period, is entrained as small bubbles in the highly turbulent flow, and emerges in the lock chamber so entrained that it merely causes the water to look milky. When the valve reaches the full open position, air ceases to be drawn through the vent and all air is rapidly purged from the culvert system still entrained in the flow as small bubbles. No operation difficulties or hazardous conditions have resulted from admitting this controlled amount of air to the culvert system during the valve opening period.

c. Thus, while pockets of air in the culvert system are very undesirable, admission of a controlled amount of air during the valve opening period has proved beneficial at high-lift locks.

2-2. Field Tests of Cavitation Conditions.

a. Tests were made at three locks: Holt on the Warrior River in Alabama, John Day on the Columbia River in Washington-Oregon, and Millers Ferry on the Alabama River in Alabama to determine conditions under which a controlled amount of air is needed to quiet the pounding noises such as those heard during initial operation of McNary Lock. A summary of pertinent findings from these experiments is given in Appendix B.

b. A particular form of Euler Number is used to evaluate the cavitation potential at various projects. The form of this cavitation parameter, σ, used for a lock culvert value is:

$$\sigma = \frac{P + (P_a - P_v)}{V_j^2 / 2g}$$

where

P = gauge pressure head at the top of the vena contracta of the jet emerging from the partially open valve, ft
P_a = atmospheric pressure head, ft
P_v = vapor pressure head of water, ft
g = acceleration due to gravity, ft/sec^2
V_j = velocity in vena contracta of the jet emerging from the partially open valve, ft/sec

$$V_j = V\left(\frac{B}{C_c\, b}\right)$$

A value of 33.0 ft is usually used for the term P_a - P_v . This probably is correct within 0.5 ft for conditions at existing locks, and available data do not warrant a more refined value. Minimum piezometric head and jet velocity are independent of local pressures on the roof of the culvert, which are influenced by changes in culvert geometry. Calculation of the piezometric head is described in Appendix C. The potential for cavitation is quantified using σ. The value of this parameter at which cavitation is incipient is termed the cavitation index, σ_i, which can vary with changes in the culvert geometry.

c. Values of cavitation parameter, σ, for tests described in Table B-2 are plotted against percent expansion of the culvert roof in Figure 2-1. Also, a line defining σ_i recommended for design purposes is shown in this figure. Since Holt Test 1 (only one boom) obviously was near conditions for incipient cavitation while John Day Test 3E (several booms) was well within cavitation conditions, there is logic in the manner in which the σ_i line is drawn. At Holt and John Day Locks where the culvert roofs slope up downstream from the filling valves, there is additional backflow of water into the low pressure zone downstream from the valve. This additional circulation, or water venting as it is sometimes called, results in an increase in pressure on the culvert roof. Measured pressure increases have been plotted as pressure drop (initial lock water surface to minimum piezometric grade line) reductions in Figure 2-2. If this pressure increase was the only quantity changed then computations with measured pressures should allow establishment of a single σ_i value for all roof geometries. This is not supported by available data. It is considered probable that both the velocity and depth at the vena contracta also are modified, but accurate measurements to establish the degree of modification would be difficult.

2-3. <u>Selection of Elevation for Culvert Valves.</u>

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

b. The lock valves must be placed either at an elevation that will result in the minimum value of σ being not less than σ_i or at an elevation that will result in negative pressures on the culvert roof and vents must be provided in the negative pressure zone. If an elevation for the culvert is determined such that the minimum value of σ equals σ_i , then the culvert should be lowered an additional distance equal to one-tenth of the lift as a safety factor. If vents are to be provided, the culvert should be placed at an elevation that will result in about 10 ft of negative pressure on the culvert roof during normal operation. In locks with lifts up to 100 ft, this will result in the pressure grade line dropping below the culvert roof when or before the valve is about 35 percent open and thus will provide aeration throughout the critical period of the operation cycle. Methods of computing the pressure head downstream of a valve are discussed in Appendix C.

c. A third alternative to the two procedures suggested in the preceding paragraph is to ignore the cavitation potential in the valve elevation design and to use a slow or delayed valve opening schedule such as is recommended for John Day Lock, see paragraph B-3h. In an existing lock, this may be necessary. However, this approach is not recommended for new designs. A fourth method that has been proposed – but that is questionable and not recommended – is water-venting by lateral inflow from the lock chamber into the low pressure zone (Fidelman 1961 and Ables 1961). Such water vents will raise the pressure in the critical zone, an asset; but also the lateral inflow will increase turbulence in this zone, a liability. Systematic field tests would be required to determine whether lateral water vents actually are beneficial or detrimental and to establish design rules for their use.

d. In addition to the requirements listed in paragraph 2-3b, in all cases, the highest point in the culvert system between the filling and emptying valves should be at least 5 ft below the lower pool to assure that air will not seep into the culverts when the lock chamber water surface is at the level of the lower pool.

e. Design examples are given in Appendix E.

2-4. Conclusions and Recommendations Regarding Admission of Air into Culvert System. It is concluded that air pockets in the culvert filling system are hazardous but that air bubbles well entrained in the flow can be beneficial. Thus it is proposed that:

a. All elements of the culvert system between the filling and emptying valves should be at least 5 ft below minimum lower pool.

b. In locks with lifts of 40 ft and less, air should be sealed from the culvert system during filling operations. In low-lift locks, where turbulence levels are low, even small amounts of air admitted during filling could collect in pockets and become dangerous. The lock valves should be placed at an elevation that will result in the minimum value of σ being greater than σ_i, and as a safety factor, the valves should be at an elevation equal to at least one-tenth of the lift less than the elevation required for minimum σ to equal σ_i. It is indicated in Example 1, Appendix E, that this will not require excessive submergence of the culverts and therefore, in most cases, should not prove costly.

c. In locks with lifts of 60 ft and greater, the valves should be placed at an elevation that will result in about 10 ft of negative pressure on the culvert roof during filling and air vents should be provided in the low pressure zone. Whitten Lock on the Tennessee-Tombigbee Waterway is an example of a project designed to draw air. This lock, which has a design lift of 84 ft, draws air into the culvert immediately downstream of the valve. The air vent is located such that the air drawn into the culvert is entrained in the form of very small bubbles, avoiding large air pockets that may cause surging in the lock chamber. An exception could be made in the very unlikely case that foundation conditions are such that it is economically desirable to place the valves very deep with respect to lower pool. Deep valve submergence prevents negative pressures low enough to cause cavitation. This design is termed a positive head valve design; wherein, the pressures during valve operation never reach a level lower than about 15 ft below the culvert roof. An example of a positive head valve on a high-lift lock is the new Bonneville Lock on the Columbia River, which has a design lift of 69.5 ft. Consideration of Example 2, Appendix E, provides insight into the submergence that would be necessary to prevent cavitation.

d. In locks with lifts of 40 to 60 ft, decision as to whether cavitation will be prevented by submergence or admission of air should be based on economic considerations for the particular project.

2-5. Design of Air Vents.

a. Because of the potential adverse impact of air flow on chamber performance in the prototype lock and concerns regarding the minimum acceptable pressure below the operating valve, design practice is generally to oversize the air vent and establish a satisfactory orifice or air-valve setting to limit air flow. The orifice sizing or valve setting is established by observation in the prototype. All filling-valve air vents should be provided with means for controlling the amount of air entering the culvert system. Bulkhead slots, valve wells, or other such openings into the culvert should never be allowed to double as air vents for the filling valves.

b. Air vents for emptying valves should be controlled, the same as for filling valves, if flow is discharged into the lower approach to the lock. However, if flow is discharged outside of the lock approach, excessive air is not likely to be harmful and bulkhead slots can be used to double as air vents.

c. Air vent design is discussed in EM 1110-2-1602 for the steady state flow design of reservoir outlet works. A straight-forward design of an air vent system for a lock valve consists of two independent 12-inch-diameter pipes entering flush with the culvert roof. The location of each pipe can range between one quarter and one third of the culvert width from each wall. A vent slot extending across the roof of the culvert as provided in flood control conduits is not required. The vents should enter the culvert roof within the low pressure zone which extends from the valve to the vena contracta of the jet passing under the valve. Location of the vena contracta varies with culvert height and valve opening but vents have performed satisfactorily when placed no more than a distance of one-half of the valve height downstream from the valve well. The vent pipes should be brought through an accessible location, such as the platform that supports the valve operating machinery, and then to openings on the outside face of the lock wall at an elevation above the maximum pool at which the lock will be operated. Openings on the top or inside face of the lock wall are nuisances to personnel on the wall or in the lock chamber. A valve should be inserted in each vent at an accessible location. At the time the lock is put in operation, hydraulic design personnel should assist in determining vent valve settings that will preclude cavitation without an excessive amount of air and thus added turbulence in the lock chamber or lower approach. This should not be difficult as past experience has shown that satisfactory performance can be obtained within a range of settings. The vent valve settings should be documented and then locked in the desired position to prevent accidental changing of the setting.

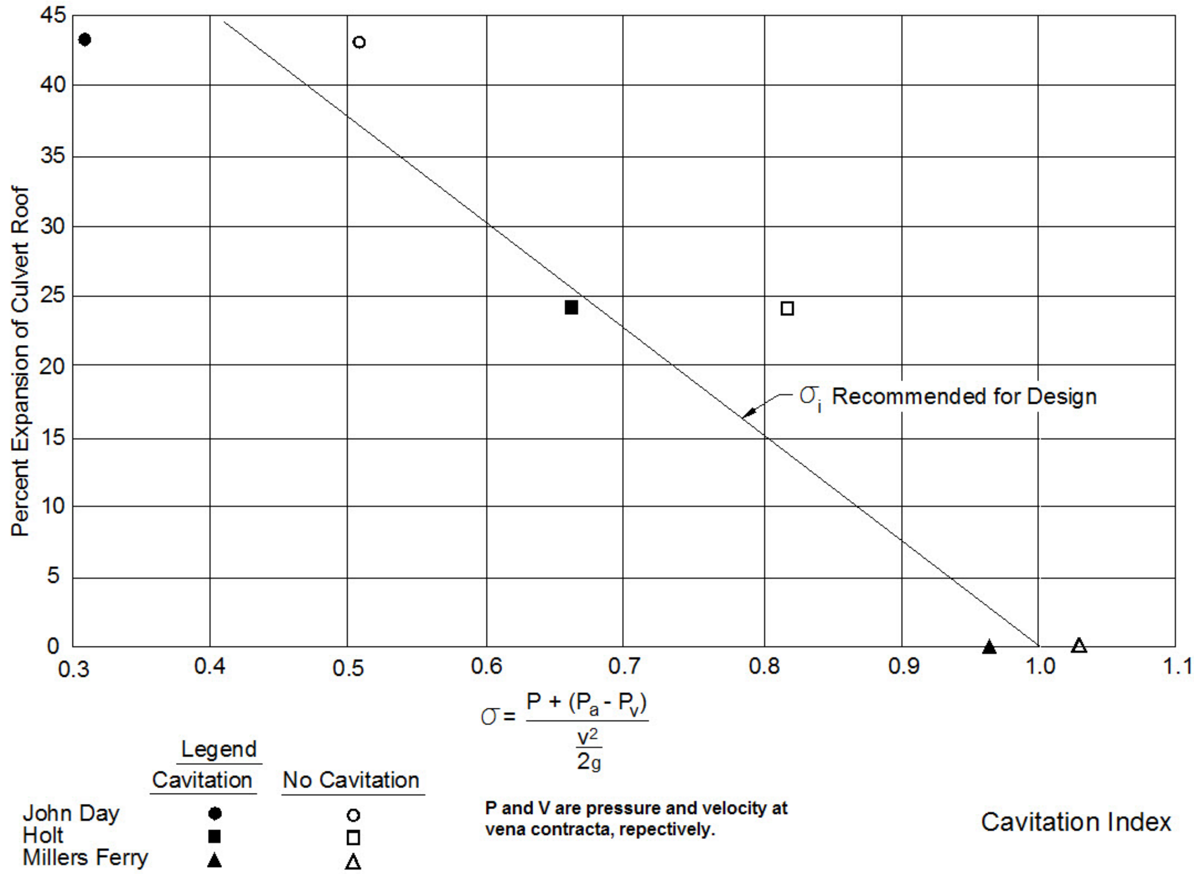


Figure 2-1. Cavitation index.

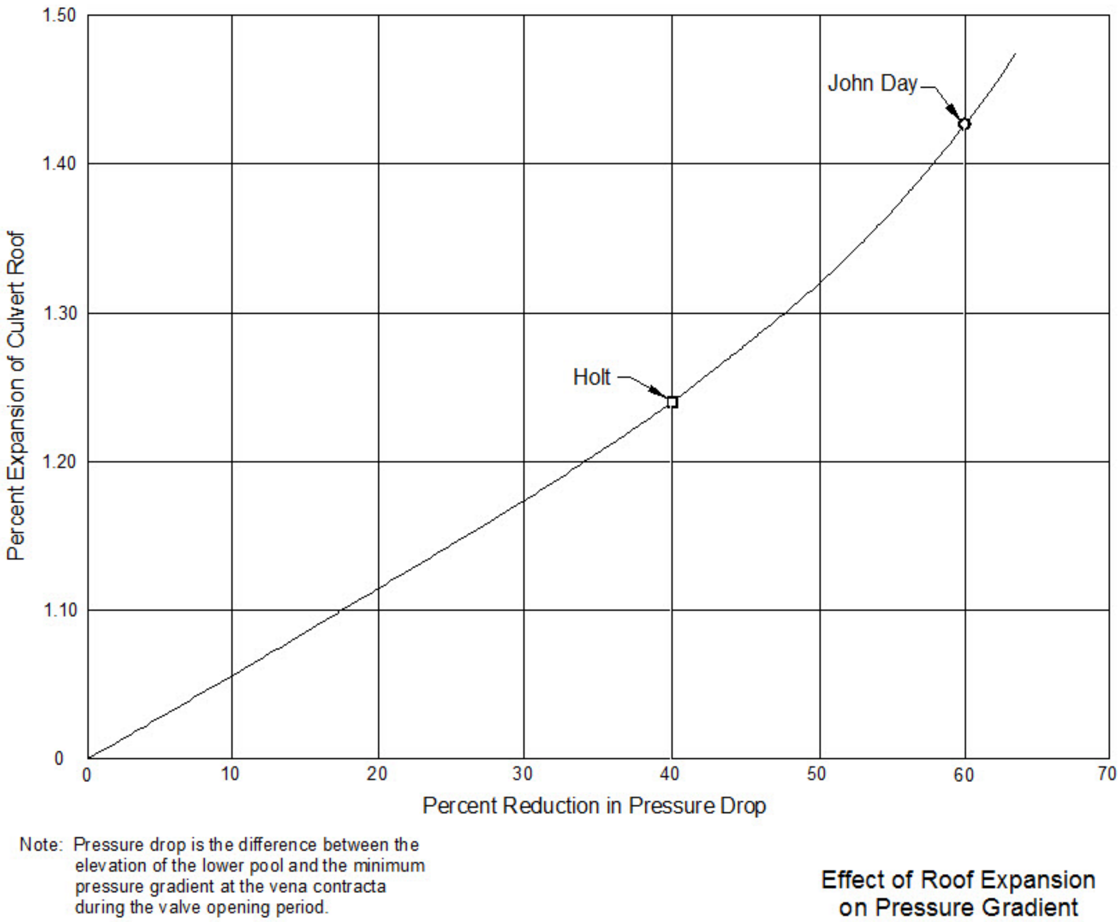


Figure 2-2. Effect of roof expansion on pressure gradient.

CHAPTER 3

Hoist Loads

3-1. Reverse Tainter Valves. Three structurally different types of reverse tainter valves (horizontally framed, double-skin plate, and vertically framed) have been used in the designs of lock filling and emptying systems (see Figure 3-1). The horizontally framed valve is desirable structurally, but the double-skin plate and vertically framed valves are less susceptible to critical hydraulic loads and load variations during the opening cycle.

3-2. Valve Hoist. The terms “valve stem,” “valve strut,” and “valve hoist mechanism” are synonyms for the steel structure that connects the mechanical operating equipment to the culvert valve. Contract drawings often use the term “strut” whereas operations personnel commonly use the word “stem.”

3-3. Hoist Forces. The total hoist load is the sum of the forces on the valve strut with flowing water and the stem load in the dry. The hydraulic forces are the sum of hydrostatic and hydrodynamic forces due to local accelerations as flow passes the valve. When hoist-load values are greater than the load due to the valve’s dry hoist load, hydraulic forces are acting to close the valve; where they are less, hydraulic forces are acting to open the valve.

3-4. Hydraulic Loads due to Flowing Water. Hydraulic loads presented herein are the summation of forces on the valve members due to flowing water considered as a single force. Downpull loads act to rotate the valve to the closed position and uplift loads act to rotate the valve to the open position. Basic data were obtained with the valve at fixed positions and under steady-flow conditions. For each valve position, hoist-load data were obtained for a range of velocities under the valve (discharge divided by total valve opening). For the plots provided in Figures 3-2 to 3-4, the velocity under the valve at each valve position was computed (see Appendix C) for different lifts in a specific lock. Actual project conditions such as head/discharge (or head/velocity) relations will vary depending not only on the lift but also on the valve operation pattern. Table 3-1 gives the relation of velocity under the valve to lift used in plotting the data in Figures 3-2 to 3-4.

Table 3-1 Velocity Under Valve, fps

Valve Open Percent	Lift, ft			
	20	40	60	100
0	0.0	0.0	0.0	0.0
10	28.5	41.0	50.0	65.0
20	27.5	39.0	49.0	63.5
30	26.0	37.0	45.5	59.5
40	26.0	37.5	46.5	60.5
50	26.5	39.0	48.5	64.0
60	27.0	40.5	50.0	66.5
70	27.5	40.5	50.5	67.0
80	26.5	39.5	49.0	65.0
90	25.0	37.0	46.5	61.0
100	23.0	34.5	43.0	57.0

a. Horizontally Framed Valve.

(1) As the name implies, the skin plate is attached directly to a series of horizontal beams and the loads are transmitted to the trunnion arms through vertical frames or girders near the sides of the valve (see Figure 3-1a).

(2) Horizontally framed valves were used almost exclusively in earlier low-lift locks and no inadequacies were indicated until locks in the medium- and high-lift category were required. Serious operational problems with the horizontally framed valve resulting from forces due to flowing water first were encountered in Lock No. 19, Mississippi River (U.S. Army Engineer Waterways Experiment Station 1961a).

(3) During trial operations at Lock No. 19 it was found that when a valve was at greater than two-thirds angular opening, flowing water caused pulsating loads which were transmitted through the strut and strut arm, resulting in reversal of load on the operating machinery and a consequent severe clattering in the gear train. The pulsations appeared to increase in magnitude with increased valve opening. The resultant loading conditions were of such severity that remedial action was necessary prior to normal operation of the project.

(4) The lift at Lock No. 19 is 38.2 ft and flow through the culverts is regulated by 14.5-ft by 14.5-ft reverse tainter valves. The valves are actuated by electric motors through strut-connected mechanical gear systems. Each valve weighs 28,350 lb, with the strut and strut arm adding weights of 3,500 and 3,100 lb, respectively. With a valve submerged in still water, the load on the hoist varied during an opening cycle from about 21 kips (1.45 kips per foot of valve

width) near the closed position to about 31 kips (2.14 kips per foot of valve width) near the open position.

(5) Model tests revealed that under normal operating conditions flowing water caused an average load on the hoist in a downpull direction from a gate opening of 0 to about 75 percent and in an uplift direction from 75 to 100 percent. Flow approaching the partially open valve divided at the upstream face of the valve with part of the flow going under the valve and part into circulation in the valve well. When this division was above the lower girder, downpull forces prevailed and below the lower girder, uplift forces occurred. Flow patterns in the valve well during downpull and uplift conditions are shown in Figure 3-5. Also, it was revealed that random variations in hoist load increased as the valve opening increased. With the valve ne ar the open position, loads on the hoist due to flowing water varied from 12 kips (0.83 kips per foot of valve width) downpull to 48 kips (3.31 kips per foot of valve width) uplift. Thus, with the submerged valve exerting a downpull load of only 31 kips on the valve hoist, it is obvious why severe clattering resulted in the gear train.

(6) Hoist loads due to flowing water obtained in a 1:12-scale model of the valve shown in Figure 3-1a at lifts of 20, 40, and 60 ft are plotted in Figure 3-2. For planning purposes, these data are considered generally applicable and the prediction of total loads for similar valves based on the width of the valve is justified by the fact that tests have revealed that modifications to valve members above the lower girder have a very small effect on hoist loads. Thus, the height of the valve has a negligible effect on hoist loads except as it modifies the velocity of approach and this is accounted for by plotting valve opening as a percentage of total opening rather than as a specific dimension.

(7) Modifications to the lower girder and the portion of the valve below the girder can have a material effect on valve loads (U.S. Army Engineer Waterways Experiment Station 1961a and Ables and Schmidtgall 1961). For instance, installation of a cover plate from the valve lip to the flange of the lower girder resulted in a 30 percent increase in peak downpull but a 35 percent decrease in both peak uplift and load variation.

(8) Modifications of the Lock No. 19 valve were made based on physical model results (U.S. Army Engineer Waterways Experiment Station 1961a). These modifications included addition of a cover plate extending from the valve lip to the lowest horizontal girder and the removal of knee braces between the lower girder and the trunnion arms. Field tests of the modified valve confirmed the elimination of objectionable oscillations.

b. Double-Skin Plate Valve.

(1) With the objective of presenting a smooth upstream surface to flow, instead of the projecting edges of the horizontal beams, the transverse beams are covered with a smooth, curved skin plate which results in a streamlining effect (see Figure 3-1b). The inside plate adds rigidity to the leaf and can be utilized in the stress analysis. It is customary to use welded construction, making the tank watertight. Thus, the valve can be operated with the tank filled with air, provided the valve has sufficient weight to counteract its buoyancy as well as the dynamic hydraulic uplift forces. In most instances, however, greater stability is needed and the

tank is filled with water.

(2) The double skin construction wraps structural members such that the valve is streamlined because fewer objects are exposed to the flow. However, the semi-circular top and bottom of the valve arms are subject to flow-control oscillations, which in turn tend to vibrate the entire valve.

(3) Double skin plate valves were the original design used at several projects. Variations of the double skin plate have been used at locks on the Columbia River (e.g. John Day, the Dallas, and McNary), the Snake River (e.g. Ice Harbor), the Tennessee River (e.g. Fort Loudoun, Wheeler, and Wilson), the Cumberland River (e.g. Cheatham and Barkley), the St. Lawrence Seaway (e.g. Eisenhower and Snell) to name a few.

(4) Performance of the double skin plate design has varied. The valves of the Barkley Lock have functioned without major operational problems. Field information about this well-performing lock system was obtained during a comprehensive prototype testing program (Neilson 1975). The testing program documented the entire filling and emptying systems but was detailed enough to provide a large volume of information on the lock culvert valves. Pressures at a point on the upstream face and three points on the downstream face of the valve's skin plate were measured. The peripheral, radial, and transverse components of the valve acceleration were recorded. The pressure at the top and bottom of the upstream, land-wall valve hydraulic cylinder were recorded as well as the stress in the lifting rods. Evaluation of the data revealed that the valves are performing as designed and do not experience vibrations. No exciting frequencies were found to be near the valve system's natural frequency. The tests found that pressure fluctuations, strains, and accelerations which might contribute to structural fatigue were relatively low and not likely to be of structural significance. Design forces obtained from a physical model study (Fidelman 1963) were found to agree reasonably well with average, measured lifting rod forces.

(5) The performance of the double skin plate valves used on John Day and the Dalles Locks have had cracks form in the steel wrapper plate of the valve members, and their structural performance has been unreliable over the years. A field inspection report reiterated that operation and maintenance of the valves have been difficult since completion of construction (North 2006). A prototype study of the John Day Lock system was conducted in 1973 (Neilson and Pickett 1986) to investigate shock waves, vibration, and noise in the lock filling system. Lock operation produces noise and vibrations during filling. The pounding noise can be reduced by opening the filling valves in stages. The valve schedules have been changed to open in a stepped fashion. The two-valve filling operation was recommended by Neilson and Pickett (1986), wherein the valves are operated to one-third open in 40 sec, holding at one-third open for a 5 min delay, and opening in 80 sec. Neilson and Pickett (1986) also recommended that a single valve could be operated in a similar schedule with a 10 min delay.

(6) General design values of hoist loads due to flowing water obtained in a 1:15-scale model of the valve shown in Figure 3-1b at lifts of 20, 40, 60, and 100 ft are plotted in Figure 3-3. Results of other tests on valves of this type are reported by U.S. Army Engineer Waterways Experiment Station (1960), Fidelman (1961), U.S. Army Engineer District, Portland (1955),

Fidelman (1963), and Neilson (1975).

c. Vertically Framed Valve.

(1) In valves of this type the skin plate is attached to a series of curved T-beam ribs along parallel vertical planes (see Figure 3-1c). The ribs are continuous over the two supporting horizontal girders and are formed of structural tees with outstanding legs welded to the skin plate. The water loads are transmitted to the trunnion arms through horizontal girders welded to the outer flanges of the ribs. Thus, open spaces where water can circulate freely are provided between the ribs, and between the skin plate and the horizontal girders. The space between the skin plate and horizontal girders is left open for free flow of water so as to minimize dynamic forces on the valve

(2) The vertical frame valve has been used on most new construction since 1970. Locks on the Black Warrior River (e.g. Bankhead and Holt), the Clinch River (Melton Hill), the Tennessee River (Chickamauga), the Tennessee-Tombigbee Waterway (e.g. Whitten and Heflin), and the Columbia River (Bonneville) have incorporated vertical frame valves in the original design.

(3) Overall, the vertical frame valve has provided reliable service. The Bankhead Lock valves have performed well, and their design is recommended by operations personnel. However, the Holt Lock valves have performed poorly and have been a maintenance problem since the lock began operations in the late 1960s. The lifting mechanisms of the filling and emptying valves vibrate during lock operations. Project personnel indicated the maintenance and repair needs for the filling and emptying valves were similar. The bulkhead covers have been removed to reduce the work required during the frequent valve repairs. Once, field personnel tested a modified valve. Plate steel was added across the bottom of a valve to stiffen and streamline it. However, the first time it was operated under head, the valve shook violently causing the lock operation house to tremble; the plate steel was removed. This shows that small changes to a valve’s shape can have adverse hydrodynamic loading consequences. The Bankhead Lock valve design is about 34% heavier than the valve design used at Holt Lock. The valves at both projects are vertically framed with similar spacing between the skin plate and the horizontal girders. The Holt valve is more curved than the Bankhead valve. The ratio of valve radius (R) to culvert height (B) of the Holt valve is smaller than that of the Bankhead design. The Holt Lock valve has a 17.0 ft radius and the culvert is 12.5 ft tall, thus the R/B is 1.36. The Bankhead Lock valve has a 20.0 ft radius and the culvert height is 14.0 ft for an R/B of 1.43. This difference in relative curvature is especially important at the valve lip and in the rate of vertical acceleration around the skin plate as flow passes the valve.

(4) General design values of hoist loads due to flowing water obtained in a 1:15-scale model of the valve shown in Figure 3-1c at lifts of 20, 40, 60, and 100 ft are plotted in Figure 3-4. The flanges on the T-beam ribs that transmit loads from the skin plate to the horizontal girders must be narrow. Flanges 2.5 inches wide were suitable in the example valve, but flanges 12 inches wide inhibited the desired circulation and were very detrimental to loading characteristics. Results of an additional test on a valve of this type are given by Ables and Schmidtgall (1961).

3-5. General Comments.

a. Average loads and maximum load variations for the three valves shown in Figure 3-1 at a 6o-ft lift are plotted in Figure 3-6 to show the relative load characteristics of each valve. Hoist loads obtained in physical model studies of thirty five different configurations including each of the basic valve designs (horizontal frame, double-skin plate, and vertical frame) are provided in Appendix D. The data in Appendix D are presented in general terms of approach velocity, relative valve opening (*b/B*), and force per unit width of valve. The model results show that small changes in valve design can lead to large differences in hoist loads and load variations.

b. For all three types of valves the two features that most affect loads on the valve hoist due to flowing water are the depth of the lower girder and the extension of the lower lip of the skin plate below the lower girder. A decrease in the depth of the lower girder results in a decrease in peak downpull and load variations and, also, a decrease in the range of valve positions at which downpull occurs and an increase in the range of positions at which uplift occurs. Data are not conclusive as to whether peak uplift is decreased. An increase in the extension of the lower lip of the valve below the lower girder decreases peak downpull and the range of valve positions at which downpull occurs but increases peak uplift and the range of valve positions at which uplift occurs (U.S. Army Engineer Waterways Experiment Station 1961a). Load variations remain essentially unchanged.

c. The effect of load reversals on the valve hoist was demonstrated dramatically at Lock No. 19 by the severe clattering in the mechanical gear system. When operation is directly from a hydraulic piston, load reversals are not readily noticeable. However, these load reversals are still undesirable as they are likely to result in excessive wear in the strut connections and could cause other structural damage.

d. It should be apparent to the designer that consideration of a horizontally framed valve should be limited to locks with lifts of no more than about 30 ft. When designed for equal lifts, the double skin-plate valve usually will be heavier and, particularly if the tank is filled with a rust inhibitor, will require greater hoist capacity than will the vertically framed valve. However, some designers consider a heavy valve to be more stable and thus worth the cost of the additional hoist capacity. Certainly the double skin-plate valve can be used successfully at all lifts. The vertically framed valve probably has economic advantages over the double skin-plate valve and maintenance on the double skin-plate valve is hindered due to lack of access to and inspection of the interior structural members. Although the single-skin design allows for inspection and spot repairs, each structural member can act as a flow obstruction and contribute to adverse loadings or vibration generated by shedding vortices. If this valve is considered for a lock with a very high lift, excess weight may be required to prevent load reversals on the valve hoist.

e. The importance of the details involving the design, fabrication, installation, and maintenance cannot be overemphasized. Success depends on communication and collaboration between the engineering, construction, operations, and maintenance departments throughout the (1) design review, (2) fabrication inspection, (3) installation, and (4) maintenance stages.

3-6. Valve Replacement. As a lock filling and emptying system reaches its design life, the original culvert valves may be replaced with new valves. Many original valves, which are of double-skin construction, are replaced with new valves of a vertical frame design because inspection and maintenance of double-skin-plate valves is difficult due to lack of access to interior structural members. Vertical frame replacement valves which have performed poorly have had plates across and/or between the ribs. Top plates, bottom plates, or stiffener plates should not be used with the vertical frame valve design because the plates block the flow up the skin plate, resulting in large uplift forces and vibrations. The risk of installing a valve that has operation or maintenance problems can be reduced if the design is model tested. A model study is recommended to confirm any design that involves large differences in structural size or shape and large velocities.

3-7. Total Hoist Loads. In determination of total hoist loads, the designer must combine the loads due to flowing water (discussed in paragraph 3-4) with loads resulting from: (a) weight of the submerged valve, (b) weight of the operating stem, (c) sliding friction of the side seals and in the trunnion (EM 1110-2-2610), and (d) head differentials across the top seal (paragraphs 4-4 and 4-4a). The actual trunnion and hoist loads will be directly affected by the valve geometry including structural members.

3-8. Prototype Values.

a. Prototype tests were conducted on the Bankhead Lock, Black Warrior River (Tool 1980). The Bankhead Lock has a design lift of 69 ft with 14-ft by 14-ft culverts with filling and emptying valves of the same size. The valves are of the vertically framed reverse tainter design. Hoist loads were measured indirectly by recording the hoist cylinder pressures. Hoist loads are presented in Figure 3-7 on which Test 33 was a 1-min, single-valve operation with an initial head of 68 ft and Test 40 was a 2-min single-valve operation with an initial head of 67 ft. The graph of hoist loads also shows predicted loads for submerged and dry valve operations as presented in the construction drawings. The forces are all directed downward. The actual loads were less than those predicted for design. The pressures in both tests follow the same trend and it is not known whether the differences are attributed to the valve opening rates or due to test data precision.

b. Experiments on the Whitten Lock, which was initially named Bay Springs Lock, determined the operating characteristics and hydraulic efficiency of the lock (McGee 1989). Particular attention was given to evaluating important design factors such as the cavitation parameter and the effects of venting and submergence of the 14-ft by 14-ft valves. The 84-ft-lift lock is a bottom longitudinal floor culvert system with vertically framed valves. Dual 12-in diameter ducts introduce air downstream of each filling and emptying valve. The reverse tainter valves have performed well, and the operating conditions are satisfactory. Hoist loads, measured during operation (Figure 3-8) were larger than those predicted by Figure 3-4. This difference is partially attributed to the fact that the loads given in Figure 3-4 do not include friction in the trunnion or sliding friction of the wear surface and side seals (discussed in EM 1110-2-2610). At no time was any uplift forces observed for the one filling valve that was instrumented. The trends of field data were in agreement with the predicted loads with the exception of the large peak loads measured at the initiation of valve opening (valve opening of

10%).

3-9. Peak Head Across Valve.

a. Near the beginning of a filling or emptying operation if a failure of the hoisting mechanism should allow a valve to slam shut, a head across the valve considerably larger than the difference between upper and lower pool would result. Time-history of pressures on each side of the valve can be developed from available formulas concerned with surges and water hammer. Pressure oscillations on each side of the valve will occur with decreasing amplitudes through several cycles. However, the periods of these oscillations are likely to be different on the two sides of the valve; and although individual peaks (positive and negative) on each side of the valve probably will occur during the first cycle, it is possible that the maximum head across the valve will occur later and be less than the difference between the first cycle peaks. Also, there are likely to be reversals in the head across the valve.

b. In a reverse tainter valve installation, the valve well would serve as a surge chamber and thereby delay and reduce the buildup of pressure on the high-head side of the valve. Although the surge in the valve well would spill out at the top of the lock wall, the pressure on the valve would result from forces causing flow up the well and could be considerably greater than the difference between the top of the wall and the valve. If the valve is not vented, the pressure on the low-head side of the valve could drop quite rapidly to about -33 ft (one atmosphere negative); with a vented valve, the pressure would drop to slightly subatmospheric.

c. Sudden closure of a valve due to breakage of the hoisting mechanism is very unlikely to occur and usually is not considered a design condition. On the other hand, operation that would produce surges is most probable. For many reasons the operator may reverse the valves during or immediately after the opening cycle. A series of tests was conducted in the Cannelton Lock model (Ables and Boyd 1966) during which the 18-ft-high by 16-ft-wide filling valves were opened at a rate to reach fully open in 2 min. Immediately upon reaching l/2, 3/4, and then fully open, the valves were reversed and closed at the same rate. The surges generated produced a peak head differential across the valve of about 1.5 times the initial lift.

d. The conditions of peak head across the valve to be used in the structural design should depend on the local situation and judgment on the part of the designers. Certainly all designs must provide for the head created by the abnormal operation described in paragraph 3-9a. The hydraulic designer should describe the possible loadings that could result from operational and accidental closure of the valves during a filling or emptying operation.

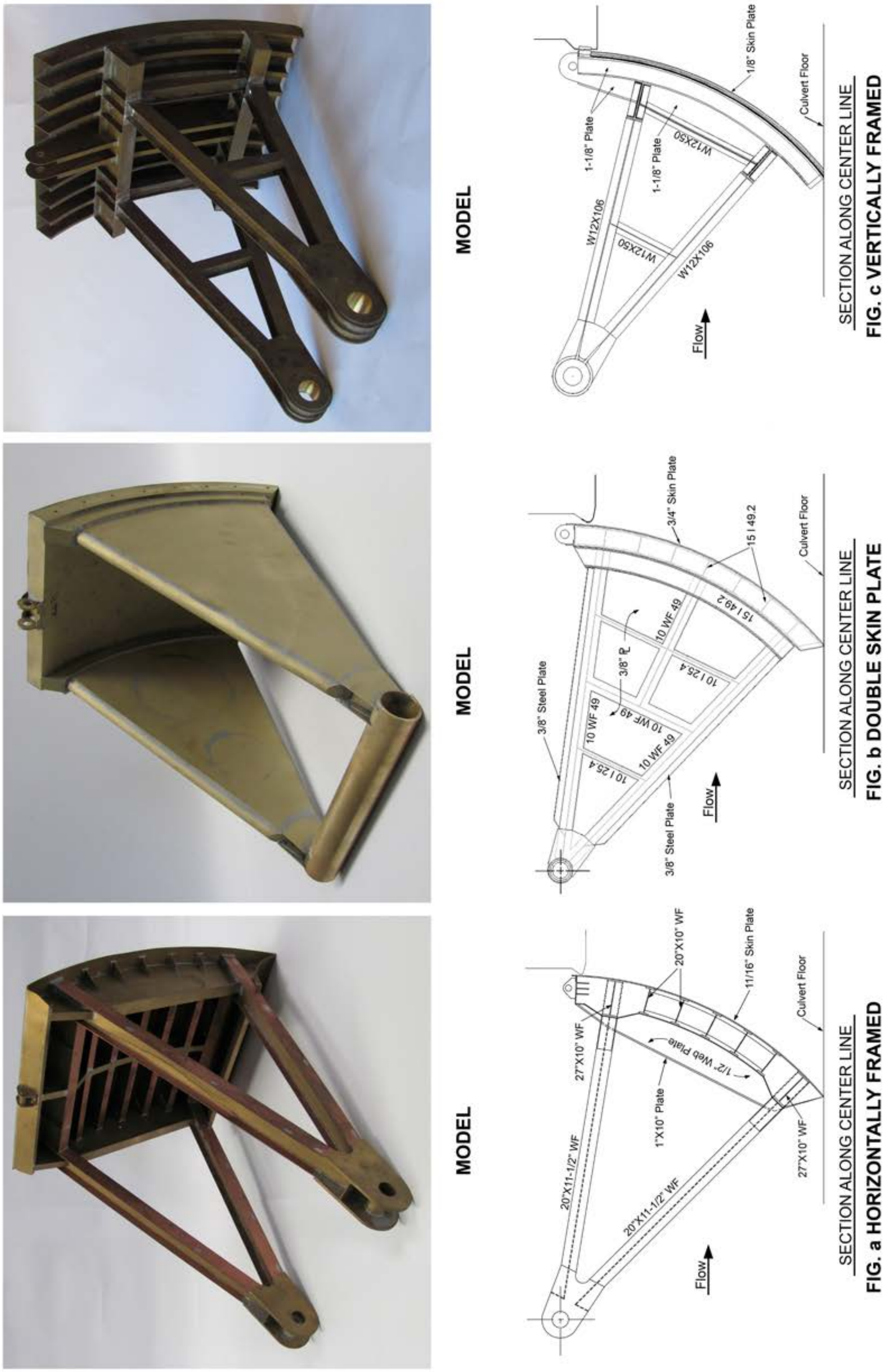


Figure 3-1. Tainter valve types.

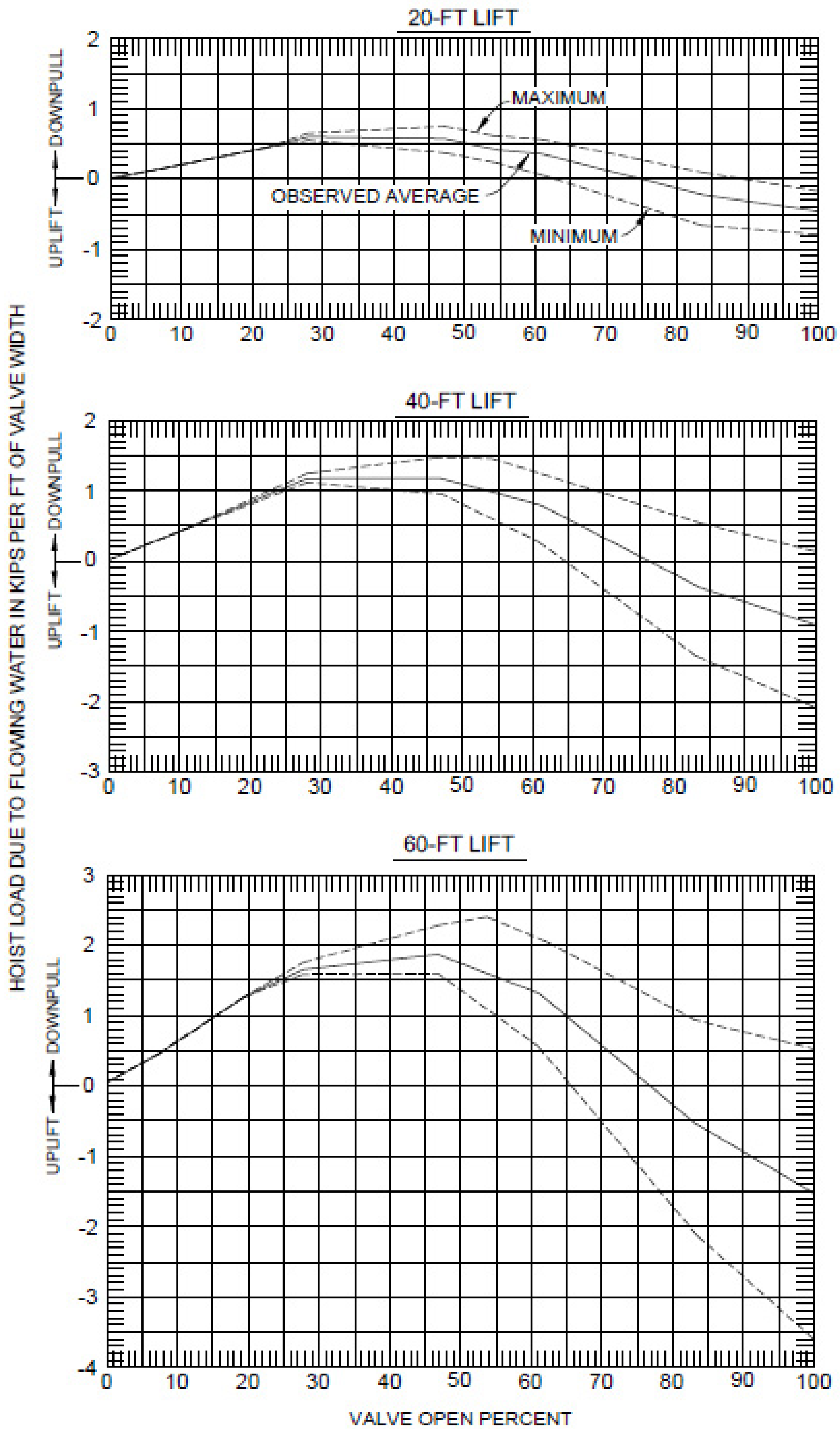


Figure 3-2. Hoist loads in a horizontally framed valve.

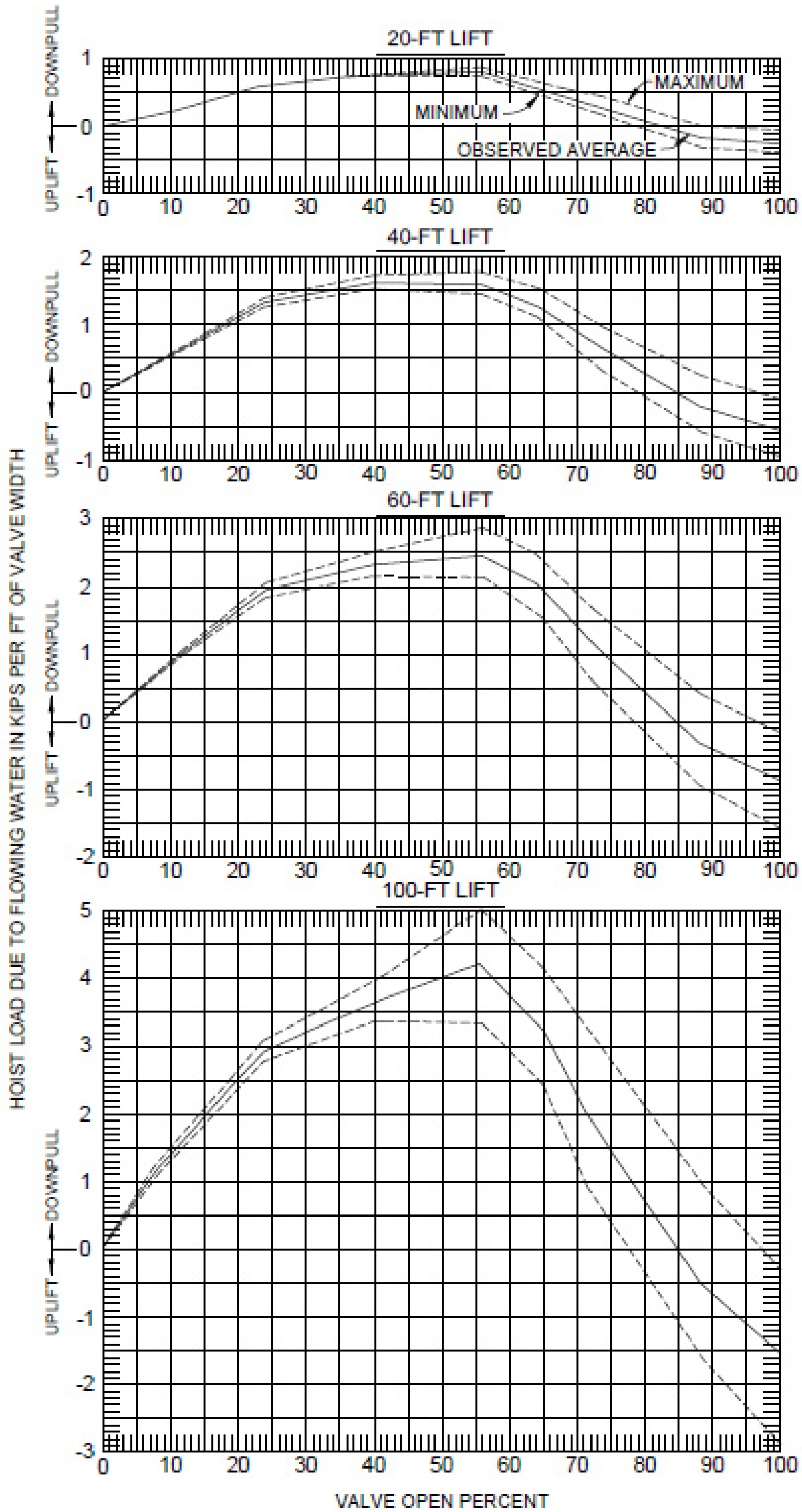


Figure 3-3. Total hoist loads on a double-skin plate valve.

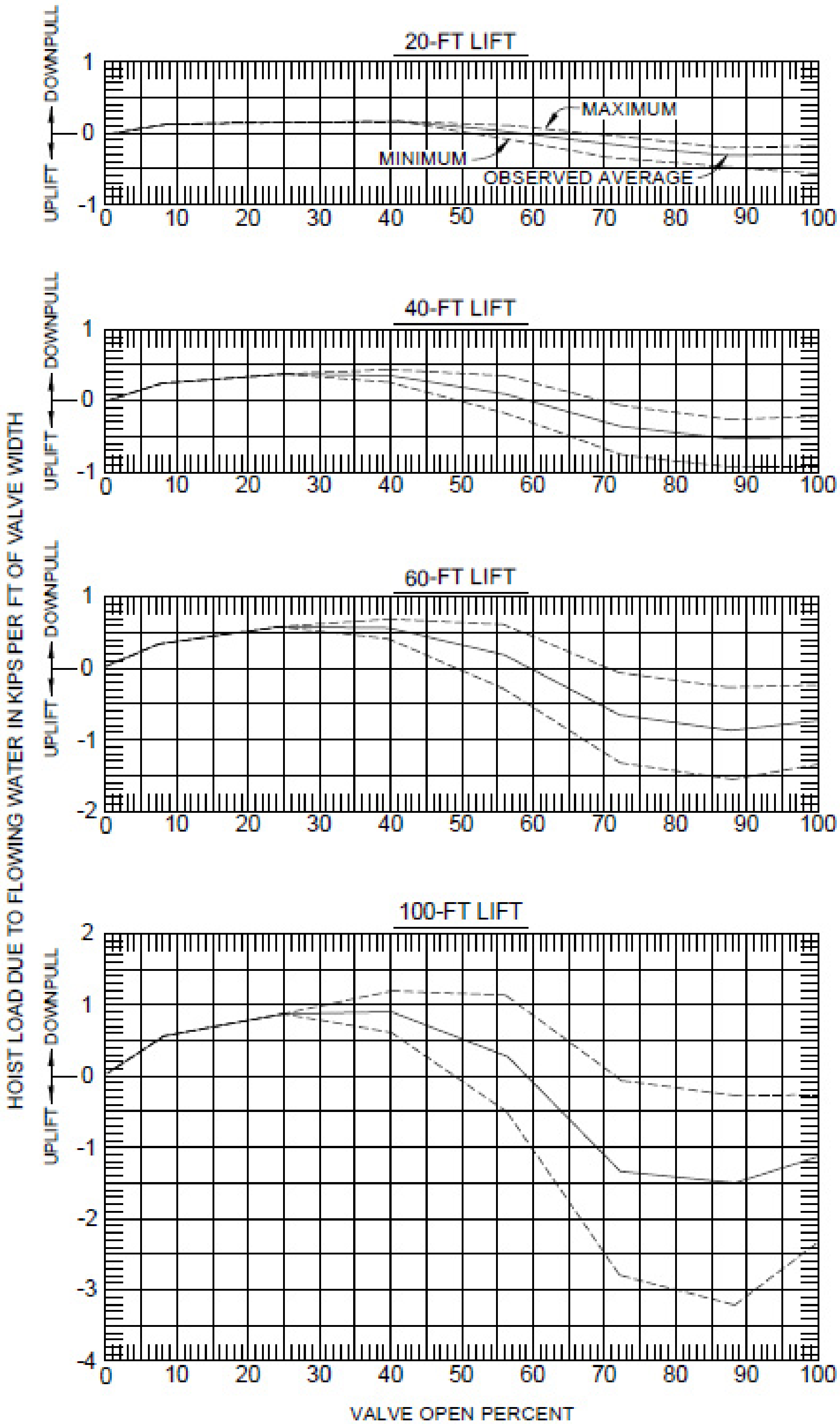


Figure 3-4. Total hoist loads on a vertically framed valve.

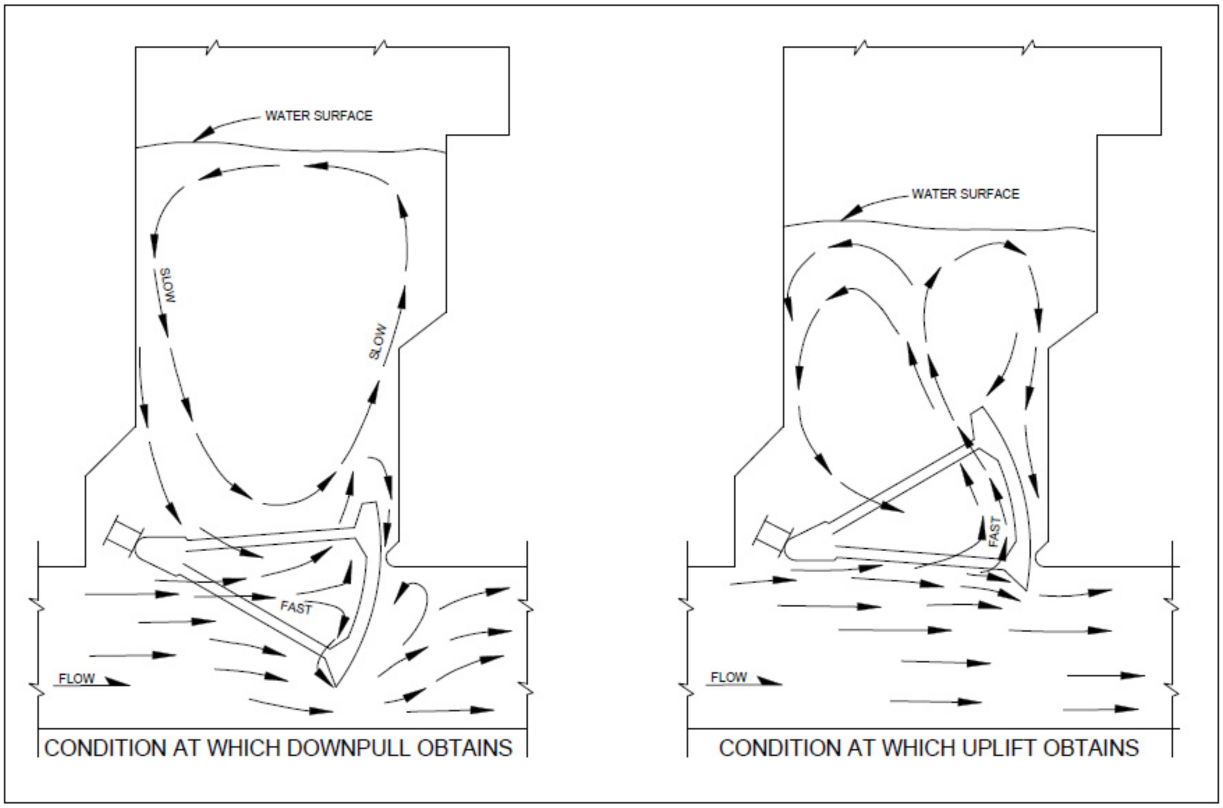
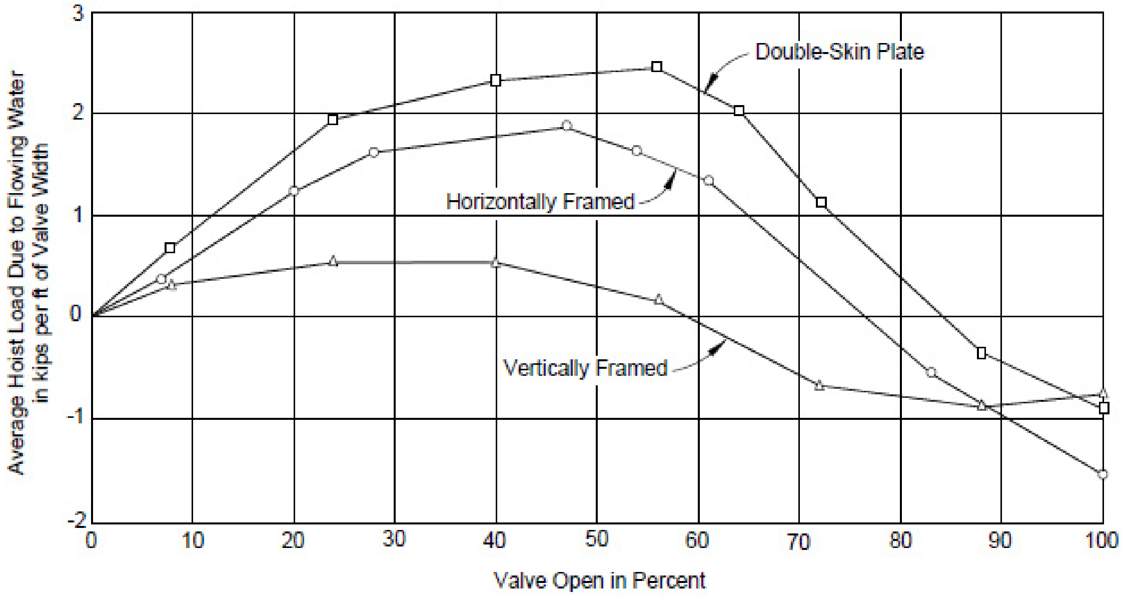


Figure 3-5. Flow patterns around reverse tainter valves.



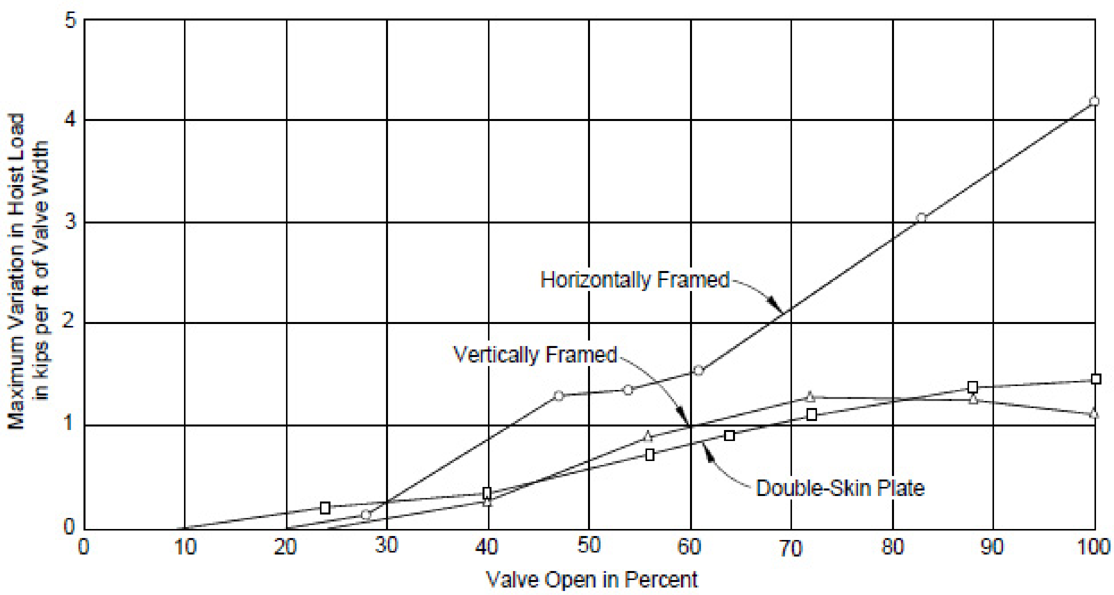


Figure 3-6. Total hoist loads, 60-ft lift.

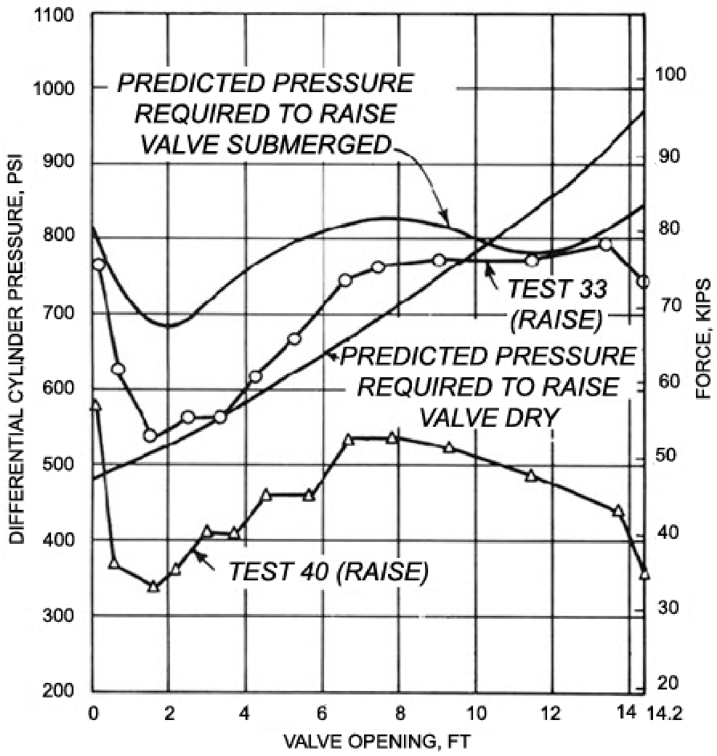


Figure 3-7. Bankhead Lock total hoist loads, design values and those measured in prototype, 1-min (Test 33) and 2-min (Test 40) single-valve operations.

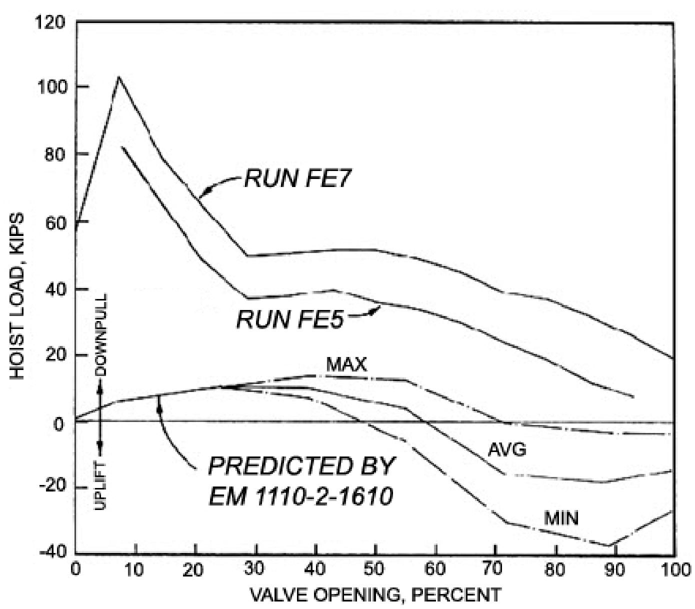


Figure 3-8. Total hoist load on Whitten Lock filling valve hoist load, prototype and design guidance, 1-min (Test FE7) and 4-min (Test FE 5) single-valve operation, 83.1-ft lift.

CHAPTER 4

Valve Seals

4-1. General. Valve seals are the responsibility, primarily, of mechanical design but the hydraulic designer should be aware of cavitation, vibration, and hoist load problems that can result from poor seals. Leaks around valves in high-lift locks can result in cavitation and possible damage to the culvert or the valve. The seals given as examples in this manual have proved satisfactory; however, other arrangements of seals have also been used successfully. It has been found that inadequate anchorage is one of the major causes of problems with embedded items. The block-outs and anchorage systems shown on the examples of seals given herein are required for proper installation.

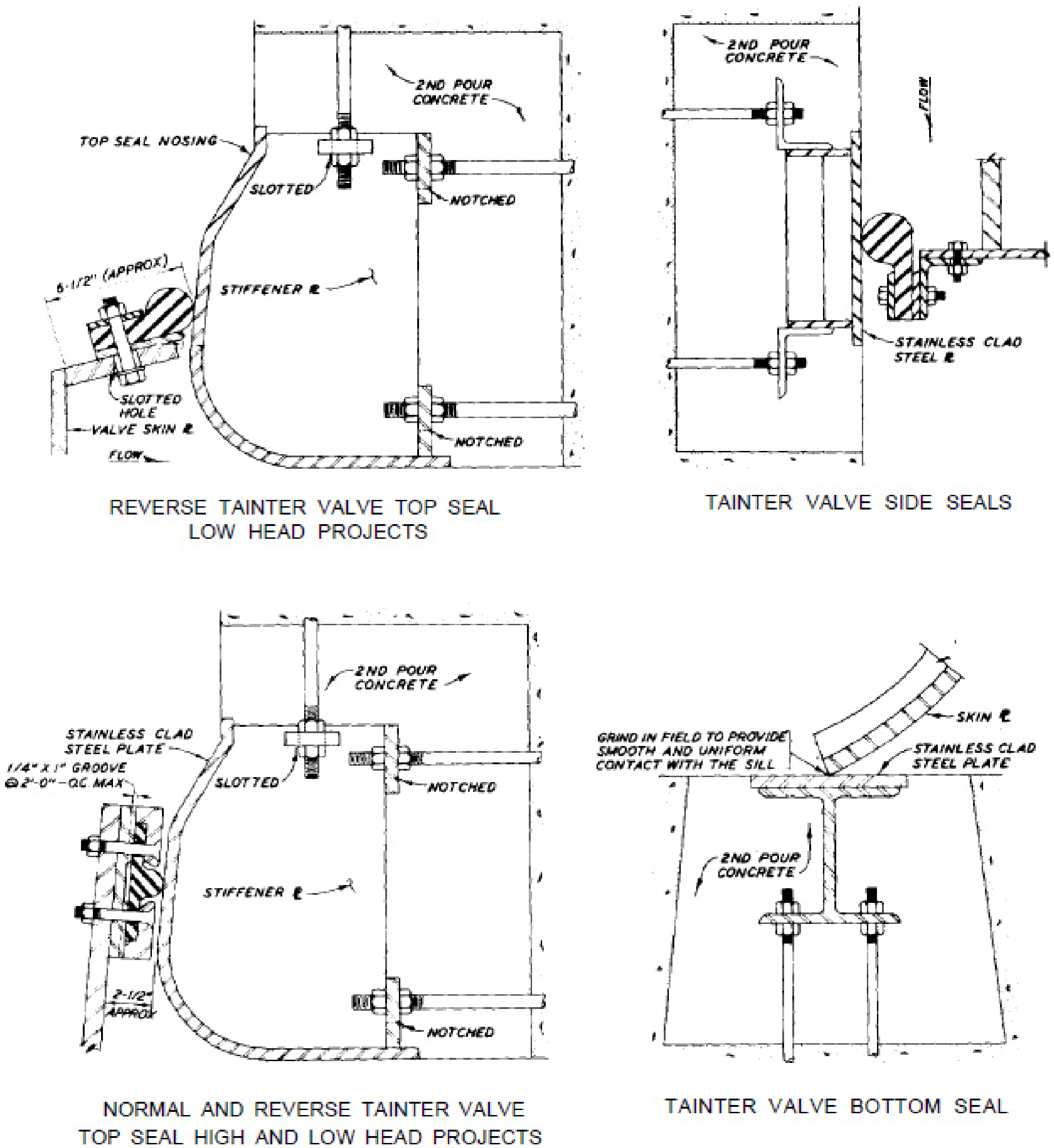
4-2. Bottom Seals. Satisfactory sealing across the bottom of a tainter valve can be accomplished by pressure contact of the lip of the valve on a metal sleeper embedded in the culvert floor (see Figure 4-1). The bottom edge of the skin plate should be ground in the field to provide a smooth and uniform contact with the sill plate. Flexible (rubber) bottom seals can be a source of serious vibrations; and since it has been demonstrated that with reasonable care good metal-to-metal contact can be obtained for the full length of the sill, use of flexible seals is not advocated. However, a compression-type rubber bottom seal has been used successfully on high-lift locks by the Walla Walla District.

4-3. Side Seals. Rubber J-type seals are recommended for the sides of the valve, Figure 4-1. These seals should bear against and slide along curved stainless steel plates embedded flush with the culvert walls. Also, these plates should extend into the valve well for the full height of the opened valve in order to provide lateral support for the valve in the open position. In several installations where lateral support was not provided for the fully open valve, the jostling action of the highly turbulent flow circulating in the valve well resulted in loosening of trunnion anchorages and other damage. The side plates should be free of irregularities that might cause the rubber seal to wear or lose contact. It is very important that the rubber seals be adjusted to maintain a relatively uniform contact with the seal plates. Loss of contact, in addition to allowing leakage, can result in seal flutter which will cause serious vibrations throughout the valve. A survey of USACE District and Division Offices concerning flow-induced vibrations (Neilson and Pickett 1980), found that seals in hydraulic structures were, by far, the most prevalent example of flow-induced vibration reported. Furthermore, it was found that the most common flow-induced vibration problem, the J-type seal, occur as a result of poor adjustment, material wear or deterioration.

4-4. Top Seals. The seal at the top of the valve is likely to present more problems than those at the sides and bottom. The top seal must mate smoothly with the top seal plate and, at the same time, allow the bottom edge of the valve to rest with sufficient pressure on the sill to seal the valve at the bottom. A prolonged rubbing contact and slow breakaway are very undesirable as they are conducive to vibration. Also, the portion of the top seal including the seal bracket that extends beyond the skin plate is exposed to an unbalanced head equal to the lift. This head decreases as the seal moves away from the top seal plate and becomes zero when the distance between the top seal and any part of the gate well face exceeds the distance between the skin plate and the seal plate. In a reverse tainter valve at the beginning of the opening cycle, the hoist must overcome this unbalanced head at the same time it is "breaking" the seals and this may result in the peak load on the hoist. Obviously, it is desirable to maintain the seal projection on the valve as short as practicable.

a. Two designs for the top seal are shown in Figure 4-1. One design is suitable only for reverse tainter valves in locks with relatively low lifts (about 40 ft or less). In this design, the seal bracket projects about 6 inches (horizontally) beyond the skin plate. The unbalanced load in pounds per foot of valve width with the valve closed is equal to 31.25 times the lift in feet. The other design is suitable for all lifts with the valve in either the reverse or normal position. The unbalanced load (downpull for reverse tainter valve, uplift for normal) on this seal in pounds per foot of valve width is only about 13 times the lift in feet. A J-type seal also can be used in high-lift projects, but the clearance between the skin plate and seal nose should not exceed about 2-l/2 inches and the seal bulb should be partially constrained to prevent excessive flutter as the seal is broken.

b. It is difficult to prevent leaks at the junction of the side and top seals. For projects with lifts up to about 40 ft, a molded corner that in effect makes a continuous seal is desirable. However, molded corners tend to transmit movement of the side seals to the top seals and have caused working and eventual failure of the top seals. An arrangement that allows independent movement of side and top seals is suggested at projects with lifts greater than about 40 ft.



NOTES: 1. PROVIDE 0.060" ABRASION RESISTANT FLUOROCARBON FILM ON RUBBER SEALS
2. SEAL RETAINER BOLTS SHOULD BE LOCKED TO PREVENT LOOSENING DUE TO VIBRATION

Figure 4-1. Valve seals (positions shown in Figure 1-6).

CHAPTER 5

Valve Stabilizers

5-1. General. Hydraulic and mechanical design of lock valves must be careful to avoid any known source of vibration. History shows that the most careful valve designs have occasionally suffered from flow-induced vibrations. Valve vibration can be a serious problem and design must be careful to avoid. Vibration is the most prevalent subject in the research literature of gates and valves, suggesting that it is one of the primary causes of valve malfunction. Vibration causes operations and maintenance problems fatiguing not only the valve proper, but can also result in premature aging of mechanical equipment.

5-2. Flow Instability. Reducing excessive vibrations in a system that is already in operation is difficult because the source of excitation is often unknown since the valves are hidden from sight during operation. However, instability-induced excitation is believed to be the largest source of vibration issues on lock valves. Here, flow instabilities such as vortex shedding from the valve lip, arms, and other structural members are the excitation source.

5-3. Dampers. The adverse effects of vibrations can be reduced using lateral dampers (dynamic vibration absorbers). The addition of dampers is usually the only remedial means of reducing excessive vibrations on valves in operation (Naudashcher and Rockwell 1994). Dampers can be mounted on the valve and ride against the wall or on the wall of the valve recess and ride on the valve edge. Design and evaluation of dynamic vibration absorbers is more in line with mechanical engineering remediation methods. Guidance on the mechanical design of lock valves can be found in EM 1110-2-2610.

5-4. Eisenhower and Snell Lock Valves. Vibration troubles on the filling and emptying valves of the Eisenhower and Snell Locks led the St. Lawrence Seaway Development Corporation to install lateral dampers. The dampers, attached to the double-skin plate valves, ride against the wall seals as shown in Figure 5-1. The dampers provided adequate reduction in harmful vibrations.

5-5. Chickamauga Lock Valves. The double-skin plated valves at the Chickamauga Lock were replaced with vertical-frame design. The replacement valves vibrated during operation and subsequent inspection found wear on the trunnion axle. So lateral dampers were added. The dampers on the Chickamauga Lock are attached to the wall of the valve recess and ride against the side ribs as shown in the photograph in Figure 5-2. Design of the valve stabilizers at the Chickamauga Lock is shown on the line drawing in Figure 5-3.

5-6. Recommended Design – Vertical Frame Reverse Tainter Valves. Of course a valve design that provides stable operations does not require dampers. Experiments have confirmed that a properly designed vertically framed valve is the least likely to have problems with flow induced vibrations. The vertical frame valve design, wherein the space between the skin plate and horizontal girders is left open for free flow of water, minimizes dynamic forces on the valve. This design prohibits the use of a top plate, a bottom plate, or any stiffener plates that would inhibit flow between the ribs along the upstream side of the skin plate.

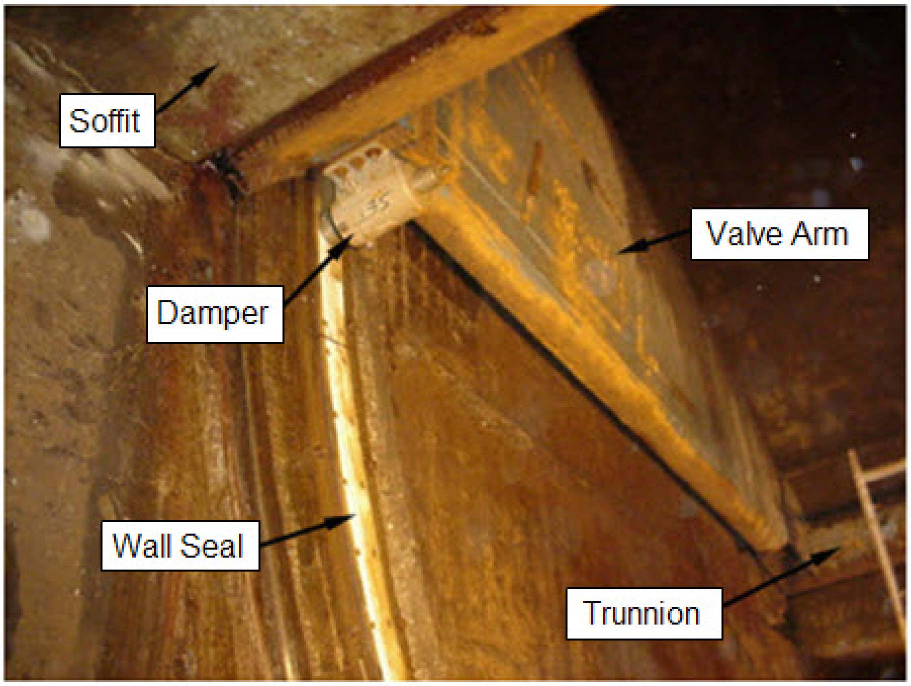


Figure 5-1. Damper attached to bottom of valve arm, Eisenhower and Snell Locks.

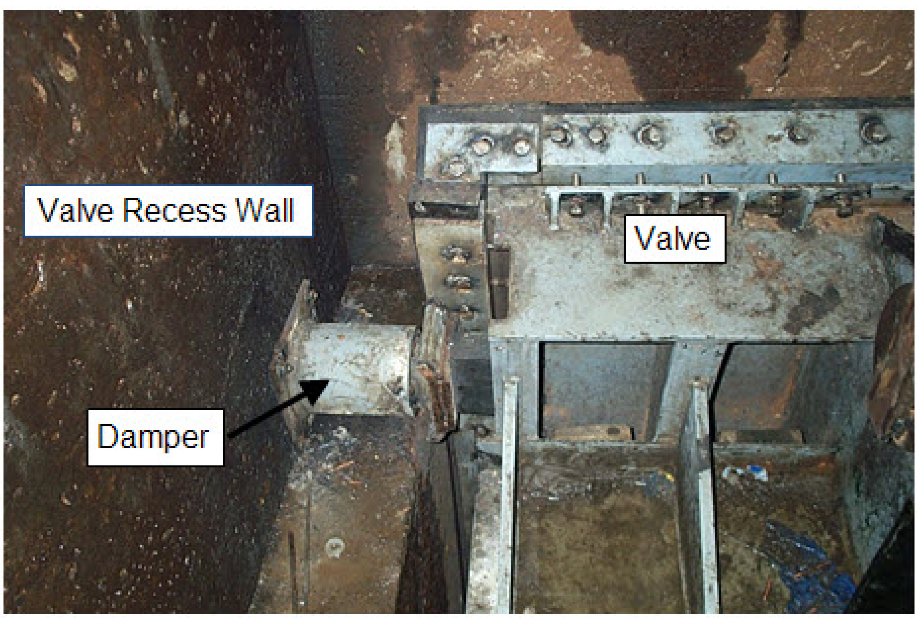


Figure 5-2. Damper attached to valve recess wall, Chickamauga Lock (top view looking downstream).

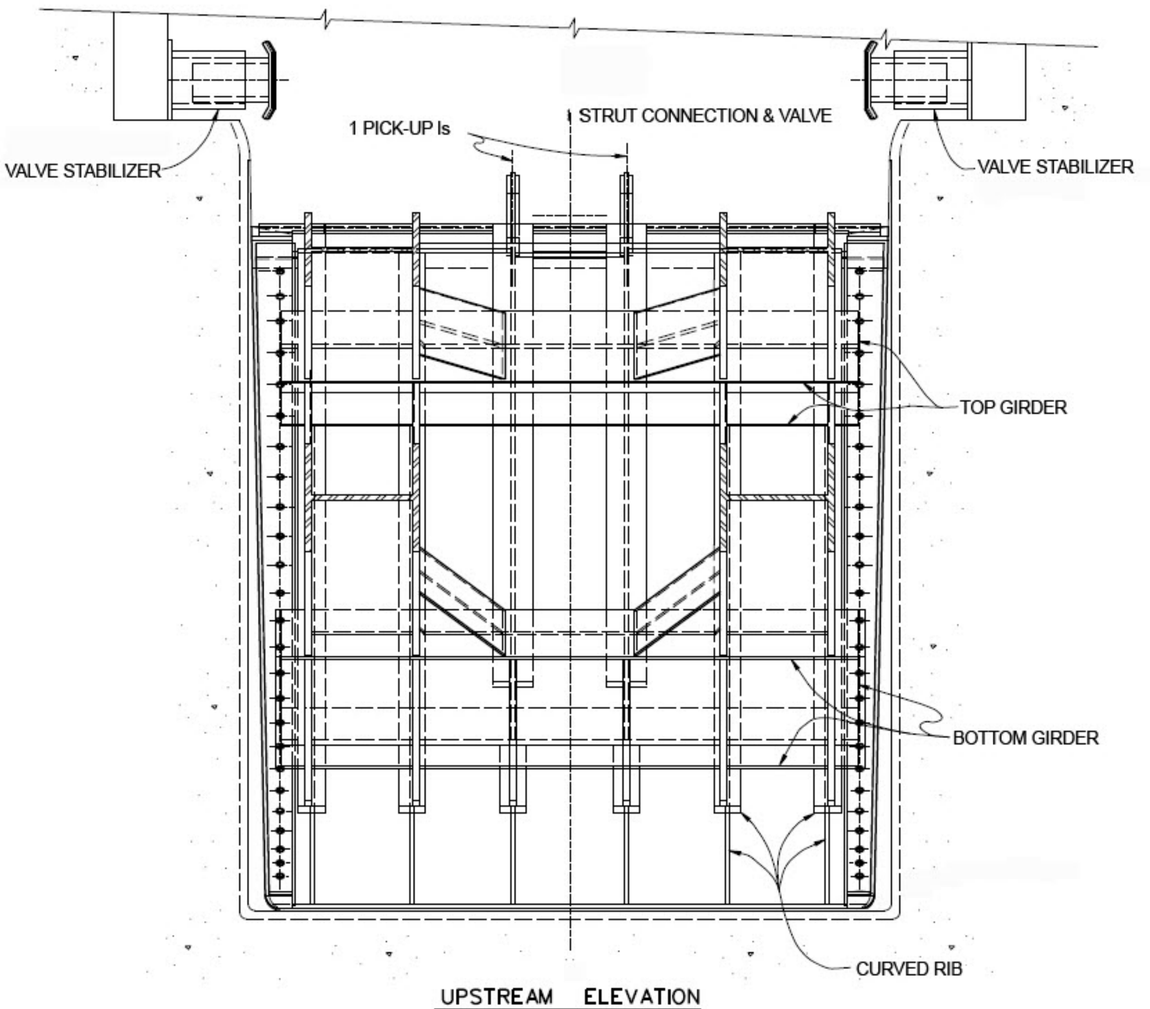


Figure 5-3. Line drawings of dampers installed on valve recess walls, Chickamauga Lock.

CHAPTER 6

Recesses for Unwatering Bulkheads

6-1. General. To allow for service and repair to a valve without taking the lock out of operation, bulkhead recesses are provided on the high- and low-head sides of each of the four valves. Each recess consists of slots in the sides of the culvert, an opening in the culvert roof, and a shaft extending to the top of the lock wall. Although it is unlikely that more than one valve will be under repair at a given time, two sets of bulkheads normally are provided at each project to block upper and lower pools from the culvert system for unwatering of the lock. For storage, the bulkheads usually are held near the top of the shafts by dogging devices (Figure 1-6).

6-2. Bulkhead Recesses. Open-well bulkhead recesses on the high-head sides of the four valves have caused no problems during filling and emptying of the lock. However, there is one known case of a surge in the bulkhead recess created by operation, as discussed in paragraph 3-6c, lifting the bulkhead off of the dogging devices and then allowing it to slam down with sufficient force to break the dogging devices and drop into the culvert. The lifting force was due primarily to the stored bulkhead restricting flow up the shaft. It is suggested that the shaft be enlarged at the position of the stored bulkhead (see Figure 1-6).

6-3. Location of Bulkhead Recesses. During the valve opening period, a zone of low and unstable pressures extends about 6-1/2 times the culvert height downstream from the valve. Usually, other considerations make it desirable to locate the bulkhead recess for the low-head side of the valve within this zone. Thus, an open well for the bulkhead recess on the low-head side of the valve would be a potential source for excess air entering the culvert system. Except for recesses on the low-head side of emptying valves discharging outside of the lower approach to the lock (see paragraphs 2-5a and b), the bulkhead recess on the low-head side of each valve should be sealed. Further, it is desirable that this seal be placed just above the level of the lower pool. If placed near the top of the lock wall, oscillations develop in the column of water in the bulkhead shaft and at some valve openings these oscillations interplay with and amplify the oscillations in the recess, causing unstable loads on the valve hoist.

APPENDIX A

References

Ables, J. H., Jr. 1961. *Intake studies, Dardanelle Lock, Arkansas River, Arkansas; hydraulic model investigation*. Technical Report No. 2-573, Jul 1961, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Ables, J. H., Jr. and T. Schmidtgall. 1961. *Filling and emptying system, New Poe Lock, St. Marys River, Sault Ste. Marie, Michigan; hydraulic model investigation*. Technical Report No. 2-561, Apr 1961, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Ables, J. H., Jr. and M. B. Boyd. 1966. *Filling and emptying system, Cannelton Main Lock, Ohio River, and generalized tests for sidewall port systems for 110- by 1200-ft locks; hydraulic model investigation*. Technical Report No. 2-713, Feb 1966, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Ables, J. H., Jr. and M. B. Boyd. 1969. *Filling and emptying system, Dardanelle Lock, Arkansas River; hydraulic model investigation*. Technical Report No. H-69-5, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Ables, J. H., Jr. and M. B. Boyd. 1966. *Filling and emptying systems, Millers Ferry and Jones Bluff Locks, Alabama River, Alabama; hydraulic model investigation*. Technical Report No. 2-718, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Chanda, A. J. and L. Z. Perkins. 1974. *Filling and emptying system John Day Lock, Columbia River, Oregon and Washington; hydraulic model investigation*. Technical Report No. 98-1, U.S. Army Engineer Division, North Pacific, Bonneville, OR.

Davis, J. P. 1989. *Hydraulic design of navigation locks*. Miscellaneous Paper HL-89-5, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Farrell, J.O. and J. H. Ables. 1968. *Effect of valve position in a sidewall port filling system, Newburgh Lock, Ohio River; hydraulic model investigation*. Technical Report H-68-4, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Fidelman, S. 1961. *Filling and emptying systems for Walter F. George Lock, Chattahoochee River, Alabama-Georgia; hydraulic model investigation*. Hydraulic Laboratory Report No. 73, Sep 1961, Minneapolis, MN: U.S. Army Engineer District, St. Paul, prepared by St. Anthony Falls Hydraulic Laboratory.

Fidelman, S. 1963. *Filling and emptying systems for Barkley Lock, Cumberland River, Kentucky; hydraulic model investigation*. Hydraulic Laboratory Report No. 75, Jun 1963, Minneapolis, MN: U.S. Army Engineer District, St. Paul, prepared by St. Anthony Falls Hydraulic Laboratory,.

George, J. F. 1984. *Filling and emptying system, Walter Bouldin Lock, and lock culvert valve for*

Coosa River Waterway, Alabama; hydraulic model investigation. Technical Report HL-84-8, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Hammack, E. A. and R. L. Stockstill. 2011. *Computational flow model of a reverse tainter valve*. ERDC/CHL CHETN-IX-27, Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Hart, E. D. and J. E. Hite, Jr. 1979. *Prototype gate vibration tests, Barkley Dam, Cumberland River, Kentucky*. Technical Report HL-79-8, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Headquarters, U.S. Army Corps of Engineers. 1988. *Hydraulic design criteria*. Eighteenth issue, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Headquarters, U.S. Army Corps of Engineers. 1980. *Hydraulic design of reservoir outlet works*. Engineer Manual No. 1110-2-1602, Washington, D.C.

Headquarters, U.S. Army Corps of Engineers. 1995. *Planning and design of navigation locks*. Engineer Manual No. 1110-2-2602, Washington, D.C.

Headquarters, U.S. Army Corps of Engineers. 1997. *Engineering and design – vertical lift gates*. Engineer Manual No. 1110-2-2701, Washington, D.C.

Headquarters, U.S. Army Corps of Engineers. 2003. *Engineering and design – lock and dam gate operating and control systems*. Engineer Manual No. 1110-2-2610, Washington, D.C.

Headquarters, U.S. Army Corps of Engineers. 2006. *Hydraulic design of navigation locks*. Engineer Manual No. 1110-2-1604, Washington, D.C.

Headquarters, U.S. Army Corps of Engineers. 2013. *Mechanical and electrical design for lock and dam operating equipment*. Engineer Manual No. 1110-2-2610, Washington, D.C.

Hebler, M. T., and F. M. Neilson, 1976. *Lock Filling and Emptying - Symmetrical Systems*. Miscellaneous Paper H-76-13, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Hite, J. and T. Waller. 2007. Memorandum for DOTS Program Manager, Dr. Doug Clarke, Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Hite, J. E., Jr. 1999. *Model study of Marmet Lock filling and emptying system, Kanawha River, West Virginia*. Technical Report CHL-99-8, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Hite, J. and S. T. Maynord. 2006. *Evaluation report, Locks and Dams 22 and 25; hydraulic evaluation of the preliminary lock design for the filling and emptying system and sill elevation*. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

McGee, R. G. 1989. *Prototype evaluation of Bay Springs Lock, Tennessee-Tombigbee Waterway, Mississippi*. Technical Report HL-89-15, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Murphy, T. E. and J. H. Ables. 1965. *Lock filling and emptying system, Holt Lock and Dam, Warrior River, Alabama, hydraulic model investigation*. Technical Report No. 2-698, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Neilson, F. M. 1975. *Barkley Lock prototype tests, Cumberland River, Kentucky*. Technical Report H-75-11, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Neilson, F. M. and E. B. Pickett. 1980. *Corps of Engineers experiences with flow-induced vibrations*. Miscellaneous Paper HL-80-2, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Neilson, F. M. and E. B. Pickett. 1986. *John Day Lock hydraulic prototype tests, Columbia River, Washington*. draft technical report, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

North, T. 2006. Inspection of the John Day Navigation Lock tainter valves, Memorandum of Design, U.S. Army Engineer Portland District.

Oswalt, N. R., J. H. Ables, Jr., and T. E. Murphy. 1972. *Navigation conditions and filling and emptying system, New Bankhead Lock, Black Warrior River, Alabama; hydraulic model investigation*. Technical Report H-72-6, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Perkins, L. Z. and H. P. Theus. 1975. *Intake manifold and emptying valves for Lower Monumental Lock, Snake River, Washington, hydraulic model investigation*. Technical Report No. 105-1, Bonneville, OR: U.S. Army Engineer Division, North Pacific.

Pickering, G. A. 1981. *Lock culvert valve loss coefficients; hydraulic model investigation*. Technical Report HL-81-10, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Pickett, E. B. and F. M. Neilson. 1988. *Lock hydraulic system model and prototype study data*. Miscellaneous Paper HL-88-1, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Pillsbury, G. B., 1915. Excess Head in the Operation of Large Locks Through the Momentum of the Column of Water in the Culverts. *U.S. Army Corps of Engineers Professional Memoirs*, Vol. 7, No., 31-36, pp. 206-212.

Schohl, G. A. 1999. *User's manual for LOCKSIM: hydraulic simulation of navigation lock filling and emptying systems*, Contract Report CHL-99-1, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Stockstill, R. L., E. A. Hammack, and J. E. Hite, Jr. 2011. *Lock culvert valves; hydraulic design considerations*. ERDC/CHL TR-11-4, Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Stockstill, R. L., E. A. Hammack, D. S. Smith, J. M. Vaughan, and K. Green. 2013. *Hydrodynamic forces on reverse tainter valves; hydraulic model investigation*. ERDC/CHL CHETN-IX-33. Vicksburg, MS: US Army Engineer Research and Development Center.

Stockstill, R. L., E. A. Hammack, T. E. Hood, and J. M. Vaughan. 2013. *Field experience with lock culvert valves*. ERDC/CHL CHETN-IX-34. Vicksburg, MS: US Army Engineer Research and Development Center.

Stockstill, R. L., E. A. Hammack, D. S. Smith, C. B. Bislip-Morales, K. Green, and J. M. Vaughan. 2015. *Hydraulic evaluation of culvert valves at Eisenhower and Snell Locks, St. Lawrence Seaway*. ERDC/CHL TR-15-7, Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Tool, A. R. 1980. *Prototype filling and emptying system measurements, New Bankhead Lock, Black Warrior River, Alabama*. Technical Report HL-80-13, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

U.S. Army Engineer Waterways Experiment Station. 1949. *Vacuum tank tests of model tainter valve for McNary Dam*. Technical Memorandum No. 2-282, Jun 1949, Vicksburg, MS.

U.S. Army Engineer District, Portland. 1955. *Navigation lock for McNary Dam, Columbia River, Oregon and Washington; hydraulic model investigation*. Report No. 26-1, May 1955, U.S. Army Engineer North Pacific Division, prepared by North Pacific Division Hydraulic Laboratory, Bonneville, OR.

U.S. Army Engineer District, Walla Walla. 1955. *Synchronization of lock filling valves, McNary Lock and Dam, Columbia River, Oregon and Washington*. Design Memorandum No. 20, U.S. Army Engineer Walla Walla District.

U.S. Army Engineer Waterways Experiment Station. 1960. *Hydraulic prototype tests of tainter valve, McNary Lock, Columbia River, Washington*. Technical Report No. 2-552, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

U.S. Army Engineer Waterways Experiment Station. 1961a. *Culvert tainter valves, New Lock No. 19, Mississippi River; hydraulic model investigation*. Technical Report No. 2-537, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

U.S. Army Engineer Waterways Experiment Station. 1961b. *Hydraulic prototype tests of tainter valve, McNary Lock, Columbia River, Washington; Appendix A, tabulated test data*. Technical Report No. 2-552, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

U.S. Army Engineer Waterways Experiment Station. 1961c. *Filling and emptying system, New Poe Lock, St. Marys River, Sault Ste. Marie, Michigan; hydraulic model investigation*. Technical

Report No. 2-561, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

U.S. Army Engineer Waterways Experiment Station. 1988. *Hydraulic design criteria*. Eighteenth issue, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

von Mises, R. 1964. *Computation of discharge and overfall coefficients*. Translation No. 64-8, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Waller, T. N. 1997. *Prototype evaluation of Bonneville Navigation Lock, Columbia River, Oregon*. Technical Report CHL-97-14, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

American Society of Civil Engineers. 1930. *Manual on lock valves*. Manuals of Engineering Practice No. 3, Committee on Lock Valves, Waterways Division, NY.

Aydin, I., I. T. Telci, and O. Dundar. 2006. Prediction of downpull on closing high head gates, *Journal of Hydraulic Research*, Vol. 44, No. 6, pp. 822-831.

Baines, W. D. 1954. *Flow through tainter valves*. Ottawa, Canada: National Research Laboratories.

Bhargava, V. P. and S. Narasimhan. 1989. Pressure fluctuations on gates. *Journal of Hydraulic Research*, vol. 27, no. 2, pp. 215-231.

Campbell, F. B. 1961. Vibration problems in hydraulic structures, *Proceedings American Society of Civil Engineers, Journal of Hydraulics Division*, Vol. 67, HY2, pp. 61-77.

Cunge, J. A., F. M. Holly, Jr., and A. Verwey. 1980. *Practical Aspects of Computational River Hydraulics*. Pittman Publishing, London.

Davis, J. P. 1980. Locks and mechanical lifts: state of the art. *National Waterways Roundtable: proceedings: history; regional development; technology; a look ahead*. Norfolk ,VA. Pp. 419-441.

Gibson, A. H. 1930. *Hydraulics and its applications,* 4th edition, p. 249, New York, NY: Van Nostrand Co., Inc.

Henderson, F. M. 1966. *Open Channel Flow*. Macmillan Publishing, New York.

Kolkman, P. A. 1970. Analysis of vibration and damping measurements on a reversed tainter valve. Publication No. 87, Reprint from Paper I.A.H.R. Symposium, Stockholm, Delft, Netherlands: Delft Hydraulics Laboratory.

Lewin, J. 1995. *Hydraulic gates and valves in free surface flow and submerged outlets*, London: Thomas Telford.

Locher, R. A. 1969. *Some aspects of flow-induced vibrations of hydraulic control gates*. Contract Report H-69-1, for U.S. Army Corps of Engineers Waterways Experiment Station, IIHR Report No. 116, Iowa Institute of Hydraulic Research, Iowa City, IA: The University of Iowa.

Luo, S., Hu, Y., B. Fan, and F. Sun. 2009. Study of flow-induced vibration of delivery valve of shiplocks. *Advances in Water Resources and Hydraulic Engineering*, Vol. VI, 2168-2173.

Murphy, T. E. 1942, *Hydraulic model investigation of lock culvert valves*. Jan 1942, Special Engineering Division, Panama Canal Zone, Diablo Heights, Canal Zone.

Naudascher, E. 1991. *Hydrodynamic forces*, International Association for Hydraulic Research, 3 Hydraulic structures design manual, Rotterdam, Netherlands: A.A. Balkema.

Naudascher, E. and D. Rockwell. 1994. *Flow-induced vibrations, and engineering guide*, Mineola, NY: Dover Publications.

Qinghua, X. and X. Guoxiang. 1998. The new methods for preventing cavitation of high-lift ship lock valves in hydro-power projects, *Water Resources Engineering 98, Proceedings of the International Water Resources Engineering Conference*, held in Memphis Tennessee, Reston, VA: American Society of Civil Engineers, pp. 1757-1762.

Rouse, H., 1946. *Elementary Mechanics of Fluids*. Wiley, NY, pp 125-132.

Schmidgall, T. 1972. Spillway gate vibrations on Arkansas River dams, *Proceedings American Society of Civil Engineers, Journal of Hydraulics Division*, Vol. 98, HY1, pp. 219-238.

Thang, N. D. and E. Naudascher. 1986. Vortex-excited vibrations of underflow gates. *Journal of Hydraulic Research*, Vol. 24, No. 2, pp. 133-151.

Thang, N. D. 1990. Gate vibrations due to unstable flow separation. *Journal of Hydraulic Engineering*, Vol. 116, No. 3, pp. 342-361.

Vrijer, A. 1979. *Stability of vertically movable gates*. 19th IAHR Congress, Karlsruhe, paper C5.

Wylie, E. B. and V. L. Streeter. 1993. *Fluid Transients in Systems*, Prentice-Hall.

APPENDIX B

Cavitation at Lock Culvert Valves

B-1. McNary Lock. During 1948, a 1:20-scale model of the 11-ft-wide by 12-ft-high valve proposed for the 92-ft lift McNary Lock on the Columbia River was tested in a vacuum tank at the U.S. Army Engineer Waterways Experiment Station. Cavitation induced in the vacuum tank occurred in the cores of large vortexes that were shed randomly from the valve lip. Test results indicated that these large cavities would occur in the prototype unless the invert of the culvert at the valve section was placed at least 163 ft below the upper pool. The prototype was constructed with the invert of the culvert at the filling valves only 112 ft below the upper pool. Six 12-inch-diameter air vents, two in the culvert roof and two in the upper portion of each sidewall, were installed immediately downstream of each valve. During initial operation of the lock, the air vents at the filling valves were capped. Pounding noises, resembling thunder or cannon shots, seemed to come from the bulkhead slots on the downstream sides of the filling valves when the valves were partially open. Certainly the collapse of large cavities, such as were indicated by the model, would be expected to result in pounding noises rather than the rattling gravel-type sounds that are heard in cavitating pumps, turbines, etc. With one 12-inch-diameter vent open in the roof of the culvert downstream from each filling valve, the pounding noises are eliminated. It is concluded that sufficient air is drawn into this vent to cushion the collapse of the large cavities, eliminate shock pressures, and thus eliminate the pounding noises.

B-2. John Day Lock. In the 113-ft lift John Day Lock on the Columbia River, the culvert valves are 12 ft wide by 14 ft high. The culvert roof slopes up at the rate of 1V on l0H, beginning 19 ft from the downstream face of the filling valve recess to a height of 20 ft. This, together with the depth at which the culvert is placed, results in positive pressure on the roof of the culvert throughout the filling cycle. Although vents are installed downstream from the valve, they do not draw air during a normal 4-min valve time filling operation; however, severe pounding noises emit from the culvert. The local average pressure in the vicinity of maximum pressure reduction just downstream of the filling valve was never high enough to prevent the formation of vapor cavities nor low enough to draw sufficient air to prevent the formation of vapor cavities or cushion their collapse at normal valve openings.

B-3. Cavitation Tests. In order to develop a method for improved operation of John Day Lock and to obtain data for design of future locks, cavitation tests were conducted at Holt, John Day, and Millers Ferry Locks.

a. General dimensions and elevations for the three locks at which tests were made are listed below:

Table B-1

Item	Holt	John Day	Millers Ferry
Location	Warrior River, Alabama	Columbia River, Washington–Oregon	Alabama River, Alabama
Chamber dimensions, ft	110 x 670	86 x 685.4	84 x 655
Type of filling system	Interlaced lateral	Split lateral	Bottom Longitudinal
Normal upper pool el	186.5	268	80
Min lower pool el	122.9	155	32
Max lift, ft	63.6	113	48
Size of reverse tainter valves, ft (width x height)	12.5 x 12.5	12 x 14	10 x 10
Reverse tainter valve design	Vertical frame	Double skin plate	Vertical frame
Culvert roof at filling valves, el	115	128	26
Size of culverts downstream from filling valves, ft (width x height)	12.5 x 15.5*	12 x 20**	10 x 10

*The culvert roof slopes up at the rate of 1V on 8H beginning at the downstream face of valve recess.

**The culvert roof slopes up at the rate of 1V on 10H beginning 19 ft from the downstream face of the valve recess.

b. During normal operation at Holt and Millers Ferry Locks, the filling valves are opened in 4 and 2 min, respectively; and a controlled amount of air is admitted to the system through vents downstream from the filling valves. Performance of the filling system at each of these locks is very satisfactory. At John Day Lock, the valves are opened in about 15 min, as pounding noises occur when the valves are opened at a faster rate.

c. Cavitation observations were made at all three locks with the air vents at the filling valves sealed; thus, no air was admitted to the culvert system during filling operations. Prior to starting each test, the filling valves were held at a small opening until the lock chamber water surface was raised to a predetermined level; the valves were closed and the system was allowed to stabilize. A normal filling operation then was performed. This procedure was repeated with various initial water-surface elevations in the lock chamber.

d. In the valve wells at Holt and Millers Ferry Locks, measurements were made of sound levels and recordings were made of sounds. Also, total valve time, constancy of valve movement, and initial water-surface elevations in the upper pool and lock chamber were noted. Formal reports were not prepared on these observations. At John Day Lock, 13 simultaneous measurements were made and recorded, both on magnetic tape and on a light-beam oscillograph. Data taken included: valve position, lock water-surface elevation, pressures in the culvert at six points, sound at top of valve well, and air flow in vents. Results of these tests are described in Neilson and Pickett (1986).

e. Two phases of the test results are of primary interest in this manual. First, pressure measurements in the culverts at John Day Lock were made to determine the magnitude of pressures concurrent with the loud booms. It was found that the booms were accompanied by rapid pressure fluctuations from one atmosphere negative to about 100 psi positive. While these pressure conditions were most severe a short distance downstream from the filling valve, they carried throughout the system and were reduced only about 50 percent in the culvert immediately upstream from the emptying valve. Certainly, pressure conditions such as these cannot be tolerated for extended periods of operation without expectancy of a structural failure somewhere in the system. In a special test, bulkheads in the slot upstream from an emptying valve were unseated by the negative phase of the pressure surge. Thus, in a lock where cavitation might occur at the filling valves, a culvert should never be used for filling when the emptying valve for that culvert is bulkheaded off for maintenance or repairs. The second item of primary interest is the determination of conditions for incipient cavitation at each of the projects.

f. Data from the two tests that bracketed incipient cavitation at each project are tabulated below:

Table B-2

Item	Holt		John Day		Millers Ferry	
	Test 2	Test 6	Test 2A	Test 3E	Test 5	Test 6
Initial Conditions (Observed)						
Upper pool el	186.3	186.3	262.3	262.8	80.3	80.3
Lock water-surface el	144.0	140.5	180.0	169.5	46.0	45.0
Lift, ft	42.3	45.8	82.3	93.3	34.3	35.3
Culvert roof at valve el	115.0	115.0	128.0	128.0	26.0	26.0
Submergence culvert roof at valve, ft	29.0	25.5	52.0	41.5	20.0	19.0
Valve time, min (Observed)	3	3	4	4	2	2
Conditions at min σ (Computed)						
Valve open, percent	61.5	61.5	57.1	57.1	59.5	59.5
P, ft	15.9	10.1	24.3	7.1	13.2	11.7
V, fps	62.0	64.8	85.6	91.7	53.8	54.7
σ (see paragraph 2-2b)	0.819	0.661	0.504	0.307	1.029	0.964
Comments	Quiet	One distinct boom	Quiet	Several loud booms	Quiet	Coughing noises

Note: *P* and *V* are pressure and velocity at the vena contracta, respectively.

g. Cavitation at Holt and John Day Locks was indicated by very similar pounding noises that resembled thunder or cannon shots. When test conditions were such that cavitation was incipient, the booms occurred only when the valve was near 60 percent open. As conditions for cavitation were made more severe, booms were observed progressively at valve positions both less and more than 60 percent open; but there was no noticeable change in the intensity of the sound of the booms. At Millers Ferry Lock, cavitation was indicated only by coughing noises; and observers questioned whether these noises were accompanied by serious pressure fluctuations. With the level rather than the upsloping roof of the culvert downstream from the Millers Ferry valve, the pressure rise in the culvert certainly is more gradual than at Holt and John Day Locks. Also, during the tests, the most severe conditions for cavitation which were allowable (lift 42.5 ft with lower pool 11.5 ft above roof of culverts at filling valves) resulted in velocities less than those at which cavitation was observed at the other locks. Thus, it is probable that the collapse of the cavities was not sudden enough to produce loud sharp booms. However, at higher velocities loud sharp booms were produced in the McNary conduit which also has a level roof.

h. Engineers of the Mobile District have concluded that optimum operating conditions result with 6-inch orifice plates at Holt and 3-inch orifice plates at Millers Ferry in the two 12-inch-diameter vents at each filling valve. It has been recommended that the valves at John Day Lock be opened to a 30 percent opening as rapidly as is feasible, maintained at this opening for 5 min, and then opened as rapidly as feasible to the fully open position. This requires a total time for opening the valves of about 6-3/4 min. During the tests it was verified that the above procedure eliminates the loud noises attributed to cavitation and results in a filling time of about 13 min rather than 16 min when the valves are opened at a constant speed in 15 min.

B-4. Bankhead Lock. During regularly scheduled maintenance of the Bankhead Lock valves, crews noticed damage to the downstream side of a valve. When the valve was removed from the culvert, it was found that the skin plate damage was more extensive than originally thought. Evidence of cavitation damage, more common on the culvert walls and soffit downstream of lock valves, was noticed on the skin-plate steel. The top third of the skin plate was removed (Figure B-1) and repaired or replaced. Most of the sharp-edged pits in the 7/8-inch thick skin plate were from 1/2 inch to 3/4 inch deep (Figure B-2). The location of damage on the Bankhead Lock valve suggests that at certain valve openings, most likely small openings, high-velocity flow passes between the downstream side the of upper portion of the valve's skin plate and the soffit seal.

B-5. Incipient Cavitation. There has been much discussion regarding the cavitation index value that is associated with incipient cavitation in unvented systems. A value of 0.61 has been used by many and this value is substantiated by the prototype study of Whitten Lock (McGee 1989). Any conditions that allow a cavitation parameter of less than 0.6 to develop is unacceptable.

Figure B-1. Repairing cavitation damage on Bankhead Lock valve skin plate.

Figure B-2. Cavitation damage on downstream face of skin plate at Bankhead Lock valve.

APPENDIX C

Calculating Flow Conditions at Valves

C-1. Computational Lock Models. Hydraulic design of lock culvert valves requires knowledge of flow conditions during lock operations. The designer needs the time-varying head/discharge relation in the form of a hydrograph during lock filling and/or emptying for various valve opening patterns (valve rate, linear stem stroke or stepped valve, etc.). This requires at least a rudimentary computational lock model. H5322 (Hebler and Neilson 1976) and LOCKSIM (Schohl 1999) are the two primary computational tools that are capable of calculating lock system flow conditions during filling and emptying. Detailed description of these computer programs is beyond the scope of this manual and the reader is referred to the user manuals of these computer programs. However, this appendix provides brief descriptions of the programs and distinguishing features of each computer program are pointed out.

C-2. H5320.

a. The USACE's computer program H5320, LOCK FILLING AND EMPTYING-SYMMETRICAL SYSTEMS (Hebler and Neilson 1976) is capable of calculating the head and discharge at valves during lock operations. A definition sketch of the simulated flow conditions at time *t* during a filling operation is shown in Figure C-1. The governing equation is

$$\left[k_1 + k_2 + k_v(t) + k_3 + k_4\right]\frac{V(t)^2}{2g} = Z_u - z(t) - H_I(t) \qquad (1)$$

where

k_1, k_2, $k_v(t)$, k_3, and k_4 = head loss coefficients,
$V(t)$ = velocity of flow at a reference location in the culvert(s) at time t,
g = acceleration due to gravity,
Z_{ref} = upper pool elevation Z_u (filling) and lower pool elevation Z_l (emptying),
$z(t)$ = water-surface elevation in the lock chamber,
$H_I(t)$ = additional head required to accelerate (H_I is positive) or decelerate (H_I is negative) the flow.

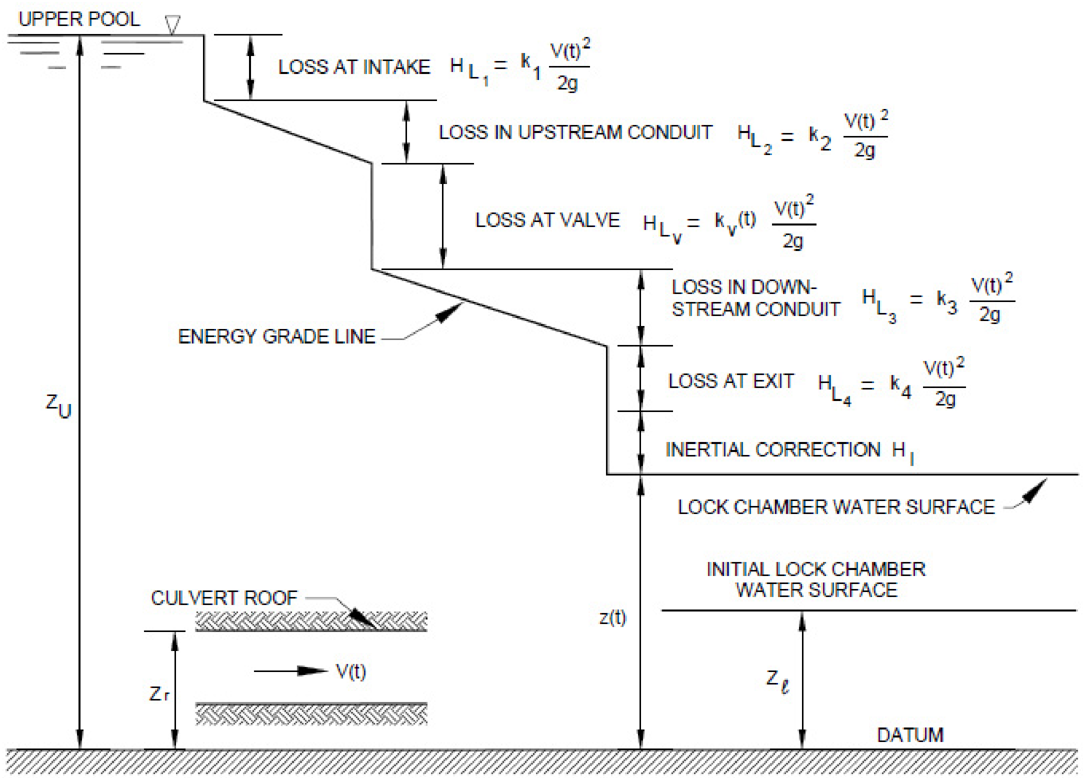


Figure C-1. Simulated flow conditions at time t.

b. H5320 represents inertia effects with an inertia head term, H_I (Rouse 1946). The value of H_I for unsteady frictionless flow in a prismatic tube of length L is

$$H_I = \frac{L}{g}\frac{\partial V(t)}{\partial t} \tag{2}$$

Substituting Equation 2 in Equation 1 gives

$$[k_1 + k_2 + k_v(t) + k_3 + k_4]\frac{V(t)^2}{2g} = Z_u - z(t) - \frac{L}{g}\frac{\partial V(t)}{\partial t} \tag{3}$$

c. The values of $z(i)$ and $V(i)$ are related by continuity as

$$A_l \frac{\partial x(t)}{\partial t} = nA_c V(t) \tag{4}$$

where

A_l = the lock chamber water-surface area,
n = the number of culverts operated, and
A_c = the culvert cross-sectional area.

In H5322 the value of A_c applies immediately below the valve well (i.e., before any change in area occurs); all velocity-dependent or area-dependent variables (loss coefficients, for example) are related to average conditions at this specific location.

d. Equations 3 and 4 are the basic relationships used in the lock filling. The valve loss coefficient $k_v(t)$ is a function only of valve position and, consequently, is known a priori for all t. The equations are solved using a predictor-corrector numerical scheme.

e. The valve opening pattern is approximated by the following equation:

$$\frac{b}{B} = \frac{t}{t_v} - A \sin\left(\frac{\pi t}{t_c}\right) \qquad (5)$$

where

b/B = the valve-opening ratio (B = culvert height),
t/t_v = valve-time ratio (t_v = valve opening time), and
A = the sag coefficient.

The value of A is obtained from the valve opening pattern; A equals (0.5 – b/B) at t/t_v = 0.5. The valve opening pattern for Millers Ferry Lock is shown in Figure C-2. Common values for the sag coefficient are provided in Table C-1.

Table C-1

Lock	A	Comment
Dardanelle	0.21	Large sag
Millers Ferry	0.13	
Bankhead	0.08	Small sag
Barkley	0.14	

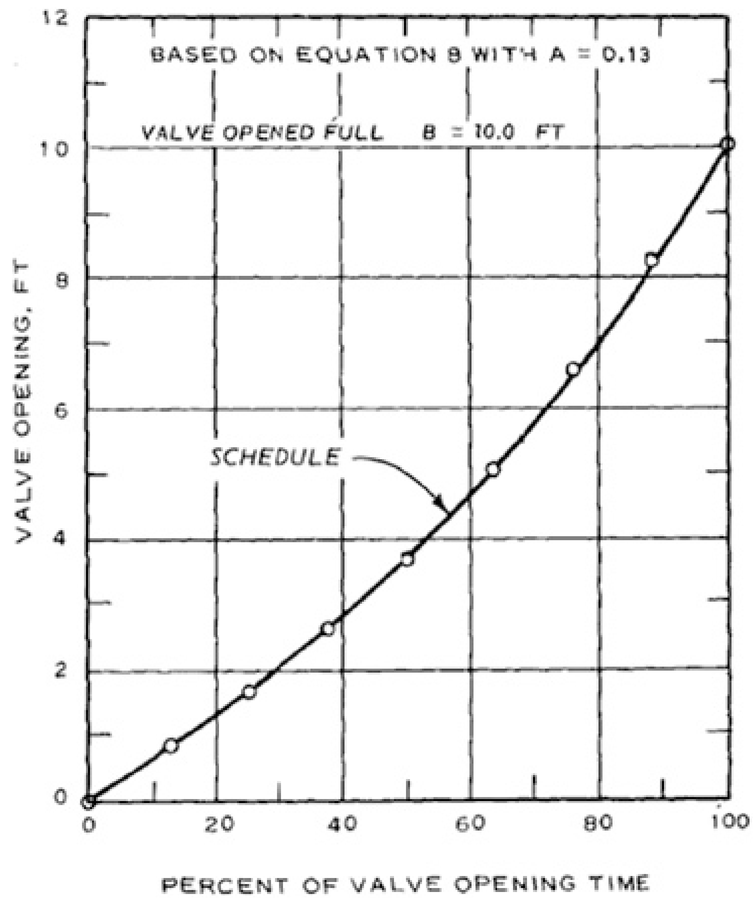


Figure C-2. Valve opening pattern at Millers Ferry Lock.

f. The parameters *B**, *C*, *D*, *E*, and *F* are used to fit a succession of curves to the valve loss coefficient (*B**, *C*) and the valve contraction coefficient (*D*, *E*, *F*) as a function of valve opening.

g. The valve loss coefficient is approximated (as shown in Figure C-3) as follows:

(a) $\frac{b}{B} = 0$ $\quad k_v = 10000$ (6)

(b) $0 < \frac{b}{B} < 0.2$ $\quad k_v = \frac{0.04}{\left(\frac{b}{B}\right)^2}\left(10^{B^* - 0.2C}\right)$ (7)

(c) $0.2 \le \frac{b}{B} \le 1.0$ $\quad k_v = 10^{B^* - C(b/B)}$ (8)

h. The following three points pertain to the above conditions as used in the computer program.

(1) B^* and C are constants ($B^* = 2.2$ and $C = 3.2$).

(2) The value at $b/B = 0$ is not used in the calculations; it is only used to fill out the array of k_v values to simplify the programming.

(3) The functions (b) and (c) are single valued and are equal at $b/B = 0.2$; the corresponding derivatives (which are not used in programming) are not equal at $b/B = 0.2$.

(4) The value at $b/B > 1.0$ is the loss coefficient due to the valve well and the full open valve.

i. The contraction coefficient, C_c, is a parameter needed for calculating the piezometric head, $(p/\gamma + Z)_r$ at the roof of the culvert immediately downstream from the filling valve and the cavitation index, C_i, for the low pressure region below the valve. The expressions used to compute these values are:

$$\left(\frac{p}{\gamma} + Z\right)_r = Z_u - (K_1 + K_2)\frac{V^2}{2g} - \left(\frac{B}{C_c b}\right)^2 \frac{V^2}{2g} \qquad (9)$$

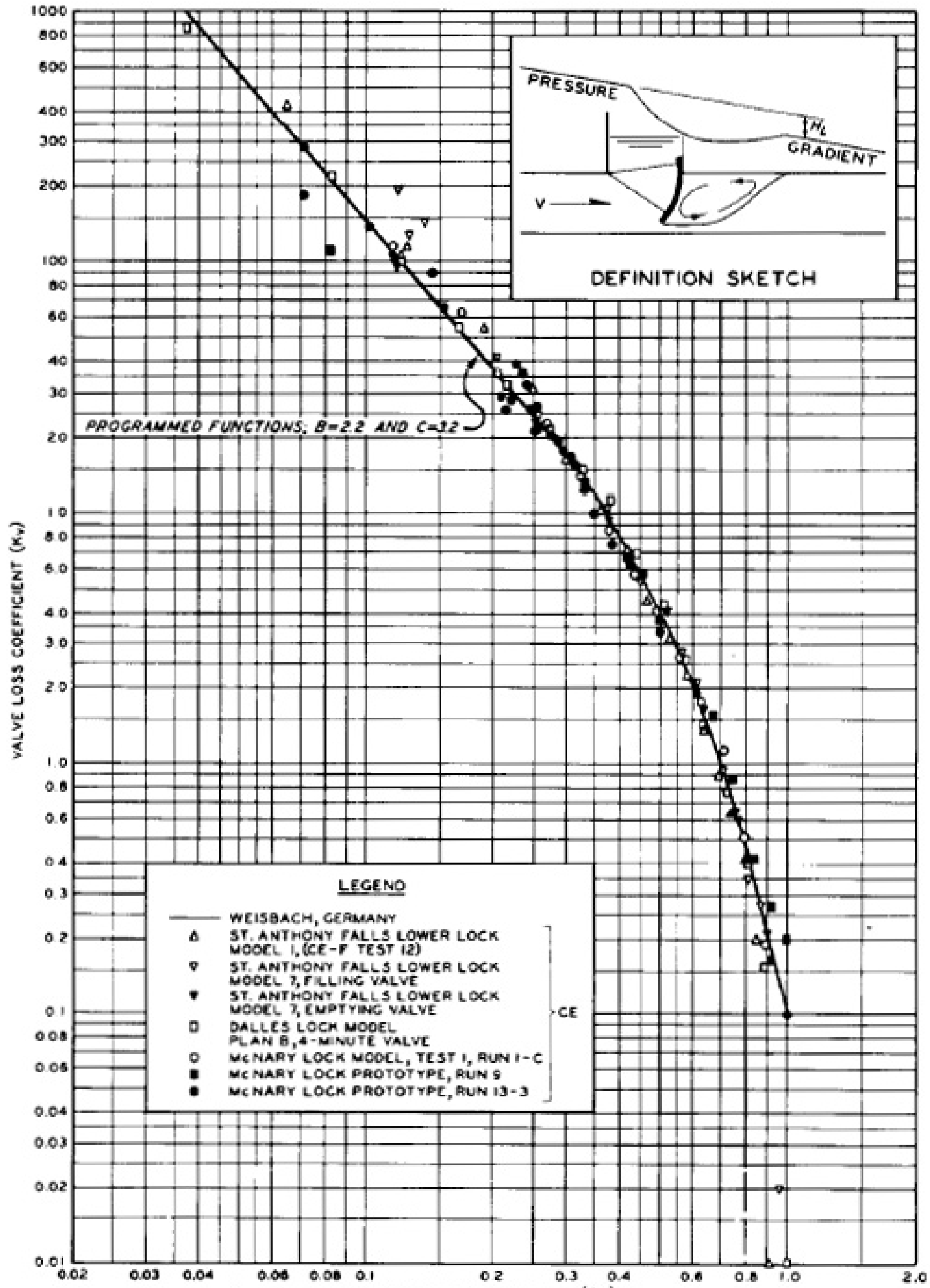
$$C_i = \frac{p}{\gamma_r} + 33.0 - B\,\frac{\left(1-\frac{C_c b}{B}\right)\left(\frac{C_c b}{B}\right)^2}{\frac{V^2}{2g}} \qquad (10)$$

j. Since the flow pattern below the valve changes as the valve opens, published contraction coefficient values are appropriately used only at intermediate values of b/B, say $0.3 < b/B < 0.7$. To fill in the values outside this range as well as to provide a reference set of values for C_c at the intermediate openings (the published data show considerable scatter) the following equations are used

$$0 \le \frac{b}{B} \le 0.2; \qquad C_c = D + (E - D)\cos\left(\frac{\pi b}{0.6B}\right) \qquad (11)$$

$$0.2 < \frac{b}{B}; \qquad C_c = F - (F - D)\cos\left(\pi\,\frac{b - 0.3B}{1.4B}\right) \qquad (12)$$

k. The intermediate values of C_c are sensitive to the value of the parameter, D; simulations of model and prototype conditions have shown that the values 0.65, 0.8, and 0.9 for D, E, and F, respectively, are adequate for most design purposes. The corresponding curves are shown in Figure C-4.



BASIC EQUATION $K_V = \frac{H_L}{V^2/2g}$

WHERE
K_V = VALVE LOSS COEFFICIENT
H_L = HEAD LOSS ACROSS VALVE IN FT OF WATER
V = AVERAGE VELOCITY IN FT/SEC
g = ACCELERATION OF GRAVITY-FT/SEC^2

Figure C-3. Loss coefficient, reverse tainter valve.

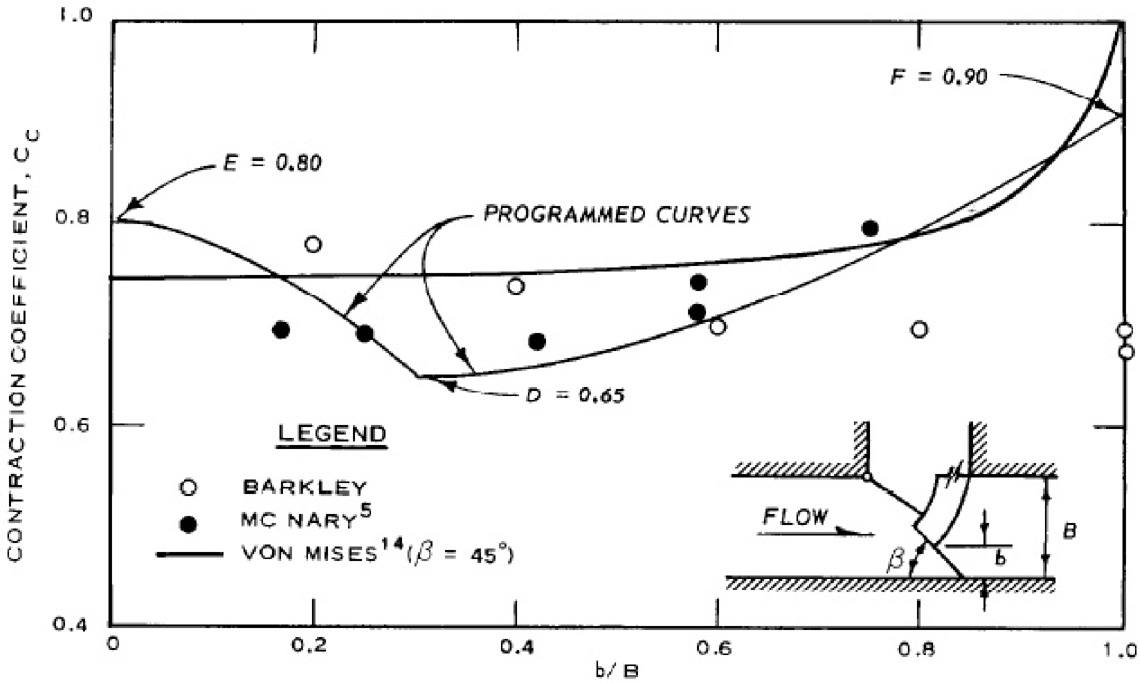


Figure C-4. Reverse tainter valve contraction coefficient.

l. Several unsteady features of the flow are not included in the H5320 mathematical model. Examples are oscillations of the water in the lock chamber; surging between the upstream pool, the lock chamber, and the valve wells; and pressure fluctuations below the filling valves. Cavitation below the filling valve (to the extent that the rate of flow through the valve is decreased) is also not included. In situations where these types of effects are of significance, the program will obviously generate erroneous values; on the other hand, when these effects are of a secondary nature (as usually is the case) and when the program is accurately validated, the calculated values appear to be as precise as any data with which they have been compared.

C-3. LOCKSIM.

a. The numerical flow model, LOCKSIM (Schohl 1999), serves as an improved evaluation tool for lock filling and emptying system designs. LOCKSIM couples the unsteady pressure-flow equations, which are applicable to the conduits within the system; with the free-surface equations describing the approach reservoirs, valve wells, and lock chamber. The model computes pressures and flow distributions throughout a lock system. LOCKSIM provides longitudinal distribution of flow and water-surface elevations in the lock chamber. The water-surface gradients are the primary driving force on vessels moored within the lock chamber.

b. LOCKSIM simulates closed-conduit components such as culverts, reverse tainter valves, pipe losses, tees, and manifolds. Free-surface components include prismatic open channels, river channels, and water storage components (which can represent reverse tainter valve wells). Individual components from these lists are connected together at nodes, where they share a common piezometric head. Distinguishing technical features of LOCKSIM include prediction of cavitation index and minimum pressure downstream from the reverse tainter valves, rigorous treatment of dividing and combining flows through tees and manifolds, and capability of including upstream and downstream approach channels in models of filling and emptying systems.

c. Discharge and piezometric head in the pipe and free-surface channel components are computed by numerically solving partial differential equations for one-dimensional unsteady flow. The relationships between discharge and piezometric head difference for valves, check valves, and pipe losses are described by algebraic energy equations. The position of a valve is prescribed as a function of simulation time using tabulated data. Functions are also used for tee and manifold components, which simulate combining and dividing flow, to describe the variation of the branch head loss coefficients with the ratios of the individual branch discharges to the combined discharge. Available time-varying numerical results include pressure, hydraulic gradeline elevation, and discharge at all computational points. The stage, velocity, depth, top width, and channel area are provided at each computational point within the free-surface components and the velocity, shear stress, and vapor cavity volume are given for each computational point within the closed-conduit components. The minimum pressures and cavitation indices in the wakes of reverse tainter valves are also computed.

d. One-dimensional unsteady flow in uniform closed conduit components is described using the mass and momentum conservation equations (Schohl 1999):

$$\frac{\partial p}{\partial t}+\frac{\rho a^2}{A}\frac{\partial Q}{\partial x}=0 \qquad (13)$$

$$\frac{\partial Q}{\partial t}+\frac{A}{\rho}\frac{\partial p}{\partial x}+gA\frac{dz}{dx}+\frac{4A\tau_o}{\rho D_h}=0 \qquad (14)$$

where

p = pressure,
Q = discharge,
x = longitudinal coordinate,
a = acoustic wave speed,
A = cross-sectional area,
D_h = hydraulic diameter,
ρ = fluid density,
z = centerline elevation, and
τ_0 = wall shear stress.

Hydraulic diameter, D_h, refers to the quantity ($4A/P$) in which P = wetted perimeter. The wall shear stress is computed using the Darcy-Weisbach formulation.

e. One-dimensional unsteady flow in open channels is modeled using the following form of the continuity and momentum equations (e.g. Cunge et al. 1980, Wylie and Streeter 1993, and Henderson 1966):

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}-q=0 \tag{15}$$

$$\frac{\partial Q}{\partial t}+\frac{Q}{A}\left(2\beta\frac{\partial Q}{\partial x}+q\right)-\beta\frac{Q^2}{A^2}\frac{\partial A}{\partial x}+gA\frac{\partial H}{\partial x}+gAS_f=0 \tag{16}$$

where

H = water surface elevation or piezometric head defined by $H = p/(\rho g) + z$,
β = momentum correction factor,
q = lateral inflow per unit length,
S_f = friction slope, and
z = bed elevation.

The free-surface equations for prismatic rectangular channels are rewritten in terms of pressure p, discharge, Q, and shear stress, τ_0, as follows:

$$\frac{\partial p}{\partial t}+\frac{\rho g}{T}\left(\frac{\partial Q}{\partial x}-q\right)=0 \tag{17}$$

$$\frac{\partial Q}{\partial t}+\frac{Q}{A}\left(2\beta\frac{\partial Q}{\partial x}+q\right)-\beta\frac{Q^2}{A^2}\frac{\partial A}{\partial x}+\frac{A}{\rho}\frac{\partial p}{\partial x}+gA\frac{dz}{dx}+\frac{4A\tau_o}{\rho D_h}=0 \tag{18}$$

in which

T = width of cross section at the water surface, and
τ_0 = bed shear stress.

f. Component head losses are determined using the energy equation:

$$\frac{Q^2}{2gA_u^2}+H_u=\frac{Q^2}{2gA_d^2}+H_d+h_l \tag{19}$$

in which

A_u = upstream flow area,

H_u = upstream piezometric head defined by $H = p/\rho g + z$,
A_d = downstream flow area,
H_d = downstream piezometric head, and
h_l = energy loss.

The energy loss, h_l, is defined by

$$h_l = \begin{cases} K \dfrac{Q|Q|}{2gA^2} & \text{L turbulent} \\ K \dfrac{\nu R_{lam} \sqrt{\pi}\, Q}{4gA^{3/2}} & \text{L laminar} \end{cases} \qquad (20)$$

in which

K = a loss coefficient,
A = flow area for which K applies,
ν = kinematic viscosity, and
R_{lam} = user-defined transition Reynolds number between laminar and turbulent flow.

Flow is assumed turbulent when the Reynolds number defined by $QD/A\nu$ where $D = (4A/\pi)^{1/2}$ exceeds R_{lam}.

g. Data for contraction coefficient, C_c, and loss coefficients, K_v, for reverse tainter valves in lock culverts are available in publications of the USACE. Figure C-5 shows two representations of the function $C_c(b/B)$. The solid line plot, described by the polynomial

$$C_c = 0.948 - 1.396\frac{b}{B} + 2.98\left(\frac{b}{B}\right)^2 - 2.918\left(\frac{b}{B}\right)^3 + 1.385\left(\frac{b}{B}\right)^4 \qquad (21)$$

is a curve-fit to prototype data shown in Figure C-4. The dashed line plot is the curve applied in H5320 (shown in Figure C-4).

h. Figure C-6 shows a representation of the function $C_{dv}(b/B)$ based on K_v data provided by USACE (1988). The prototype data are sparse and scattered for b/B values less than 0.2 and greater than 0.9. In order to obtain reasonable values of the cavitation index for small valve openings, the curve in Figure C-6 was extended to b/B equal to 0 by assuming that the entire velocity head at the vena contracta is lost when the flow expands to fill the culvert. The prototype data suggest that the value of K_v for a fully open (b/B equal to 1) reverse tainter valve is between 0.01 and 0.2. A K_v value of 0.1 equates to a C_{dv} equal to 3.16.

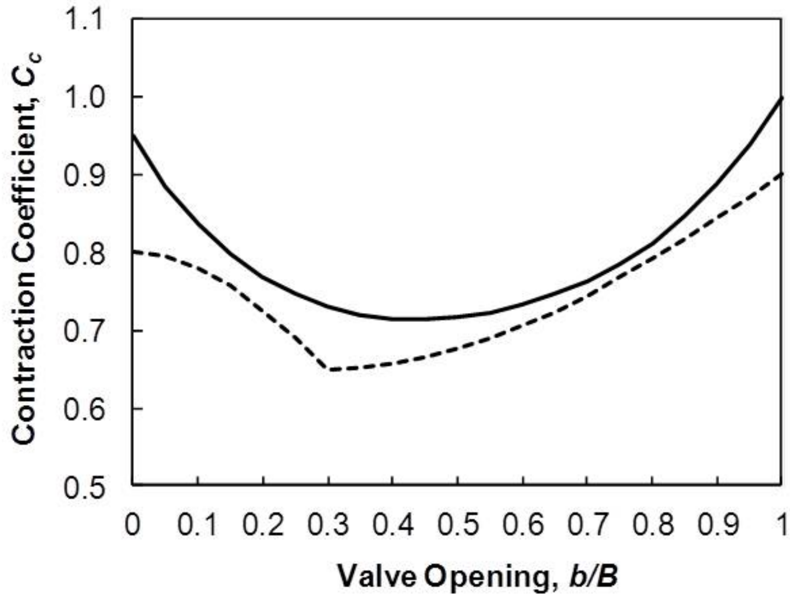


Figure C-5. Contraction coefficient for reverse tainter valve.

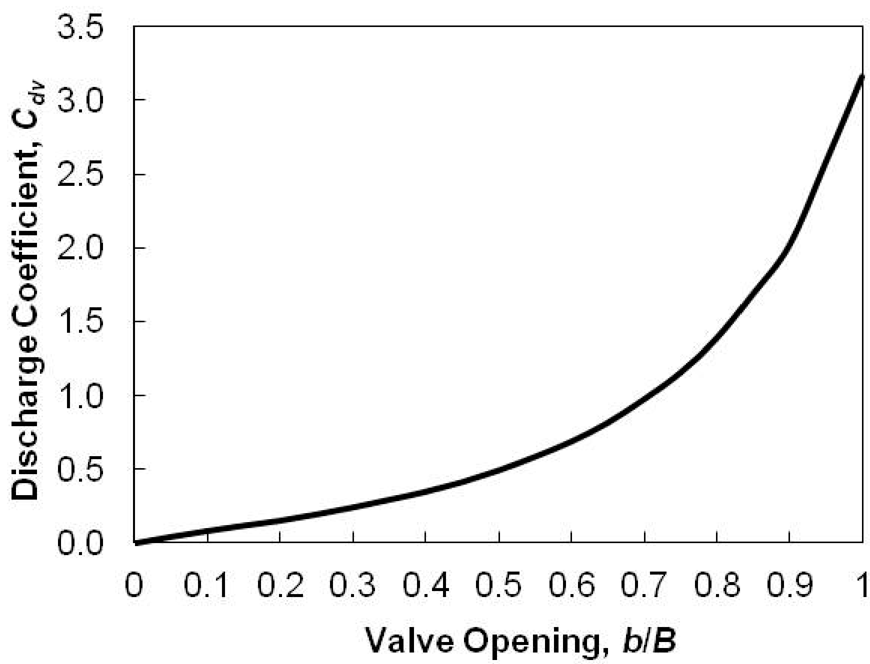


Figure C-6. Discharge coefficient for reverse tainter valve

APPENDIX D

Hoist Loads from Hydraulic Model Studies

D-1. Site Specific Studies.

a. Results from four physical model studies are presented in this appendix. Forces measured during site specific physical model studies illustrate the differences in hoist loads that simple design changes can make. Primary parameters of reverse tainter valves (Figure 1-5) are the culvert width (*W*), culvert height (*B*), valve opening (*b*), valve radius (*R*), and valve curvature (1/*R*). Secondary parameters are the relative valve opening (*b/B*) and the radius to culvert height ratio (*R/B*).

b. The hoist loads are presented in terms of average velocity in the culvert upstream of the valve and relative valve opening (*b/B*). Loads are given in force per unit width of valve so as to be more general and useful to designers. The hydraulic load is defined as the total force measured minus the force measured with a dry valve at particular opening positions.

c. The relevant parameters of the hydraulic physical model studies are listed below. The bibliographic information for the model reports are among the list of references in Appendix A. Line drawings of the various valve designs, tables of hoist load data, and graphs of forces for discharges associated with specific valve times follow.

Hydraulic Model Study Designs

Project	Model Study Report	Lift, ft	Valve Radius, *R*, ft	Culvert Height, *B*, ft	Valve Curvature, *R/B*	Designs Reported
Lock No. 19	U.S. Army Engineer Waterways Experiment Station (1961a)	38.2	21.0	14.5	1.45	Types 1-17
Poe Lock	U.S. Army Engineer Waterways Experiment Station (1961c)	21.0	21.0	14.5	1.45	Types 1-4
Holt Lock	Murphy and Ables (1965)	63.5	17.0	12.5	1.36	Types 1-7
Snell Lock	Stockstill et al. (2015)	49.0	21.0	14.0	1.50	Types 1-7

D-2. Lock No. 19 Hydraulic Model Investigation. Physical model study of the Lock No. 19 culvert valves was reported in U.S. Army Engineer Waterways Experiment Station (1961a). The Lock No. 19 valves are of the horizontally framed reverse tainter design. The particular geometrical and hydraulic conditions of the Lock No. 19 include a culvert height of 14.5 ft with a valve radius of 21.0 ft (*R/B* of 1.45). Hoist loads were measured for various discharges with a design lift of 38.2 ft.

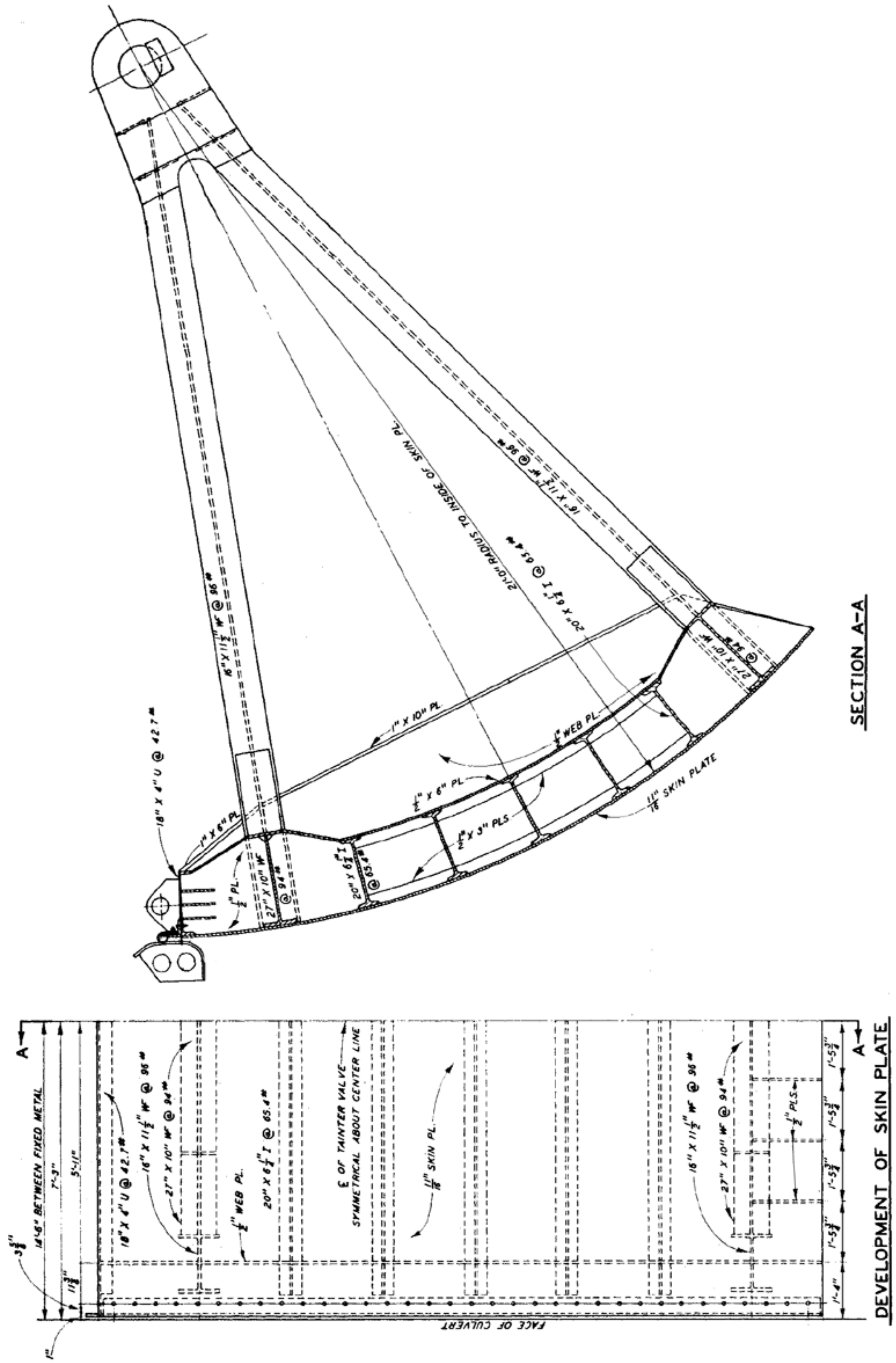


Figure D-1. Tainter Valve, Lock No. 19, Type 1 Design.

Table D-1. Hoist Loads, Lock No. 19, Type 1 Design.

Valve Open, b/B	Culvert Velocity, fps	Hoist Load, kips per ft of Valve Width					
			Hydraulic				
		Dry Valve	Minimum	Maximum	Observed Average	Variation
0.07	1.8	1.66	----	----	-0.041	----
	2.3		----	----	-0.007	----
	2.8		----	----	0.021	----
0.13	3.4	1.69	----	----	0.003	----
	4.2		----	----	0.190	----
	5.0		0.307	0.362	0.307	0.055
0.20	5.3	1.70	0.137	0.219	0.199	0.083
	6.6		0.295	0.350	2.028	0.055
	7.9		0.647	0.688	0.661	0.041
0.28	7.4	1.73	0.349	0.411	0.390	0.062
	9.2		0.708	0.790	2.476	0.083
	11.1		1.032	1.101	1.080	0.069
0.34	4.8	1.75	0.324	0.414	0.366	0.090
	6.2		0.662	0.738	2.455	0.076
	7.6		1.007	1.083	1.062	0.076
0.40	10.6	1.77	0.244	0.451	0.327	0.207
	13.2		0.396	0.754	2.386	0.359
	15.8		0.879	1.058	0.968	0.179
	18.3		1.451	1.775	1.617	0.324
0.47	12.5	1.81	0.388	0.629	0.498	0.241
	15.5		0.450	0.891	2.441	0.441
	18.6		0.829	1.367	1.029	0.538
	21.4		1.339	1.677	1.505	0.338
0.54	14.4	1.84	0.110	0.379	0.227	0.269
	17.8		0.227	0.751	2.276	0.524
	21.4		0.275	1.323	0.751	1.048
	24.7		0.634	1.827	1.158	1.193
0.61	16.2	1.88	-0.091	0.316	0.171	0.407
	20.1		-0.112	0.599	2.179	0.710
	24.1		0.006	0.971	0.481	0.966
	27.8		0.006	1.495	0.840	1.490
0.72	19.1	1.97	-0.621	0.310	-0.097	0.931
	23.7		-0.759	0.641	1.869	1.400
	28.4		-1.166	1.454	0.027	2.621
	32.7		-1.814	1.786	0.165	3.600

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.83	22.0	2.09	-0.927	-0.120	-0.451	0.807
	27.3		-1.548	0.073	1.510	1.621
	32.8		-1.906	0.259	-0.644	2.166
	37.7		-2.148	0.618	-0.741	2.766
0.95	9.5	2.22	-1.094	-0.356	-0.735	0.738
	14.3		-2.259	-0.211	1.276	2.048
	19.0		-2.880	0.168	-1.308	3.048
	23.8		-3.211	0.299	-1.404	3.510
1.03	26.5	2.51	-1.379	-0.545	-0.876	0.834
	33.0		-2.310	-0.400	1.393	1.910
	39.6		-3.310	0.531	-1.593	3.841

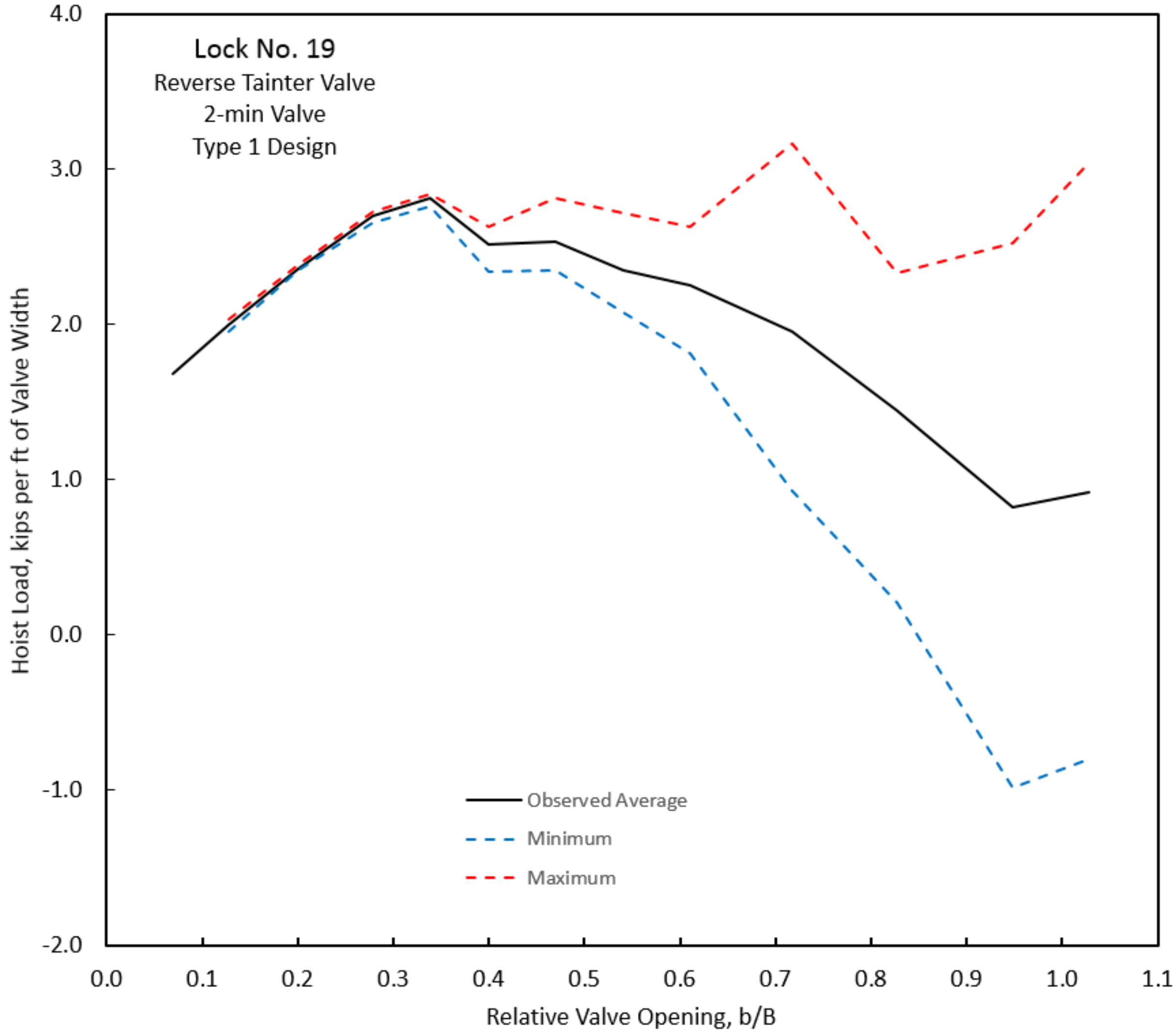


Figure D-2. Hoist loads, Lock No. 19, Type 1 Design, 2-min Valve.

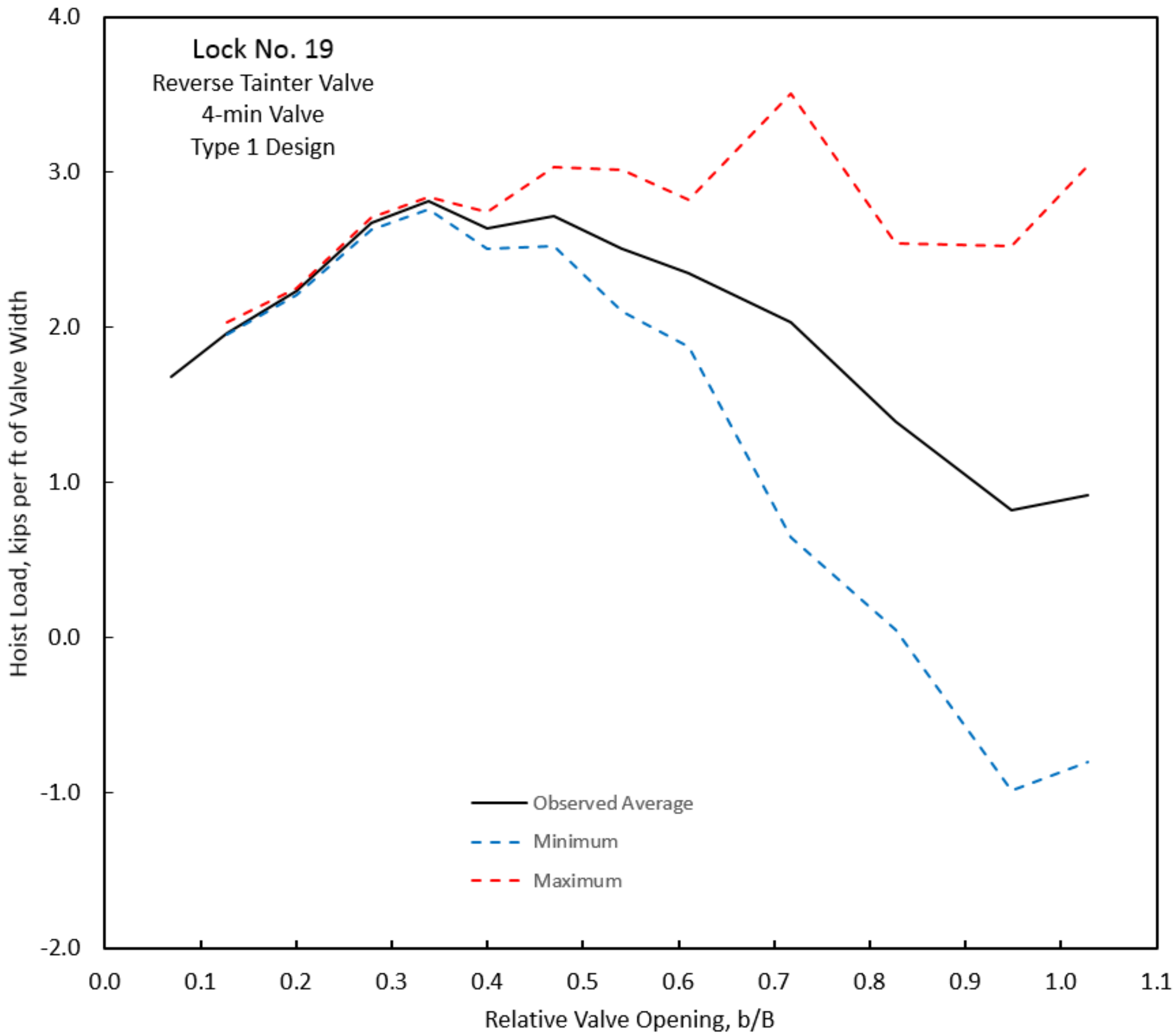


Figure D-3. Hoist loads, Lock No. 19, Type 1 Design, 4-min Valve.

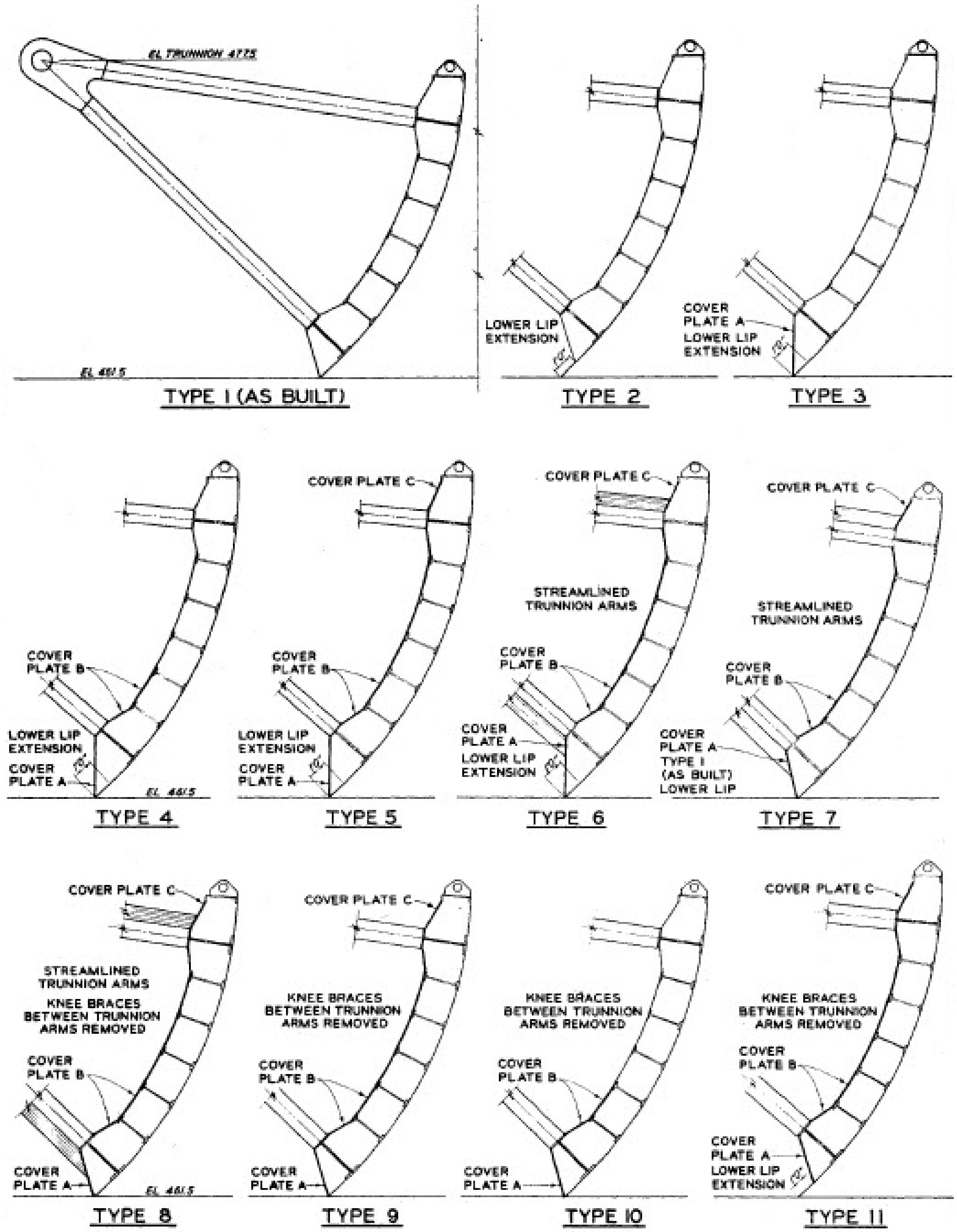


Figure D-4. Tainter Valves, Lock No. 19, Types 1-11 Designs.

Table D-2. Hoist Loads, Lock No. 19, Type 2 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.27	7.3	1.73	-0.003	0.039	0.025	0.041
	9.0		0.128	0.259	0.204	0.131
	10.9		0.301	0.487	0.390	0.186
0.57	15.2	1.89	-0.379	-0.117	-0.206	0.262
	18.9		-0.592	0.187	-0.117	0.779
	22.7		-0.641	0.221	-0.089	0.862
	26.2		-0.779	0.414	0.001	1.193
0.71	18.9	2.03	-0.770	-0.197	-0.390	0.572
	23.5		-1.342	0.230	-0.218	1.572
	28.3		-2.177	0.617	-0.390	2.793
	32.7		-2.314	0.851	-0.625	3.166
0.87	22.9	2.30	-1.266	-0.217	-0.645	1.048
	28.4		-1.597	-0.217	-0.569	1.379
	34.2		-2.500	-0.169	-1.121	2.331
	39.5		-2.790	1.645	-1.597	4.434
0.94	25.1	2.49	-1.118	-0.408	-0.642	0.710
	31.1		-2.049	-0.359	-1.070	1.690
	37.3		-2.739	-0.477	-1.428	2.262

Table D-3. Hoist Loads, Lock No. 19, Type 3 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.28	7.3	1.79	-1.794	-1.794	0.103	0.000
	9.1		-1.794	-1.794	0.248	0.000
	11.0		-1.794	-1.794	0.468	0.000
0.57	15.2	1.92	-0.097	0.006	-0.042	0.103
	18.9		-0.049	0.137	0.075	0.186
	22.2		-0.014	0.296	0.172	0.310
	26.2		0.006	0.682	0.351	0.676
0.72	19.1	2.06	-0.461	-0.310	-0.392	0.152
	23.7		-0.599	-0.241	-0.358	0.359
	28.4		-0.737	0.097	-0.330	0.834
	32.7		-0.868	0.118	-0.282	0.986
0.88	23.2	2.32	-0.855	-0.559	-0.669	0.297
	28.8		-1.228	-0.524	-0.738	0.703
	34.6		-1.379	-0.524	-0.855	0.855
	40.0		-1.834	-0.152	-1.000	1.683
0.95	25.3	2.52	-1.052	-0.721	-0.962	0.331
	31.3		-1.445	-0.700	-1.079	0.745
	37.6		-2.148	-0.838	-1.259	1.310
	43.4		-2.521	-0.017	-1.438	2.503

Table D-4. Hoist Loads, Lock No. 19, Type 4 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.28	7.3	1.86	-1.859	-1.859	0.065	0.000
	9.1		0.196	0.251	0.223	0.055
	11.0		0.368	0.437	0.396	0.069
0.57	15.2	2.02	-0.330	-0.199	-0.268	0.131
	18.9		-0.289	-0.137	-0.206	0.152
	22.2		-0.289	0.090	-0.151	0.379
	26.2		-0.434	0.421	-0.027	0.855
0.72	19.1	2.16	-0.528	-0.314	-0.411	0.214
	23.7		-0.528	-0.197	-0.342	0.331
	28.4		-0.887	0.065	-0.314	0.952
	32.7		-1.128	0.244	-0.411	1.372
0.88	23.2	2.41	-0.854	-0.565	-0.710	0.290
	28.8		-1.165	-0.544	-0.896	0.621
	34.6		-1.399	-0.420	-0.896	0.979
	40.0		-1.972	-0.303	-1.137	1.669
0.95	25.3	2.63	-1.123	-0.786	-0.944	0.338
	31.3		-1.551	-0.786	-1.117	0.766
	37.6		-1.834	-0.786	-1.296	1.048
	43.4		-2.599	-0.096	-1.475	2.503

Table D-5. Hoist Loads, Lock No. 19, Type 5 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.28	7.3	1.98	-0.053	0.009	-0.019	0.062
	9.1		0.126	0.188	0.154	0.062
	11.0		0.306	0.395	0.361	0.090
	12.7		0.437	0.540	0.485	0.103
0.57	15.2	2.15	-0.123	-0.006	-0.027	0.117
	18.9		-0.027	0.111	0.056	0.138
	22.2		0.008	0.373	0.173	0.366
	26.2		-0.068	0.732	0.352	0.800
0.72	19.1	2.29	-0.474	-0.247	-0.323	0.228
	23.7		-0.454	-0.116	-0.261	0.338
	28.4		-1.095	0.574	-0.261	1.669
	32.7		-0.895	0.215	-0.247	1.110
0.88	23.2	2.56	-0.845	-0.534	-0.652	0.310
	28.8		-1.134	-0.383	-0.776	0.752
	34.6		-1.369	-0.528	-0.955	0.841
	40.0		-1.790	-0.479	-1.010	1.310
0.95	25.3	2.76	-1.152	-0.793	-0.910	0.359
	31.3		-1.448	-0.793	-1.090	0.655
	37.6		-1.924	-0.910	-1.510	1.014
	43.4		-2.303	-0.255	-1.269	2.048

Table D-6. Hoist Loads, Lock No. 19, Type 6 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.28	7.3	2.51	-0.252	-0.197	-0.225	0.055
	9.1		0.003	0.051	0.023	0.048
	11.0		0.189	0.292	0.244	0.103
0.57	15.2	2.74	-0.280	-0.163	-0.239	0.117
	18.9		-0.190	0.017	-0.059	0.207
	22.2		-0.114	0.244	0.065	0.359
	26.2		-0.294	0.672	0.244	0.966
0.72	19.1	2.93	-0.573	-0.435	-0.490	0.138
	23.7		-0.980	-0.028	-0.373	0.952
	28.4		-1.325	0.310	-0.552	1.634
	32.7		-1.125	0.117	-0.366	1.241
0.88	23.2	3.28	-1.139	-0.842	-1.021	0.297
	28.8		-1.380	-0.787	-1.083	0.593
	34.6		-1.497	-0.773	-1.139	0.724
	40.0		-1.980	-0.787	-1.263	1.193
0.95	25.3	3.58	-1.389	-1.079	-1.258	0.310
	31.3		-1.679	-0.982	-1.382	0.697
	37.6		-2.154	-1.079	-1.617	1.076
	43.4		-2.679	-0.720	-1.561	1.959

Table D-7. Hoist Loads, Lock No. 19, Type 7 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.28	7.3	2.49	0.302	0.392	0.330	0.090
	9.1		0.709	0.881	0.778	0.172
	11.0		1.516	1.785	1.633	0.269
	12.7		2.226	2.668	2.440	0.441
0.57	15.2	2.68	0.221	0.462	0.290	0.241
	18.9		0.593	1.041	0.724	0.448
	22.7		0.924	2.069	1.545	1.145
	26.2		1.338	3.117	2.379	1.779
0.71	18.9	2.82	-0.149	0.210	0.030	0.359
	23.5		-0.411	0.954	0.389	1.366
	28.3		0.030	1.320	0.630	1.290
	32.7		-0.266	2.092	1.044	2.359
0.87	22.9	3.10	-0.906	-0.181	-0.547	0.724
	28.4		-1.050	-0.002	-0.430	1.048
	34.2		-1.264	0.288	-0.492	1.552
	39.5		-1.643	0.432	-0.430	2.076
0.94	25.1	3.31	-1.217	-0.527	-0.823	0.690
	31.1		-1.727	-0.354	-0.879	1.372
	37.3		-2.237	-0.168	-1.182	2.069
	43.2		-3.561	1.432	-0.623	4.993

Table D-8. Hoist Loads, Lock No. 19, Type 8 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.28	7.3	2.44	0.488	0.592	0.578	0.103
	9.1		0.881	0.971	0.937	0.090
	11.0		1.999	2.178	2.026	0.179
	12.7		1.847	2.081	2.006	0.234
0.57	15.2	2.62	0.274	0.543	0.377	0.269
	18.9		0.660	1.088	0.881	0.428
	22.7		0.957	1.674	1.377	0.717
	26.2		1.177	2.150	1.667	0.972
0.71	18.9	2.76	-0.138	0.145	-0.014	0.283
	23.5		-0.352	0.855	0.255	1.207
	28.3		-0.076	1.297	0.579	1.372
	32.7		0.103	1.897	1.000	1.793
0.87	22.9	3.02	-0.629	-0.270	-0.257	0.359
	28.4		-0.988	-0.036	-0.394	0.952
	34.2		-0.988	0.199	-0.270	1.186
	39.5		-0.988	0.440	-0.036	1.428
0.94	25.1	3.21	-0.819	-0.606	-0.702	0.214
	31.1		-1.302	-0.343	-0.819	0.959
	37.3		-1.599	-0.281	-0.819	1.317
	43.2		-2.516	0.967	-0.771	3.483

Table D-9. Hoist Loads, Lock No. 19, Type 9 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.28	7.3	1.86	0.583	0.611	0.604	0.028
	9.1		0.983	1.052	1.018	0.069
	11.0		1.446	1.528	1.480	0.083
	12.7		2.025	2.142	2.101	0.117
0.57	15.2	1.99	0.230	0.410	0.327	0.179
	18.9		0.541	0.851	0.706	0.310
	22.7		0.996	1.541	1.306	0.545
	26.2		1.189	2.403	1.844	1.214
0.71	18.9	2.10	-0.138	0.214	0.000	0.352
	23.5		-0.021	0.669	0.241	0.690
	28.3		-0.021	1.028	0.538	1.048
	32.7		0.145	1.372	0.772	1.228
0.87	22.9	2.29	-0.543	-0.185	-0.385	0.359
	28.4		-0.923	0.057	-0.247	0.979
	34.2		-1.137	0.270	-0.302	1.407
	39.5		-1.854	0.891	-0.364	2.745
0.94	25.1	2.44	-1.072	-0.334	-0.630	0.738
	31.1		-1.403	-0.217	-0.810	1.186
	37.3		-1.886	0.046	-0.989	1.931
	43.2		-2.982	1.666	-0.451	4.648

Table D-10. Hoist Loads, Lock No. 19, Type 10 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.28	7.3	1.80	0.594	0.635	0.608	0.041
	9.1		1.008	1.056	1.021	0.048
	11.0		1.463	1.518	1.477	0.055
	12.7		1.959	2.118	2.021	0.159
0.57	15.2	1.93	0.387	0.504	0.435	0.117
	18.9		0.677	0.911	0.814	0.234
	22.7		1.125	1.628	1.352	0.503
	26.2		1.435	2.380	1.952	0.945
0.71	18.9	2.03	-0.121	0.189	0.058	0.310
	23.5		0.003	0.596	0.237	0.593
	28.3		0.003	1.003	0.534	1.000
	32.7		0.230	1.541	0.837	1.310
0.87	22.9	2.21	-0.569	-0.155	-0.417	0.414
	28.4		-0.893	0.052	-0.417	0.945
	34.2		-0.955	0.203	-0.300	1.159
	39.5		-1.845	0.659	-0.590	2.503
0.94	25.1	2.37	-1.000	-0.331	-0.572	0.669
	31.1		-1.117	-0.228	-0.690	0.890
	37.3		-1.641	-0.310	-0.869	1.331
	43.2		-2.738	1.083	-0.828	3.821

Table D-11. Hoist Loads, Lock No. 19, Type 11 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.28	7.3	1.93	-0.061	-0.041	-0.048	0.021
	9.1		-0.006	0.063	0.014	0.069
	11.0		0.083	0.152	0.118	0.069
0.57	15.2	2.09	-0.396	-0.217	-0.334	0.179
	18.9		-0.554	-0.127	-0.396	0.428
	22.2		-0.617	-0.044	-0.423	0.572
	26.2		-0.927	0.142	-0.396	1.069
0.72	19.1	2.23	-0.731	-0.421	-0.600	0.310
	23.7		-0.993	-0.434	-0.717	0.559
	28.4		-1.517	-0.303	-0.841	1.214
	32.7		-1.628	-0.283	-1.021	1.345
0.88	23.2	2.50	-1.165	-0.441	-0.813	0.724
	28.8		-1.392	-0.682	-0.986	0.710
	34.6		-2.358	-0.441	-1.192	1.917
	40.0		-3.027	-0.572	-1.668	2.455
0.95	25.3	2.72	-1.372	-0.703	-1.048	0.669
	31.3		-1.931	-0.593	-1.200	1.338
	37.6		-2.883	-0.572	-1.503	2.310
	43.4		-3.531	0.014	-1.738	3.545

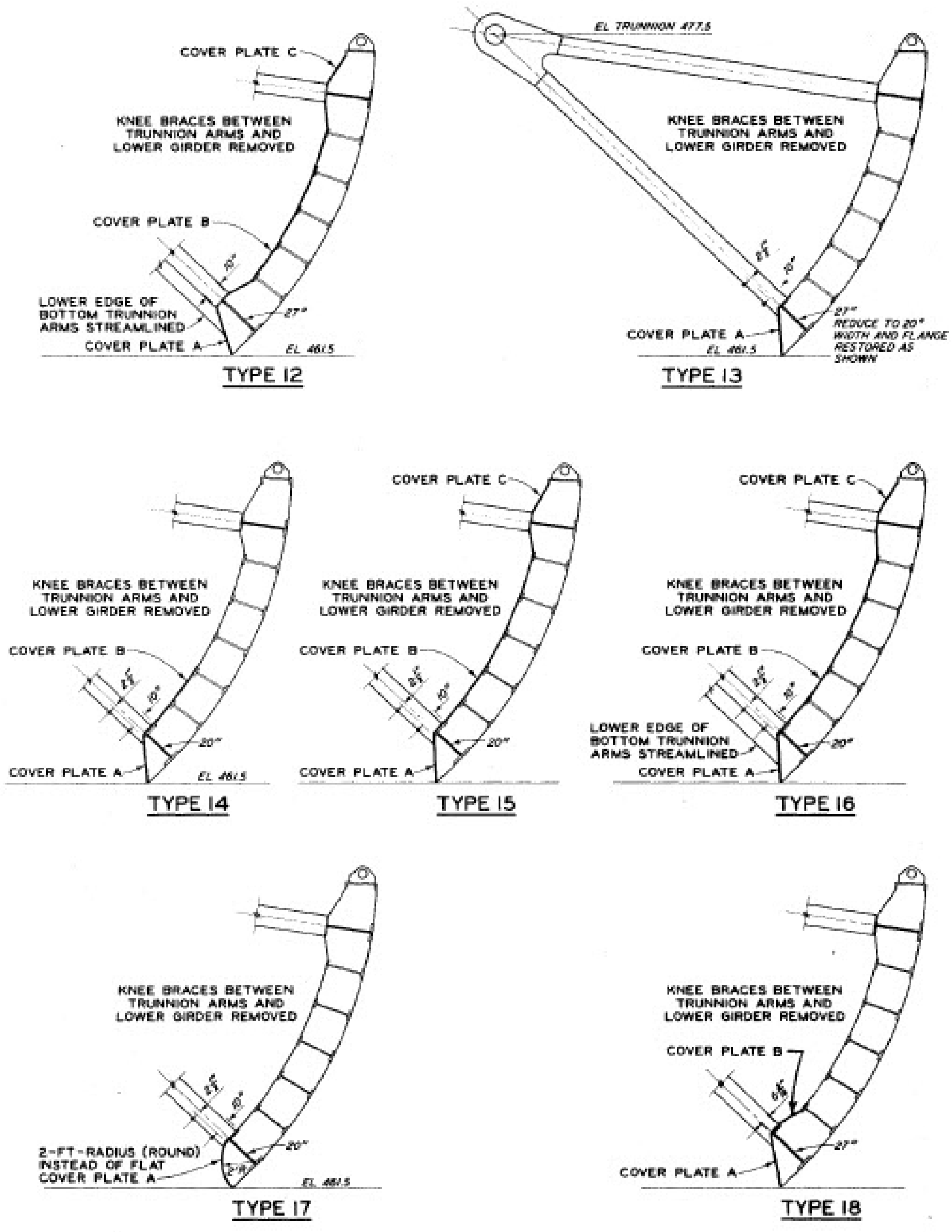


Figure D-5. Tainter Valves, Lock No. 19, Types 12-18 Designs.

Table D-12. Hoist Loads, Lock No. 19, Type 12 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.28	7.3	1.88	0.557	0.626	0.599	0.069
	9.1		0.992	1.130	1.054	0.138
	11.0		1.530	1.661	1.606	0.131
	12.7		2.047	2.199	2.137	0.152
0.57	15.2	2.01	0.331	0.503	0.428	0.172
	18.9		0.690	1.048	0.869	0.359
	22.7		1.159	1.766	1.407	0.607
	26.2		1.648	2.814	2.241	1.166
0.71	18.9	2.13	-0.009	0.308	0.157	0.317
	23.5		-0.133	1.039	0.515	1.172
	28.3		-0.009	1.370	0.812	1.379
	32.7		-0.002	2.170	1.308	2.172
0.87	22.9	2.35	-0.485	-0.002	-0.126	0.483
	28.4		-0.533	0.426	-0.126	0.959
	34.2		-0.864	0.577	-0.126	1.441
	39.5		-1.319	0.950	-0.306	2.269
0.94	25.1	2.52	-0.686	-0.183	-0.410	0.503
	31.1		-0.886	-0.052	-0.472	0.834
	37.3		-1.362	0.176	-0.528	1.538
	43.2		-2.548	1.493	-0.472	4.041

Table D-13. Hoist Loads, Lock No. 19, Type 13 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.28	7.3	1.67	0.298	0.346	0.332	0.048
	9.1		0.560	0.622	0.594	0.062
	11.0		0.870	1.001	0.926	0.131
	12.7		1.243	1.374	1.312	0.131
0.57	15.2	1.79	0.076	0.241	0.117	0.166
	18.9		0.241	0.476	0.359	0.234
	22.7		0.366	0.897	0.655	0.531
	26.2		0.469	1.517	0.924	1.048
0.71	18.9	1.88	-0.215	-0.022	-0.139	0.193
	23.5		-0.560	0.440	-0.022	1.000
	28.3		-1.050	1.047	0.192	2.097
	32.7		-0.629	1.047	0.337	1.676
0.87	22.9	2.05	-0.732	-0.326	-0.470	0.407
	28.4		-0.926	-0.277	-0.588	0.648
	34.2		-1.208	-0.194	-0.615	1.014
	39.5		-1.519	-0.015	-0.850	1.503
0.94	25.1	2.20	-0.861	-0.406	-0.585	0.455
	31.1		-1.240	-0.419	-0.764	0.821
	37.3		-1.833	-0.523	-0.999	1.310
	43.2		-2.074	0.429	-0.999	2.503

Table D-14. Hoist Loads, Lock No. 19, Type 14 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.28	7.3	1.74	0.308	0.357	0.329	0.048
	9.1		0.584	0.639	0.605	0.055
	11.0		0.894	0.977	0.943	0.083
	12.7		1.267	1.384	1.336	0.117
0.57	15.2	1.86	0.058	0.182	0.148	0.124
	18.9		0.251	0.527	0.368	0.276
	22.7		0.444	0.892	0.713	0.448
	26.2		0.548	1.382	1.017	0.834
0.71	18.9	1.96	-0.243	-0.043	-0.161	0.200
	23.5		-0.699	0.591	-0.043	1.290
	28.3		-0.933	1.150	-0.002	2.083
	32.7		-0.464	1.032	0.288	1.497
0.87	22.9	2.15	-0.648	-0.413	-0.496	0.234
	28.4		-0.765	-0.289	-0.586	0.476
	34.2		-1.006	-0.289	-0.648	0.717
	39.5		-1.248	-0.289	-0.889	0.959
0.94	25.1	2.28	-0.849	-0.504	-0.621	0.345
	31.1		-1.132	-0.539	-0.773	0.593
	37.3		-1.490	-0.477	-1.014	1.014
	43.2		-2.346	0.179	-0.952	2.524

Table D-15. Hoist Loads, Lock No. 19, Type 15 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.28	7.3	1.84	0.310	0.358	0.337	0.048
	9.1		0.599	0.654	0.641	0.055
	11.0		0.910	1.013	0.951	0.103
	12.7		1.254	1.420	1.344	0.166
0.57	15.2	1.95	0.059	0.197	0.121	0.138
	18.9		0.239	0.480	0.370	0.241
	22.7		0.432	0.928	0.666	0.497
	26.2		0.652	1.535	1.073	0.883
0.71	18.9	2.07	-0.288	-0.060	-0.150	0.228
	23.5		-0.653	0.478	-0.060	1.131
	28.3		-0.963	1.154	0.085	2.117
	32.7		-0.784	1.457	0.237	2.241
0.87	22.9	2.26	-0.541	-0.397	-0.452	0.145
	28.4		-0.803	-0.279	-0.541	0.524
	34.2		-1.017	-0.231	-0.659	0.786
	39.5		-1.521	-0.162	-0.838	1.359
0.94	25.1	2.43	-0.783	-0.548	-0.617	0.234
	31.1		-1.190	-0.383	-0.831	0.807
	37.3		-1.431	-0.500	-1.072	0.931
	43.2		-1.728	0.024	-1.238	1.752

Table D-16. Hoist Loads, Lock No. 19, Type 16 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.28	7.3	1.88	0.379	0.421	0.414	0.041
	9.1		0.690	0.752	0.724	0.062
	11.0		1.028	1.103	1.083	0.076
	12.7		1.407	1.497	1.476	0.090
0.57	15.2	2.01	0.166	0.297	0.255	0.131
	18.9		0.407	0.641	0.524	0.234
	22.7		0.586	1.207	1.034	0.621
	26.2		0.945	1.572	1.297	0.628
0.71	18.9	2.12	-0.121	0.051	-0.052	0.172
	23.5		-0.487	0.582	0.003	1.069
	28.3		-0.859	1.189	0.237	2.048
	32.7		-0.418	1.148	0.389	1.566
0.87	22.9	2.34	-0.570	-0.322	-0.426	0.248
	28.4		-0.763	-0.191	-0.453	0.572
	34.2		-0.929	-0.122	-0.453	0.807
	39.5		-1.288	0.250	-0.453	1.538
0.94	25.1	2.48	-0.699	-0.471	-0.574	0.228
	31.1		-1.078	-0.312	-0.602	0.766
	37.3		-1.319	-0.361	-0.837	0.959
	43.2		-1.719	0.591	-0.423	2.310

Table D-17. Hoist Loads, Lock No. 19, Type 17 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.28	7.3	1.71	0.600	0.648	0.634	0.048
	9.1		1.076	1.124	1.097	0.048
	11.0		1.676	1.772	1.697	0.097
	12.7		2.386	2.510	2.428	0.124
0.57	15.2	1.83	0.543	0.633	0.599	0.090
	18.9		0.950	1.137	1.019	0.186
	22.7		1.433	1.792	1.612	0.359
	26.2		1.937	2.440	2.268	0.503
0.71	18.9	1.92	0.123	0.358	0.206	0.234
	23.5		0.344	0.682	0.523	0.338
	28.3		0.627	1.234	0.986	0.607
	32.7		1.054	1.841	1.461	0.786
0.87	22.9	2.12	-0.308	-0.094	-0.190	0.214
	28.4		-0.259	0.086	-0.108	0.345
	34.2		-0.335	0.596	0.010	0.931
	39.5		-0.583	0.727	0.072	1.310
0.94	25.1	2.25	-0.535	-0.225	-0.356	0.310
	31.1		-0.652	-0.080	-0.356	0.572
	37.3		-0.894	0.010	-0.321	0.903
	43.2		-1.156	0.920	-0.177	2.076
1.02	27.1	2.46	-0.985	-0.626	-0.771	0.359
	33.5		-1.509	-0.612	-0.861	0.897
	39.5		-1.557	-0.626	-0.985	0.931
	40.4		-1.530	-0.495	-1.040	1.034

D-3. Poe Lock Hydraulic Model Investigation. Results from a physical model study of the culvert valves for the new Poe Lock are given in U.S. Army Engineer Waterways Experiment Station (1961c). The model study used the valve testing facility previously employed in the Lock No. 19 study having a culvert height of 14.5 ft and valve radius of 21.0 ft for a *R/B* ratio of 1.45. Horizontally and vertically framed reverse tainter valve designs were tested. Discharges resulting from a 21.0 lift and a 4-min valve operation schedule were calculated, hoist loads were interpolated from the tabulated data, and comparison were made between the various designs. The recommended design valve was vertically framed valve.

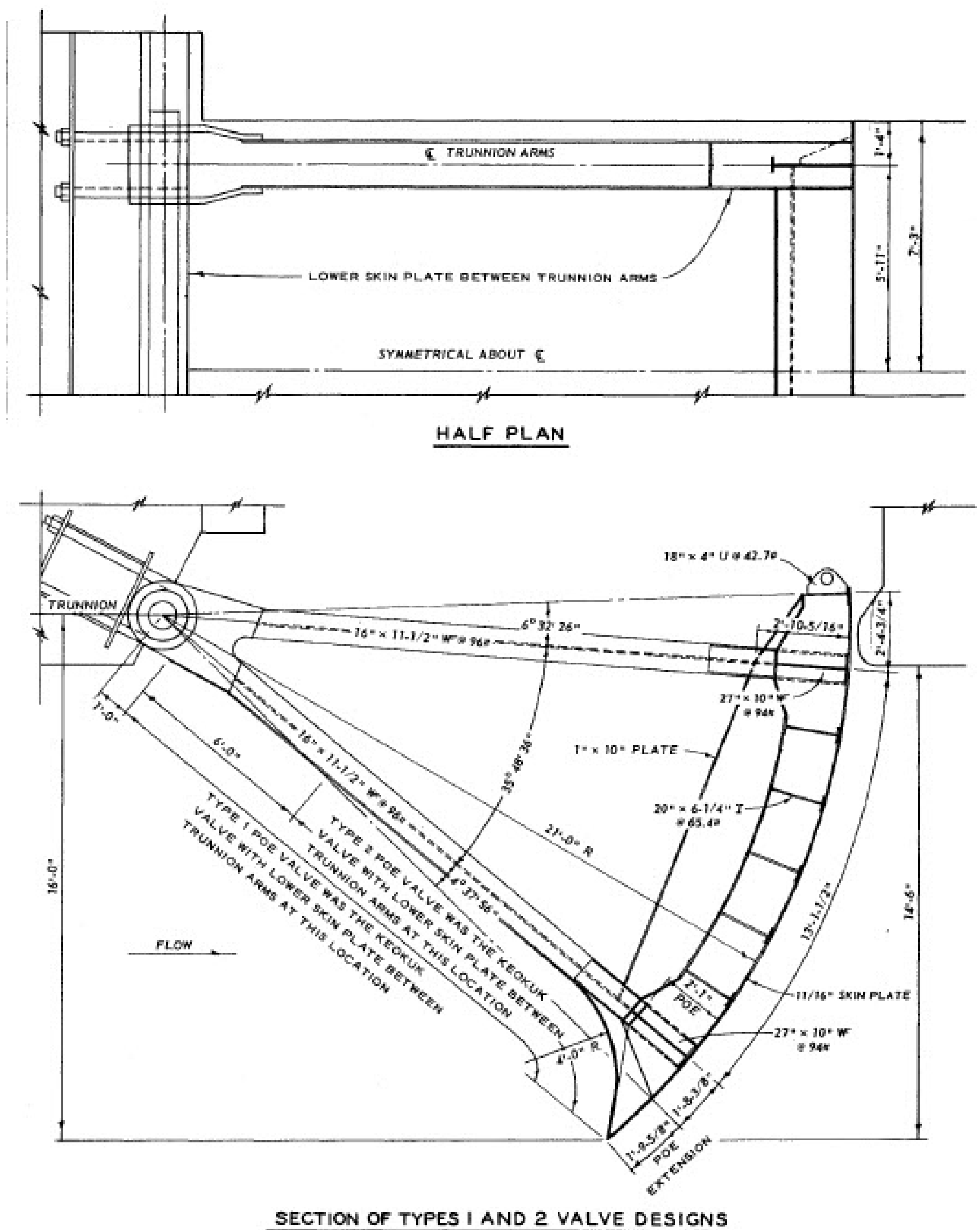


Figure D-6. Tainter Valves, Poe Lock, Types 1 and 2 Designs.

Table D-18. Hoist Loads, Poe Lock, Type 1 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.04	1.0	1.91	----	----	-0.257	----
	1.2		----	----	-0.271	----
	1.4		----	----	-0.292	----
0.06	1.4	1.92	----	----	-0.181	----
	2.1		----	----	-0.160	----
	2.9		----	----	-0.167	----
0.12	3.3	1.96	----	----	-0.078	----
	4.0		----	----	-0.016	----
	4.3		----	----	0.005	----
	5.0		----	----	0.170	----
0.20	4.8	2.00	----	----	0.197	----
	5.7		----	----	0.218	----
	6.7		----	----	0.308	----
	7.6		----	----	0.446	----
	8.6		----	----	0.528	----
0.26	6.7	2.03	----	----	0.146	----
	7.6		----	----	0.229	----
	8.6		----	----	0.312	----
	9.5		----	----	0.360	----
	10.5		----	----	0.422	----
0.36	9.5	2.08	0.197	0.300	0.238	0.103
	10.7		0.197	0.390	0.293	0.193
	11.9		0.245	0.472	0.348	0.228
	13.1		0.266	0.528	0.431	0.262
	14.3		0.183	0.672	0.438	0.490
0.42	11.4	2.13	0.052	0.259	0.190	0.207
	12.8		0.114	0.390	0.245	0.276
	14.3		0.100	0.362	0.245	0.262
	15.7		0.066	0.424	0.266	0.359
	17.1		-0.079	0.762	0.341	0.841
0.49	13.3	2.18	-0.072	0.190	0.052	0.262
	14.7		-0.182	0.252	0.032	0.434
	16.2		-0.182	0.246	0.004	0.428
	17.6		-0.258	0.190	-0.044	0.448
	19.0		-0.327	0.156	-0.092	0.483

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.56	15.2	2.26	-0.389	0.025	-0.251	0.414
	17.1		-0.492	-0.072	-0.279	0.421
	19.0		-0.541	-0.058	-0.279	0.483
	20.9		-0.941	-0.086	-0.472	0.855
	22.8		-0.927	-0.113	-0.541	0.814
0.62	17.1	2.33	-0.674	-0.150	-0.364	0.524
	19.0		-0.771	-0.247	-0.488	0.524
	20.9		-1.012	-0.426	-0.757	0.586
	22.8		-1.343	-0.633	-0.964	0.710
	24.7		-1.523	-0.750	-1.081	0.772
0.70	19.0	2.44	-0.774	-0.277	-0.588	0.497
	21.4		-1.160	-0.588	-0.926	0.572
	23.8		-1.546	-0.829	-1.208	0.717
	26.2		-2.043	-1.236	-1.629	0.807
	28.5		-2.222	-1.457	-1.926	0.766
0.78	19.0	2.62	-0.932	-0.401	-0.698	0.531
	22.8		-1.588	-1.043	-1.346	0.545
	26.6		-2.457	-1.477	-1.946	0.979
	30.4		-3.036	-2.077	-2.663	0.959
	33.5		-4.746	-3.332	-3.857	1.414
0.82	19.0	2.72	-1.012	-0.488	-0.771	0.524
	23.8		-2.185	-0.819	-1.488	1.366
	28.5		-3.109	-2.323	-2.681	0.786
	33.3		-4.226	-3.778	-5.054	0.448
	38.0		-6.957	-5.192	-6.123	1.766
0.90	19.0	2.98	-1.088	-0.323	-0.681	0.766
	24.7		-2.447	-1.081	-1.750	1.366
	30.4		-3.371	-2.585	-2.943	0.786
	36.1		-4.881	-3.185	-3.806	1.697
	40.9		-6.123	-3.778	-4.840	2.345
0.95	19.0	3.16	-0.820	-0.061	-0.399	0.759
	24.7		-2.275	-0.558	-1.179	1.717
	30.4		-2.606	-1.227	-2.130	1.379
	36.1		-7.448	-2.558	-3.323	4.890
0.99	19.0	3.39	-0.356	0.486	0.106	0.841
	24.7		-1.273	0.106	-0.383	1.379

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
	30.4		-2.390	-0.508	-1.321	1.883
	36.1		-3.390	-0.370	-2.632	3.021
1.04	19.0	3.68	0.117	0.992	0.565	0.876
	24.7		-0.580	0.758	0.206	1.338
	30.4		-1.146	0.565	-0.387	1.710
	36.1		-1.890	0.586	-0.621	2.476

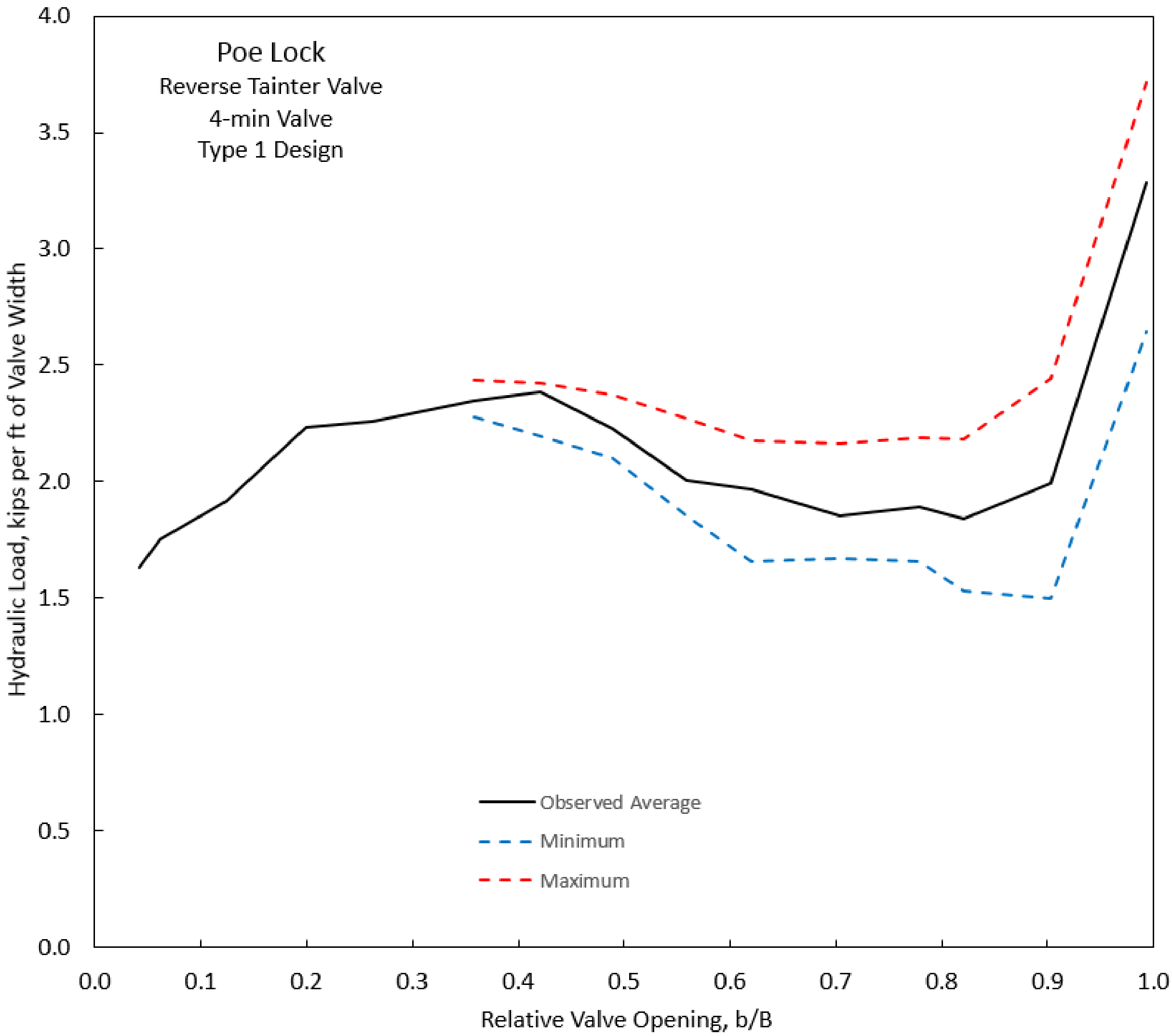


Figure D-7. Hoist loads, Poe Lock, Type 1 Design, 4-min Valve.

Table D-19. Hoist Loads, Poe Lock, Type 2 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.04	1.0	1.87	----	----	-0.099	----
	1.2		----	----	-0.092	----
	1.4		----	----	-0.050	----
0.06	1.4	1.88	----	----	-0.159	----
	2.1		----	----	-0.159	----
	2.9		----	----	-0.062	----
0.12	3.3	1.92	----	----	-0.160	----
	4.0		----	----	0.081	----
	4.3		----	----	0.040	----
	5.0		----	----	0.061	----
0.20	4.8	1.95	----	----	0.039	----
	5.7		----	----	0.101	----
	6.7		----	----	0.156	----
	7.6		----	----	0.246	----
	8.6		----	----	0.259	----
0.26	6.7	1.98	----	----	0.216	----
	7.6		----	----	0.285	----
	8.6		----	----	0.402	----
	9.5		----	----	0.512	----
	10.5		----	----	0.595	----
0.36	9.5	2.04	----	----	0.272	----
	10.7		----	----	0.334	----
	11.9		----	----	0.397	----
	13.1		----	----	0.472	----
	14.3		----	----	0.576	----
0.42	11.4	2.09	0.087	0.328	0.239	0.241
	12.8		0.177	0.487	0.349	0.310
	14.3		0.232	0.570	0.390	0.338
	15.7		0.190	0.639	0.466	0.448
	17.1		0.239	0.825	0.466	0.586
0.49	13.3	2.14	-0.015	0.309	0.143	0.324
	14.7		-0.070	0.274	0.116	0.345
	16.2		-0.215	0.350	0.074	0.566
	17.6		-0.146	0.412	0.468	0.559
	19.0		-0.167	0.543	0.164	0.710

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.56	15.2	2.20	-0.419	0.230	-0.108	0.648
	17.1		-0.419	0.202	-0.053	0.621
	19.0		-0.612	0.209	-0.129	0.821
	20.9		-0.605	0.154	-0.226	0.759
	22.8		-0.901	0.119	-0.322	1.021
0.62	17.1	2.28	-0.551	-0.068	-0.317	0.483
	19.0		-0.792	-0.254	-0.496	0.538
	20.9		-0.854	-0.254	-0.496	0.600
	22.8		-1.151	-0.254	-0.675	0.897
	24.7		-1.268	-0.372	-0.854	0.897
0.70	19.0	2.40	-0.926	-0.347	-0.574	0.579
	21.4		-1.312	-0.450	-0.809	0.862
	23.8		-1.906	-0.574	-1.285	1.331
	26.2		-2.002	-0.809	-1.526	1.193
	28.5		-2.423	-0.926	-1.706	1.497
0.78	19.0	2.56	-1.067	-0.432	-0.708	0.634
	22.8		-1.901	-0.826	-1.363	1.076
	26.6		-2.570	-1.150	-2.081	1.421
	30.4		-3.115	-1.529	-2.674	1.586
	33.5		-4.763	-3.150	-3.805	1.614
0.82	19.0	2.65	-1.316	-0.412	-0.840	0.903
	23.8		-2.033	-0.840	-1.557	1.193
	28.5		-3.033	-1.985	-2.626	1.048
	33.3		-5.750	-3.509	-4.061	2.241
	38.0		-7.274	-4.157	-5.730	3.117
0.90	19.0	2.93	-1.132	-0.366	-0.656	0.766
	24.7		-2.511	-1.132	-1.725	1.379
	30.4		-3.277	-2.277	-2.918	1.000
	36.1		-5.187	-3.132	-3.752	2.055
	40.9		-6.042	-3.518	-4.511	2.524
0.95	19.0	3.10	-0.919	-0.202	-0.443	0.717
	24.7		-1.919	-0.678	-1.278	1.241
	30.4		-3.064	-1.630	-2.464	1.434
	36.1		-4.016	-2.850	-3.540	1.166
0.99	19.0	3.34	-0.323	0.394	0.036	0.717
	24.7		-1.633	0.036	-0.681	1.669

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
	30.4		-2.612	-0.488	-1.633	2.124
	36.1		-3.302	-1.157	-2.702	2.145
1.04	19.0	3.60	-0.048	0.718	0.359	0.766
	24.7		-0.717	0.690	0.001	1.407
	30.4		-1.620	0.594	-0.599	2.214
	36.1		-3.075	-0.048	-1.192	3.028
	40.9		-3.096	0.718	-1.668	3.814

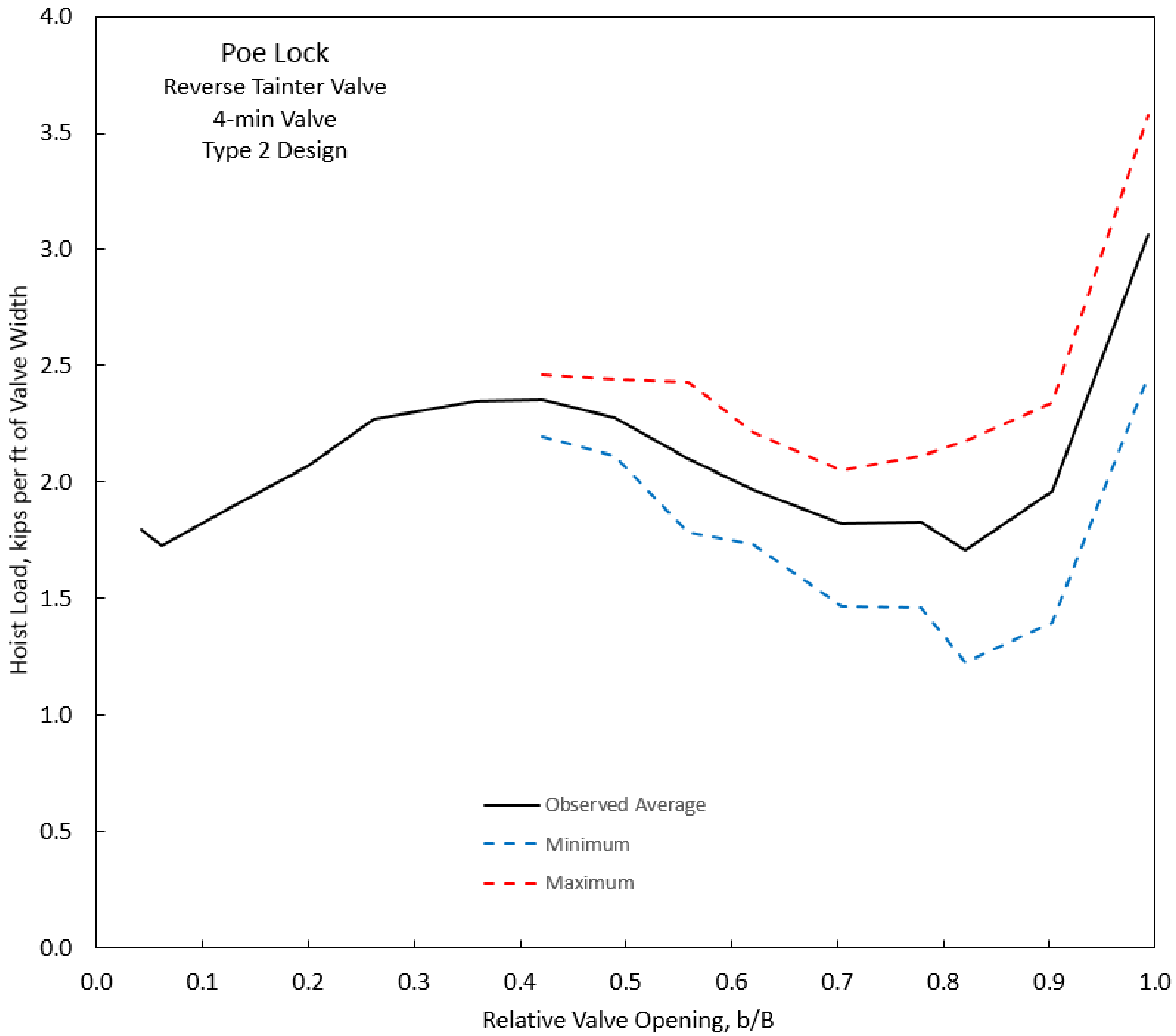


Figure D-8. Hoist load, Poe Lock, Type 2 Design, 4-min Valve.

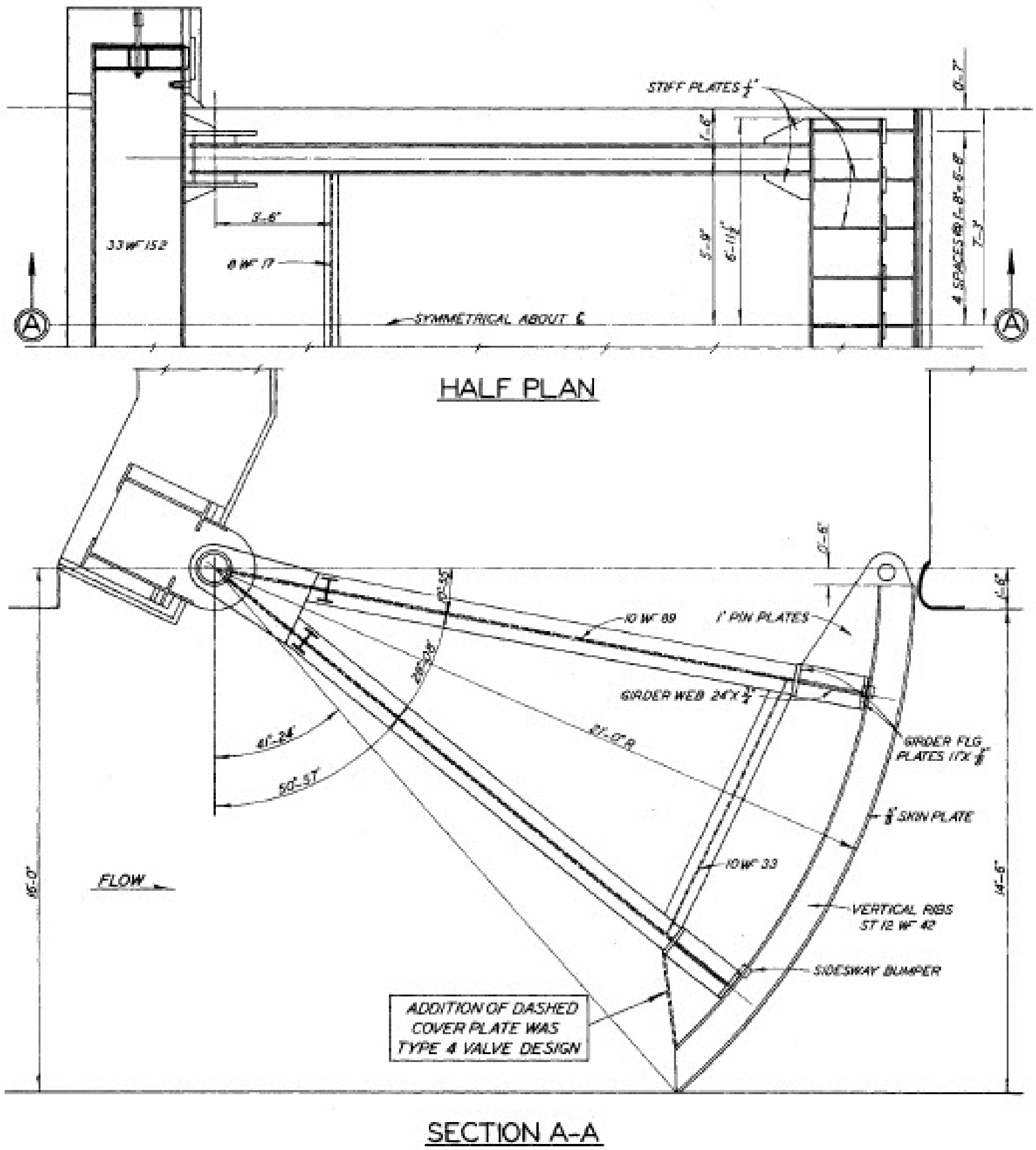


Figure D-9. Tainter Valves, Poe Lock, Types 3 and 4 Designs.

Table D-20. Hoist Loads, Poe Lock, Type 3 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.03	0.7	1.43	----	----	-0.223	----
	1.2		----	----	-0.223	----
	1.7		----	----	-0.230	----
0.07	1.4	1.44	----	----	-0.201	----
	2.1		----	----	-0.181	----
	2.9		----	----	-0.132	----
0.12	2.9	1.45	----	----	-0.192	----
	3.6		----	----	-0.164	----
	4.3		-0.150	-0.137	-0.143	0.014
	5.0		-0.116	-0.102	-0.109	0.014
0.20	4.8	1.47	-0.148	-0.113	-0.127	0.034
	5.7		-0.092	-0.065	-0.079	0.028
	6.7		-0.017	0.025	0.004	0.041
	7.6		0.046	0.087	0.066	0.041
	8.6		0.066	0.114	0.087	0.048
0.29	6.7	1.48	-0.166	-0.104	-0.139	0.062
	7.6		-0.132	-0.077	-0.104	0.055
	8.6		-0.097	-0.042	-0.070	0.055
	9.5		-0.063	-0.001	-0.035	0.062
	10.5		-0.042	0.048	0.006	0.090
0.34	8.6	1.50	-0.163	-0.115	-0.136	0.048
	10.0		-0.122	-0.074	-0.101	0.048
	11.4		-0.094	-0.005	-0.060	0.090
	12.8		-0.088	0.030	-0.026	0.117
	13.8		-0.053	0.078	0.016	0.131
0.40	10.2	1.53	-0.181	-0.105	-0.139	0.076
	11.7		-0.167	-0.050	-0.105	0.117
	13.3		-0.174	0.012	-0.077	0.186
	15.0		-0.160	0.061	-0.050	0.221
	16.6		-0.126	0.157	0.006	0.283
0.47	11.9	1.54	-0.268	-0.144	-0.206	0.124
	13.6		-0.275	-0.089	-0.179	0.186
	15.2		-0.275	-0.089	-0.179	0.186
	16.9		-0.275	-0.034	-0.144	0.241
	18.5		-0.317	0.021	-0.144	0.338

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.54	12.8	1.56	-0.286	-0.154	-0.223	0.131
	15.0		-0.286	-0.154	-0.223	0.131
	17.1		-0.320	-0.134	-0.237	0.186
	19.3		-0.354	-0.120	-0.251	0.234
	21.4		-0.417	-0.106	-0.265	0.310
0.61	14.7	1.60	-0.349	-0.177	-0.273	0.172
	17.1		-0.390	-0.156	-0.301	0.234
	19.5		-0.452	-0.087	-0.301	0.366
	21.9		-0.521	-0.135	-0.370	0.386
	24.3		-0.597	-0.108	-0.397	0.490
0.68	16.6	1.63	-0.426	-0.205	-0.350	0.221
	19.5		-0.536	-0.226	-0.377	0.310
	22.4		-0.619	-0.239	-0.412	0.379
	25.2		-0.708	-0.205	-0.336	0.503
	28.1		-0.874	-0.129	-0.667	0.745
0.75	17.6	1.69	-0.499	-0.272	-0.361	0.228
	21.6		-0.706	-0.286	-0.451	0.421
	25.7		-0.920	-0.299	-0.541	0.621
	29.7		-1.403	-0.327	-0.692	1.076
	33.8		-1.382	-0.272	-0.982	1.110
0.83	16.6	1.76	-0.570	-0.391	-0.419	0.179
	22.4		-0.736	-0.329	-0.508	0.407
	28.1		-1.074	-0.405	-0.694	0.669
	33.8		-1.557	-0.329	-0.832	1.228
0.91	16.6	1.88	-0.524	-0.352	-0.414	0.172
	22.4		-0.655	-0.414	-0.510	0.241
	28.1		-0.890	-0.352	-0.621	0.538
	33.8		-1.428	-0.366	-0.572	1.062
0.96	16.6	1.95	-0.492	-0.354	-0.417	0.138
	22.4		-0.658	-0.354	-0.479	0.303
	28.1		-0.906	-0.396	-0.623	0.510
	33.8		-1.451	-0.410	-0.775	1.041
1.00	16.6	2.03	-0.468	-0.350	-0.412	0.117
	22.4		-0.661	-0.385	-0.481	0.276
	28.1		-0.943	-0.350	-0.612	0.593
	33.8		-1.088	-0.419	-0.757	0.669

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
1.04	16.6	2.12	-0.439	-0.335	-0.383	0.103
	22.4		-0.618	-0.383	-0.473	0.234
	28.1		-0.859	-0.425	-0.597	0.434
	33.8		-1.218	-0.383	-0.714	0.834

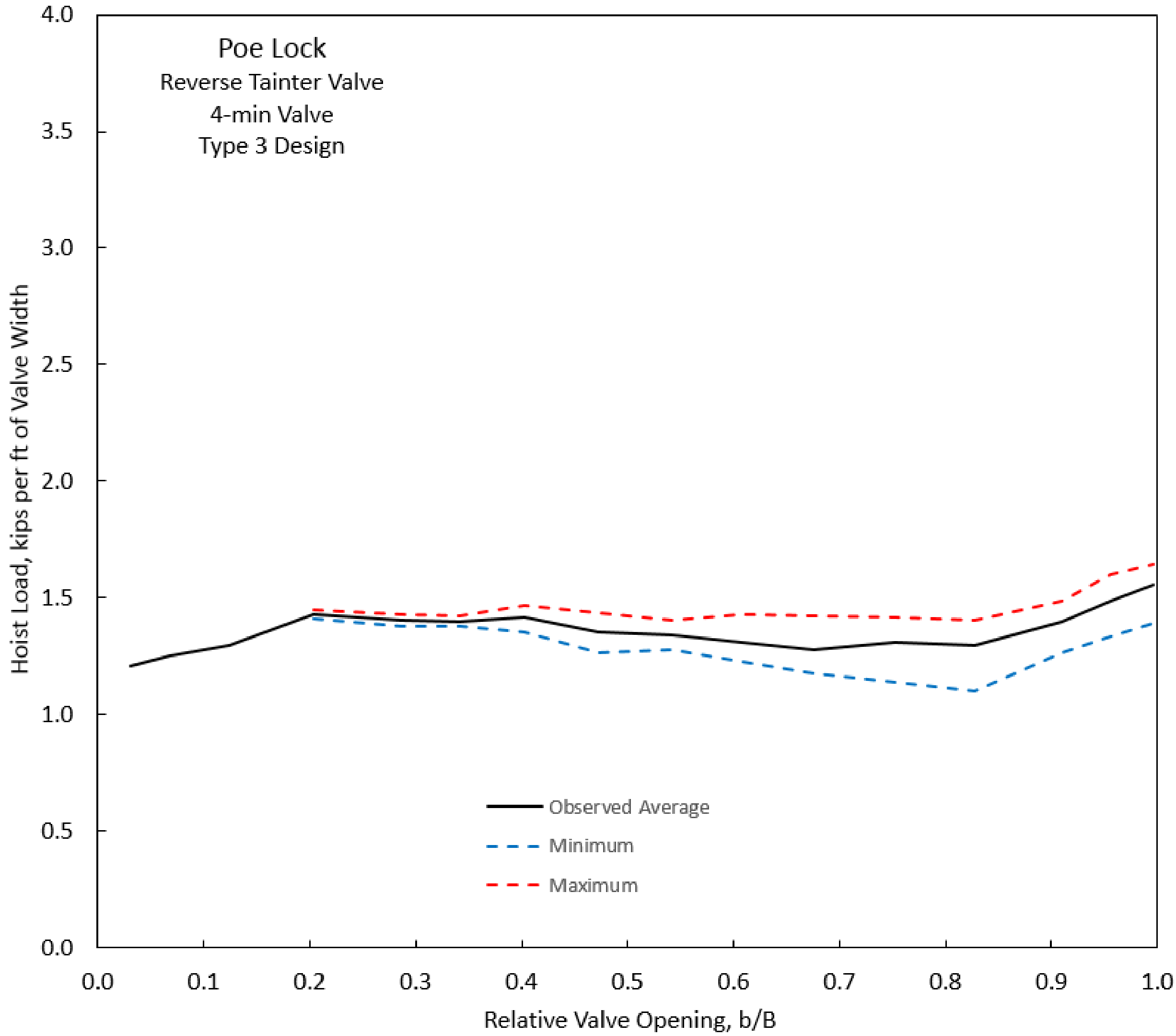


Figure D-8. Hoist load, Poe Lock, Type 3 Design, 4-min Valve.

Table D-21. Hoist Loads, Poe Lock, Type 4 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.03	0.7	1.48	----	----	-0.188	----
	1.2		----	----	-0.188	----
	1.4		----	----	-0.174	----
0.07	1.2	1.50	----	----	-0.187	----
	1.9		----	----	-0.159	----
	2.6		----	----	-0.125	----
	3.3		----	----	-0.090	----
0.12	1.9	1.51	----	----	-0.190	----
	2.9		----	----	-0.148	----
	3.8		----	----	-0.100	----
	4.8		----	----	-0.010	----
0.20	4.3	1.53	----	----	-0.168	----
	5.7		-0.133	-0.099	-0.119	0.034
	7.1		-0.064	0.019	-0.023	0.083
	8.1		-0.002	0.088	0.039	0.090
0.29	4.8	1.55	----	----	-0.152	----
	6.2		-0.152	-0.117	-0.131	0.034
	7.6		-0.131	-0.076	-0.103	0.055
	9.0		-0.076	-0.014	-0.041	0.062
	10.5		-0.034	0.048	0.007	0.083
0.34	4.8	1.57	-0.196	-0.182	-0.189	0.014
	7.1		-0.196	-0.127	-0.161	0.069
	9.5		-0.141	-0.065	-0.148	0.076
	11.9		-0.127	-0.010	-0.065	0.117
	13.8		-0.127	0.059	-0.037	0.186
0.40	4.8	1.59	-0.257	-0.229	-0.243	0.028
	7.1		-0.270	-0.201	-0.236	0.069
	9.5		-0.257	-0.194	-0.222	0.062
	11.9		-0.270	-0.153	-0.215	0.117
	14.3		-0.319	-0.126	-0.222	0.193
	16.6		-0.388	-0.077	-0.236	0.310
0.47	7.1	1.61	-0.292	-0.202	-0.243	0.090
	9.5		-0.292	-0.209	-0.250	0.083
	11.9		-0.333	-0.209	-0.271	0.124
	14.3		-0.381	-0.202	-0.292	0.179

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
	16.6		-0.437	-0.202	-0.319	0.234
	19.0		-0.554	-0.140	-0.423	0.414
0.54	9.5	1.63	-0.323	-0.295	-0.309	0.028
	11.9		-0.392	-0.295	-0.343	0.097
	14.3		-0.474	-0.295	-0.385	0.179
	16.6		-0.509	-0.309	-0.406	0.200
	19.0		-0.619	-0.323	-0.474	0.297
	21.4		-0.709	-0.323	-0.516	0.386
0.61	9.5	1.67	-0.379	-0.269	-0.324	0.110
	12.4		-0.414	-0.276	-0.345	0.138
	15.2		-0.503	-0.297	-0.400	0.207
	18.1		-0.566	-0.359	-0.462	0.207
	20.9		-0.800	-0.283	-0.503	0.517
	23.8		-0.972	-0.200	-0.648	0.772
0.68	9.5	1.71	-0.326	-0.270	-0.298	0.055
	13.3		-0.450	-0.284	-0.367	0.166
	17.1		-0.567	-0.326	-0.415	0.241
	20.9		-0.746	-0.319	-0.505	0.428
	24.7		-1.043	-0.326	-0.657	0.717
	28.5		-1.401	-0.326	-0.746	1.076
0.75	9.5	1.77	-0.317	-0.275	-0.296	0.041
	14.3		-0.413	-0.234	-0.303	0.179
	19.0		-0.565	-0.330	-0.413	0.234
	23.8		-0.792	-0.330	-0.510	0.462
	28.5		-1.054	-0.351	-0.689	0.703
	33.3		-1.882	-0.213	-1.041	1.669
0.83	9.5	1.84	-0.326	-0.243	-0.284	0.083
	14.3		-0.436	-0.291	-0.367	0.145
	19.0		-0.594	-0.326	-0.463	0.269
	23.8		-0.808	-0.339	-0.629	0.469
	28.5		-1.043	-0.339	-0.629	0.703
	33.3		-1.574	-0.388	-0.926	1.186
0.91	9.5	1.97	-0.301	-0.273	-0.287	0.028
	14.3		-0.411	-0.314	-0.328	0.097
	19.0		-0.666	-0.356	-0.473	0.310
	23.8		-0.832	-0.397	-0.625	0.434

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
	28.5		-1.190	-0.390	-0.742	0.800
	33.3		-1.487	-0.425	-0.949	1.062
0.96	9.5	2.04	-0.314	-0.280	-0.301	0.034
	14.3		-0.425	-0.308	-0.370	0.117
	19.0		-0.604	-0.356	-0.480	0.248
	23.8		-0.839	-0.425	-0.604	0.414
	28.5		-1.356	-0.397	-0.783	0.959
	33.3		-1.577	-0.473	-0.963	1.103
1.00	9.5	2.12	-0.336	-0.301	-0.315	0.034
	14.3		-0.439	-0.336	-0.398	0.103
	19.0		-0.570	-0.377	-0.494	0.193
	23.8		-0.791	-0.432	-0.612	0.359
	28.5		-1.157	-0.363	-0.791	0.793
	33.3		-1.557	-0.446	-0.970	1.110
1.04	9.5	2.21	-0.358	-0.296	-0.330	0.062
	14.3		-0.434	-0.351	-0.392	0.083
	19.0		-0.558	-0.379	-0.468	0.179
	23.8		-0.696	-0.365	-0.558	0.331
	28.5		-1.013	-0.406	-0.682	0.607
	33.3		-1.413	-0.337	-0.799	1.076

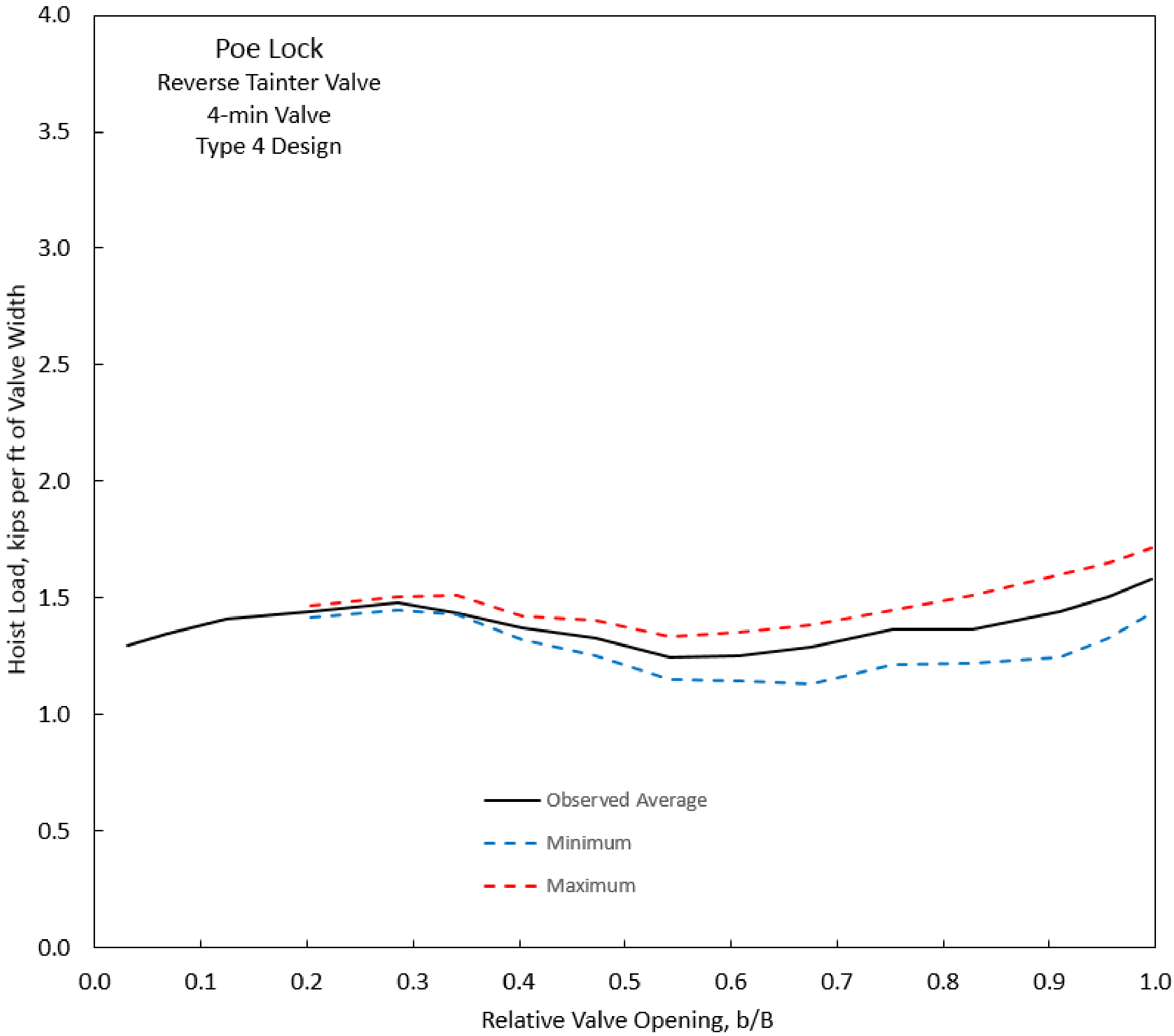


Figure D-9. Hoist load, Poe Lock, Type 4 Design, 4-min Valve.

D-4. Holt Lock Hydraulic Model Investigation. The model study of the Holt Lock filling and emptying system reported by Murphy and Ables (1965) included a separate model of the lock culvert valve. Hoist loads were measured for various designs of a reverse tainter valve having a radius of 17.0 ft and culvert height of 12.5 ft, a radius to culvert height of 1.36. The study concentrated on refining a vertically framed valve design. However, additional experiments documented the hoist loads with a double skin plate valve to provide designers with generalized information. Hoist loads were measured at a range of valve opening positions for various discharges associated a 63.5 ft lift.

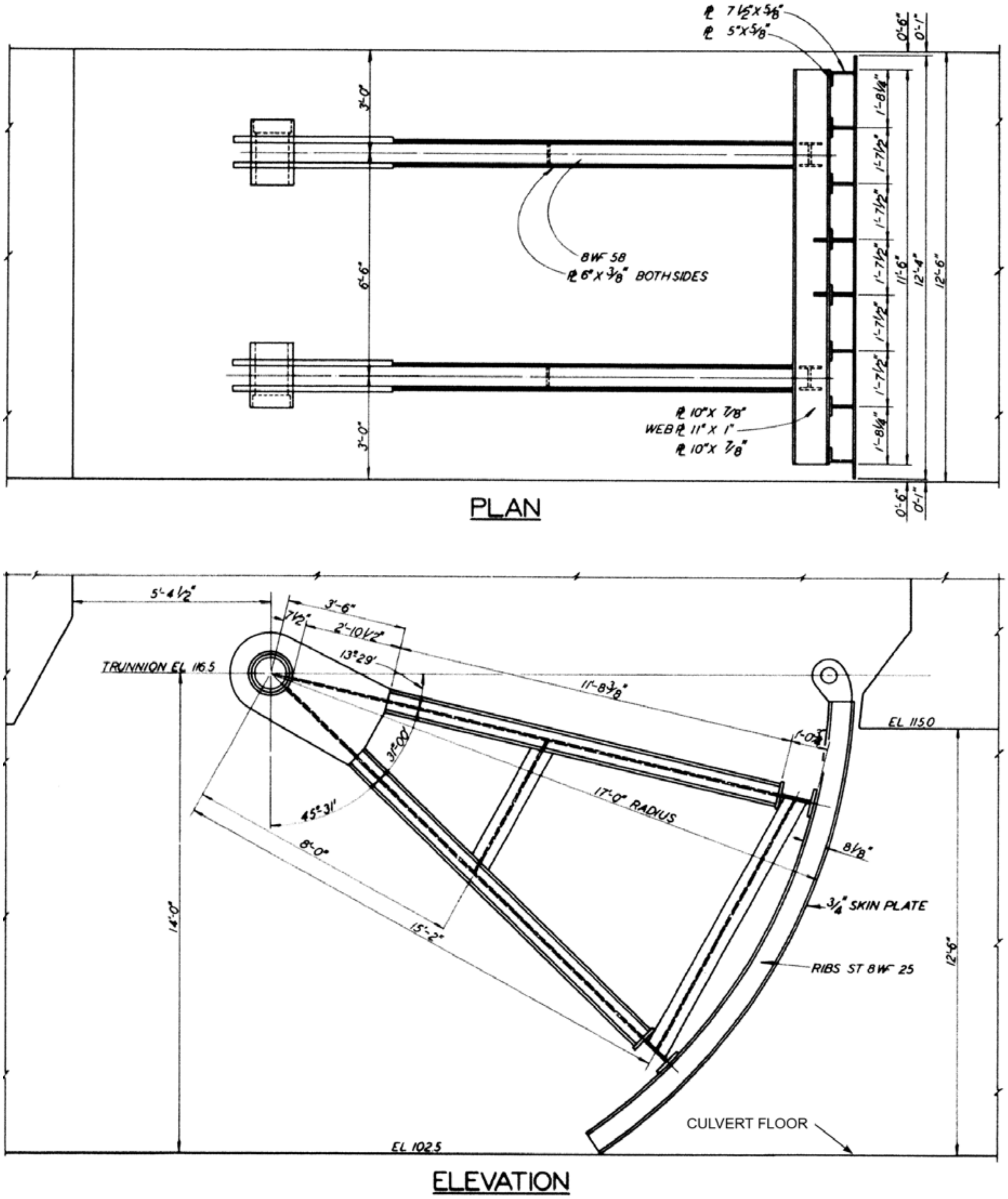


Figure D-10. Tainter Valve, Holt Lock, Type 1 Design.

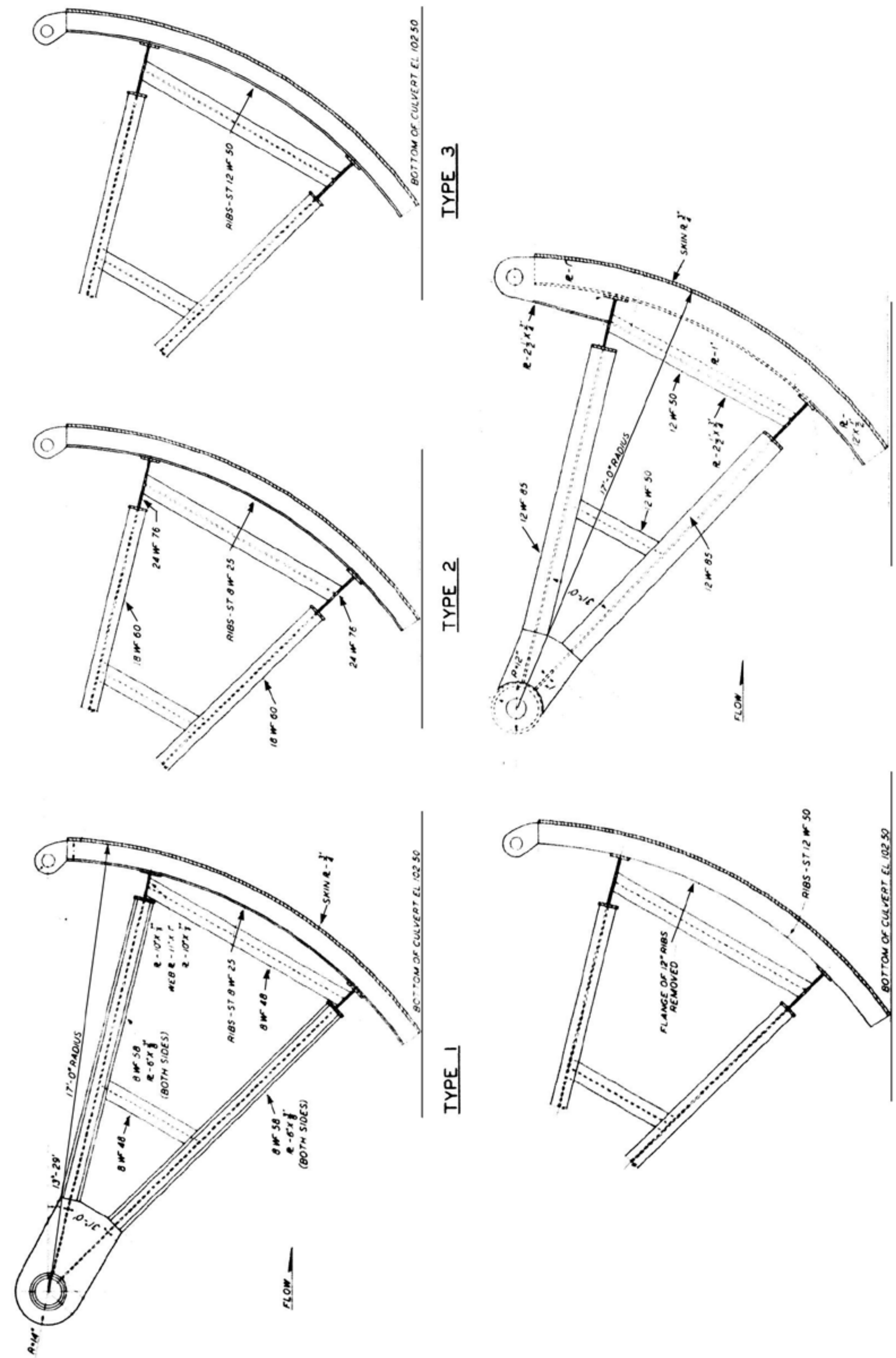


Figure D-11. Tainter Valves, Holt Lock, Types 1-5 Designs.

Table D-22. Hoist Loads, Holt Lock, Type 1.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.08	1.9	1.61	-0.192	-0.184	-0.184	0.008
	2.6		-0.160	-0.152	-0.160	0.008
	3.2		-0.136	-0.128	-0.128	0.008
	3.8		-0.088	-0.072	-0.080	0.016
	4.5		-0.056	-0.032	-0.048	0.024
0.16	3.8	1.65	-0.160	-0.160	-0.160	0.000
	5.1		-0.120	-0.104	-0.112	0.016
	6.4		-0.096	-0.080	-0.088	0.016
	7.7		-0.032	-0.008	-0.016	0.024
0.24	5.8	1.67	-0.152	-0.144	-0.152	0.008
	7.7		-0.064	-0.048	-0.064	0.016
	9.6		-0.040	0.000	-0.024	0.040
0.32	6.4	1.70	-0.432	-0.224	-0.224	0.208
	9.6		-0.200	-0.184	-0.192	0.016
	12.8		-0.144	-0.128	-0.136	0.016
0.40	9.6	1.77	-0.240	-0.216	-0.232	0.024
	12.8		-0.240	-0.160	-0.200	0.080
	16.0		-0.240	-0.080	-0.152	0.160
	19.2		-0.240	-0.024	-0.144	0.216
0.48	12.8	1.79	-0.312	-0.256	-0.272	0.056
	16.0		-0.344	-0.224	-0.288	0.120
	19.2		-0.384	-0.160	-0.264	0.224
	22.4		-0.512	-0.136	-0.288	0.376
0.56	19.2	1.84	-0.592	-0.256	-0.440	0.336
	22.4		-0.624	-0.200	-0.400	0.424
	25.6		-0.752	-0.216	-0.456	0.536
	28.8		-0.840	-0.192	-0.496	0.648
0.64	22.4	1.90	-0.800	-0.400	-0.528	0.400
	25.6		-0.944	-0.368	-0.616	0.576
	28.8		-1.016	-0.456	-0.704	0.560
	32.0		-1.184	-0.408	-0.760	0.776
	35.2		-1.368	-0.680	-0.888	0.688
0.72	25.6	1.94	-0.768	-0.392	-0.560	0.376
	28.8		-1.000	-0.440	-0.664	0.560
	32.0		-0.992	-0.400	-0.704	0.592

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
	35.2		-1.112	-0.496	-0.816	0.616
	38.4		-1.384	-0.448	-0.904	0.936
0.80	32.0	1.98	-0.904	-0.272	-0.592	0.632
	35.2		-1.016	-0.408	-0.680	0.608
	38.4		-1.200	-0.448	-0.752	0.752
	41.6		-1.416	-0.544	-0.928	0.872
	44.8		-1.688	-0.624	-1.032	1.064
0.88	35.2	2.02	-1.064	-0.424	-0.712	0.640
	38.4		-1.200	-0.504	-0.808	0.696
	41.6		-1.488	-0.536	-0.968	0.952
	44.8		-1.760	-0.528	-1.088	1.232
	48.0		-1.824	-0.680	-1.208	1.144
0.96	38.4	2.09	-1.104	-0.400	-0.736	0.704
	41.6		-1.320	-0.464	-0.800	0.856
	44.8		-1.392	-0.520	-0.904	0.872
	48.0		-1.936	-0.568	-1.040	1.368
	51.2		-2.016	-0.416	-1.064	1.600
1.00	41.6	2.14	-1.304	-0.360	-0.744	0.944
	44.8		-1.328	-0.400	-0.816	0.928
	48.0		-1.552	-0.408	-0.880	1.144
	51.2		-1.760	-0.408	-0.960	1.352
	54.4		-2.008	-0.472	-1.112	1.536

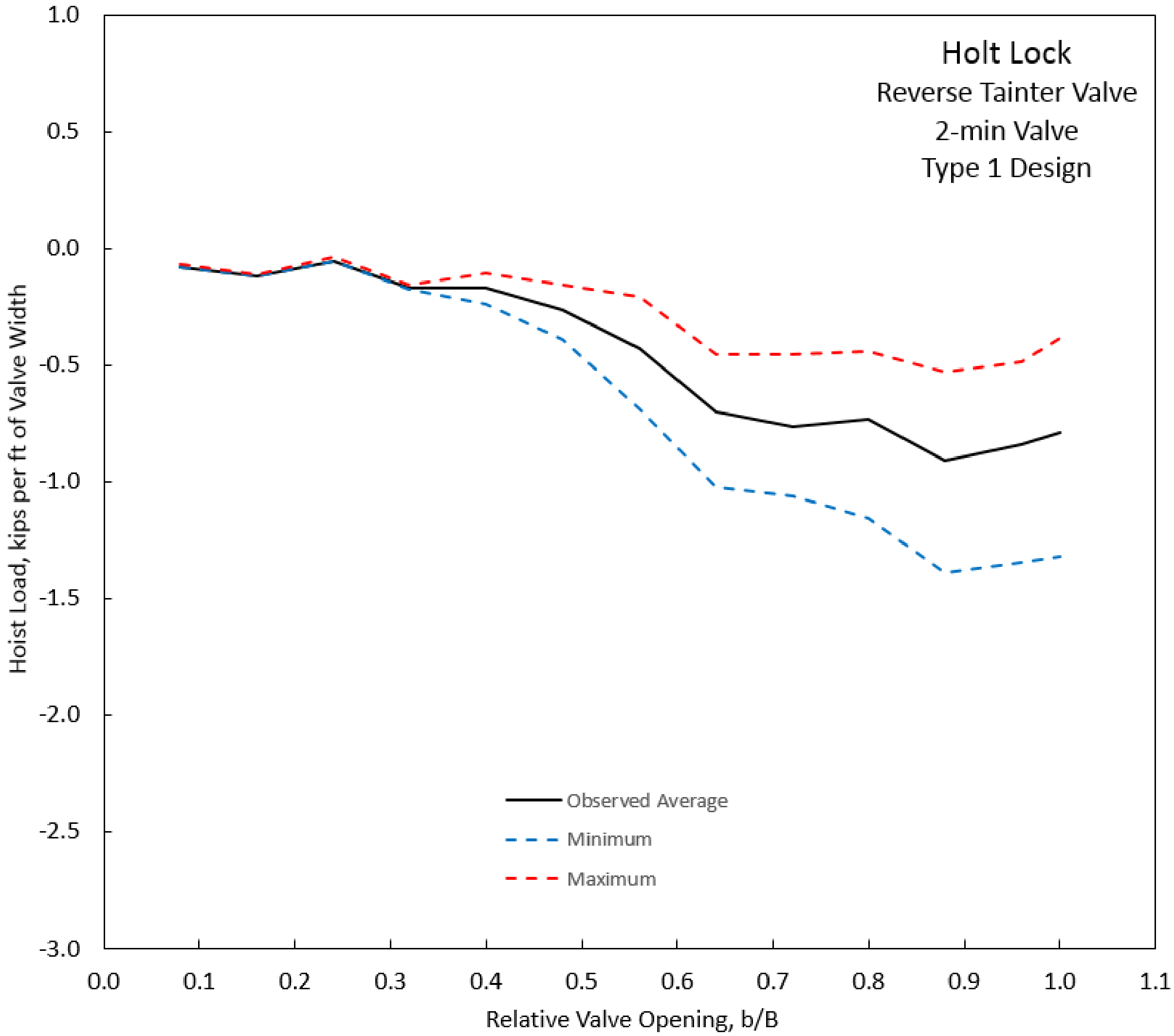


Figure D-12. Hoist load, Holt Lock, Type 1 Design, 2-min Valve.

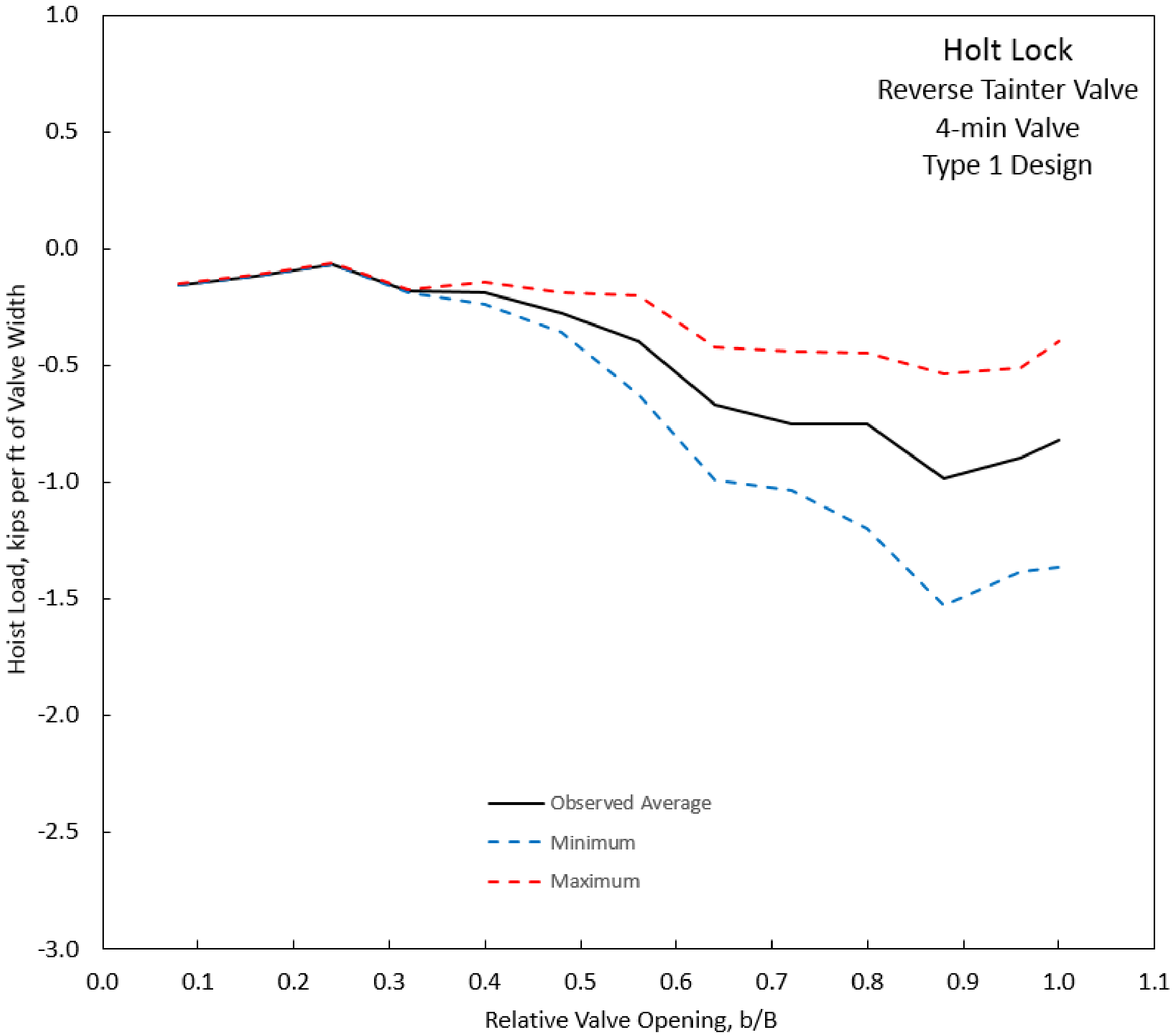


Figure D-13. Hoist load, Holt Lock, Type 1 Design, 4-min Valve.

Table D-23. Hoist Loads, Holt Lock, Type 2.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.08	1.9	1.66	----	----	-0.176	----
	2.6		-0.168	-0.152	-0.160	0.016
	3.2		-0.128	-0.112	-0.120	0.016
	3.8		-0.096	-0.080	-0.088	0.016
	4.5		-0.064	-0.040	-0.056	0.024
0.16	3.8	1.70	-0.168	-0.144	-0.160	0.024
	5.1		-0.136	-0.112	-0.128	0.024
	6.4		-0.088	-0.048	-0.064	0.040
	7.7		-0.048	0.040	-0.008	0.088
0.24	5.1	1.76	-0.192	-0.176	-0.184	0.016
	6.4		-0.152	-0.136	-0.144	0.016
	7.7		-0.144	-0.120	-0.136	0.024
	9.0		-0.128	-0.088	-0.104	0.040
	10.2		-0.104	-0.032	-0.064	0.072
0.32	6.4	1.80	-0.232	-0.208	-0.224	0.024
	8.3		-0.216	-0.184	-0.200	0.032
	10.2		-0.216	-0.144	-0.184	0.072
	12.2		-0.208	-0.088	-0.152	0.120
	14.1		-0.208	-0.040	-0.120	0.168
0.40	9.6	1.83	-0.272	-0.224	-0.240	0.048
	12.8		-0.328	-0.144	-0.240	0.184
	16.0		-0.392	-0.120	-0.248	0.272
	19.2		-0.480	0.040	-0.240	0.520
0.48	12.8	1.87	-0.296	-0.200	-0.248	0.096
	16.0		-0.344	-0.160	-0.248	0.184
	19.2		-0.528	-0.064	-0.248	0.464
	22.4		-0.608	-0.032	-0.248	0.576
0.56	19.2	1.91	-0.720	-0.232	-0.424	0.488
	22.4		-0.968	-0.112	-0.504	0.856
	25.6		-1.144	-0.032	-0.576	1.112
	28.8		-1.536	0.208	-0.616	1.744
0.64	22.4	1.97	-0.928	-0.296	-0.592	0.632
	25.6		-1.272	-0.432	-0.776	0.840
	28.8		-1.752	-0.280	-0.864	1.472
	32.0		-2.248	-0.392	-1.008	1.856

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
	35.2		-2.384	-0.664	-1.056	1.720
0.72	25.6	2.02	-1.088	-0.336	-0.672	0.752
	28.8		-1.304	-0.392	-0.800	0.912
	32.0		-1.392	-0.400	-0.896	0.992
	35.2		-1.688	-0.264	-0.960	1.424
	38.4		-2.104	-0.416	-1.136	1.688
0.80	32.0	2.08	-1.384	-0.472	-0.920	0.912
	35.2		-1.552	-0.464	-1.032	1.088
	38.4		-1.784	-0.528	-1.216	1.256
	41.6		-2.576	-0.544	-1.432	2.032
	44.8		-2.664	-0.624	-1.576	2.040
0.88	35.2	2.14	-1.672	-0.592	-1.064	1.080
	38.4		-2.000	-0.576	-1.192	1.424
	41.6		-2.440	-0.656	-1.344	1.784
	44.8		-2.528	-0.552	-1.480	1.976
	48.0		-2.872	-0.808	-1.720	2.064
0.96	38.4	2.21	-1.872	-0.632	-1.120	1.240
	41.6		-1.920	-0.688	-1.272	1.232
	44.8		-2.544	-0.656	-1.496	1.888
	48.0		-2.640	-0.752	-1.640	1.888
	51.2		-2.912	-0.752	-1.776	2.160
1.00	41.6	2.27	-1.968	-0.568	-1.184	1.400
	44.8		-2.160	-0.744	-1.280	1.416
	48.0		-2.776	-0.744	-1.560	2.032
	51.2		-2.992	-0.784	-1.656	2.208
	54.4		-3.512	-0.472	-1.752	3.040

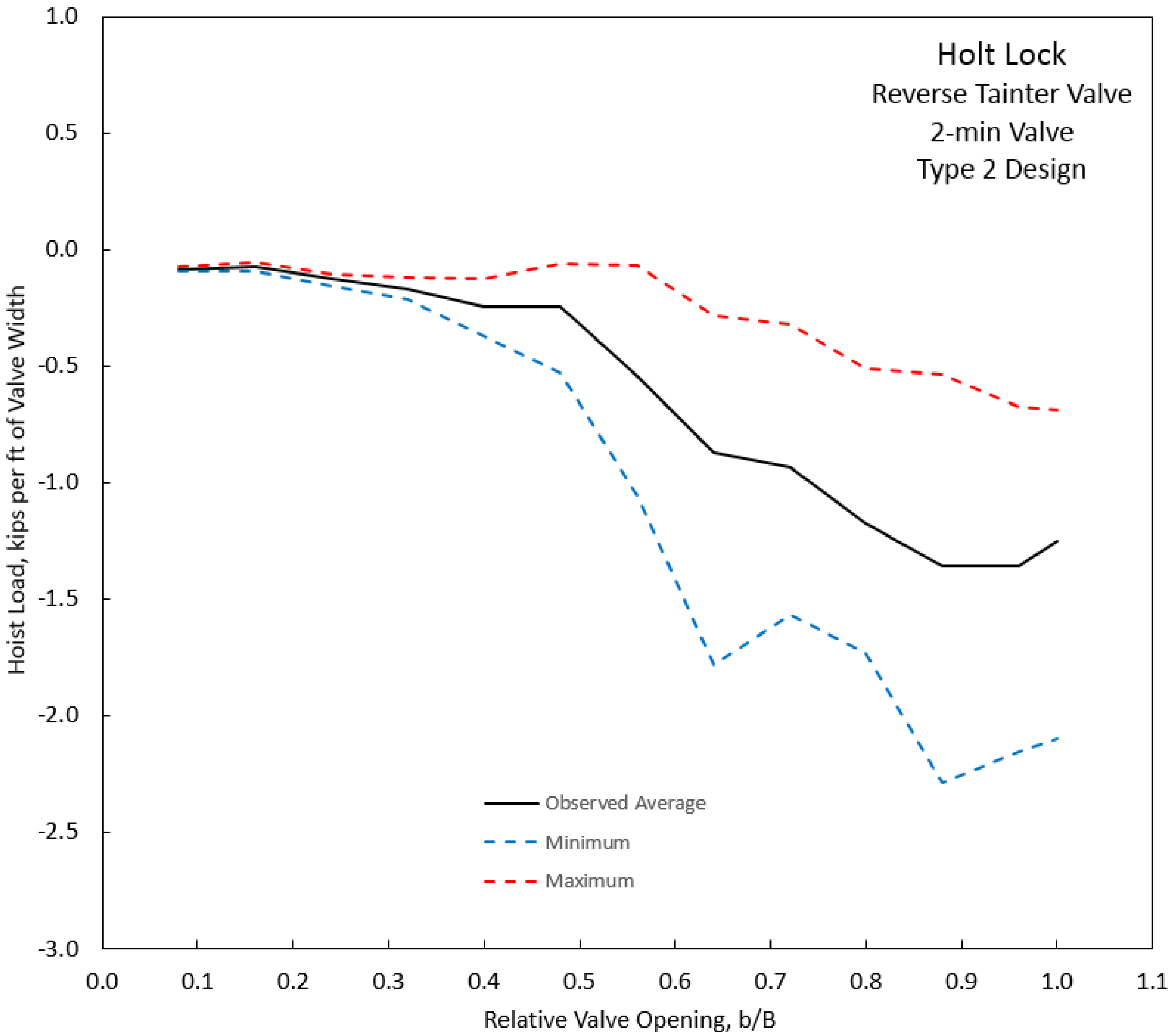


Figure D-14. Hoist load, Holt Lock, Type 2 Design, 2-min Valve.

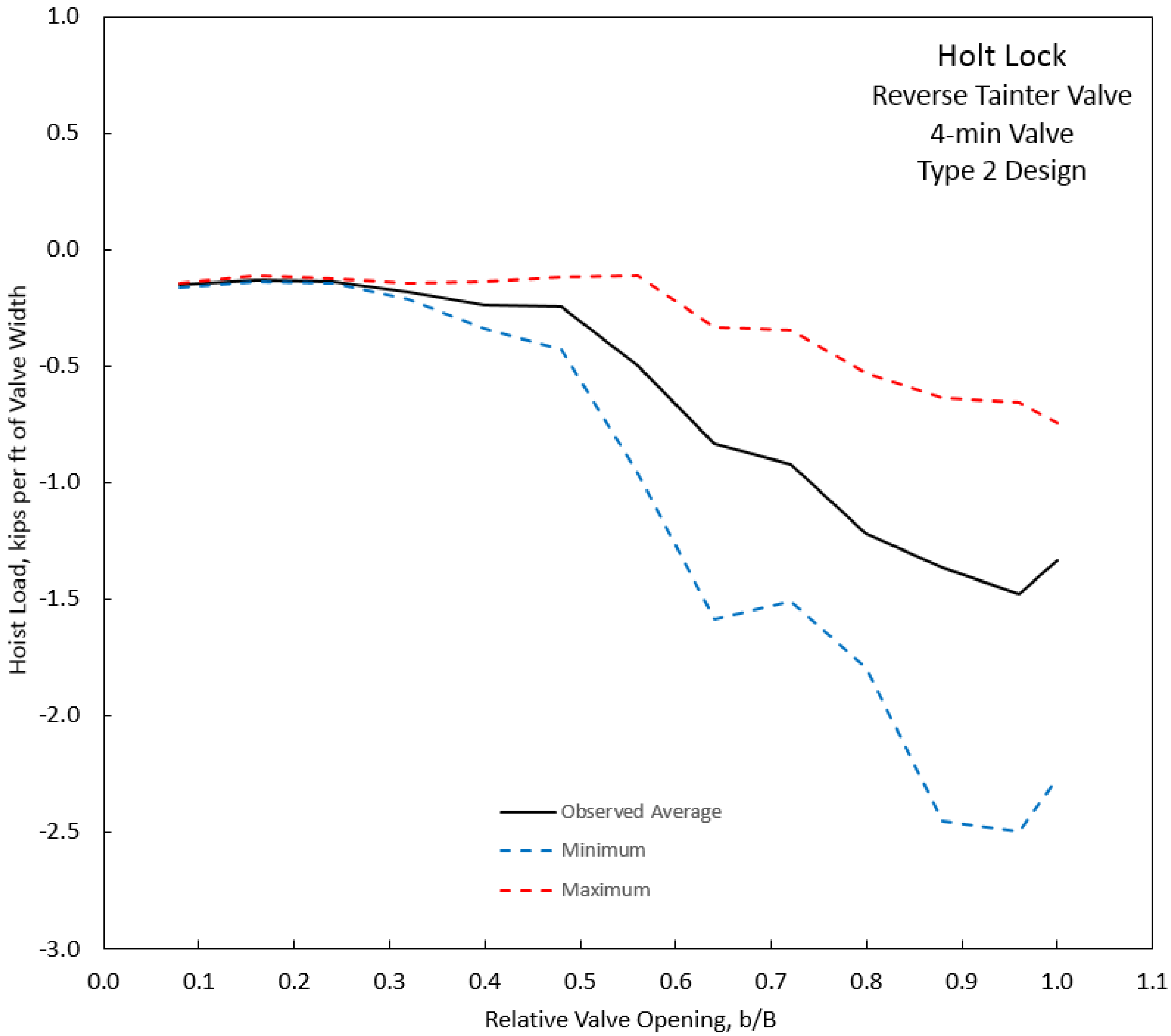


Figure D-15. Hoist load, Holt Lock, Type 2 Design, 4-min Valve.

Table D-24. Hoist Loads, Holt Lock, Type 3.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.08	1.9	1.77	-0.024	-0.016	-0.024	0.008
	2.6		0.064	0.080	0.072	0.016
	3.2		0.160	0.176	0.168	0.016
	3.8		0.264	0.288	0.272	0.024
	4.5		0.360	0.384	0.376	0.024
0.16	3.8	1.80	-0.016	0.000	-0.008	0.016
	5.1		0.056	0.120	0.096	0.064
	6.4		0.232	0.280	0.256	0.048
	7.7		0.312	0.368	0.336	0.056
0.24	5.1	1.85	-0.088	-0.064	-0.080	0.024
	6.4		0.000	0.048	0.024	0.048
	7.7		0.064	0.104	0.080	0.040
	9.0		0.128	0.184	0.152	0.056
	10.2		0.216	0.296	0.256	0.080
0.32	6.4	1.89	-0.088	-0.048	-0.072	0.040
	8.3		-0.040	0.016	-0.016	0.056
	10.2		0.008	0.120	0.072	0.112
	12.2		0.064	0.200	0.144	0.136
	14.1		0.144	0.408	0.272	0.264
0.40	9.6	1.93	-0.152	-0.056	-0.104	0.096
	12.8		-0.216	0.040	-0.064	0.256
	16.0		-0.136	0.168	0.032	0.304
	19.2		-0.192	0.328	0.048	0.520
0.48	12.8	1.97	-0.304	-0.104	-0.208	0.200
	16.0		-0.400	-0.016	-0.208	0.384
	19.2		-0.648	0.032	-0.248	0.680
	22.4		-0.688	0.176	-0.264	0.864
0.56	19.2	2.02	-0.584	-0.184	-0.384	0.400
	22.4		-0.856	-0.048	-0.480	0.808
	25.6		-1.192	-0.104	-0.624	1.088
	28.8		-1.616	0.144	-0.712	1.760
0.64	22.4	2.06	-1.032	-0.248	-0.616	0.784
	25.6		-1.304	-0.216	-0.728	1.088
	28.8		-1.632	-0.216	-0.872	1.416
	32.0		-1.960	-0.216	-0.968	1.744

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
	35.2		-2.528	-0.064	-1.104	2.464
0.72	25.6	2.11	-1.264	-0.216	-0.688	1.048
	28.8		-1.432	-0.344	-0.824	1.088
	32.0		-1.704	-0.336	-0.992	1.368
	35.2		-2.288	-0.384	-1.200	1.904
	38.4		-2.832	-0.400	-1.384	2.432
0.80	32.0	2.17	-1.840	-0.552	-1.056	1.288
	35.2		-2.112	-0.600	-1.296	1.512
	38.4		-2.344	-0.688	-1.384	1.656
	41.6		-3.152	-0.688	-1.688	2.464
	44.8		-3.424	-0.760	-1.856	2.664
0.88	35.2	2.23	-1.744	-0.576	-1.056	1.168
	38.4		-2.000	-0.576	-1.248	1.424
	41.6		-2.576	-0.688	-1.432	1.888
	44.8		-2.936	-0.608	-1.576	2.328
	48.0		-3.384	-0.704	-1.856	2.680
0.96	38.4	2.30	-1.824	-0.504	-1.120	1.320
	41.6		-2.312	-0.496	-1.264	1.816
	44.8		-2.544	-0.512	-1.360	2.032
	48.0		-2.792	-0.544	-1.544	2.248
	51.2		-3.624	-0.440	-1.640	3.184
1.00	41.6	2.37	-2.032	-0.360	-1.032	1.672
	44.8		-2.384	-0.328	-1.112	2.056
	48.0		-2.432	-0.248	-1.168	2.184
	51.2		-2.760	-0.328	-1.288	2.432
	54.4		-2.984	-0.232	-1.360	2.752

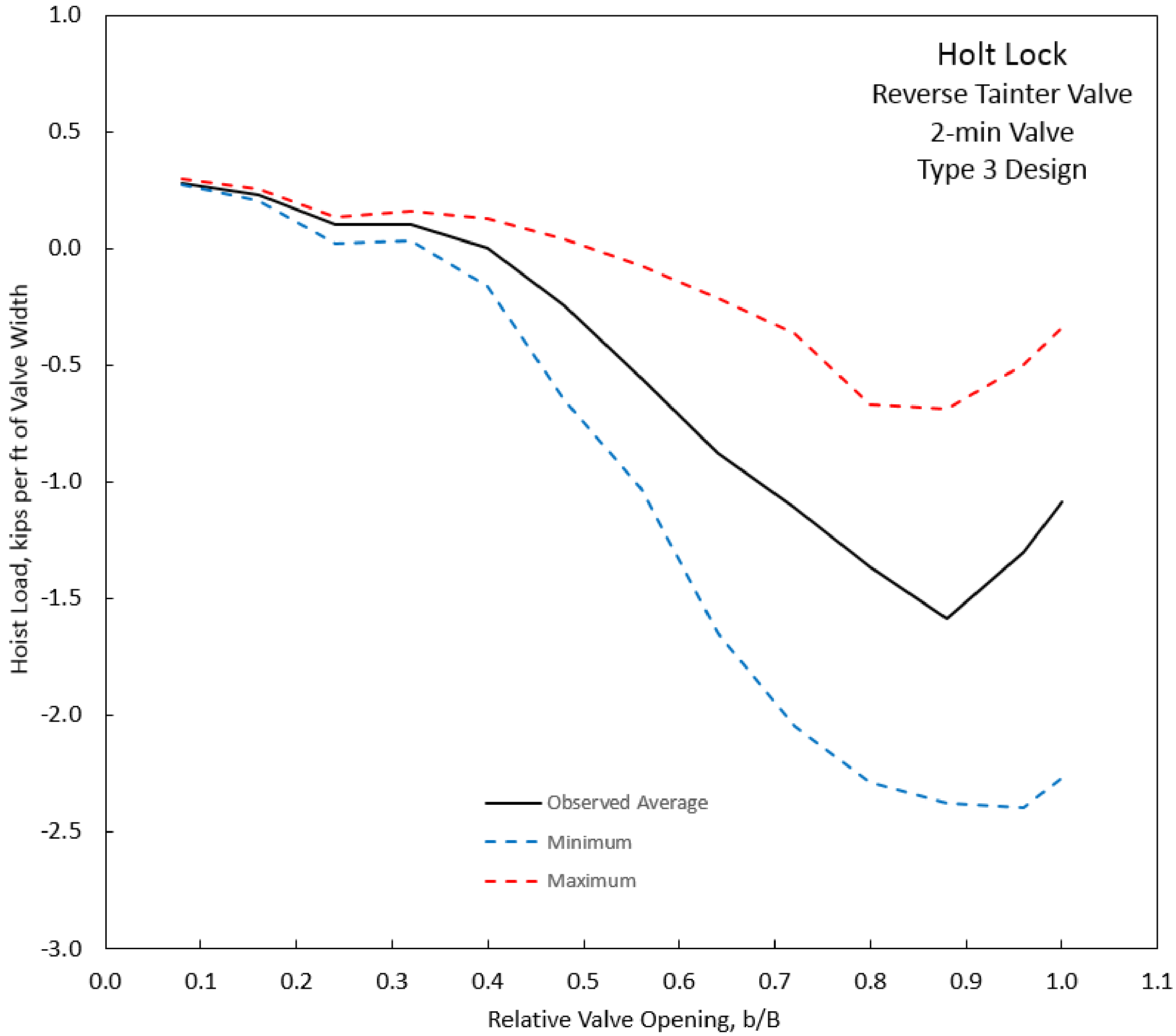


Figure D-16. Hoist load, Holt Lock, Type 3 Design, 2-min Valve.

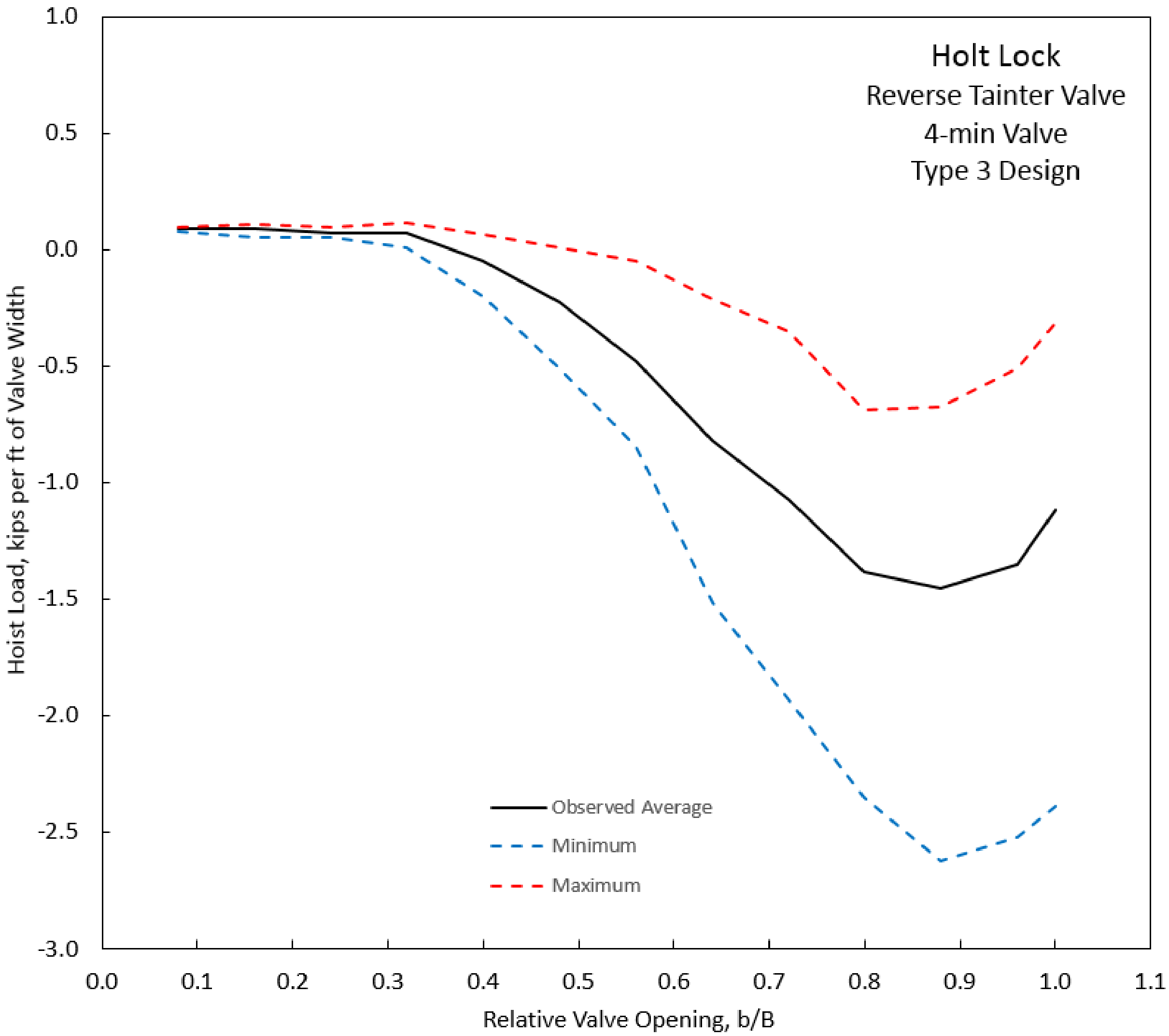


Figure D-17. Hoist load, Holt Lock, Type 3 Design, 4-min Valve.

Table D-25. Hoist Loads, Holt Lock, Type 4.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.08	1.9	1.52	-0.056	-0.040	-0.048	0.016
	2.6		0.032	0.048	0.040	0.016
	3.2		0.088	0.120	0.112	0.032
	3.8		0.312	0.336	0.320	0.024
	4.5		0.368	0.408	0.392	0.040
0.16	3.8	1.55	0.000	0.016	0.008	0.016
	5.1		0.112	0.136	0.128	0.024
	6.4		0.224	0.264	0.240	0.040
	7.7		0.304	0.360	0.336	0.056
0.24	5.1	1.59	-0.016	0.008	0.000	0.024
	6.4		0.056	0.080	0.064	0.024
	7.7		0.136	0.200	0.168	0.064
	9.0		0.216	0.296	0.264	0.080
	10.2		0.304	0.400	0.344	0.096
0.32	6.4	1.63	-0.056	-0.032	-0.048	0.024
	8.3		-0.008	0.040	0.016	0.048
	10.2		0.080	0.224	0.144	0.144
	12.2		0.168	0.336	0.232	0.168
	14.1		0.248	0.488	0.368	0.240
0.40	9.6	1.66	-0.056	0.016	-0.024	0.072
	12.8		-0.024	0.184	0.080	0.208
	16.0		0.048	0.344	0.208	0.296
	19.2		0.112	0.560	0.336	0.448
0.48	12.8	1.70	-0.136	0.008	-0.072	0.144
	16.0		-0.144	0.136	-0.008	0.280
	19.2		-0.200	0.272	0.032	0.472
	22.4		-0.336	0.448	0.080	0.784
	25.6		-0.608	0.800	0.128	1.408
0.56	19.2	1.73	-0.456	0.104	-0.160	0.560
	22.4		-0.728	0.192	-0.160	0.920
	25.6		-0.832	0.400	-0.208	1.232
	28.8		-1.184	0.424	-0.256	1.608
0.64	22.4	1.77	-0.752	0.008	-0.352	0.760
	25.6		-0.944	0.016	-0.408	0.960
	28.8		-1.104	0.064	-0.448	1.168

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
	32.0		-1.248	0.144	-0.544	1.392
	35.2		-1.416	0.272	-0.608	1.688
0.72	25.6	1.82	-0.824	-0.160	-0.488	0.664
	28.8		-1.048	-0.080	-0.584	0.968
	32.0		-1.320	-0.136	-0.640	1.184
	35.2		-1.448	-0.104	-0.736	1.344
	38.4		-1.600	-0.080	-0.832	1.520
0.80	32.0	1.87	-1.352	-0.304	-0.776	1.048
	35.2		-1.592	-0.352	-0.864	1.240
	38.4		-1.856	-0.352	-0.928	1.504
	41.6		-1.992	-0.296	-1.128	1.696
	44.8		-2.536	-0.192	-1.312	2.344
0.88	35.2	1.90	-1.592	-0.360	-0.904	1.232
	38.4		-1.896	-0.368	-1.000	1.528
	41.6		-1.984	-0.448	-1.072	1.536
	44.8		-2.272	-0.440	-1.328	1.832
	48.0		-2.528	-0.568	-1.400	1.960
0.96	38.4	1.96	-1.504	-0.376	-0.824	1.128
	41.6		-1.408	-0.400	-0.840	1.008
	44.8		-2.000	-0.488	-1.136	1.512
	48.0		-2.352	-0.464	-1.232	1.888
	51.2		-2.496	-0.272	-1.368	2.224
1.00	41.6	2.01	-1.744	-0.416	-0.992	1.328
	44.8		-1.888	-0.376	-1.088	1.512
	48.0		-2.184	-0.440	-1.232	1.744
	51.2		-2.440	-0.496	-1.280	1.944
	54.4		-2.464	-0.384	-1.320	2.080

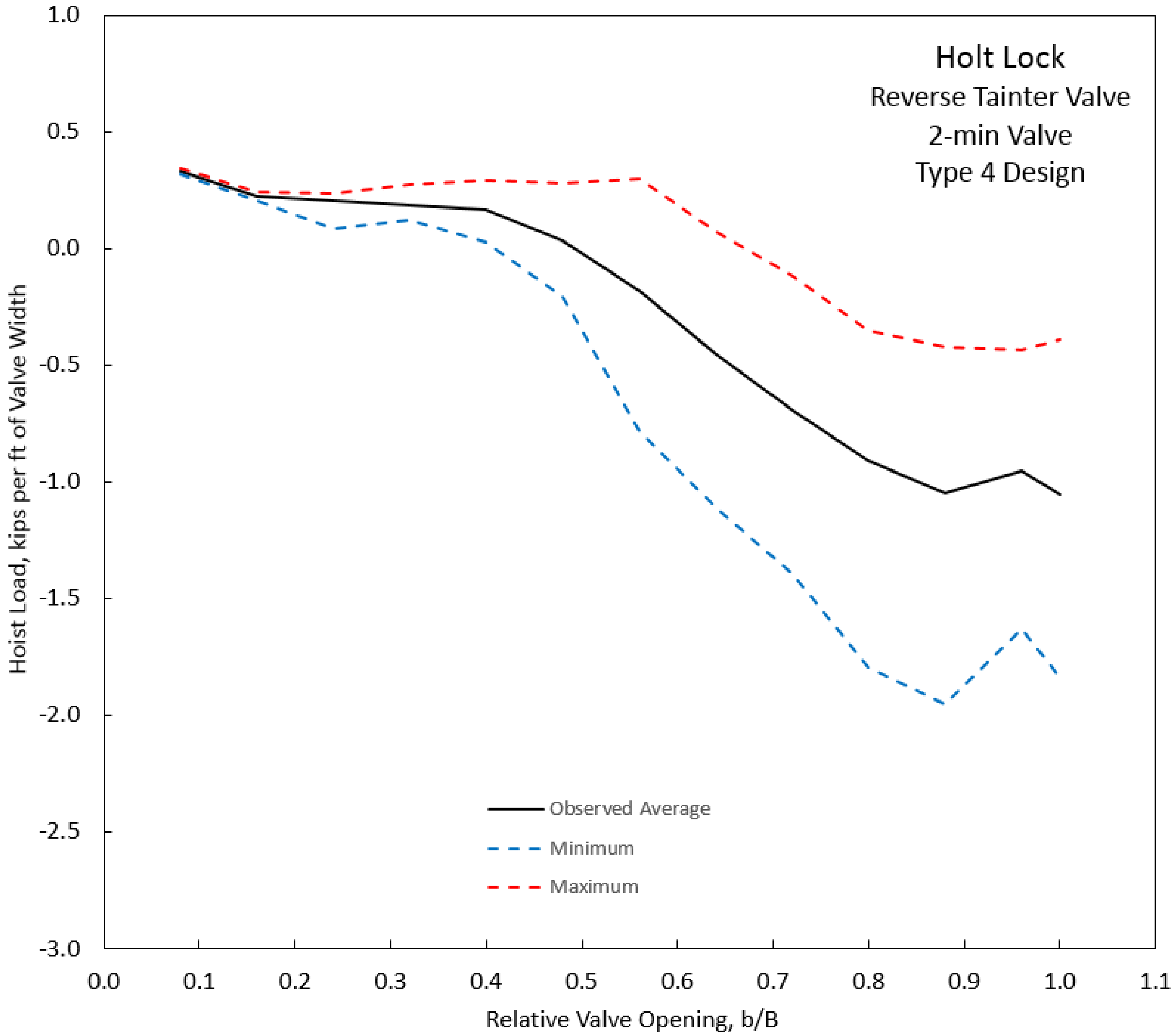


Figure D-18. Hoist load, Holt Lock, Type 4 Design, 2-min Valve.

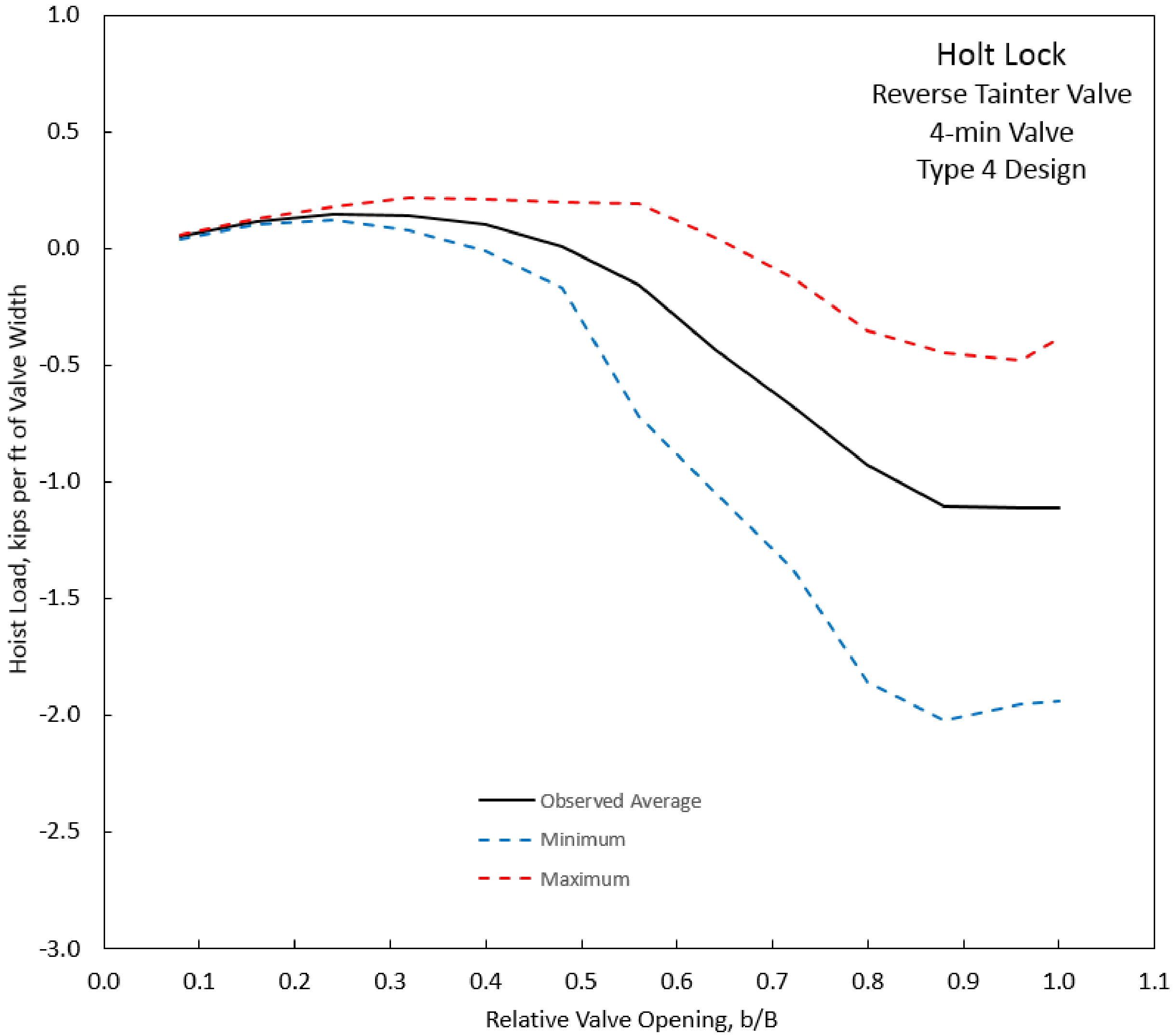


Figure D-19. Hoist load, Holt Lock, Type 4 Design, 4-min Valve.

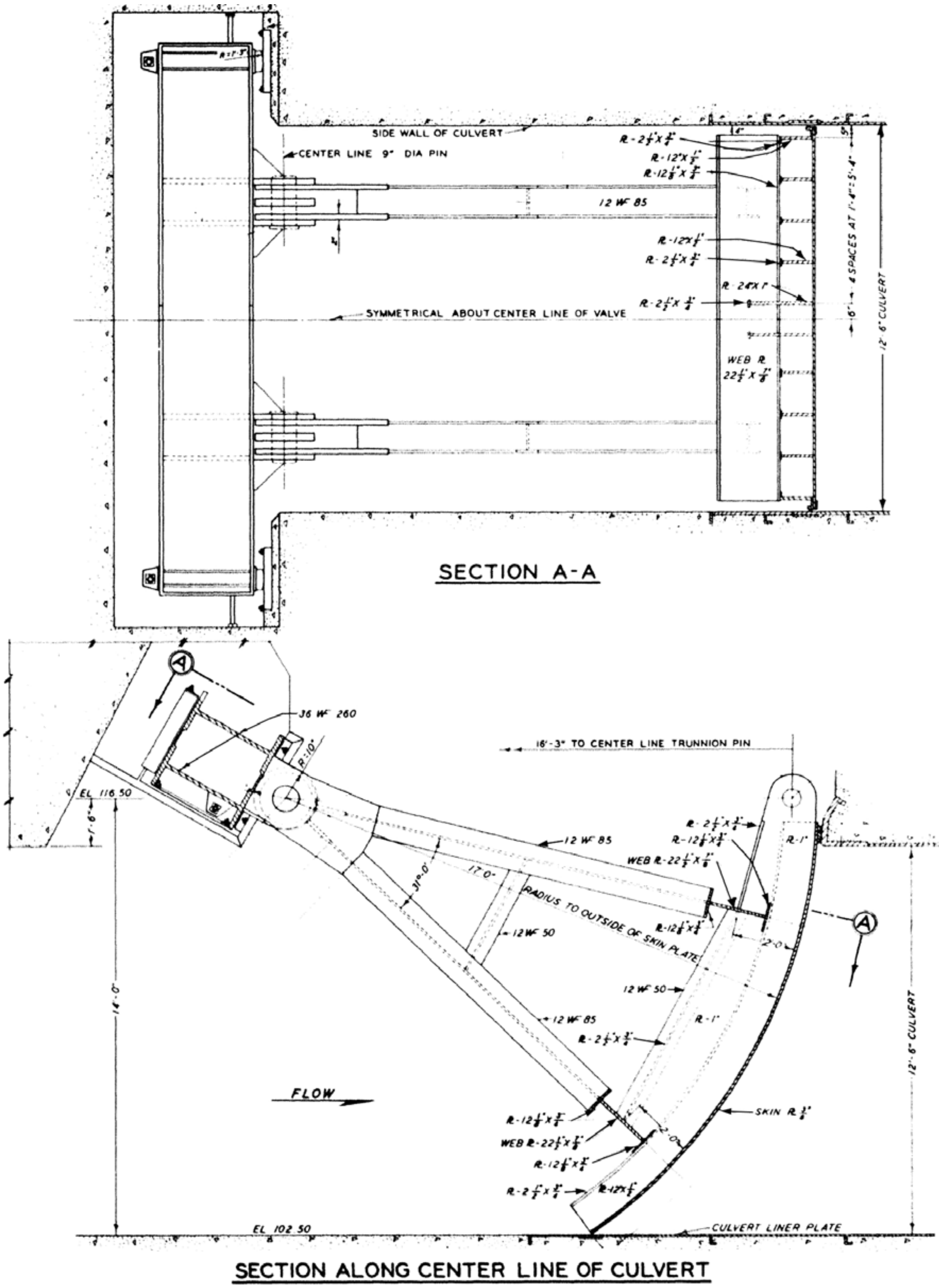


Figure D-20. Tainter Valve, Holt Lock, Type 5 Design.

Table D-26. Hoist Loads, Holt Lock, Type 5 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.08	1.9	2.08	-0.200	-0.184	-0.192	0.016
	2.6		-0.112	-0.096	-0.104	0.016
	3.2		-0.040	-0.024	-0.032	0.016
	3.8		0.032	0.056	0.040	0.024
	4.5		0.144	0.168	0.152	0.024
	5.1		0.192	0.216	0.200	0.024
0.16	3.8	2.15	-0.160	-0.152	-0.152	0.008
	5.1		-0.080	-0.064	-0.072	0.016
	6.4		0.064	0.088	0.080	0.024
	7.7		0.184	0.240	0.208	0.056
0.24	5.1	2.22	-0.216	-0.200	-0.208	0.016
	6.4		-0.096	-0.072	-0.088	0.024
	7.7		-0.024	0.016	0.000	0.040
	9.0		0.064	0.120	0.080	0.056
	10.2		0.136	0.216	0.176	0.080
0.32	6.4	2.27	-0.184	-0.160	-0.176	0.024
	8.3		-0.104	-0.048	-0.080	0.056
	10.2		-0.032	0.048	0.008	0.080
	12.2		0.064	0.200	0.144	0.136
	14.1		0.176	0.344	0.264	0.168
0.40	9.6	2.35	-0.192	-0.120	-0.160	0.072
	12.8		-0.112	-0.008	-0.056	0.104
	16.0		0.000	0.192	0.104	0.192
	19.2		0.088	0.440	0.272	0.352
0.48	12.8	2.41	-0.272	-0.152	-0.208	0.120
	16.0		-0.248	0.000	-0.128	0.248
	19.2		-0.192	0.112	-0.024	0.304
	22.4		-0.224	0.392	0.056	0.616
	25.6		-0.424	0.672	0.200	1.096
0.56	19.2	2.49	-0.448	-0.096	-0.272	0.352
	22.4		-0.464	0.072	-0.216	0.536
	25.6		-0.592	0.144	-0.216	0.736
	28.8		-0.672	0.344	-0.184	1.016
	32.0		-0.704	0.480	-0.080	1.184

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.64	22.4	2.53	-0.592	-0.192	-0.408	0.400
	25.6		-0.808	-0.104	-0.480	0.704
	28.8		-1.008	-0.112	-0.512	0.896
	32.0		-1.176	-0.032	-0.544	1.144
	35.2		-1.368	0.000	-0.568	1.368
0.72	25.6	2.60	-0.960	-0.344	-0.640	0.616
	28.8		-1.080	-0.328	-0.728	0.752
	32.0		-1.248	-0.360	-0.784	0.888
	35.2		-1.536	-0.288	-0.904	1.248
	38.4		-2.104	-0.432	-1.104	1.672
	41.6		-2.296	-0.360	-1.136	1.936
0.80	32.0	2.69	-1.424	-0.528	-0.904	0.896
	35.2		-1.520	-0.464	-0.976	1.056
	38.4		-1.704	-0.560	-1.096	1.144
	41.6		-2.032	-0.376	-1.224	1.656
	44.8		-2.200	-0.480	-1.312	1.720
	48.0		-2.752	-0.520	-1.568	2.232
0.88	35.2	2.77	-1.416	-0.608	-0.960	0.808
	38.4		-2.056	-0.568	-1.120	1.488
	41.6		-1.920	-0.664	-1.224	1.256
	44.8		-2.208	-0.632	-1.368	1.576
	48.0		-2.736	-0.472	-1.504	2.264
	51.2		-3.120	-0.592	-1.616	2.528
0.96	38.4	2.86	-1.600	-0.544	-0.936	1.056
	41.6		-1.688	-0.560	-1.072	1.128
	44.8		-2.144	-0.424	-1.184	1.720
	48.0		-2.288	-0.552	-1.288	1.736
	51.2		-2.568	-0.280	-1.392	2.288
1.00	41.6	2.92	-1.688	-0.664	-1.104	1.024
	44.8		-1.840	-0.608	-1.160	1.232
	48.0		-2.032	-0.616	-1.280	1.416
	51.2		-2.312	-0.344	-1.344	1.968

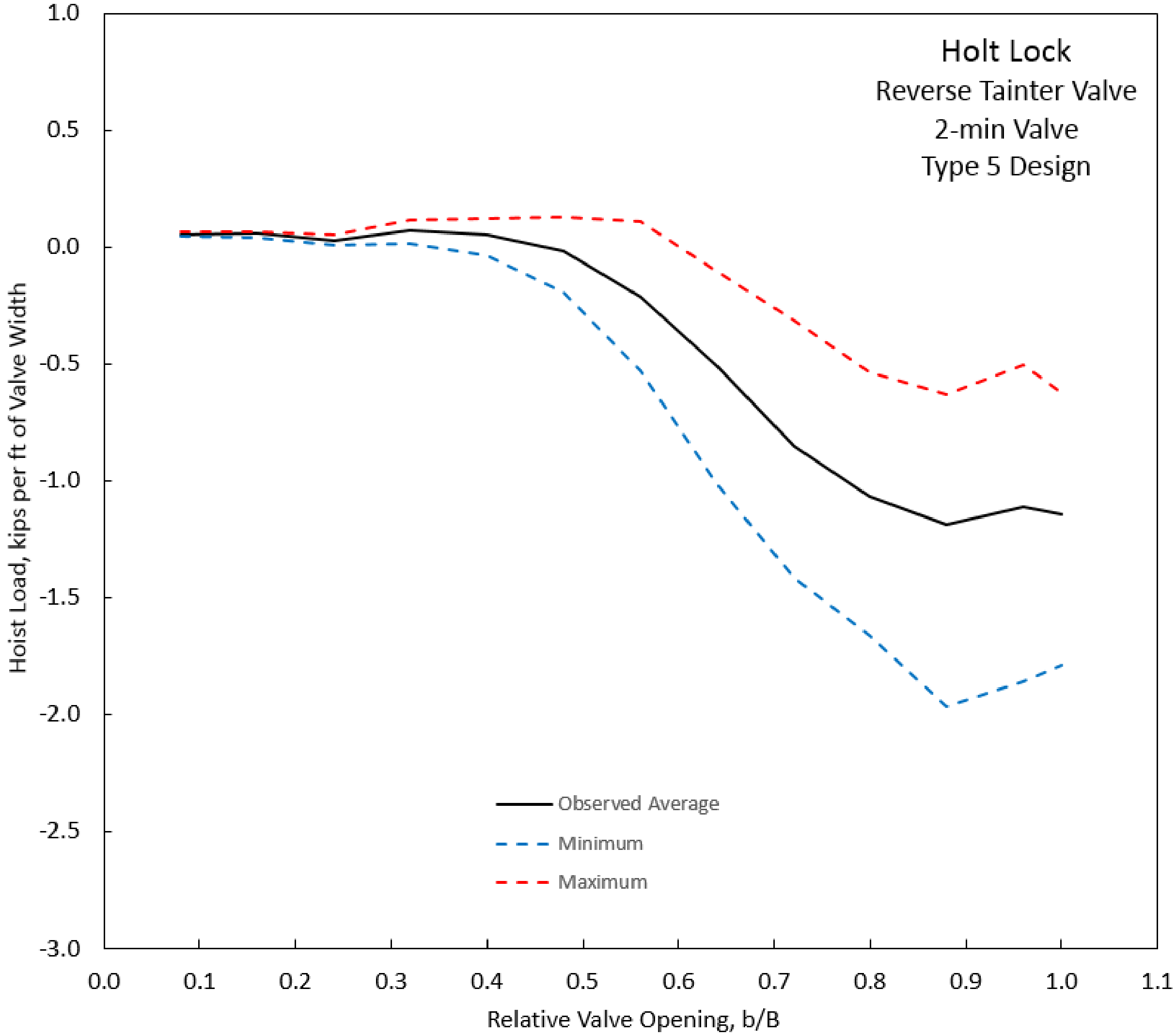


Figure D-21. Hoist load, Holt Lock, Type 5 Design, 2-min Valve.

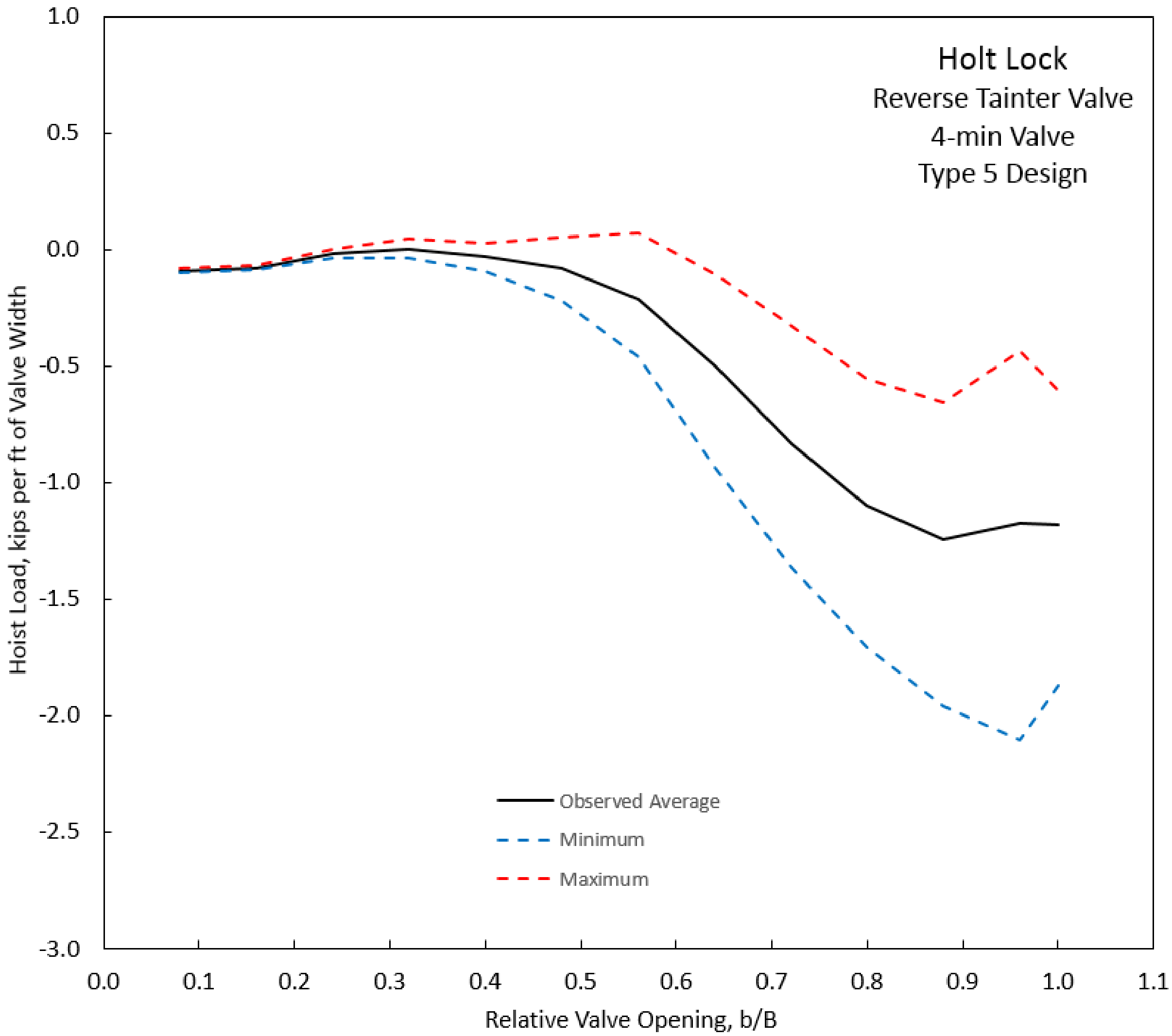


Figure D-22. Hoist load, Holt Lock, Type 5 Design, 4-min Valve.

Table D-27. Hoist Loads, Holt Lock, Type 6 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.08	1.9	2.04	-0.184	-0.184	-0.184	0.000
	2.6		-0.112	-0.112	-0.112	0.000
	3.2		-0.040	-0.024	-0.032	0.016
	3.8		0.000	0.016	0.008	0.016
	4.5		0.112	0.136	0.128	0.024
	5.1		0.176	0.200	0.184	0.024
0.16	3.8	2.10	-0.144	-0.144	-0.144	0.000
	5.1		-0.056	-0.048	-0.048	0.008
	6.4		0.072	0.112	0.096	0.040
	7.7		0.168	0.208	0.184	0.040
0.24	5.1	2.18	-0.128	-0.128	-0.128	0.000
	6.4		-0.088	-0.048	-0.072	0.040
	7.7		0.000	0.048	0.016	0.048
	9.0		0.056	0.120	0.088	0.064
	10.2		0.128	0.224	0.184	0.096
0.32	6.4	2.25	-0.128	-0.112	-0.120	0.016
	8.3		-0.096	-0.056	-0.072	0.040
	10.2		0.000	0.072	0.024	0.072
	12.2		0.088	0.224	0.152	0.136
	14.1		0.152	0.352	0.256	0.200
0.40	9.6	2.30	-0.136	-0.072	-0.104	0.064
	12.8		-0.072	0.048	-0.016	0.120
	16.0		0.008	0.232	0.120	0.224
	19.2		0.096	0.392	0.240	0.296
0.48	12.8	2.38	-0.248	-0.152	-0.200	0.096
	16.0		-0.208	0.000	-0.128	0.208
	19.2		-0.240	0.104	-0.056	0.344
	22.4		-0.192	0.280	0.024	0.472
	25.6		-0.504	0.728	0.144	1.232
0.56	19.2	2.44	-0.360	-0.032	-0.216	0.328
	22.4		-0.496	0.048	-0.200	0.544
	25.6		0.048	0.272	-0.176	0.224
	28.8		-0.864	0.376	-0.136	1.240
	32.0		-0.848	0.552	-0.080	1.400
0.64	22.4	2.52	-0.728	-0.200	-0.408	0.528

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
	25.6		-0.864	-0.096	-0.456	0.768
	28.8		-0.936	-0.056	-0.488	0.880
	32.0		-1.008	0.048	-0.528	1.056
	35.2		-1.144	0.120	-0.544	1.264
0.72	25.6	2.61	-0.952	-0.320	-0.584	0.632
	28.8		-1.096	-0.352	-0.672	0.744
	32.0		-1.416	-0.376	-0.744	1.040
	35.2		-1.360	-0.344	-0.816	1.016
	38.4		-1.728	-0.248	-0.896	1.480
	41.6		-2.144	-0.320	-1.096	1.824
0.80	32.0	2.68	-1.232	-0.480	-0.848	0.752
	35.2		-1.448	-0.528	-0.952	0.920
	38.4		-1.936	-0.408	-1.040	1.528
	41.6		-2.104	-0.464	-1.160	1.640
	44.8		-2.288	-0.392	-1.232	1.896
	48.0		-2.512	-0.144	-1.376	2.368
0.88	35.2	2.78	-1.528	-0.616	-0.928	0.912
	38.4		-1.632	-0.480	-1.040	1.152
	41.6		-1.952	-0.376	-1.232	1.576
	44.8		-2.440	-0.544	-1.392	1.896
	48.0		-2.864	-0.480	-1.472	2.384
	51.2		-3.288	-0.336	-1.504	2.952
0.96	38.4	2.87	-1.648	-0.560	-1.056	1.088
	41.6		-2.064	-0.576	-1.192	1.488
	44.8		-2.208	-0.520	-1.336	1.688
	48.0		-2.488	-0.560	-1.408	1.928
	51.2		-2.768	-0.384	-1.472	2.384
1.00	41.6	2.94	-1.816	-0.648	-1.152	1.168
	44.8		-2.120	-0.648	-1.208	1.472
	48.0		-2.336	-0.648	-1.408	1.688
	51.2		-2.472	-0.512	-1.440	1.960
	54.4		-2.896	-0.512	-1.464	2.384

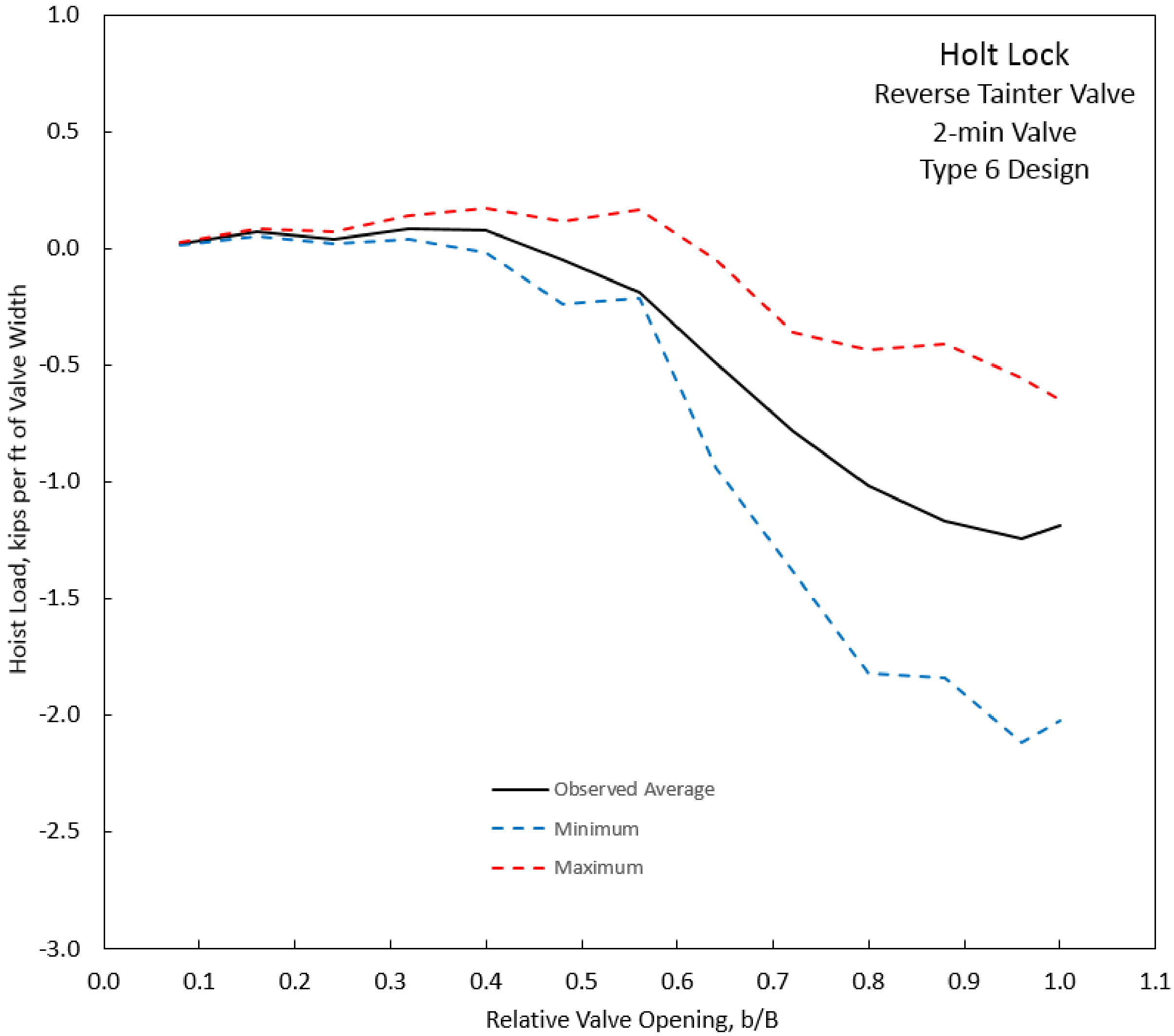


Figure D-23. Hoist load, Holt Lock, Type 6 Design, 2-min Valve.

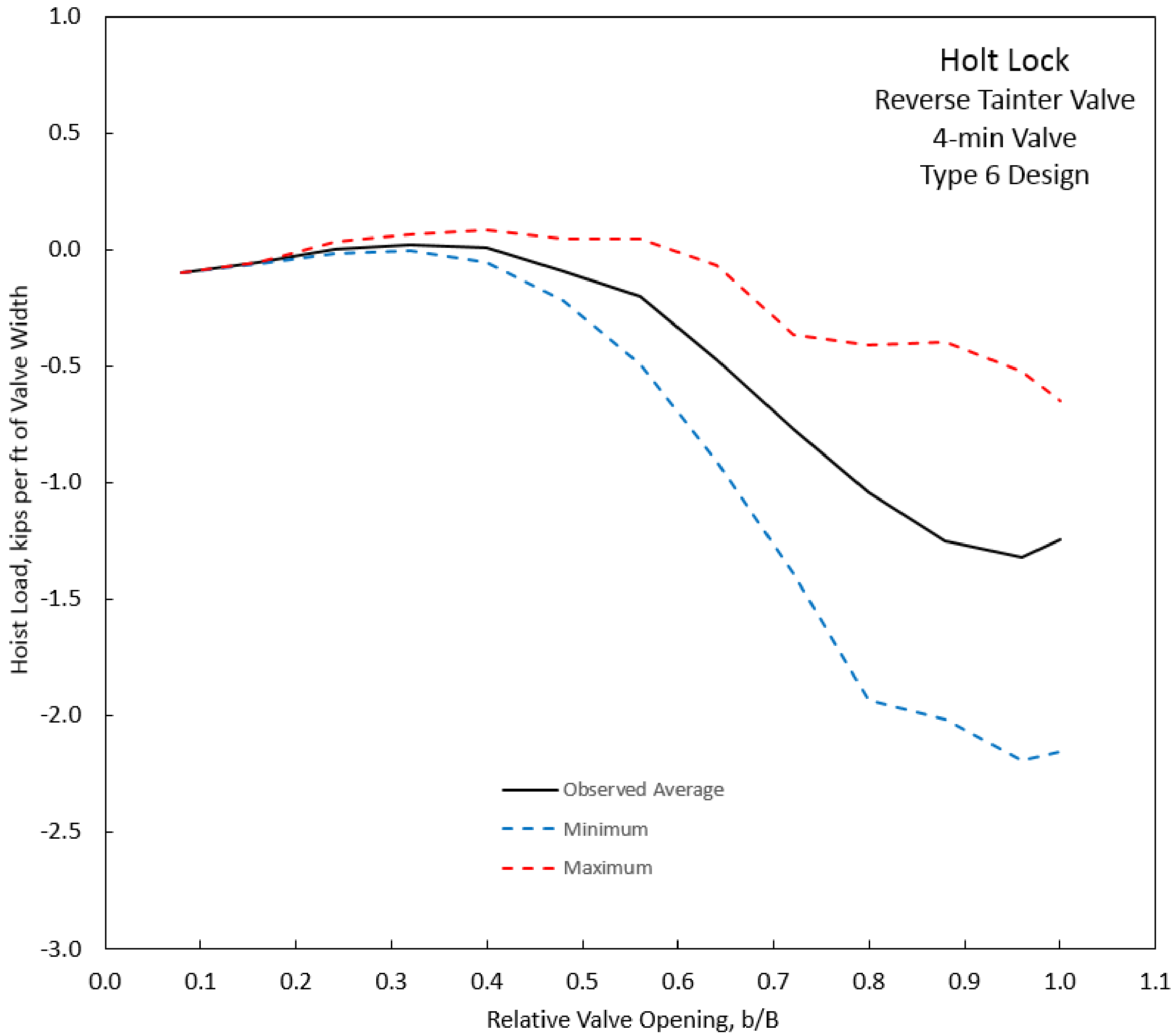


Figure D-24. Hoist load, Holt Lock, Type 6 Design, 4-min Valve.

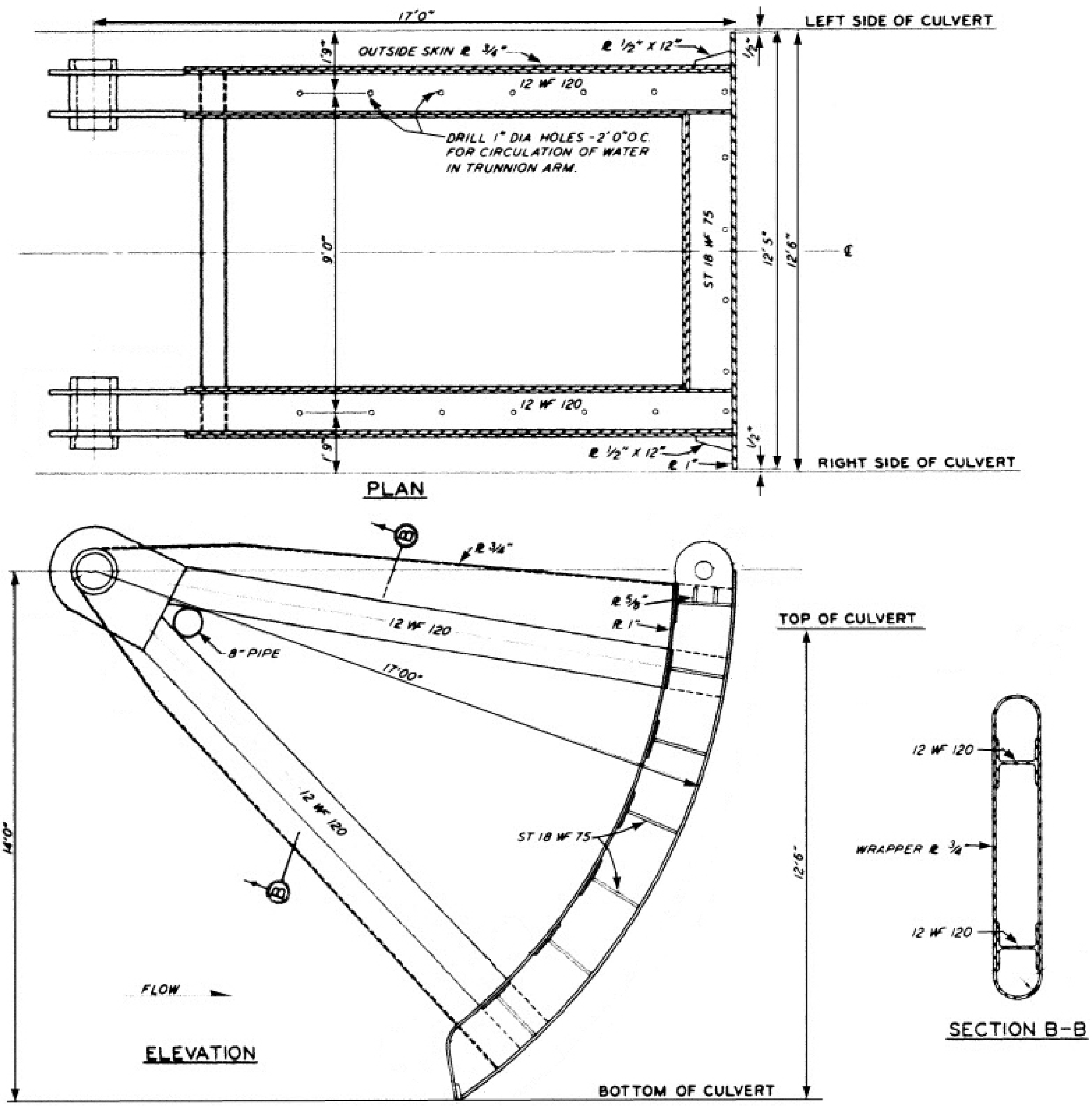


Figure D-25. Tainter Valve, Holt Lock, Type 7 Design.

Table D-28. Hoist Loads, Holt Lock, Type 7 Design, Air in Compartments.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.08	1.9	3.61	-1.816	-1.816	-1.816	0.000
	2.6		-1.720	-1.696	-1.712	0.024
	3.2		-1.576	-1.528	-1.552	0.048
	3.8		-1.416	-1.336	-1.376	0.080
	4.5		-1.072	-0.960	-1.016	0.112
	5.1		-0.896	-0.648	-0.776	0.248
	5.8		-0.624	-0.416	-0.528	0.208
0.16	3.8	3.74	-1.712	-1.696	-1.704	0.016
	5.1		-1.464	-1.400	-1.424	0.064
	6.4		-1.072	-0.984	-1.040	0.088
	7.7		-0.616	-0.464	-0.544	0.152
	9.0		-0.216	0.024	-0.096	0.240
0.24	5.1	3.86	-1.648	-1.608	-1.632	0.040
	6.4		-1.520	-1.456	-1.480	0.064
	7.7		-1.128	-1.016	-1.072	0.112
	9.0		-0.856	-0.728	-0.792	0.128
	10.2		-0.448	-0.312	-0.384	0.136
	11.5		-0.056	0.184	0.072	0.240
	12.8		0.168	0.352	0.264	0.184
0.32	6.4	3.99	-1.808	-1.760	-1.784	0.048
	8.3		-1.464	-1.368	-1.424	0.096
	10.2		-1.224	-1.104	-1.160	0.120
	12.2		-0.664	-0.464	-0.576	0.200
	14.1		-0.136	0.112	-0.016	0.248
	16.0		0.248	0.696	0.456	0.448
	17.9		0.632	1.136	0.880	0.504
0.40	9.6	4.13	-1.696	-1.600	-1.648	0.096
	12.8		-1.160	-0.944	-1.048	0.216
	16.0		-0.560	-0.296	-0.440	0.264
	19.2		-0.032	0.384	0.136	0.416
	22.4		0.672	1.232	0.904	0.560
0.48	12.8	4.26	-1.688	-1.576	-1.632	0.112
	16.0		-1.272	-1.008	-1.160	0.264
	19.2		-0.824	-0.488	-0.680	0.336

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
	22.4		-0.360	-0.032	-0.184	0.328
	25.6		-0.032	0.496	0.216	0.528
	28.8		0.360	1.232	0.808	0.872
0.56	19.2	4.40	-1.448	-1.168	-1.312	0.280
	22.4		-1.096	-0.608	-0.888	0.488
	25.6		-0.680	-0.048	-0.440	0.632
	28.8		-0.256	0.456	0.080	0.712
	32.0		0.056	1.152	0.656	1.096
0.64	22.4	4.54	-1.768	-1.432	-1.624	0.336
	25.6		-1.656	-1.024	-1.288	0.632
	28.8		-1.376	-0.528	-0.952	0.848
	32.0		-1.208	-0.112	-0.672	1.096
	35.2		-1.024	0.456	-0.248	1.480
	38.4		-0.672	1.408	0.224	2.080
0.72	25.6	4.72	-2.376	-1.808	-2.080	0.568
	28.8		-2.304	-1.528	-1.984	0.776
	32.0		-2.544	-1.320	-1.840	1.224
	35.2		-2.328	-1.112	-1.672	1.216
	38.4		-2.440	-0.504	-1.504	1.936
	41.6		-2.528	0.016	-1.320	2.544
	44.8		-2.304	0.128	-1.040	2.432
0.80	32.0	4.86	-2.920	-2.008	-2.456	0.912
	35.2		-3.064	-1.728	-2.432	1.336
	38.4		-3.200	-1.616	-2.376	1.584
	41.6		-3.344	-1.376	-2.344	1.968
	44.8		-3.480	-1.152	-2.328	2.328
	48.0		-3.624	-0.952	-2.320	2.672
	49.9		-3.760	-0.704	-2.288	3.056
0.88	35.2	5.03	-3.560	-2.576	-3.072	0.984
	38.4		-3.912	-2.400	-3.112	1.512
	41.6		-4.240	-2.464	-3.280	1.776
	44.8		-4.240	-2.440	-3.392	1.800
	48.0		-4.656	-2.296	-3.480	2.360
	51.2		-4.856	-1.736	-3.504	3.120
0.96	38.4	5.22	-4.224	-2.816	-3.520	1.408
	41.6		-4.504	-2.888	-3.800	1.616

Valve Open, b/B	Culvert Velocity, fps	Hoist Load, kips per ft of Valve Width: Dry Valve	Hydraulic: Minimum	Hydraulic: Maximum	Hydraulic: Observed Average	Hydraulic: Variation
	44.8		-4.896	-2.904	-3.872	1.992
	48.0		-4.920	-3.024	-3.936	1.896
	51.2		-5.160	-2.928	-3.984	2.232
	54.4		-4.752	-1.584	-4.248	3.168
1.00	41.6	5.34	-4.544	-3.280	-3.920	1.264
	44.8		-4.696	-3.280	-3.976	1.416
	48.0		-5.096	-3.320	-4.216	1.776
	51.2		-4.992	-3.248	-4.176	1.744
	54.4		-5.288	-3.280	-3.696	2.008

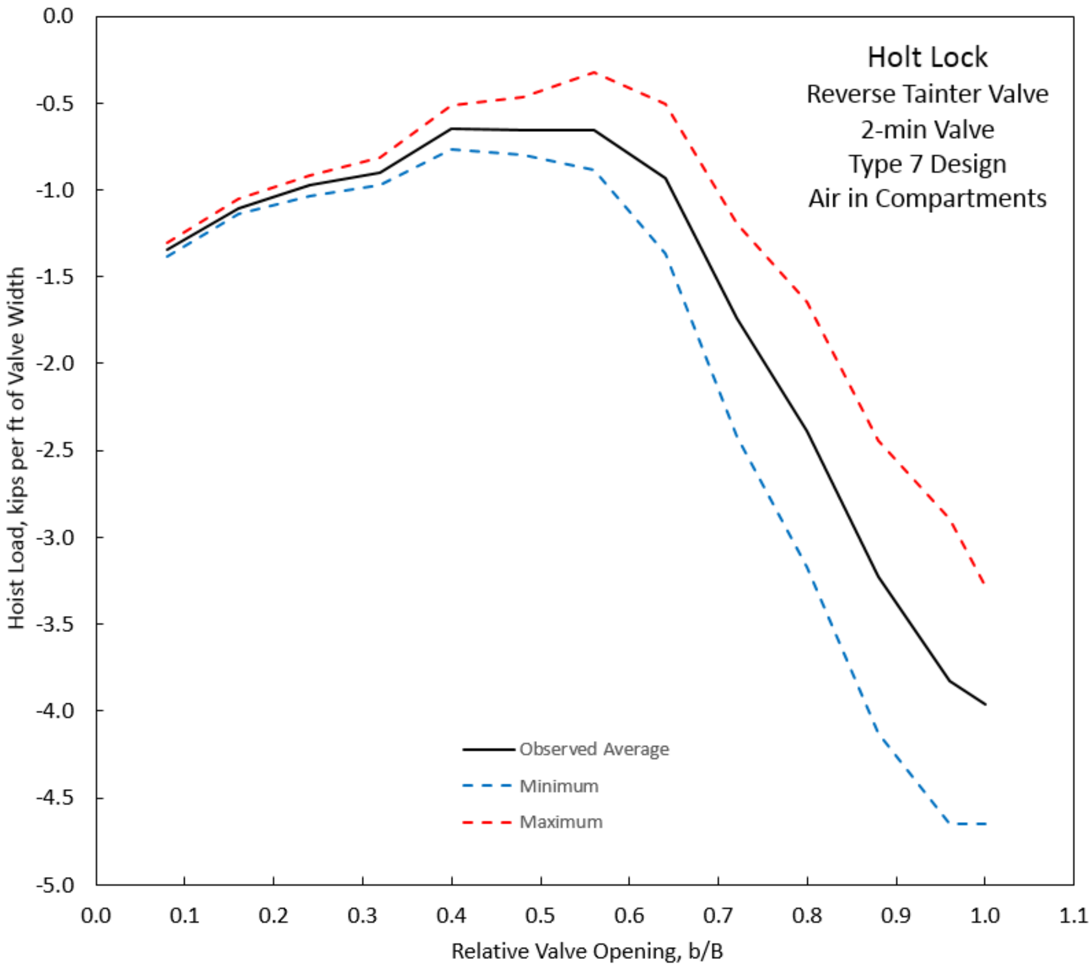


Figure D-26. Hoist load, Holt Lock, Type 7 Design, 2-min Valve, Air in Compartments.

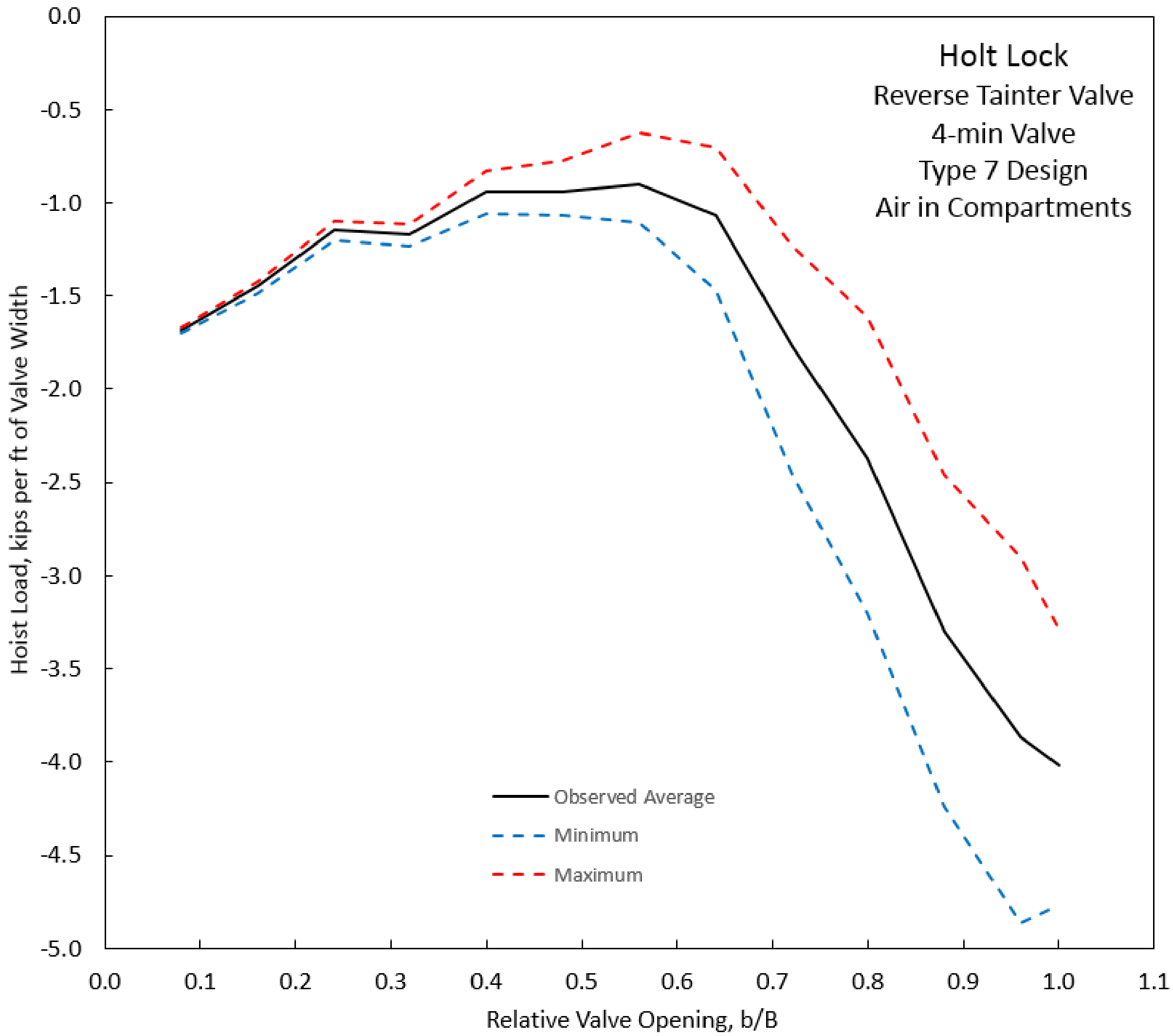


Figure D-27. Hoist load, Holt Lock, Type 7 Design, 4-min Valve, Air in Compartments.

D-5. Snell Lock Hydraulic Model Investigation. Hoist loads for the Snell Lock culvert valves were reported by Stockstill et al. (2015). Hoist loads were measured for several design variations of a vertically framed valve and one double skin plate design. The reverse tainter valve had a radius of 21.0 ft and the Snell Lock culvert is 14.0 ft tall, a radius to culvert height of 1.50. The design lift of the Snell Lock is 49 ft.

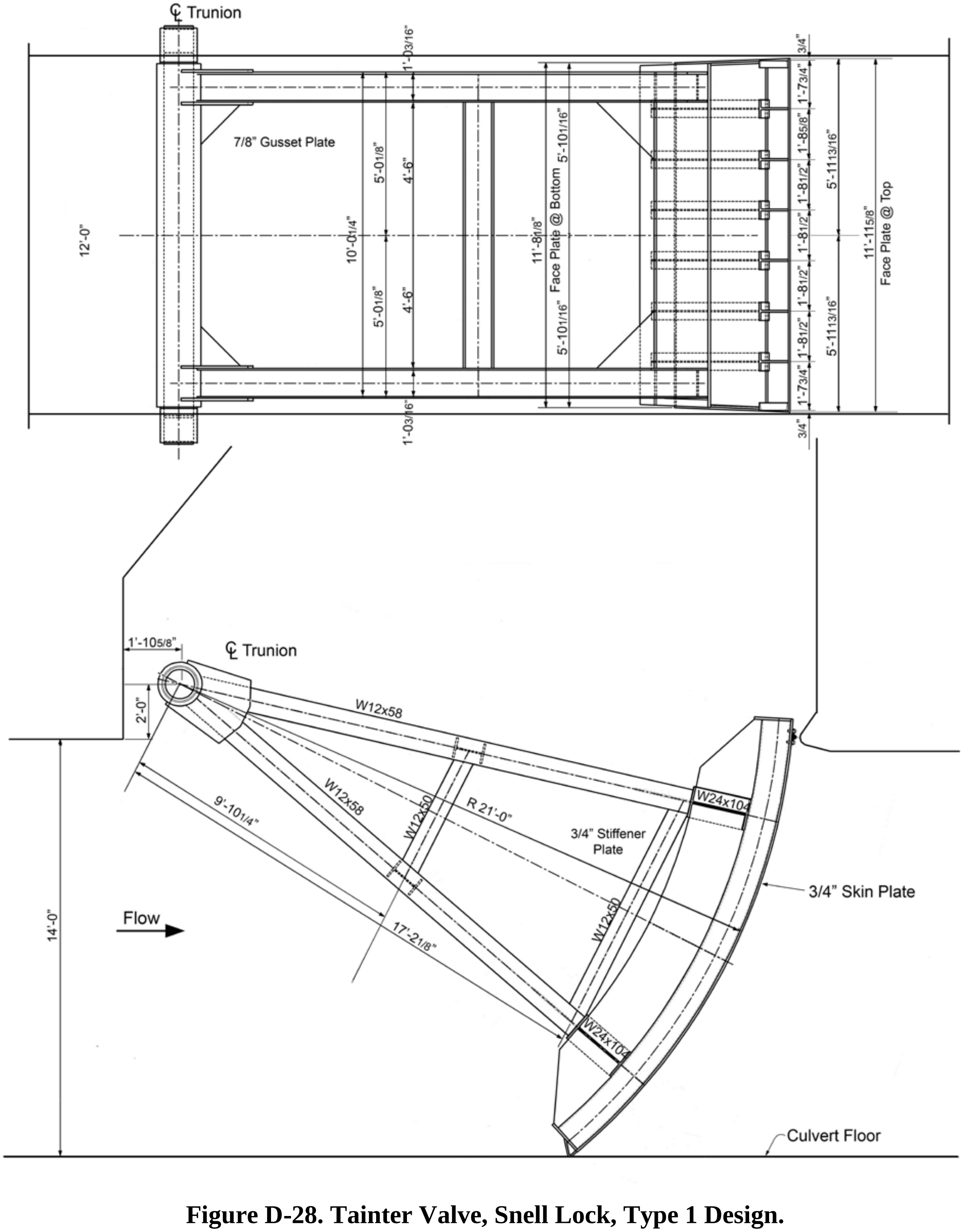


Figure D-28. Tainter Valve, Snell Lock, Type 1 Design.

Table D-29. Hoist Loads, Snell Lock, Type 1 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.09	3.8	2.50	-0.429	-0.367	-0.401	0.062
	4.3		-0.189	-0.079	-0.140	0.110
	5.4		-0.134	-0.024	-0.088	0.110
	6.5		0.017	0.155	0.079	0.137
0.19	7.4	2.56	-0.062	0.075	0.003	0.137
	7.6		-0.021	0.089	0.031	0.110
	9.2		0.144	0.295	0.216	0.151
	11.1		0.405	0.638	0.512	0.233
0.40	10.8	2.69	-0.232	-0.040	-0.145	0.192
	13.5		-0.081	0.166	0.014	0.247
	16.3		0.111	0.414	0.253	0.302
0.64	15.3	2.86	-0.373	-0.126	-0.274	0.247
	19.1		-0.332	-0.057	-0.200	0.275
	22.9		-0.263	0.080	-0.089	0.343
	28.4		0.012	0.588	0.311	0.577
0.89	19.8	3.15	-0.661	-0.359	-0.498	0.302
	24.8		-0.675	-0.290	-0.493	0.385
	29.8		-0.798	-0.194	-0.482	0.604
	39.5		-0.009	0.403	0.201	0.412
	42.2		-1.203	0.115	-0.502	1.318
1.01	23.9	3.35	-0.702	-0.400	-0.552	0.302
	29.9		-1.142	-0.277	-0.669	0.865
	36.0		-1.430	-0.249	-0.732	1.181
	38.6		-1.197	-0.297	-0.708	0.900
	41.9		-1.005	-0.442	-0.676	0.563
	44.3		-1.375	-0.222	-0.744	1.154

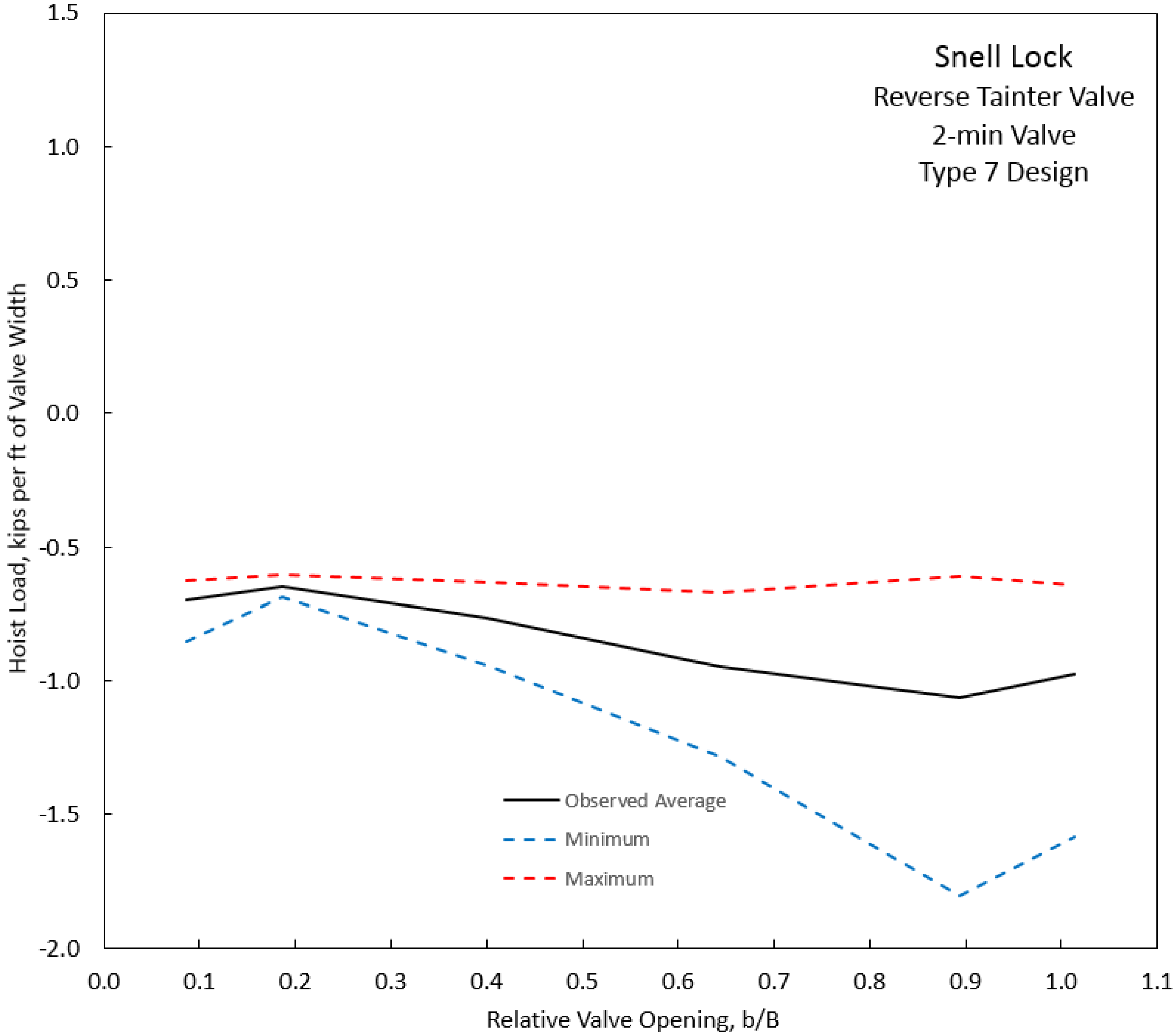


Figure D-29. Hoist load, Snell Lock, Type 1 Design, 2-min Valve.

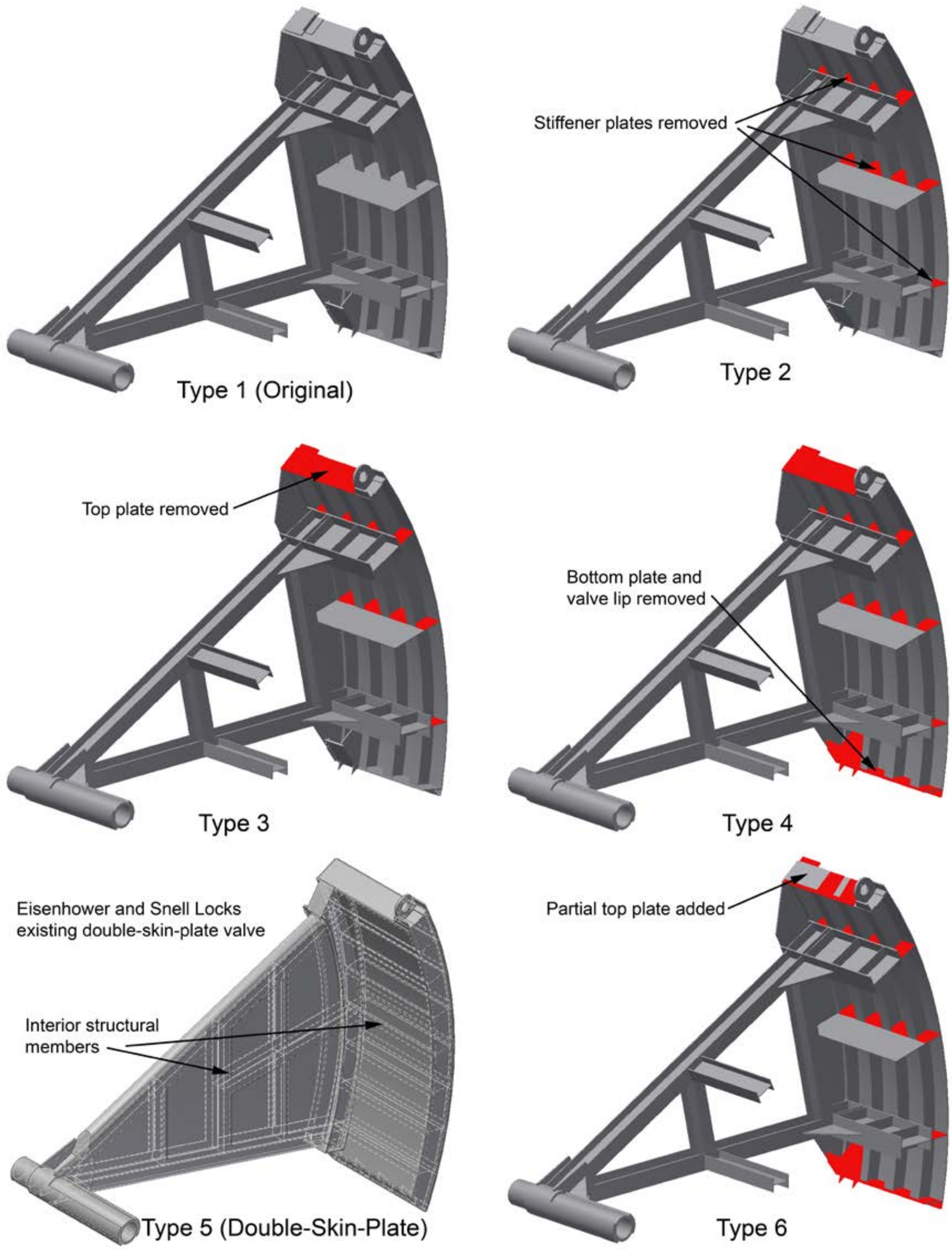


Figure D-30. Tainter Valves, Snell Lock, Type 1-6 Designs.

Table D-30. Hoist Loads, Snell Lock, Type 2 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.09	4.3	2.42	-0.269	-0.125	-0.193	0.144
	5.4		-0.084	0.033	-0.023	0.117
	6.5		0.191	0.314	0.249	0.124
0.19	7.4	2.52	-0.238	-0.135	-0.189	0.103
	7.6		-0.115	-0.018	-0.071	0.096
	9.2		-0.005	0.133	0.061	0.137
	11.1		0.126	0.318	0.209	0.192
0.40	10.8	2.62	-0.348	-0.211	-0.278	0.137
	13.5		-0.197	-0.012	-0.110	0.185
	16.3		-0.039	0.187	0.072	0.227
	16.3		0.263	0.579	0.420	0.316
0.64	15.3	2.79	-0.446	-0.253	-0.354	0.192
	19.1		-0.549	-0.267	-0.409	0.282
	22.9		-0.418	-0.102	-0.283	0.316
	28.4		-0.150	0.433	0.114	0.584
0.89	19.8	3.06	-0.707	-0.432	-0.566	0.275
	24.8		-0.714	-0.364	-0.539	0.350
	29.8		-0.927	-0.171	-0.529	0.755
	39.5		-1.078	-0.103	-0.582	0.975
	42.2		-1.215	-0.130	-0.617	1.085
1.01	23.9	3.26	-0.853	-0.502	-0.669	0.350
	29.9		-1.182	-0.331	-0.709	0.851
	36.0		-1.642	-0.111	-0.739	1.531
	38.6		-1.251	-0.406	-0.787	0.845
	41.9		-1.004	0.246	-0.694	1.250
	44.3		-1.519	-0.296	-0.842	1.222

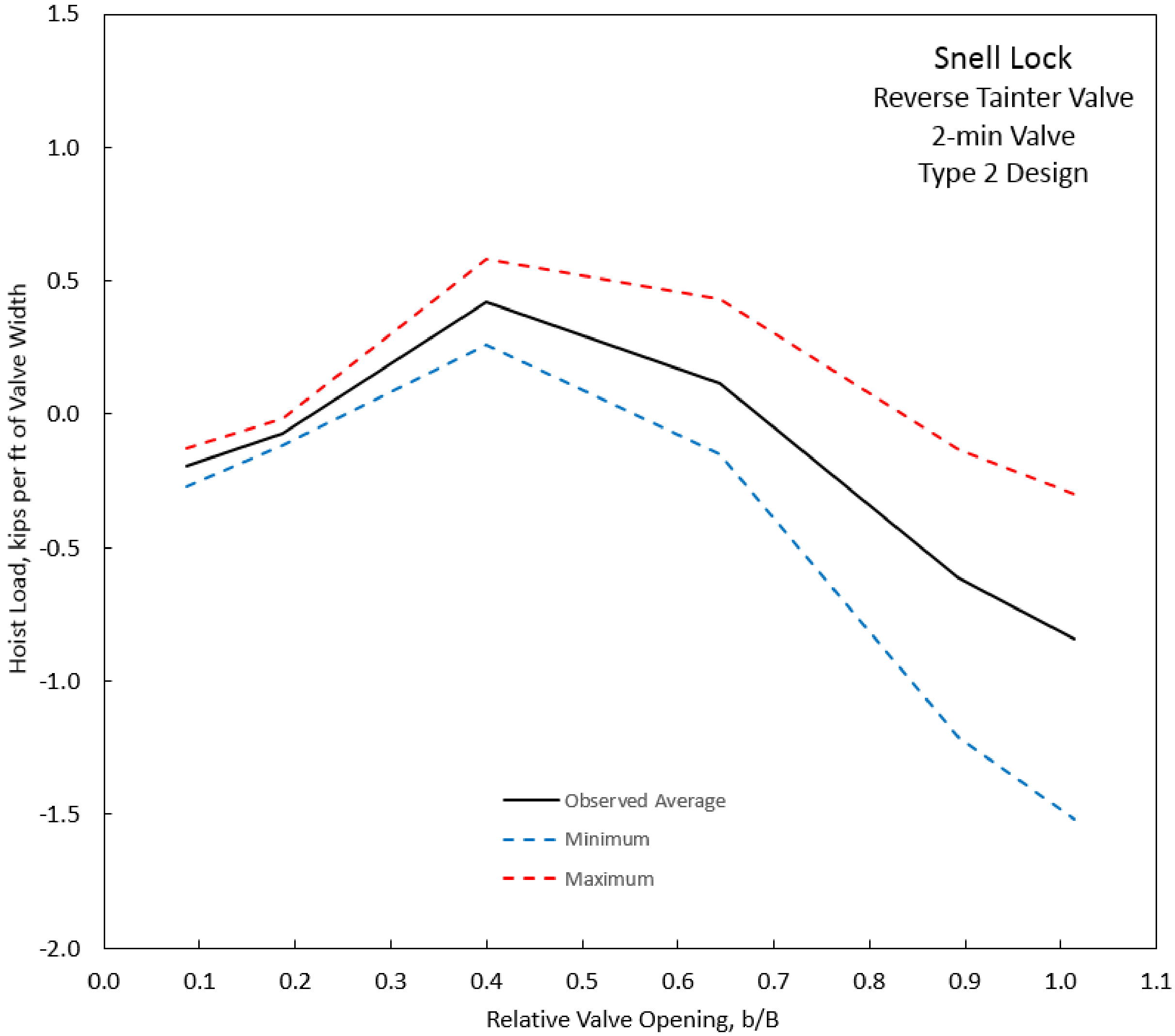


Figure D-31. Hoist load, Snell Lock, Type 2 Design, 2-min Valve.

Table D-31. Hoist Loads, Snell Lock, Type 3 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.09	4.3	2.33	-0.134	-0.051	-0.090	0.082
	5.4		-0.031	0.086	0.031	0.117
	6.5		0.072	0.182	0.131	0.110
0.19	7.4	2.41	-0.060	0.036	-0.014	0.096
	7.6		0.146	0.256	0.198	0.110
	9.2		0.174	0.304	0.232	0.130
	11.1		0.194	0.387	0.285	0.192
0.40	10.8	2.53	-0.227	-0.090	-0.164	0.137
	13.5		-0.090	0.068	-0.011	0.158
	16.3		0.054	0.294	0.171	0.240
	16.3		0.713	1.084	0.876	0.371
0.64	15.3	2.69	-0.461	-0.317	-0.391	0.144
	19.1		-0.372	-0.152	-0.263	0.220
	22.9		-0.249	0.033	-0.109	0.282
	28.4		0.143	0.692	0.406	0.549
0.89	19.8	2.95	-0.651	-0.390	-0.513	0.261
	24.8		-0.665	-0.308	-0.480	0.357
	29.8		-0.885	-0.171	-0.524	0.714
	39.5		-0.885	0.145	-0.335	1.030
	42.2		-0.919	0.235	-0.331	1.154
1.01	23.9	3.12	-0.709	-0.421	-0.558	0.288
	29.9		-1.094	-0.173	-0.597	0.920
	36.0		-1.334	-0.070	-0.610	1.263
	38.6		-1.045	-0.173	-0.530	0.872
	41.9		-0.881	-0.324	-0.581	0.556
	44.3		-1.286	-0.084	-0.568	1.202

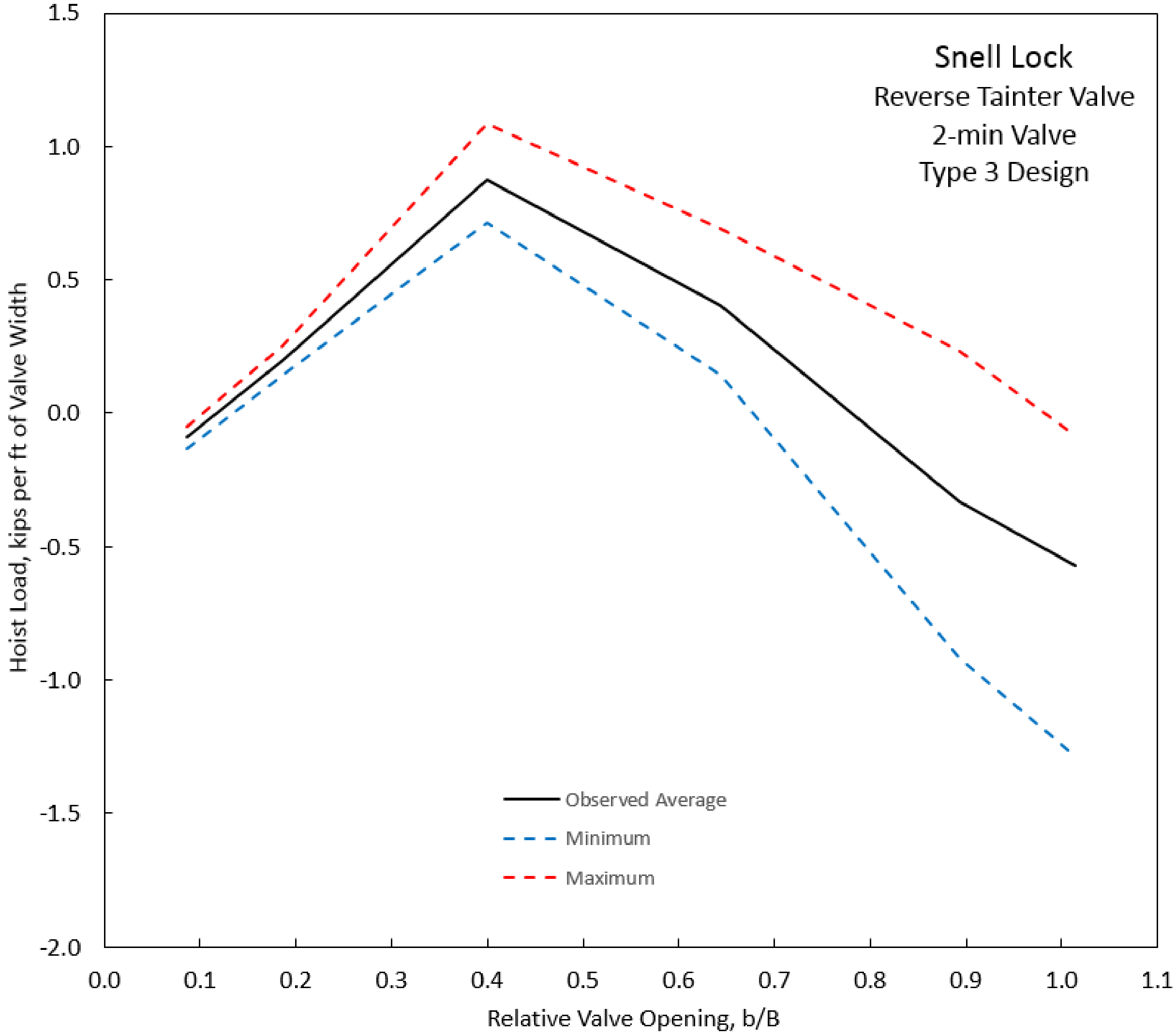


Figure D-32. Hoist load, Snell Lock, Type 3 Design, 2-min Valve.

Table D-32. Hoist Loads, Snell Lock, Type 4 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.09	4.3	2.24	-0.692	-0.569	-0.637	0.124
	5.4		-0.459	-0.363	-0.411	0.096
	6.5		0.159	0.269	0.218	0.110
0.19	7.4	2.29	-0.631	-0.562	-0.598	0.069
	7.6		-0.445	-0.363	-0.409	0.082
	9.2		-0.534	-0.404	-0.468	0.130
	11.1		-0.404	-0.301	-0.355	0.103
0.40	10.8	2.40	-0.625	-0.529	-0.583	0.096
	13.5		-0.632	-0.501	-0.565	0.130
	16.3		-0.632	-0.453	-0.548	0.179
	16.3		-0.474	-0.261	-0.369	0.213
0.64	15.3	2.53	-0.749	-0.605	-0.673	0.144
	19.1		-0.797	-0.577	-0.678	0.220
	22.9		-0.797	-0.563	-0.672	0.233
	28.4		-0.914	-0.392	-0.618	0.522
0.89	19.8	2.74	-0.864	-0.513	-0.630	0.350
	24.8		-0.891	-0.575	-0.700	0.316
	29.8		-1.186	-0.596	-0.800	0.591
	39.5		-0.664	0.208	-0.149	0.872
	42.2		-1.420	-0.328	-0.753	1.092
1.01	23.9	2.91	-0.904	-0.589	-0.725	0.316
	29.9		-1.268	-0.575	-0.825	0.694
	36.0		-1.605	-0.438	-0.819	1.167
	38.6		-0.836	0.036	-0.321	0.872
	41.9		-1.172	-0.664	-0.867	0.508
	44.3		-1.365	-0.307	-0.659	1.057

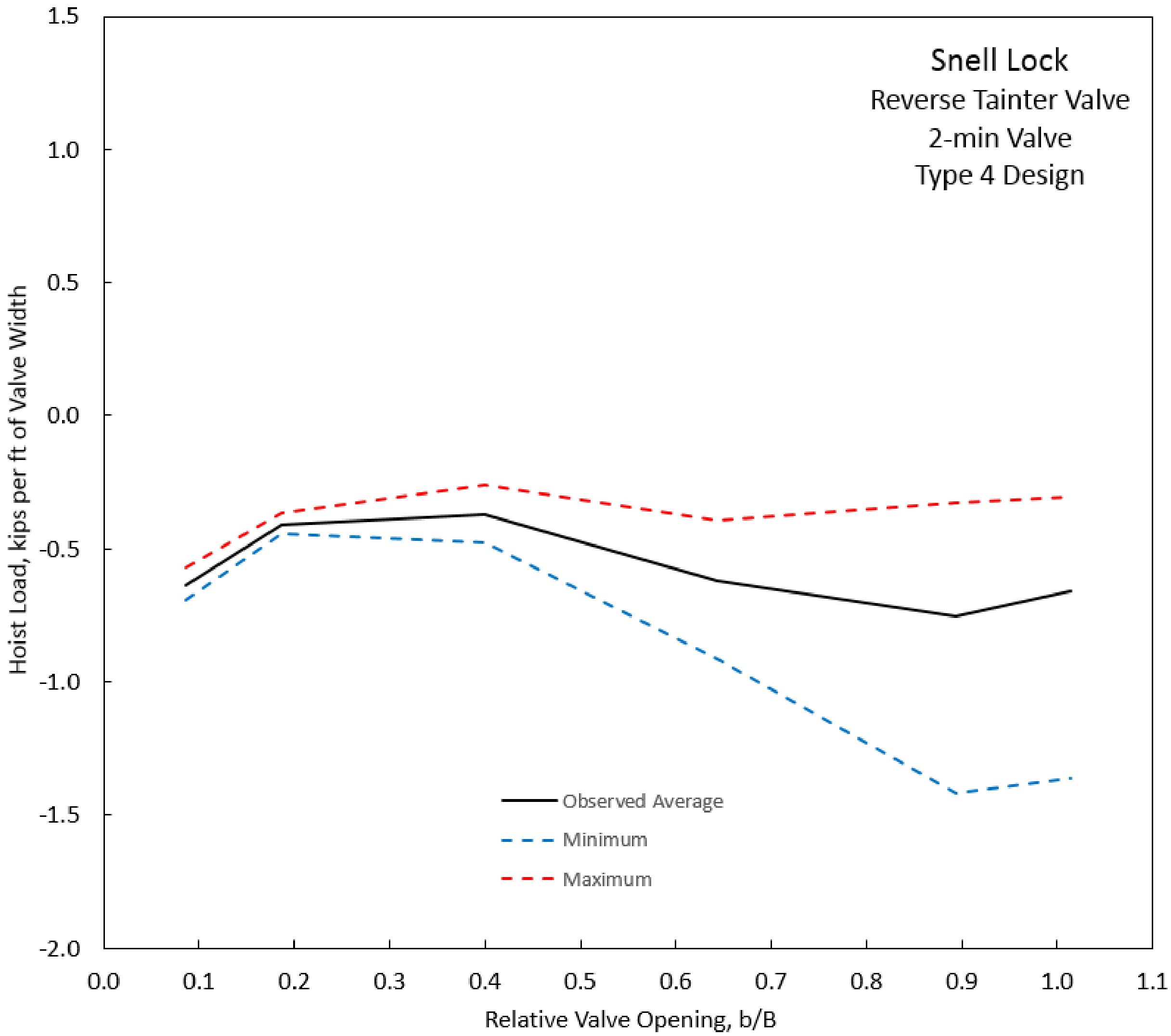


Figure D-33. Hoist load, Snell Lock, Type 4 Design, 2-min Valve.

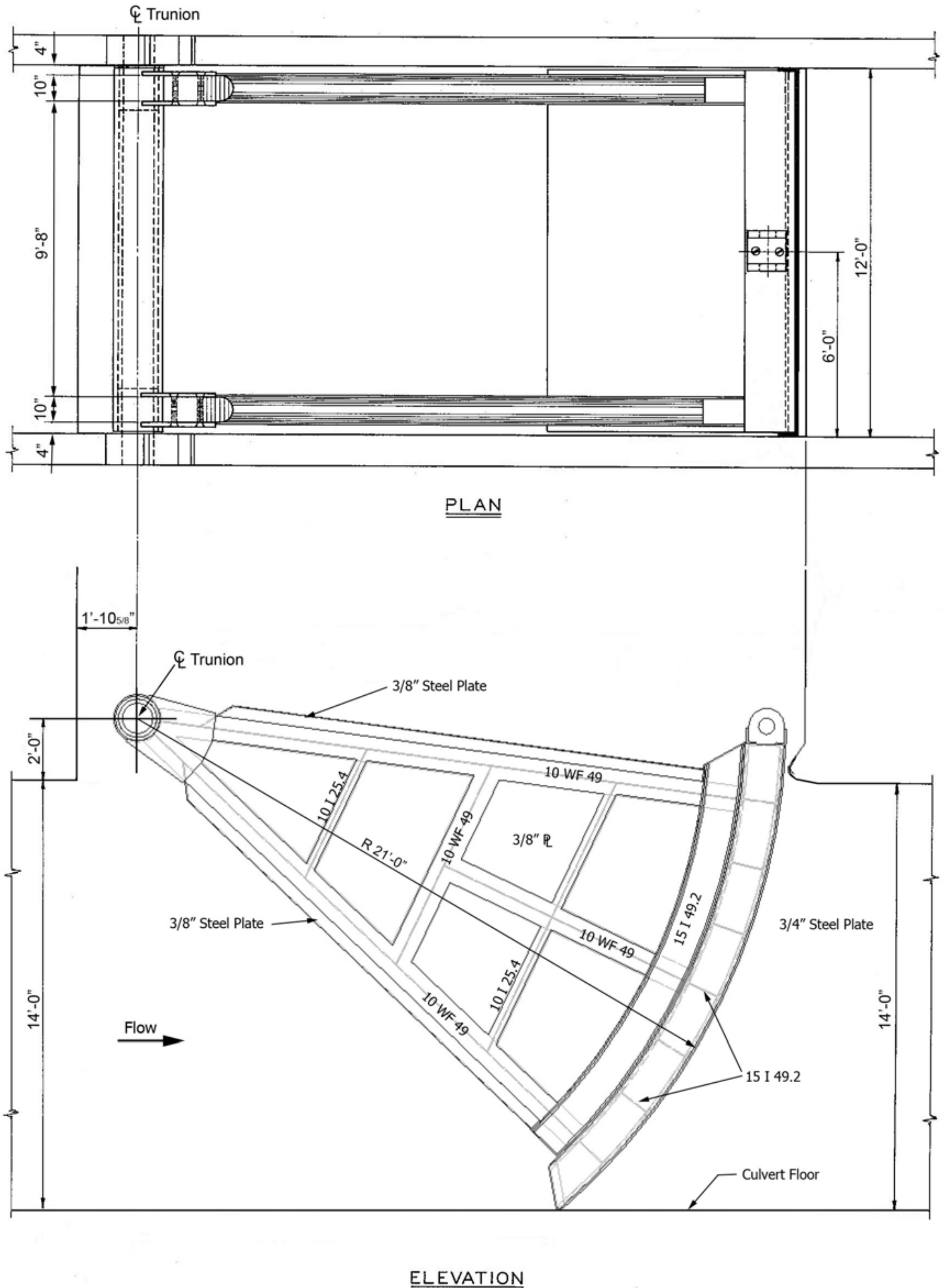


Figure D-34. Tainter Valve, Snell Lock, Type 5 Design.

Table D-33. Hoist Loads, Snell Lock, Type 5 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.09	3.8	3.60	-1.083	-1.029	-1.060	0.055
	4.3		-0.747	-0.568	-0.675	0.179
	5.4		-0.726	-0.582	-0.653	0.144
	6.5		-0.582	-0.424	-0.508	0.158
0.19	7.4	3.70	-0.979	-0.883	-0.930	0.096
	7.6		-0.917	-0.841	-0.881	0.076
	9.2		-0.835	-0.711	-0.768	0.124
	11.1		-0.608	-0.464	-0.531	0.144
0.40	10.8	3.88	-1.129	-1.060	-1.099	0.069
	13.5		-1.074	-0.971	-1.024	0.103
	16.3		-0.930	-0.820	-0.874	0.110
	16.3		-0.566	-0.367	-0.475	0.199
0.64	15.3	4.12	-1.390	-1.281	-1.339	0.110
	19.1		-1.329	-1.191	-1.261	0.137
	22.9		-1.281	-1.129	-1.213	0.151
	28.4		-0.848	-0.463	-0.676	0.385
0.89	19.8	4.53	-1.671	-1.506	-1.591	0.165
	24.8		-1.664	-1.465	-1.566	0.199
	29.8		-1.719	-1.362	-1.538	0.357
	39.5		-1.506	-0.984	-1.238	0.522
	42.2		-1.602	-0.977	-1.286	0.625
1.01	23.9	4.82	-2.008	-1.775	-1.903	0.233
	29.9		-2.057	-1.493	-1.782	0.563
	36.0		-2.317	-1.130	-1.776	1.188
	38.6		-1.679	-1.267	-1.469	0.412
	41.9		-1.995	-1.665	-1.814	0.330
	44.3		-1.823	-1.281	-1.525	0.542

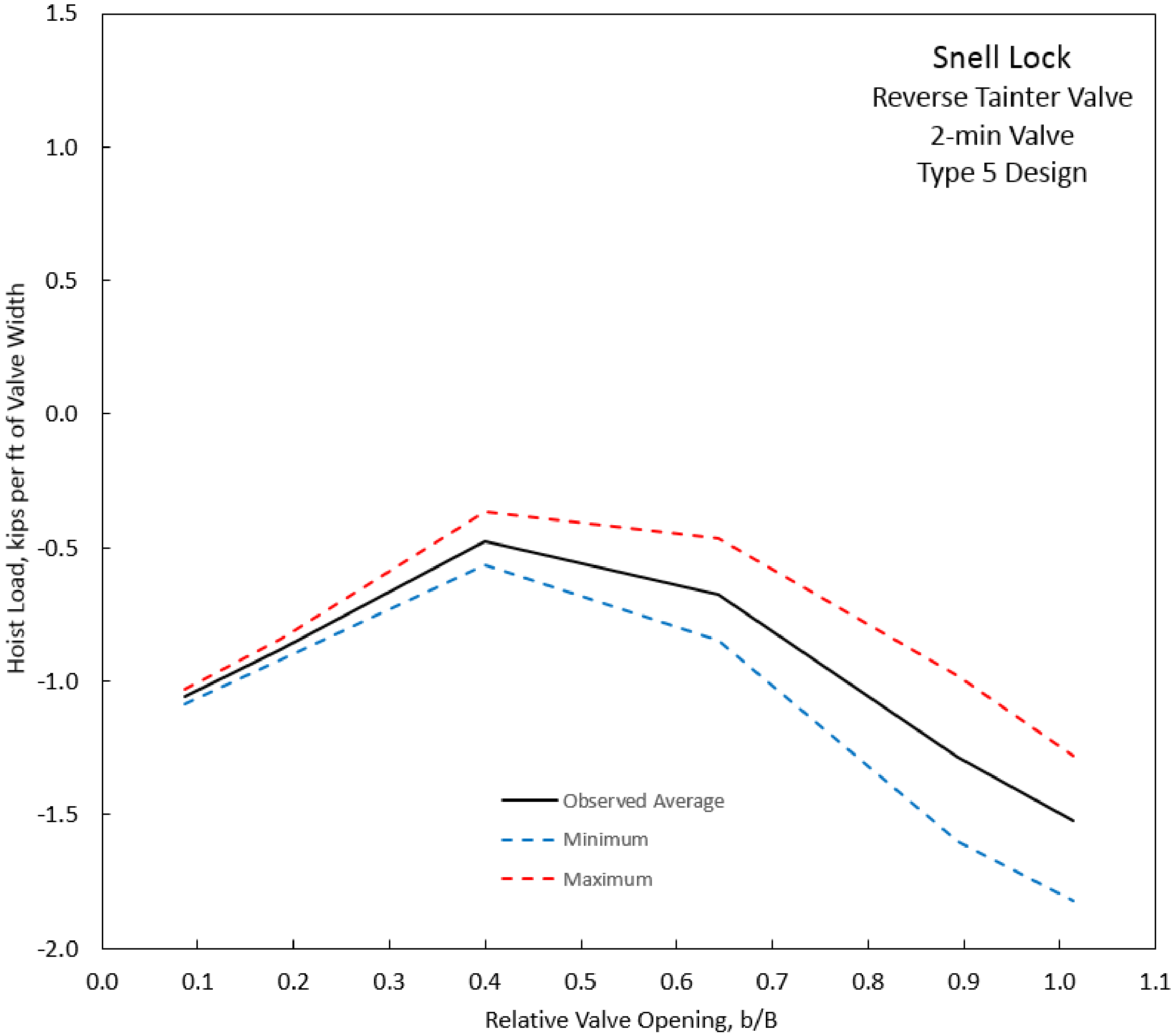


Figure D-35. Hoist Loads, Snell Lock, Type 5 Design, 2-min Valve.

Table D-34. Hoist Loads, Snell Lock, Type 6 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.09	4.3	2.30	-0.581	-0.505	-0.545	0.076
	5.4		-0.560	-0.478	-0.519	0.082
	6.5		-0.526	-0.443	-0.486	0.082
0.19	7.4	2.37	-0.570	-0.474	-0.529	0.096
	7.6		-0.426	-0.343	-0.388	0.082
	9.2		-0.494	-0.398	-0.452	0.096
	11.1		-0.419	-0.316	-0.374	0.103
0.40	10.8	2.47	-0.464	-0.347	-0.406	0.117
	13.5		-0.450	-0.312	-0.384	0.137
	16.3		-0.457	-0.271	-0.362	0.185
	16.3		-0.450	-0.196	-0.323	0.254
0.64	15.3	2.62	-0.620	-0.469	-0.541	0.151
	19.1		-0.668	-0.441	-0.542	0.227
	22.9		-0.730	-0.414	-0.535	0.316
	28.4		-0.846	-0.325	-0.561	0.522
0.89	19.8	2.86	-0.771	-0.510	-0.621	0.261
	24.8		-0.812	-0.475	-0.608	0.336
	29.8		-1.025	-0.462	-0.688	0.563
	39.5		-1.416	-0.386	-0.754	1.030
	42.2		-1.505	-0.345	-0.803	1.160
1.01	23.9	3.03	-0.810	-0.494	-0.603	0.316
	29.9		-1.160	-0.418	-0.687	0.742
	36.0		-1.380	-0.377	-0.713	1.003
	38.6		-1.215	-0.391	-0.666	0.824
	41.9		-0.947	-0.466	-0.650	0.481
	44.3		-1.496	-0.343	-0.723	1.154

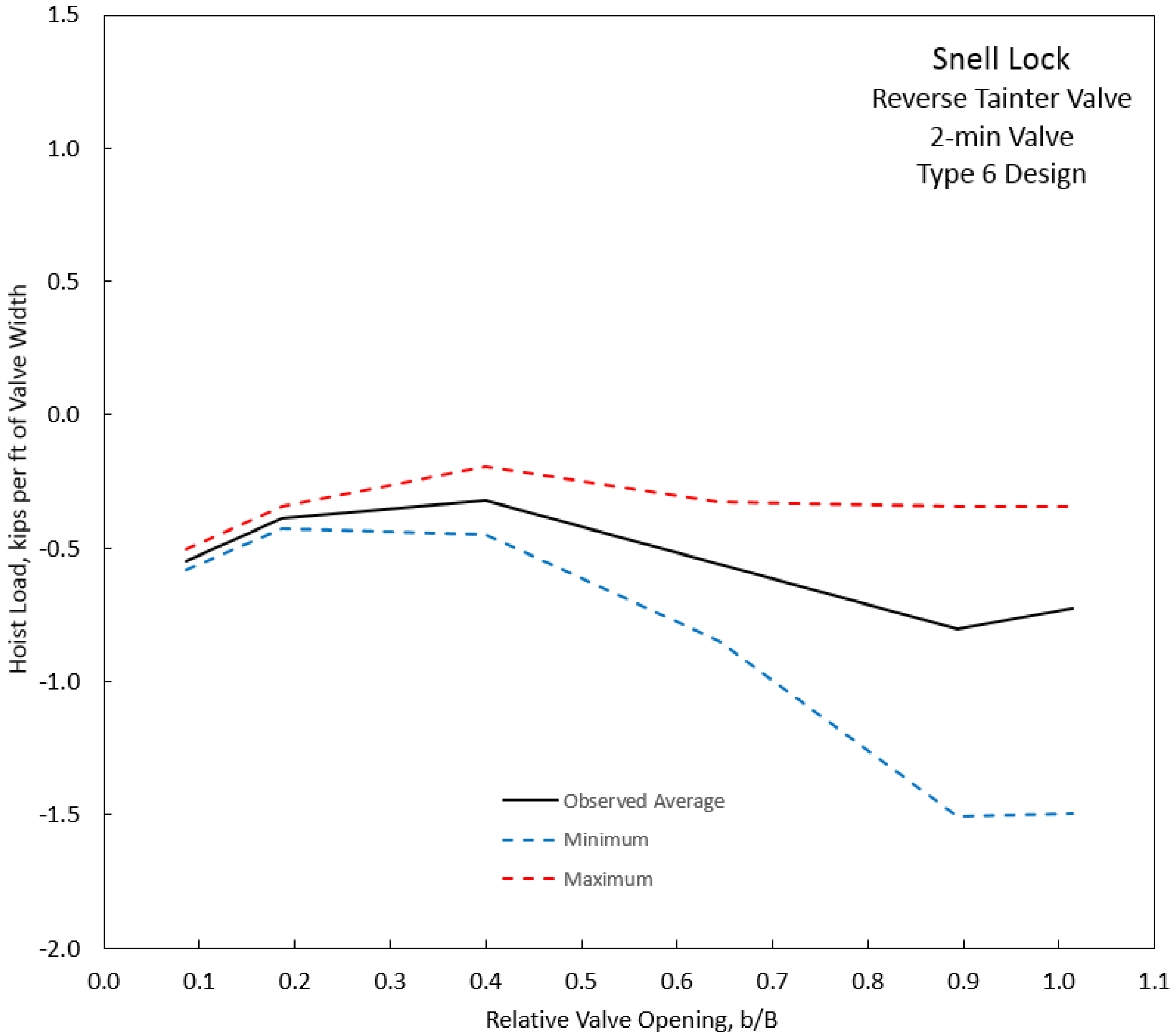


Figure D-36. Hoist load, Snell Lock, Type 6 Design, 2-min Valve.

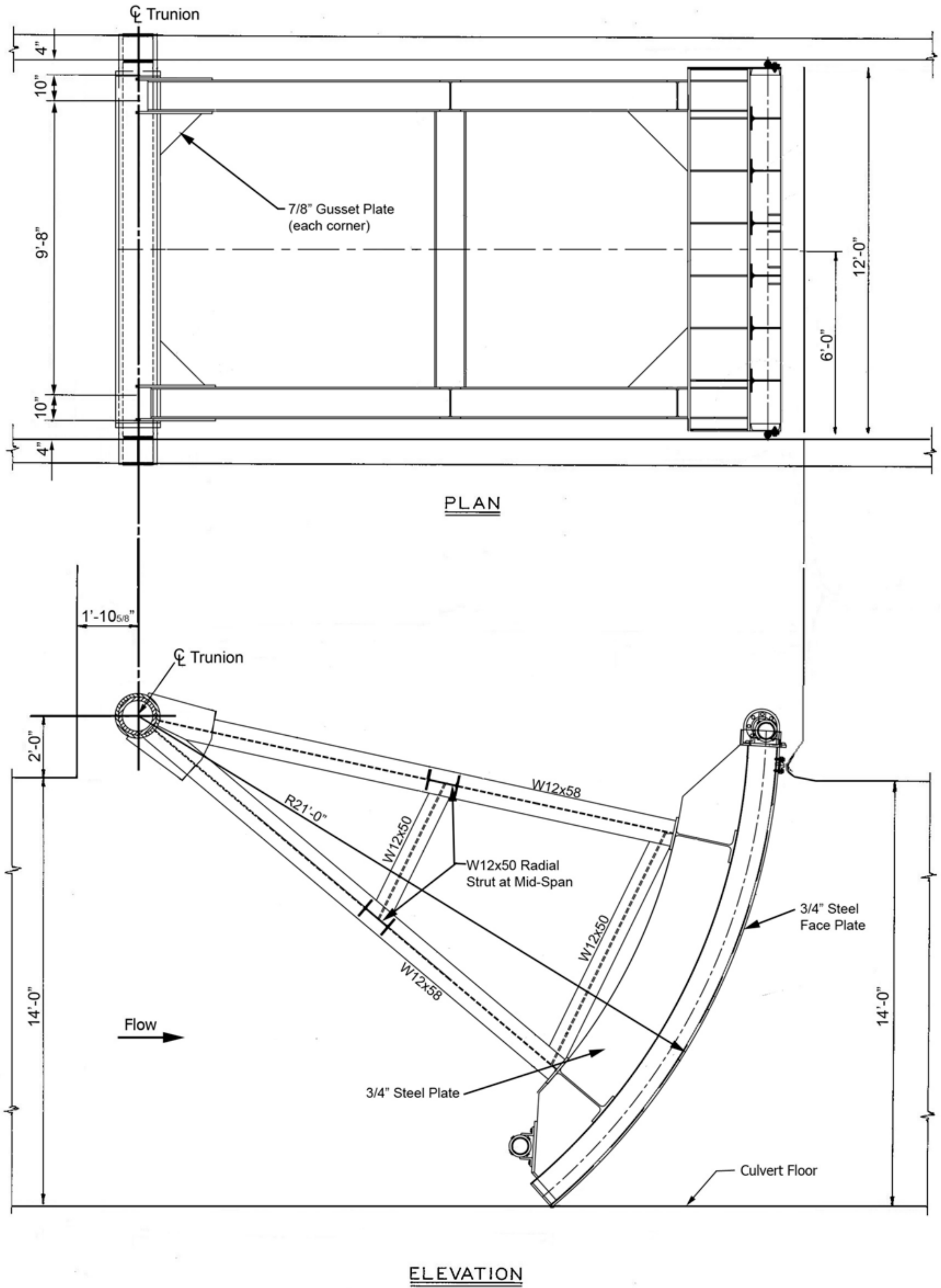


Figure D-37. Tainter Valve, Snell Lock, Type 7 Design.

Table D-35. Hoist Loads, Snell Lock, Type 7 Design.

		Hoist Load, kips per ft of Valve Width				
			Hydraulic			
Valve Open, b/B	Culvert Velocity, fps	Dry Valve	Minimum	Maximum	Observed Average	Variation
0.09	3.8	2.56	-0.852	-0.626	-0.695	0.227
	4.3		-0.894	-0.770	-0.830	0.124
	5.4		-0.880	-0.777	-0.819	0.103
	6.5		-0.852	-0.770	-0.811	0.082
0.19	7.4	2.63	-0.747	-0.658	-0.700	0.089
	7.6		-0.685	-0.603	-0.647	0.082
	9.2		-0.761	-0.665	-0.709	0.096
	11.1		-0.761	-0.665	-0.709	0.096
0.40	10.8	2.78	-0.729	-0.647	-0.685	0.082
	13.5		-0.722	-0.612	-0.663	0.110
	16.3		-0.709	-0.585	-0.641	0.124
	16.3		-0.942	-0.633	-0.763	0.309
0.64	15.3	2.95	-0.933	-0.733	-0.806	0.199
	19.1		-0.933	-0.727	-0.810	0.206
	22.9		-0.967	-0.713	-0.818	0.254
	28.4		-1.283	-0.672	-0.946	0.611
0.89	19.8	3.23	-0.925	-0.699	-0.790	0.227
	24.8		-0.967	-0.685	-0.792	0.282
	29.8		-1.111	-0.562	-0.760	0.549
	39.5		-1.317	-0.383	-0.740	0.934
	42.2		-1.804	-0.610	-1.062	1.195
1.01	23.9	3.49	-0.771	-0.483	-0.604	0.288
	29.9		-1.046	-0.558	-0.739	0.488
	36.0		-1.197	-0.504	-0.748	0.694
	38.6		-1.286	-0.483	-0.761	0.803
	41.9		-1.417	-0.469	-0.774	0.948
	44.3		-1.582	-0.641	-0.973	0.941

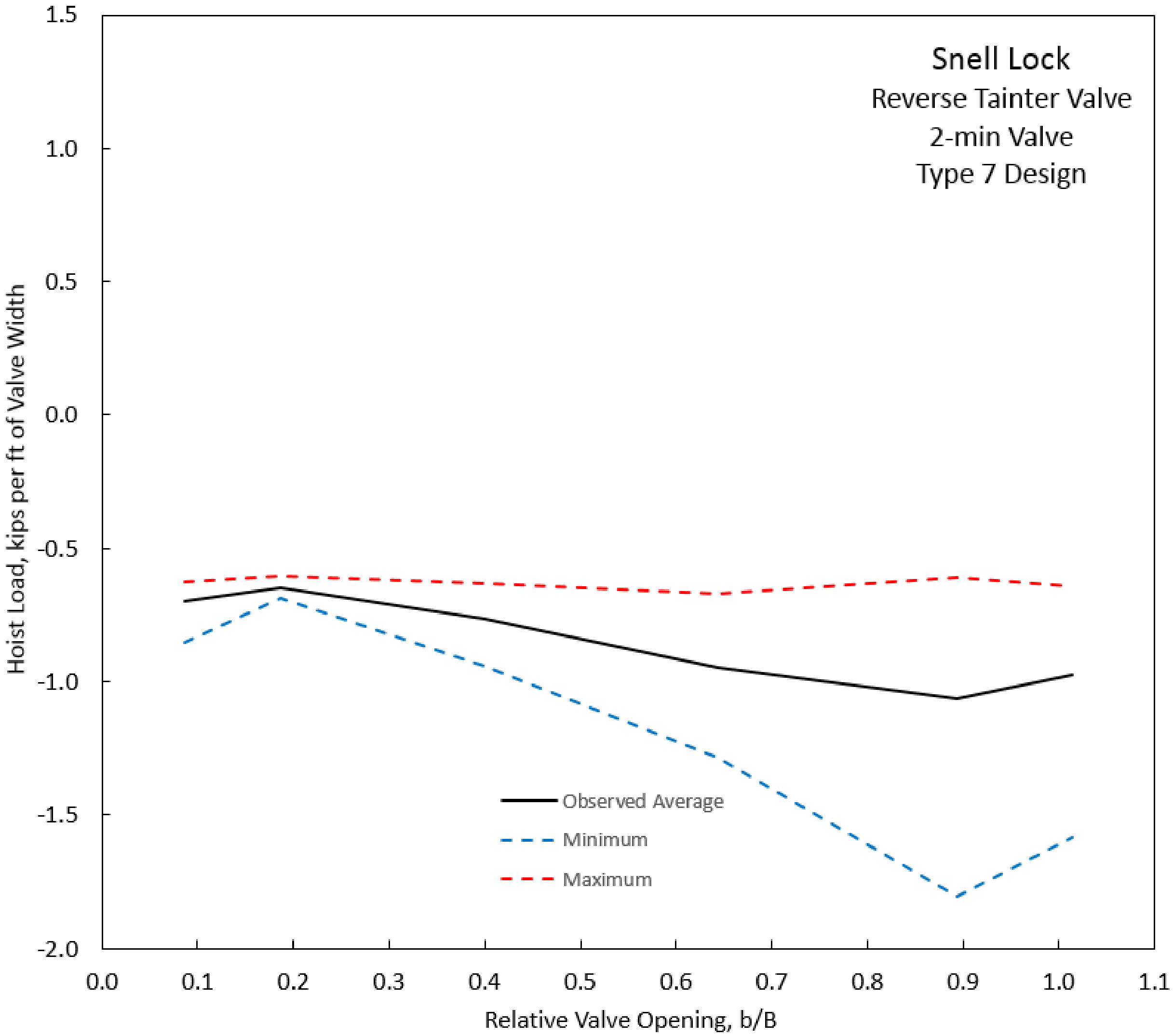


Figure D-38. Hoist load, Snell Lock, Type 7 Design, 2-min Valve.

APPENDIX E

Design Examples

E-1. Problem. Determine maximum elevation of culvert at filling valves for cavitation-free operation.

E-2. Previously Developed Data.

Upper pool - el 160
Lower Pool - el 120
Lift - 40 ft
Lock Chamber - 670 ft by 110 ft
Two Culverts
Valves 12.5 by 12.5 ft
Loss Coefficients for Filling

Intake	0.200 $V^2/2g$
Upstream conduit	0.050 $V^2/2g$
Downstream conduit	0.380 $V^2/2g$
Chamber manifold	1.000 $V^2/2g$
Valve (full open)	0.100 $V^2/2g$
Total (valve open)	1.730 $V^2/2g$

E-3. Example 1.

a. Develop Hydraulic Data. Assume culvert roof at filling valves at el 115 and no roof expansion downstream from the valves. (This is the maximum elevation permissible dictated by criterion of 5 ft of submergence of the culvert system at lower pool.) Use computer program H5320 (Appendix C) to develop hydraulic conditions during filling. The results from these computations pertinent to this example are listed in Table E-l.

Table E-1

Time, min	Valve Open, percent	Contraction Coefficient	Inflow, cfs	At Vena Contracta: Pressure Gradeline, el	At Vena Contracta: Pressure on Culvert Roof, ft
0.0	0.000	0.800	0	120.0	5.00
0.1	0.025	0.799	322	118.6	3.61
0.2	0.051	0.795	650	118.4	3.37
0.3	0.077	0.788	991	117.9	2.94
0.4	0.106	0.778	1,350	117.2	2.25
0.5	0.137	0.763	1,731	116.2	1.22
0.6	0.171	0.744	2,138	114.7	− 0.30
0.7	0.207	0.720	2,554	113.2	− 1.76
0.8	0.248	0.690	2,928	113.1	− 1.90
0.9	0.292	0.656	3,375	110.2	− 4.78
1.0	0.340	0.651	3,916	109.6	− 5.39
1.1	0.392	0.655	4,565	108.9	− 6.06
1.2	0.448	0.664	5,326	107.8	− 7.20
1.3	0.507	0.677	6,188	106.8	− 8.18
1.4	0.571	0.695	7,117	106.7	− 8.29
1.5	0.637	0.718	8,053	108.1	− 6.88
1.6	0.706	0.747	8,918	111.3	− 3.67
1.7	0.777	0.780	9,641	116.1	1.13
1.8	0.851	0.818	10,179	121.8	6.83
1.9	0.925	0.858	10,530	127.6	12.61
2.0	1.000	0.900	10,746	132.7	17.74

b. Determine Minimum Value of Cavitation Parameter, σ. From consideration of pressures in Table E-l, it appears that σ should be minimum within the time period of 1.2 to 1.5 min. Thus, from data in Table E-l:

Table E-2

Time, min	Valve Open, ft	At Vena Contracta Depth*, ft	V**, fps	$\frac{V^2}{2g}$, ft	P***, ft	σ
1.2	5.60	3.72	57.29	50.97	1.58	0.678
1.3	6.34	4.29	57.69	51.68	0.03	0.639
1.4	7.14	4.96	57.39	51.14	– 0.75	0.631
1.5	7.96	5.72	56.34	49.29	– 0.10	0.668

* Valve open in feet times contraction coefficient.
** Inflow divided by product of number of culverts (2) times width of a culvert (12.5 ft) times depth at vena contracta.
*** Pressure on culvert roof plus depth of culvert (12.5 ft) minus depth at vena contracta.

Since the minimum value of σ, 0.631, is less than σ_i, 1.000, (Figure 2-1) the culvert must be lowered or expanded along the roof immediately downstream from the valve.

c. Determine Elevation for Level Roof. Pressure required at vena contracta for minimum σ to equal σ_i is determined from equation for cavitation parameter (paragraph 2-2b).

$$1.000 = \frac{P + 33}{51.14}$$

$$P = 18.14 \text{ ft}$$

Then the roof of the culvert must be at the elevation of the lower pool minus the pressure drop (Table C-l, 120.00 - 106.7 = 13.30 ft), minus P, plus distance from vena contracta to roof of culvert (12.5 - depth of vena contracta) or el 120.00 - 13.30 - 18.14 + 12.5 - 4.96 = el 96.10. But the factor of safety (paragraph 2-4b, one-tenth lift) of 4.00 ft should be subtracted and therefore culvert roof must not be higher than el 92.10.

d. Determine Elevation for Roof at Valve with Culvert Roof Downstream Sloped Up 5.0 ft (40 percent Expansion). From Figure 2-1, σ_i = 0.470. Loss coefficients in paragraph E-2 must be re-evaluated and, for this example, become:

e.

Intake	0.200 $V^2/2g$
Upstream conduit	0.050 $V^2/2g$
Downstream conduit	0.320 $V^2/2g$
Chamber manifold	0.630 $V^2/2g$
Valve (full open)	0.100 $V^2/2g$
Total (valve open)	1.300 $V^2/2g$

f. Develop New Hydraulic Data and Determine Elevation for Expanded Roof. Repeat the use of computer program H5320 (Appendix C) to develop hydraulic conditions during filling. Again σ is a minimum at a time of 1.4 min, but at the vena contracta the pressure drop now is 18.4 ft and the velocity head is 55.48 ft. As in paragraph E-3c:

$$0.470 = \frac{P + 33}{55.48}$$

$$P = -6.92 \text{ ft}$$

Culvert roof at valve:
el 120.00 – (– 18.4) – 6.92 + 12.5 – 4.96 = el 116.06 (safety factor) = el 112.06

Since this would place the roof of the expanded culvert at el 117.06, less than 5 ft below the lower pool elevation, the culvert roof at the valve must not be higher than el 110, which allows for the required minimum submergence.

g. Maximum Feasible Elevation for Culvert Roof. An expansion of 4.25 ft would result in the requirements for no cavitation plus the safety factor matching the criterion for minimum submergence of the culvert system and would place the culvert roof at the valves at maximum feasible elevation of 110.75.

E-4. Example 2. The project data is identical to Example 1 except that the upper pool is at el 180 and thus a lift of 60 ft.

a. Level Roof. Computations as in Example 1 reveal that with a level roof and a safety factor of 6.0 ft (one-tenth lift) the culvert roof must be placed no higher than el 51.69 to provide submergence needed to prevent cavitation. An alternative would be to provide air vents downstream from the valve and place the culvert at an elevation where air will be drawn in the vents during the critical portion of the valve opening period. Computations have revealed that the pressure drop (lower pool to minimum gradient at vena contracta) would be 23.10 ft. Thus to provide the desired 10 ft of negative pressure on the roof (paragraph 2-3b) the culvert roof should be 13.10 below lower pool or at el 106.90.

b. Roof Sloped Up 5 ft (40 percent Expansion). If the roof is sloped up 5 ft, loss coefficients are reevaluated as in paragraph E-3d and computations indicate that the roof of the culvert at the valves can be placed no higher than el 81.76 to meet submergence requirements for cavitation-free operation. In this case, if the alternative of providing air vents is adopted then the recomputed pressure drop, 31.80 ft, must be reduced by 58 percent (Figure 2-2) due to the 40 percent culvert expansion.

Thus the pressure drop becomes 13.4 ft and to provide 10 ft of negative pressure would require placing the roof of the culvert at the valves only 3.4 ft below lower pool. Obviously, this does not meet minimum submergence requirements and expansion of the roof by 5 ft is not feasible for venting.

c. Maximum Feasible Elevation for Culvert Roof. For this example, a roof expansion of 2.75 ft would be optimum and would allow the vented roof of the culvert at the valve to be at el 112.25.