

THE MANIFOLD PROBLEM IN LOCK DESIGN

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The scope implied by the title of my paper covers practically every phase of lock construction and would enter into the fields of structural, mechanical, and electrical design which I do not feel qualified, nor does time permit me, to discuss. The feature of locks in which I have been particularly interested, and to which I will limit my discussion in this paper, is the problem of designing hydraulic systems for filling and emptying locks, in raising or lowering craft from one water level to another in a navigation course.

In the early days of transportation over natural inland waterways, navigation was limited to those sections of the rivers, or to those seasons of the year, which provided unobstructed depths sufficient to float the vessels used. Increasing demand for more dependable service prompted construction of artificial controls for assisting traffic over shallow places. So-called staunches or barriers with flood gates were constructed above shoal places to store water which could be released as a wave on which the vessels could ride over bars or rapids where the water was otherwise of insufficient depth. These staunches were also used as means for impounding the river over shallow reaches to permit boats to travel on slack water from one staunch to the next one upstream or downstream. Having only one gate at each control, it was necessary to empty completely the pool above in order to pass craft through the staunch. Thus, upstream traffic, after passing the staunch, would have to wait until the pool was filled before proceeding to the next one above. This method was necessarily slow, particularly in rivers of considerable channel storage or low rates of discharge. To overcome this delay, two barriers were built close together, with gates in each, and

it became necessary only to store or waste water in a lockage in the amount of the capacity of the channel between the controls. As economy of water became more important, the capacity of the reservoir between staunches was decreased by constructing parallel walls in the stream or to one side with gates at either end to retain the water in the chamber and for passing boats into and out of it. This was the beginning of the present lock.

The filling systems in the early locks were very simple. In small locks with low lifts the lock gates themselves could be opened manually to allow the chamber to fill or empty. Larger locks with greater lifts required auxiliary filling valves, usually placed in the main gates and operated by hand. The operation was slow, and, as faster movement of traffic and higher lifts became necessary, more efficient hydraulic systems were required. Without going into further details regarding development of the various systems used in filling or emptying locks, suffice it to say that today there are four general types in use:

a. Filling through the upper end of the lock either by means of valves in the gate, by using the gate itself, or by means of culverts and valves in the sill.

b. Stub or loop culverts around the upper gate bay, which conduct the water from the upper pool into the upper end of the lock chamber and controlled by valves in the culverts.

c. Longitudinal culverts within the walls of the lock connected to the pool both above and below the lock and connected to the chamber by means of short lateral ports. Appropriate arrangements of valves at the upper and lower ends of the culverts permit this manifold system to be used for both filling and emptying the lock.

d. Longitudinal culverts in the floor of the lock open to the upper pool and connected to the chamber by vertical ports. The emptying system may be combined with the filling system or separate, as loop culverts around the gate bay or under the gate sill.

It is not the province of this paper to discuss the various types of filling systems, or to prove which system is the best. It is my opinion that each design has certain adaptations peculiar to itself which make it fitted to certain locations where others would not be, and it is also my belief that any of the various systems suggested here can, by careful analysis and study, be designed to give adequate and satisfactory service.

fically, the design depends on the nature of the waterborn traffic, the required width and length of the lock chamber, the type of waterway, whether canal or river, with different physical properties and stability of channel conditions.

The type of filling system to be selected for any particular case will depend upon the local situation. Each type has individual merits and one may be suited to a project where the others are not. In general the criteria to use in determining which design should be adopted would be threefold:

- (1) It should be economical in construction;
- (2) It should fill and empty the lock without creating surges or turbulence detrimental to craft in lockage;
- (3) It should effect its function as rapidly as is consistent with demands of traffic and economy in construction. The local conditions will indicate the relative importance of these criteria and will influence the selection of a type which will most adequately satisfy the requirements. All of the types indicated are commonly used in this country although type (c), the manifold system with side-wall culverts and lateral chamber ports, has been more generally adopted during the past 20 years than the others. The majority of locks constructed during this period have been built by the Corps of Engineers of the United States Army, particularly in the Ohio and Upper Mississippi River waterways, and since the side-wall culvert system was found adequate for the size of lock, lift, and type of traffic, which factors were all quite similar at most of the locations, this type was adopted as standard construction.

Type (d), the floor culvert system, has been used with various modifications at the Sault Ste. Marie locks, Keokuk locks, Panama Canal lock and more recently in the Bonneville lock.

Types (a) and (b) are less common in this country but have been used extensively in European practice.

Hydraulics as applied to filling and emptying locks of the type used in the inland waterways of the United States has been the subject of comprehensive model studies conducted by the U. S. Corps of Engineers in the laboratory of the Iowa Institute of Hydraulic Research. The primary purpose of this investigation was to study the various factors influencing the flow of water in the composite conduit system used in operation of river locks and to establish bases for correct design of its component units in order that the optimum

efficiency in operation of the system as a whole, commensurate with economy in construction, might be achieved.

In 1929 a model was constructed simulating a side-wall culvert or manifold system in which the basic characteristics of the hydraulic system were investigated, and as improvements were indicated they were introduced and tested in the model.

The model was constructed to simulate a standard lock 360 ft. long by 56 ft. wide, with a lift of 40 ft. The fullsize dimensions of the side culverts were 8 by 10 ft. Fourteen ports, 4 by 4 ft., equally spaced on each side, connected the culverts with the lock chamber. The scale of the model was 1 to 15. The culverts and ports were constructed so as to readily permit alterations in the size, shape, and spacing of the ports or any part of the culvert system. Sections of the culvert and certain of the ports were made of transparent pyralin to permit visual observation of flow conditions in the system. Several piezometers were installed in one culvert, in the lock chamber, and in a few ports for observation of pressures. Stages and surges in the lock chamber during lockage operations were recorded automatically by an electric spark device.

The filling ports in a lock with longitudinal culverts play an important part in the performance of the lock and yet their hydraulic design with a view toward efficiency has received very little consideration. The port entrances have been formed with square corners, almost exclusively, or, as in some rare cases, with slightly chamfered corners. In general the ports have been uniformly spaced with the size and number determined by the arbitrary rule that the combined port area in each wall should be about 50 per cent in excess of the culvert area so as to compensate for entrance losses and provide a port velocity somewhat lower than the culvert velocity. In 16 locks representative of construction practice in the Mississippi, Ohio, Tennessee, Kanawha, Allegheny, and Warrior Rivers, the ratio of port area to culvert area varied from 1.50 to 2.20, with an average of 1.65. The ratio in most common use was 1.50. In the model constructed in the laboratory the port area was 2.8 times the area of the culvert, but arrangements were made to permit wide variation in this ratio by closing any number of the ports.

It has been assumed that the capacity of the port is governed by the size only, disregarding the fact that capacity can also be modified considerably by shaping the port so as to eliminate friction

and eddy losses. In addition to affecting the capacity of the hydraulic system and the efficiency of the lock, the shape of the port also has a very important bearing upon the turbulence and disturbance in the lock chamber and upon any craft, particularly small ones, that may be in the chamber.

Operation of the model at once indicated an uneven distribution of discharge through the ports with more rapid filling at the downstream end than upstream. The effect in the chamber was very undesirable because of excessive turbulence in the downstream end and a considerable current in the upstream direction.

The pressure gradient in the culvert observed on the manometers had an upward slope in the downstream direction indicating a greater head on ports located near the downstream end of the culvert than at the upstream end, hence, the unbalanced distribution of flow. The velocities of the jets issuing into the lock chamber from the port were also measured, using pitot tubes, and the character of flow in the transparent culvert section and ports was observed by using dye, confetti, and short yarns. The velocity measurements made under static pool conditions at 4 different heads indicated a flow-distribution pattern in the ports of the manifold which was identical for all of the heads tested. The variation in head on the ports and the consequent difference in discharge through the ports is obviously due to conversion of energy in the column of water flowing within the culvert. The depletion of water from the column at the entrance to each successive port causes a reduction in velocity head which is accompanied by an increase in the pressure head, provided the friction and eddy losses from one port to the next do not exceed the reduction in velocity head at the port—a condition which did not exist in any of the tests conducted in the model discussed in this paper.

The increment of pressure is not, however, necessarily a function of the change in velocity head alone. If the column of water was flowing at super-critical velocity there was no definite relation between these two factors, but from the point of approximately critical velocity to the closed end of the culvert an almost straight-line relationship existed.

Much the same condition occurs when the lock is emptying. The accumulative discharge in the culvert, flowing in the downstream direction, increases the velocity with the result that the greatest pressure drop between the lock chamber and the culvert occurs at

the last port in which the greatest discharge also takes place. The pressure gradient in the culvert on emptying the lock drops considerably more abruptly than the gradient rises in the filling operation. The relative distribution of discharge in the upper and lower halves of the lock on filling were 29 and 71 per cent, respectively, and on emptying about 22 and 78 per cent.

In order to maintain constant pressures in the culvert and thus attain even distribution of flow through the ports, it would be necessary either to make the culvert so large that the change in velocity head would be negligible, or to reduce the area of the culvert at each port in proportion to the per cent of total discharge depleted from the culvert by the respective ports, with proper allowance made for the head losses occurring in the intervening section of culvert. Both of these solutions are impractical: the first, because it would require a culvert of such dimensions as could not be accommodated in the lock wall and the second, because when the same culverts are used for both filling and emptying the lock, the correction satisfactory for one operation would not work for the other. Fortunately the emptying operation presents the lesser problem with respect to disturbances in the lock chamber. The operation begins with a deep cushion of water under the craft and the slight downstream drag of the water in the chamber has no harmful effects. Sudden opening of the valves may under certain conditions set up oscillatory waves that can produce critical hawser stresses or distress the boats by undue tossing, but this might occur with almost any type of emptying system no matter how carefully it was designed.

Uniform distribution of flow into the lock in the filling operation can be obtained with square-cornered ports by varying the size, or by varying the spacing between them until the distribution of area along the length of lock becomes inversely proportional to the discharge capacity of the ports. However, it is important not only to provide uniform distribution of inflow but also to secure this condition with the minimum of energy loss in the hydraulic system and to effect the dissipation of the energy of the incoming jets with a minimum of turbulence in the lock. The model experiments have led to development of a port design which not only conserves the hydraulic energy in the filling system and minimizes the turbulent effect of the jets in the lock, but also tends to equalize the flow of water through the ports.

An apparatus was constructed in which individual ports could be tested under conditions simulating those existing at any port in a lock. The pressures upstream and downstream from the port, the velocity past the face of the port, and the depth of submergence of the outlet could all be adjusted to any desired values. In this apparatus the coefficients of discharge of various shapes of ports were investigated, particularly to determine the correlation, if any, between the coefficient of the port and its transfacial velocity. These tests disclosed the interesting fact that the discharge coefficient of a square-cornered port is adversely affected by flow past its entrance, the coefficient decreasing with increasing velocity, the pressure head remaining constant. A well-rounded entrance on a port with a straight bore indicated no change in the coefficient throughout the range of velocities tested while a port well rounded at the entrance and expanded toward the lock chamber, referred to as a fully streamlined port, indicated a greater coefficient with increasing transfacial velocity. Hence, streamlined ports partially effect equalization of flow into a lock chamber and, by virtue of the rounded entrances, reduce hydraulic energy losses. The expanding bore of the ports decreases the exit velocity and disperses the jet more rapidly in the lock chamber, thus dissipating its energy sooner and with less turbulence than a port with uniform or contracted bore. Visual observation of the flow conditions inside of the pycnolite ports of the various shapes described indicated that a square-cornered port at the upstream end of the lock had an effective area equivalent to about 20 or 25 per cent of its actual area, the ratio increasing in the downstream direction. Eddies occupied the upstream side of the port while the water drawn from the culvert entered the lock chamber as a thin sheet along its downstream side. The rounded and streamlined ports, on the other hand, indicated no eddies or reverse flow unless the port area had been over-designed.

The ratio of total port area to culvert area is important. The arbitrary rule for square-cornered ports of allowing 50 per cent more port area than culvert area, which has been established through many years of cut and try in prototypes, is probably very nearly correct. For a streamlined port the area should be no greater than the culvert area and in some cases a smaller area would prove better. In the absence of design data applicable to a particular project, the use of model tests in determining the proper areas, both for culverts and

ports is strongly recommended. In a specific case the port area had been determined by use of a model, but in construction the ports were made larger so that the aggregate area was about 25 per cent larger than specified in the design. Tests were made in the prototype to determine the quantity of flow from each port for comparison with the model and it was found that the three upstream ports, having an area equal to 25 per cent of the total port area, contributed no flow into the lock during the entire filling period. On the contrary, they were discharging water from the lock chamber back into the culvert during most of the time.

Various types of valves have been used for operating manifold hydraulic systems, stoney valves, butterfly, tainter, thimble, cylinder valves, etc. The tainter valve is in most common use and has become standard in Mississippi River construction.

It is important in a manifold system that the culvert from a point upstream from the valve to the lower end be located below tailwater level. In locks where this has not been done, considerable difficulty and loss of efficiency have been experienced due to entrapment of air in the culvert, causing restriction to flow and blowing of air from the port with consequent disturbances in the lock chamber. Elaborate venting systems have been installed to relieve this situation and at considerable expense, especially where it was undertaken as a necessary measure after construction of the lock was completed.

During the period that the valve is being opened, as velocities under the full head of the lock are concentrated through a small opening, the pressure drop in the culvert may approach the full static head and, unless the culvert at the valve is submerged below the lowest point on the hydraulic gradient, air will be drawn into the culvert through the valve shaft or through the lower stop-log recess. The cost of lowering the culvert to correct this feature would in most cases be prohibitive and would entail numerous other construction difficulties. The model has indicated a very simple solution—one that provides other inherent benefits to the operation of the lock. Heretofore, the tainter valves have been placed in the same position in the lock culverts as they normally occupy in a dam. By reversing the position of the valve, placing the trunnions upstream instead of downstream, a water seal in the valve shaft is obtained which prevents passage of air into the culvert. However, if the downstream

stop-log recess is placed near the valve, as is usually the case, it will be necessary to seal this opening also. Pickwick Lock in the Tennessee River was the first to be constructed this way and it has performed in the prototype to every expectation indicated by the model. With this arrangement a venting system would not be necessary, because, if it functions properly, there will be no entrapped air to release from the culvert. Since Pickwick Lock was the first structure to use this innovation it was decided to install vents as a precautionary measure, but there has been no evidence of air escaping from the vents. A removable diaphragm was placed in the stop-log recess above tailwater level for sealing and, for the purpose of comparing the behavior of the lock with the "closed" and "open" systems, the diaphragm was opened up so as to permit the entrance of air to the culvert at this point. There was violent spouting in the vents as they discharged alternately large volumes of air and water. Blowing of air from the ports into the lock chamber was also evident. In addition to eliminating the problem of air in the filling system, the reversed tainter valve permits the shaft to be used as a surge chamber in the event of accidental or sudden closure of the valve, relieving, to some extent at least, water-hammer forces on the valve. The emptying valve in this type of hydraulic system should be treated the same way as the upstream valve.

I have by no means covered all the manifold problems in lock design nor have all the practical problems confronting the designing engineer been exhausted. It is true, however, that the use of models has enabled us to advance materially in the solution of many problems which have heretofore been hidden mysteries. As to the reliability of models as a means of predicting the behavior of full-size hydraulic structures, a question which is moot in the minds of many engineers even today, may I cite only a few comparisons which substantiate the transferability of results from similar structures.

The time to fill and empty a lock checked the model within 1 per cent, maximum rates of rise and fall checked within 5 and 3 per cent, respectively, and the filling and emptying coefficients of the lock checked within 2 and 5 per cent, respectively.

Visual inspection of the behavior of the hydraulic system, turbulence in the chamber and lower approach indicated a marked degree of similarity between the model and prototype.

