INTRODUCTION: The U.S. Army Corps of Engineers (USACE) is responsible for the nation’s inland navigation infrastructure. Navigation locks are an essential asset to the waterway system, and hydraulic design of new locks and extension of existing locks, as well as assessment of locks in operation, require evaluation of the locks’ manifolds. Hydraulic evaluation of a lock manifold requires the calculation of flow rate and pressure distributions throughout the manifold. A set of energy equations (one written for flow through each port) and the continuity equation provide a means of calculating the flow distribution. Analytical solutions of lock manifold flow are given by Stockstill et al. (1991), Allen and Albinson (1955), Webster et al. (1946), Soucek and Zelnick (1945), and Zelnick (1942). One-dimensional (1-D) numerical flow solvers such as LOCKSIM (Schohl 1999) are also used to calculate the flow and pressures in lock manifolds. Each of these evaluation techniques requires knowledge of energy loss coefficients for multi-ported manifolds. The purpose of this technical note is to provide a single source of loss coefficient information for lock manifold ports. Coefficients have been gathered from technical reports, laboratory experiments, and computational models. The sizes and shapes of culverts and ports are described using dimensionless terms. This technical note includes loss coefficient information required for hydraulic analysis of manifold flow.

PORT HEAD LOSS: Hydraulic and geometric variables in the vicinity of a single port are defined in Figure 1. The head loss as flow passes from the culvert to the lock chamber through a port is shown as $\Delta H'$ in Figure 1. The head loss for flow through individual ports of the manifold can be computed in terms of the culvert velocity head as:

$$\Delta H' = K_1 \frac{Q_1^2}{2g A_1^2}$$

where:

$\Delta H'$ = the head loss;
$K_1$ = the loss coefficient;
$g$ = the acceleration due to gravity;
$Q_1$ = the culvert discharge upstream from the port; and
$A_1$ = the culvert area upstream from the port.

This same head loss can be expressed in terms of the velocity head in the port as:
Figure 1. Definition sketch of hydraulic and geometric variables at a single port (lock filling).

\[ \Delta H' = K_3 \frac{Q_3^2}{2g A_3^2} \]  

(2)

where:

\( K_3 \) = the loss coefficient;
\( Q_3 \) = the port discharge; and
\( A_3 \) = the port area.

The form losses computed using either Equation (1) or (2) require knowledge of the loss coefficient. Dimensional analysis shows that the loss coefficient is a function of the geometrical relations between the culvert parameters \( (W_1 \text{ and } D_1) \) and those of the port \( (W_3, D_3, \text{ and } L_3) \), as illustrated in Figure 1. A two-dimensional potential flow solution of lateral flow reveals that the coefficient is also a function of the flow division at the port. This division is expressed as the
ratio of the port discharge \((Q_3)\) to the culvert discharge upstream from the port \((Q_1)\). The functional relation for a port loss coefficient, \(K\), is:

\[
K = f_n \left( \frac{Q_3}{Q_1}, \frac{W_3}{W_1}, \frac{D_3}{D_1}, \frac{L_3}{L_1} \right)
\]

(3)

Other geometrical considerations, such as rounding of the port entrance and flaring of the port walls, roof, or invert, influence the loss coefficient. For a given manifold geometry, \(K\) becomes a function of \(Q_3/Q_1\). Data required to define this function have been obtained in laboratory studies and computational models.

**LOSS COEFFICIENTS FOR LOCK MANIFOLD PORTS:** Graphs of loss coefficients for various lock manifold designs are provided in Figures 2-11. Each figure includes a sketch of the particular port shape and a graph of the head loss coefficient expressed both in terms of the velocity head of the main culvert upstream from the port, \(K_1\) as defined in Equation (1), and the port velocity head, \(K_3\) as defined in Equation (2). The values of \(K_1\) are more reliable for small discharge ratios whereas \(K_3\) values are more reliable for large ratios.

**Square Ports.** Zelnick (1942) presents discharge coefficients measured on a model representing lock manifold ports. The shapes tested included square-edged and round-edged ports. Each port cross section was square, but three port width-to-culvert width and port height-to-culvert height ratios were tested. The discharge coefficients are given as a function of the port discharge-to-culvert discharge ratio. The actual laboratory data was included in the Zelnick (1942) report, so the head loss coefficients could be calculated in addition to the published discharge coefficients. The energy loss coefficients for the square ports are provided in Figures 2-7. The loss coefficients decreased as the relative port size increased. Lock manifold guidance suggests that the sum of the port areas should be about equal to the culvert cross sectional area (Headquarters, USACE 2006). So, the proper port size depends on the culvert size and the number of ports used to distribute flow along the length of the chamber. Figures 3, 5, and 7 illustrate that the round-edged ports are significantly more efficient than the square-edged ports (Figures 2, 4, and 6). The loss coefficients for the round-edge ports are about one-half as large as those for the square-edged ports.

**ILCS Ports.** Energy loss coefficients for generalized In-chamber Longitudinal Culvert System (ILCS) port shapes are provided in Hite and Stockstill (2004). The ILCS uses two ports at each ported station, one on either wall, as illustrated in Figures 8 and 9. Each port is located at the mid-height of the culvert walls. Yanes (1951) studied the influence of two symmetrically placed ports. The basis of his analysis was the comparison of the two ports with a single port having an area equal to the two symmetrical ports. He concluded that, for port discharge-to-culvert discharge ratios less than 0.25, the results were identical. The symmetrical ports were as much as nine percent more efficient than the single port for discharge ratios between 0.25 and 0.70. However, the data for discharge ratios greater than 0.70 indicated that the symmetrical ports had a comparatively large loss. Yanes (1951) concluded that the pressure rise across divergent symmetrical ports at most of the ported stations along the manifold can be approximated from the results of a single port. So, the pair of ILCS ports is treated as a single port for head loss calculation.
Figure 2. Loss coefficients for a square port, $W_3/W_1 = 0.333$, $D_3/D_1 = 0.333$, square edges.
Figure 3. Loss coefficients for a square port, \( W_3/W_1 = 0.333, D_3/D_1 = 0.333, \) round edges.
Figure 4. Loss coefficients for a square port, $W_3/W_1 = 0.458$, $D_3/D_1 = 0.458$, square edges.
Figure 5. Loss coefficients for a square port, $W_3/W_1 = 0.458$, $D_3/D_1 = 0.458$, round edges.
Figure 6. Loss coefficients for a square port, \( W_3/W_1 = 0.583 \), \( D_3/D_1 = 0.583 \), square edges.
Figure 7. Loss coefficients for a square port, $W_3/W_1 = 0.583$, $D_3/D_1 = 0.583$, round edges.
Figure 8. Loss coefficient for ILCS port, without extensions.
Figure 9. Loss coefficients for ILCS port, with extensions.
Figure 10. Loss coefficients for a sidewall port, Cannelton Lock.
Figure 11. Loss coefficients for a sidewall port, Lock 22/25 Mississippi River.
Two port designs are used in each ILCS lock chamber manifold. Sketches of the port shapes, shown in dimensionless form, are provided in Figures 8 and 9, with the graphs of the loss coefficients for flow through the ports. Again, the head loss is given relative to the upstream velocity head \( (K_1) \) and port velocity head \( (K_3) \) as functions of the port-to-culvert discharge ratio \( (Q_3/Q_1) \).

The ILCS design has the ports in two groups centered at the one-third points along the length of the chamber. Port extensions are needed on the upstream port group to direct the jet flow normal to the lock centerline. This jet direction helps distribute the flow more evenly in the upper end of the chamber and provides a more balanced flow over the entire chamber length. The ILCS port throat length is rather short because it is only as long as the culvert wall is thick. The short throat causes the jet to be directed more downstream than desired during filling. Additional hydraulic design guidance for the ILCS can be found in EM 1110-2-1604 (Headquarters, USACE 2006). Loss coefficients for ports in the downstream group of the ILCS (ports without extensions) are given in Figure 8, and those for the upstream group of ports (ports with extensions) are provided in Figure 9. The throat extensions do not affect the head loss in flow through the port. Flow through an ILCS port experiences the same head loss whether the port has an extension or not.

**Sidewall Ports.** Stockstill and Hammack (2012) have shown that a three-dimensional (3-D) Reynolds Averaged Navier-Stokes (RANS) computational flow model can be used to calculate loss coefficients for lock manifold ports. The modeling process was validated with ILCS laboratory data. After the modeling system was validated, port configurations for the sidewall port type culvert system were simulated. The sidewall port system was chosen because this filling and emptying system design is used for more than half of the USACE locks.

**Cannelton Lock.** Ables and Boyd (1966) conducted a generalized testing program using a physical model of the Cannelton Lock, Ohio River, to develop design guidance for 110- by 1200-ft medium lift locks. The resulting sidewall port system recommended the port that is illustrated in dimensionless form in Figure 10. The port is flared such that the throat width near the culvert wall is narrower than the width near the chamber wall. The shape is further streamlined with rounding of each of the edges. The Cannelton Lock system performed best using a port-to-culvert area ratio of 0.97. Loss coefficients for the Cannelton Lock port were obtained using the 3-D RANS modeling procedure. Loss coefficients for the standard sidewall port design are given on the graphs in Figure 10.

**Lock 22/25.** A port configuration proposed for the extension of Locks 22 and 25 on the Mississippi River is shown in Figure 11 (Sanchez 2009). These lock extensions will use much of the existing culvert system, so the design is required to match the existing structure. A common culvert and port size and shape were proposed for inclusion in the hydraulic design of both Lock 22 and Lock 25 extensions. Portions of the manifold have circular culverts and rectangular ports. The culvert and port widths shown on the plan view of the sketch in Figure 11 is the culvert and port diameters, respectively. The port height-to-width ratio is 0.67, whereas the USACE guidance calls for ports that are taller than they are wide. The relatively narrow width recommended in EM-1110-2-1604 (Headquarters, USACE 2006) helps the jet direction to be directed more normal to the lock wall. The Lock 22/25 port was relatively wide and short because the locks’ submergence was small. Here, the submergence is defined as the distance from the lower pool to the top of the port. Generally, acceptable chamber performance requires sufficient submergence.
SUMMARY AND CONCLUSIONS: This technical note provides head loss coefficients for ten lock manifold port configurations. The geometrical description of the culvert and port shapes and sizes are given in dimensionless form. These dimensionless coefficients are needed to calculate the flow in manifolds using analytical procedures or one-dimensional flow models. The coefficients are expressed in terms of the culvert velocity head, $K_1$, and the port velocity head, $K_3$. The former is more reliable for small values of port-to-culvert ratios and the latter for large values. The coefficients were gathered from laboratory and computational model studies. The port designs include the most recently developed In-chamber Longitudinal Culvert System and the design used on the majority of USACE locks, the sidewall port lock filling and emptying systems. Square port shapes, with and without rounded edges, are also provided because they are useful for general lock manifold studies.

ADDITIONAL INFORMATION: This CHETN is a product of the Hydraulic Design Guidance for Locks and Dams work unit of the Navigation Systems Research Program being conducted at the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. Questions about this technical note can be addressed to Dr. Richard L. Stockstill (601-634-4251; e-mail: Richard.L.Stockstill@usace.army.mil). For information about the Navigation Systems Research Program, contact the Program Manager, Charles E. Wiggins at (601-634-2471, e-mail: Charles.E.Wiggins@usace.army.mil). This technical note should be cited as follows:


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**ACRONYMS AND ABBREVIATIONS**

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<tr>
<th>Term</th>
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<tbody>
<tr>
<td>CAD*</td>
<td>Computer Aided Design</td>
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<tr>
<td>CHETN*</td>
<td>Coastal and Hydraulics Engineering Technical Notes</td>
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<tr>
<td>CHL</td>
<td>Coastal and Hydraulics Laboratory</td>
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<tr>
<td>ERDC*</td>
<td>Engineer Research and Development Center</td>
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<td>ILCS*</td>
<td>In-chamber Longitudinal Culvert System</td>
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<tr>
<td>LOCKSIM*</td>
<td>LOCK SIMulator</td>
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<tr>
<td>RANS*</td>
<td>Reynolds-Averaged Navier-Stokes</td>
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