APPENDIX B

LOCK FILLING PROGRAM

MEMORANDUM FOR RECORD 8 March 1974

SUBJECT: Engineering Summary of Lock-Filling Program "FLOCK" (Millers Ferry Prototype Test Conditions)

OVERVIEW

1. Introduction. This FORTRAN program has been used primarily to simulate existing model and prototype test data. The input format is designed for expedient time-share operation and permits convenient changes in the values of flow coefficients, in the basic lock geometry, and in selecting which computed values are to be printed or plotted. The four primary deficiencies of the program in regards to being a comprehensive lock design program are as follows:

a. Type of lock operation. The program is for filling only; no allowance is made for emptying operations.

b. Valve schedules. Single valving and synchronous valving are included; nonsynchronous, stepped, or nonsimilar (land wall different than river wall) valving is not programmed.

c. Culvert geometry. The two culverts are identical; that is, the length, width, and height of the land-wall culvert is the same as that of the river-wall culvert; and the intake, conduit, and manifold loss coefficients of the two culverts are equal. These conditions are generally no drawback in analyzing a symmetrical filling system (Dardanelle Lock, Arkansas, for example); for contradictions to these conditions (a split lateral system, for example), average values are used as input data.

d. Calibration. The model should be calibrated for single-valve and synchronous-valve operation in order to accurately evaluate the flow coefficients. This may be done by means of (1) prototype tests, (2) model tests, or (3) using values pertinent to similar systems that have either model or prototype data available. A good estimate of the total loss coefficient may be calculated if the traditional lock-filling coefficient is known.

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2. The first three deficiencies are prograrmnable; the fourth one will be resolved as more model and prototype data for different types of filling systems are inspected. Time and need permitting, a computer program will be constructed that will overcome the programmable deficiencies. Meanwhile the program "FLOCK" has accomplished the following:

a. The general mathematical formulation (an unsteady-flow problem is simulated by a succession of steady-flow situations; each steady-flow solution is modified to include an approximate inertial-correction term) has proven to be a reliable representation of the performance of the prototype and model locks studied.

b. The stepped predictor-corrector scheme used in the calculations has been shown to provide a sufficiently accurate solution.

c. A means of determining the pressures immediately below the valves (based on experimentally determined contraction coefficients) has been established.

d. The effects that the valve opening time, the loss coefficients, the lock and culvert geometry, and the head loss through the culverts have on filling time, overtravel, pressure below the valves, lock chamber rate-of-rise, and other dependent phenomena have been observed in some detail.

3. Since "FLOCK" is relatively small and convenient (compared with a program that incorporates the three programmable deficiencies listed above), it will probably be retained intact. The purpose of this memorandum is to briefly describe the computational techniques, and the input data required in order to run the program. Millers Ferry Lock, Alabama, is used for illustrative purposes. The reader is assumed to have some familiarity with the FORTRAN computer language and with time-shared computer operations.

MATHEMATICAL MODEL

4. Introducton. A definition sketch of the simulated flow conditions at time, t , during a filling operation is shown in Figure B-l. The governing equation is

$$[K_1 + K_2 + K_v(t) + K_3 + K_4] \frac{V(t)^2}{2g} = Z_u - z(t) - H_I(t) \qquad \text{(B1)}$$

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in which
(intake, K_1, K_2, $K_v(t)$, K_3, and K_4 are head loss coefficients respectively); V(t) is the average velocity at a reference location in the culvert(s); g is the gravitational acceleration (32.2 ft/sec^2); Zu is the upstream pool. elevation; z(t) is the elevation of the water surface in the lock chamber; and $H_I(t)$ is the head (effective inertia) required to accelerate (H_I is positive) or decelerate (H_I is negative) the flow.

5. The value of H_I for unsteady frictionless flow in a prismatic tube of length L is(1)

$$H_I = \frac{L}{g}\frac{\partial V(t)}{\partial t} \tag{B2}$$

Substituting Equation B2 in Equation B1 gives

$$[K_1 + K_2 + K_v(t) + K_3 + K_4]\frac{V(t)^2}{2g} = Z_u - z(t) - \frac{L}{g}\frac{\partial V(t)}{\partial t} \tag{B3}$$

6. The values of z(t) and V(t) are related by continuity, that is

$$A_l \frac{\partial z(t)}{\partial t} = nA_c V(t) \tag{B4}$$

in which Al is the lock chamber water-surface area, n is the number (1 or 2) of culverts operated, and A_c is the culvert cross-sectional area. In programming "FLOCK" 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.

7. Equations B3 and B4 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 .

8. Computational sequence. All variables are known at an initial time, t_{i-1}, the time is incremented by a set amount, ΔV , to the time of

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interest $t_i = t_{i-1} + \Delta t$. The corresponding increase in velocity, $\Delta V = V_i - V_{i-1}$ is to be determined using finite differences to simulate the differentials in Equations B3 and B4.

9. In the case of Equation B4

$$z_i = z_{i-1} + \frac{nA_c}{A_1}\left(V_{i-1} + \frac{\Delta V}{2}\right)\Delta t \qquad \text{(B5)}$$

10. In the case of Equation B3, a backwards difference is used to represent the partial differential, Equation B5 if substituted for $z(t)$, and the terms are rearranged to give the following first approximation for ΔV.

$$\Delta V^2 + \Delta V\left[2V_{i-1} + \frac{2g}{K_i}\left(\frac{nA_c\Delta t}{2A_1} + \frac{L}{g\Delta t}\right)\right] + \left[V_{i-1}^2 - \frac{2g}{K_i}\left(Z_u - z_{i-1} - \frac{nA_c\Delta t V_{i-1}}{A_1}\right)\right] = 0 \qquad \text{(B6)}$$

ΔV is the positive real root of Equation B6; this value is used to obtain a first estimate of v_i and z_i .

11. Moving ahead one time interval and letting $\Delta V_+ = V_{i+1} - V_i$, a similar approximate solution at t_{i+1} is

$$\Delta V_+^2 + \Delta V_+\left[2V_i + \frac{2g}{K_{i+1}}\left(\frac{nA_c\Delta t}{2A_1} + \frac{L}{g\Delta t}\right)\right] + \left[V_i^2 - \frac{2g}{K_{i+1}}\left(Z_u - z_i - \frac{nA_c\Delta t V_i}{A_1}\right)\right] = 0 \qquad \text{(B7)}$$

V_{i+1} is calculated once ΔV_+ , which is the positive real root of Equation B7, is known.

12. Now a central difference is used to obtain a better estimate of ΔV and of the conditions at time t_i ; that is

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$$\Delta V^2 + \Delta V \left[2V_{i-1} + \frac{2g}{K_i}\left(\frac{nA_c\Delta t}{2A_1}\right)\right] + \left[\frac{L\left(V_{i+1} - V_{i-1}\right)}{2g\Delta t} + V_{i-1}^2 - \frac{2g}{K_i}\left(Z_u - z_{i-1} - \frac{nA_c\Delta t V_{i-1}}{A_1}\right)\right] = 0 \qquad \text{(B8)}$$

The program "FLOCK" solves Equations B7 and B8 sequentially to give an accurate evaluation ΔV . Equations B6, B7 and B8 provide a simple predictor-corrector numerical solution(2) to Equation B3.

13. Starting and stopping the solution. In the program, the calculations are initiated at $i = 2$ and time $t = \Delta t$ All necessary conditions at $i - 1 = 1$ are known; that is $V_1 = t_1 = 0$ and z_1 equals the initial lock chamber water-surface elevation. The solution terminates whenever i attains a value preselected by the operator (whenever the complete filling time is not required) or whenever either ΔV or ΔV_+ has an imaginary value ($V_i < 0$)--the latter situation is a complete lock filling.

OBSERVATIONS REGARDING ACCURACY AND CONVERGENCE

14. General remarks. Several unsteady features of the flow are not included in the 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 calibrated, the calculated values appear to be as precise as any data with which they have been compared.

15. A maximum time step interval (Δt) of 15 set is recommended; Figure B-2a illustrates the effect that changing the time step size has on convergence (with regard to filling time and cavitation index*) for one test condition at Millers Ferry Lock. As indicated in Figure B-2a

* The procedure for evaluating the cavitation index is given in paragraph 30; a minimum value is of interest.

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the primary benefit of using a small At is simply to force a value of t_i to be near the time that the cavitation index is actually near its minimum value. The effects of looping through the predictor-corrector scheme for the same test conditions are tabulated below; soon after the flow begins to decelerate (after i = 17 in the example), the value of ΔV reaches a nearly constant value (-1.09991 in the example) and the need for the correcting procedure no longer exists.

Table B-l. Significance of the Predictor-Corrector Scheme
(Millers Ferry Tests 1, 3, and 7 Test Conditions)

i	V_i fps	$(\Delta V)_3$* fps/l5-set	$(\Delta V)_3 - (\Delta V)_2$
1	0.00	--	--
2	3.12	3.12408	0.00000
3	6.47	3.34137	0.00000
4	9.73	3.26082	0.00000
5	13.95	4.22720	-0.00001
6	20.13	6.17296	-0.00004
7	27.40	7.27577	0.00036
8	32.97	5.56575	0.00105
9	35.47	2.49839	0.00110
10	35.04	-0.42901	0.00021
11	34.06	-0.97256	0.00005
12	32.99	-1.07507	0.00001
13	31.89	-1.09888	0.00000
14	30.80	-1.09969	0.00000
15	29.70	-1.09986	0.00000
16	28.60	-1.09990	0.00000
17	27.50	-1.09991	0.00000

* The subscripts 2 and 3 refer to the results of the second and third loop through the predictor-corrector sequence, respectively.

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DATE FILE "LOCKD"

16. Introduction. All data which are needed to describe the lock geometry, the operating conditions, and the hydraulic characteristics are placed in this data file. Keyboard input during a run is limited to items having to do with the number and size of the computational steps and with plot and print options. An example of "LOCKD" is shown below; the items in the file are described in the following paragraphs.

```
100 80.34 38.77 26.00   2.00 2 MILLERS FERRY TEST NO. 5
102 377.00 10.00 10.00 655.00 84.00
104   0.20   0.05   0.70   0.25   0.13
106   2.20   3.20   0.65   0.80   0.90
```

17. The first number (100, 102, etc.) in each row is the reference line number and is not read as data. In addition, the first space following the line number is outside the format field and must be left blank.

18. Line No. 100. The format is (4F7.2, 12, 7A5); these data are read at line No. 170 in the main program "FLOCK." The items, identified by the FORTRAN symbol used in the program, are as follows:

Value	Units	Symbol	Description
80.34	Ft-Datum	ZU	Upper pool elevation
38.77	Ft-Datum	AL	Initial lock chamber elevation
26.00	Ft-Datum	ZR	Culvert roof (at valve) elevation
2.00	Minutes	VOT	Valve opening time
2	--	NC	No. of culverts operated
MILLERS, etc.	--	RUN (7)	Title of condition being studied

19. Line No. 102. The format is (5F7.2); the data are read at line No. 175 in "FLOCK." The items are as follows:

Value	Units	Symbol	Description
377.00	Ft	XL1	Length of culvert
10.00	Ft	XL2	Width of culvert (at valve)
10.00	Ft	XL3	Height of culvert (at valve)
655.00	Ft	XL4	Length of lock chamber (average)
84.00	Ft	XL5	Width of lock chamber

20. The preliminary evaluation of XL1 is simply the distance between the station at the downstream end of the intake manifold and the one at

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the center line of the crossover culvert (balanced flow system); or the average distance between the stations at the downstream ends of the intakes and the ones at the first lateral culverts (split lateral system). However, since irregularities in culvert geometry (location of the valve wells, expansions, etc.) also influence the inertial effect (see paragraph 5 and reference 3), the value of XL1 may be changed (usually decreased) from this simplified interpretation.

21. The amount of overfill is a measure of the momentum of the flow in the culverts; a comparison of observed and calculated (with no adjustments to the defined XL1 values) overfill follows.

Symmetrical Systems		XL1, ft	Overfill, ft Calculated	Overfill, ft Observed
Dardanelle prototype	(1 valve)	404.10	0.74	0.5[4]
	(2 valves)	404.10	1.14	1.1
Millers Ferry prototype	(1 valve)	377.00	0.46	0.4[5]
	(2 valves)	377.00	0.80	0.7
Bankhead model	(1 valve)	404.00	0.61	0.6[6]
	(2 valves)	404.00	0.96	1.2
Nonsymmetrical System				
Barkley prototype	(L/W valve)	650.00	1.25	0.79*[7]
	(2 valves)	422.00	1.59	1.10*

* Miter gates open before maximum overfill occurs.

22. Line No. 104. The format is (5F7.2); the data are read at line No. 180 in "FLOCK." The items are as follows:

Value	Units	Symbol	Description
0.20	None	XK1	Intake loss coefficient (K_1 in Figure B-1)
0.05	None	XK2	Upstream conduit loss coefficient (K_2 in Figure B-1)
0.70	None	XK3	Downstream conduit loss coefficient (K_3 in Figure B-1)
0.25	None	XK4	Manifold loss coefficient (K_4 in Figure B-1)
0.13	None	A	Valve pattern coefficient (sag coef.)

23. The best way to precisely evaluate the loss coefficient values for an existing lock is to calibrate the program by adjusting the coefficients

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until a computed filling time equals a measured filling time. However, even without these data reasonably accurate, values may be obtained using the following relationships.

a. The sum of the four coefficients added to the loss coefficient of the fully open valve equals $1/c_L^2$ where C_L is the traditional lock coefficient.

b. The sum, $K_1 + K_2$, usually is approximately equal to 0.25.[8]

c. The values of K_2 and K_3 are estimated from the Darcy-Weisbach coefficient, fl/D, where f is the friction coefficient, 1 is the appropriate conduit length, and D is the hydraulic diameter of the culvert.

d. The value of K_4 is largely dependent on $(A_c/A_p)^2$ in which A_C is the culvert area and A_p is the corresponding discharge port area.

e. Minor losses (due to bends, expansions, etc.) may contribute to any of the four coefficients.

24. A brief listing of the loss coefficients for four locks is given below. For the first three locks the values are derived from items a.-e. above; for Barkley Lock the values are derived from prototype test data.

Symmetrical Systems	K_1	K_2	K_3	K_4	Kt*	Lock Coefficient, CL: Program**	Lock Coefficient, CL: Observed***
Dardanelle prototype (9)							
(1 valve)	0.20	0.05	0.75	0.30	1.40	0.85	--
(2 valves)	0.20	0.05	0.75	0.70	1.80	0.75	0.66[4]
Millers Ferry prototype (10)							
(1 valve)	0.20	0.05	0.80	0.35	1.50	0.82	--
(2 valves)	0.20	0.05	0.80	0.55	1.70	0.77	0.72[5]
Bankhead model							
(1 valve)	0.20	0.05	1.18	0.20	1.73	0.76	--
(2 valves)	0.20	0.05	1.18	0.70	2.23	0.67	0.67[6]

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Non-symmetrical System	K_1	K_2	K_3	K_4	Kt*	Lock Coefficient, C_L Program**	Observed***
Barkley prototype(7)							
(1 valve)	0.20	0.08	0.42	0.86	1.66	0.78	- -
(2 valves)	0.20	0.08	0.22	0.86	1.46	0.83	0.75(11)

* $K_t = K_1 + K_2 + K_3 + K_4 + K_v(t_v)$; 0.10 is the value assumed for $K_v(t_v)$.

** $C_L = \sqrt{1/K_t}$.

*** The observed values of C_L are from model tests.

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

$$\frac{b}{B} = \frac{t}{t_v} - A \sin\left(\frac{\pi t}{t_c}\right) \tag{B9}$$

in which b/B is the valve-opening ratio (B = XL3 = culvert height); t/t_v is valve-time ratio (t_v = VOT = valve opening time); and A is the sag coefficient. The calculation is at line No. 240 in "FLOCK." The value of A is obtained from the valve opening pattern; A equals (0.5 - b/B) at $t/t_v = 0.5$.

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

26. The valve opening pattern for Millers Ferry Lock is shown in Figure B-2b.

27. Line No. 106. The format is (5F7.2); the data are read at line No. 185 in "FLOCK." These values (termed B*, C, D, E, and F, respectively) 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. For data analysis purposes, the effects of

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altering these values are often of interest; for design purposes the tabulated values are adequate.

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

(a) $\frac{b}{B} = 0$ $\qquad K_v = 10000.$

(b) $0 < \frac{b}{B} < 0.2$ $\qquad K_v = \frac{0.04}{\left(\frac{b}{B}\right)^2} \left(10^{B^* - 0.2C}\right)$ (B10)

(c) $0.2 \leq \frac{b}{B} \leq 1.0$ $\qquad K_v = 10^{B^* - C(b/B)}$ (B11)

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

a. 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.

b. 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 .

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

30. As used in "FLOCK" 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:

$$\left(\frac{p}{\gamma} + Z\right)_r = Z_u - \left(K_1 + K_2\right) \frac{V^2}{2g} - \left(\frac{B}{C_c b}\right)^2 \frac{V^2}{2g} \qquad \text{(B12)}$$

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$$C_i = \frac{p}{\gamma_r} + 33.0 - B\left(1 - \frac{C_c b}{B}\right)\left(\frac{C_c b}{B}\right)^2 \Bigg/ \frac{V^2}{2g} \qquad \text{(B13)}$$

31. Since the flow pattern below the valve changes as the valve opens, published contraction coefficient values are appropriately used in Equation B11 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

$$0 \le \frac{b}{B} \le 0.2 \; ; \qquad C_c = D + (E-D)\cos\left(\frac{\pi b}{0.6B}\right) \qquad \text{(B14)}$$

$$0.2 < \frac{b}{B} \; ; \qquad C_c = F - (F-D)\cos\left(\pi\,\frac{b - 0.3B}{1.4B}\right) \qquad \text{(B15)}$$

32. The intermediate values of C_c are sensitive to the value of the parameter, D , in Equations B14 and B15; simulations of model and prototype test 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 B-4.

33. Program Output. Three unsubscripted variables are computed and printed as follows:

Program Variable Name	Description
XKT	XKT is the sum of the loss coefficients; i.e., XKT = K_t in paragraph 24.
I	I is a variable subscript; for example filling time is between $(I-2)\Delta t$ and $(I-1)\Delta t$* during the filling operation.
ZOT	Lock chamber overfill; ZOT is the difference between the lock-chamber water-surface and the upper pool elevations at time $M\Delta t$ where M is a value of I that terminates the computations.

* At is the incremental time.

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34. The subscripted output variables are as follows:

Program Variable Name	Dimmensions	Evaluation--Dimension Conversions Are Omitted Here
CI	--	Equation B13, C
H	Ft	$Z_u - z_i$
HI	Ft	Equation B2, H_I
HL1	Ft	$K_1 V^2/2g$
HL2	Ft	$K_2 V^2/2g$
HL3	Ft	$K_3 V^2/2g$
HL4	Ft	$K_4 V^2/2g$
HLT	Ft	$K_t V^2/2g$
HLV	Ft	$K_{vi} V^2/2g$
PVC	Ft	Equation B12, $(P/\gamma)_r$
Q	Ft^3/sec	$nV_i A_c$
RUN	--	Title (see para. 18)
RR	Ft/min	Q/A_ℓ
V	Ft/sec	$V_{i-1} + \Delta V$
VH	Ft	$V^2/2g$
XBB	--	Equation B8, b/B
XCC	--	Equations B14 and B15, C_c
XKV	--	Equations B10 and B11, K_v
XT	Min	$t_{i-1} + \Delta t$
Z	Ft-Datum	Equation B5, z
ZV	Ft-Datum	$(p/\gamma + Z)_r$
ZW	Ft-Datum	$Z_u - (1 + K_1 + K_2)V^2/2g$

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STATUS

35. The program is set up for 600-series time-sharing computer operation at the U. S. Army Engineer Waterways Experiment Station.

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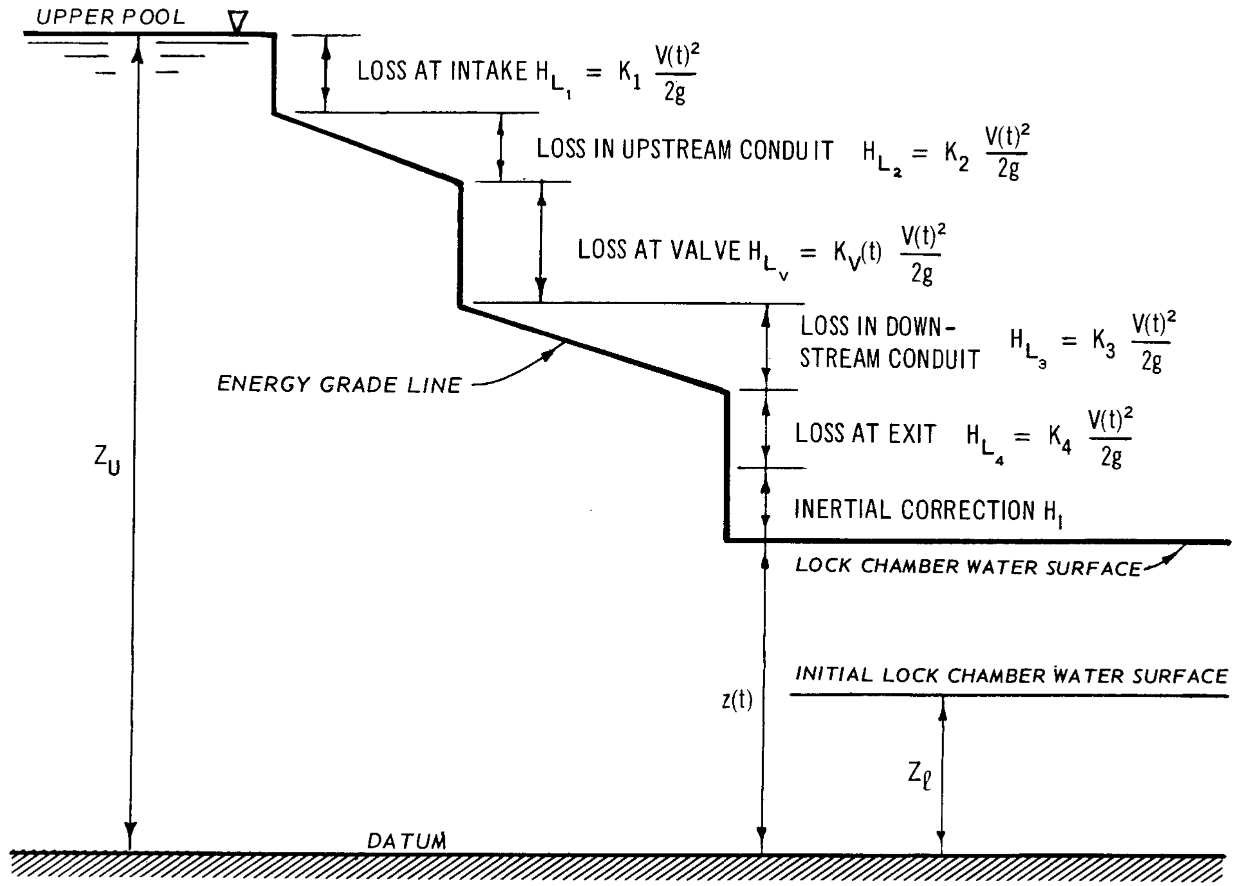
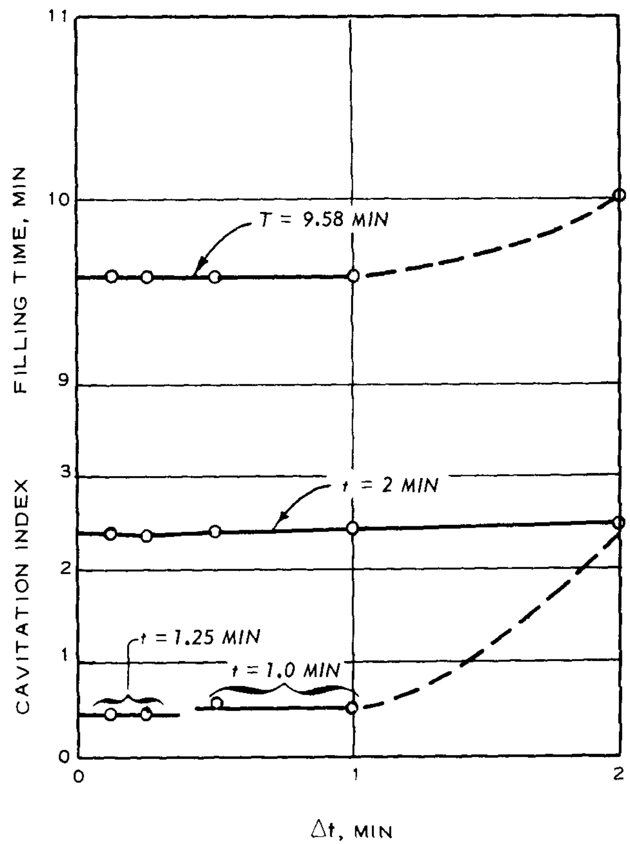
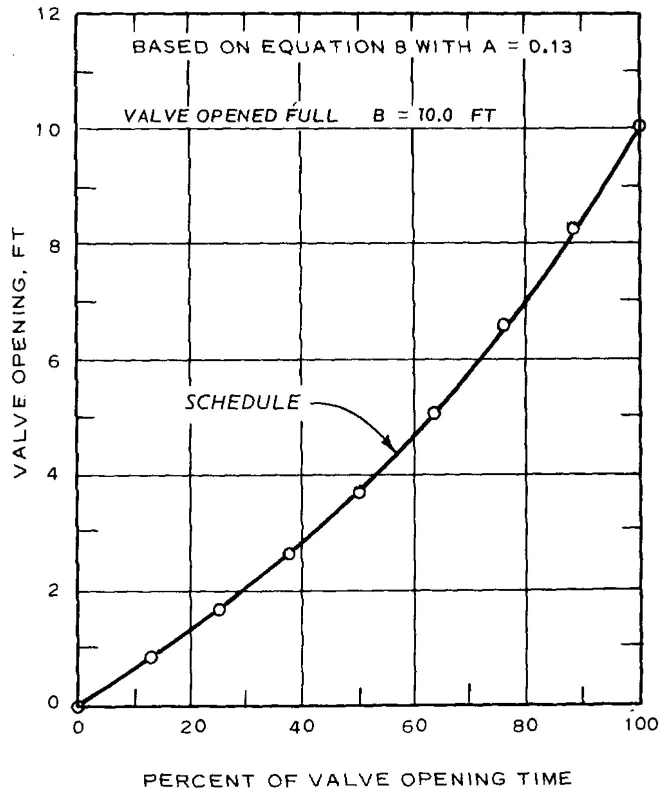


Figure B-1. Simulated flow conditions at time t



a.



b.

Figure B-2. Effect of time step size on accuracy (a) and valve opening pattern (b) at Millers Ferry Lock

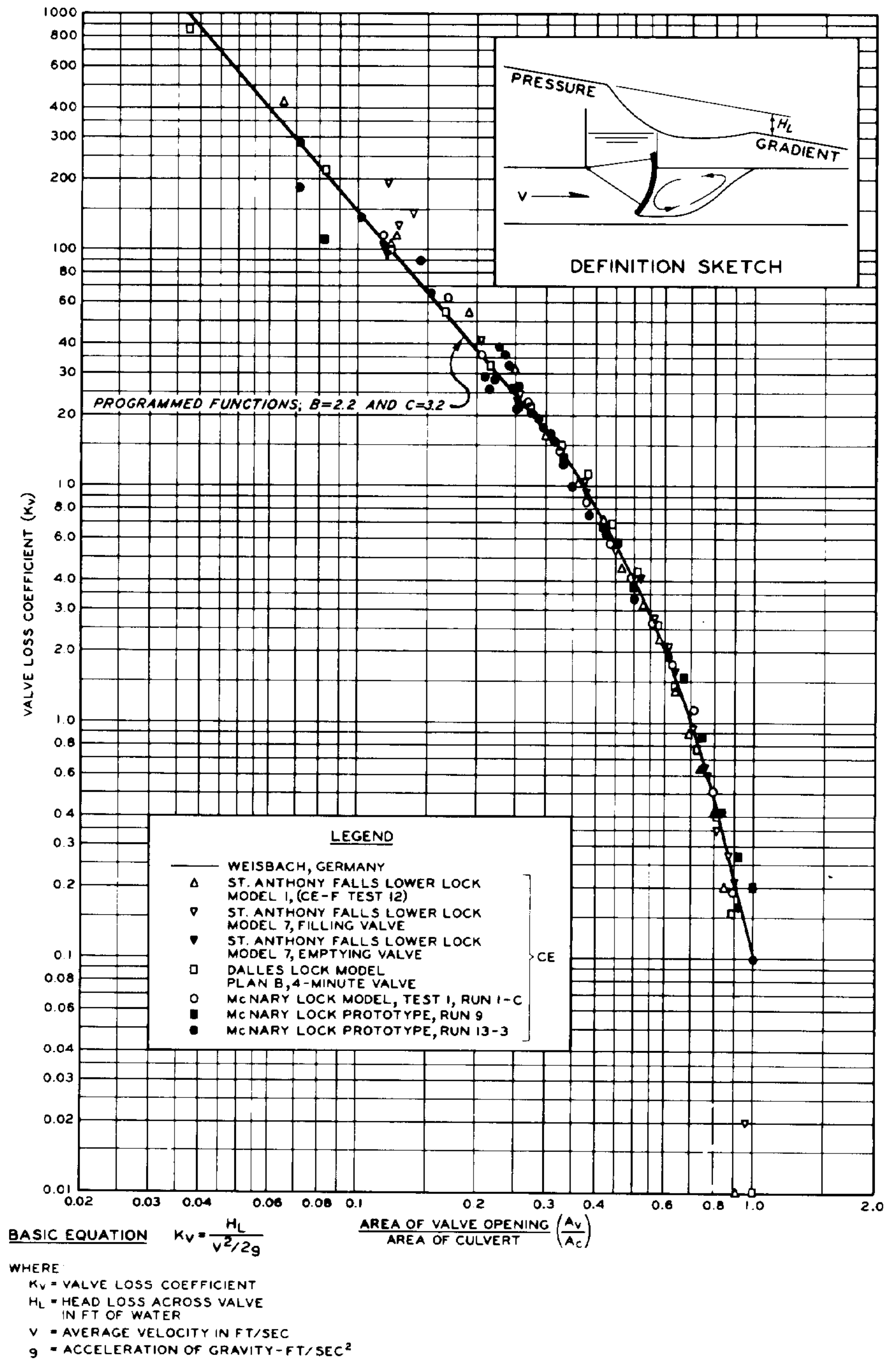


Figure B-3. Loss coefficient

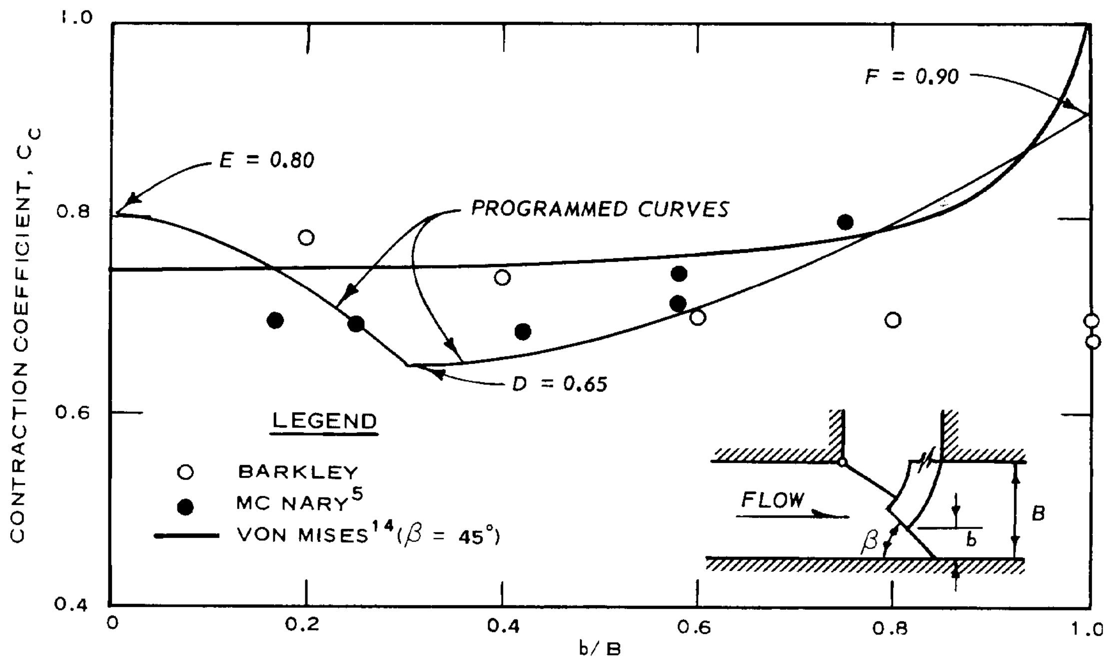


Figure B-4. Reverse tainter valve contraction coefficient