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STUDY OF INTAKE LAG IN CONVENTIONAL STREAM-GAGING STILLING WELLS

By

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ABSTRACT

This study investigated the relation between lag, or head loss (h_L), in a typical stilling-well intake system of a stream-gaging station and rate of change of stage ($\Delta H/\Delta t$) of the stream. The purpose of the study was to define such a relation in general terms and thus provide a rational procedure for intake design. The relation between head loss and rate of change of stage was determined by isolating the effects of the various components in the intake system, so that equations could be derived that enable one to compute the head loss in an intake system composed of any combination of these components. In the derivation of the equations steady-state flow conditions were assumed, and the components considered were those most commonly used in Geological Survey gaging stations--static tubes, 3-way steamcock valves, and side-outlet tees.

The method of analysis of intake lag as outlined in this report can be used in investigating many types of intake systems. Modification of the equations is necessary if they are applied to intake-systems that differ from those described herein.

INTRODUCTION

The typical Geological Survey gaging station consists of a float-operated water-stage recorder placed over a stilling well. The stilling well is usually connected to the stream by an intake system of one or more pipes, with a flushing system at the well end and so-called static tubes at the stream end. A true representation of fluctuations of the stream stage is sought, but differences between the water level in the stilling well and that of the stream frequently occur. During periods of rapid change of stage, levels in the stilling well lag behind those in the stream because of head loss in the intake system. This report deals only with the study of head loss in the intake system and does not include analysis of the more complicated problems of drawdown caused by the disturbance to flow created by the protruding end of the intake.

The magnitude of the head loss in the intake system, commonly referred to as intake lag, is a function of the rate of change of stage; the number, size, and components of the intakes; and the size of the stilling well. The purpose of this study is to define the magnitude of intake lag for a typical intake and well system and to isolate the effects of various components, thereby establishing relations which will be useful in the design of intake systems. Design criteria to be considered are the probable rate of change of stage for the stream under study, the allowable error in the recorded stage, and the size of stilling well to be used.

This investigation was made in the California district of the Water Resources Division, U.S. Geological Survey, as one of several small projects sponsored by the Hydrologic Studies Section, Surface Water Branch, Washington, D.C. These projects were intended to provide information for use in a new stream-gaging manual. The report was prepared under the immediate supervision of Walter Hofmann, district chief.

TEST PROGRAM

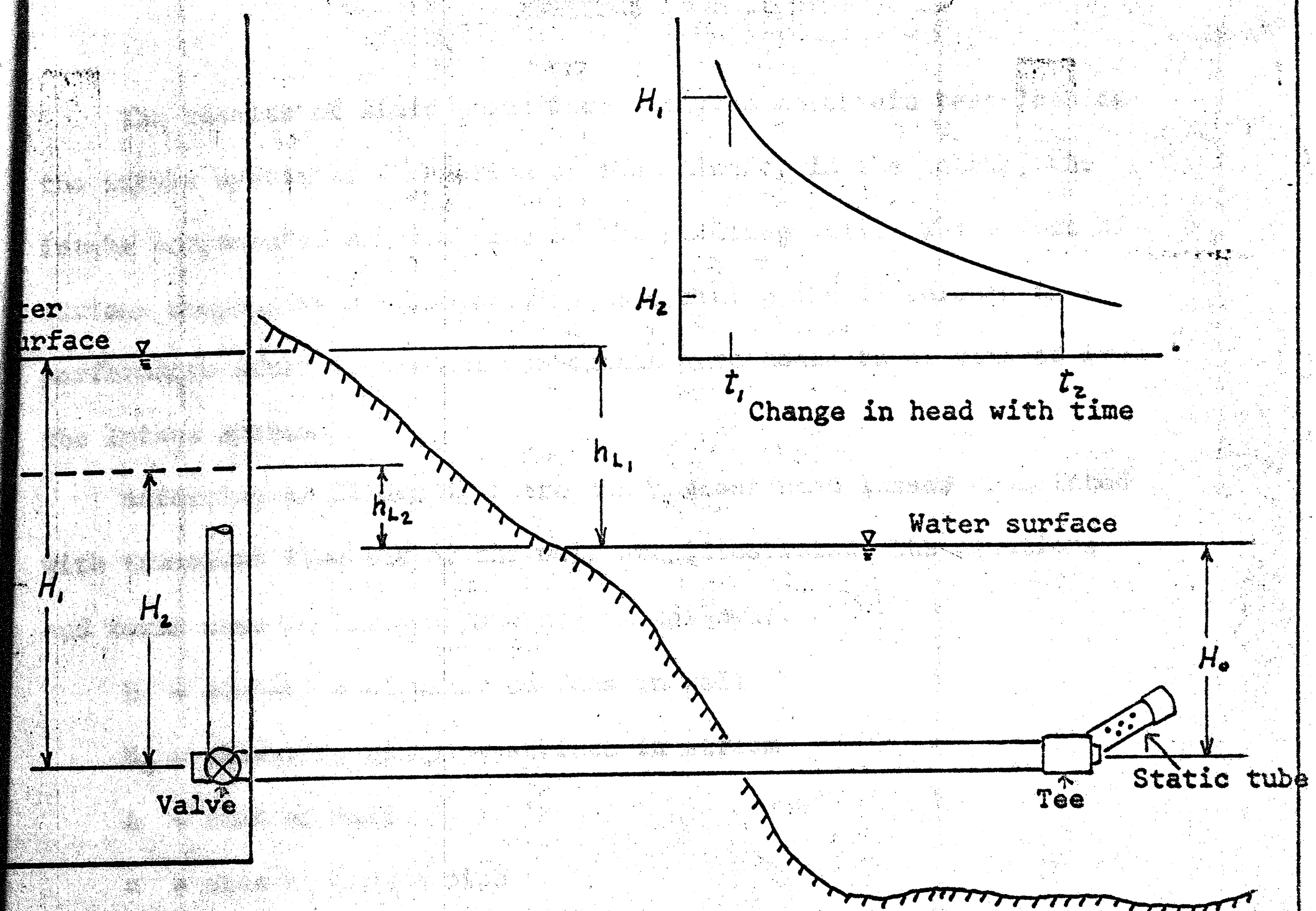
Equipment used in the test program consisted of a 48-inch corrugated-metal-pipe stilling well connected to the stream by an intake system, a Stevens A-35 water-stage recorder with an expanded time scale, and a portable pump.

The test procedure to duplicate conditions during falling stage was as follows:

1. Water was pumped into the well, with the intake closed until a head of 2 to 3 feet was attained.
2. The pump was shut off, the intake was opened, and the trace of head versus time, in the well, was recorded as the water flowed out through the intake.
3. Stream stage was recorded separately during the tests.

This same procedure was followed to duplicate rising stage, except that water was pumped out of the well until a sizable differential head was reached.

Tests were run in this manner with several lengths of intake pipe and several combinations of components--static tubes, steamcock valves, and tees. For example, in the initial test run an 8.7-foot length of 2-inch-diameter intake pipe was used, a 3-way steamcock valve was attached to the intake inside the well, and a side-outlet tee and static tube were attached to the outer end of the pipe. Additional tests were made by adding or removing various intake components, and using several combinations of these components--including various lengths of pipe. Figure 1 shows the head differential between the water surface in the well and that in the stream. Included in the figure is a curve illustrating the changes in head with time and the basic equations used to analyze the total head loss through the intake system.



BASIC EQUATIONS

$$h_L = H - H_o = K' \frac{v^2}{2g}$$

$$K' = K_o + K_v + K_P + K_{SOT} + K_{ST} + K_E$$

$$K' = \left(\frac{a}{A}\right)^2 \frac{g}{2} \left(\frac{t_2 - t_1}{h_{L1}^{1/2} - h_{L2}^{1/2}}\right)^2 \quad \text{where} \quad \begin{aligned} h_{L1} &= H_1 - H_o \\ h_{L2} &= H_2 - H_o \end{aligned}$$

Figure 1.-- Sketch of stilling well and the basic equations used to analyze total head loss in the intake system.

ANALYSIS

The results of field tests were analyzed to obtain head loss in the intake system as a function of the velocity in the intake, the intake components, and the size of the stilling well. The effect of various components was isolated by determining the difference in performance after individual components were added to or removed from the intake system.

Referring to figure 1, where the various head losses associated with transient flow out of the well are illustrated, the equations and terms used in the analysis are as follows:

H = elevation of water surface in well

H_o = elevation of water surface in stream

A = area of well

a = area of intake pipe

d = diameter of intake pipe

W = volume of water in well above the outside water-surface elevation

q = rate of flow out of well

and

t = time, in seconds.

Using this notation,

$$q = \frac{dW}{dt} = -Ch_L^{\frac{1}{2}} \qquad (1)$$

C is a constant and h_L is a head loss, $H - H_o$.

Then, substituting the relation

$$dW = Adh_L \tag{2}$$

in equation 1:

$$A\frac{dh_L}{dt} = -Ch_L^{\frac{1}{2}} \tag{3}$$

and

$$\frac{dh_L}{h_L^{\frac{1}{2}}} = \frac{-C}{A}dt \tag{4}$$

Integrating during the period $t_2 - t_1$,

$$\int_{h_{L1}}^{h_{L2}} \frac{dh_L}{h_L^{\frac{1}{2}}} = -\int_{t_1}^{t_2} \frac{C}{A}dt$$

which yields

$$2(h_{L2}^{\frac{1}{2}} - h_{L1}^{\frac{1}{2}}) = -\frac{C}{A}(t_2 - t_1) + C_1 \tag{5}$$

where C_1 = constant of integration.

Solving for C_1 when: $(t_2 - t_1)$ and $(h_{L2} - h_{L1})$ are both 0, $C_1 = 0$ and can, therefore, be dropped from equation 5.

Changing the directional axis and dropping the minus sign the following equation is developed:

$$C = \frac{2A(h_{L1}^{\frac{1}{2}} - h_{L2}^{\frac{1}{2}})}{(t_2 - t_1)} \tag{6}$$

Referring now to the intake system as a unit and considering the components illustrated in figure 2, at any given time head loss can be expressed by equation:

$$h_L = K' \frac{V^2}{2g} \tag{7}$$

where

$$K' = K_O + K_V + K_P + K_{SOT} + K_{ST} + K_E \tag{8}$$

and

K_O = 0.50(assumed) = entrance-loss coefficient

K_V = loss coefficient in 3-way steamcock valve

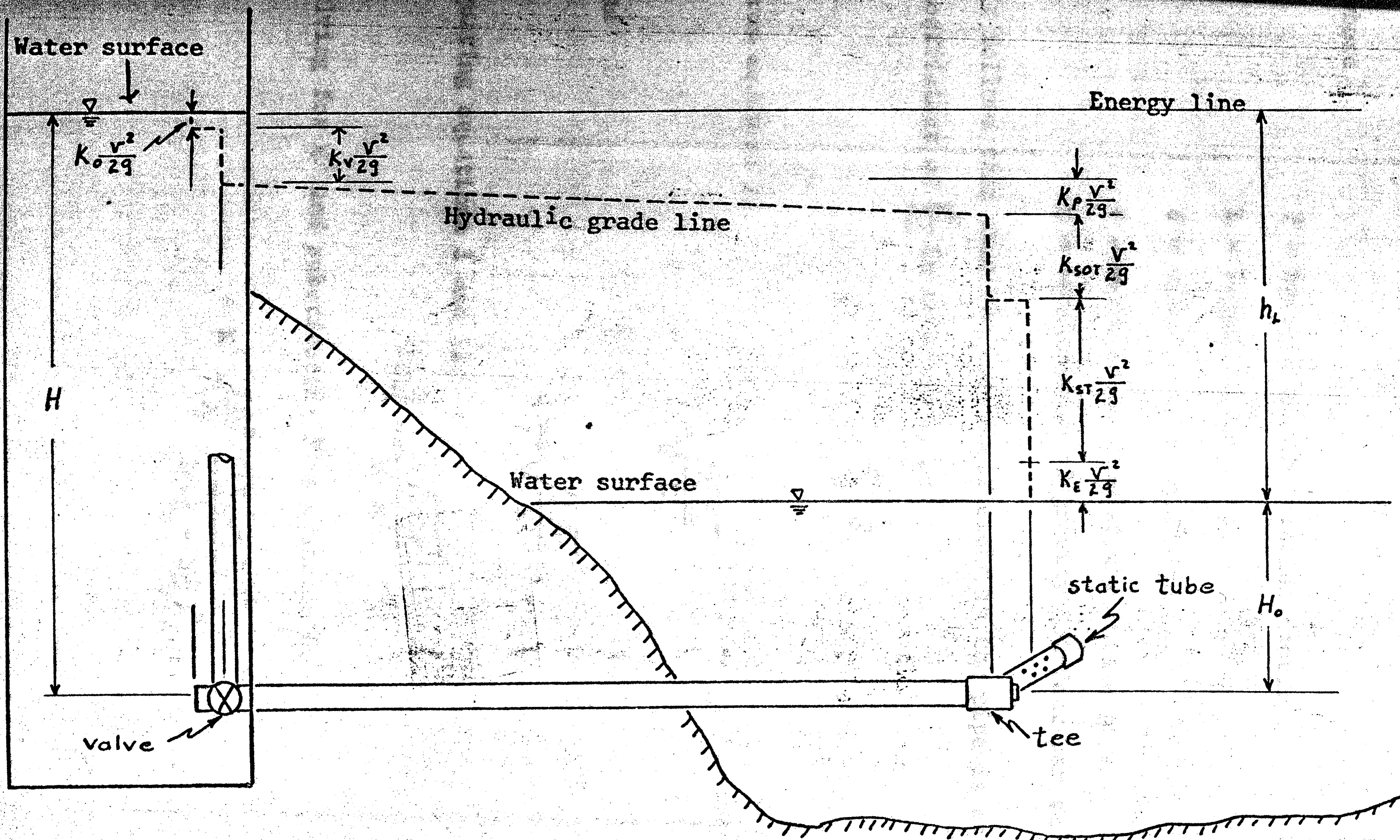
K_P = loss coefficient in pipe

K_{SOT} = loss coefficient in side-outlet tee

K_{ST} = loss coefficient in static tube

and

K_E = 1.0(assumed) = exit-loss coefficient.



$$h_L = \frac{V^2}{2g}\left(K_o + K_V + K_P + K_{SOT} + K_{ST} + K_E\right) = K' \frac{V^2}{2g}$$

Figure 2.-- Diagram of head loss in the intake system.

The head loss in the pipe (h_{Lp}) is usually computed by the Darcy-Weisbach equation:

$$h_{Lp} = f\frac{L}{d}\frac{V^2}{2g} \tag{9}$$

where

f = Darcy-Weisbach friction factor

L = length of intake pipe

d = diameter of intake pipe

V = velocity of flow in the intake pipe

g = acceleration of gravity (32 feet per second per second)

It follows then that the loss coefficient in the pipe is equal to the coefficient of $\frac{V^2}{2g}$ in equation 9, or

$$K_p = f\frac{L}{d} \tag{10}$$

From equation 7:

$$V = \sqrt{\frac{2gh_L}{K'}} \tag{11}$$

and

$$q = a\sqrt{\frac{2gh_L}{K'}} \tag{12}$$

Equating equations 1 and 12:

$$-Ch_L^{\frac{1}{2}} = a\sqrt{\frac{2gh_L}{K'}} \tag{13}$$

Solving for K' and substituting from equation 6:

$$K' = \left(\frac{a}{A}\right)^2 \frac{g(t_2 - t_1)^2}{2(h_{L_1}^{\frac{1}{2}} - h_{L_2}^{\frac{1}{2}})^2} \tag{14}$$

For the 48-inch-diameter well and the 2-inch-diameter galvanized intake pipe used in field tests, equation 14 can be evaluated:

$A = 12.830\ ft^2$ (based on average inside diameter of 48½ inches)

$a = 0.0233\ ft^2$

$$K' \equiv 5.310 \times 10^{-5} \frac{(t_2 - t_1)^2}{(h_{L_1}^{\frac{1}{2}} - h_{L_2}^{\frac{1}{2}})^2} \quad (15)$$

Assuming steady-state conditions over a short interval of time, Δt, equation 2 gives:

$$\frac{\Delta W}{\Delta t} = \frac{A \Delta h_L}{\Delta t} = aV$$

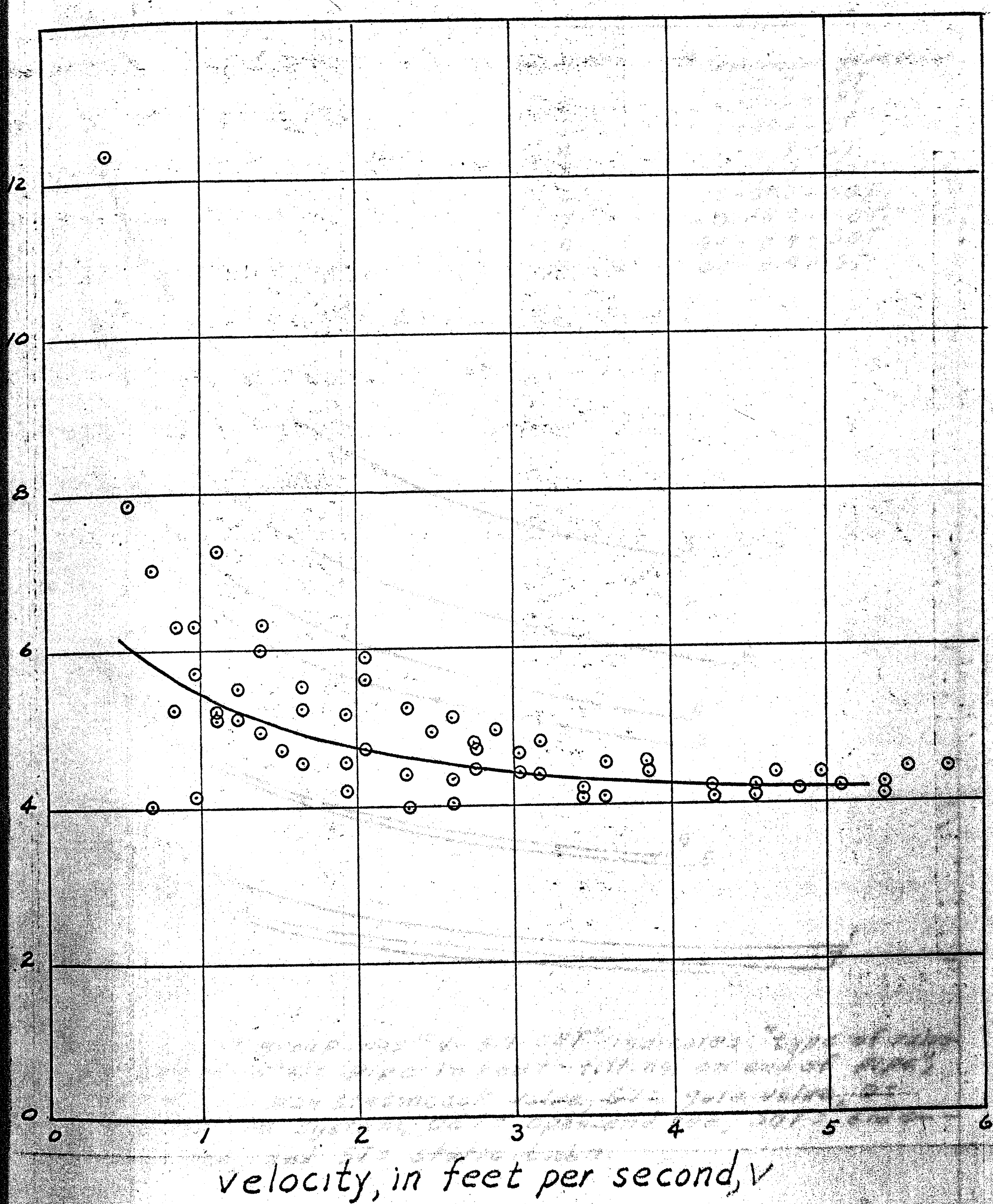
and

$$V = \frac{A}{a} \frac{\Delta h_L}{\Delta t} \quad (16)$$

For the 48-inch well and 2-inch intake, equation 16 reduces to:

$$V = 5.506 \times 10^2 \frac{\Delta h_L}{\Delta t} \quad (17)$$

Equations 15 and 17 were used to relate head losses in the system o the velocity of flow in the intake. As these equations are valid only ver incremental periods of time, the recorder trace of head (H) versus ime (t) was divided into short periods, and the corresponding values for ' and V were computed over these intervals. Figure 3 shows a typical urve of K' and V for a 2-inch-diameter intake equipped with a steamcock alve, an 8.7-foot pipe, and an open-end tee. Figure 4 shows a group of urves of K' and V for the nine intake-pipe systems investigated in this tudy. The description of the nine component groupings is shown on igure 4. The test results indicate no discernible differences in K' or flow into or out of the well, so results for each intake system ere therefore grouped together.



ure 3.--Typical curve relating K' to V for an intake, 2 inches in diameter and 8.7 feet long, equipped with a 3-way steamcock valve and open-end tee.

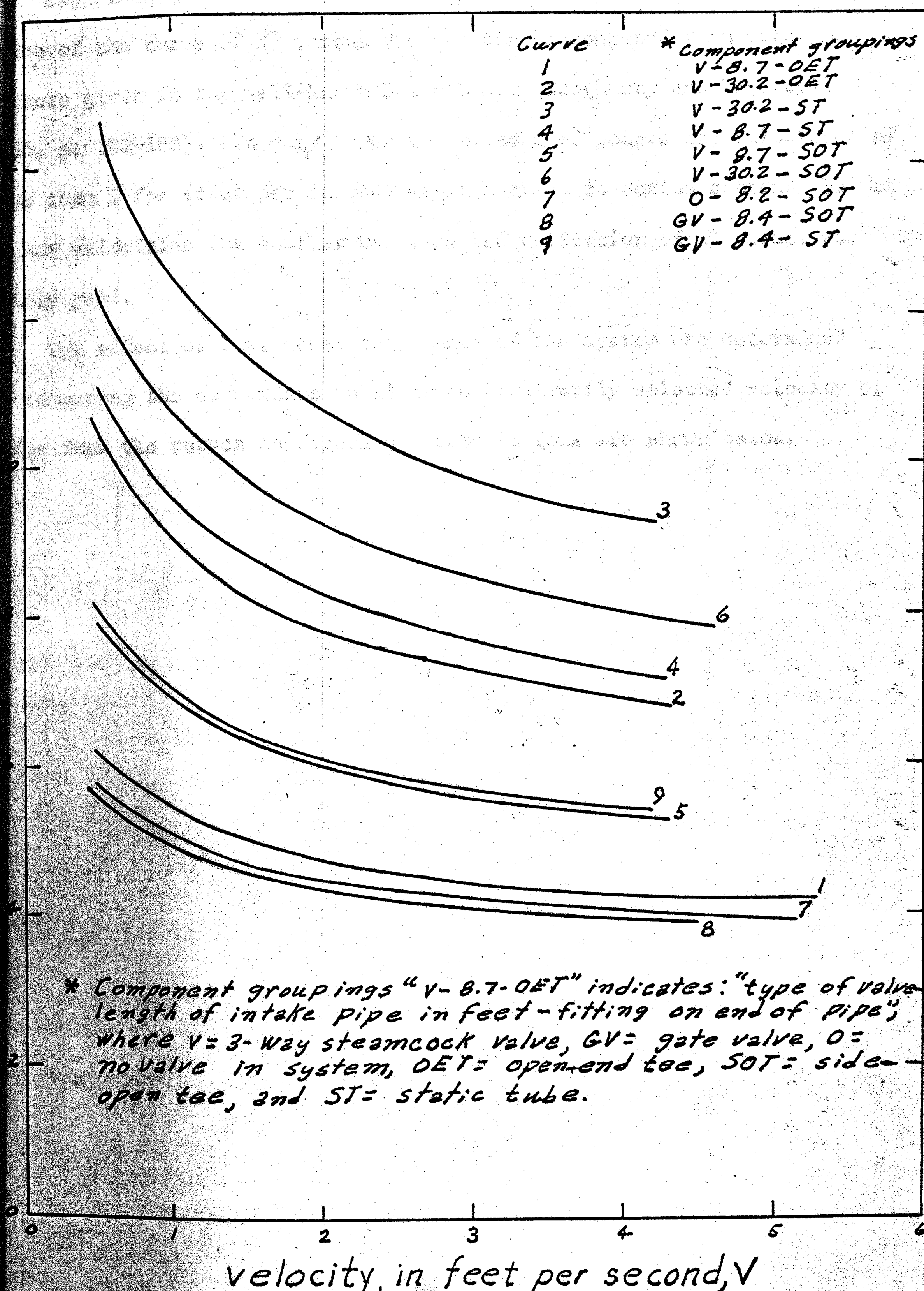


Figure 4.--Curves of K' versus V for the nine intake systems investigated.

Experimental data, as shown in figure 3, conform in general to the shape of the curve of K' versus V which can be computed from friction factors given in the well-known Moody Chart (Daugherty and Ingersoll, 1954, p. 182-183). In many cases the scatter of points for velocities of less than 3 fps (feet per second) was too great to define a trend, but at higher velocities the scatter was less and definition of K' values was fairly good.

The effect of individual components of the system was determined by computing the difference in K' at an arbitrarily selected velocity of 4 fps from the curves in figure 4. Computations are shown below.

I. Computation of pipe-loss coefficient (K_P):

Curve number (fig. 4)	K'	Component grouping (fig. 4)
2	6.85	V - 30.2 - OET
1	4.25	V - 8.7 - OET
	K_P = 2.60 for	21.5 feet of 2-inch pipe
3	9.30	V - 30.2 - ST
4	7.20	V - 8.7 - ST
	K_P = 2.10 for	21.5 feet of 2-inch pipe
6	8.00	V - 30.2 - SOT
5	5.30	V - 8.7 - SOT
	K_P = 2.70 for	21.5 feet of 2-inch pipe
Average	$K_P = \frac{2.60+2.10+2.70}{3} = 2.47$ for	21.5 feet of 2-inch pipe

II. Computation of pipe friction factor (f):

From equation 10,

$$f = K_P \frac{d}{L}$$

Therefore,

$$f = 2.47 \frac{0.172}{21.5} = 0.020$$

Thus the experimental data indicate that this 2-inch pipe, carrying flow at a mean velocity of 4 fps, has a friction factor of 0.020. The Moody Chart shows f = 0.028 with an ϵ/d (relative roughness) ratio of 0.0030 (Daugherty and Ingersoll 1954, p. 182-183), a mean velocity of 4 fps, and a pipe diameter of 2 inches (Vd = 8.0). The difference between Moody's f and the experimental value of f, 0.020, may represent experimental error or it may be due to silt lining the intake pipe. The silt could conceivably form a smooth uniform surface on the inside of the pipe, thereby reducing the friction factor. Smooth pipe conditions, with f equaling 0.020, have been assumed for all subsequent computations of head loss in the intake.

III. Computation of loss coefficient in the side-open tee (K_{SOT}):

Curve number (fig. 4)	K'	Component grouping (fig. 4)
5	5.30	V - 8.7 - SOT
1	4.25	V - 8.7 - OET
K_{SOT} =	1.05	
6	8.00	V - 30.2 - SOT
2	6.85	V - 30.2 - OET
K_{SOT} =	1.15	

$$\text{Average } K_{SOT} = \frac{1.05 + 1.15}{2} = 1.10$$

IV. Computation of loss coefficient in static tube (K_{ST}):

Curve number (fig. 4)	K''	Component grouping (fig. 4)
3	9.30	V - 30.2 - ST
6	8.00	V - 30.2 - SOT
	K_{ST} = 1.30	
4	7.20	V - 8.7 - ST
5	5.30	V - 8.7 - SOT
	K_{ST} = 1.90	
9	5.40	GV - 8.4 - ST
8	3.90	GV - 8.4 - SOT
	K_{ST} = 1.50	

$$\text{Average } K_{ST} = \frac{1.30 + 1.90 + 1.50}{3} = 1.57$$

V. Computation of loss coefficient in valves:

A. Three-way steamcock valve (K_V).

This computation is based on the summation of loss coefficients in the intake system,

$$K_V = K' - (K_O + K_P + K_{SOT} + K_{ST} + K_E) = K' - \Sigma K.$$

From computation of pipe-loss coefficient (I.)

$K_P = 2.47$ for 21.5 feet of 2-inch pipe.

Similarly,

$$K_P = 2.47 \frac{8.7}{21.5} = 1.00 \text{ for 8.7 feet of 2-inch pipe}$$

and

$$K_P = 2.47 \frac{30.2}{21.5} = 3.47 \text{ for 30.2 feet of 2-inch pipe.}$$

From computations III. and IV.,

$K_{SOT} = 1.10$

and

$K_{ST} = 1.57.$

Therefore, computation of K_V for the 3-way valve assumes this form:

Curve number (fig. 4)	K'	Component grouping (fig. 4)	K_O	K_P	K_{SOT}	K_{ST}	K_E	ΣK	K_V
1	4.25	V - 8.7 - OET	0.5	1.00	0	0	1.00	2.50	1.75
2	6.85	V - 30.2 - OET	.5	3.47	0	0	1.00	4.97	1.88
3	9.30	V - 30.2 - ST	.5	3.47	1.10	1.57	1.00	7.65	1.66
4	7.20	V - 8.7 - ST	.5	1.00	1.10	1.57	1.00	5.17	2.03
5	5.30	V - 8.7 - SOT	.5	1.00	1.10	0	1.00	3.60	1.70
6	8.00	V - 30.2 - SOT	.5	3.47	1.10	0	1.00	6.07	1.93
							Average		1.82

B. Gate valve (K_{GV}).

Curve number (fig. 4)	K'	Component grouping (fig. 4)
8	3.90	GV - 8.4 - SOT
7	4.00	0 - 8.2 - SOT
K_{GV} = -0.10		

This result, indicating that the addition of a gate valve decreases flow resistance, is paradoxical. The apparent inconsistency arises from the fact that the effect of adding the gate valve to the overall system is too slight to be defined, within the precision of the study.

Loss coefficients for the components investigated in this study are summarized in the following table.

Intake component	Average loss coefficient (K)
3-way steamcock valve	1.82
Gate valve[1]	(a)
Side-outlet tee	1.10
Static tube	1.57

[1]Gate valve replaced 3-way steamcock valve for this determination.

a. Negligible.

Based on these results an equation can be derived for head loss in a typical intake system equipped with a 3-way steamcock valve, a side-outlet tee, and a static tube. From equations 7, 8, and 10:

$$h_L = (K_O + K_V + f\frac{L}{d} + K_{SOT} + K_{ST} + K_E)\frac{V^2}{2g} \qquad (18)$$

Substituting the several computed values of K:

$$h_L = (5.99 + f\frac{L}{d})\frac{V^2}{2g} \qquad (19)$$

DESIGN COMPUTATIONS

The magnitude of lag (h_L) for 2-inch intakes with static tubes, tee couplings, and 3-way valves can be computed as a function of the rate of change of stage ($\Delta H/\Delta t$) using equation 19, if the size of the stilling well and the roughness, length, and number of intake pipes are known. This computation is predicated on the assumption of steady-state flow conditions in the intake system, where the water level in the well lags behind the level in the stream by a constant amount, during a period when the stage is changing. Thus, h_L is constant and $\Delta H/\Delta t$ inside the well is equal to $\Delta H/\Delta t$ in the stream.

Application of equation 19 requires that velocities in each intake pipe be assumed so that friction factors can be computed from the Moody Chart. Since values of h_L can be computed as a function of V and, for n intakes, $q = a_1 V_1 + a_2 V_2 + \cdots a_n V_n = \frac{\Delta H}{\Delta t} A$, the relation between h_L and $\Delta H/\Delta t$ can be obtained. Computation steps required for n intakes of equal diameter are summarized below:

Given:

(a) Cross-sectional area of well, in square feet = A

(b) Number of intake pipes = n

(c) Length of each intake pipe, in feet: L_1, L_2 -- L_n

(d) Diameter of intake pipes, in feet: d_1, d_2, -- d_n

1. Assume velocity of flow in pipe (V), in feet per second.

2. Determine the friction factor, *f*, from the Moody Chart (Daugherty and Ingersoll, 1954, p. 182), after first obtaining the roughness factor (ϵ) from a standard graph of roughness factors for commercial pipes (for example, Daugherty and Ingersoll, 1954, fig. 8.9, p. 183).

3. Compute h_L for each pipe from equation

$$h_L = \frac{V^2}{2g} (5.99 + f\ L/d).$$

4. Repeat steps 1-3 for several selected values of V.

5. Plot curve of h_L versus V for each pipe.

6. Assume h_L.

7. From curve of h_L versus V (step 5), pick off V_1, V_2, --- V_n for assumed h_L.

8. Determine total discharge through intakes: $q = a_1V_1 + a_2V_2 + \text{---} a_nV_n$.

9. Compute rate of change of stage in well, in feet per hour:

$$\frac{\Delta H}{\Delta t} = \frac{q}{A} (3{,}600)$$

10. Repeat steps 6-9 for several selected values of h_L.

11. Plot curve of h_L versus $\frac{\Delta H}{\Delta t}$.

Figures 5 and 6 illustrate the design computations. The computation procedures are summarized in the table below for a well and intake system given the following values:

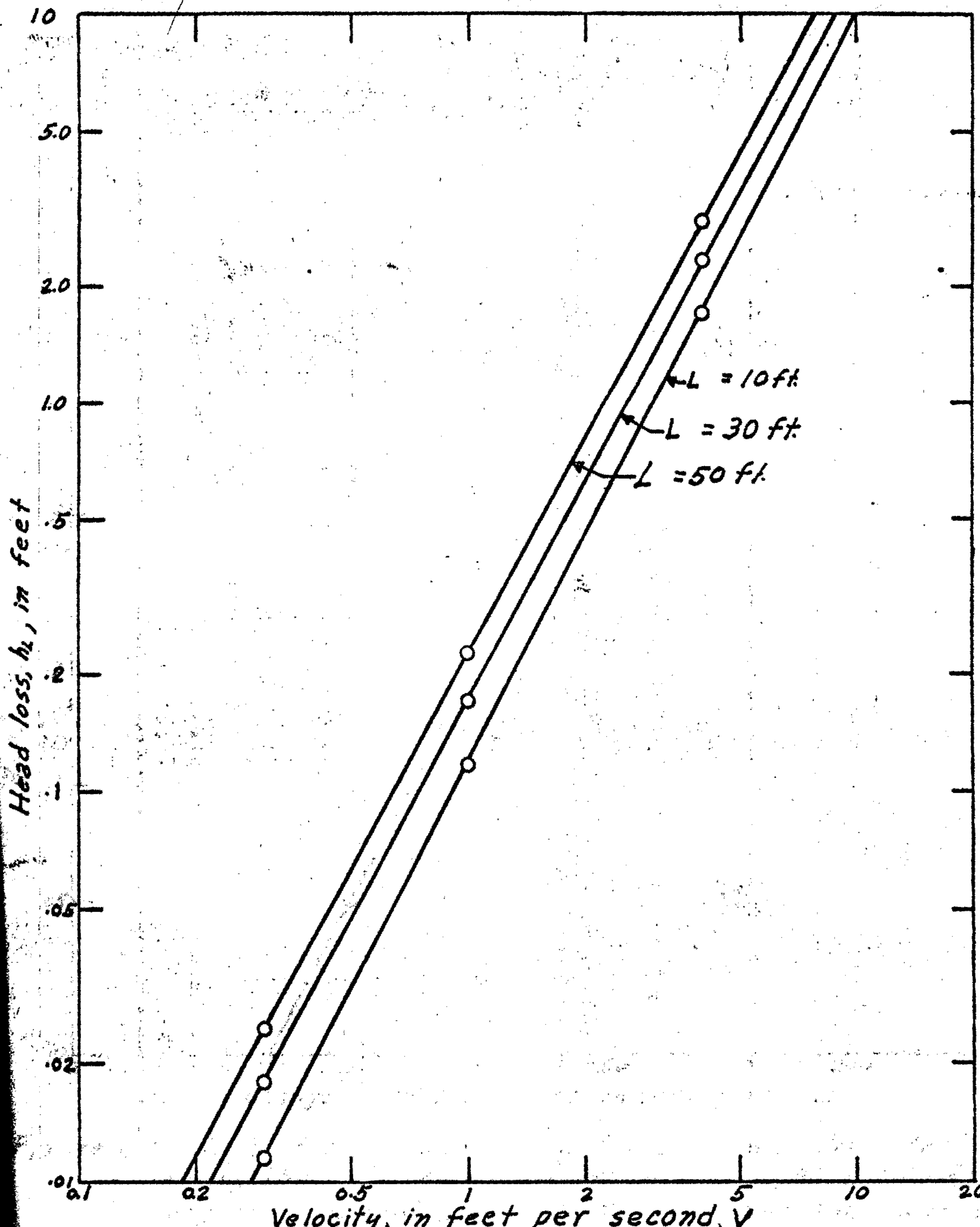


Figure 5.-- Curves of h_L versus V for a 48-inch-diameter well having three 2-inch-diameter intakes 10, 30, and 50 feet long, and each equipped with a 3-way steamcock valve and a static tube.

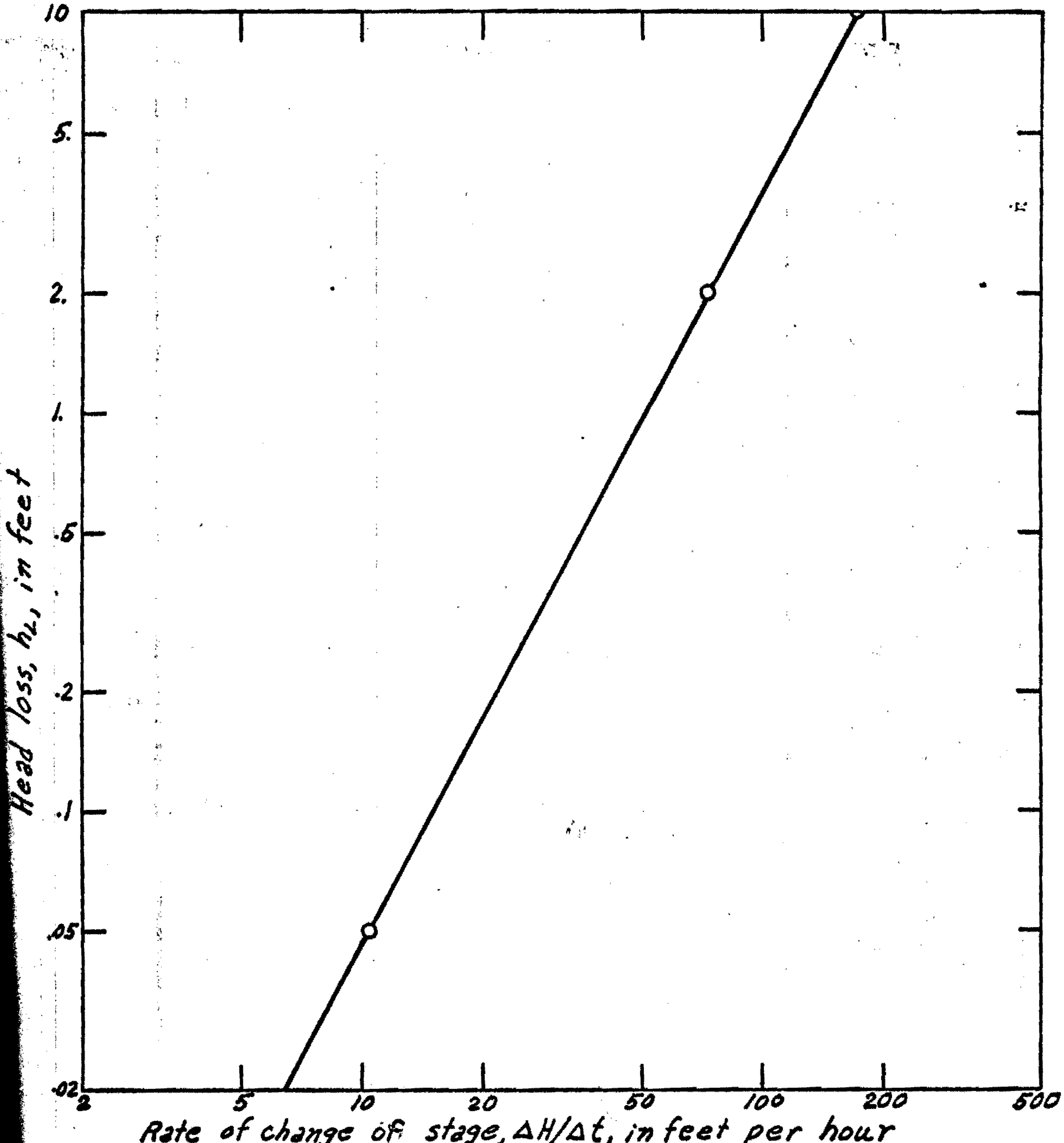


Figure 6.--Curves of h_L versus $\Delta H/\Delta t$ for a 48-inch-diameter well having three 2-inch-diameter intakes 10, 30, and 50 feet long, and equipped with a 3-way steamcock valve and a static tube.

If the intakes are of equal length and diameter, equation 19 can be modified and the computation procedure reduced to a 3-step operation:

$$V_1 = V_2 = V_n = V$$

$$q = naV$$

$$\frac{\Delta H}{\Delta t} = \frac{q}{A} = n\left(\frac{a}{A}\right)V$$

or

$$V = \frac{A}{a}\,\frac{1}{n}\,\frac{\Delta H}{\Delta t}. \qquad (20)$$

Substituting in equation 19

$$h_L = \frac{\left[\frac{A}{a}\,\frac{1}{n}\,\frac{\Delta H}{\Delta t}\right]^2}{2g}\,(5.99 + fL/d). \qquad (21)$$

For a given rate of change of stage, V in equation 20 must be evaluated so that the friction factor (f) can be picked from the Moody Chart for use in calculating h_L in equations 19 or 21. The curves shown in figures 7 and 8 were computed in this manner.

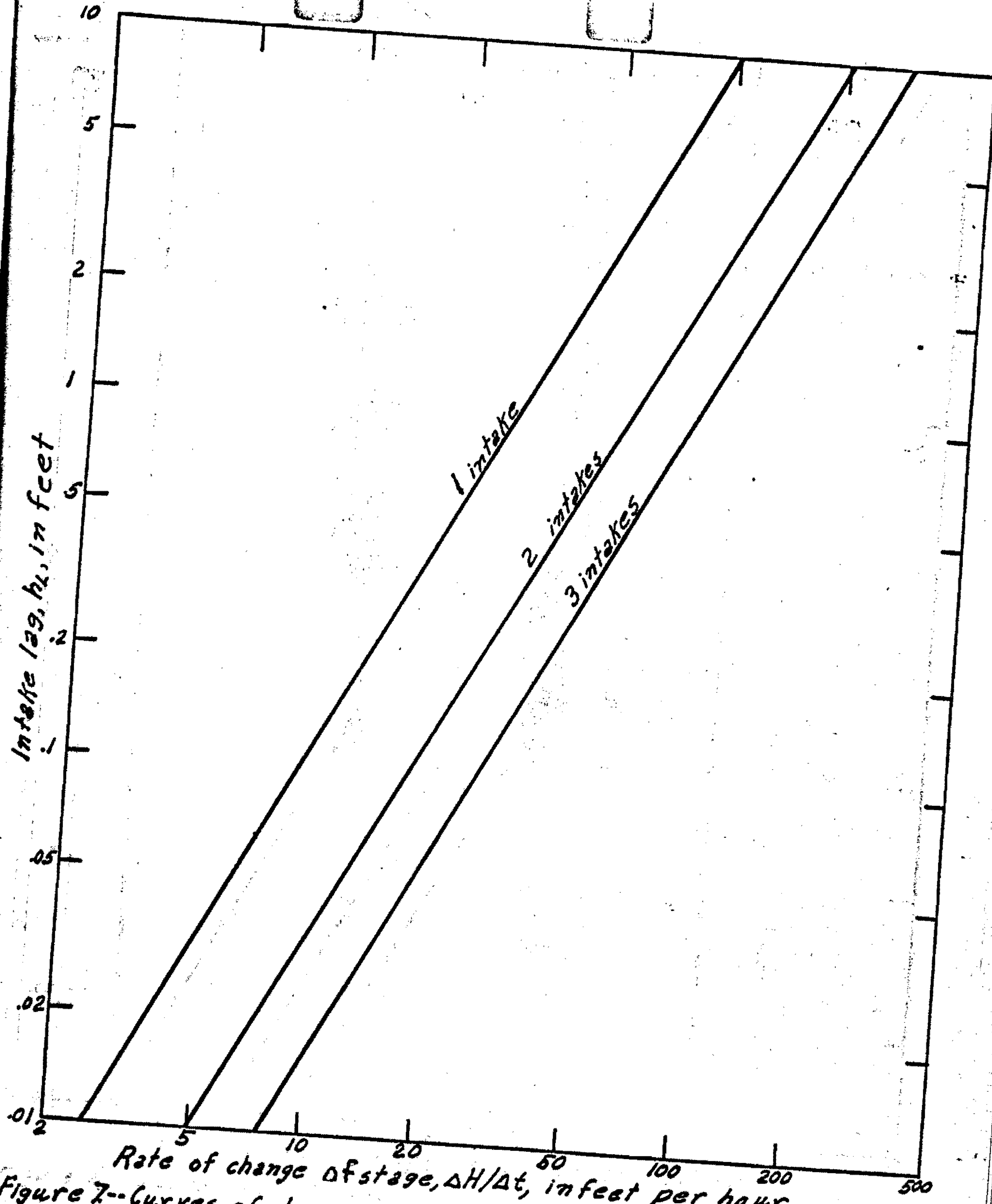


Figure 7--Curves of h_L versus $\Delta H/\Delta t$ for a 36-inch-diameter well having 1, 2, and 3 two-inch-diameter intakes, each 30 feet long and equipped with a 3-way steamcock valve and a static tube.

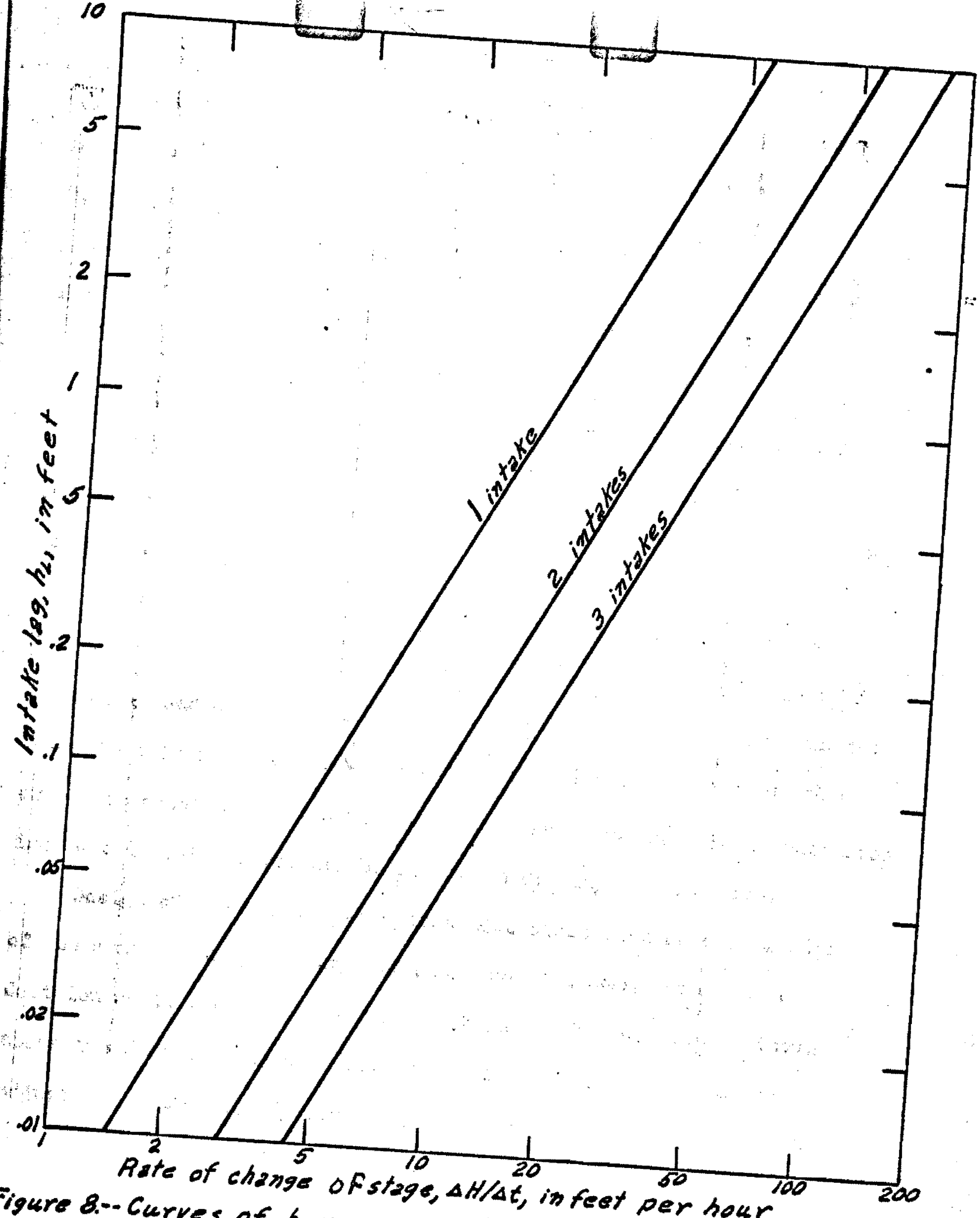


Figure 8.--Curves of h_L versus ΔH/Δt for a 48-inch-diameter well having 1, 2, and 3 two-inch-diameter intakes, each 30 feet long and equipped with a 3-way steamcock valve and a static tube.

CONCLUSION

Equation 21 shows that, if we ignore the variation of *f* with velocity, the intake lag for a given rate of change of stage varies inversely with the square of the number of intakes used and in direct proportion to the square of the ratio of well area to intake area. Thus intake lag for a given well would be reduced by a factor of 4 if 2 intakes were used instead of 1, and by a factor of 9 if 3 intakes were used. Similarly the lag is increased by a factor of about 3 when well size is increased from a 3-foot diameter to a 4-foot diameter. These approximate ratios can be verified by examination of the curves in figures 7 and 8.

It should be emphasized that equation 19 applies to the standard Geological Survey stilling-well intake system which includes 3-way steamcocks and static tubes. Where static tubes and tees are omitted from the intake system or where flush-mounted intakes or gate valves are used, equation 19 must be modified. Data and analytical procedures included in this report can be used in modifying the equation.

Design of a given intake system must start with some knowledge of the maximum rate of change of stage to be accommodated and a decision as to the magnitude of lag which can be tolerated. Given these two factors, the well size and intake requirements can be adjusted so that satisfactory stage recording can be accomplished.

SYMBOLS

a	Area of intake pipe
A	Cross-sectional area of well
C	Constant
d	Diameter of intake pipe
f	Darcy-Weisbach friction factor
g	Acceleration of gravity
h_L	Head loss
H	Elevation of water surface in well
H_o	Elevation of water surface in stream
K	Loss coefficient
K'	Total loss coefficient
K_E	Exit-loss coefficient
K_{GV}	Loss coefficient in gate valve
K_O	Entrance-loss coefficient
K_P	Loss coefficient in pipe
K_{SOT}	Loss coefficient in side-outlet tee
K_{ST}	Loss coefficient in static tube
K_V	Loss coefficient in 3-way steamcock valve
L	Length of intake pipe
n	Number of intake pipes
q	Rate of flow out of well
t	Time
V	Velocity of flow in the intake pipe
W	Volume of water in well above the outside water-surface elevation

REFERENCE

Daugherty, R. L., and Ingersoll, A. C., 1954, Fluid Mechanics: New York, McGraw-Hill, 472 p.