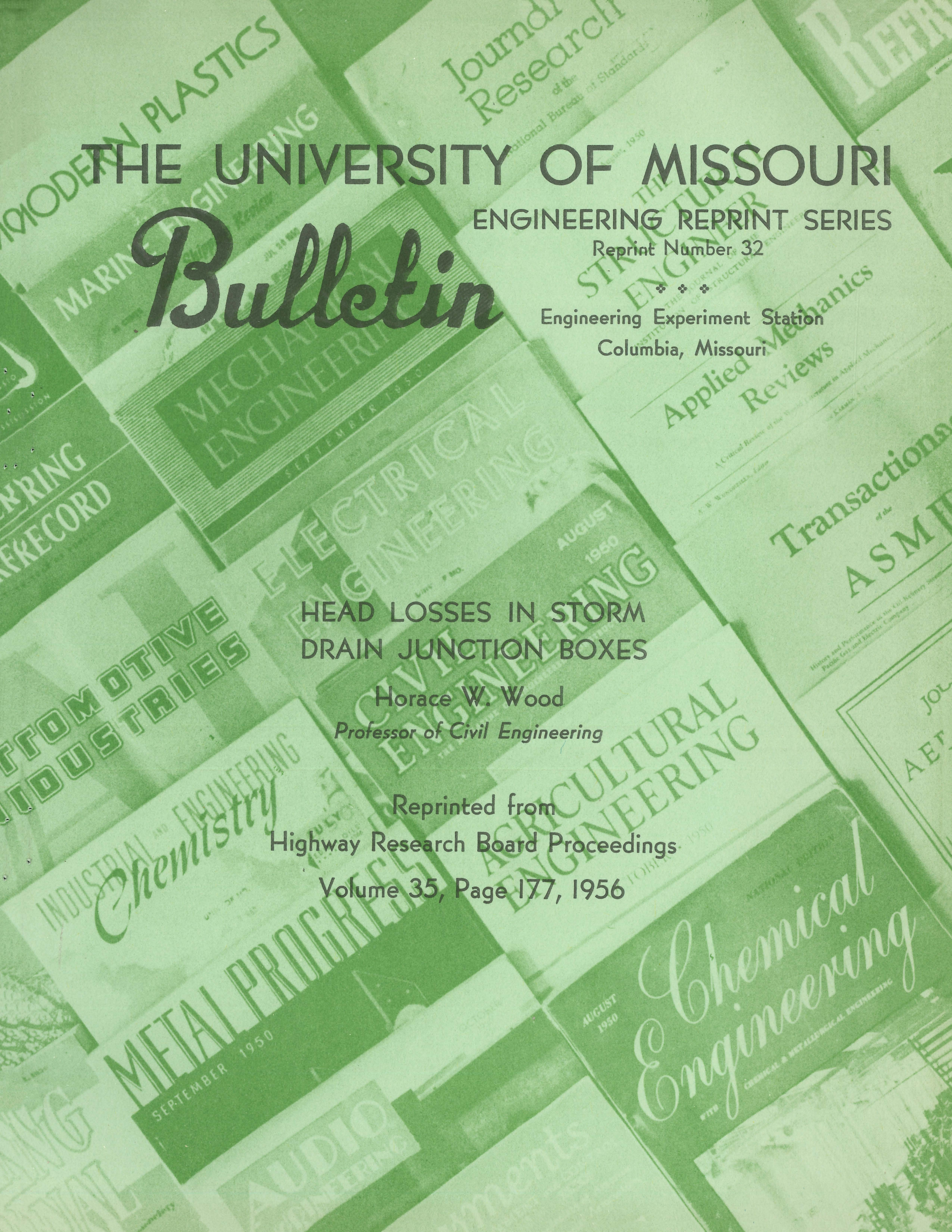

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HEAD LOSSES IN STORM DRAIN JUNCTION BOXES

Horace W. Wood
Professor of Civil Engineering

Reprinted from
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Head Losses in Storm Drain Junction Boxes

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The paper outlines results of model studies of a junction box designed primarily for urban highway storm drains. Only full-flowing pipes are included. Loss coefficients are derived from consideration of total head loss across the junction box for straight-through flow, for flow from a 90° lateral, and for combining flow from both directions, using various combinations of pipe sizes and flow rates. An example illustrates the use of the loss coefficient charts. The study also recognizes certain advantages in direct use of pressure losses. Close correlation is found between pressure loss and momentum change for straight-through flow, but the method has not yet been perfected for lateral and mixed flow.

● IN the spring of 1953 an investigation was instituted at the University of Missouri in Columbia for the purpose of obtaining accurate information on head losses occurring in junction boxes used in highway drainage structures. The work was undertaken by the Engineering Experiment Station under the sponsorship of the Missouri State Highway Department in cooperation with the U. S. Bureau of Public Roads.

Although the investigation is still in progress, it is believed that certain information has been developed that may be of value if released at this time. This paper will, therefore, relate only findings which have been well established. It will deal with scale model studies, simulating a standard type junction box.

OBJECTIVES

The standard junction box which was selected for investigation is one widely used by the Missouri State Highway Department. It measures 2 feet across in the direction of traffic and averages 5 feet in the transverse direction. The box varies in depth and is provided with a drop inlet grate. The first objective has been to determine head loss resulting from flow across the junction box without any flow entering through the top grate. The box may receive water from one or two inlet pipes and discharges through a single outlet. Later tests will determine the effect of surface drainage entering through the grate.

The flow problem under consideration here is restricted to pipes flowing full as a result of some downstream condition. Under such conditions, a knowledge of the head loss across the junction becomes important since overflow of the box should be avoided.

The ultimate objective is to determine a satisfactory method, supported by laboratory data, for anticipating the level of water in a submerged junction box.

APPARATUS

A 1:4 model scale was chosen since this was the largest scale feasible with the laboratory facilities at hand and with model materials available in the market. Flow rates are measured by means of calibrated venturi and orifice meters.

The model was constructed of ⅜-inch Plexiglas plates (Figure 1) and several sizes of Lucite tubing fitted with flanges to facilitate the interchange of pipes of the various sizes (Figure 2). Since the tubing is manufactured to standard outside dimensions, it is not possible to obtain stock tubing in dimensions exactly corresponding to all commercial pipe sizes. Four inside diameters were selected. These were 3.00, 3.75, 4.75, and 5.72 inches. These sizes correspond to prototype dimensions of 12, 15, 19, and 22.9 inches, respectively. By making use of dimensionless ratios, the results can be applied to 12, 15, 18, 21, and 24-inch standard pipe sizes in any usual size combinations.

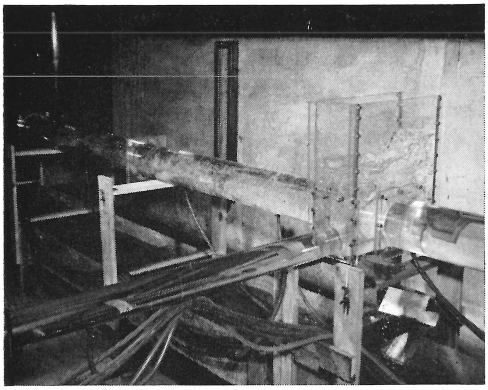

Figure 1. Plastic model junction box and tubing.

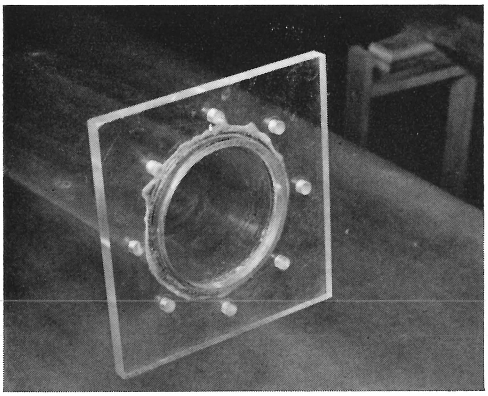

Figure 2. Plastic coupling flange cemented to tubing.

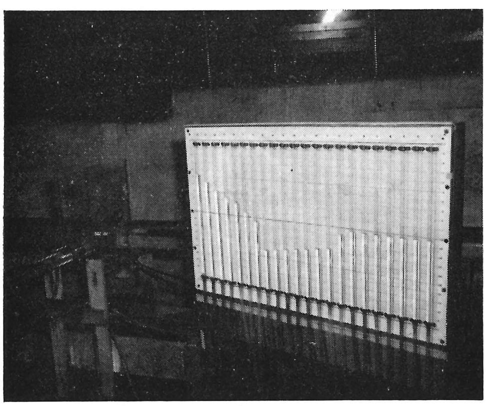

Figure 3. Manometer battery for indicating pressures.

The piezometric head line is determined with a battery of open manometers connected with pressure stations on the flow line by means of flexible plastic tubing

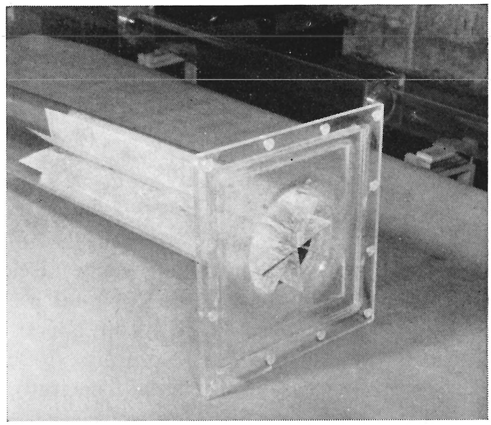

Figure 4. Rounded flange and straightening vane for header box connection.

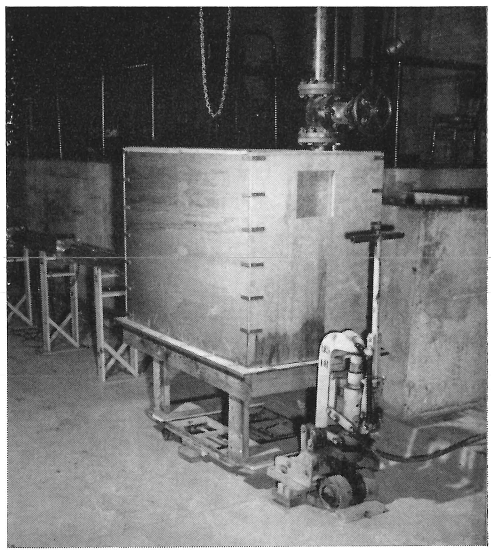

Figure 5. Hydraulic jack and adjustable supports.

(Figure 3). Tests indicated that length-to-diameter ratios not less than about 40:1 are desirable for the flow lines.

Water enters the inflow lines through well-rounded entrances from header boxes fitted with copper screen baffles and straightening vanes (Figure 4). Provision is made for adjustment of box and pipe elevations as pipe sizes are changed (Figure 5). For convenience in changing pipe sizes, all pipes are fitted to the junction box in such manner that the flow lines are flush with the floor of the box. A plastic gate box is provided at the downstream end of the outfall pipe for the purpose of con-

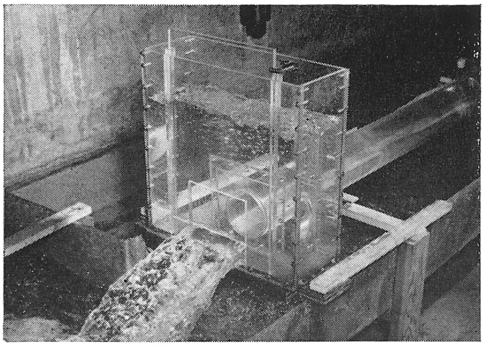

Figure 6. Gate box for controlling submergence.

trolling backwater pressure and submergence in the junction box (Figure 6).

NOTATION

D_1 = diameter of upstream main inlet pipe.
D_2 = diameter of downstream outlet pipe.
D_3 = diameter of upstream lateral inlet pipe.
Q = discharge in gpm or cfs.
H = loss of total head across junction box.
h = loss of pressure head across junction box.
K = energy loss coefficient.
K' = pressure loss coefficient.
V = average velocity at a pipe cross section.
g = acceleration of gravity.
b = width of box in direction of outlet pipe.
e = protrusion of outlet pipe into box.
F = the Froude number.
y = depth of water in the junction box.

ANALYSIS

At the outset of the investigation the factors which seemed to be of primary importance included: (1) the rate of flow in the pipe supplying the junction box, Q; (2) the diameter of the inlet pipe, D_1; (3) the diameter of the outlet pipe, D_2; (4) the depth of the water in the junction box (hereinafter termed submergence), y; (5) the loss of total head through the box, H_1; (6) the length of protrusion of the outlet pipe into the box, e; and (7) the acceleration of gravity, g. The roughness of the box and possibility of its influence on the loss are recognized but were not investigated. Preliminary tests showed that the amount of submergence, y, is related to the downstream conditions in the outlet pipe and does not influence the loss across the box unless the submergence is very low.

A dimensional analysis includes seven variables (Q, g, D_1, D_2, b, e, H_1), all kinematic in dimension. The term Q may be replaced with a velocity term V_2. Then

$$f\left(\frac{V_2^2}{gD_2}, \frac{D_1}{D_2}, \frac{b}{D_2}, \frac{e}{D_2}, \frac{H_1}{D_2}\right) = 0 \quad (1)$$

The Froude number F may be expressed as $V_2^2/2g$ and the dimensionless term containing H_1 may be expressed as the loss coefficient

$$K_1 = \frac{H_1}{V_2^2/2g}$$

$$K_1 = \phi\left(F, \frac{D_1}{D_2}, \frac{b}{D_2}, \frac{H_1}{D^2}\right) \quad (2)$$

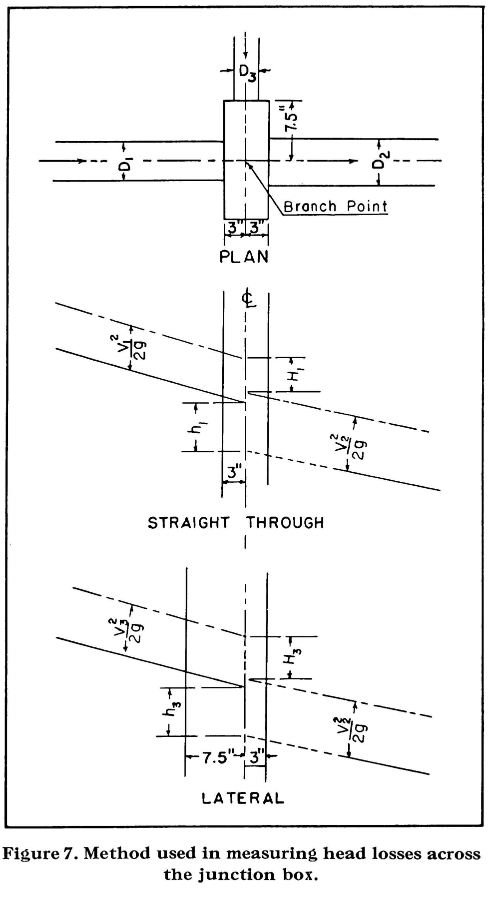

Figure 7. Method used in measuring head losses across the junction box.

In the laboratory investigation the effects of these four parameters were investigated.

Introduction of inflow supplied by a third pipe of diameter D_3 entering the junction box at 90 degrees with the outlet pipe introduces an additional parameter, D_3/D_2, and a head loss term $(H_3/V_2^2/2g)$.

Loss of Total Head

The loss across the junction box might be expressed as either a loss of total head H or a loss of pressure head h involving a change in momentum.

When the flow is combining across the junction box, the head loss is measured as indicated in Figure 7. The total head loss coefficient may be computed as follows:

$$H_1 + \frac{V_2^2}{2g} = h_1 + \frac{V_1^2}{2g} \tag{3}$$

$$K_1 = \frac{H_1}{V_2^2/2g}$$

$$= \frac{h_1}{V_2^2/2g} + \left(\frac{Q_1}{Q^2}\right)^2 \left(\frac{D_2}{D_1}\right)^4 - 1 \tag{4}$$

The loss coefficient K_1 is a quantity which, when multiplied by the velocity head in the outlet pipe, gives the loss of total energy straight across the box. It is shown graphically in Figures 8 and 9.

In like manner, the loss coefficient, K_3, for flow across the box from the lateral inlet pipe-3 is

$$K_3 = \frac{H_3}{V_2^2/2g}$$

$$= \frac{h_3}{V_2^2/2g} + \left(\frac{Q_3}{Q_2}\right)^2 \left(\frac{D_2}{D_3}\right)^4 - 1 \tag{5}$$

The above rational development checks quite rigidly the experimental values of K_1 and K_3.

Loss of Pressure Head

According to the law of conservation of momentum, the change in the momentum of water entering from the main inlet pipe-1 and discharging through the outlet pipe-2 is balanced by the change in pressure across

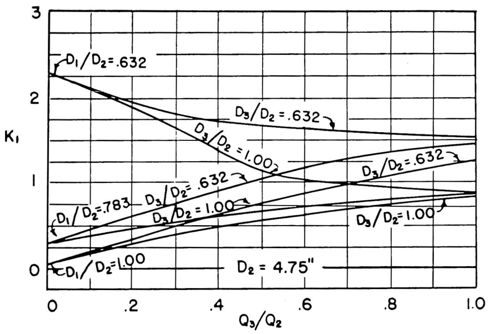

Figure 9. Loss coefficient K_1 when a smaller outlet pipe is used.

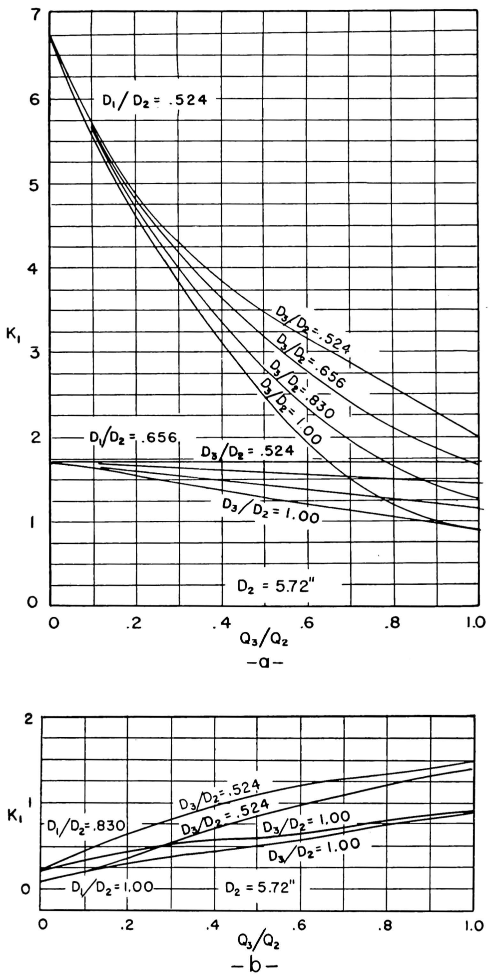

Figure 8 (a and b). Loss coefficient K_1 when a large outlet pipe is used.

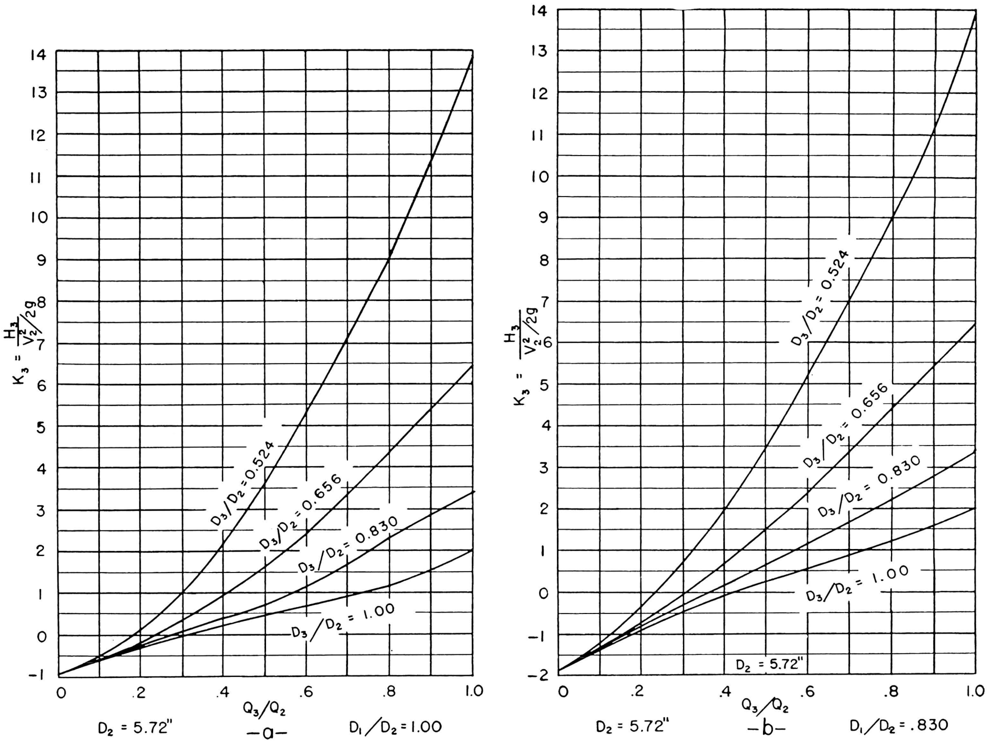

Figure 10 (a & b). Loss coefficient K_3 when a large outlet pipe is used.

the box. Any inflow from the lateral pipe-3 has no component of momentum in the direction of the main line but will contribute to the total flow in the outlet pipe. The following relations exist between lines 1 and 2 for expanding flow, and appear to hold closely for moderately contracting flow.

$$Q_1 + Q_3 = Q_2 \tag{6}$$

and

$$(p_1 - p_2)A_2 = \frac{w}{g}(A_2V_2^2 - A_1V_1^2) \tag{7}$$

then

$$h_1 = \frac{p_1}{w} - \frac{p_2}{w} = \frac{A_2V_2^2}{A_2 g} - \frac{A_1V_1^2}{A_2 g} \tag{8}$$

$$h_1 = \frac{2V_2^2}{2g} - 2\left(\frac{D_1}{D_2}\right)^2 \frac{V_1^2}{2g} \tag{9}$$

but

$$V_1 = \frac{Q_1}{A_1} = \frac{Q_2}{A_1}\frac{Q_1}{Q_2} = \frac{Q_2}{A_2}\frac{A_2}{A_1}\frac{Q_1}{Q_2} \tag{10}$$

then

$$V_1 = \frac{A_2V_2}{A_2}\left(\frac{D_2}{D_1}\right)^2 \frac{Q_1}{Q_2} = \left(\frac{D_2}{D_1}\right)^2 \frac{Q_1}{Q_2} V_2 \tag{11}$$

Substituting this value of V_1 :

$$h_1 = 2\frac{V_2^2}{2g} - 2\left(\frac{D_1}{D_2}\right)^2\left(\frac{D_2}{D_1}\right)^4\left(\frac{Q_1}{Q_2}\right)^2\frac{V_2^2}{2g} \tag{12}$$

$$\frac{h_1}{V_2^2/2g} = 2 - 2\left(\frac{D_2}{D_1}\right)^2\left(\frac{Q_1}{Q_2}\right)^2 \tag{13}$$

$$K_1' = \frac{h_1}{V_2^2/2g} = 2\left[1 - \left(\frac{D_2}{D_1}\right)^2\left(\frac{Q_1}{Q_2}\right)^2\right] \tag{14}$$

When all the flow is straight across the junction box

$$Q_1 = Q_2$$

and the equation for the loss coefficient re-

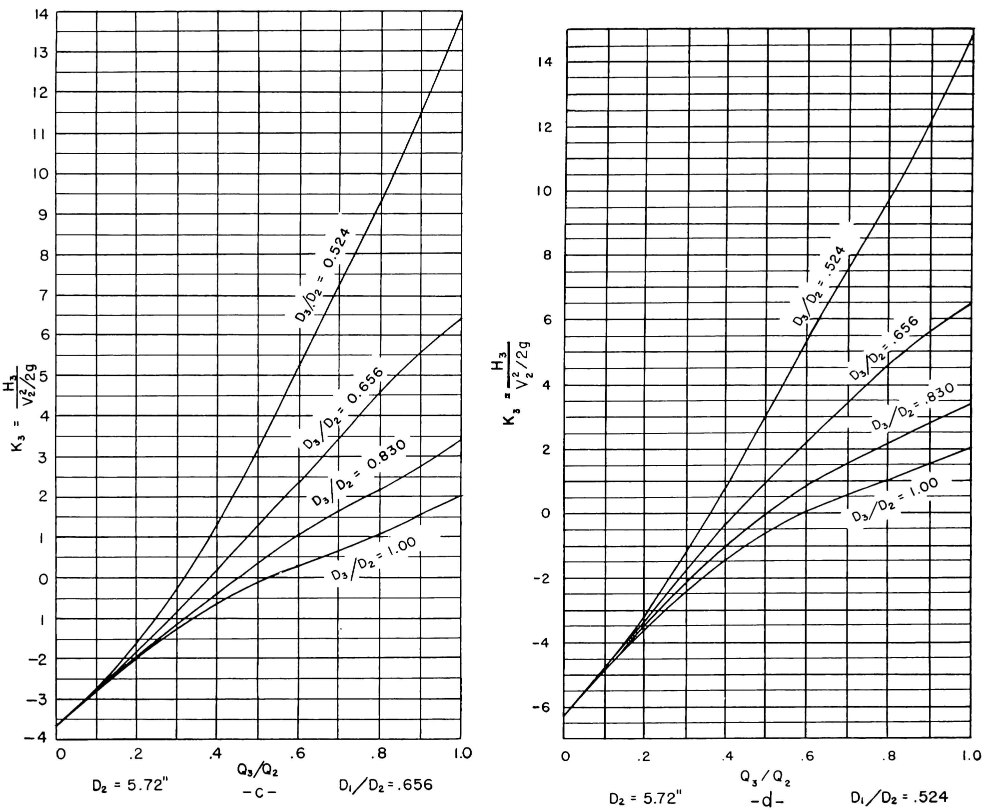

Figure 10 (c & d). Loss coefficient K_3 when a large outlet pipe is used.

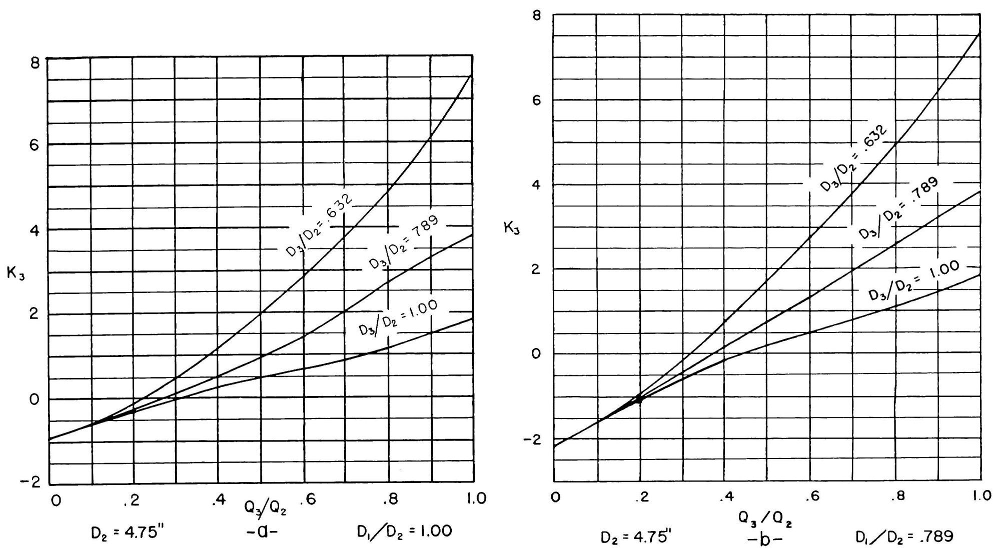

Figure 11 (a & b). Loss coefficient K_3 when a smaller outlet pipe is used.

duces to

$$K_1' = \frac{h_1}{V_2^2/2g} = 2\left[1 - \left(\frac{D_2}{D_1}\right)^2\right] \quad (15)$$

A graph of this equation is shown in Figure 12.

When flow is combining across the junction box, the simple momentum relation still holds fairly well for K_1' if Q_3/Q_2 is not greater than about 25 percent. Studies indicate that this may be true for loss from the lateral direction also. However, when the percentage of flow from the lateral increases, the values of K_1' and K_3' deviate considerably. It is probable that experimental curves will be developed which will indicate pressure losses in either direction when the flow is divided. This is under investigation.

LABORATORY INVESTIGATION

The tests discussed herein were not necessarily conducted in the order listed. It was found early in the test program that difficulty in reading manometers made it advisable to establish a normal piezometric slope for each diameter pipe and each rate of discharge. This is particularly desirable on large diameter pipes for which the length-to-diameter ratio is less than for smaller pipes. These slopes, composites of a large number of tests, were checked by removing the junction box and testing long lines. The standard slope is fitted to the plotted points for determination of head loss across the box.

The proper point of tangency to be used in plotting the normal piezometric grade line was found to be quite consistent in the case of of smaller pipes, but uncertain with large diameter outlet pipes. In the upstream portion of the outfall pipe, the actual piezometric line does not coincide with the standard slope which is tangent to the piezometric line at some point downstream. This point was established by similitude using a 3-inch outfall line and noting the point beyond which the slope becomes normal and corresponds to the established slope. Carrying this slope line up to the junction box permits inclusion of the loss occurring in the outfall pipe caused by the junction box.

In construction of pipe drains, the crowns of the pipes are generally placed at the same elevation. Maintaining crown alignment in the model was found to impose difficulties

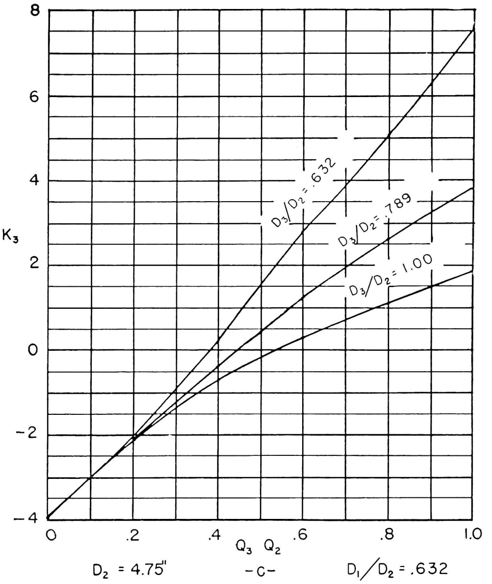

Figure 11 (c). Loss coefficient K_3 when a smaller outlet pipe is used.

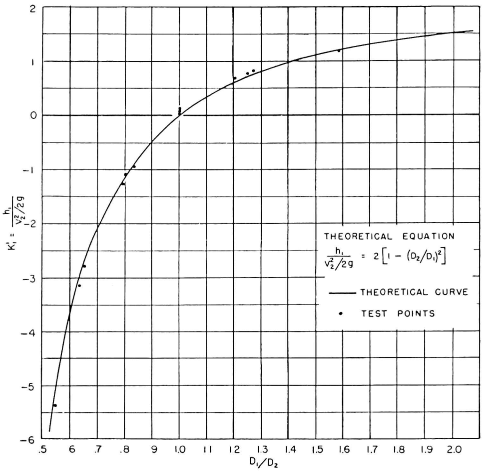

Figure 12. Loss coefficient K_1' for direct determination of pressure loss. $Q_1 = Q_2$.

when changing pipe sizes. Tests were made to determine whether the head loss would be appreciably different under the two methods.

When using a 5.72-inch outlet and 3.00-inch inlet, the loss coefficient was found to average 2.3 percent greater for crown alignment than for flow-line alignment. The magnitude of the coefficient was of the order of 7.0.

When the inlet pipe was increased to 4.75 inches, the average loss coefficient was about 10 percent greater for crown alignment but the magnitude of the coefficients was of the order of 0.2. In both of the extreme diameter ratios the difference was considered to be negligible, and all subsequent tests were made with flow lines in alignment.

In the earlier phases of the analysis, the energy grade lines were projected to the upstream inner face of the junction box for measurement of head loss. Later investigation indicates that loss measurements taken at the intersection of the center lines of the pipes referred to as the "Branch Point" by John S. McNown (1) give very nearly the same results. This branch point reference has been used subsequently because of the ease of use in design (Figure 7). The same reference point was used in subsequent analysis of combining flow from the straight-through line with flow from a 90-degree lateral.

OBSERVED RESULTS

Straight-Through Flow (Figure 13)

This configuration, without a lateral pipe, was investigated in several series of tests. Beginning with a D_2/D_1 ratio of 1.00, all combinations of sizes of inlet and outlet pipes were used except the D_2/D_1 ratio of 3.75:5.72 which is very close to the ratio of 3.00:4.75. It is recognized that values of D_2/D_1 less than 1.00 are not commonly used in practice, but the full range was included in order to find the general trend of the influence of pipe diameter ratios. Figure 14 indicates the value of the energy loss coefficient K_1, for flow straight across the box when D_2/D_1 is greater than 1.00. Figure 15 shows the coefficient K_1 when D_2/D_1 is less than 1.00, and Figure 16 when D_2/D_1 is equal to 1.00. It will be noted that the loss coefficient is practically independent of the value of the Froude number. Even when D_2/D_1 is less than 1.00 (Figure 15), the loss coefficient does not vary appreciably in absolute value with the Froude number.

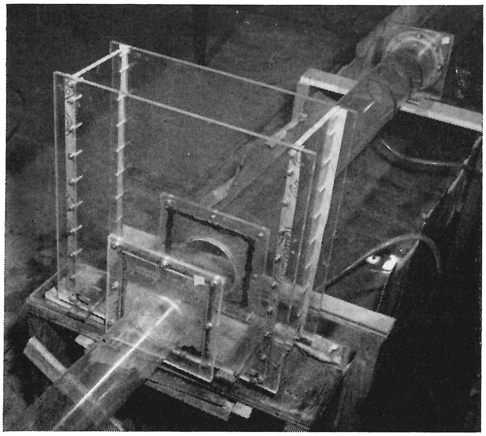

Figure 13. Model junction box arranged for straight-through flow.

Figure 17 shows the same data plotted on a Cartesian scale. The latter indicates that within the limits of the tests the loss is practically independent of the b/D_2 ratio and that the value of K_1 is primarily a function of the pipe diameter ratio D_2/D_1. This does not preclude the possibility that the distance through the junction box may exert an appreciable influence if increased beyond the limits tested thus far.

The effect of the diameter of the pipe is reflected in the slight dispersion of K_1 values evident in the logarithmic chart (Figure 16) where $D_2/D_1 = 1.00$. The absolute value of this difference is quite small, and it appears that a single Cartesian graph (Figure 17) will be adequate for practical design purposes.

While it appears that within the test range the effect of the through-flow distance is not a critical issue, the effect of the b/D ratio was further investigated by running a series of tests duplicating the previous series, but with attached collars simulating re-entrant pipes protruding into the junction box from the downstream face (Figure 18). the 1½-inch length and the thickness equal to 1/12 of the inside diameter simulate a 6-inch prototype protrusion and standard pipe wall thicknesses. Only the extreme sizes were tested. Figure 16 indicates slightly lower loss when the collars are used reflecting the shorter travel distance across the box to the outlet with somewhat less expansion of the shorter jet.

Combining Flow (Figure 1)

The configuration was the same as for straight-through flow alone, but with a lateral pipe entering at 90 degrees at the end of the box. The lateral line was fitted with a header box similar to the original header box and a calibrated orifice meter was used to measure the flow.

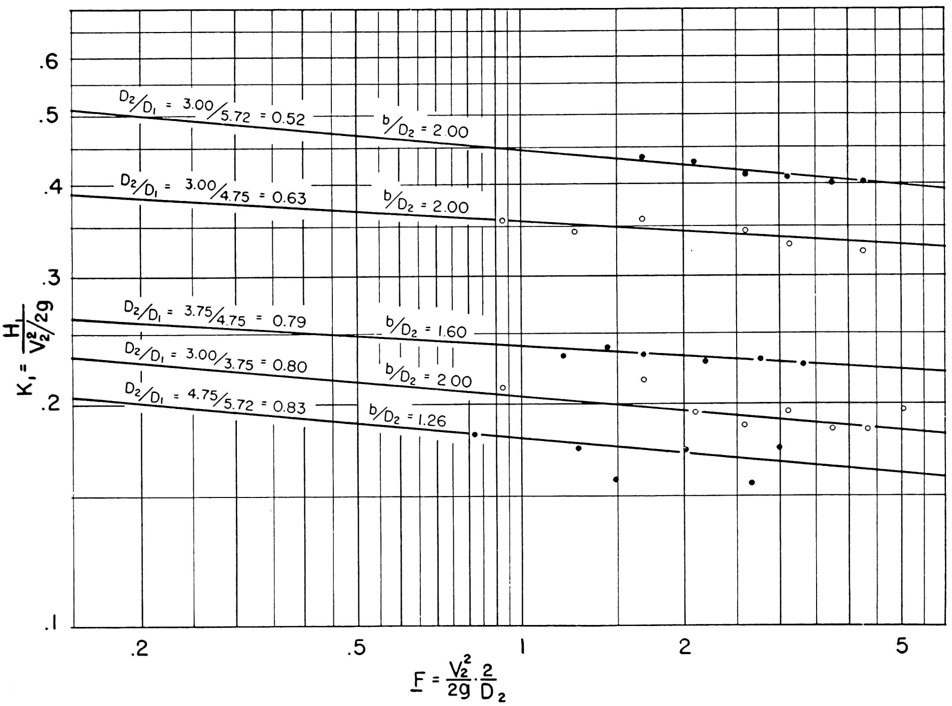

Figure 14. Loss coefficient K_1 as related to the Froude number when D_2/D_1 is greater than 1.00. $Q_1 = Q_2$.

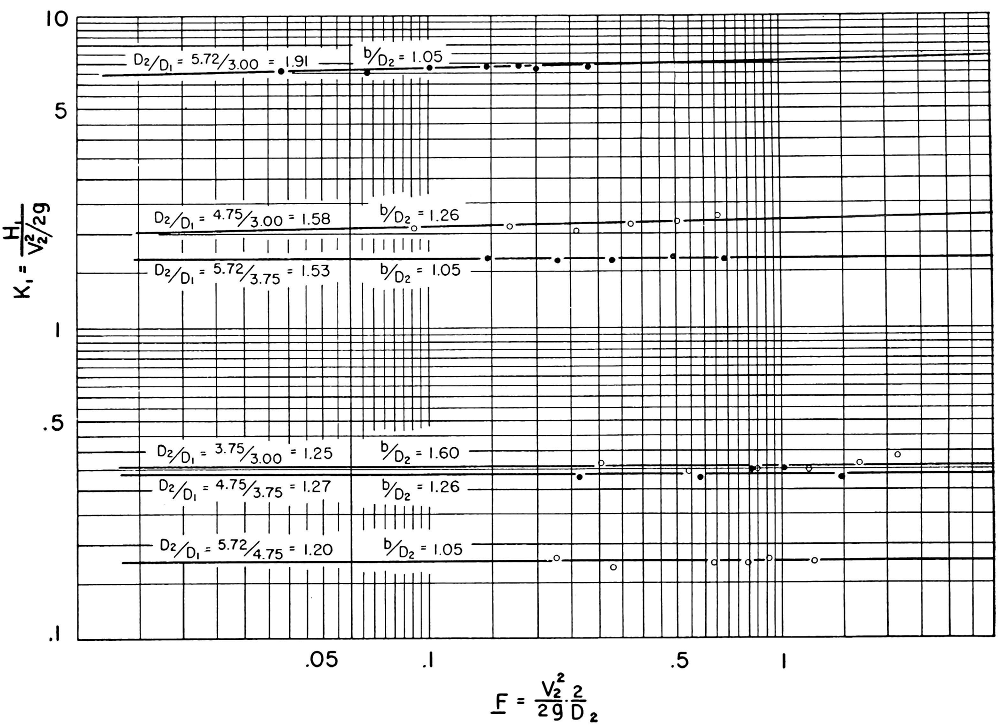

Figure 15. Loss coefficient K_1 as related to the Froude number when D_2/D_1 is less than 1.00. $Q_1 = Q_2$.

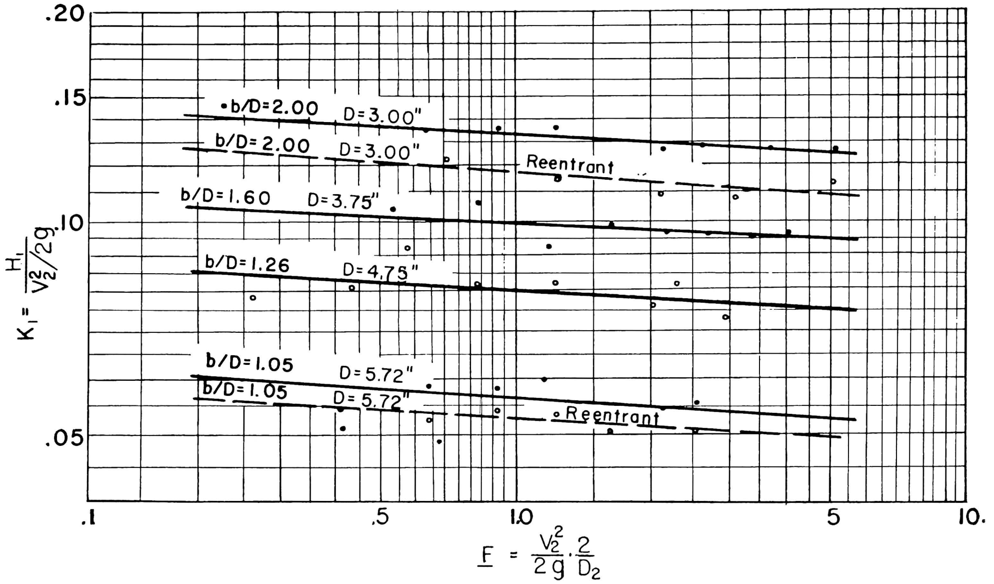

Figure 16. Loss coefficient K_1 as related to the Froude number when D_2/D_1 is equal to 1.00. $Q_1 = Q_2$.

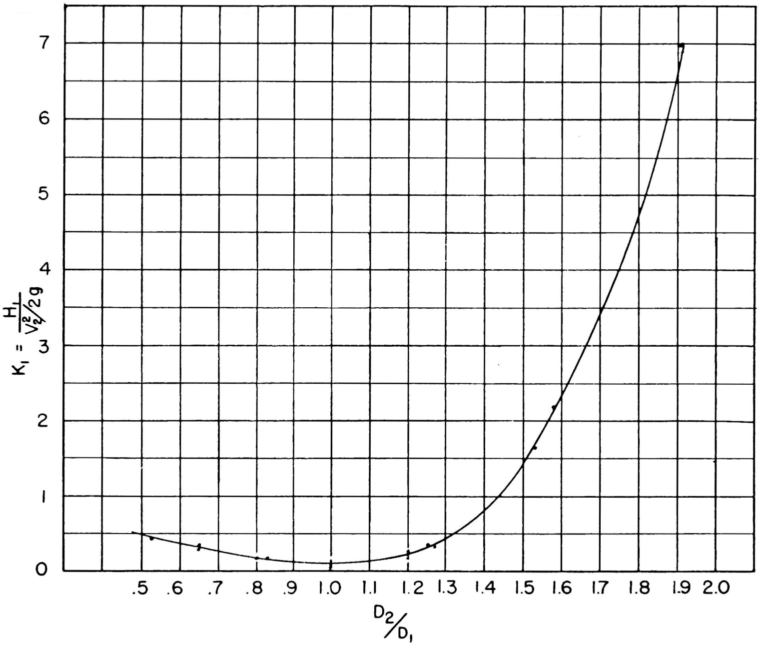

Figure 17. Loss coefficient K_1 as related to the D_2/D_1 ratio. $Q_1 = Q_2$.

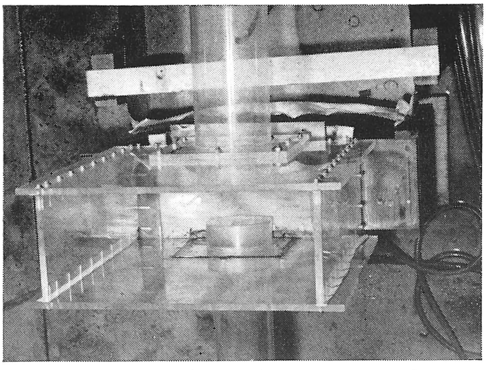

Figure 18. Junction box with re-entrant outlet pipe.

A single 5.72-inch outfall line was used throughout this series of tests. All four pipe diameters were used in the lateral line and three diameters, 5.72, 4.75, and 3.00-inch, in the upstream main line. The 3.75-inch pipe was omitted because sufficiently complete information was obtained without it. For the condition of no flow from the lateral pipe the loss had already been found for straight-through flow from the 3.75-inch pipe. By interpolation the missing data have been supplied.

This interpolation is made on the assumption that the loss coefficient is primarily a function of the ratio of the diameters of the inflow and outflow pipes. There are two loss coefficients in this configuration; one, K_1, for straight-through flow, and the other, K_3, for flow from the lateral pipe. By plotting D_1/D_2 and D_3/D_2 against both K_1 and K_3 from actual test data, for all Q_3/Q_2 ratios, the resulting set of auxiliary curves can be used to determine coefficients for any other diameter ratio without regard to actual diameters.

The coefficient K_1 when a 5.72-inch outlet pipe is used is plotted in Figure 8. It is expressed as a factor to be multiplied by the downstream velocity head, $V_2^2/2g$, to determine the head loss H_1. In this set of curves, all graphs representing $D_3/D_2 = 5.72:5.72 = 1.00$ ratio converge closely near the value $K_1 = 0.9$ as the Q_3/Q_2 ratio approaches 1.00. On the other hand, when $D_3/D_2 = 3.00:5.72 = 0.524$, the K_1 values appear dispersed and difficult to interpret when the velocity head in pipe-1 is very small. This indicates that the high velocity of the jet from the lateral pipe affects the loss straight across the box differently for different sizes of main inlet pipe-1.

Some of the intermediate combinations having 3.75 and 4.75-inch pipes in the lateral line have been omitted from the graph where the total spread is small.

Figure 9 was prepared by interpolation to represent the straight-through loss coefficient K_1 for configurations using 4.75-inch pipe for the outfall. Since this combination had not been tested, a few check tests were run to establish the accuracy of the interpolation. It was found that for Q_3/Q_2 ratios above 0.5 the D_3/D_2 ratio governs the interpolation almost exactly. For Q_3/Q_2 of zero the D_1/D_2 ratio governs. Between zero and 0.5, the interpolated values are influenced by both ratios.

In some respects the auxiliary curves of K vs D_3/D_2 and K vs D_1/D_2 would be more convenient for interpolation than using Q_3/Q_2 for the abscissa scale. However, it is believed that a new set of curves with K plotted against Q_3/Q_2 and interpolated to conform to commercial pipe combinations will be more useful whenever the energy method is employed.

The loss coefficients K_3 for computing head loss across the junction box from the lateral pipe-3 to the outfall pipe-2 are represented in Figure 10. The entire range includes 3.00 to 5.72-inch pipes in the lateral branch and in the main line upstream while in all cases the outfall pipe is 5.72 inches.

The apparent negative values of the coefficient K_3 are the result of referring the loss to the total head in the outfall pipe-2. When the portion of flow in the lateral pipe-3 is approaching zero, the dynamic head in the outfall pipe stems increasingly from the flow entering the junction box from the main inlet line-1. The negative value of the coefficient does not hinder its use in determining the elevation of the piezometric and total energy lines in the lateral pipe-3. When K_3 is negative, the total energy line in the lateral pipe is lower than that in the outfall at the junction box, and approaches the piezometric line in the lateral as the lateral flow Q_3 approaches zero.

A chart showing the lateral coefficient K_3 for a system using a 4.75-inch outfall pipe is shown in Figure 11. This chart was first prepared by the method of interpolation described above and then verified almost exactly by laboratory tests. It is feasible to combine the separate charts such as those in Figure 10 into a single superimposed chart.

Effect of Length of Junction Box

In order to determine the effect of the length of the junction box measured at right angles to the outfall line, the model was blocked off to measure 6 by 6 inches. The lateral line was attached to a temporary baffle instead of to the end of the 15-inch box.

Under such conditions less turbulence is noted and less consequent air entrainment than when the full 15-inch length is used. Figure 19 shows a somewhat constant reduction in K_3 for the short box when there is an appreciable percentage of flow from the lateral pipe.

In Figure 20 the loss coefficient K_1 for straight-through flow also is shown to be lower in the short 6-by-6-inch box. While these energy loss coefficients are consistently lower in the short box than in the 15-inch box, the actual numerical difference is not great. Since the velocity heads remain unchanged, the reduction in total head loss must reflect a

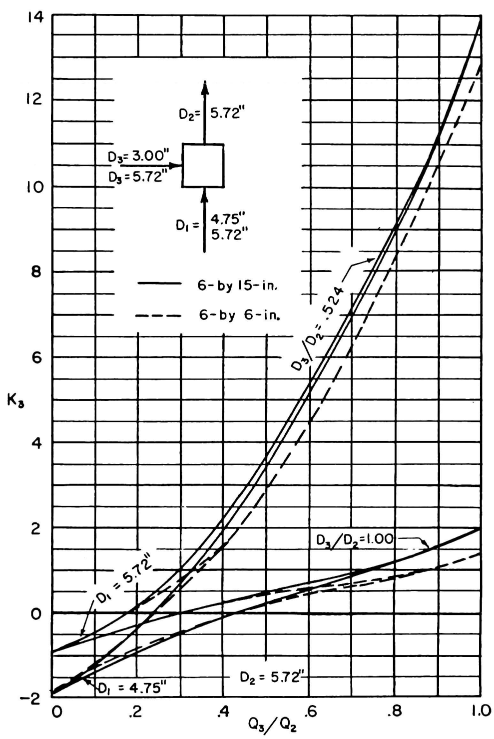

Figure 19. Effect of box length on loss coefficient K₃ .

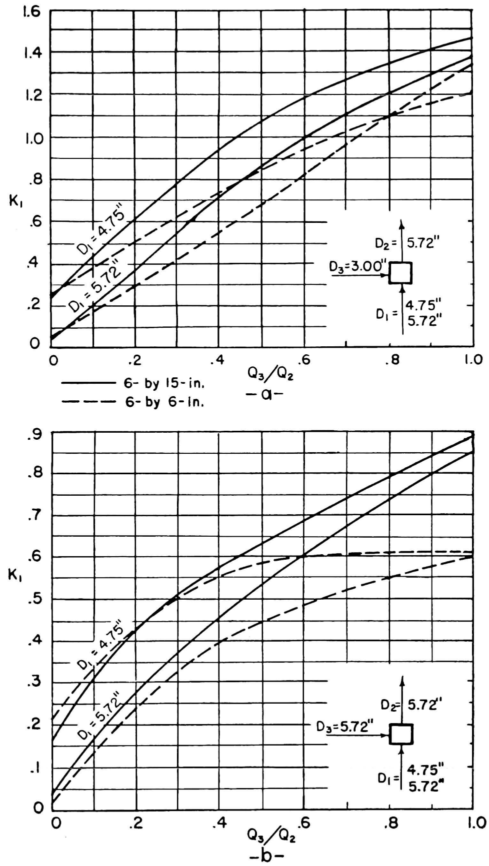

Figure 20 (a and b). Effect of box length on loss coefficient K₁ .

reduced pressure loss. Where physical conditions and maintenance methods permit the use of a small junction box without an inlet grating on top, it appears that slightly less resistance occurs in both straight-through and lateral flow.

Re-Entrant Outfall Pipes

Earlier in the program a few tests were run to determine the effect of permitting the outfall pipe to protrude into the junction box (Figure 18). These early tests were made for straight-through flow only, and a slight reduction of loss was observed when the reentrant extension was used and the flow distance through the box thus shortened. While the loss was small, it was consistent and significant in that it suggests that a greater

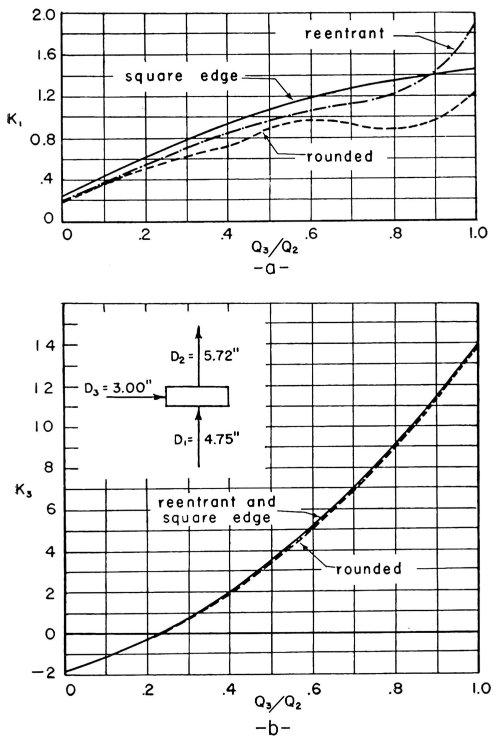

Figure 21 (a and b). Effect of outlet condition upon loss coefficients K_1 and K_3 when the lateral pipe-3 is small.

through dimension might result in a greater loss.

In order to establish more clearly the effect of the protruding pipe upon the straight-through loss and also to study its effect upon the lateral loss coefficient, a series of tests was run using the same 1.5-inch re-entrant collar representing a prototype length of 6 inches. Two sets of tests were made using a 4.75-inch upstream main pipe-1 and a 5.72-inch downstream outfall pipe-2. To set up extreme conditions, in one set a 5.72-inch lateral was used, and in the other, a 3.00-inch lateral. For direct comparison of results the tests were made over the same range of Q_3/Q_2 ratios, using the same discharge rates that had been used without the re-entrant collar.

These tests indicate (Figure 21) that a definite but rather inconsistent difference in K_1, mostly a reduction, was caused by the presence of the protruding pipe end when the small lateral was used. No measurable changes resulted when the lateral pipe was large (Figure 22). The value of the lateral loss coefficient K_3 appears not to have been affected by the re-entrant collar. While these tests covered only two pipe configurations, it was thought that this range was adequate to justify the conclusion that the re-entrant pipe end is not objectionable so far as the hydraulic head loss is concerned.

Rounded Outlet

A rounded flange was fitted to the 5.72-inch outfall pipe. This flange was built up of several sheets of Plexiglas cemented together and the edge rounded to a radius of $0.125D$ or 0.71 inches.

These tests duplicated the flow rates and the Q_3/Q_2 ratios used in previous sets in one of which the downstream pipe protruded into the junction box, and in the other, the square edge of the pipe was flush with the inner face of the box.

It will be observed in Figure 21 that when a small lateral pipe is used, the lateral loss coeffi-

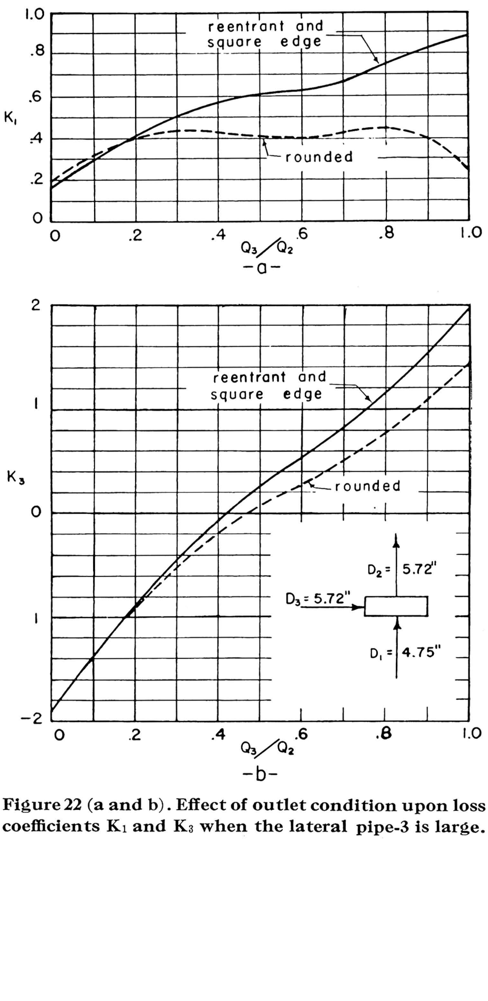

Figure 22 (a and b). Effect of outlet condition upon loss coefficients K_1 and K_3 when the lateral pipe-3 is large.

cient K_3 is only slightly reduced by the rounded outlet. When the larger lateral pipe is used (Figure 22), the rounded exit reduces the coefficient K_3 by a small amount. The maximum reduction is in the order of 0.70, increasing from zero with the percentage of lateral flow. The coefficient K_1 for straight-through flow is appreciably reduced by the rounding of the outlet indicating that the expanding jet is not dispersed but enters the rounded outlet.

An apparent inconsistency is found in the K_1 value at $Q_3/Q_2 = 0.8$. Here K_1 drops below the values at 0.6 and 1.0. These results have been carefully rechecked in the laboratory and can be duplicated. Similar reversals have been found in other configurations, but not always at the same Q_3/Q_2 ratio. The exact cause of such reversals is not apparent at present but they appear to be associated with certain Q_3/Q_2 ratios in any given configuration regardless of the total quantity of water.

APPLICATION OF METHODS

An illustration of the use of the total head loss and the pressure head loss methods will be given. Since the charts were prepared directly from the results of the model study, the examples will be confined to the model dimensions.

A 6-by-15-inch junction box connects a 4.75-inch inlet pipe with a 5.72-inch outlet pipe discharging 0.78 cubic foot per second straight through the box. The conditions downstream are such that the piezometric line for the outlet pipe intersects the branch point 1.25 feet above the bottom of the box. It is required to determine the elevation of the piezometric line for the upstream pipe.

1. Considering the problem from the viewpoint of total energy loss let $Q = 0.78$ cubic foot per second:
Whence

$$V_2^2/2g = 0.30, \quad \text{and} \quad V_1^2/2g = 0.62.$$

Elevation of total head in line-2 = 1.25 + 0.30 = 1.55 feet.

From Figure 8,

$$K_1 = 0.22$$

$$H_1 = K_1V_2^2/2g = 0.22 \times 0.30 = 0.06 \text{ foot.}$$

Elevation of total head in line-1 = 1.55 + 0.06 = 1.61 feet.

Elevation of piezometric line, pipe-1 = 1.61 − 0.62 = 0.99 foot.

2. Considering the problem from the viewpoint of loss of pressure:
Elevation of piezometric line in pipe-2 = 1.25 feet as before.

From Figure 12,

$$K_1' = -0.90.$$

The pressure head loss is then

$$h_1 = K_1'V_2^2/2g = -0.9 \times 0.30 = -0.27 \text{ foot.}$$

Elevation of piezometric line in pipe-1 = 1.25 − 0.27 = 0.98 foot.

3. Considering that a 3.75-inch lateral pipe is added to the above configuration and that the 0.78 cubic foot per second flow is divided between the two inlet pipes so that 40 percent enters the box from the lateral pipe, then:

$$Q_1 = 0.468 \text{ cfs}, \qquad Q_2 = 0.78 \text{ cfs},$$

and

$$Q_3 = 0.312 \text{ cfs.}$$

from which:

$$V_1^2/2g = 0.224, \qquad V_2^2/2g = 0.30,$$

and

$$V_3^2/2g = 0.257.$$

From Figure 8,

$$K_1 = 0.80 \quad \text{and} \quad K_3 = 0.70.$$

Then, to find the elevation of the pressure line in pipe-1,
Elevation of total head in pipe-2 = 1.25 + 0.30 = 1.55 feet.

Head loss from pipe-1,

$$H_1 = K_1V_2^2/2g = 0.80 \times 0.30 = 0.24 \text{ foot.}$$

Elevation of total head in pipe-1 = 1.55 + 0.24 = 1.79 feet.
Elevation of pressure line in pipe-1 = 1.79 − 0.22 = 1.57 feet.

To find the elevation of the pressure line in pipe-3,

Head loss from pipe-3,

$$H_3 = K_3V_2^2/2g = 0.70 \times 0.30 = 0.21 \text{ foot.}$$

Elevation of total head in pipe-3 = 1.55 + 0.21 = 1.76 feet.

Elevation of pressure line in pipe-3 = 1.76 − 0.26 = 1.50 feet.

CONCLUSIONS

The use of the scale model makes possible the determination of loss coefficients which indicate the head loss across the junction box, helping to determine the piezometric grade line and free water surface. Thus, if the charts developed in this study are used in conjunction with standard pipe flow charts, it is possible to design a storm drain system which will carry any prescribed flow of water without danger of overflowing the junction boxes. The method used for interpolation permits the determination of the junction box loss coefficients for any ordinary pipe combination and makes it possible to prepare charts for various standard pipe configurations.

When all the flow is straight through the junction box, the use of the pressure loss coefficient K_1' simplifies the process of tracing the piezometric line through the box. It is possible that in the study of the laboratory data a method will be found for making use of the momentum relation where the inflow is the combined discharge of two or more pipes and a top grate, thus simplifying the problem of design. Until this has been worked out more satisfactorily than at present, the energy method can be relied upon to give close results whenever any part of the flow enters the box from the lateral direction.

ACKNOWLEDGMENTS

The assistance and cooperation of Carl F. Izzard and Herbert G. Bossy of the Bureau of Public Roads, L. R. Burns of the Missouri State Highway Department, and Prof. W. M. Sangster of the University of Missouri are gratefully acknowledged. Laboratory tests and computations of data were under the direction of James E. Moulder of the Engineering Experiment Station.

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DISCUSSION

Herbert G. Bossy, *Highway Research Engineer, Bureau of Public Roads, Washington, D. C.*—This paper presents initial design data in a field where authoritative information has been completely lacking. Professor Wood has ably presented the first results of this investigation, which will continue with the objective of deriving design solutions for a variety of storm drain junction types.

Earlier experiments seem to have been restricted to closed pipe systems, in which the pipes were joined directly or with usual pipe fittings. Storm drain junctions are more complex because the shapes of the conduits are radically changed at the junction, and the water surface in the box is open to atmospheric pressure.

The paper presents results from the model study in the form of head loss coefficients, a procedure that has been used almost universally in the past for problems in flow through transitions of various types. The head loss coefficient, multiplied by the downstream conduit velocity head, gives the loss of total head from that upstream conduit to the one downstream attributable to the junction form and distribution of flow. The head loss, in feet of water, may be conveniently applied as a vertical offset of the two total head lines at the center line of the junction. If the pressure elevation, or hydraulic grade line, in an upstream conduit is desired, the upstream conduit velocity head is subtracted from the total head elevation at any point.

The head loss coefficients of the paper apply only to a system with all pipes flowing full. Since the head loss values were found to differ between the 6 by 15 inch and 6 by 6 inch model junction box sizes with the same pipe size combination, it is clear that the effect of size of junction, and possibly its shape, must be explored further. The smaller box size is most effective in reducing the pressure of the lateral pipe, and the reduction is most significant when the lateral velocity is materially greater than that of the outlet pipe.

At the time of preparation of this first report, the model investigation had been concerned primarily with the effect of various pipe size combinations and flow distributions on head loss through the rectangular junction box. The head loss coefficients K_1 and K_3 reported in the paper in the form of graphs were derived from the pressure change across the junction by the methods described. Although the change in pressure at the branch point for each test run is not reported here, the complete data will be published in the final report of the investigation.

The complete experimental data were available to the writer and provided the basis for this discussion which will be primarily concerned with an analysis on the basis of pressure changes rather than total head loss. All tests were run with a range of discharge rates, and tests were repeated to improve the accuracy of determination of pressure change at the junction. As might be expected, a given test condition seldom gave exactly the same change in pressure at the branch point. Therefore, the head loss coefficient curves of the paper, and the pressure loss coefficient curves derived by the writer, all contain some element of personal judgment in fitting the experimental data.

Referring to the paper, it will be noted that the range of total head loss coefficients for the three-pipe system is quite wide, ranging from about -6 to $+14$. Also, these coefficients are applicable only to the pipe size ratios of the model. Computation of loss of head for a field structure will require interpolation between the curves of Figures 8 to 11. The considerable difficulty in making a reliable interpolation for K_1 with pipe 1 discharge less than one-half the total, or for K_3 with pipe 3 discharge more than one-half is evident from the figures. The author describes a method for interpolation requiring the construction of auxiliary curves.

Subsequently this discussion will show that interpolation may be avoided and a loss coefficient obtained directly by use of pressure change coefficients rather than total head loss coefficients. The pressure change analysis also permits design solutions for three-pipe systems with an upstream pipe larger than the downstream, although the present model tests did not include this combination.

The negative values of the lateral pipe head loss coefficient K_3 appearing in Figures 10 and 11 seem quite surprising at first glance, but may be readily explained. Where the lateral carries no flow, it fills with water from the junction box as the flow is brought to the desired rate. Then it is under the same pressure as water in the box, which in turn stands at a depth equal to pressure in the upstream supply line. Therefore, pressure in lateral 3 at no flow corresponds to the pressure line elevation of pipe 1 conveying the flow. The author has pointed out that the total head line for the lateral coincides with the pressure line for pipe 1 for the case of no flow. The situation would be illustrated on Figure 7 if h_3 equals h_1, and H_3 were zero.

An example will illustrate the reason for the negative K_3 of 0.9 on Figure 10*a* for $D_1 = D_2$ and no lateral flow. It may be noted that the lateral head loss coefficient is independent of pipe 3 size at zero discharge. Figure 12 of the paper or Figure 23 of this discussion shows that the pressure loss coefficient K_1' for through flow with D_1 equal to D_2 is zero, and thus the theoretical pressure loss is zero. The actual pressure loss observed was very small. The head loss coefficient for this case is also practically zero, as shown in Figure 17, 8*b*, or 9 for $D_1/D_2 = 1$. The pressure line of in-line pipe 1 is one velocity head below the total head line of pipes 1 and 2. Since the pressure in lateral 3 equals the pressure in pipe 1, and the lateral velocity head is zero, it follows that the total head line of 3 is one velocity head below the total head line of outlet pipe 2, and therefore the head loss coefficient K_3 should approach -1.0 which it does in Figure 10*a*.

Where upstream in-line pipe 1 is smaller than pipe 2 and all flow is straight through, the lateral head loss coefficient for $Q_3/Q_2 = 0$ has a large negative value. Figure 10*c* shows K_3 is -3.7 for such a case with $D_1/D_2 = 0.656$. Following the method used in the previous example and referring to the same figures, it is found that the pressure change for pipe 1 is -2.7 and the head loss is $+1.7$ velocity heads. The velocity head in pipe 1 is 1.53^4 or 5.4 times velocity head in pipe 2. Therefore, the pressure line in pipe 1 is $5.4 - 1.7$ or $3.7\ V_2^2/2g$ below the total head line of pipe 2. If the pressure line of 3 coincides with that of pipe 1, and pipe 3 carries no flow, then the total head of 3 is 3.7 velocity heads below that of pipe 2, and K_3 will be -3.7, as is shown by Figure 10*c*.

The close agreement of experimental results with the theoretical solution shown by Figures

12 or 23 for all flow straight through a junction box, where flow distance across the box does not exceed twice the upstream pipe diameter, is very significant. The examples given above illustrate the point quite well. It is clear that the flow issuing from an upstream pipe of smaller diameter travels across the junction box with virtually no change in diameter and expands within the larger downstream pipe. Therefore, the rise in pressure line, proceeding downstream, occurs in pipe 2 below the junction, and pressure in the junction must be the same as in pipe 1 immediately above. The fact that the tests conclusively show the pressure in lateral pipe 3 with no flow to be equal to pipe 1 pressure proves this to be the case.

If the opposite situation is examined, that is, all flow through the 90-degree lateral, Figures 10 and 11 show all positive head losses with values of K_3 ranging up to $+14$. When the pressure losses of the model test data are examined, it is evident that all pipe size combinations result in a lateral pressure loss of about twice the outlet pipe velocity head. That is, the pressure loss coefficient K_3' is constant at $+2.0$, with deviations generally not exceeding 20 percent.

Equation (3) may be written to apply to pipes 3 and 2 and transformed to:

$$K_3 = K_3' - 1 + \left[\frac{D_2}{D_3}\right]^4 \qquad (16)$$

If K_3' is 2.0, equation (16) may be applied to the pipe size ratios D_3/D_2 of Figure 10 and the head loss coefficients computed to be 2.0, 3.1, 6.4, and 14.2. These values correspond closely to the experimental values shown by the figures for $Q_3/Q_2 = 1.0$. It will be noted that a deviation of 20 percent in pressure loss in the case of the smaller lateral pipe will result in a K_3 value ranging from 13.8 to 14.6.

The author, in his conclusion, refers to a determination of elevation of the water surface in the junction box. The experimental data are not reported, but reference to these has revealed the factors controlling the water surface elevation. In through flow with aligned pipes, the water surface corresponds to the pressure line elevation of the upstream pipe, whether the pressure line drops in the downstream direction with D_1 greater than D_2, or rises with D_1 smaller. In combining flow, the water surface will correspond to the common elevation of the upstream and lateral pipe pressure lines if these coincide, or in case of divergence it will lie between, with some tendency exhibited to conform more closely to the lateral pipe pressure. When 80 percent or all of the flow is carried by the lateral, the water surface is nearly always above the higher of the two upstream pipe pressure lines. The amount higher may be about 0.5 the outlet velocity head. In general, it may be concluded that determination of the water surface elevation in the junction box offers no problem once the pipe pressure line elevations are computed.

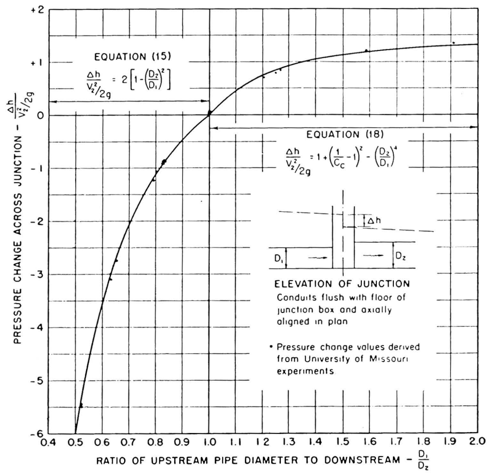

Figure 23. Pressure increase or decrease for flow straight through a junction box.

Some further consideration might be given to the methods of pressure plus momentum analysis the author used in developing equation (14), and its more simple form in equation (15) for all flow straight through the junction. In constructing Figure 12 the author uses (15) in the range of D_1 larger than D_2 although he points out that it is not strictly applicable.

A theoretical equation for pressure loss for through flow from a larger upstream pipe to a smaller downstream pipe can be developed. In this case the flow entering the outlet pipe will contract to an area less than that of the pipe and then expand to fill the conduit. A loss of energy occurs as a result of the expansion. The head loss will be:

$$H = \frac{(V_j - V_2)^2}{2g}$$

where V_j is the velocity in the contracted jet of entering flow. The jet velocity is discharge divided by jet area, and jet area may be defined by entrance area times the von Mises contraction coefficient C_c. The latter is determined by the relative areas of pipes 1 and 2 if the junction box has no effect on the flow pattern. If no loss of energy occurs from the end of the upstream pipe to the section of contracted flow in the outlet pipe, the above equation is the loss of total head and may be converted to:

$$H_1 = \left[\frac{1}{C_c} - 1\right]^2 \frac{V_2^2}{2g} \qquad (17)$$

Substituting (17) in equation (3) and solving for the pressure loss, we obtain:

$$\frac{\Delta h}{V_2^2/2g} = 1 + \left[\frac{1}{C_c} - 1\right]^2 - \left[\frac{D_2}{D_1}\right]^4 \qquad (18)$$

In the terms used in the paper, the left side of the equation is K_1', and Δh is h_1.

The two equations for change of pressure in flow straight through a junction box are plotted in Figure 23. Equation (15) is limited to expanding flow, and equation (18) is used for contracting flow. The pressure losses derived from the test data by the writer are shown for comparison. It is clear that the junction boxes used had no appreciable effect on the magnitude of pressure loss. The loss is evidently the result of the change in pipe size at the junction and can be predicted accurately by theoretical methods. It may be noted that the theoretical zero loss coefficient for equal size pipes is actually about 0.05 in the model tests.

Confirmation of the theoretical equations for through flow leads to the interesting possibility that the method may be applied to combining flow. Consider the case of a junction box receiving flow from an in-line upstream pipe, a lateral pipe, and through a top grate, with a single outlet pipe, all arranged similar to the model described in the paper. If the lateral is at 90 degrees to the through line, and its flow and that through the grate have no velocity component in line with the outlet pipe, it would appear that the method of analysis used for the simple case of straight through flow would apply, with proper allowance for the reduced momentum of the upstream in-line pipe, now carrying only a part of the total flow.

Usually such a storm drain arrangement would involve an upstream main equal to or smaller than the outfall main. Under these conditions we may expect the author's equation (14) to apply. Where the lateral or top inlet discharge rates are relatively small and neither velocity is very great, conditions are favorable for an accurate solution by the theoretical equation. As these discharges increase, forces other than those involved in deriving the equation may be created.

A general solution for pressure loss in a combining flow system with D_1 less than D_2 may be obtained from equation (14). However, with D_1 greater than D_2, equation (18) does not reach the value of 2 velocity heads pressure loss for a large D_1/D_2 ratio as the tests show is the case when Q_3 approaches Q_2. At present no method is apparent for modifying the derivation of equation (18) to introduce a reduction of upstream momentum as Q_1 is reduced. An expedient would be to use a pressure loss of 2 velocity heads for all flow through the lateral, and reduce this pressure with some in-line flow by the effect of upstream in-line momentum in accordance with equation (14). Some minor modification of the result is necessary as Q_1 approaches Q_2 in order to match the solution of equation (18) which is correct for all flow straight through.

The graphical result of equations (14) and (18) and a modification in the area where D_1 is larger than D_2, is shown in Figure 24. Use of this graph will permit direct determination of the change of pressure from upstream in-line supply pipe to outfall pipe in field size ratios for a junction box comparable to the

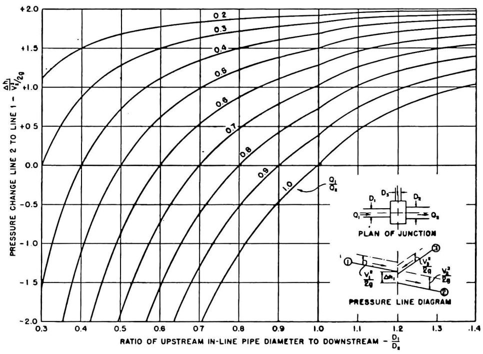

Figure 24. Pressure increase or decrease for in-line or lateral pipe at rectangular junction box on through line and 90-degree lateral.

rectangular one tested. The graph applies for all flow straight through or for part supplied through a lateral pipe at 90 degrees. Although model tests with a portion of the flow supplied through a grate at the top of the junction box have not been made, it may be assumed with reasonably good foundation that Figure 24 will also apply in this case.

The test data, not included in the report, show a close agreement with Figure 24 over a wider range of relative pipe sizes and flow distributions than might be anticipated. With the rectangular junction box and any size of lateral pipe the agreement is very good where the rate of flow in the lateral is sufficiently small to hold its velocity to less than that of the upstream main. For higher lateral pipe velocities, some deviation both below and above the theoretical values is evident. The tests of the small square junction box with the 5.72-inch outlet pipe, placing the box wall very close to the pipe wall, show a considerable deviation of the pressure loss from the theoretical values. Perhaps this case involves a departure from the assumption made in deriving the equation, in that the flow from the lateral pipe reaches the opposite wall and is deflected in such a pattern that a portion of its momentum is effective in the direction of flow in the outfall.

The investigation of head losses in other forms of storm drain junctions is continuing under the direction of Professor Wood. The results of further tests may modify to some degree the conclusions drawn in the paper and in this discussion. As the theoretical analyses proceed and are verified by experimental results, it may be expected that simple methods of design applicable to a variety of storm drain structures will be evolved.

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