

Hydraulics of Box Culverts with Fish-Ladder Baffles

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The placement of transverse baffles in box culverts for the purpose of providing for traverse of fish has become increasingly necessary in recent years. Consequently, model studies were made to determine design factors for baffled culverts as related to baffle height and spacing, and to develop hydraulically efficient baffle shapes for use in the culverts. The results of the studies, based on the treatment of the baffles as roughness in a rectangular conduit, were obtained in the form of velocity-head coefficients; one dependent upon and the other independent of friction effects. The first of these is given in the form of a Darcy-Weisbach friction factor, and the second, which accounts for energy components at entrance and outlet, in the form of an "energy coefficient."

The studies were conducted under the auspices of the Engineering Experiment Station of Oregon State College, and were jointly sponsored by the Oregon State Highway Commission and the U.S. Bureau of Public Roads.

● DURING recent years a problem has arisen in Oregon and other coastal states in connection with obstruction of fish passages in natural streams by various hydraulic structures. In this respect, box culverts on steep grades in mountainous county provide an obstacle to passage of migratory fishes because of the inability of the fish to negotiate the shallow and rapid stream flow which occurs in the culverts under normal conditions. Because it is necessary for many of the migratory fishes to travel in coastal streams for great distances to spawn, an increasingly important problem arises in making many of the box culverts required for highway drainage traversable by fish.

A means selected for aiding passage of fish through a box culvert is the creation of successive pools throughout the length of the culvert by means of transverse notched baffles. Several such culverts have been constructed in Oregon and Washington by state and federal agencies.

The presence of baffles in the bottom of a culvert creates an obstruction to flow occurring during flood conditions and causes a reduction in the capacity of the conduit. Prior to the reported experiments, there had been no data available upon which to base the calculation of discharges through culverts pro-

vided with fish-ladder baffles and flowing full under head.

In order to obtain design data for box culverts with fish-ladder baffles, the Oregon State Highway Commission and the Bureau of Public Roads initiated a jointly-sponsored project to conduct, through the Engineering Experiment Station, model studies in the hydraulics laboratory of Oregon State College. Experiments were begun in January 1953 and were completed in February 1954.

The design of the fish-ladder baffles for a given box culvert is based upon a minimum specified length of pool, a minimum depth at the upstream end of the pool, and a maximum difference in elevation between successive pools. Thus, for any given culvert grade, there is a certain range of combinations of baffle spacings and heights which will satisfy the foregoing requirements. Before the initiation of the project it was concluded that a variation in the spacing and height of a series of baffles could have an effect upon the resistance to culvert flow caused by the baffles, and that the experiments should be based upon the range of baffle arrangements contemplated for most ordinary cases of culvert design. Consequently, plans were made for the construction and testing of a model box culvert in which full-width transverse baffles of various heights could be arranged at different spacings.

The following factors, based upon actual design conditions, were considered in the choice of baffle heights and spacings for the experiments:

1. Consideration limited to single square box culverts from 4 feet by 4 feet to 12 feet by 12 feet.

2. Grade to be considered was 1 percent minimum to 10 percent maximum.

3. Full-width baffles to be installed at right angles to the culvert axis.

4. Maximum difference in elevation of successive pools to be 1 foot at no flow.

5. Minimum pool depth to be 8 inches.

From these criteria, and from experience in previous culvert installations, it was decided that the ratios of baffle to culvert height to be tested should be 0.1, 0.2, and 0.3, and spacings should be one, two, and four times the height of the culvert barrel. Because of the limitation of time available for the study, the effect of notches in the baffles was disregarded.

It was decided at the start of the project to make use of a model available in the hydraulics laboratory to determine factors to be considered in planning experiments and designing the model to be used for testing effects of baffle height and spacing. This model was a 4- by 4-inch Plexiglas box culvert, having a barrel 82 inches long, provided with an inlet designed according to Oregon State Highway Commission Drawing 9656, and laid on a flat grade. Suitable means for measurement of head and discharge were available. Rectangular wooden baffles $\frac{1}{4}$ and $\frac{1}{8}$ the height of the culvert were installed at different spacings and their effects upon discharge capacity and general flow characteristics of the culvert were noted. In addition, variations in the shape of the baffles were made in order to determine the necessity for experiments involving baffle shape before conducting baffle height and spacing studies.

The general conclusions from the preliminary experiments were as follows:

1. The general shape of baffle could have a significant effect upon the discharge capacity of a culvert. Therefore, limited tests of baffle shapes would be warranted.

2. A length of culvert of approximately 20 diameters would be required for precision of measurement because of the relative magnitudes of the losses and other energy components.

3. A head of approximately six times the culvert height would be required for precision of measurement of losses and other energy components.

4. Baffle locations at the extremes of the culvert were critical. It was decided, therefore, to retain the same relative baffle location in the future model, regardless of baffle height and spacing.

5. It would be advisable to provide wing walls and an apron at the outlet of the model and permanently locate a baffle at the end of the outlet apron.

In view of the foregoing conclusions, it was decided to divide the experiments into two phases: (1) a limited study of the effect of baffle shape upon the resistance to flow through the culvert, and (2) a study of baffle height and spacing. These experiments will be discussed separately on the following pages.

BAFFLE SHAPE EXPERIMENTS

Objective

The objective of the baffle shape experiments was to obtain information from a limited number of baffle shapes that would aid in the selection of a hydraulically-efficient baffle suitable for use in box culverts. The method chosen for the studies consisted of investigations of the operation of from one to three baffles of each shape to be considered when installed in two-dimensional flow models.

Theory

The major problem of the shape experiments appeared to be the establishment of criteria for evaluation of the various baffle shapes under consideration. Preliminary experiments with rectangular baffles in a 4-inch-square model culvert indicated that the flow through such a conduit, baffled only on one side, could be characterized by a series of accelerations and decelerations of the fluid stream occasioned by the periodic restrictions provided by the baffles. The magnitude of the restriction of flow caused by a single baffle appeared to be a function of a contraction of the jet issuing from the area directly above the baffle.

Assuming major energy losses in a baffled conduit occur chiefly as a result of sudden deceleration of the water beyond the vena contracta of the jet, it was theorized that the most efficient baffle shape from the stand-

point of minimum flow obstruction would be one which would cause least contraction of the jet. This would limit the magnitude of the periodic variation of velocities in the main stream passing through the conduit.

Apparatus

Two types of apparatus were employed in the baffle experiments, both of which were based upon a two-dimensional flow analysis.

The first of these was an aerodynamic smoke tunnel ordinarily used for classroom demonstrations of streamline flow around airfoils of various types. This smoke tunnel consisted of an enclosed chamber approximately 18 inches in length and 1 foot in height, with a space of 1 inch between a black velvet background and a plate-glass face. Air was drawn longitudinally through the device by means of an exhaust fan and baffles were provided at the intake and outlet to smooth the flow. Kerosene smoke was injected at the intake end through a manifold provided with small nozzles spaced approximately $\frac{1}{2}$ inch apart along a vertical line. Plexiglas models were installed in the tunnel above a longitudinal strip of Plexiglas simulating the invert of a culvert. Photographs taken of the smoke patterns were used for evaluation of the effects of changes in baffle shape.

The second model was a horizontal Plexiglas conduit 2 inches wide by 8 inches high and 4 feet long. This was connected to a head tank through a transition section. The tank was sufficiently high to allow a submergence of the

entrance to the model of approximately $3\frac{1}{2}$ feet. A double vertical sluice gate was installed at the outlet to provide headwater control, and additional regulation was provided by means of a valve in the supply line to the head tank. A specially calibrated triangular weir was used to measure discharges from the model.

Pressure connections were provided at the ends of the bottom and at quarter points, top and bottom. Piezometer connections were made internally to the baffles as close as possible to the most probable point of separation. In the rectangular baffles, holes were drilled in the top just beyond the upstream face, and in all others as close to the downstream face as possible. Pressure differences were measured by means of a sensitive differential manometer and headwater elevations were measured by a piezometer column connected to the head tank.

Baffle Shapes

The shapes of baffles considered in these experiments were limited to practical designs which would be feasible in actual culvert construction; therefore, only plane sections and circular curves were employed.

Because the preliminary tests showed variations in shape of the downstream face to have a negligible effect upon discharge, all baffles tested in water were designed with vertical downstream faces. In the smoke tunnel test, only the upstream face was considered. The height of all baffles was 2 inches, and rounded baffles were constructed so the curve at the downstream edge (or summit) was tangent to a horizontal line. Table 1 describes the baffles tested and indicates the testing conditions.

TABLE 1
BAFFLE SHAPES

Baffle Type	Description (All baffles 2 in. high)	Model in Which Tested
A	Rectangular, thickness $\frac{1}{2}$ height	Smoke tunnel and water
B	Quadrant, 2-inch radius	Smoke tunnel and water
C	Same thickness as Type A, but with top rounded on a radius equal to thickness, vertical upstream face below curve	Smoke tunnel and water
D	One-inch radius quadrant on top of a 1-inch-square base (radius of rounding equal to $\frac{1}{2}$ the height)	Smoke tunnel and water
E	Same as Type D, but with a 1-inch radius reverse curve below the quadrant (on lower half)	Smoke tunnel and water
F	One-half quadrant with the 2-inch side vertical, 2-inch radius top rounding	Water only
G	Type A baffle with a 2-inch high fillet having a 1:1 slope attached to the upstream face	Smoke tunnel and water

Experimental Procedure

The experimental approach utilized several methods, as outlined in the following:

Smoke Tunnel Tests. Attempts were made to compare the bottom contractions occurring in the streams of air flowing over different baffles. For these observations a camera was located in a position normal to the face of the tunnel and photographs were taken of configurations of smoke streams passing over the various baffle shapes. The photographs were superimposed upon a grid which provided a reference for the measurement of the distance

between the bottom plate and the bottom of the jet at its highest point.

Water Tests. Several methods were employed to indicate the degree of contraction of the jet in each case. In these studies a maximum of three baffles was used on the premise that the smaller number of baffles would be more satisfactory for the type of study involved.

After some preliminary tests it was concluded all results should be based upon the operation of the baffle farthest upstream when there was more than one installed in the model. This was because the approach conditions upstream of this baffle would provide the greatest tendency for contraction of the jet. Furthermore, after various shapes of baffles were tested it became apparent that this upstream baffle was the only one for which the approach conditions were independent of the shape of baffle. Since comparisons between contractions were selected as criteria for evaluation of baffle shapes, it was considered that similarity of approach conditions was of primary importance.

The following experiments were conducted in the water model:

1. Pressure difference tests. As previously mentioned, pressure connections were made internally at the top of the baffle and at the top of the culvert at the same section, and a sensitive differential manometer was installed between these two connections. The measurements were taken on the theory that the pressure difference between these two locations in the jet would be a function of the degree of contraction at the location of the baffle connection, in addition to being an indication of the direction of streamlines adjacent to the connection. The discharge through the conduit was varied through a wide range, and a series of pressure difference readings was taken for each baffle shape.

In these tests three baffles were installed at quarter-points in the model, with no measurements being taken from the two downstream baffles because preliminary tests showed pressure readings from these to be inconsistent. The purpose of including these baffles was to provide proper exit conditions from the first baffle. Discharge was controlled by the inlet valve, and head was controlled by the sluice gate at the outlet.

2. Dye tests. Potassium permanganate dye was injected into the stagnant area down-

stream of the first baffle and photographs were taken on film insensitive to red. The camera location was kept the same for all these photographs so that the degree of contraction as indicated by the dye could be determined approximately from enlargements of the negatives. Pictures of the contraction were taken at two discharges for each baffle tested.

3. Free jet experiments. As another possible indication of contraction from a baffle, a series of photographs was taken of the free jet discharging from a single baffle installed at the outlet of the model. These photographs, which were taken at two rates of discharge for each baffle shape, were enlarged and measured to indicate the degree of bottom contraction of the jet. The head above the bottom of the conduit was recorded for each condition.

Results

Contraction Photographs. The results from the dye injection, smoke tunnel, and free jet tests are summarized in Figure 1. In this chart, contraction is expressed as a percentage of the height of the baffle for different baffles tested. Comparative results of these three studies are shown to be inconsistent from the standpoint

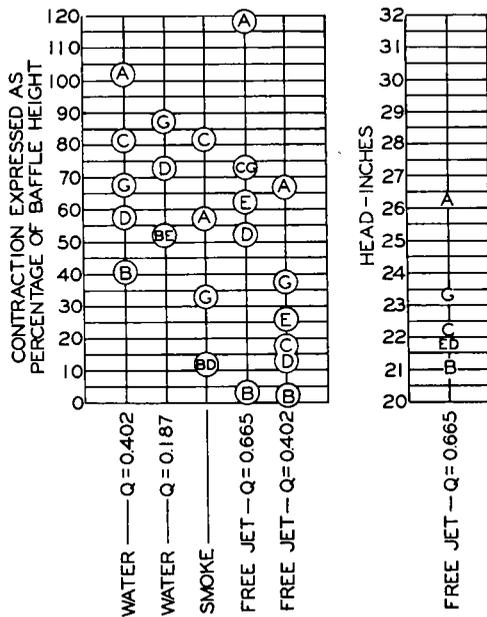


Figure 1. Summary of contraction characteristics of various types of fish-ladder baffles.

of absolute values. They do show, however, that the Type B (quadrant) baffle causes the least contraction in each case, with the Type D baffle (1-inch radius top rounding) apparently second best.

Pressure Differences. Measurements of the pressure differential between the top of the baffles and the culvert top were consistent and confirmed visual observations of the nature of contraction from the baffles. Sufficient variation of pressure difference with discharge was obtained for each baffle to make possible a comparison of these results by graphical plot. In the plots all baffles except the quadrant baffles showed identical trends in pressure difference versus discharge. The quadrant baffles showed a much smaller differential at a given discharge (on the order of 50 percent of that obtained from the rectangular baffles), in addition to a much more gradual increase in pressure differential with discharge.

The rectangular baffles (Type A) consistently gave the greatest pressure difference, followed by Type C and then Types D, E, and G, the latter group having the same pressure differential at any given discharge. No measurements were taken from the half-quadrant baffles (Type F) since in most cases a contraction occurred at the upstream edge, and the operation was unstable.

Observations were made at the top of each baffle during both dye tests and free jet tests to ascertain the degree of separation upstream of the highest point on the baffle. Little or no separation occurred upstream of the summit of the quadrant and Type G baffles, while separation occurred about $\frac{1}{4}$ inch upstream of the summits of the Types D and E baffles, and about $\frac{5}{16}$ to $\frac{3}{8}$ inch upstream of the summit of the Type C baffles.

Pressure differences discussed above seem to correspond to the relative location of the separation point with respect to piezometer location, and appear to have very little value otherwise.

Rating Curves. The head-discharge relationships for the model with three baffles installed were inconclusive because the control for all cases was at the sluice gate at the end of the conduit. All points fell very closely to the same line, showing that the major losses occurred at the outlet, thereby masking any losses caused by the baffles. The model was not operated without the sluice gate.

The head-discharge relationships with only one baffle installed at the outlet (free jet) were satisfactory, although percentagewise the differences were small. Results from measurements at one discharge are shown in Figure 1, and the trend is much the same as for the contraction tests.

Conclusions and Recommendations

The results of these experiments are purely qualitative because insufficient information is available to link the contraction from a single baffle with discharge characteristics of a large number of identical baffles. The hypothesis that the major losses occur almost entirely as a result of successive contractions is based upon the assumption that similar approach conditions exist upstream of each baffle except the first. Observation of dye injected into the 4-inch culvert model confirms this assumption to a certain degree.

The general hypothesis is strengthened by the relationship of the operation of the rectangular and beveled (Type G) baffles in both water models. A distinct increase in discharge capacity was obtained from the 4-inch culvert model when the Type G baffles were substituted for rectangular baffles. If the contraction from a single baffle can be related even approximately to the loss from a series of baffles, the quadrant baffles or the Type D baffles may be expected to be much more satisfactory than the Type G baffles from the standpoint of resistance to flow.

While the quadrant baffle seems to be the most logical choice from the standpoint of hydraulic efficiency, the proportions of this baffle are such that the overall size would be objectionable from an economical standpoint in cases where high baffles are installed in a large culvert. The Type D baffles would appear to be the second-best choice, and were selected for use in subsequent experiments with baffle height and spacing. There is some question as to whether or not the thickness and top radius should be varied with the height of baffle since it is logical to assume that the ideal rounding should vary as the size of the opening above the baffle. It should be noted, however, that as the baffle becomes lower, the tendency for contraction should diminish because of the change in approach conditions. A baffle design for which the top radius was constant would probably produce the most consistent

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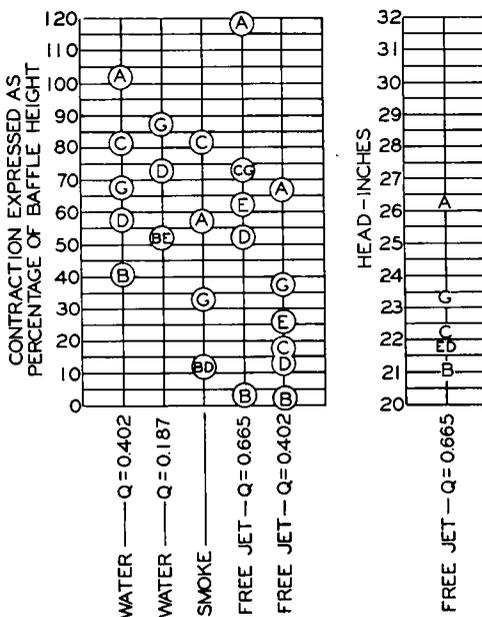


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results in the laboratory model because the effective variation of rounding with respect to the size of the opening above the baffle would be small. It was decided, therefore, that the lowest baffle be a quadrant and that variations in height would be accomplished by variations of height of rectangular sections under the quadrants.

The limitations of time prevented any further consideration of baffle shapes. The results of this study indicated that there would be ample justification for further experiments for a full-length model in which a larger number of baffles would be installed.

BAFFLE HEIGHT AND SPACING EXPERIMENTS

Objective

The specific objective of height and spacing experiments was to obtain information to be used in the hydraulic design of culverts provided with fish-ladder baffles. Particularly desired were data to aid in the evaluation of energy losses caused by the baffles, obtained from experiments with a model culvert.

In any conduit discharging a fluid under head, the energy losses may be subdivided into two categories; (1) losses caused by turbulence induced at entrance, and (2) losses

caused by friction resulting from roughness of the conduit.

While a baffled culvert might not be considered entirely analogous to a pipe because of the magnitude and regularity of the "roughness," it was considered that an analysis of energy distribution, considering the culvert as a rough pipe, would be the most feasible. Results presented in this manner satisfactorily lend themselves to use in conventional design practice and, at the same time, are suitable for comparison with available pipe flow data. Accordingly, energy losses caused by the baffles were considered as conduit friction losses and data were obtained in such a manner as to make possible the separation of friction and other losses.

The Model

The hydraulic model used in these experiments was a 4 by 4-inch conduit constructed of Plexiglas and provided with a removable false bottom to which baffles were attached. As shown in Figure 2, the conduit comprised flanged sections, an inlet and outlet section, and two barrel sections, so that it could be tested in three different lengths. The inlet and outlet sections were provided with aprons having wing walls at an angle of 8:12 with

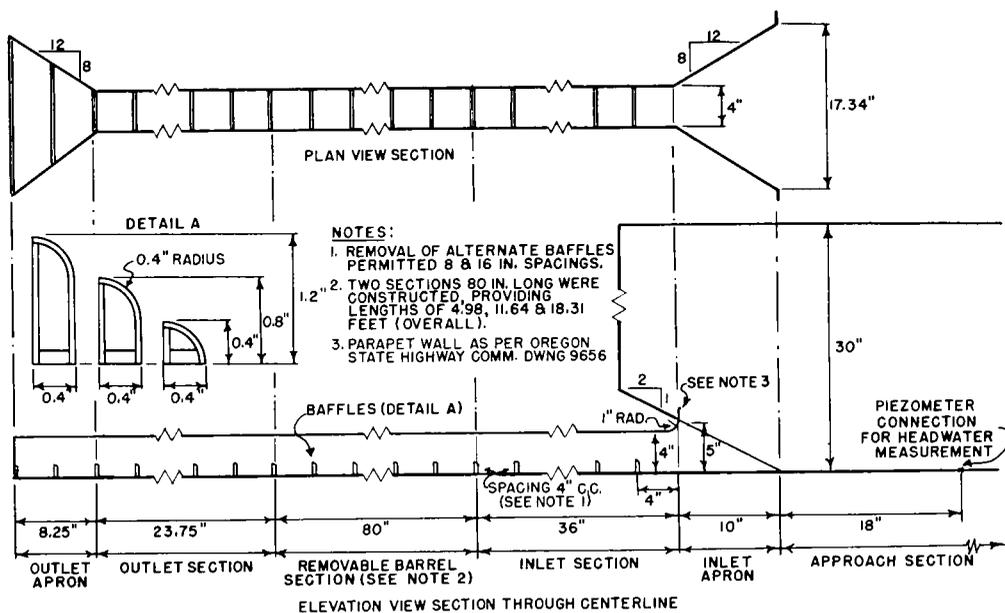


Figure 2. Model used for baffle height and spacing experiments.

the culvert axis, the inlet wing walls conforming to a 2:1 embankment slope. Top of the entrance was rounded to a radius of $\frac{1}{4}$ the height of the culvert so that the entrance was 5 inches in height and 4 inches in width. No rounding was provided at the outlet. All experiments were run with the culvert barrel on a flat grade.

Water entered the model from a large tank and was discharged into a flume leading to a calibrated triangular weir. The relatively large area of the tank (5 by 14 feet) damped fluctuations in the supply and provided stability in headwater pool level.

Baffles tested in the culvert model were constructed of Plexiglas and designed on the basis of the previously discussed experiments with baffle shape. Three heights of baffles were made; 0.1, 0.2, and 0.3 times the height of the culvert barrel (i. e., $0.1D$, $0.2D$, and $0.3D$). This range of baffle heights encompassed the range encountered in practice. All baffles were provided with a rounding of their upstream faces equal to $\frac{1}{10}$ the height of the culvert, so that the lowest baffle was a quadrant while the two higher ones were comprised of quadrants placed on rectangular sections having heights of $0.1D$ and $0.2D$, with a thickness of $0.1D$ for both.

Baffle Spacing and Arrangement

Culvert lengths were constructed in such a manner that in each section baffles could be installed at spacings of $1D$, $2D$, and $4D$. The length of section was selected so that a similar arrangement of baffles could be made in each section for the three spacings chosen. The inlet section was 36 inches in length, with a baffle permanently installed at a location 4 inches downstream of the entrance and at the outlet. Each of the two barrel sections was 80 inches in length with a permanent baffle at the outlet end. The outlet section, including the outlet apron, was 32 inches in length, with a permanent baffle at the end of the apron. The lengths of sections of baffled culvert barrel as installed were, respectively, for the inlet and outlet sections, one barrel section added and two barrel sections added—4.98, 11.64, and 18.31 feet.

Measurements and Testing Procedure

The principal information sought through measurements was the drop in the energy grade line over a given length of baffled culvert

barrel for each baffle arrangement. Because of the complex turbulence existing within the culvert barrel, it was concluded that pressure measurements at locations between the ends of the culvert would be meaningless as indications of the location of the hydraulic grade line.

The energy loss in each barrel section was determined by analytical methods based upon discharge rating curves for the three culvert lengths tested. Thus, for all tests the only measurements taken were headwater level (by water column connected to the head tank) and discharge (by calibrated weir and hook gage). Readings were taken for steady-state conditions only, and experimental rating curves were plotted concurrently with test runs as a check on the consistency of the data.

For each baffle height and spacing and for each length of conduit, the head was varied in five or more steps from the minimum required for the culvert to flow full for its entire length to the maximum available. In terms of culvert height, the approximate range of heads was from $1.5D$ to $7.5D$ above the invert.

Analytical Procedure and Results

The objectives in the analysis of the data from the experiments were: (1) to determine the friction factor f in the Darcy-Weisbach formula

$$h_f = f \frac{LV^2}{D2g} \quad (1)$$

where h_f is loss in head caused by friction, L the length of conduit, D the diameter of pipe (4 times the hydraulic radius of noncircular pipes), and $V^2/2g$ the gross section velocity head in the conduit; and (2) to determine approximately the remaining coefficients of the velocity head in the conduit (See Figure 3.)

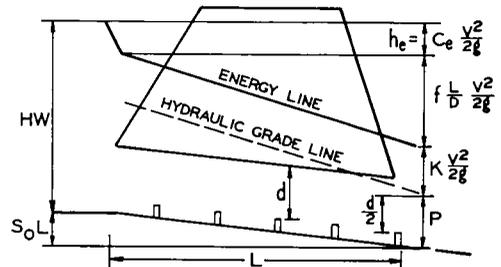


Figure 3. Illustration of terms in the energy equation.

Two different analytical approaches were used to determine the friction factor, both based upon the following assumptions:

1. Friction loss was directly proportional to the velocity head based upon the gross area of the culvert.

2. Slope of the energy grade line was constant for a given discharge over the total length of the culvert, except for a sudden drop at the inlet due to entrance losses.

3. Uniform flow conditions existed throughout the length of the culvert except at the inlet.

4. Entrance losses and outlet effects were independent of friction loss.

The first analysis was based upon assumption 3—the premise that uniformly turbulent conditions existed in the culvert barrel by the time the water passed through the inlet section, which was 36 inches in length.

A typical rating curve, as shown in Figure 4, is given here as an illustration of the procedure used in the determination of the friction factor for a certain baffle spacing and height arrangement.

The three curves shown are for the different lengths of culvert barrel; Curve C, or the lowest, being for the short section; B for the intermediate length; and A for the long section. At a given discharge, such as 0.35 cubic feet per second in Figure 4, three heads may be read from the curves—each head representing for each length the sum of friction and inlet losses plus outlet velocity head. Because inlet loss and outlet velocity head should be the same for the three lengths at a given discharge, the difference in head between any two adjacent curves should represent the friction loss chargeable to one barrel section. As the barrel length increments were the same, the two loss increments should be identical.

In analysis of the data, a set of rating curves was plotted for each baffle arrangement, and from each set of these rating curves readings of friction head loss were measured for five different discharges. For a given discharge, readings were taken separately for each barrel length and then averaged. Subsequently, the head losses, divided by the increment of barrel length, were plotted against velocity head based upon full culvert area.

According to the basic assumptions, plots of head loss versus velocity head should yield straight lines, the slope of which is the friction

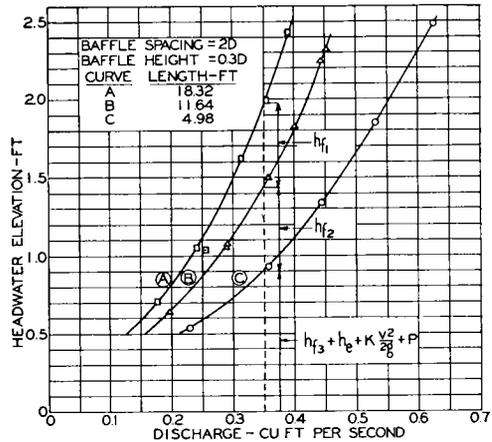


Figure 4. Typical discharge rating curve for one arrangement of baffles in the model culvert illustrating the measurement of head losses.

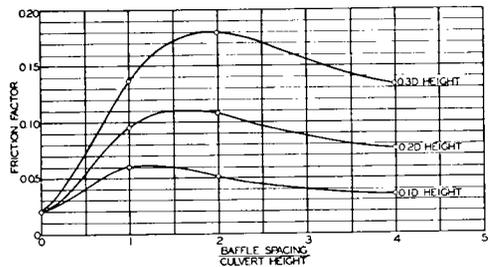


Figure 5. Variation of Darcy-Weisbach friction factor with baffle spacing.

factor f divided by the “diameter” of the culvert and, since entrance loss and outlet velocity head are excluded, the lines should intersect at the origin. This was found to be the case for practical purposes, except the plots for very few of the baffle arrangements had slight upward curvatures. This is presumed to be due to a slight error in assumption 1. In all cases, however, slopes of the lines were determined without difficulty, and it is believed that within the range of discharges employed in these experiments the results are suitably accurate.

The friction factors determined in the foregoing manner are shown graphically in Figure 5 in relation to the spacing between baffles; values at zero spacing being estimated on the basis of Plexiglas conduit ($f = 0.019$) having a cross section equal to the gross culvert area. On the basis of the most probable trends,

based on the limited number of points, the curves are seen to have a maximum value at a spacing between $1D$ and $2D$, beyond which there is a gradual decrease. It appears from the trends shown that, as the baffle spacing is varied, the principal factors causing friction losses change to a considerable degree. At closer spacings it seems likely the loss is caused largely by roughness, and this should increase sharply with an increase in spacing, then decrease because of the presence of fewer baffles in a given length of culvert barrel.

It will be noted that as the spacing is increased there is more opportunity for the contracted jet forming beyond the top of each baffle to re-expand to the full area of the culvert barrel. It is conceivable that at the larger spacings, flow through the culvert is characterized by a series of accelerations and decelerations of the fluid. The changes of momentum involved in this type of flow undoubtedly contribute to the energy losses in varying degrees dependent upon baffle spacing.

The second analysis served not only to provide independent determinations of the friction factor, but also provided means for evaluation of other energy components characterizing the flow through the culvert. In this analysis a linear variation was assumed between total head acting on the culvert and gross section velocity head. For this assumption the energy equation for flow through the culvert can be written as

$$HW = \left(K + C_e + f \frac{L}{D} \right) \frac{V^2}{2g} + \text{constant} - S_0L \quad (2)$$

$$HW = m \frac{V^2}{2g} + P - S_0L$$

where HW is the headwater elevation above the invert at the culvert entrance and the other terms are as shown in Figure 3.

In equation (2) the coefficient f is dependent upon culvert barrel friction alone, and C_e and K are functions of inlet and outlet conditions, respectively. Since it was not considered feasible to attempt separation of the latter two coefficients, the sum $(C_e + K)$ was considered as a separate "energy coefficient" C_a ; a quantity independent of the effects of barrel friction. The objective of the analysis was to determine f and C_a as coefficients of gross culvert section velocity head.

The constant P in equation (2) is a function of outlet conditions and is thus independent of friction slope and the slope of the headwater versus velocity head curves. Selection of values of this constant for energy calculations must be made upon the basis of the outlet conditions for the particular case being studied. A reasonably accurate approximation of P would be the distance from the invert to the center of the opening above a baffle, since observations of dye injections into the baffle shape model indicated that a distinct jet continued beyond a point half way between the baffles. This condition also would justify the use of equation (2) in the same form, whether or not a baffle was located in the plane of the outlet, providing the last baffle was located at the end of the outlet apron. The term S_0L was neglected, of course, since the culvert model was on flat grade.

The first step in the analysis was to plot headwater elevation against velocity head and average straight lines through the points. (All of which had a slight upward curvature.) The slope of each of these lines was, therefore, the mean sum of the coefficients of the velocity head over the range of headwater levels used in the plot. For each baffle arrangement a different value of slope was obtained for each of the three lengths involved. Next, these values were plotted against length of culvert barrel, giving lines having the equation

$$m = C_a + \frac{fL}{D}$$

The quantity C_a can be recognized as the y -intercept, and the quantity f/D the slope of the m versus length lines.

The values of f/D checked very closely with those obtained from the first analysis, establishing the validity of the two methods of approach.

The values of C_a from the foregoing analysis, plotted against baffle spacing, are shown in Figure 6. It will be noted that the curves for all three baffle heights follow the same trend; first dropping rapidly, then at a reduced rate as baffle spacing is increased. Insufficient data are available to provide a satisfactory explanation for the trend of these curves. It would appear that at zero spacing the coefficient should approach that of a culvert reduced in section by the height of a baffle. Therefore, C_a should be relatively low.

A factor that should be considered in this respect is the change in velocity head reference with baffle spacing. At long spacings there is little doubt the coefficient should be based upon culvert velocity head, while at zero spacing the velocity head in the reduced section must be considered. This velocity head increases with the square of the reduction of area and, for a constant coefficient, the product of C_a and velocity head should increase proportionally. Because only the smaller velocity head was considered in this analysis, C_a possibly would increase at a greater rate when spacing was decreased below a certain minimum value.

With data from only three baffle spacings and heights, it is impossible to confirm the foregoing hypothesis, but within the range of these experiments the values of C_a obtained should be sufficiently accurate for design purposes.

Limited tests were inconclusive on the effect of location of the first upstream baffle upon entrance loss. At a $1D$ baffle spacing and the long and intermediate culvert lengths, removal of the first baffle had a negligible effect upon the discharge capacity of the culvert.

Application of the Data

In a typical design of a baffled culvert, three initial quantities are known; (1) flood discharge, (2) maximum headwater tolerable, and (3) length and grade of culvert. The range of baffle heights and spacings for a given grade is determined at no flow by the criteria discussed in the introduction to this paper and the limitations illustrated in Figure 2. It will be noted that the no-flow pool elevations are established by the height of crests of notches in the baffles; the notches being placed with respect to the culvert centerline according to the judgment of the designer. The required additional height of baffle above the notch crest will be determined by normal stream discharge.

Reference is now made to equation (2) in the form

$$HW = \left(C_a + f \frac{L}{D} \right) \frac{V^2}{2g} + P - S_0 L \quad (2a)$$

in which the terms are as illustrated in Figure 3. Dimensions of the culvert may be determined by a series of trial and error calcula-

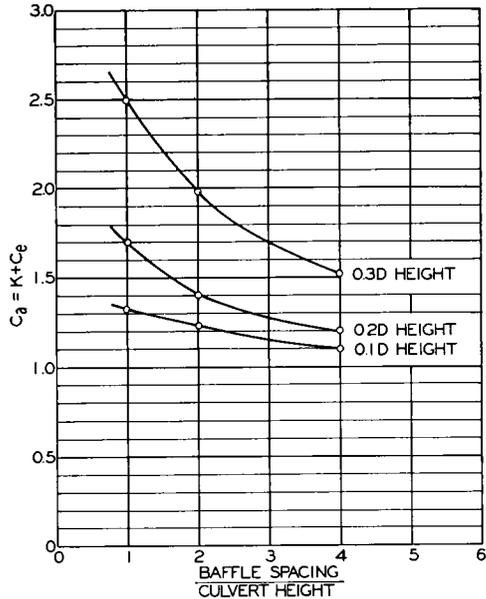


Figure 6. Energy coefficients for various baffle arrangements.

tions starting with an assumed culvert cross section and a baffle height and spacing. Coefficients f and C_a are chosen from Figures 5 and 6, after which a headwater calculation is made by means of equation (2a) using the given discharge. This calculated level should be checked against the maximum allowable and sufficient trials made until a satisfactory result is obtained since, for a given culvert length and grade, several evaluations of culvert size may be necessary in order to determine the most economical installation.

The designer should note that the data shown in Figures 5 and 6 for use in equation (2a) were obtained from tests on a box culvert of square cross section, and therefore should be applicable only to square box culverts. However, the flow through a baffled culvert could be considered as two-dimensional, since the "roughness" of the baffles exceeds so greatly the roughness of the sides. A close approximation of the design of a non-square box culvert is therefore possible on the basis of the assumption that a culvert a given percentage wider than a square box of the same height will carry a correspondingly greater discharge at the same headwater elevation. An exact design would, of course, require data from model

studies of a culvert having the same height and width proportions.

Conclusions and Recommendations

Results from these experiments should provide satisfactory information for the design of box culverts with fish-ladder baffles, providing baffle heights and spacings are kept within the limits of the experiments.

Check calculations of headwater level made from the coefficients given in Figures 5 and 6 indicate that above a headwater level of approximately 2.5 times the height of the culvert (above the invert), the error is less than 5 percent of the actual level. Below the level of $2.5D$, it is recommended that calculated headwater levels be increased by 10 percent for design purposes.

Additional data for a wider variety of baffle shapes, heights, and spacings would provide a wider latitude for design and would undoubtedly clarify the theory underlying the character of the energy losses in conduits such as considered in this paper.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to those whose assistance contributed to the outcome of these studies. Technical assistance from C. F. Izzard, Bureau of Public Roads, R. C. Edgerton, Oregon State Highway Commission, and Professor L. A. Clayton, Oregon State College, was greatly appreciated. Paul Hyde and Malcolm Karr of Oregon State College provided valuable aid in the construction of the model and in the preparation for the experiments.

DISCUSSION

W. R. MCKINLEY, *Engineer, Stream Improvement Division, Washington State Department of Fisheries*—There are obviously two major interests in this problem of fish passage through culverts. One is the interest of fisheries agencies in the passage of migratory fish. The other, naturally, is that of the highway or road agencies which build culverts and are responsible for their function of passing the maximum design flow. It is noted that only the latter was involved in the sponsorship of the study by Mr. Shoemaker. These two interests are somewhat opposed in purpose and concern. The fisheries requirements in culverts encompass low or moderate flows which occur generally during the salmon migration period. The highway agencies, on the other hand, are concerned primarily with maximum design flows. Building an economical culvert which will discharge this flow calls for a structure of minimum cross-section which will provide a rapid passage for water. To insure the passage of fish the culvert must be installed on either a flat grade with some type of control at the downstream end to pool water through it or, when the culvert is placed on a significant grade, there must be some device incorporated on the culvert invert to slow the velocity to a magnitude which is negotiable by fish.

The general type of low baffle transverse to the culvert axis which is used in Mr. Shoemaker's study has been employed in field installations in past years. These baffles have many limitations which detract from their efficiency as a fish passage device. The original intent of the use of these baffles was to create a pool and weir type fishway within a culvert without unduly restricting the cross section. This condition generally limits the pool depth to one foot or less.

A pool and weir fishway is designed to have sufficient depth to dissipate the energy of the falling water in each pool. Plunging flow describes the action of the water as it flows over a weir into a pool, impinges successively on the pool floor and the downstream weir, then returns upon itself at the surface and comes to rest. The water next passes over the succeeding downstream weir and continues the cycle. In a pool and weir fishway an excess of water over the weir causes streaming flow which tends to

skim over the top of the static water surface and continue downstream at an unreduced velocity. This streaming flow could be expected in a baffled culvert at relatively low discharge, as there is insufficient depth or volume in the pools to dissipate the energy of the jet. In the transition between plunging and streaming flow there is a range of unstable flow which results in surge.

Another reason for the inefficiency of this type of baffling is that the limited depth of water in the pools restricts the leaping ability of the fish. Upstream migrant salmon and steelhead generally range from 2 to 3 feet in length. Fish of this size have difficulty in leaping from a pool only 8 to 12 inches deep. In addition to the above points, required resting area would be unobtainable in such shallow pools. Because of the above reasons these transverse low baffles are no longer used in the state of Washington.

Experimentation by the Washington State Department of Fisheries (1) has led to the conclusion that fish should be allowed to swim freely through a culvert rather than be forced to leap barriers. In other words, baffling should be designed so that the fish could swim through openings in the baffles.

It is the author's opinion that Mr. Shoemaker has approached the job of investigating the hydraulics of a culvert under maximum discharge conditions in a thorough manner. This is one facet of the culvert problem with which fisheries interests are only indirectly involved. This discussion is offered in the form of constructive criticism rather than difference of opinion as to Mr. Shoemaker's paper. It should be pointed out again that fish passage must be considered as part of the efficiency of a culvert when the culvert is in the path of fish migration. It is hoped that the statements made herein will further the understanding of both highway and fisheries agencies as regards this problem common to both parties.

REFERENCE

1. MCKINLEY, W. R., AND WEBB, R. D., "A Proposed Correction of Migratory Fish Problems in Box Culverts, Washington State Department of Fisheries," Fisheries Research Papers, Vol. 1, No. 4, 1956.

ROY H. SHOEMAKER, JR., *Closure*—Apparently there is a need for clarification of the objectives of this study from the standpoint of the "major interests" discussed by McKinley in regard to the problem of fish passage through box culverts.

The principal concern of the fisheries agencies is obviously that of maintaining free access for anadromous fishes to the upper reaches of small streams, while that of the highway agencies is of providing for adequate and economical drainage for road beds. In cases where fishways must be provided in box culverts on steep grades, the major hydraulic problem of the culvert designer lies in satisfactory determination of minimum dimensions for such culverts consistent with their required discharge capacities. A lack of information concerning the hydraulic characteristics of box culverts with fishways suggested the need for the studies reported herein.

Prior to the start of the experimental studies of the hydraulics of box culverts with fish-ladder baffles, a study was made to investigate the possible types of fishways suitable for use

in box culverts. It was concluded from this preliminary study that transverse baffles would exhibit to a safe degree the same hydraulic characteristics with respect to flow resistance in a full culvert, as most types of culvert fishways which have been used in the past or which might be contemplated for use in the future. Therefore, the results of these experiments are assumed to be applicable to fishways consisting of different types of baffle arrangements which would offer approximately the same character of flow resistance as transverse baffles. The proper hydraulic design of culverts having types of fishways offering a markedly different character of flow resistance would require data from additional experimental studies similar to those reported in this paper.

The reader should note carefully that the reported experiments were designed with the objective of determining the hydraulic characteristics of baffled culverts and not, as might be construed, to develop a fishway suitable for use in box culverts.