FLOW CHARACTERISTICS OF WATER AT THE ENTRANCE TO A CIRCULAR DROP-INLET

by

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INTRODUCTION

Drop-inlet spillways have been used in Kansas for many years. The use of dams with drop-inlet spillways has evolved from the small earth dam known as the "gully plug". Dams with drop-inlet spillways in effect reduce the gradient of the ditch channel, where the "gully plug" just moved the ditch to a new location. The drop-inlet is used in various types of dams, such as detention, stockwater, and erosion control. In Kansas the erosion control dam is probably the type of dam in which the drop-inlet spillway is used most often, although practically all structures in the State's watershed program use drop-inlets as the primary spillway.

The drop-inlet in this paper is assumed as a vertical pipe, known as the riser, connected to a horizontal pipe, known as the barrel. The drop-inlet assumes the characteristics of a siphon when the spillway operates with pressures less than atmospheric. Blaisdell (8) defines the part of the spillway controlling the head-discharge relationship as a weir at the conduit entrance, an orifice at the conduit entrance, a section of conduit acting as a short tube, or conduit flowing as a full pipe.

The economics of dam construction, when erosion control dams are being designed, is controlled mainly by pipe or drop-inlet size. The design has changed many times; at one time the flow was calculated for the barrel and then the riser diameter was designed as 1.25 times the barrel diameter. Another was to design for full pipe flow and check capacity at the entrance for weir flow and at the elbow for orifice flow. Now, in Kansas, the design is for full pipe flow and the inlet is checked for capacity at the entrance for weir and orifice flow, and at the elbow for orifice flow. The erosion control dams are designed to carry approximately a 5-year frequency storm through the primary spillway, which means that on the average the emergency spillway will be used only once in 5 years. Thus, in some cases, large pipes up to 60 inches in diameter have had to be used. If the pipe size could be made smaller a great benefit to the Kansas farmer and the Federal government would be realized.

STATEMENT OF PROBLEM

Although drop-inlet spillways have been used in Kansas for many years and work in the laboratory has been done on the design of them, questions still arise on the design. The most economical design has been proven to be when the drop-inlet spillway operates as a full tube. Thus, the controlling criterion in the design of the primary spillway was to make full-tube flow the controlling flow. In the design of the spillway, checks are made at critical points to see that they do not restrict flow. Until recently the entrance to the riser was considered a weir and no thought was given to the fact that the vertical pipe could act as an orifice at the entrance. When it was recognized that the entrance could be an orifice it posed a problem for the designers. They had used procedures that seemingly worked, with most of the trouble being related directly to poor construction. Whether or not orifice flow was a controlling factor was unknown. But because of the need for assurance of a proper design, the checking of the entrance of the drop-inlet for orifice flow control was begun. As a result of orifice flow considerations, larger diameter risers sometimes had to be used. This increased the cost of the dam.

The question of whether or not checking orifice control at the entrance was a proper design procedure remained. Therefore, this study was undertaken for the purpose of studying the drop-inlet spillway to find out if orifice flow is obtained at the entrance and if it is ever a controlling factor.

REVIEW OF LITERATURE

The first reported information on the design of drop-inlet spillways was in 1933. The study was made on models by a group of engineers from Wisconsin and their findings were written by L. H. Kessler (21). From his paper the following results were obtained. For the design of a prototype a ratio of head to diameter (H/D_v) equal to 1.2 should provide a sufficient head over the lip to cause any standard drop-inlet to flow full. Tests on bends or elbows indicate that the loss caused by the elbow is not in the elbow, but occurs as additional friction forces due to increased disturbances set up for some distance downstream from the elbow. Also the barrel needs to be 30 diameters in length to overcome this elbow effect. It was recommended that the barrel slope not exceed the hydraulic gradient of the barrel.

Beasley (1) ran many tests on drop-inlet spillways and although he generalized his work, the results are significant. He stated the capacity of a tube structure varies directly with the head of water causing flow. If the tube does not flow full, the head is the vertical distance between the center of the tube at its entrance and the water surface above the entrance. If the tube flows full, the head is the vertical distance between the center of its outlet end and the water surface above the entrance. If the outlet end is submerged, the head is the vertical distance between the water surface at the outlet and the water surface above the entrance. Another important fact is that when the tube is flowing full, increased friction loss in the tube will tend to decrease its capacity. This will be more than offset, however, by the increased capacity due to the higher head. Thus, maximum capacity for a given tube will be obtained if the entrance is designed to make the tube flow full. It is desirable to have the tube flow full with as shallow a depth as possible over the entrance. This will reduce the cost of construction and avoid difficulties encountered with impounding greater depths of water.

Beasley found also that a greater depth of water over the entrance and in the riser was required to cause the tube to flow full as the height of the vertical riser measured from the center of the tube to the top of the entrance was increased. The diameter of the risers used in Beasley's (1) tests were 2.5 inches, 3.0 inches, and 3.5 inches with a 2.0-inch barrel in all cases. The riser lengths were varied from 2.5 inches to 10 inches. The height of water over the two largest diameter risers needed to cause full pipe flow was the same, but a greater height was needed when the 2.5-inch diameter riser was used. As the slope in the tube (barrel) was increased, a greater depth of water over the entrance was required to cause the tube to flow full. It was found that length of tube had little effect. It was recommended that a ratio of 1.5 to 1 (riser diameter to barrel diameter) be used in design work, and, that the depth of water over the riser be at least 3/4 the diameter of the tube.

Important work on drop-inlets has been done by F. W. Blaisdell (8) at the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota. As stated earlier, Blaisdell stated there are four main types of control, (1) weir control, (2) orifice control, (3) short tube control, and (4) full pipe control. He gives a very good description of the types of flow and the conditions under which they exist.

> When the flow to the spillway is greater than 0.9 [0.9 cfs.] the head will increase first along the weir curve to its intersection with the orifice curve then along the orifice curve. At some unknown pond or reservoir level the outflow rate will jump abruptly from the orifice curve to the pipe curve. The pipe may control the discharge if the rate of inflow to the pond is great enough. If the outflow rate exceeds the inflow rate, the reservoir is drawn down first along the pipe flow curve to its intersection with the weir curve then along the weir flow curve. The flow may stabilize on the weir flow curve or it may jump to either the short tube or orifice curves, possibly resulting in a further buildup of the head pool level and repetition of the cycle. As observed to date, the jump across is always to the pipe curve from either the orifice or short tube curves and never to the short tube curve from the orifice curve.

Blaisdell goes on to say that the short tube effect cannot be reached directly. It can exist only after having full pipe flow and the pool level is drawn down along the weir curve. If orifice or short tube control exists, a constant head above the inlet may never exist, even if the inflow is the same as the outflow, because there may be a constant rising and falling from weir flow to one of these controls. However, if the spillway is designed so that orifice control or short tube control can never exist, then a definite relationship can be established between head and discharge, provided that inflow and outflow are equal and a constant pool level can be obtained. For the two main flows, weir and full pipe flow, the basic equations have been derived. For weir flow

$$Q = CL \sqrt{2g}H^{3/2} \tag{1}$$

and for pipe flow

$$Q = \frac{\pi D^2}{4}\sqrt{\frac{2gH+}{K_r+K_o+f\frac{l}{D}+f_r\frac{l_r}{4R_r}(\frac{A}{A_r})^2}} \tag{2}$$

where

$$H_t = \left[K_r+K_o+f\frac{l}{D}+f_r\frac{l_r}{4R_r}(\frac{A}{A_r})^2\right]\frac{V_r^2}{2g} \tag{3}$$

From the weir equation a semi-dimensionless form has been obtained by dividing each side by $D^{5/2}$ thus obtaining

$$\frac{Q}{D^{5/2}} = C\frac{L}{D}\left(\frac{H}{D}\right)^{3/2} \tag{4}$$

where

A = area of barrel, in feet squared

A_r = area of riser, in feet squared

C = discharge coefficient

D = conduit diameter, in feet (riser)

g = acceleration of gravity, in feet per second squared

f = Darcy-Weisbach friction factor for barrel

f_r = Darcy-Weisbach friction factor for riser

H_t = total head in feet

K_r = entrance loss coefficient

K_o = outlet loss coefficient

l = length of conduit in feet

V_r = velocity in riser, feet per second

l_r = length of riser in feet

L = crest length, in feet

Q = discharge in cfs.

Plastic pipe was used for some of the tests and was considered smooth - then later it was tested and proven to be smooth. The tests showed that pipes laid on slopes steeper than that of the hydraulic grade line and discharging freely may flow completely full. This was contrary to beliefs before Blaisdell's tests. As shown by the tests, small models can be used to predict the performance of their prototypes even though air is mixed with the water and vacuums are present in the structure. It was found also that the barrel length had to be only 20 diameters for the elbow effect to be non-significant as compared to 30 diameters as stated by Kessler (21).

Binnie (3) from England ran tests on a trumpet mouth vertical tube 5 feet long. The object of these tests was to determine the relation between the discharge Q and the head H of the water above the top of the pipe. The relationship between the head and the discharge rate was found to be the same whether the head was rising or falling. At heads slightly greater than the critical, the flow was sometimes disturbed by transient vortices.

Later Binnie and Hooking (4) did work on vortices at the University of Cambridge. They found that a vortex greatly reduced the discharge, the decrease being more marked with the shallow than with the deep trumpet. At low heads, where the flow was controlled by the weir action of the trumpet crest, the discharge varied with the shape of the crest as well as with the entrance coefficient C and the head. At high heads with the trumpet flooded, the throat controlled the flow. Within certain limits, the discharge was dependent chiefly upon C and the head, measured with the throat as the datum. Also an approximate theory which ignores friction was verified. Two types of instability, "surfing" at low heads and "spluttering" at high heads, were examined. Both were due to the collapse and subsequent re-formation of feeble vortices, which caused the discharge to vary with time in a periodic manner.

Culp (11) gives a method for designing drop-inlets with detention above them. The detention storage is the storage space between the normal pool level and the actual water surface during flood flow. This is a way of cutting down pipe size, but more earth fill must be made as the dam itself will have to be made higher. The design of these is the same as for other dams, that is, full flow is the limiting factor.

Dodge (13) studied models of drop-inlets and applied the Bernoulli theorem to the problem. He used the following dimensionless terms

$$\frac{Q}{Q_m} = \frac{V}{V_m}\left(\frac{D}{D_m}\right)^2 \qquad (5)$$

where

$$\frac{V}{V_m} = \sqrt{\frac{H\left[1.4 + 0.01\left(\frac{L}{D}\right)\right]}{H_m\left[1.4 + 0.01\left(\frac{L_m}{D_m}\right)\right]}} \qquad (6)$$

where

0.01 = friction (f) for the pipe

H = entrance loss + conduit friction loss + elbow loss + exit loss

The subscript, m, stands for model.

Nelson (23) used a 6-inch by 6-inch square Lucite drop-inlet to run tests. He found in his search that the drop-inlet, as such, has over 18 different names used in the literature. He defines five different types of flows. Type I was called weir flow with clinging nappe; this type of flow occurred at low heads (below 0.12 feet). The weir action over the spillway crest seemed to be responsible for maintaining this flow regime. Type II was called weir flow with aerated nappe; this was the regime most commonly observed. This type of flow depended on the critical depth located either on or immediately upstream from the lip. Type III was called orifice flow; it was a direct result of increasing the head from the Type II flow. An increase in the vortex action was noticed in the transition between Type II flow and Type III flow. Type IV was called vortex flow; it was produced by a vortex of relatively high strength. During this type of flow, unsteady heads were typical of this regime. Type V was called full flow; this occurred when there was no vortex core in the spillway tower. Nelson (23) concluded that further study, using models of drop-inlet spillways, should be made.

It can be seen that there is no general agreement on the types of flow in the drop-inlet spillway or on correct design procedures.

EQUIPMENT AND PROCEDURE

It was decided that this problem could be handled with dimensional analysis and a model to expedite the experimental work. Reference to ASCE Hydraulic Circular No. 25 (20) led to the decision that the drop-inlet spillway would follow the Froude Model Law more closely than any other; this assumes that the force of gravity is the only force producing motion. Other forces are neglected, and within certain limits this is approximately true.

In making the dimensional analysis of the problem, the following factors were considered:

D_r = diameter of riser - L

D_b = diameter of barrel - L

L_r = length of riser - L

L_b = length of barrel - L

μ = dynamic viscosity - $FL^{-2}T$

σ = surface tension of fluid - FL^{-1}

g = gravitational force - LT^{-2}

ρ = mass density of water - $FL^{-4}T^{2}$

V = velocity of fluid - FL^{-1}

e = roughness of the pipe - 1

H = head - L

Using Buckingham's Pi theorem it was seen that there are eleven unknowns with three basic dimensions so there will be eight dimensionless terms.

$$Q = f\left(e, \frac{D_r}{D_b}, \frac{L_r}{D_r}, \frac{L_b}{D_r}, \frac{H}{D_r}, N_R, N_W\right) \sqrt{g}\, D_r^{5/2} \tag{7}$$

Because the Froude Model Law was used and similarity between the model and prototype assumed, Weber's number (N_W) and Reynold's number (N_R) were neglected. If a smooth pipe model is related to a smooth pipe prototype, the roughness (e) can be dropped as a significant variable. Thus, discharge for the smooth model (Q_{ms}) equals some scale factor n times the discharge for the smooth prototype (Q_{ps}); if this were to be related to a rough pipe prototype the roughness would have to be included as a variable. In this problem roughness was not taken into account. Also, when the length of the barrel is 20 diameters or more the barrel effect can be neglected, Blaisdell (8). In the tests where the barrel was used the length was 27 diameters, therefore, $\frac{L_b}{D_r}$ was considered insignificant and neglected. This leaves the following functional equation

$$\frac{Q}{\sqrt{g}\, D_r^{5/2}} = f'\left(\frac{D_r}{D_b}, \frac{L_r}{D_r}, \frac{H}{D_r}\right) \qquad (8)$$

In all tests $\frac{D_r}{D_b}$ was held constant at 1.34, and $\frac{L_r}{D_r}$ was varied at values of 1.25, 3.73 and 5.92. $\frac{H}{D_r}$ was varied between limits of 0.1 and 4.01 for each series of tests. Twenty tests per series were used at first, then as the experiment proceeded and when it was known approximately where the critical points would be, the number of tests per series was reduced to ten. As stated above this model cannot be used to relate discharge and head on any prototype except for one with a smooth pipe, but the types of flow obtained in the model should be the same as in a smooth or rough prototype. It was assumed that the change in the characteristic flows could be determined by the curves and their slopes.

The equipment used in the tests was of a simple nature. A common 6-foot diameter tank 2 feet deep was used as the pool or stilling area as shown in Plate I. A 2 feet by 2 feet sheet metal plate was fixed to the bottom in the center of the tank so that the seams of the tank would not affect the flow. A 3 1/16-inch hole was made in the center of the

EXPLANATION OF PLATE I

The testing equipment for the drop-inlet, including the weighing equipment used in calibration of the triangular weir.

PLATE I

plate and in the bottom of the tank to receive the drop-inlet to be tested. A five-foot circle of rocks, four inches thick and 1 1/2-feet high, was placed around the small hole in the center to reduce the water's energy. Plate II shows the metal in the bottom and the arrangement of the circle of rocks.

A way of measuring the head on the drop-inlet was needed. Since direct measurement inside the tank would be bothered by waves and vibrations, a method for measuring outside the tank was devised. A 3/8-inch hole was made in the tank as shown in Plate II. The hole had a small copper tube attached to it, and then a hose connected the copper tube to a gallon can on the outside of the tank as shown in Plate III. Thus, the water level in the tank could be measured with a hook gage at any time and not be bothered with small fluctuations, if any were present. The hook gage was read just as the hook was about to form a dimple in the water surface. The gallon can could be raised with blocks if the head inside the tank exceeded the height of the can. The zero reading of the hook gage for the inlet was determined with a surveying level. A reading was taken on the inlet, the target was fixed and then the rod was moved to the hook gage where the zero reading on the gage was determined. The hook gage was read to 0.001 foot.

Water was supplied to the tank from a 4-inch galvanized steel pipe which was connected to the 6-inch main line in the laboratory. The 4-inch line made a T-joint just above the tank thus enabling the flow to be more evenly distributed around the tank (Plate I). The 4-inch pipe outlets were about 2 inches from the bottom of the tank, and two 5-inch diameter pipes 4 inches high were placed around the 4-inch pipe to dissipate some of the energy of the water as it was leaving the pipe.

EXPLANATION OF PLATE II

View of the stilling tank from the top. The 3/8-inch hole is up and to the right of the entrance to the model.

PLATE II

EXPLANATION OF PLATE III

The picture shows the gallon can which is connected to the 3/8-inch hole in the tank and the hook gage which was used to determine the water level inside the can.

PLATE III

An anti-vortex device was used in all the tests since it was not the object of these tests to determine what a vortex does to the flow. Also, an anti-vortex device is used under most field conditions. The anti-vortex device used was 3 1/2-inches by 6-inches by 1/32-inch piece of metal and was suspended from a 1 1/2-inch by 1 1/2-inch by 7-foot stick across the top of the tank (Plate II). This made it easy to remove and it was, from time to time, just for the writer's curiosity.

The tank was located 28 1/2-inches off the floor; this was accomplished by using two rows of concrete blocks 3 courses high with two 2-inch by 4-inch boards on top of them (Plate I). Six aluminum T-beams were used to support the tank.

At first it was thought that the venturi meter could be used for measuring flow, but it was not accurate enough for low flows. It was decided to use the triangular weir that Spomer (27) had built and calibrated the year before. The weir had been calibrated in a tank and then placed in the channel (Plate IV). Since there was some doubt as to whether the channel had an effect on the flow, the weir was calibrated in place. To do this a weighing device consisting of a tank 7-feet by 2 1/2-feet by 10-inches placed on a 1,000-pound-capacity Fairbanks-Morse scales (Plate I) was used. After a few trials, the channel was blocked 15 feet up channel from the weir so that less time was required for the head on the weir to come to equilibrium. This also reduced the wave action in the channel. A perforated pipe was used from the weighing tank to the channel to minimize the splash effects. A rock baffle 6 inches thick was placed in the channel 6 feet above the weir and the hook gage used in determining the head was placed 4 feet above the weir

EXPLANATION OF PLATE IV

The triangular weir operating in the channel where calibrated.

PLATE IV

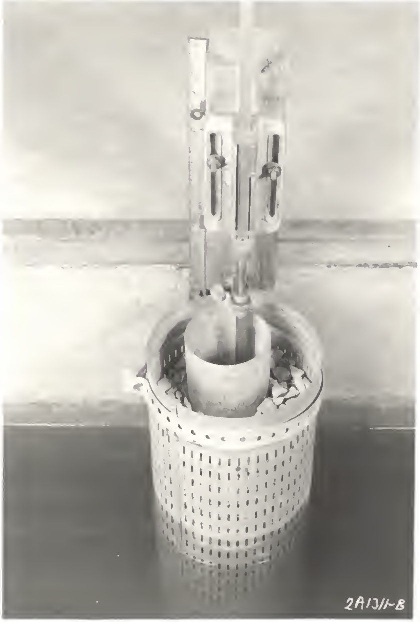
so that the draw down of the weir would have no effect on its reading. The hook gage (Plate V) was located inside two perforated tubes which had approximately 2 inches of crushed rock between them. The zero reading of the weir was determined by removing water until the water level above the weir was just even with the lowest point of the weir notch, then a hook gage reading was taken to determine the zero reading. The hook gage was read to 0.001 foot.

The model of the drop-inlet structure was made of clear plastic. One barrel 40 inches long and 1 33/64-inches in diameter was obtained. The elbow was machined from a block of clear plastic and then polished. Three different lengths of risers were obtained with a diameter of 2 1/32-inches. The lengths were 12-inches, 7 9/16-inches and 2 5/8-inches. Tests were run on each riser by itself and with each riser with the barrel in place. This gave 6 different series of tests. The risers were held in place by using two rubber gaskets and a circular plastic clamp down device, which provided a water-tight band between the tank and the vertical tube. A picture of the risers, elbow, barrel, and clamping device is shown in Plate VI. The risers were clamped in place so that the top edge was about 1/2-inch above the clamping device. This was to prevent the clamping device from having an effect on the inflow. The plastic tube had a wall thickness of approximately 1/4-inch, thus it can be seen that it was a broad crested weir and not a sharp edged weir when the structure functioned as a weir. The riser in place can be seen in Plate II as viewed from the top. The elbow and tubes were made with screw fittings so they could be put on or taken off as desired. A small amount of grease was used on the fittings for ease of assembly and for water tightness.

EXPLANATION OF PLATE V

The hook gage used to determine the head on the weir and also the stilling basin for the gage.

PLATE V



EXPLANATION OF PLATE VI

The testing equipment used for the model and the device used for placing the model in the bottom of the stilling tank.

PLATE VI

Tests were run at the same time on the medium riser with the elbow and barrel and for the calibration of the weir. A Hill-Tripp pump operated by a 40 horsepower rheostat controlled three-phase induction motor was used to provide flow. The discharge from the pump was regulated by two valves and the rheostat. When the head in the tank came to equilibrium, as determined by checks at least one minute apart, the hook gage reading for the inlet was taken. Then by the same method, when it was determined that the head on the weir was in equilibrium, the hook gage in the channel was read. A quantity of water, 300-400 pounds depending on flow rate, was collected for a timed period and weighed. This was done by placing the rubber gasket and stopper, as shown beside the tank in Plate I, in place and then setting the scales on some even quantity. As the arm of the scales moved up, the stopwatch, which read to 0.01 of a minute, was punched and the timing begun. The scales were then set for 300 or 400 pounds more weight and as the arm moved up the stopwatch was stopped. Thus weight and time were recorded and the discharge rate in cubic feet per second was easily calculated. Since the head on the weir for that particular flow was known, the relationship of discharge versus head on the weir was determined. The rest of the series were run exactly as stated above, changing head on the inlet and measuring the discharge by the triangular weir, except that the weighing device was not used. Tests were run for each riser and for each riser with the barrel attached. The time for each test ranged from 10 minutes to one hour, depending on the type of flow.

The temperature was taken each day to determine if there would be any noticable change in viscosity.

RESULTS

The results for calibration of the triangular weir are shown as a curve in Fig. 1, where discharge versus the head on the weir is plotted. The equation of the curve was obtained by the use of curvilinear regression, a statistical method of using the least squares. The equation determined was

$$Q = 2.20H^{2.46} \qquad (9)$$

where

Q = discharge in cubic feet per second

H = head on the weir in feet

The fit of the points to the curve was very good with a correlation coefficient, r, of 0.998. The equation obtained compares closely with the theoretical, the theoretical being

$$Q = 2.5H^{2.5} \qquad (10)$$

for a 90° notch, from King (22). The points taken for the calculated equations were in the range of the head needed for the experiment. Also equation (9) compares well with Spomer's (27) equation

$$Q = 2.57H^{2.49} \qquad (11)$$

Spomer did his calibration work with the weir in a tank and not in the channel; he also used a wider range of heads on the weir than was used for the equation (9).

The weir was used for the calculation of discharge for the rest of the experiment and the equation (9) as calculated was used for determining the discharge. The heads read and discharges computed from weighing with the prefix BB shown in Table I, were used in calibration of the triangular weir.

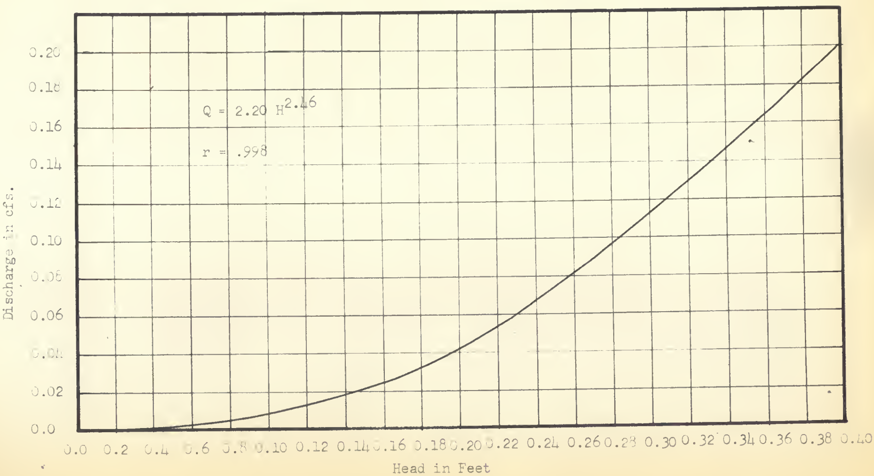


Figure 1. Head-Discharge for a Triangular Weir.

Table 1. Table of individual tests and the calculated dimensionless terms.

Test No.	Head on Weir	cfs.	Head on Inlet	$\frac{Q}{\sqrt{g}\, D^{5/2}}$	D_r/D_b *	L_r/D_r	H/D_r
A1	.076	.004	.019	.019	-	1.25	.11
A2	.125	.011	.026	.052	-	1.25	.15
A3	.133	.014	.030	.067	-	1.25	.18
A4	.137	.016	.035	.076	-	1.25	.21
A5	.141	.018	.036	.086	-	1.25	.21
A6	.145	.019	.039	.090	-	1.25	.23
A7	.157	.023	.044	.110	-	1.25	.26
A8	.152	.021	.037	.100	-	1.25	.22
A9	.191	.037	.056	.176	-	1.25	.33
A10	.202	.043	.062	.205	-	1.25	.37
A11	.212	.049	.067	.233	-	1.25	.40
A12	.220	.053	.208	.252	-	1.25	1.23
A13	.223	.055	.233	.262	-	1.25	1.38
A14	.227	.057	.253	.271	-	1.25	1.50
A15	.250	.074	.434	.352	-	1.25	2.57
A16	.226	.057	.248	.271	-	1.25	1.47
A17	.217	.051	.194	.243	-	1.25	1.15
A18	.204	.044	.138	.210	-	1.25	.82
A19	.168	.027	.051	.129	-	1.25	.30
A20	.115	.009	.021	.043	-	1.25	.12
A21	.163	.025	.044	.119	-	1.25	.26
A22	.190	.037	.055	.176	-	1.25	.33
A1a	.117	.011	.031	.052	-	1.25	.18
A2a	.175	.030	.054	.143	-	1.25	.32
A3a	.204	.044	.072	.210	-	1.25	.43
A4a	.229	.059	.082	.281	-	1.25	.49
A5a	.243	.068	.089	.324	-	1.25	.53
A6a	.267	.086	.178	.410	-	1.25	1.05
A7a	.282	.098	.297	.467	-	1.25	1.76
A8a	.296	.110	.429	.524	-	1.25	2.54
A9a	.277	.094	.253	.448	-	1.25	1.50
A10a	.270	.088	.196	.419	-	1.25	1.16
AA1	.129	.014	.037	.067	1.34	1.25	.22
AA2	.152	.021	.046	.100	1.34	1.25	.27
AA3	.173	.030	.053	.143	1.34	1.25	.31
AA4	.195	.039	.085	.186	1.34	1.25	.50
AA5	.208	.046	.236	.219	1.34	1.25	1.69
AA6	.222	.054	.435	.257	1.34	1.25	2.57
AA7	.215	.050	.331	.238	1.34	1.25	1.96
AA8	.196	.040	.084	.190	1.34	1.25	.50

*When D_r/D_b has a dash, this means the elbow and barrel were not used.

Table 1 (cont.)

Test No.	Head on Weir	cfs.	Head on Inlet	$\frac{Q}{\sqrt{g}\, D^{5/2}}$	D_r/D_b *	L_r/D_r	H/D_r
AA9	.167	.027	.049	.129	1.34	1.25	.29
AA10	.138	.017	.039	.081	1.34	1.25	.23
B1	.092	.006	.020	.029	-	3.73	.12
B5	.174	.030	.051	.143	-	3.73	.30
B7	.122	.012	.029	.057	-	3.73	.17
B8	.128	.014	.032	.067	-	3.73	.19
B9	.178	.031	.054	.148	-	3.73	.32
B10	.203	.044	.065	.210	-	3.73	.38
B11	.229	.059	.078	.281	-	3.73	.46
B12	.250	.073	.087	.348	-	3.73	.51
B13	.274	.091	.098	.433	-	3.73	.58
B14	.303	.123	.113	.586	-	3.73	.67
B15	.332	.145	.422	.690	-	3.73	2.50
B16	.340	.155	.565	.738	-	3.73	3.34
B17	.332	.145	.473	.690	-	3.73	2.80
B18	.315	.129	.213	.614	-	3.73	1.26
B19	.289	.103	.106	.490	-	3.73	.63
B20	.265	.084	.096	.310	-	3.73	.57
B21	.221	.054	.075	.257	-	3.73	.44
B22	.180	.032	.054	.152	-	3.73	.32
B23	.138	.017	.035	.081	-	3.73	.21
B24	.126	.013	.030	.062	-	3.73	.18
B1a	.121	.012	.022	.057	-	3.73	.13
B2a	.149	.020	.036	.095	-	3.73	.21
B3a	.174	.030	.056	.143	-	3.73	.33
B4a	.202	.043	.125	.205	-	3.73	.79
B5a	.216	.051	.197	.243	-	3.73	1.17
B6a	.232	.060	.291	.286	-	3.73	1.72
B7a	.248	.072	.421	.343	-	3.73	2.49
B8a	.227	.057	.256	.271	-	3.73	1.52
B9a	.197	.040	.115	.190	-	3.73	.68
B10a	.161	.025	.042	.119	-	3.73	.24
BB1	.082	.005	.018	.024	1.34	3.73	.11
BB2	.114	.010	.026	.048	1.34	3.73	.15
BB3	.127	.013	.032	.062	1.34	3.73	.19
BB4	.160	.024	.046	.114	1.34	3.73	.27
BB5	.194	.039	.062	.186	1.34	3.73	.37
BB6	.214	.049	.075	.233	1.34	3.73	.44
BB7	.231	.060	.110	.286	1.34	3.73	.65
BB8	.248	.071	.490	.338	1.34	3.73	2.90
BB9	.243	.070	.409	.333	1.34	3.73	2.42

*When D_r/D_b has a dash, this means the elbow and barrel were not used.

Table 1 (Cont.)

Test No.	Head on Weir	cfs.	Head on Inlet	$\frac{Q}{\sqrt{g}\,D^{5/2}}$	D_r/D_b *	L_r/D_r	H/D_r
BB10	.217	.051	.079	.242	1.34	3.73	.47
BB11	.233	.063	.194	.300	1.34	3.73	1.15
BB12	.191	.037	.061	.176	1.34	3.73	.36
BB13	.172	.028	.050	.133	1.34	3.73	.30
BB14	.150	.020	.040	.096	1.34	3.73	.24
BB15	.126	.014	.043	.067	1.34	3.73	.25
BB16	.173	.029	.051	.138	1.34	3.73	.30
BB17	.188	.036	.060	.171	1.34	3.73	.36
BB18	.193	.040	.064	.190	1.34	3.73	.38
BB19	.234	.061	.181	.290	1.34	3.73	1.07
BB20	.297	.072	.466	.343	1.34	3.73	2.76
C1	.099	.007	.019	.033	-	5.92	.11
C2	.127	.014	.031	.067	-	5.92	.18
C3	.192	.038	.058	.180	-	5.92	.34
C4	.217	.051	.072	.243	-	5.92	.43
C5	.243	.068	.083	.324	-	5.92	.49
C6	.266	.085	.093	.405	-	5.92	.55
C7	.339	.154	.234	.733	-	5.92	1.38
C8	.348	.158	.294	.752	-	5.92	1.74
C9	.340	.155	.248	.738	-	5.92	1.47
C10	.353	.170	.490	.809	-	5.92	2.90
C11	.336	.150	.190	.714	-	5.92	1.12
C12	.301	.114	.109	.543	-	5.92	.64
C13	.284	.099	.099	.471	-	5.92	.59
C14	.269	.088	.094	.419	-	5.92	.56
C15	.250	.073	.086	.348	-	5.92	.51
C16	.219	.053	.070	.252	-	5.92	.41
C17	.177	.031	.051	.148	-	5.92	.30
C18	.147	.019	.037	.090	-	5.92	.22
C19	.119	.012	.026	.057	-	5.92	.15
C20	.130	.015	.032	.071	-	5.92	.19
CC1	.118	.012	.026	.057	1.34	5.92	.15
CC2	.131	.015	.031	.071	1.34	5.92	.18
CC3	.162	.025	.043	.119	1.34	5.92	.25
CC4	.192	.038	.054	.181	1.34	5.92	.32
CC5	.204	.044	.064	.210	1.34	5.92	.38
CC6	.236	.063	.079	.300	1.34	5.92	.47
CC7	.247	.070	.102	.333	1.34	5.92	.60
CC8	.257	.078	.385	.371	1.34	5.92	2.28
CC9	.226	.085	.678	.405	1.34	5.92	4.01
CC10	.264	.084	.579	.400	1.34	5.92	3.43

*When D_r/D_b has a dash, this means the elbow and barrel were not used.

Table 1 (concl.)

Test No.	Head on Weir	cfs.	Head on Inlet	$\frac{Q}{\sqrt{g}\,D^{5/2}}$	D_r/D_b *	L_r/D_r	H/D_r
CC11	.255	.077	.316	.367	1.34	5.92	1.87
CC12	.233	.061	.078	.290	1.34	5.92	.46
CC13	.223	.055	.074	.262	1.34	5.92	.44
CC14	.215	.050	.069	.238	1.34	5.92	.41
CC15	.194	.040	.063	.190	1.34	5.92	.37
CC16	.169	.028	.047	.133	1.34	5.92	.28
CC17	.149	.020	.037	.095	1.34	5.92	.22
CC18	.121	.012	.026	.057	1.34	5.92	.15
CC19	.174	.030	.049	.233	1.34	5.92	.29
CC20	.193	.040	.059	.281	1.34	5.92	.35

*When D_r/D_b has a dash, this means the elbow and barrel were not used.

Table I also shows the heads obtained on the inlet and triangular weir, and the calculated discharge for the remainder of the tests. The computed dimensionless terms are also shown in this table. The test numbers are shown with either a single or double letter preceding the numerical number; this designates the size of riser and whether or not a barrel was connected to the riser. The letter A was for the short riser, B for the medium riser, and C for the long riser. A single letter preceding the numerical number means the riser alone was used for the test, and a double letter preceding the numerical number means the elbow and barrel were connected to the riser.

The results of plotting the dimensionless terms are shown as a group of curves in Fig. 2. Table II gives the equations and the type of flow observed for each curve; linear regression, a statistical method, was used in determining these equations. The correlation coefficients show a good fit of the points to the curves in all cases and extremely good on some curves. The explanation of these curves in Fig. 2 will be the same as those in Fig. 3. Table III gives the formulas for the equations of the curves in Fig. 3.

Definitions of the different types of flow as observed should be given. There were five basic types: (1) clinging nappe, (2) weir flow with aerated nappe, (3) orifice flow at the inlet's entrance, (4) the vertical tube flowing full with no air, and (5) the riser, elbow, and barrel flowing full.

Clinging nappe flow occurred when the water first started over the crest of the inlet as shown in Fig. 2 of Plate VII. If not disturbed it would continue until full pipe flow of either the riser or barrel became the controlling factor. There was always air in the

Table 2 (concl.)

Equation Number	Type of Flow	D_r/D_b *	L_r/D_r	Equation Obtained	Correlation Coefficient
20	Full tube	1.34	5.92	$\frac{Q}{\sqrt{g}\, D_r^{5/2}} = .322 + .022\,(H/D_r)$	r = .879
21	Orifice Flow	-	-**	$\frac{Q}{\sqrt{g}\, D_r^{5/2}} = .146 + .081\,(H/D_r)$	r = .997

*When D_r/D_b has a dash, this means the elbow and barrel were not used or had no effect.

**The ratio of L_r/D_r had no effect.

Table 2. Equations obtained with dimensional analysis with the different types of flow.

Equation Number	Type of Flow	D_r/D_b*	L_r/D_r	Equation Obtained	Correlation Coefficient
12	Weir & clinging nappe	-	1.25	$\frac{Q}{\sqrt{g}\,D_r^{5/2}} = -.038 + .602(H/D_r)$	r = .843
13	Full tube	-	1.25	$\frac{Q}{\sqrt{g}\,D_r^{5/2}} = .333 + .076\ (H/D_r)$	r = .994
14	Full tube	1.34	1.25	$\frac{Q}{\sqrt{g}\,D_r^{5/2}} = .172 + .033\ (H/D_r)$	r = .856
15	Weir & clinging nappe	-	3.73	$\frac{Q}{\sqrt{g}\,D_r^{5/2}} = .087 + .787\ (H/D_r)$	r = .960
16	Full tube	-	3.73	$\frac{Q}{\sqrt{g}\,D_r^{5/2}} = .547 + .055\ (H/D_r)$	r = .992
17	Full tube	1.34	3.73	$\frac{Q}{\sqrt{g}\,D_r^{5/2}} = .267 + .026\ (H/D_r)$	r = .976
18	Weir & clinging nappe	-	5.92	$\frac{Q}{\sqrt{g}\,D_r^{5/2}} = -.093 + .887\ (H/D_r)$	r = .887
19	Full tube	-	5.92	$\frac{Q}{\sqrt{g}\,D_r^{5/2}} = .660 + .052\ (H/D_r)$	r = .998

*When D_r/D_b has a dash, this means the elbow and barrel were not used or had no effect.

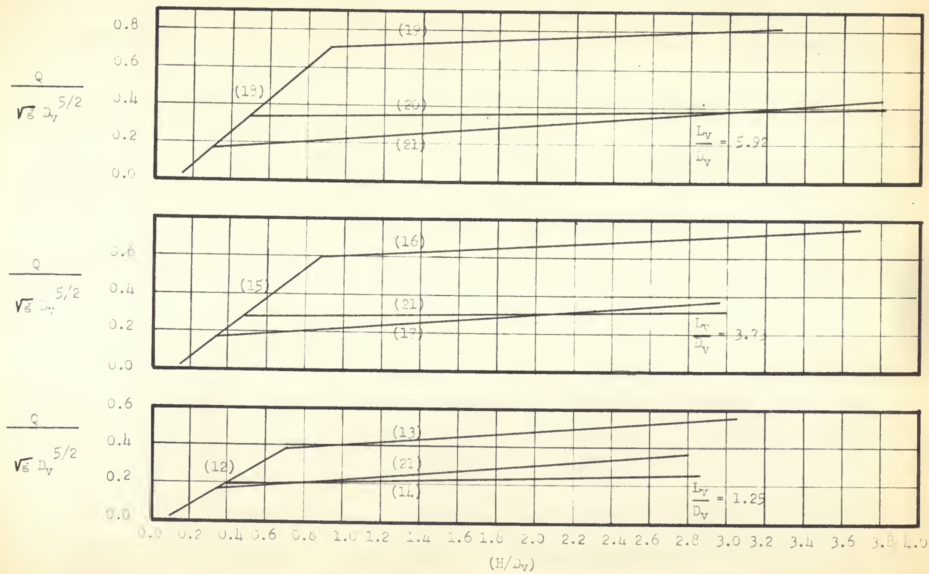


Figure 2. Head-Discharge Curves Using Dimensionless Terms.
$D_V/D = 1.34$ in all cases.

Table 3. Relationship between different types of flows and with different lengths of risers.

Equation Number	Equation Obtained	Inlet Tested and Type of Flow
22	$Q = 18.1\ H^{2.14}$	Short riser, weir and clinging nappe
23	$Q = .14\ H^{.28}$	Short riser, full tube
24	$Q = .06\ H^{.18}$	Short riser with barrel, full tube
25	$Q = 3.41\ H^{1.60}$	Medium riser, weir and clinging nappe
26	$Q = .086\ H^{.13}$	Medium riser, full tube
27	$Q = .164\ H^{.13}$	Medium riser with barrel, full tube
28	$Q = 3.41\ H^{1.57}$	Long riser, weir and clinging nappe
29	$Q = .088\ H^{.10}$	Long riser, full tube
30	$Q = .19\ H^{.13}$	Long riser with barrel, full tube
31	$Q = .098\ H^{.39}$	Orifice flow for all lengths

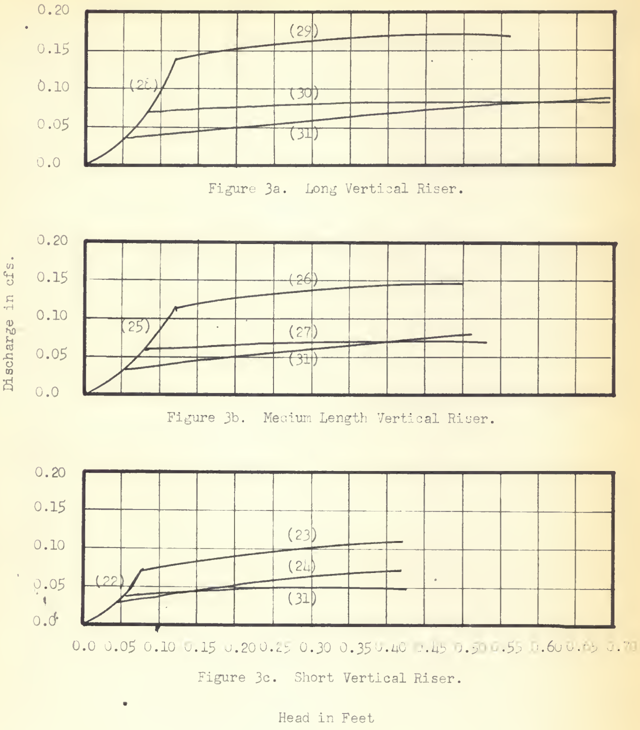


Figure 3. Head-Discharge for Model.

EXPLANATION OF PLATE VII

Fig. 1. Orifice flow from the 12-inch riser.

Fig. 2. Weir flow from the 12-inch riser.

PLATE VII

Fig. 1

Fig. 2

center of the tube when the clinging nappe was the controlling flow regime. The discharge during this type of flow varied with the head above the entrance to the 1.6 power.

The weir flow with aerated nappe is not shown, but its flow looked like that in Fig. 1 of Plate VII which is orifice flow. This type of flow was not usually obtained, but could be made to occur by splashing the water across the entrance with the anti-vortex device to permit air to enter next to the pipe itself. Weir flow with aerated nappe was obtained from the clinging nappe type flow and once it had occurred the tube had to be made to flow full before the clinging nappe flow regime could be regained. This type of flow also varied approximately to the 1.6 power.

The orifice flow, as shown in Fig. 1 of Plate VII was obtained the same way as the aerated weir flow and was not a natural flow, but the clinging nappe flow could be induced to change to orifice flow. As with the aerated weir flow the pipe had to flow full before the clinging nappe flow would be the controlling flow regime after orifice flow had been obtained. The discharge with this type of flow varied to the 0.4 power of the head above the inlet entrance.

The full pipe flow of the vertical riser, when no air was entering the tube, was obtained from a transition from clinging nappe or orifice flow after a certain head was obtained on the inlet's entrance. This head varied with different lengths of risers. The discharge varied with the 0.10 to the 0.28 power of the head above the entrance, depending on the length of the riser.

The full flow for the riser, elbow, and barrel had the same characteristics as the full flow regime of the riser alone. However, in this

EXPLANATION OF PLATE VIII

Fig. 1. Weir flow with the barrel flowing only partly full.

Fig. 2. Full flow with no air in the drop-inlet.

PLATE VIII

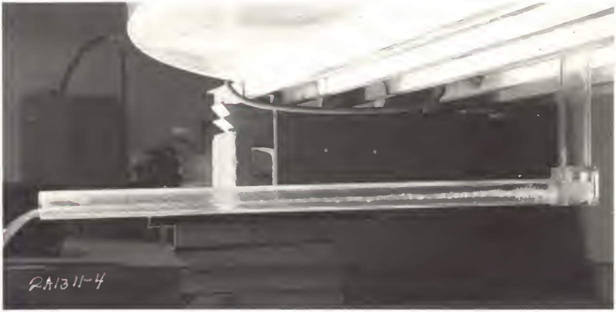


Fig. 1

Fig. 2

case the barrel was the controlling factor. Fig. 2 of Plate VIII shows full pipe flow with no air mixed with the water in the tube.

Equations 22, 25, and 28 and their respective curves, Fig. 3, show a combination of weir flow and clinging nappe flow. The equations show that as the tube length becomes shorter the discharge will vary with a larger power of the head. Also, the curves show that as the length of the riser gets longer a larger head and discharge will be obtained before full flow is obtained.

Full pipe flow for the vertical riser is shown by equations 23, 26, and 29 and their respective curves. In general, as the length of the tube increases the discharge will vary with a smaller power of the head above the entrance.

Full pipe flow for the riser, elbow, and barrel are shown by equations 24, 27, and 30 and their respective curves. The same was true for them as for the full pipe flow of the vertical riser given above.

Equation 31 and its respective curve was for orifice flow. It was the same for all the risers since the diameter of each of the risers was the same. The length of the riser had no effect on the orifice flow as the restriction was at the entrance, but the head at which orifice flow changed to full flow was effected by the length of the riser. From the curve sheet, Fig. 3, it is plainly seen that for the longer riser the intersection of the orifice flow curve and the full flow curve occurs at a greater head. As stated before, orifice flow did not occur naturally; this was true whether the head was increasing or decreasing. Not obtaining orifice flow naturally was contrary to what the writer expected.

EXPLANATION OF PLATE IX

Fig. 1. Weir flow with riser partly full. Notice the air bubble path in the barrel.

Fig. 2. Orifice flow with the elbow full. Notice the turbulence in the barrel.

PLATE IX

Fig. 1

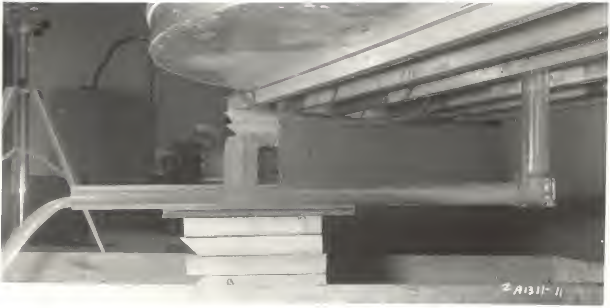


Fig. 2

Fig. 1 of Plate VII and Fig. 2 of Plate IX show orifice flow, and Fig. 1 of Plate VIII and Figs. 1 and 2 of Plate IX show clinging nappe flow. Fig. 2 of Plate VIII shows full pipe flow with no air in the drop-inlet. It was interesting to note the thin glass-like flow of orifice flow, which was a very smooth flow and nice to watch. In Figs. 1 and 2 of Plate IX the air bubbles show a well defined flow pattern in the barrel. Special attention should be given to the elbow and the first six inches of the barrel as this is very turbulent flow.

Transitions between clinging nappe flow and full flow were very noisy when a slug of air followed by a slug of water entered the drop-inlet. The noise was of a "surging" or "sucking" sound. At certain heads, different for each length riser, the noise grew louder as the head was increased to a point and then decreased gradually as the head was increased further until full flow was obtained in the pipe. This type of noise occurred when going from full flow to clinging nappe flow also. The transition between these two types of flow was the only one with noticable noise or that took a prolonged time. All other transitions between other types of flow were sudden and with little or no noise.

When flows were in the full flow regime at least an hour was needed to make a test as the head over the inlet entrance was very slow in coming to equilibrium.

The heads for all the different flows were taken from the lip of the entrance, since the entrance was being studied and seemed to be the most appropriate common datum for comparison of results.

SUMMARY AND CONCLUSIONS

Although drop-inlet spillways have been used in Kansas for many years the actual types of flow in these spillways still remain a problem. The design has changed through the years as more knowledge is obtained on flow characteristics, but some still wonder if orifice flow at the entrance is a controlling factor.

The purpose of this project was to determine if orifice flow is obtained at the entrance or if it is ever a controlling factor.

The use of dimensional analysis and a model was applied to facilitate experimentation. Simple equipment was used in the study. The head on the drop-inlet and the discharge as calculated from the weir, which had been calibrated in the channel, were the only measurements made on each separate test.

The results from the dimensional analysis were the same as when the head was plotted versus the discharge for the model, therefore only the explanation for the head-discharge relationship is given.

The results show that during the experiment five basic flows were obtained: (1) clinging nappe, (2) aerated weir flow, (3) orifice flow controlled at the entrance, (4) full flow when the riser was used alone, (5) full flow when the riser, elbow, and barrel were all used together. An anti-vortex device was used on all tests.

It was found that aerated weir flow and orifice flow did not occur naturally in the drop-inlet spillway, but could be made to be a controlling factor in the model. It is believed by the writer that orifice flow does not exist under actual field conditions. This is offered with no proof except that observation of the size of wave it took to make the clinging nappe flow change to orifice flow on the model studied. To make sure, studies should be made in the field or on a model in which true similitude is obtained or in which the degree of distortion is determined.

Other conclusions are:

(1) If orifice flow is a controlling factor, then the greater the length of riser to the diameter of riser ratio, the greater the probability of orifice flow being a critical factor.

(2) As the length of the riser increases, a larger head and discharge will be obtained before full flow is the controlling factor.

(3) If orifice flow is a controlling factor at the entrance, it will be obtained at the same head no matter what length of riser is used.

(4) When a vertical pipe alone is used, the longer the pipe the more discharge will be obtained for a given head over the entrance during full flow conditions.

(5) The findings of this project probably can be related directly to a smooth prototype, but this was not confirmed by experimental work. The roughness factor would have to be taken into account if a model were to be related directly to angular corrugated metal pipe.

No noticable change in the temperature was noticed; it stayed approximately constant at 25°C.

SUGGESTIONS FOR FUTURE RESEARCH

The triangular weir was calibrated for a given range of heads, which were in the lower part of the weir notch. If the weir is to be used for larger heads and discharges, it should be calibrated for the larger heads. When calibrating the triangular weir, care should be taken to eliminate as much of the channel as possible and still get a smooth flow. This should decrease the time it would take for the head on the weir to come to equilibrium, and also eliminate some waves which might travel the length of the channel. When delivering water to the channel care should be taken to cause as little disturbance as possible.

The model drop-inlet spillway has many possibilities for future research. The dimensional analysis could be carried out completely. A series of tests could be run on the different ratios of riser diameter to barrel diameter and it is suggested that a smaller ratio than that used in this experiment be used first. Another interesting project would be to use corrugated pipe in the model and see if it could be related to an angular corrugated metal drop-inlet of prototype size. The writer believes that this can be done, and, if so, almost all design problems could be solved with this model. If corrugated tubing could not be obtained, it has been suggested that plastic pipe be used and a tool be made for a lathe so the corrugations could be made the exact size wanted.

The problem that was investigated in this project could also be studied under field conditions. Does orifice flow exist in field installations? If done in the field, it could take quite a long time, if one depended on rain as the source of water. A twelve-inch angular corrugated metal pipe could probably be tested in the laboratory at Kansas State University, but the capacity of the pump should be checked first.

Another very important factor which needs studying is the elbow. At what degree of curvature is the flow least restricted by the elbow? This is probably a variable and would change with different velocities and sizes of pipes. A theoretical analysis followed by laboratory experiment would appear to be a logical approach.

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FLOW CHARACTERISTICS OF WATER AT THE ENTRANCE TO A CIRCULAR DROP-INLET

by

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The purpose of this project was to determine whether or not orifice flow exists at the entrance of a drop-inlet spillway and, if it does, whether or not it is ever a controlling factor in the quantity of discharge.

Dimensional analysis and a model were used to expedite the experiment. The functional equation derived after neglecting some of the less significant factors is

$$Q = f'\left(\frac{D_r}{D_b}, \frac{L_r}{D_r}, \frac{H}{D_r}\right) \quad \sqrt{g}\, D^{5/2}$$

where

Q = discharge

g = gravitational force

D_r = diameter of riser

D_b = diameter of barrel

H = head over the drop-inlet entrance

This equation, valid in any consistent system of units, follows the Froude Model Law very closely. The term $\frac{D_r}{D_b}$ was held constant at 1.34, and $\frac{L_r}{D_r}$ was varied at 1.25, 3.73, or 5.92. $\frac{H}{D_r}$ was varied at different values between 0.1 and 4.01 for each test.

The quantities measured for each test were head over the inlet's entrance and discharge, as calculated from a 90° triangular weir, which was calibrated in the channel in which it was operated.

Since a vortex was not wanted, an anti-vortex device was used on all the tests. A series of tests were run on the risers by themselves and then with the elbow and barrel attached to the risers. Each series consisted of 10 or 20 tests. The time for each test ranged from 10 minutes to 1 hour; test conditions for full flow were very slow in coming to equilibrium.

Plots were made of the calculated dimensionless terms and their equations were determined by linear regression. The correlation coefficients were determined also. Since the direct plots of head versus discharge give the same basic information as the dimensionless term equations they were used for the explanation of the different types of flows.

Five types of flows were observed during the experiment. They are (1) clinging nappe, (2) aerated weir flow, (3) orifice flow controlled at the entrance, (4) full flow when the riser was used alone, and (5) full flow when the riser, elbow, and barrel were used together.

The aerated weir flow and the orifice flow did not occur naturally, but could be made to be the controlling factors by splashing the water with the anti-vortex device. It is believed by the writer that orifice flow does not exist in field installations, except perhaps in very rare instances. The opinion is reinforced by the relization of the magnitude of the disturbance that must take place on a full size inlet to cause the change from clinging nappe to orifice flow as compared to the disturbance needed on the model. To substantiate this, a study should be made in the field on actual drop-inlet spillways, or tests should be run in the laboratory on true models or on models in which the degree of distortion is known.

Other conclusions are

(1) If orifice flow is a controlling factor, then the greater the ratio of $\frac{L_r}{D_r}$ the greater the probability of orifice flow being a critical factor.

(2) As the length of the riser increases a larger head and discharge will be obtained before full flow is the controlling factor.

(3) If orifice flow is a controlling factor at the entrance, it will be obtained at the same head no matter what length of riser is used.

(4) The longer the riser, the greater the discharge obtained for a given head over the entrance during the full flow conditions.

(5) The head-discharge relationship of the model can probably be related directly to a smooth full scale inlet, but this was not confirmed by experimental work.

The fact that orifice flow did not occur naturally as a flow regime is contrary to the writer's interpretation of previously reported research.