ROUGHNESS ELEMENTS AS ENERGY DISSIPATORS OF FREE-SURFACE FLOW IN CIRCULAR PIPES

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WATER flowing at high velocities can cause considerable erosion. This erosion, or scour, can occur at the outlet of drainage structures such as chutes and culverts on steep slopes and cause maintenance problems and occasional displacement of pipe. The erosive capability of flowing water is characterized by its velocity, which in turn gives the flow a high kinetic energy.

Reduction of the kinetic energy and velocity of flow to more acceptable levels with regard to scour nearly always requires the formation of a hydraulic jump. The hydraulic jump is a phenomenon that converts shallow, high-velocity flow to deeper, low-velocity flow while considerable kinetic energy is lost through the generation of extreme turbulence. Many outlet protection devices are stilling basins, designed so that the hydraulic jump is forced to form in the basin, and the soil materials of the drainage channel downstream is thus protected.

If the jump can be forced to form in the chute or the culvert itself, near the outlet, the stilling basin structure can be simplified or even eliminated. Studies have been under way for some time at Virginia Polytechnic Institute and State University on the use of large roughness bars, like sills, in steep, rectangular, open channels for conveyance of water to the downstream channel at safe velocities. These bars, called roughness elements, form a succession of small hydraulic jumps in the channel to cause the phenomenon known as "tumbling flow" (1). The results of these studies are summarized in other papers (2, 3). In general the use of properly designed roughness elements as energy-dissipation devices seems to be quite effective and economical under many conditions.

This report describes experiments on peripheral rings used in smooth, circular pipes, as roughness elements to reduce the velocity of flow. The studies pertain only to culverts flowing under inlet control on steep slopes, that is, pipes functioning as open channels with supercritical flow.

Model tests were made to investigate the feasibility of roughness elements as energy dissipators to reduce the kinetic energy of high-velocity, free-surface flows in pipes. Tests were made by using a 6-in. diameter Plexiglas pipe, 28 ft long, in the Hydraulics Laboratory. The model tests included 3 sizes of roughness elements and several different configurations of element spacing, location, and number. The model tests were performed at several discharges and slopes for each configuration.

In addition to the model tests, a short series of tests was performed on a 32-ft, 18-in. concrete pipe at the Industry Center. These tests, referred to as the prototype tests, were made to verify the model-prototype scaling ratios and to determine whether the pipe material significantly affected the results.

The purpose of the research, to dissipate the kinetic energy of high velocity flows, required steep slopes for all tests. Accordingly, the usual case was one of critical flow at the entrance of the pipe, with flow accelerating down the length of the pipe until the first roughness element was reached. At that point a forced hydraulic jump was formed, with extreme turbulence. The flow then typically encountered another rough-

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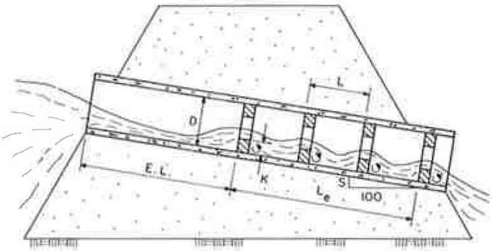

E.L. = ENTRANCE LENGTH
L_e = LENGTH OF ELEMENTS

Figure 1. Tumbling flow in pipe culvert.

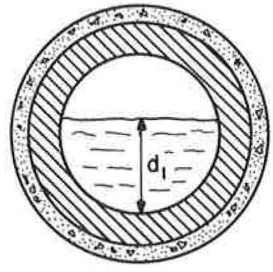

Figure 2. Roughness element in pipe.

ness element while still in the agitated condition from the first, and this pattern of action was repeated until a cyclic condition was reached, where the flow conditions around a roughness element were the same as those around another. This agitated flow—somewhat characterized by a greater depth over the element than before it, a fall into the "valley" between elements, and a form resembling a hydraulic jump before the element—is called "tumbling flow" by Morris (2). This then is the purpose of the roughness element: to cause an agitated condition that is the mechanism for a rapid decrease in the energy of the fluid flow, thus reducing the velocity of the flow at the exit of the pipe.

THEORETICAL CONSIDERATIONS

Consider a steeply sloping pipe culvert, containing bed roughness elements at regular intervals, as shown in Figure 1.

The pipe is laid on a slope of S percent and has an internal diameter of D ft. The roughness elements are spaced at a distance L and have square cross sections K on each side. The control depth d_1 is measured from the water surface to the upstream corner of the element crest at the pipe centerline (Fig. 2).

One repeating cycle of the tumbling flow is shown to a large scale in Figure 3. Distances are measured parallel to, and normal to, the pipe axis, which makes an angle θ with the horizontal. The percentage of slope is equal to 100 tan θ.

The momentum equation can be written for the body of water in 1 cycle, assuming that cyclically uniform flow has been established, as follows:

$$W \sin \theta - F_D - \tau_o LP = 0 \qquad (1)$$

in which W is the total weight of water in one repeating cycle, F_D is the drag force on the element, τ_o is the average bed shear stress over the spacing L, and P is the average wetted perimeter. W is equal to γAL, where A is the average cross-sectional area in length L, and R represents A/P, the average hydraulic radius in the length L; therefore, Eq. 1 becomes

$$F_D = PL(\gamma R \sin \theta - \tau_o) \qquad (2)$$

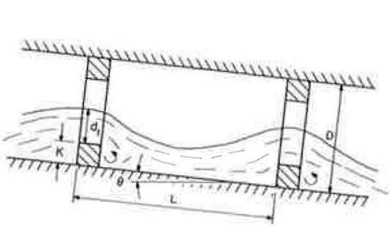

Figure 3. Tumbling flow cycle in pipe.

It is probable that in most cases τ_o will be small relative to $\gamma R \sin \theta$. If so, then approximately

$$F_D \cong \gamma AL \sin \theta = \gamma A(\Delta H) \qquad (3)$$

in which ΔH is the drop in channel-bed elevation in the length L.

The area A is impossible to determine without actual measurements of the flow profile, but it would certainly be less than the cross section of the pipe itself. Therefore, the maximum possible drag force on an individual element could be calculated as

$$F_{D_{max}} = (1/4)(\pi D^2)(\gamma \Delta H) \tag{4}$$

The actual drag force would have to be determined experimentally and undoubtedly varies with the channel slope and discharge as well as with geometry of the roughness elements.

The energy equation can also be written for 1 cycle of the tumbling flow as follows:

$$H_J = L \sin \theta = \Delta H \tag{5}$$

In this equation, H_J represents the head lost in the hydraulic jump and associated phenomena in the 1 cycle. Because the flow is cyclically uniform, the entire gain in energy resulting from the drop in bed elevation must be exactly offset by the energy dissipated in the cycle.

Unless the elements are quite far apart, each element and its associated jump will interfere to some extent with the next jump and, thus, restrict the full development of the energy loss that could theoretically be induced by a single roughness element in a sloping channel. Consequently, H_J will be less than, or at most equal to, the head loss that could be caused by a single isolated element. It would seem, therefore, that both economy and smoothness of operation would require elements to be spaced as far apart as possible while the cyclically uniform tumbling flow is still maintained. This optimum spacing, however, must be determined experimentally because no data are now available with which to calculate it.

Finally, the process equation for cyclically uniform tumbling flow in a pipe culvert can be written as follows:

$$f(\rho, V_1, K, L, D, S, \gamma) = 0 \tag{6}$$

It is assumed here that K, the element height, is the single most important dimension of the flow geometry, to which the other dimensions L and D can be referenced. The reference velocity V_1 is the velocity at the control section on the element. Other velocities in the flow field can be referenced to this through the equation of continuity. The fluid density ρ is the basic physical property used in specifying the inertial forces and kinetic energies of the flow. The only other force of importance is that of gravity, represented by γ, the specific weight. The forces of viscosity, elasticity, and surface tension, though present and acting, are assumed to be relatively unimportant in comparison with inertial and gravitational forces, which determine the basic flow structure. The effect of potential energy in the flow is included by means of the slope term S.

By dimensional analysis, Eq. 6 can be modified to the following:

$$f(L/K, D/K, S, V_1^2/gK) = 0 \tag{7}$$

Each term in this function is now dimensionless. Such functions can often be determined explicitly by model testing. The last term can be extracted and set equal to a function of all the others. Thus,

$$V_1^2/gK = f(L/K, D/K, S) \tag{8}$$

Because Q is equal to $A_1 V_1$, this may be written as

$$Q^2 = gKA_1^2 f(L/K, D/K, S) \tag{9}$$

A_1 is the area of flow at the control section and is, of course, primarily a function of the control depth d_1.

In a relation that is established between pipe size D and roughness element size K, the ratio of d_1 to K is some constant. This is so because d_1 depends on given hydraulic parameters (discharge and slope) and geometry (pipe diameter and roughness element size). Thus, for a given value of discharge and slope

$$A_1 = m(b_1 d_1) = m(b_1)(nK) \tag{10}$$

where b_1 is the surface width at the control section and m and n are constants. The constants can all be incorporated in the functional expression, and Eq. 9 can then be modified to the following:

$$K = (Q/b_1\sqrt{g})^{2/3} f(L/K, D/K, S) \tag{11}$$

Equation 11 can be understood as the desired process equation for tumbling flow, specifying the required K for a given Q to ensure tumbling flow in the culvert. That is, if K is smaller than specified by Eq. 11, the flow would become supercritical and the distinct jumps would be eliminated. However, Eq. 11 requires an objective, experimental determination of the bounds of tumbling flow because the assumption underlying the development of the equation is the existence of the tumbling flow regime. Although tumbling flow can be observed, the point of beginning of tumbling flow relative to a parameter change is difficult to determine. Nevertheless, it is possible to make a positive statement about the occurrence of tumbling flow within constraints imposed by the experiments reported here. The experiments were generally in the tumbling flow regime, and the data show a narrow range of Froude numbers at the upstream position, that is, upstream of the first element before its effect is felt by the flow. Those numbers varied from more than 3 for the condition of 4 percent slope to nearly 6 for that of 10 percent slope. Thus, if there are sufficiently high upstream Froude numbers and the proper range of discharge and if the configuration of the roughness elements (L/K, K/D, number of elements at the downstream end) is within the range of the experiments, then tumbling flow will occur.

The tests performed indicated that a strong tumbling action occurred for a specific configuration of roughness elements. Specifically, 5 roughness elements in the downstream end of a pipe on steep slope with inlet control will produce tumbling flow when the ratio K/D is in the range 0.104 to 0.146 and the ratio L/K in the range 12.1 to 17.1. Accordingly, Eq. 9 can be rewritten

$$f[(Q^2/gA_1^2 K), S] = 0 \tag{12}$$

This modification of Eq. 9 is possible because D/K and L/K are relatively constant and the behavior of the flow does not change much over the tested range of D/K and L/K. Furthermore, under conditions of tumbling flow over the roughness elements, the area and top width are functions of the pipe diameter D for fixed K/D ratio and for given discharge. Therefore, one can write Eq. 12 as

$$f[Q/(D^2\sqrt{gD}, S] = 0 \tag{13}$$

a design equation under the constraints elaborated on earlier.

MODEL APPARATUS AND PROCEDURES

The model study portion of this project was performed in the Hydraulics Laboratory.

Water Supply

The water supplied to the experimental culvert was pumped from the sump in the laboratory to a constant head tank approximately 60 ft above the test flume. From the head tank the water was routed to a small, open forebay and then passed through the test culvert before it was returned to the sump. The flow was measured by a calibrated venturi meter and controlled at the flume by an 8-in. butterfly valve.

Test Flume

The model culvert pipe was placed in a 30-ft rectangular tilting flume capable of a slope range from horizontal to 25 percent (3 in./ft). The slope indicator on the flume was calibrated by using a cathometer prior to the experiments. The slopes tested were 4, 6, 8, and 10 percent respectively. The water, before entering the model pipe, entered a small open-head tank on the flume and was allowed to become quiescent before entering the model. A headwall was constructed in the flume with the pipe projecting through the headwall and into the flow. The headwall was sealed with a neoprene gasket to ensure that no leakage occurred.

Model Pipe

Concrete culvert pipe was modeled by using 6-in. diameter clear Plexiglas pipe sections joined by a bolted collar. Clear pipe was chosen for visual and photographic observations. A 6-in. section was chosen because the laboratory flow supply was inadequate for a complete range of flow conditions in a larger pipe. The length of the model pipe was originally 32 ft for the first test series (K = 0.375 in.), but later the pipe was shortened to 28 ft so that depth and velocity measurements could be made at the last element. The pipe extended 1 ft beyond the headwall forming a projected entrance condition. The outlet condition was a free overfall.

Holes were drilled on the bottom on 1-in. centers along half the length of the pipe. The roughness elements were held in place by a screw through the bottom of the pipe and into each element; plastic tape was placed over the holes so that no leakage would occur.

A ¼-in. slot was machined in the top of the pipe about midlength and over the last roughness element. Thus, measurements of depth and velocity could be made upstream of the elements and at the last roughness elements.

Roughness Elements

The roughness elements were peripheral rings, square in cross section, machined from sheet Plexiglas. Table 1 gives the dimensions and other geometric properties of all the rings tested. The rings were fastened to the pipe with a small screw. This method of fastening proved adequate, for the rings showed no tendency to move during or after the experiment. The last element had a portion of the top of the ring removed so that depth and velocity readings could be made directly over the ring.

The downstream element was, generally speaking, at the end of the pipe. In practice, the distance of the downstream face of the element from the plane of the outlet was about the relative distance K, the thickness of the element. This seemed to produce as much reduction in velocity as any other location.

TABLE 1

DIMENSIONS AND PROPERTIES OF ROUGHNESS ELEMENTS

Test	K (in.)	L (in.)	L/K	Number of Elements	K/D	L_e/D	E.L. (percent)
Model	0.375	2	5.33	96	0.0625	32	50
	0.625	9	14.4	4	0.104	6	90
	0.625	9	14.4	5	0.104	7.5	87.2
	0.875	6	6.88	30	0.146	30	46.8
	0.875	12	13.76	4	0.146	4	87.5
	0.875	12	13.76	5	0.146	10	83.6
	0.875	12	13.76	15	0.146	30	46.8
	0.875	15	17.1	5	0.146	12.5	80.1
	0.875	18	20.6	5	0.146	15.0	76.8
Prototype	1.875	27	14.4	5	0.104	7.5	65
	2.625	36	13.7	5	0.146	10	53

Measuring Apparatus

A minimum amount of instrumentation was needed to obtain the experimental data. The depth of flow over the element and in the pipe before the elements was measured by an electric point gage that could measure depths to 0.001 ft. The velocity of flow was measured by a pitot tube at mid-depth with 2 piezometer tubes. The piezometer tubes could be backflushed and vented to the atmosphere so that no air would be in the pitot tube or the piezometer tubes.

Experimental Procedure

After the rings were established in their desired positions and the pipe installed in the flume, the venturi's manometer was bled of all air, and water was allowed to enter the test flume. From the steepest slope, the flow was set so that at the last ring the pipe was flowing nearly or completely full. The depth and mid-depth velocity were recorded at the upstream position and at the last element. The flow was reduced and the depth and velocity were measured at the same upstream and downstream positions. This procedure was repeated for the subsequent slopes; however, the flow rates were the same as for the steepest slope.

Visual observations were also made. Included were position of the hydraulic jump at the lead element, strength of hydraulic jump between elements, and degree of turbulence indicated by the amount of air entrainment.

PROTOTYPE TESTS

Prototype tests were performed on an 18-in. concrete pipe at the Industry Center.

Apparatus

An 18-in. concrete pipe of four 8-ft sections was used for the prototype tests. The pipe lay in steel framework and was flush-mounted into a steel head box. The frame and head box acted as a unit supported at the midspan of the frame and by an elbow section of the main supply pipe bolted to the side of the head tank. With the use of a heavy-duty forklift truck, the entire frame and head box could be rotated about the pipe elbow to the desired slope. The slope range of the prototype tests was from the horizontal to 15 percent ($1\frac{3}{4}$ in./ft). The slope was measured with a steel scale and carpenter's level.

Water supplied to the tests was pumped from the Blackstone River by 2 vertical turbine pumps into the head box on the frame. The flow was measured by a calibrated orifice meter and controlled by a 24-in. butterfly valve.

Prototype Pipe

Four 8-ft sections of pipe of the tongue-and-groove type were used for the prototype tests. They were sealed together with neoprene O-rings, and no leakage occurred during the tests. The entrance was flush with the head box, and the exit was a free overfall. A hole was drilled in the pipe about midlength so that velocity and depth measurements could be made upstream of the roughness elements. Another hole was drilled in the pipe about 10 ft from the end of the pipe so that the flow over the elements in the pipe could be observed.

Roughness Elements

The roughness elements were made of laminated plywood, machined to the correct size, and coated with an epoxy paint. Two sizes of roughness elements were used and their geometric properties are also given in Table 1. They were positioned in the pipe by industrial banding or strapping material laid along the invert and top of the pipe. The banding was brought outside the pipe at the outlet and the second joint and finally fastened to the exterior of the pipe. This procedure was satisfactory, for the elements remained stationary and the banding did not interfere with the flow.

Measuring Apparatus

These tests were similar to the model tests in that a minimum amount of instrumentation was used to obtain the experimental data. The upstream depth was measured with the use of a rod lowered to the pipe invert and then raised to the water surface. A mark was inscribed on the rod indicating the pipe invert; the change in elevation of the inscribed mark above a datum on the exterior of the pipe to the water surface was measured with a steel scale to within $^1/_{16}$ in. The change in elevation was a measure of the depth of flow in the pipe. The outlet depth at the last element was measured in a similar fashion but by using the downstream pitot tube rather than a rod.

Velocity measurements were taken at mid-depth with pitot tubes. The downstream pitot tube was connected to a calibrated differential pressure transducer, and the pressure difference was registered on a Sanborn 150 recorder. The upstream pitot tube was connected to 2 piezometer tubes similar to those used for the model tests.

The experimental procedure used for the prototype tests was the same as that used for the model test.

ANALYSIS OF DATA

An attempt to reduce the experimental data to design formulas was made. Some of the plastic pipe data plots drawn for this purpose are shown. Figure 4 shows a graph of the computer friction factor f versus the Reynolds number N_R, both based on velocity and depth (through the hydraulic radius) over the last roughness element. The different symbols indicate the slope of the pipe. The legend gives the configuration of the roughness elements. No trend is discernible.

Figure 5 shows the friction factor plotted versus the Froude number N_F for the same data shown in Figure 4. Again, no trend is found. This is expected in the case of the Froude number because the flow over the elements in the fully developed tumbling condition should be similar to flow over a fall, and the Froude number should be close to one. Such is the case. Similarily, when the Chezy resistance formula, in the form $C/\sqrt{g}$, is plotted against the Reynolds and the Froude numbers, no trend is evident (Fig. 6).

An attempt was made to correlate an index of efficiency of element configurations versus the slopes tested. Because velocity reduction was the primary cri-

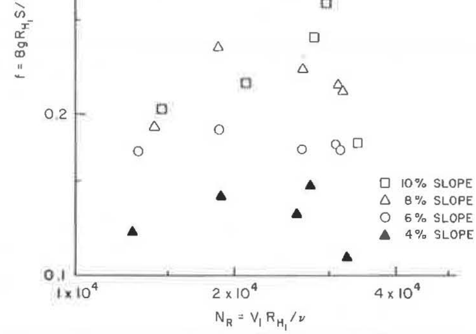

Figure 4. Friction factor versus outlet Reynolds number.

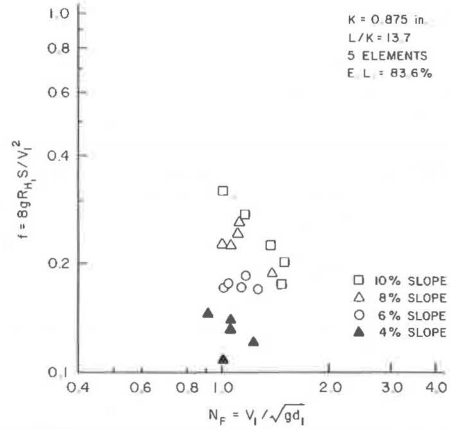

Figure 5. Friction factor versus outlet Froude number.

terion of the study, the percentage reduction of velocity was used as a measure of efficiency. Defining the velocity upstream of the first element as V_0 and the velocity at the last element as V_1, the percentage of velocity reduction is defined as $(V_0 - V_1)/V_1$. Figures 7 and 8 show that no functional relationship existed between percentage of velocity reduction versus slope for the elements tested.

The experimental data illustrate several points that should be noted. First the theory of hydraulic modeling and similitude indicates that the ratio of prototype discharge to model discharge should be equal to the length ratio to the $^5/_2$ power if the scaling relationship is governed by the Froude number. The data show that, for matched conditions of slope, roughness configuration, and Froude number at the upstream position, the discharge ratios for model and prototype are as predicted by the model ratio. Some of the upstream Froude numbers in the model tests were not taken in the same relative position as in the prototype because the relative entrance length for the plastic model pipe was so much longer. In these cases, a one-step, gradually varied flow calculation was made to find the Froude number in the model at an entrance length corresponding to that in the prototype. One group of tests was made by measuring the upstream Froude number at the location corresponding to the measuring point in the concrete pipe.

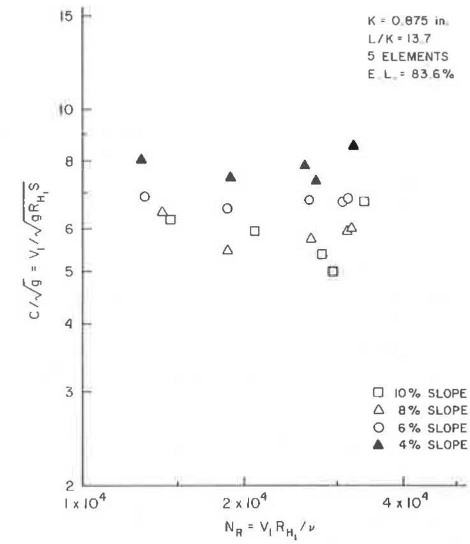

Figure 6. Chezy resistance coefficient versus outlet Reynolds number.

Another point in interpretation of the data is the reduction in velocity from the values of V_0 to those of V_1. (The values of percentage of reduction of velocity are significant because the high velocity at the outlet is the erosive mechanism.) Figures 7 and 8 show the range of velocity reduction.

A third set of items of data that should be noted are the Froude numbers at exit N_{F_1}. Those values are near unity, very nearly the optimum value.

Most of the data exhibited tumbling flow characteristics at the downstream elements as nearly as could be determined (necessarily a subjective judgment). Initially, tests

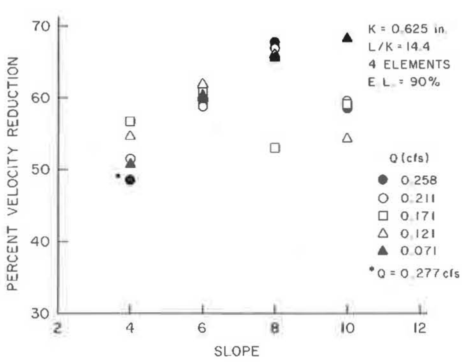

Figure 7. Percentage of velocity reduction versus slope for four 0.625-in. elements.

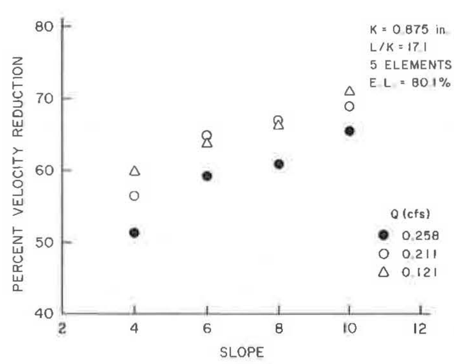

Figure 8. Percentage of velocity reduction versus slope for five 0.875-in. elements.

were run with entrance lengths in the plastic pipe only about half the length of the pipe. When later tests showed that nearly cyclic tumbling flow occurred with less elements (a total of four or five), most tests were made with the lesser numbers of elements. In order to justify a design containing only 5 elements, a further series of tests was made with 15 elements to determine the degree of velocity reduction and then to compare it to the velocity reduction attained with 5 elements. For a range of 4 values of slope and 5 values of discharge for each slope, the average increase in velocity reduction by 15 elements over the velocity reduction by 4 elements was approximately 5 percent. Therefore, there was only a marginal increase in velocity reduction for a much greater number of elements.

For most of the plastic-pipe tests the pipe was not flowing full at the exit. Although few of the data showed the full-flow condition, it was observed in some of the tests that sporadically the pipe went under pressure during conditions of high discharge. This pressurization occurred only in the lower end of the pipe, in the region of the roughness elements. The pressurization was more easily attained (that is, with lower discharges) for smaller slopes than for larger ones. The range of the tests was stopped at the point of sporadic pressurization. The next condition that would prevail with increasing discharge is complete pressurization with the pipe running full, and the hydraulic jump from rapid, free-surface flow to the full condition would move upstream to an equilibrium position.

The methods of measuring depths and velocities given in the description of the experiments were not sophisticated. However, the extreme turbulence of the flow, especially in the tumbling regime, and the resulting roughness of the water surface obviated the usefulness of refinement in the methods.

Although the experiments did not yield design equations by analysis of the figures shown, the subjective observation of tumbling flow did establish some bounds to the relations of discharge to Froude number and slope. This relation is discussed in the next section, but simply the relation of Eq. 13 was assumed to be independent of slope, and the data were examined for values of the parameter $Q/(D^2\sqrt{gD})$.

Because of concern regarding the ability of the flow to clean the pipe of material accumulating ahead of the roughness elements, a qualitative test was run. Several shovels full of gravel were placed in the pipe barrel of the prototype, and a flow of about 3 ft^3/sec was discharged through the pipe for 5 min. At the end of that time no gravel whatever remained in the pipe. It seems clear that gravel and silt deposits will not build up but rather will be washed out by the extreme turbulence of the flow.

Although the experiments indicate that gravel and similar deposits will wash out of the pocket formed by the roughness elements, it is possible that water would stand upstream of the elements, possibly causing problems in freezing and thawing situations or in insect control cases. The formation of a slot in the ring at the invert to permit complete drainage would not hamper the hydraulic performance of the design. An alternative would be a "flat" on the ring at the invert.

DESIGN METHOD

It is obvious that the introduction of roughness elements will increase the friction loses through the pipe barrel. The increased rate of energy loss through the region of the roughness elements will not change conditions upstream of the elements as long as the total loss in head from the jump at the first element to the pipe outlet is not greater than the head available at the point upstream of the first element. For increasing discharge, however, the rate of head loss will become greater, and the pipe will then flow full in the region of the roughness elements and upstream of them in an attempt to gain sufficient energy head to overcome the losses. Accordingly, it is readily apparent that for a given pipe diameter the upper limit of discharge is quite fixed if tumbling flow is to occur. This, of course, assumes that there is a proper range of K/D and L/K ratios as well as very steep slopes (greater than 4 percent). The data provided values of the parameter that would permit pipe size selection, values of $Q/(D^2\sqrt{gD})$. For the model-pipe tests the maximum values of this parameter ranged from 0.257 for 10 percent slopes to 0.210 for 4 percent slopes. For the prototype tests the value was 0.317 for

14.7 and 8.3 percent slopes. It is possible that the discharges for the prototype pipe were relatively larger because the determination of the transition from tumbling flow to full flow was more difficult to determine. Thus, higher relative discharges were permitted.

Even so, a simple design technique is available, the criterion being Eq. 13 rewritten as

$$D = (Q^2/0.0625g)^{1/5} \quad (14)$$

or

$$Q/(D^2\sqrt{gD}) = 0.25$$

which is valid for slopes greater than 4 percent, and with K/D ratios from 0.104 to 0.146 and L/D from 1.5 to 2.5 (corresponding to K/D = 0.104 and L/K = 14.4 and to K/D = 0.146 and L/K = 17.1 respectively).

CONCLUSIONS

The following conclusions can be made based on this research:

1. Peripheral roughness elements of proper relative size and spacing and of square cross section will cause considerable reduction of exit velocity in the case of pipes on steep slopes under inlet control and free exit, i. e., flowing partly full. The exit Froude number can be reduced to nearly unity.
2. The Froude law relationship is an accurate scaling parameter within the range of conditions studied in this report.
3. A satisfactory condition of tumbling flow will occur when 5 roughness elements of relative size K/D = 0.104 to 0.146 and L/D = 1.5 to 2.5 are used at the downstream end of the pipe and the pipe slope is greater than approximately 4 percent.
4. The size of pipe can be selected through the empirical criterion of Eq. 14.

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