Depth of Flow as a Design Criterion for Channels With Artificial Liners

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Six artificial liners were investigated to develop design criteria for erodible channels. Liners installed on flat-bottom earth channels, 2 ft wide, 60 ft long, and on slopes up to 0.125 were subjected to increasing flows to channel failure. Test sections of sand to heavy clay were inserted in the channel floor and the effectiveness of the liners observed. Measurements consisted of flow rates, channel and water surface profiles, and test section erosion. For each flow rate, values were determined for depth of flow, mean velocity, hydraulic radius, slope, and erosion. Failure of the test sections and liners was noted.

A regression analysis was used to fit the data for each liner to $\log V = \log a + b \log R + c \log S$. A high correlation of variables was obtained. The coefficient and exponents for this formula are included.

Maximum permissible depth (a criterion expressing failure) was considered to be a function of slope. These variables were examined in a depth-slope plot with upper and lower parallel limits which reflect the erosion characteristics of the test soils. The depth criterion, along with the flow rating curves, can be applied to the design of artificially lined channels of any shape.

•ENGINEERS are concerned with developing plans for water disposal systems which drain runoff. Design is based on stability limits of the channel, design discharge, and economic factors. In some situations, vegetation is desirable as a lining to obtain stability in erodible channels. Present designs are based on established vegetative conditions although it is recognized that a destructive runoff event may occur before the vegetation has developed sufficient protection to obtain channel stability. Various porous covers are being used in attempting to maintain stability until vegetation is fully developed.

A need was recognized for more accurately defining the stability limits of various soils covered by temporary liners. This subject was studied by McWhorter, Carpenter, and Clark (1) in order to determine the permissible velocity for channels treated with various liners on several textural classes of soils and also to determine the value of Manning's coefficient of resistance for the several materials. The results of this work indicated that maximum depth of flow was an appropriate criterion for describing failure limits of channels with artificial liners. The purpose of this paper is to report on this aspect of the work and to introduce this criterion into design procedures for the treatments studied.

EXPERIMENTATION

All experimental tests were conducted in an outdoor hydraulic laboratory at Mississippi State University.

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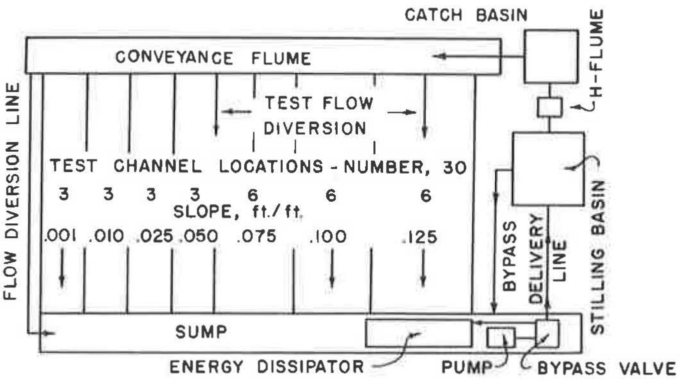


Figure 1. Flow diagram of laboratory system.

Laboratory

A flow diagram of the laboratory is shown in Figure 1. Each test channel is 60 ft long and the soil base in the entire channel area is Houston clay soil (heavy clay).

Tests were conducted in 2-ft wide rectangular channels with portable, aluminum sidewalls which were inserted into the channel bed.

The flow system consisted of a 28,000-gal sump, pumping capacity up to 11 cfs, stilling basin with a 2-ft calibrated H-flume attached, a 2-ft wide conveyance flume for delivery of test flows, appropriate gates, and a flow diversion system around the test channels. Flow could be regulated to the desired test discharge.

A digital instrumentation system (2) developed by Carpenter and Fox was used to measure erosion in the test section (station 0 + 38) and for recording soil and water surface elevations over a 20-ft length (station 0 + 28 to 0 + 48). Station 0 + 60 was a free outfall into the sump.

Test Materials

Ten different textural classes of soils, ranging from coarse-grained sand and gravel to fine-grained cohesive materials, were used. Samples of each were air dried, pulverized, and passed through a $\frac{1}{4}$-in. screen into a mold to form 18- by 30- by 6-in. deep test sections. These were wet to saturation and allowed to "season" before insertion in the test channel beds at 0 + 38 station.

The specifications for the temporary liners reported in this paper follow. Erosionet is manufactured from a paper yarn which is approximately 0.05 in. in diameter and is woven into a net with openings of $\frac{7}{8}$ by $\frac{1}{2}$ in. It weighs about 0.20 lb/sq yd. Jute mesh consists of jute yarn which varies in size from $\frac{1}{8}$ in. to $\frac{1}{4}$ in. in diameter. The openings are about $\frac{3}{8}$ by $\frac{3}{4}$ in. and the material weighs approximately 0.80 lb/sq yd. Stranded fiberglass is a hair-like fiberglass material which was applied as a mulch to the channel with an air gun applicator at the rate of 1 lb/sq yd. Two thicknesses of fiberglass mat, $\frac{3}{8}$ in. and $\frac{1}{2}$ in., with respective weights of 0.11 and 0.35 lb/sq yd were used. The appearance is similar to air filter material. Excelsior mat consists of approximately 0.8 lb/sq yd of excelsior (dried, shredded wood) covered with a net with 1- by 3-in. openings. The net is woven with a fine paper thread. Common oat straw was used as a channel cover at the rate of 1.24 lb/sq yd.

These materials constituted the treatments studied. In the case of the stranded fiberglass and straw mulch treatment, each material was covered with Erosionet, which was pinned to the channel floor at 1-ft intervals along the sides and center of the channel. A complete transverse pinning was used at 12-ft intervals and at the ends of the channel. This same pinning arrangement was used with the other materials.

Experimental Procedure

A standard procedure was used in preparing for each test. Five steps were involved: preparation of the test channel, installation of the test section, installation of the flume walls, placement of the liner, and setting up the instrumentation. All tests were conducted according to a uniform procedure.

The entire 60-ft channel length was tilled to a 2-in. depth, smoothed to a uniformly sloping plane, and saturated with water at a low sprinkle rate. The channel was allowed to season and compacted with a smooth roller. The soil test section was inserted in the channel bed at station 0 + 38. Flume walls were inserted into the channel bed 2 ft apart, aligned parallel, and braced. The liner was then installed and the channel subjected to a low flow for 5 minutes. Instrumentation was then installed and checked. For each test, the slope of the channel bed, the channel flow rate, and mean depth of flow were measured. Erosion of the test soil was estimated by taking integrated surface elevations over the test section.

In the conduct of a test, the channel was inspected and instrumentation referenced to a datum. Channel bottom readings were recorded and an integrated profile measurement of the test section was made. The desired constant flow rate was regulated to the required head on the H-flume. The flow was then diverted into the test channel and water surface readings were recorded when the flow became steady. At the end of the test period (10 min), the flow was diverted and the test channel allowed to drain. Test section profile measurements were taken to determine erosion or deposition. This procedure was repeated with increasing flow rates until the channel failed. The following flow rate schedule was used:

0.10 - 1.00 cfs in 0.10 cfs increments
1.00 - 2.00 cfs in 0.20 cfs increments
2.00 - 4.00 cfs in 0.25 cfs increments
4.00 - 10.50 cfs in 0.50 cfs increments

Data Reduction

For each test flow, measurements and computation of pertinent variables were tabulated. This included the discharge flow rate, mean depth of flow, mean velocity of flow, and hydraulic radius. Hydraulic radius was computed by a method suggested by Johnston (3) and used by Fenzel and Davis (4) which considers the effect of sidewall resistance in narrow channels. Manning's n was calculated by the Manning equation and VR, the product of velocity and hydraulic radius, was tabulated. The accumulated average erosion of the test section beginning with the initial test flow was also tabulated. The test section was deemed to have failed when the accumulated erosion amounted to 0.031 ft ($^3/_8$ in.).

RESULTS

The relation of n to VR has received considerable acceptance in the design of vegetative channels; therefore, the study data were examined in order to determine if this relationship would hold for the channel linings studied. It was concluded that n vs VR did not express a relationship that could be accepted for design purposes. Also, the specific values of n for a given treatment were not obtainable.

The V vs R relationship (velocity versus hydraulic radius) is well established in describing hydraulic conditions in channels. Manning's equation considers these variables along with slope, S, and can be expressed in this form

$$V = a\,R^b\,S^c \tag{1}$$

where a, b, and c are constants for a given channel lining. It is convenient to express Eq. 1 in the linear form

$$\log V = \log a + b \log R + c \log S \tag{2}$$

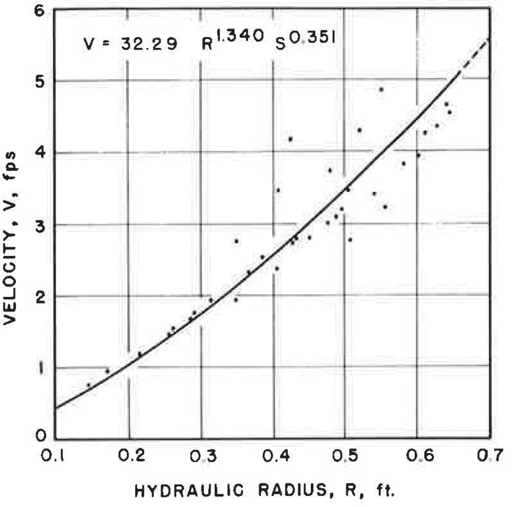


Figure 2. Relation of velocity and hydraulic radius for 2.5 percent slope, excelsior (dashed line extrapolated beyond data).

TABLE 1

VALUES OF a, b, AND c FOR EQUATION 1 OR 2 FOR THE SEVERAL TREATMENTS

Treatment	a	b	c
Erosionet	41.45	0.855	0.400
Jute mesh	61.53	1.028	0.431
Stranded fiberglass[a]	26.05	0.687	0.359
Fiberglass mat, ⅛ in.	73.53	1.330	0.512
Fiberglass mat, ½ in.	14.84	1.235	0.086
Excelsior mat	32.29	1.340	0.351
Straw and Erosionet	70.76	1.455	0.529

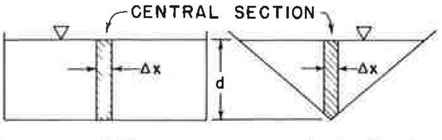
[a] Covered with Erosionet and pinned to channel bed.

A statistical regression technique was used to fit the data to Eq. 2. This method utilized only the data obtained before the failure limits were reached. Figure 2 shows only the data points obtained on a 2.5 percent slope for the excelsior mat treatment. All of the data below the failure limit for this treatment were used in a regression analysis to determine the coefficients for Eq. 2. The coordinates for a 2.5 percent slope were determined from the equation and the resulting curve fits the data points well.

Table 1 gives the results of the statistical treatment. V vs R curves for desired slopes can be prepared for each of the liners studied.

In determining the coefficients for Eq. 2 for the several treatments, it was found that the results were highly significant. The F test was applied to each correlation and revealed that the relationships were significant at a level greater than 99.5 percent.

The tractive force theory states, for a given slope and channel lining, that the unit tractive force on the channel bottom is proportional to the depth of flow (5). The analysis of the data in this study indicated that a depth of flow was more appropriate for describing channel failure limits than maximum permissible velocity of flow. It is assumed that in channels for any shape, for a given slope, depth, and liner the vertical velocity distribution in the central and deepest section, where wall effects are at a minimum, should be identical (6). It is suggested that the location of the first scour occurs in the central section, since the mean velocity derived from the vertical velocity distribution is greater than the mean channel velocity. Now, consider these two channels.



If the depth of flow, slope, and liner are equal in both channels, then the flow rate, mean channel velocity, and coefficient of resistance, n, will be different; however, the velocity distribution (and its mean) will be identical in the central section of each channel. Also, the hydraulic radius of the central sections equals d since,

$$R = \frac{A}{P} = \frac{d(\Delta x)}{(\Delta x)} = d \tag{3}$$

Based on the preceding discussion, it can be stated that the depth at which failure was determined to have occurred for a given liner and slope is the limiting depth for a channel of any shape. Depths of flow that were observed for the test flows preceding the flow which produced failure were noted and examined in a regression analysis which considered depth of flow to be a function of slope.

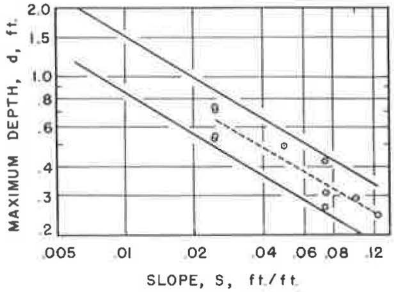


Figure 3. Maximum permissible depth of flow on soils in test channels lined with excelsior mat.

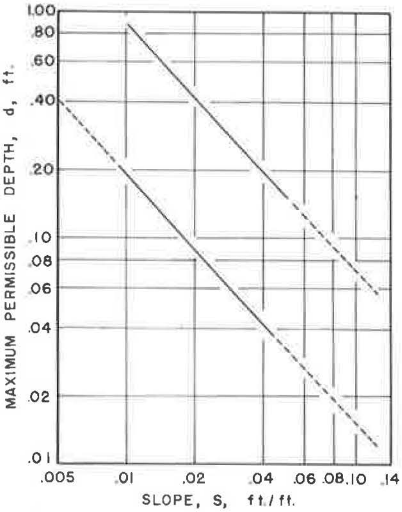


Figure 4. Maximum permissible depth of flow on soils in test channels lined with Erosionet (dashed line extrapolated beyond data).

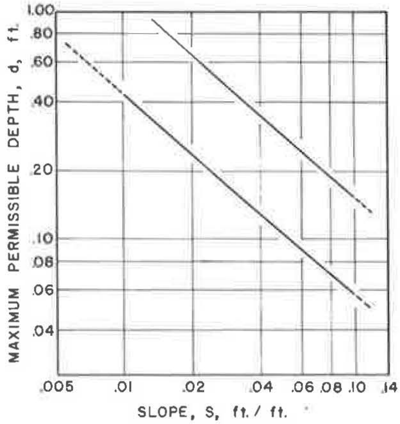


Figure 5. Maximum permissible depth of flow on soils in test channels lined with jute mesh (dashed lines extrapolated beyond data).

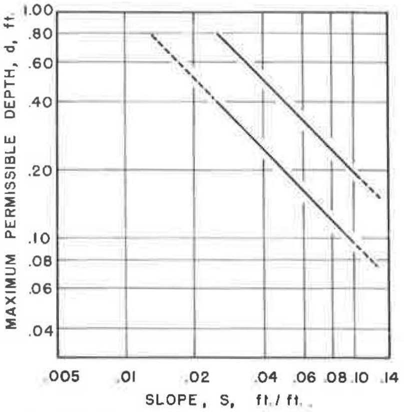


Figure 6. Maximum permissible depth of flow on soils in test channels lined with stranded fiberglass (dashed lines extrapolated beyond data).

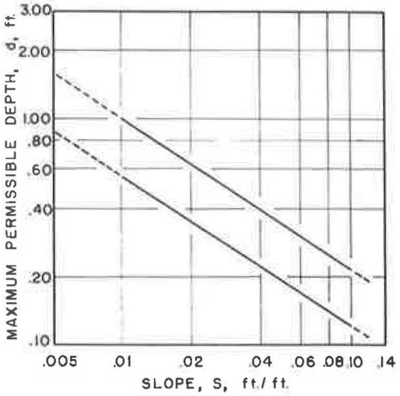


Figure 7. Maximum permissible depth of flow on soils in test channels lined with $^3/_8$-in. fiberglass mat (dashed lines extrapolated beyond data).

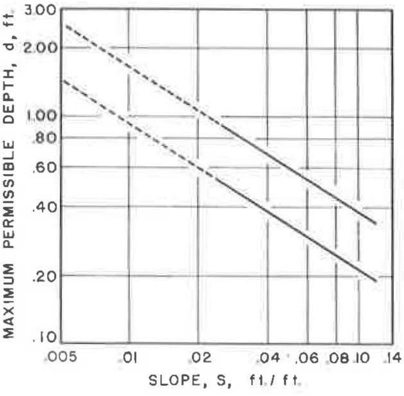


Figure 8. Maximum permissible depth of flow on soils in test channels lined with $^1/_2$-in. fiberglass mat (dashed lines extrapolated beyond data).

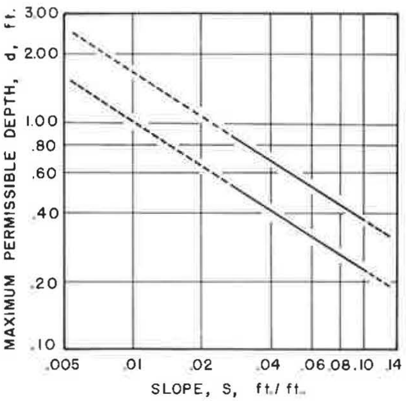


Figure 9. Maximum permissible depth of flow on soils in test channels lined with straw and Erosionet (dashed lines extrapolated beyond data).

Figure 3 shows a logarithmic plot of maximum permissible depth versus slope for several test soils containing clay in the excelsior mat treatment. A regression analysis by the least squares method fitted the data points to the dotted line. The data of this study did not precisely define the depth limits for the test soils used with a given liner; therefore, it was deemed desirable to express the permissible depth as a lower limit and an upper limit. In Figure 3, these limits were drawn parallel to and equidistant from the best fit line (dotted). The location of the limits was based on the plotted data points and in general, the limits bracketed the points. Only those test soils which contained some clay were used in the regression analysis to determine the position of the dotted line. Erosion-resistant soils were considered to be represented by the upper limit; while the lower limit represented the erodible soils.

The same procedure described for processing the excelsior mat data was used for the other treatments. The logarithmic plots of a maximum permissible depth versus slope for these treatments are shown in Figures 4 through 9.

CONCLUSIONS

To utilize the findings presented in this paper for the design of channels with artificial liners, it would be helpful to prepare V-R curves for each treatment. The coefficients shown in Table 1 for Eq. 1 or Eq. 2 can be used to develop coordinates for any slope for a particular liner. Figure 2 shows a plot of V vs R for a 2.5 percent slope. It is suggested that other slopes be plotted, for instance, 1, 5, 7.5, 10, and 12.5 percent. This will result in a family of curves that will yield mean velocity for various values of R; thus, "rating" curves can be developed for each treatment.

If we accept the concept of maximum permissible depth of flow as the design criterion, we can now develop designs for channels using the liners described in this paper. For instance, known values would be design discharge, channel slope, erodible character of the soil, channel slope, and liner material. From Figures 3 through 9, the design depth of flow can be determined. By a first trial, we determine the values of cross-sectional area, A, and R. We now enter Figure 2 or other prepared figures, which represent the liner in question, at the value of R and determine V for the design channel slope. We now substitute the determined values in the equation $Q = A/V$ and solve for Q. If the calculated value is not equal to the design Q, new channel dimensions are tried (the value of d, maximum permissible depth, remains constant for all trials) until the continuity equation is satisfied for the design discharge.

The trial and error solution can be expedited by the preparation of nomographs or tables that will yield values of A and R for given channel depths and cross sections.

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