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SUBCRITICAL FLOW OVER HIGHWAY EMBANKMENTS

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INTRODUCTION

At Utah State University, considerable effort has been devoted to the analysis of submerged flow at open channel constrictions. A method of analyzing subcritical (submerged) flow has been developed for flumes.[3] Because of previous findings, it was felt that this method of analyzing submerged flow could be applied to highway embankments.

A highway embankment, when overtopped by flood waters, is a form of broad-crested weir. Being a weir, the flood discharge over the embankment is only a function of the upstream depth for free flow conditions. This paper will present a method for determining the discharge under submerged flow conditions using the upstream and downstream depths. Thus, postflood field measurements and observations, when properly obtained, will provide the necessary information for an accurate determination of the flood discharge for either free or submerged flow conditions.

One of the earliest studies regarding flow over an embankment was reported by Yarnell and Nagler.[4] More recent experimental data have been reported by Kindsvater.[5] The data collected by Kindsvater have been re-

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[3] Skogerboe, G. V., and Hyatt, M. L., "Analysis of Submergence in Flow Measuring Flumes," Journal of the Hydraulics Division, ASCE, Vol. 93, No. HY4, Proc. Paper 5348, July, 1967, pp. 183-200.

[4] Yarnell, D. L., and Nagler, F. A., "Flow of Flood Waters Over Railway and Highway Embankments," Public Roads, Vol. 11, No. 2, April, 1930, pp. 30-34.

[5] Kindsvater, C. E., "Discharge Characteristics of Embankment-Shaped Weirs," Water Supply Paper 1617-A, Geological Survey, U. S. Dept. of Interior, Washington, D. C., 1964.

analyzed in this paper according to recent developments.

The experimental models studied by Kindsvater[5] are comparable to a secondary highway embankment. The data resulting from the model studies have been subjected to the method of submerged flow analysis previously employed with flow measuring flumes.[3] The consistency of the data, both for free flow and submerged flow, reflects the quality of the experimental design and procedures used in collecting the data. Although the data presented in this paper apply only to various forms of secondary road embankments, the method of analysis is general.

EXPERIMENTAL MODELS

The basic embankment design used in the study conducted by Kindsvater is illustrated in Fig. 1, and the embankment design variations are listed in Table 1. The basic model was constructed at a 1:9 scale. In the original model, the intersections of the shoulder, embankment, and pavement surfaces were sharp and precise. Subsequent use and polishing rounded these intersections, but the results of Kindsvater[5] gave no significant effects due to the rounding.

The principal variables used to describe flow over an embankment are also illustrated by Fig. 1. Throughout the study, scale-model tests were made on 17 variations of the basic embankment design. These tests were made by varying the hydraulic parameters illustrated in Fig. 1 as well as by testing various roughness elements. The laboratory facilities were such that the discharge and degree of submergence could be controlled.

FLOW REGIMES

The two most significant flow regimes or conditions are free flow and submerged flow. The distinguishing difference between the two is the fact that critical depth occurs on the roadway for the free flow condition, usually near the crown line. This critical-flow control on the roadway requires only the measurement of a depth upstream from the point of critical depth for determination of the discharge. When the downstream or tailwater depth is raised sufficiently, the flow depth at the crown line becomes greater than critical depth, and submerged flow conditions exist. With submerged flow, a change in the tailwater depth also affects the upstream depth and a rating for the embankment will require that two flow depths be measured, one upstream and one downstream from the crown line. The flow condition at which the regime changes from free flow to submerged flow is a transition state, and the value of submergence at which this condition occurs is often referred to as the transition or incipient submergence. The writers prefer the designation of transition submergence symbolized by S_t. The transition from free to submerged flow is somewhat unstable and is difficult to produce in the laboratory.

CONCEPTS OF SUBMERGED FLOW AND FREE FLOW

Dimensional analysis was first applied to a trapezoidal flume[3] to develop the dimensionless parameters which describe submerged flow. Manipulation

TABLE 1.—SUMMARY OF DESIGNS TESTED[4]

Model	Investigator	Height, P, in feet		Pavement cross slope, S_p		Shoulder slope, S_s		Surface roughness	Remarks
		Prototype	Model	Inches: feet[a]	Nondimensional	Inches: feet[a]	Nondimensional		
A-1	Davidian	10.5	1.17	1.5:9	0.014	4.5:6	0.062	Smooth	Basic design
A-2	Prawel	10.5	1.17	1.5:9	0.014	4.5:6	0.062	Smooth	Basic design
A-3	Prawel	10.5	1.17	1.5:9	0.014	4.5:6	0.062	Smooth	Basic design
A-4	Emmett	10.5	1.17	1.5:9	0.014	4.5:6	0.062	Smooth	Basic design
B	Prawel	7.88[b]	0.875[b]	1.5:9	0.014	4.5:6	0.062	Smooth	Effect of P
C	Prawel	5.25[b]	0.583[b]	1.5:9	0.014	4.5:6	0.062	Smooth	Effect of P
D	Prawel	2.62[b]	0.292[b]	1.5:9	0.014	4.5:6	0.062	Smooth	Effect of P
E	Prawel	10.5	1.17	0:9[b]	0.000[b]	4.5:6	0.062	Smooth	Effect of S_p
F	Prawel	10.5	1.17	0.9:9[b]	0.008[b]	4.5:6	0.062	Smooth	Effect of S_p
G	Prawel	10.5	1.17	2.2:9[b]	0.020[b]	4.5:6	0.062	Smooth	Effect of S_p
H	Prawel	10.5	1.17	2.8:9[b]	0.026[b]	4.5:6	0.062	Smooth	Effect of S_p
I	Prawel	10.5	1.17	1.5:9	0.014	1.0:6[b]	0.014[b]	Smooth	Effect of S_s
J	Prawel	10.5	1.17	1.5:9	0.014	5.7:6[b]	0.079[b]	Smooth	Effect of S_s
K-1	Davidian	10.5	1.17	1.5:9	0.014	-----	----	Smooth	c
K-2	Prawel	10.5	1.17	1.5:9	0.014	-----	----	Smooth	c
L	Prawel	10.5	1.17	1.5:9	0.014	4.5:6	0.062	Smooth	d
M	Prawel	10.5	1.17	1.5:9	0.014	4.5:6	0.062	Smooth	e
AA-1	Davidian	10.5	1.17	1.5:9	0.014	4.5:6	0.062	Window screen (all surfaces)	
AA-2	Emmett	10.5	1.17	1.5:9	0.014	4.5:6	0.062	Window screen (all surfaces)	
AB	Emmett	10.5	1.17	1.5:9	0.014	4.5:6	0.062	Birdshot (except on pavement)	
AC	Emmett	10.5	1.17	1.5:9	0.014	4.5:6	0.062	Birdshot (all surfaces)	
KA	Davidian	10.5	1.17	1.5:9	0.014	----	----	Window screen (all surfaces)	c

[a] Dimensions given in prototype units.
[b] Shape detail differs from basic design.
[c] Rounded transition between upstream embankment and shoulder surfaces.
[d] Trip wire on downstream edge of downstream shoulder.
[e] Berm on embankment slopes.

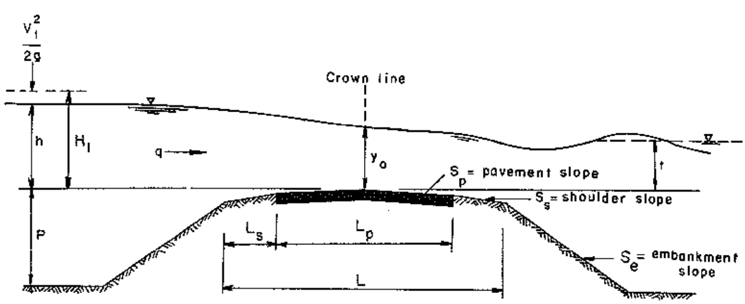

FIG. 1.—PRINCIPAL PARAMETERS DESCRIBING FLOW OVER AN EMBANKMENT

of the equations relating the dimensionless parameters yields a submerged flow discharge equation which is dependent upon only the upstream and downstream flow depths. The general form of the submerged flow equation can be expressed as

$$Q = \frac{C_1 (y_1 - y_2)^{n_1}}{[-(\log y_2/y_1 + C_2)]^{n_2}} \quad \text{(1)}$$

in which y_1 and y_2 are flow depths measured upstream and downstream from the point of minimum flow depth; C_1 and C_2 are coefficients which depend upon the geometry of the structure; and n_1 and n_2 are exponents which are also related to the structure geometry. The coefficient C_1 is a constant for any particular flume geometry, while the coefficient C_2, which is a function of submergence, approaches zero as the submergence approaches 100%.[3] The calibration curves depicting this relationship are a family of curves obtained by plotting discharge, Q, as the ordinate; difference between upstream and downstream depths of flow, $y_1 - y_2$, as the abscissa, and submergence, y_2/y_1, as the varying parameter.

The free flow equation for flow measuring flumes can be expressed by

$$Q = C\, y_1^{n_1} \quad \text{(2)}$$

One noteworthy factor discovered from the flume studies[3] is that the exponent on the $y_1 - y_2$ term in the submerged flow equation (Eq. 1) is identical to the exponent on the y_1 term in the free flow equation (Eq. 2) for any given flume.

THEORETICAL FREE FLOW EQUATION

For the problem of flow over a highway embankment, a theoretical free flow equation can be developed by assuming one-dimensional, steady, frictionless flow with uniform velocity distribution and hydrostatic pressure distribution. The resulting equation, which is listed by Kindsvater,[5] is

$$q = \frac{2}{3}\left(\frac{2g}{3}\right)^{1/2} H_1^{3/2} = 3.09\ H_1^{3/2} \quad \text{(3)}$$

in which H_1 is the total head (flow depth plus velocity head, $V^2/2g$). The similarity between Eqs. 2 and 3 should be noted. The free flow equations derived by the authors from Kindsvater's data have used the upstream flow depth, h, rather than the total head, H_1.

MOMENTUM THEORY APPLIED TO EMBANKMENTS

Momentum theory can be applied to develop submerged flow discharge equations for embankment-shaped weirs. Such equations are useful and instructive for comparison with the empirical approach developed from dimensional analysis. A control volume of fluid will be used which, as shown in Fig. 2, is bounded by the vertical sections at 1 and 2, the water surface, and the surface of the embankment.

A solution will be developed for the horizontal component of the form resistance force, F_{e_x}, due to the embankment. A generalized diagram of the force of the embankment acting on the fluid is shown in Fig. 3, in which

$$F \text{ (lb per ft)} = \left[\gamma\ y + \frac{\gamma\ (y + P) - \gamma\ y}{2}\right] \frac{P}{\sin\lambda}$$

$$= \frac{\gamma\ P}{\sin\lambda}\left(y + \frac{P}{2}\right) \quad \ldots\ldots (4)$$

and $$F_x \text{ (lb per ft)} = \frac{\gamma\ P}{\sin\lambda}\left(y + \frac{P}{2}\right)\sin\lambda = \gamma\ P\left(y + \frac{P}{2}\right) \quad \ldots\ldots (5)$$

The force of the embankment on the fluid will be designated as F_u for the upstream slope and F_d for the downstream slope. Assume that the pressure acting on the upstream slope of the embankment is hydrostatic and due to the water surface elevation at section 1, and that the pressure acting on the downstream slope of the embankment is hydrostatic and due to the water surface

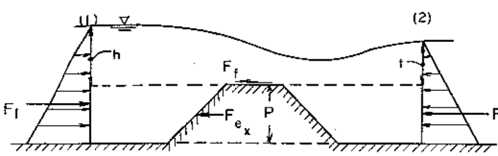

FIG. 2.—CONTROL VOLUME FOR ANALYSIS OF EMBANKMENT-SHAPED WEIR

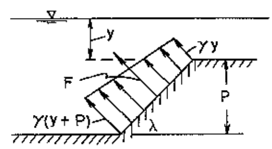

FIG. 3.—DEFINITION SKETCH FOR FORCE ACTING ON THE FLUID DUE TO EMBANKMENT

elevation at section 2. Then the horizontal components of F_u and F_d can be developed from similarity with Eq. 5 for F_x, i.e.,

$$F_{u_x} = \gamma\ P\left(h + \frac{P}{2}\right) \quad \ldots\ldots (6)$$

$$F_{d_x} = \gamma\ P\left(t + \frac{P}{2}\right) \quad \ldots\ldots (7)$$

and $$F_{e_x} = \gamma\ P\left(h + \frac{P}{2}\right) - \gamma\ P\left(t + \frac{P}{2}\right) = \gamma\ P\ (h - t) \quad \ldots\ldots (8)$$

The forces acting on the control volume at sections 1 and 2 (Fig. 2) can be determined by assuming hydrostatic pressure distributions such that

$$F_1 = \frac{\gamma\ (h + P)^2}{2} \quad \ldots\ldots (9)$$

and $$F_2 = \frac{\gamma\ (t + P)^2}{2} \quad \ldots\ldots (10)$$

If friction losses are neglected ($F_f = 0$), the summation of forces in the horizontal direction is

$$\Sigma F_x = F_1 - F_2 - F_{e_x} \qquad (11)$$

and
$$\Sigma F_x = \frac{\gamma\,(h + P)^2}{2} - \frac{\gamma\,(t + P)^2}{2} - \gamma\,P\,(h - t) = \gamma\,\frac{(h^2 - t^2)}{2} \qquad (12)$$

Assuming uniform velocity distributions at sections 1 and 2, the momentum equation can be written

$$\Sigma F_x = q\,\rho\,(V_2 - V_1) \qquad (13)$$

The summation of horizontal forces given by Eq. 12 is

$$\frac{\gamma\,(h^2 - t^2)}{2} = q\,\rho\,(V_2 - V_1) \qquad (14)$$

Assuming steady flow, the continuity equation, $q = V_y$, can be used; hence,

$$q = V_1\,(h + P) = V_2\,(t + P) \qquad (15)$$

The continuity equation can be substituted into Eq. 14 to give

$$\frac{\gamma\,(h^2 - t^2)}{2} = q\,\frac{\gamma}{g}\left[\frac{q}{t + P} - \frac{q}{h + P}\right] \qquad (16)$$

in which

$$q = \left(\frac{g}{2}\right)^{1/2}\sqrt{(h + t)\,(t + P)\,(h + P)} \qquad (17)$$

Manipulation of Eq. 17 yields

$$q = \frac{(g/2)^{1/2}\,(h - t)^{3/2}}{\sqrt{\dfrac{(1 - S)^3}{(1 + S)(S + P/h)(1 + P/h)}}} \qquad (18)$$

in which S is the submergence, t/h.

EQUATION CHARACTERISTICS

Although the assumptions made in the development of the theoretical submerged flow equation are not entirely valid, Eq. 18 does contain certain characteristics which can be compared with the submerged flow equation developed from dimensional analysis. In order to make a comparison between the two submerged flow equations (Eqs. 1 and 18), assume $C_2 = 0$ in Eq. 1. This assumption will later prove to be valid for the embankment-shaped weirs under study. Define the denominator of Eq. 1 as

$$f\,(S) = \frac{1}{-\log S} \qquad (19)$$

Define the denominator of Eq. 18 as

$$\phi_m(S) = \frac{1}{\sqrt{\dfrac{(1 - S)^3}{(1 + S)\,(S + P/h)(1 + P/h)}}} \qquad (20)$$

A test of the relationship between f (S) and $\phi_m(S)$ can be made by assigning arbitrary values of S in Eq. 19 and values of S and P/h in Eq. 20.

The comparison between f (S), ϕ_m (S), and P/h is shown in Fig. 4. For $P/h = 0$, an equation between f (S) and ϕ_m (S) can be written as

$$\phi_m (S) = 0.403 [f (S)]^{1.50} \quad (21)$$

For $P/h > 0$, the lines of constant P/h for the logarithmic plot of Fig. 4 are curved. The lines of constant P/h have a constant slope of 1.50 when $f(S)$

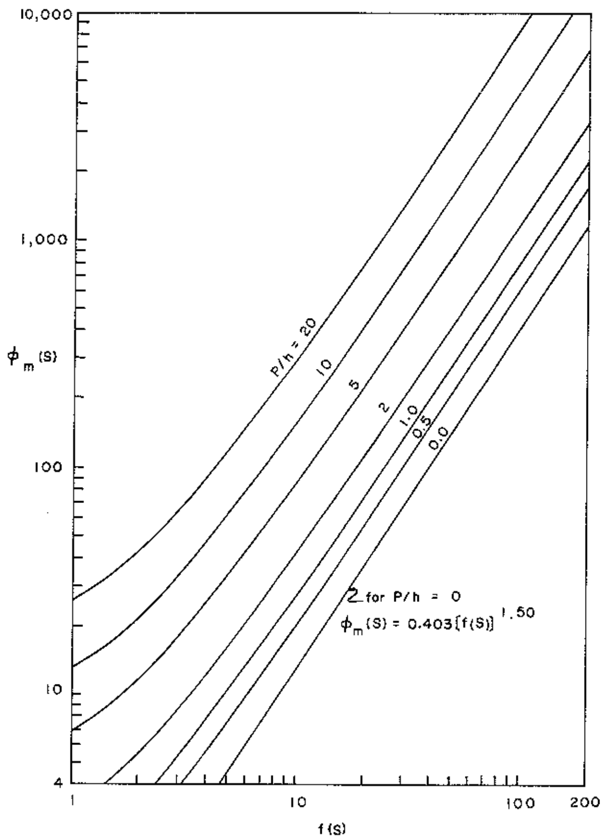

FIG. 4.—RELATIONSHIP BETWEEN $f(S)$, $\phi_m(S)$, AND P/h FOR EMBANKMENT-SHAPED WEIRS

> 10. When f $(S) = 10$, the submergence is approximately 80%. As will be shown later, submerged flow exists for the embankments under study when the submergence exceeds 85% or 86% [f (S) approximately equal to 15]. Consequently, for the purposes of this paper, only the portions of the curves in Fig. 4 where f $(S) > 15$ are of importance. Therefore, a relationship similar to Eq. 21 can be written for each line of constant P/h in Fig. 4 for the portions of the curves where $f(S) > 10$. The actual relationship between $f(S)$, $\phi_m(S)$, and P/h is not of great importance, only the fact that a simple relationship does exist.

FREE FLOW EVALUATION

The discharge data available from Kindsvater[5] were used for the free flow evaluation of the models listed in Table 1, except for models A-1, K-1, AA-1,

TABLE 2.—COEFFICIENTS AND EXPONENTS FOR MODEL FREE FLOW EQUATIONS

Model	C	n_1
A-1	----	----
A-2	3.19	1.53
A-3	3.19	1.53
A-4	3.19	1.53
B	3.25	1.53
C	3.43	1.56
D	3.62	1.59
E	3.24	1.54
F	3.24	1.54
G	3.24	1.54
H	3.24	1.54
I	3.24	1.54
J	3.24	1.54
K-1	----	----
K-2	3.24	1.54
L	3.24	1.55
M	3.21	1.52
AA-1	----	----
AA-2	3.22	1.56
AB	3.17	1.53
AC	3.15	1.55
KA	----	----

and KA. The free flow data were plotted with q as the ordinate, and h, the upstream depth, as the abscissa on logarithmic paper. All of the plots resulted in straight lines with the data showing little deviation. The equations resulting from these plots were of the form

$$q = C\,h^{n_1} \qquad (22)$$

Table 2 lists the values of C and n_1 for the various models analyzed. As is shown, there is some variation in both C and n_1 values for the various models. The variations in the free flow equations will be considered after analyzing the submerged flow data.

SUBMERGED FLOW EVALUATION

The submerged flow data for each model were plotted on logarithmic paper with the discharge per foot of length of embankment, q, as the ordinate, the change in water surface elevation, $h - t$, as the abscissa, and t/h, the sub-

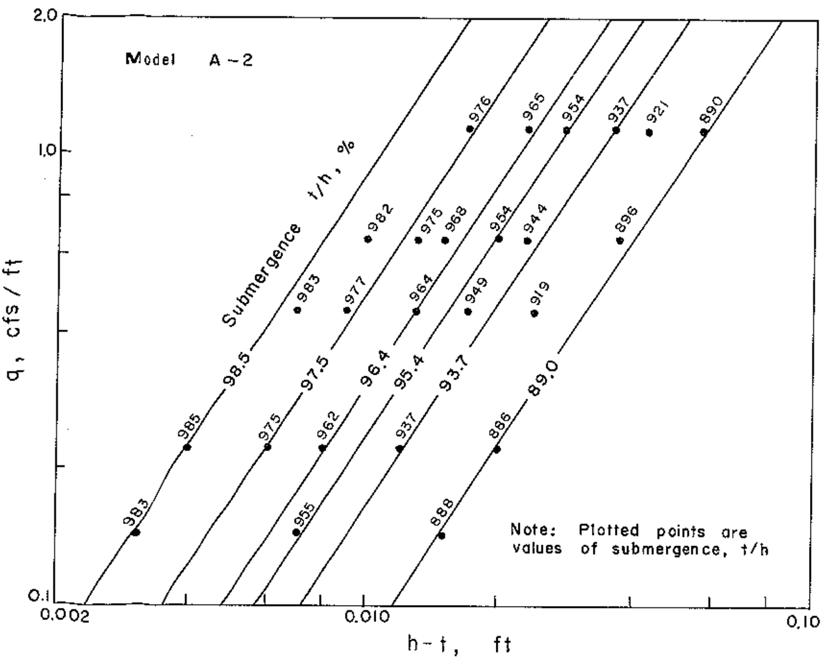

FIG. 5.—PLOT OF SUBMERGED FLOW DATA FOR MODEL A-2

mergence, as the varying parameter. Essentially, such plots are the graphical presentation of the submerged flow equation (Eq. 1). Typical of such plots is Fig. 5, which is a plot of the data for model A-2. Lines of constant submergence which best fit the data are drawn with a slope corresponding to the exponent of h in the free flow equation for the same model. For example, the constant submergence lines of 89.0, 93.7, 95.4, 96.4, 97.5, and 98.5% have been drawn in Fig. 5 for model A-2. The slope of these lines of constant submergence is 1.53, which corresponds with the exponent of h in the free flow equation for model A-2 (Table 2).

The general submerged flow equation for each of the models is of the form

$$q = \frac{C_1 \, (h-t)^{n_1}}{(-\log t/h)^{n_2}} \quad \ldots\ldots (23)$$

and exponents in the free flow equations (Table 2), and the coefficients and exponents in the submerged flow equations (Table 3).

Models B, C, and D were studied to illustrate the effect of embankment height on the discharge equations. The fact that the embankment height has a marked and definite effect on the discharge relationship is readily apparent. A comparison between the A-models and model B, using the extreme fluctuations in flow depths which could actually occur, results in the discharge, q, being 2% to 11% greater in model B. For similar extreme fluctuations in flow depth, model C could result in flow rates as much as 26% greater than the A-models, while the discharge over model D would vary from 10% smaller

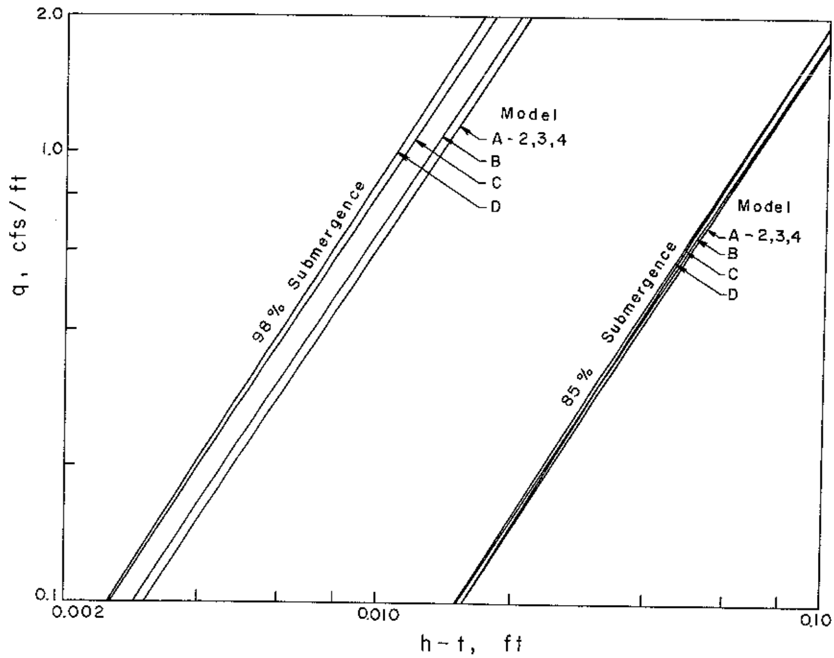

FIG. 7.—PLOT OF 85% AND 98% SUBMERGENCE LINES FOR BASIC MODEL DESIGN AND MODELS B, C, AND D

to 32% greater than the A-models. The effect of embankment height is illustrated in Fig. 7 for submergences of 85% and 98%. The 85% submergence line was chosen because it represents the transition submergence. Essentially, the variation in the 85%-submergence lines represents the differences in the free flow equations for the models. The differences in the 98%-submergence lines illustrate the condition of nearly maximum variation between the models.

Models E, F, G, H, I, J, K-1, and K-2 were constructed to evaluate the effects of pavement slope, S_p, and shoulder slope, S_s, on the discharge characteristics of embankment-shaped weirs. The discharge equations for models E, F, G, H, I, J, and K-2 are identical. The equation for those models could result in a discharge which varies from 4% less to 13% greater than the discharge through model A-2.

Model L is different from the basic model only in that it has a trip wire on the downstream edge of the downstream shoulder. The equations which describe the discharge through model L vary little from those describing the flow in the basic model. Actually, in the extreme cases of flow depths, the discharge would only be about 5% less in model L. This could indicate that the trip wire may act in a manner which increases the submergence of the flow.

Model M differs in geometry from the A-models in that berms have been constructed on the embankment slopes. The berms have an effect on the discharge over the model as compared with the basic model embankment. The submerged flow coefficient, C_1, is much less and the submergence exponent, n_2, much greater in model M than in model A-2. Under extreme flow conditions, the discharge over model M could be 16% greater than the flow over model A-2.

EMBANKMENT ROUGHNESS

Models AA-2, AB, and AC were constructed to evaluate the effect of roughness. The models were roughened either by birdshot or window screen. Model AA-2 had a screen-wire roughness on all surfaces. Both the exponent of the change in water surface elevation, n_1, and the submergence exponent, n_2, for model AA-2 are greater in value than exponents for the basic embankment model. Further evaluation discloses that the discharge over model AA-2 will be 2% to 14% lower than the flow over model A-2.

Models AB and AC had birdshot (No. 9 with 0.080-in. diam) glued to their surfaces. Model AC had birdshot placed on all surfaces while model AB did not have birdshot placed on the pavement. A difference exists in the discharge equations for models AB and AC. Model AB gives discharge values which are 2% lower to 4% greater than the basic embankment model, whereas model AC yields discharges which vary from 3% to 11% less than the basic model. Also, model AC gives flow rates which are less than the flows passing over model AB. Consequently, the increased roughness on the pavement does have a significant effect in retarding the flow.

CONCLUSIONS

An analytical method of evaluating submerged flow over a highway embankment has been illustrated. The method of analysis is an extension of the writers' earlier efforts regarding side contractions (flumes) in open channels. Since the submerged flow analysis has worked well for embankment-shaped weirs, there is no reason to believe that it would not work for other weir forms. The analytical techniques used have demonstrated that the height and surface roughness of the embankment does have a significant effect on the discharge.

ACKNOWLEDGMENTS

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APPENDIX.—NOTATION

The following symbols are used herein:

C = coefficient in free flow equation;
C_1, C_2 = coefficient in numerator and denominator of submerged flow equation, respectively;
F = force;
F_1, F_2 = hydrostatic force at sections 1 and 2, respectively;
F_d = force of downstream embankment slope acting on fluid;
F_{e_x} = embankment form resistance acting on fluid in horizontal direction;
F_f = boundary frictional force;
F_u = force of upstream embankment slope acting on fluid;
F_x = force acting in horizontal direction;
g = acceleration due to gravity;
h = upstream depth of flow measured from crown line elevation;
H_1 = total energy head at upstream section referenced to crown line elevation;
L = total width of roadway (pavement plus two shoulders);
L_p = pavement width;
L_s = shoulder width;
n_1 = exponent in free flow equation and numerator of submerged flow equation;
n_2 = exponent in denominator of submerged flow equation;
P = height of embankment;
Q = total flow rate, or discharge;
q = discharge per foot of length of embankment;
S = submergence, which is ratio of a downstream depth to an upstream depth with both depths referenced to a common elevation;
S_e = embankment slope;
S_p = pavement cross slope;
S_s = shoulder slope;
S_t = transition submergence;
t = downstream depth of flow measured from crown line elevation;
V = average velocity;
V_1, V_2 = average velocity at sections 1 and 2, respectively;
y = flow depth;
y_1, y_2 = flow depth at sections 1 and 2, respectively;
y_o = flow depth at crown line;
γ = specific weight of fluid;
λ = embankment slope;
ρ = density of fluid;
$f(S)$ = $1/(-\log S)$; and
$\phi_m(S)$ = $1/\sqrt{(1 - S)^3/S\ (1 + S)}$.

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KEY WORDS: channels (waterways); embankments; floods; flow measurement; highways; hydraulics; subcritical flow; submerged flow; weirs

ABSTRACT: A highway embankment, when overtopped by flood waters, is a form of broad-crested weir. As a weir, the flood discharge over the embankment is only a function of an upstream depth for free flow conditions. Free flow exists when critical depth occurs on the roadway, usually near the crown line. If a structure or vegetation downstream from the embankment "controls" the stage-discharge relationship, the depth of flow at the embankment may be raised sufficiently to prevent the occurrence of critical depth on the roadway. If critical depth does not occur, then subcritical (submerged) flow exists over the embankment. A method for determining the discharge under submerged flow conditions using an upstream and a downstream flow depth is presented. The method is illustrated using data collected from model highway embankments.

REFERENCE: Skogerboe, Gaylord V., and Hyatt, M. Leon, "Subcritical Flow Over Highway Embankments," Journal of the Hydraulics Division, ASCE, Vol. 93, No. HY6, Proc. Paper 5564, November, 1967, pp. 65-78.