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A method for determining critical depth for a cross section of any shape is presented. The method is incorporated in the U.S. Army Corps of Engineers, Hydrologic Engineering Center's Water Surface Profile Computer Program (HEC-2). The method proposed determines the minimum specific energy by using a parabolic interpolation.

15. SUBJECT TERMS
critical depth, HEC-2, backwater, mathematical models, minimum specific energy, parabolic equation, coriolis coefficient, open channel hydraulics

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CRITICAL WATER SURFACE BY MINIMUM SPECIFIC ENERGY USING THE PARABOLIC METHOD

by

Bill S. Eichert(1)

GENERAL - The critical state of flow is defined as the condition at which a maximum discharge is obtained with a given energy, or where a minimum energy is required to produce a given discharge. For a simple geometric channel (rectangular, trapezoidal, semi-circular, etc.) the critical velocity (V_c) may be computed from the area (A) and top width (TW) by the formula: $\frac{V^2_c}{2g} = \frac{A}{2TW}$. For complex cross sections, where channel and overbank flows both occur, this equation can give answers which are greatly in error due to the ability of the hydraulic radius to increase materially with only a small change in area. For a cross section that has horizontal overbanks, the formula will erroneously show that the critical discharge flowing at the top of the banks is greater than the critical discharge when flowing at just above the banks. This condition can be properly evaluated for a given discharge using a cross section of any shape by dividing the cross section into several subsections in order to define the nonuniform velocity distribution, and by determining the critical water surface elevation that corresponds to the minimum specific energy. For a complex cross section, the energy gradient and the water surface elevation are usually assumed constant across the entire width of the cross section, and the energy gradient is then equal to the water surface elevation plus a weighted velocity head.

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As a result of nonuniform distribution of velocities over a cross section, the velocity head of a cross section ($V^2/2g$) is generally greater than the value computed by dividing the square of the mean velocity (Q/A) of the cross section by twice the gravitational constant (g). This statement is true because the square of the average velocity is less than the weighted average of the squares of the point velocities. The true velocity head may be expressed as $\alpha V^2/2g$, where alpha is the energy-head coefficient, or Corioli's coefficient. The method presented in this paper does not assume a Corioli's coefficient of unity as most hand methods do, but accounts for the nonuniform velocity distribution between the subsections by assuming that the weighted velocity head of the cross section (WHV) is equal to the average velocity head for each subsection of the cross section when the subsection velocity head is weighted in proportion to the discharge capacity of the subsection. The discharge capacity of each subsection (Q) equals the product of its area (A) and its average velocity (V), or using Manning's formula, $Q = AV = (1.486A\, R^{2/3}S^{1/2})/n$. For an assumed water surface elevation the area (A), hydraulic radius (R) and Manning's roughness coefficient (n) are known. Initially, an index slope of the energy gradient (S_1) is established such that $S^{1/2} = .01$ (subscript 1 on Q_1, V_1, R_1, S_1 indicates index values), and the resulting index discharge (Q_1) is computed for each subarea and totaled for the entire cross section. Since the actual discharge which is to be used in the backwater computations, (ΣQ) equals the sum of the discharge through the subsection, and since the area, hydraulic radius and roughness coefficient are equal, the slope (S) can be computed from the following equation:

$$\frac{Q_1}{Q} = \frac{S^{1/2}{}_1}{S^{1/2}}$$

Thus:

$$S = [(.01 \quad \Sigma Q) / \Sigma Q1]^2$$

The velocity head of each subsection, based on uniform velocity distribution within the subsection, is:

$$HV = (Q/A)^2 \ / \ 2g$$

The weighted velocity head for the cross section is therefore:

$$WHV = (\Sigma \ (Q \times HV \times COR) \ ) / \ \Sigma \ Q = \Sigma \ (QHV) \ / \Sigma \ Q$$

where: COR = Corioli's coefficient

PARABOLIC METHOD - The relationships between the water surface elevation and the energy gradient is approximated by the parabolic equation using an optimization routine that converges rapidly upon the desired critical condition.

The parabolic method of determining the minimum energy elevation (EG) requires three water surface elevations and the corresponding energy elevations (EG1, EG2, EG3) which are obtained by adding the water surface elevations to the weighted velocity heads. A special case which simplifies the formula for the parabolic estimate of the minimum energy occurs when the three estimates of water surface elevation are separated by two equal intervals of elevation (HTINC). The procedure of assuming three water surface elevations equally spaced followed by an estimate using the parabolic equation is referred to as a cycle during the rest of this paper. The basic formula for the water surface elevation at the minimum energy point (based on a true parabola) was derived as follows:

let k = critical water surface elevation

h = minimum energy elevation

y = any water surface elevation

x = the energy elevation corresponding to y

p = constant for the parabola

From the basic equation of the parabola:

$$(y - k)^2 = 2p\ (x - h)$$

Equations for any three estimates of the water surface elevations (y_1, y_2, y_3) are:

$$(y_1 - k)^2 = 2p(x_1 - h)$$
$$(y_2 - k)^2 = 2p(x_2 - h)$$
$$(y_3 - k)^2 = 2p(x_3 - h)$$

Since there are three equations and 3 unknowns (k,h,p), these equations may be solved simultaneously, by standard methods not shown here to yield:

$$\frac{y_1^2 - 2y^2_2 + y^2_3 - 2k(y_1 - 2y_2 + y_3)}{(y_1 - y_2)(y_1 + y_2 - 2k)} = \frac{x_1 - 2x_2 + x_3}{x_1 - x_2}$$

Since the value of k (the only unknown) is in both numerator and denominator and the equation apparently is in its simplest form, the equation will have to be solved by successive approximations. However, if a uniform increase is made between y_1, y_2, and y_3 such that:

$$y_2 = y_1 + \Delta y$$
$$y_3 = y_1 + 2\Delta y$$

Then, by combining the three equations above, simplifying and solving for k, we find:

$$k = y_1 + .5\Delta y + \left(\frac{x_1 - x_2}{x_1 - 2x_2 + x_3}\right) \Delta y$$

or, in terms used during rest of paper:

$$WSEL = WSEL1 + .5 * HTINC - \frac{D1}{D3} * HTINC$$

where:

WSEL = parabolic estimate of water surface elevation

WSEL1 = first assumption of water surface elevation in each cycle

HTINC = constant increment of height added to first and second WSEL

D1 = difference in energy gradients for the second and first assumptions (EG2 - EG1)

D2 = difference in energy gradients for the third and second assumptions (EG3 - EG2)

D3 = difference between D2 and D1

The value of HTINC should be chosen very carefully an its magnitude may double or triple the number of iterations required to determine critical depth. For this application, HTINC is assumed equal to 5% of the difference between the water surface elevation assumed (WSEL1) and the minimum elevation in the cross section (ELMIN). Since the assumed water surface elevation changes for each optimization cycle (set of three or more guesses), the value of HTINC also varies for each cycle.

The first assumed water surface elevation for the first cycle is made without knowledge of the parabolic parameters, and is made as close as possible to the true answer in order to reduce the number of iterations.

In this application, the initial assumption normally made is that the critical depth for the current section is equal to the critical depth at the previous section. The next two assumptions increase the estimates by a fixed amount (HTINC), while the fourth estimate is based on the equation of the parabola.

If the quantity (D2 - D1) is positive, the optimization procedure is converging and the above equation is appropriate. From Exhibit 1, note that for subcritical flow (depth greater than critical) D1 and D2 are positive and that D1 must be less than D2 for convergence while for super-critical flow D2 and D1 are negative and D2 must be numerically smaller than D1 for convergence.

If (D2 - D1) is not positive, then the function is not converging (possibly due to some local irregularities in the cross section) and the next extimate of the water surface should be a large step in the direction of decreasing energy. (A limit of 50 percent in any step is used in order not to bypass the minimum energy point in the case of highly irregular functional relationships.)

The value of D1 is used to indicate the direction of the change. Positive values of D1 indicate that the trials are on the subcritical flow side and that the estimates of water surface elevation should be decreased. Negative values of D1 are indicative of trials in the super-critical flow range and indicate that the estimates of water surface elevation should be increased.

If D2 and D1 are both equal to zero, critical depth has been found. If they are equal to each other, but not equal to zero, then a negative value of D1 indicates an increase is needed and a positive value indicates a decrease.

If the estimate based on the parabolic method (EGC) produces an energy gradient that is greater than the first estimate of this cycle (EG1), then the estimated change is too large and has passed beyond the critical water surface elevation. When this condition occurs, the estimated water surface elevation is changed so that the magnitude of change from the first estimate of the last cycle is reduced by 70 percent (WSEL = .3 WSEL + .7 WSEL1). If this condition occurs on the next try also, then the previous estimated change is again reduced by 70 percent. This reduction process may be used up to 5 consecutive times which would provide a minimum change of .002 ($.3^5$) times the change indicated by the parabolic equation.

When the estimate from the parabolic method given an energy gradient which is less than the first assumption of the cycle, the estimate is converging toward critical depth. This estimate is either accepted as being close enough to the minimum specific energy or another complete cycle is made using the previous estimate as the first assumption (WSEL1). The above process is repeated until the answer is within acceptable limits.

The estimated critical water surface elevation is accepted in this application when:

(1) The difference between the last two estimates by the parabolic method, or the last 70 percent reduction of that estimate, (WSEL - WSEL1) is less than the smaller of .5 foot or 2.5 percent of the estimated depth from the critical water surface elevation to the minimum elevation in the cross section, and

(2) When the last energy gradient elevation for the estimate by the parabolic method (or the last reduction of that estimate) was an improvement over the energy gradient elevation for the previous cycle (EG1), or was no worse than .01 of a foot.

Numerical examples are shown on Exhibit 3 for 3 typical problems. In Example 2, the first estimate of the critical water surface elevation was so close that only one cycle was necessary to determine the critical condition. In Example 3, the estimate by the parabolic equation was not controlling in the entire process since it required a change greater than 50 percent of the depth each time it was computed. A description of the cross sections used in the three examples is shown in Exhibit 4.

CRITICAL DEPTH DETERMINATION FOR COMPLEX CROSS SECTION

ELEV (1)	ELE-MENT (2)	HT (3)	AREA (4)	WETTED PERIM. (5)	HYDRAU RADIUS (HR) (6)	$(HR)^{2/3}$ (7)	MANNING'S n (8)	$S^{1/2}=.01$		Q (11)	V (12)	V^2Q (13)	HV (14)	ENERGY GRADIENT (15)
								V_1 (9)	Q_1 (10)					
124.20	L.O.B.	4.2	1260	304.20	4.13	2.58	.05	.766	966	4,230	3.36	47,800		
	CH	24.2	2420	140.00	17.25	6.70	.02	4.98	12,100	52,960	21.85	25,400,000		
	R.O.B.	4.2	840	204.2	4.12	2.58	.05	.766	644	2,810	3.36	31,700		
									13,710	60,000		25,478,500	6.60	130.80

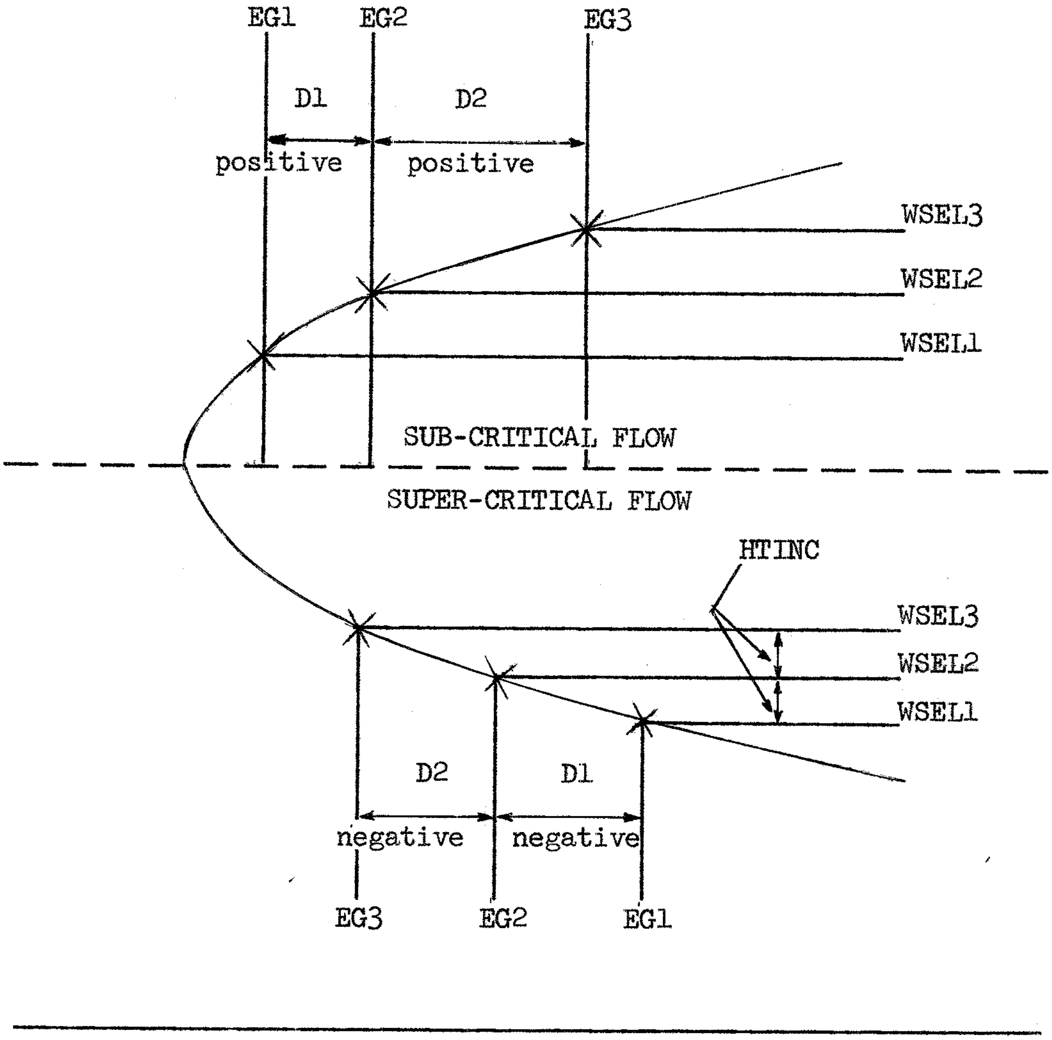
Col 9 = $V_1 = \frac{1.486}{n} R^{2/3}(.01)$, Col 10 = $Q_1 = AV_1$, Col 11 = $Q_{CH} = \frac{Q_{1CH}}{Q_{1TOTAL}} Q$,

Col 12= $V_{CH} = \frac{Q_{CH}}{A_{CH}}$, Col 14 = $HV = \frac{\Sigma V^2 \cdot Q}{64 \cdot 4Q}$, Col 15 = EG = ELEV + HV

EXHIBIT 1

EXHIBIT 2

SPECIFIC ENERGY CURVE



ENERGY GRADIENT ELEVATION

EXHIBIT 3

CRITICAL WATER SURFACE BY PARABOLIC METHOD

(1) TRIAL NO	(2) TYPE ASSUMPTION	(3) WATER SURFACE EL ASSUMED	(4) ENERGY GRADIENT EL COMPUTED	(5) INCREMENT OF HEIGHT CHANGE	(6) WEIGHTED VELOCITY HEAD	(7) D1	(8) D2	(9) D3	(10) BASIS OF ESTIMATE
Example 1 - (100' BW rectangular section, invert el - 1200)									
1	2	1215	1216.76674	.75	1.767				Reasonable estimate
2	3	1215.75	1217.35248	.75	1.602				Increase by .75
3	4	1216.50	1217.96011		1.460	.585	.608	.022	" " "
4	2	1207.5	1214.56694	.825	7.067				Parabolic*
5	3	1208.32	1214.06069	.825	5.736				Increase by .825
6	4	1209.15	1213.89801		4.748	-.506	-.163	.344	Increase by .825
7	2	1209.13	1213.89892	.457	4.771				Parabolic
8	3	1209.59	1213.91189	.457	4.326				Increase by .457
9	4	1210.04	1213.98421		3.941	.013	.072	.059	Increase by .457
10	5	1209.26	1213.89588		4.639				Parabolic

*Estimate limited to a change of 50% depth

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Example 2									
1	2	157.00	164.130	.900	7.129				Reasonable guess
2	3	157.90	164.190	.900	6.290				Increase by .900
3	4	158.80	164.385		5.585	.061	.195	.134	Increase by .900
4	5	157.04	164.129		7.089				Parabolic equation
Example 2									
1	2	170.62	170.845	1.452	.227				Reasonable guess
2	3	172.07	172.237	1.452	.168				Increase by 1.452
3	4	173.52	173.649		.127	1.393	1.411	.019	Increase by 1.452
4	5	156.09	223.475		67.380				Parabolic Equation*
5	6	166.26	176.974		10.713				Reduce by 70%
6	2	169.31	169.617	1.598	.306				" " "
7	3	170.91	171.121	1.598	.214				Increase by 1.598
8	4	172.51	172.659		.154	1.505	1.538	.033	" " "
9	5	155.44	233.052		77.612				Parabolic Equation*
10	6	165.115	178.357		13.207				Reduce by 70%
11	7	168.06	175.618		7.556				" " "
12	8	168.94	175.296		6.360				" " "
13	9	169.20	169.513		.315				" " "

*parabolic assumption was limited to change of 50% depth

EXHIBIT 3
Page 2 of 2

EXAMPLE CROSS SECTION DATA

EXAMPLE 1

Elev	Station
1215	0
1200	0
1200	100
1215	100

EXAMPLE 2

Elev	Station
160	557
146	560
139	581
139	585
142	591
143	599
166	605

EXAMPLE 3

Elev	Station
(1)183.57	0
173.57	103.86
162.57	259.64
161.57	266.57
153.57	270.37
148.57	273.84
147.57	275.91
142.57	278.68
141.57	281.80
145.57	288.38
160.57	291.84
162.57	294.26
163.57	346.19
153.57	484.67
153.57	519.29
173.57	657.76
183.57	692.38
193.57	692.38

(1)The implied accuracy of one hundredeth of a foot is misleading since this cross section was obtained by the computer by interpolation between two given cross sections.

EXHIBIT 4

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