SUBDIVISION FROUDE NUMBER

COE Technical Paper No. 110
October 1985

US Army Corps
of Engineers

The Hydrologic
Engineering Center

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INTRODUCTION

The standard step method calculates one-dimensional steady state water surface profiles by iterating upon the equations for energy conservation and head loss between adjacent cross sections (3). These calculations begin at and proceed away from the controlling boundary cross section. If the flow regime is subcritical the calculations proceed upstream from the downstream boundary, and if the flow regime is supercritical the calculations proceed downstream from the upstream boundary. But this procedure must in some sense be invalid for compound sections in which both flow regimes may occur in different portions of a cross section. Usually when this occurs, the flow in the main channel is in the supercritical regime and the flow in the overbanks is in the subcritical regime (6).

The development and testing of a subdivision Froude number with which the flow regime in each of the three major cross-sectional subdivisions (the two overbanks and the main channel) can be identified is described. This Froude number is compatible with HEC2, a widely used model that employs the standard step method (3,4). The determination of a Froude number for each flow subdivision can enhance the engineer's ability to evaluate the validity of a one-dimensional analysis.

FROUDE NUMBERS

The Froude number indicates the flow regime. A value less than one indicates subcritical flow, and a value of greater than one indicates supercritical flow. The simplest definition of the Froude number assumes a uniform velocity distribution so that

$$F = \frac{V}{\sqrt{gD}} \qquad (1)$$

in which F = Froude number; V = mean velocity; g = gravitational acceleration; and D = hydraulic depth (area divided by top width) (5). A Froude number that considers a nonuniform velocity distribution is

$$F = V\left(\frac{\alpha}{gD}\right)^{1/2} \qquad (2)$$

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Note.—Discussion open until December 1, 1985. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on February 27, 1984. This paper is part of the *Journal of Hydraulic Engineering*, Vol. 111, No. 7, July, 1985. ©ASCE, ISSN 0733-9429/85/0007-1099/$01.00. Paper No. 19826.

in which α = Coriolis coefficient. Petryk and Grant (6) developed a Froude number that is the discharge-weighted average of the simple Froude number of Eq. 1 within every subsection. Blalock and Sturm (1) derived a composite Froude number that accounts for the variation of the Coriolis coefficient as a function of the water surface elevation.

Froude number is related to the slope of the specific energy curve. Both Henderson (5) and Blalock and Sturm (2) show for their Froude numbers that

$$\frac{dE}{dy} = 1 - F^2 \qquad (3)$$

in which E = the specific energy

$$E = y + \alpha \frac{V^2}{2g} \qquad (4)$$

and y = depth. Therefore, when the slope of the specific energy curve is positive, the flow is subcritical, and when the slope is negative, the flow is supercritical.

Subdivision Froude Number

A problem in developing a subdivision Froude number is that the discharge in a subdivision is dependent on the water surface elevation. Therefore the two simple Froude numbers that are defined by Eqs. 1 and 2 are not appropriate for subdivisions of a cross section. Considering subdivision discharge to be a function of the water surface elevation also invalidates the Froude number of Petryk and Grant (6), which Blalock and Sturm (1) showed was inaccurate. Blalock and Sturm's (1) composite Froude number is accurate for an entire cross section, but it is not accurate for subdivisions because it also fails to consider the change of subdivision discharge with water surface elevation.

A subdivision Froude number which allows the discharge to vary with the water surface elevation can be derived from the definition of specific energy. The derivative of specific energy in a subdivision with respect to depth is taken, and both the Coriolis coefficient and the subdivision velocity are assumed to vary with depth. The derivative is substituted into Eq. 3 to arrive at the expression for the subdivision Froude number

$$F = \left\{ \frac{\alpha V_{sd}}{g A_{sd}} \left[\frac{Q}{K^2} \left(K_{sd} \frac{dK}{dy} - K \frac{dK_{sd}}{dy} \right) + V_{sd} T_{sd} \right] - \frac{V_{sd}^2}{2g} \frac{d\alpha}{dy} \right\}^{1/2} \qquad (5)$$

in which V_{sd} = subdivision velocity; A_{sd} = subdivision area; Q = cross section discharge, K = cross section conveyance; K_{sd} = subdivision conveyance; and T_{sd} = subdivision top width. The derivatives of subdivision conveyance and Coriolis coefficient are given elsewhere (1,7). The complete derivation of Eq. 5 is given by Schoellhamer (7).

Blalock and Sturm used the same approach to derive their compound Froude number and showed that it was in agreement with experimental results (1). They later stated that use of a celerity that is derived from the method of characteristics produces the identical Froude number (2). Because the compound and subdivision Froude numbers are very similar, the method of characteristics would also be expected to show that the subdivision Froude number is correct. In addition, testing shows that the subdivision Froude number is compatible with both the velocity and the specific energy that one finds in a subdivision.

Testing Subdivision Froude Number

The sample trapezoidal cross section of Fig. 1 was initially used to test the subdivision Froude number (7). Five flow rates were tested—100, 1,000, 5,000, 10,000, and 50,000 cfs (1 cfs = 0.028 m^3/s). These flow rates represent extremely low flow, critical depth in the main channel, multiple critical depths, critical depth above the main channel, and extremely high flow, respectively. Each flow rate was tested over a wide range of depths. Two subdivision Froude numbers were calculated, one for the main channel and one for the two identical overbanks. In addition, both the specific energy (Eq. 4) and the derivative of the specific energy were calculated in both subdivisions.

The results of applying the subdivision Froude number to the main channel are very good. For the three largest flow rates, the subdivision Froude number correctly indicates the depth at which the specific energy in the main channel is a minimum, as shown in Table 1. The subdivision Froude number is also compatible with the calculated specific energy for all depths, thus demonstrating the validity of the energy approach used to derive the subdivision Froude number.

The results of applying the subdivision Froude number to the overbank are quite interesting. As shown in Table 2, when the depth in the overbank is very shallow, less than 1.3 ft (0.40 m) for this cross section, the derivative of specific energy with respect to depth is greater than one. This occurs because the velocity head in the overbank increases with depth up to 1.3 ft (0.40 m) and decreases for greater depths. And because the velocity distribution in the overbank is nearly uniform, the velocity behaves like the velocity head. The increase in velocity head over shallow depths in the overbank is intuitively reasonable.

Because the derivative of specific energy is greater than one, Eq. 3 shows that the Froude number squared is equal to a negative number. For this condition Eq. 5 shows that

$$K_{sd}\left(T_{sd} - \frac{A_{sd}}{K}\frac{dK}{dy} + \frac{A_{sd}^3}{2\alpha}\frac{d\alpha}{dy}\right) < A_{sd}\frac{dK_{sd}}{dy} \qquad (6)$$

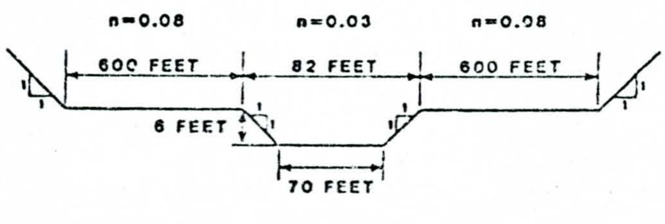

FIG. 1.—Trapezoidal Test Section (1 ft = 0.3 m)

TABLE 1.—Subdivision Froude Number, Main Channel Results*

Flow rate (cfs) (1)	Depth (ft) (2)	Subdivision F (3)	E (ft) (4)	dE/dy (5)
5,000	6.5	1.071	7.837	−0.146
	6.6	1.049	7.825	−0.100
	6.7	1.019	7.818	−0.038
	6.8	0.983	7.818	0.034
	6.9	0.944	7.825	0.108
	7.0	0.904	7.839	0.183
10,000	7.9	1.114	9.555	−0.240
	8.0	1.062	9.536	−0.128
	8.1	1.013	9.529	−0.027
	8.2	0.968	9.530	0.064
	8.3	0.924	9.541	0.145
	8.4	0.884	9.559	0.219
50,000	13.1	1.057	16.686	−0.116
	13.2	1.034	16.676	−0.069
	13.3	1.012	16.672	−0.025
	13.4	0.991	16.671	0.018
	13.5	0.971	16.675	0.058
	13.6	0.951	16.683	0.096

*1 cfs = 0.028 m^3/s, 1 ft = 0.3 m

TABLE 2.—Subdivision Froude Number, Overbank Results*

Flow (cfs) (1)	Depth (ft) (2)	Velocity (fps) (3)	Subdivision F (4)	E (ft) (5)	dE/dy (6)
5,000	1.0	0.827	b	1.011	1.002
	1.1	0.836	b	1.111	1.002
	1.2	0.840	b	1.211	1.001
	1.3	0.841	0.010	1.311	1.000
	1.4	0.840	0.027	1.411	0.999
	1.5	0.836	0.035	1.511	0.999
10,000	1.0	1.655	b	1.043	1.011
	1.1	1.672	b	1.143	1.007
	1.2	1.681	b	1.244	1.003
	1.3	1.683	0.019	1.344	1.000
	1.4	1.680	0.054	1.444	0.997
	1.5	1.672	0.070	1.543	0.995
50,000	1.0	8.273	b	2.063	1.278
	1.1	8.359	b	2.185	1.164
	1.2	8.403	b	2.296	1.069
	1.3	8.414	0.095	2.399	0.991
	1.4	8.398	0.268	2.495	0.928
	1.5	8.360	0.349	2.585	0.878

*1 cfs = 0.028 m^3/s, 1 fps = 0.3 m/s, 1 ft = 0.3 m.

bImaginary number.

Note: The datum for depth and specific energy is the bottom of the overbank.

Eq. 6 shows that the range of depths over which the subdivision Froude number is imaginary is independent of the cross section discharge. This independence has already been implicitly assumed and is confirmed by the results.

When the two sides of Eq. 6 are equal, the subdivision Froude number equals zero and the derivative of specific energy equals one. The depth at which the derivative in the overbank exactly equals one is the depth at which the derivative of the velocity head in Eq. 5 equals zero. This is the depth of maximum overbank velocity head, which for all practical purposes is the depth of maximum overbank velocity, as verified by Table 2.

Thus an imaginary subdivision Froude number indicates that the velocity head is increasing with depth, and therefore the depth in the floodplain is relatively shallow. For this condition it can be concluded that the flow in the overbanks is subcritical because the derivative of specific energy is positive. An imaginary subdivision Froude number may indicate that the overbank flow is too shallow to be modeled properly by the standard step method.

Five test problems containing 193 cross sections were run with a modified version of HEC2 which calculated subdivision Froude numbers. The first test problem was the Red Fox River, which is a problem used by the Hydrologic Engineering Center in training courses on HEC2. Four other test cases were chosen from the test data that is provided to users with each copy of the program (4). These tests (numbers 1, 5, 14, and 15) provided a wide variety of both natural and artificial cross sections. Of the cross sections tested, eleven had a mixed flow regime and 36 had at least one imaginary subdivision Froude number.

Conclusion

A subdivision Froude number has been developed and tested. A knowledge of the magnitude of the subdivision Froude numbers improves the engineer's ability to identify mixed flow regimes and shallow floodplain flow, both of which invalidate the assumptions of the standard step method. A two-dimensional analysis is probably more appropriate in these circumstances.

Acknowledgments

The Hydrologic Engineering Center provided computer facilities used during this investigation. In addition, the writers would like to thank Bill Eichert, Richard Hayes, and Al Montalvo of the Hydrologic Engineering Center and Johannes DeVries, of the University of California, Davis, for their valuable assistance.

Appendix I.—References

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Appendix II.—Notation

The following symbols are used in this paper:

A = cross section area;
A_{sd} = subdivision area;
D = hydraulic depth (area divided by top width);
E = specific energy;
F = Froude number;
g = acceleration of gravity;
K_{sd} = subdivision conveyance;
K = cross section conveyance (sum of K's);
Q_{sd} = subdivision discharge;
Q = cross section discharge;
T_{sd} = subdivision top width;
V = mean cross section velocity;
V_{sd} = mean subdivision velocity;
y = water depth; and
α = Coriolis coefficient.

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4. TITLE *(and Subtitle)* Subdivision Froude Number		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) David H. Schoellhamer, John C. Peters and Bruce E. Larock		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of California, Davis, CA and US Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Corps of Engineers Hydrologic Engineering Center Davis, California		12. REPORT DATE October 1985 13. NUMBER OF PAGES 6
14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

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This is Paper No. 19826, published in Vol. 111, No. 7 of the ASCE Journal of Hydraulic Engineering, July, 1985.

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Froude No., flow regime, open channel flow

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

A Froude number that is applicable to subdivisions of a cross section is developed assuming one-dimensional flow. The subdivision Froude number is shown to be an accurate index of the flow regime in subdivisions of a cross section. An imaginary Froude number in a flood plain indicates that the velocity is increasing with depth and that a one-dimensional flow assumption may be invalid. Mixed flow regimes at a cross section which

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20. Abstract (continued)

invalidate assumptions associated with the standard step method can be recognized with the subdivision Froude number. A total of 193 cross section-discharge combinations were tested with a modified version of HEC2; 11 had a mixed flow regime and 36 had at least 1 imaginary Froude number.

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