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# Standard Guide for Analysis and Interpretation of Test Data for Articulating Concrete Block (ACB) Revetment Systems in Open Channel Flow[1]

This standard is issued under the fixed designation D7276; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

## 1. Scope

1.1 The purpose of this guide is to provide recommended guidelines for the analysis and interpretation of hydraulic test data for articulating concrete block (ACB) revetment systems under steep slope, high velocity flow conditions in a rectangular open channel. Data from tests performed under controlled laboratory conditions are used to quantify stability performance of ACB systems under hydraulic loading. This guide is intended to be used in conjunction with Test Method D7277.

1.2 This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This document cannot replace education or experience and should be used in conjunction with professional judgment. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which adequacy of a given professional service must be judged, nor can this document be applied without considerations of a project's many unique aspects. The word "Standard" in the title of this document means only that the document has been approved through the ASTM consensus process.

1.3 The values stated in inch-pound units are to be regarded as standard. The user of the standard is responsible for any and all conversions to other systems of units. Reporting of test results in units other than inch-pound shall not be regarded as nonconformance with this test method.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

## 2. Referenced Documents

2.1 *ASTM Standards:*[2]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D6026 Practice for Using Significant Digits in Geotechnical Data

D6684 Specification for Materials and Manufacture of Articulating Concrete Block (ACB) Revetment Systems

D6884 Practice for Installation of Articulating Concrete Block (ACB) Revetment Systems

D7277 Test Method for Performance Testing of Articulating Concrete Block (ACB) Revetment Systems for Hydraulic Stability in Open Channel Flow

## 3. Terminology

3.1 For definitions of common terms used in this standard, see Terminology D653.

## 4. Summary of Guide

4.1 The analysis and interpretation of data from hydraulic tests of articulating concrete block (ACB) revetment systems is essential to the selection and design of a suitable system for a specific application. This guide provides guidelines for assisting designers and specifiers in developing a correspondence between the test data and the stability parameters used for design.

4.2 This standard addresses the analysis of hydraulic test data that is generated from a test or series of tests conducted in accordance with Test Method D7277.

## 5. Significance and Use

5.1 This standard is intended for use by researchers and designers to assess the stability of articulating concrete block (ACB) revetment systems in order to achieve stable hydraulic performance under the erosive force of flowing water.

[1] This guide is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.25 on Erosion and Sediment Control Technology.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

5.2 An articulating concrete block system is comprised of a matrix of individual concrete blocks placed together to form an erosion-resistant revetment with specific hydraulic performance characteristics. The system includes a filter layer compatible with the subsoil which allows infiltration and exfiltration to occur while providing particle retention. The filter layer may be comprised of a geotextile, properly graded granular media, or both. The blocks within the matrix shall be dense and durable, and the matrix shall be flexible and porous.

5.3 Articulating concrete block systems are used to provide erosion protection to underlying soil materials from the forces of flowing water. The term "articulating," as used in this standard, implies the ability of individual blocks of the system to conform to changes in the subgrade while remaining interconnected by virtue of block interlock or additional system components such as cables, ropes, geotextiles, geogrids, or other connecting devices, or combinations thereof.

5.4 The definition of articulating concrete block systems does not distinguish between interlocking and non-interlocking block geometries, between cable-tied and non-cable-tied systems, between vegetated and non-vegetated systems or between methods of manufacturing or placement. This standard does not specify size restrictions for individual block units. Block systems are available in either open-cell or closed-cell varieties.

## 6. Procedure

6.1 *Data Analysis:*

6.1.1 This section describes the analysis and interpretation of the data collected during a test, including the determination of hydraulic conditions, qualitative observations and descriptions of any damage to the revetment system, and quantification of threshold hydraulic stability values resulting from this analysis that are characteristic of the tested system.

6.1.2 Typical test environments incorporate a flow regime that is supercritical, characterized by high velocities with relatively shallow depths of flow. In supercritical flow, small variations in measured depth can result in relatively large variations in calculated energy and shear stress. The analytical methods suggested in this section have been selected based on their suitability to analyze these hydraulic conditions.

6.2 *Hydraulic Conditions:*

6.2.1 Accurately quantifying the hydraulic conditions that existed during the test is fundamental to the establishment of stability performance thresholds. The important hydraulic variables that characterize open channel flow include total discharge $Q$, section-averaged velocity $V$, flow depth $y$, slope of the energy grade line $S_f$, resistance coefficient (for example, Manning $n$-value), and boundary shear stress $\tau$.

6.2.2 *Total Discharge, Q,* is determined by use of a primary flow measurement device such as an in-line flow meter, weir, Parshall flume, or other device appropriate to the facility's means for delivering water to the test section. Alternatively, the discharge may be computed at each of the measurement cross-sections by the continuity equation:

$$Q = A(V_{0.6}) \tag{1}$$

where:

$V_{0.6}$ = centerline point velocity at six-tenths of the depth of flow at each station, ft/s, (L/T), and
$A$ = the cross-sectional area of flow at the same station, measured perpendicular to the direction of flow, ft$^2$ (L$^2$).

6.2.2.1 The accuracy of the discharge measurement shall be reported as described in Section 7 of this standard.

6.2.3 *Flow Depth, y,* is computed as the difference in the measured centerline water surface elevation and the elevation of the revetment surface, corrected for the slope angle θ as appropriate, at each measurement station:

$$y_i = (h_i - z_i)\cos\theta \tag{2}$$

where:

$y_i$ = depth of flow at station $i$ (perpendicular to the bed), ft (L),
$h_i$ = water surface elevation at station $i$, ft (L),
$z_i$ = bed elevation (top of blocks) at station $i$, ft (L), and
$\theta$ = slope angle measured from the horizontal.

6.2.4 *Energy Grade Slope, $S_f$,* at each measurement station is calculated from other measured or computed variables as:

$$S_{fi} = \left[\frac{n(V_i)}{K_u}\right]^2 \frac{1}{y_i^{4/3}} \tag{3}$$

where:

$S_{fi}$ = slope of the energy grade line at station $i$, ft/ft (L/L),
$n$ = Manning's resistance coefficient,
$V_i$ = velocity at station $i$, ft/s (L/T), and
$K_u$ = units conversion coefficient, equal to 1.486 for U.S. Customary Units and 1.0 for SI Units.

6.2.4.1 Eq 3 assumes that the flume walls are significantly smoother than the revetment surface, such that the total resistance is due solely to the roughness of the bed.

6.2.5 *Step-Forewater Analysis*—Knowing the total discharge $Q$, flume width $b$, and the elevations of the water surface and revetment surface at each of the measurement stations, a forewater calculation can be performed to obtain the optimal value of the Manning's $n$ coefficient.

6.2.5.1 For supercritical flow, it is recommended that the water surface profile be computed by solving the momentum equation using the standard step method and proceeding in the downstream direction:

$$h_2 = h_1 + \frac{1}{2g}(v_1 + v_2)(v_1 - v_2) - \frac{L}{2}(S_{f1} + S_{f2}) \tag{4}$$

where:

$h_1$, $h_2$ = upstream and downstream water surface elevations at stations 1 and 2, ft (L),
$v_1$, $v_2$ = upstream and downstream velocity at stations 1 and 2, ft/s (L/T),
$Ls$ = slope length between stations 1 and 2, ft (L), and
$S_{f1}$, $S_{f2}$ = upstream and downstream energy grade slopes at stations 1 and 2 as defined by Eq 3, ft/ft (L/L).

NOTE 1—Other numerical methods are available for computing the water surface profile, for example the direct step method. The standard step method is being recommended here because it allows computation of hydraulic conditions at the actual locations of the flume measurement stations.

6.2.5.2 The objective function to be minimized is defined as:

$$\xi = \sum_{i=i_1}^{i_n} \text{abs}(h_{pred} - h_{obs}) \quad (5)$$

where:

$i_1$ = beginning station for analysis,
$i_n$ = ending station for analysis,
$h_{pred}$ = predicted water surface elevation at station $i_i$, ft (L), and
$h_{obs}$ = observed water surface elevation at station $i_i$, ft (L).

6.2.5.3 By examining a range of Manning's $n$ values, the optimal Manning's $n$ is identified as that which yields the minimum value of the objective function defined by Eq 5. The optimal Mannings $n$ value is then used to calculate the water surface elevation that best fits the observed data. An example of such a forewater calculation is provided in Appendix X1.

6.2.6 *Section-Average Velocity, $V_{ave}$,* is computed as discharge $Q$ (determined above) divided by the cross-sectional area $A$, normal to the embankment surface, at each measurement station along the test section.

6.2.7 *Energy Grade Line Elevation, EGL,* is determined at each measurement station by the following equation:

$$EGL_i = z_i + y_i(\cos\theta) + \frac{(V_i)^2}{2g} \quad (6)$$

where:

$EGL_i$ = elevation of the energy grade line at station $i$, ft (L), and
$g$ = gravitational constant, 32.2 ft/s$^2$ (L/T$^2$).

6.2.7.1 The procedure for determining energy slope should be performed for the data representing the flow field on the downstream slope of the test section. If a measurement station happens to coincide with the point of the break in slope, data from that station should not be used because of the severe flow curvature at that location.

6.2.8 *Shear Stress, $\tau_0$*—If gradually varied flow characterizes the flow field, the maximum boundary shear stress at the bed, $\tau_0$, is determined from measured or calculated variables as:

$$\tau_0 = \gamma(y)\,(S_f) \quad (7)$$

where:

$\tau_0$ = bed shear stress, lb/ft$^2$ (F/L$^2$),
$\gamma$ = unit weight of water, 62.4 lb/ft$^3$ (M/L$^3$),
$y$ = depth of flow measured perpendicular to the bed, ft (L), and
$S_f$ = slope of energy grade line as defined by Eq 3.

6.2.8.1 The above equation requires the use of representative data from two or more stations on the downstream slope to determine the slope of the energy grade line $S_f$, and the representative depth associated with that determination. Typically, a linear regression is performed to determine the slope of the energy grade line. The measured depths from the stations used in this regression analysis are averaged to determine the representative depth $y$ in order to calculate the bed shear stress.

6.2.8.2 Alternatively, the momentum equation across a representative control volume of finite length $L$ may be used to calculate $\tau_0$:

$$\tau_0 = \frac{\gamma}{2}(y_1 + y_2)\sin\theta + \frac{1}{L}\left[\frac{\gamma}{2}(y_1^2 - y_2^2)\cos\theta - \rho q^2\left(\frac{1}{y_2} - \frac{1}{y_1}\right)\right] \quad (8)$$

where:

$\gamma$ = unit weight of water, 62.4 lb/ft$^3$ (M/L$^3$),
$y_1$, $y_2$ = flow depths at the upstream and downstream ends of the control volume, respectively, ft (L),
$v_1$, $v_2$ = flow velocity at the upstream and downstream ends of the control volume, respectively, ft/s (L/T),
$L$ = length of the control volume along the slope, ft (L),
$\rho$ = unit mass of water, 1.94 slugs/ft$^3$ (M/L$^3$), and
$q$ = unit discharge, ft$^3$/s per foot width (L$^3$/T per L width).

6.2.8.3 Both methods given above for quantifying shear stress depend on the judgment of the practitioner to define the data that best represents the stable performance of the block system. In practice, many data sets will include one or more points where the energy grade is not consistent with the expected trend. In most cases, outliers can be most readily identified by plotting the elevation of the energy line versus distance along the embankment. Note that when Eq 8 is used, the $x$-axis plotting position for the calculated shear stress $\tau_0$ is located halfway between stations 1 and 2.

6.2.8.4 Appendix X1 provides an example of such a plot, and illustrates the use of the step-forewater analysis procedure to quantify the hydraulic conditions in areas where data variability exists. Fig. 1 provides a definition sketch for the variables presented in this section.

6.3 *Qualitative Observations of Stability:*

6.3.1 The hydraulic conditions at the threshold of failure determine the hydraulic stability parameters that characterize the revetment system's performance. Both shear stress and velocity at the threshold of failure are typically used for purposes of developing selection and design criteria for a particular block system.

6.3.2 The researcher's determination of "failure" of a revetment system during a test is somewhat subjective, and depends on his interpretation of the point on the embankment at which "loss of intimate contact" between the revetment system and the subgrade soil occurred. In practice, all of the following conditions have been used as guidance for this interpretation (listed in decreasing order of frequency of occurrence):

6.3.2.1 Vertical displacement or loss of a block (or group of blocks).

6.3.2.2 Loss of soil beneath the geotextile, resulting in voids.

6.3.2.3 Liquefaction and mass slumping/sliding of the subsoil.[3][4][5]

6.4 *Stability Threshold Conditions:*

[3] Chen, Y. H., and Anderson, B. A., "Development of a Methodology for Estimating Embankment Damage due to Flood Overtopping," Final Report, Simons, Li & Associates, Inc., Fort Collins, CO. Prepared for the Federal Highway Administration and U.S. Forest Service, Report No. FHWA-RD-86-126, March, 1986.

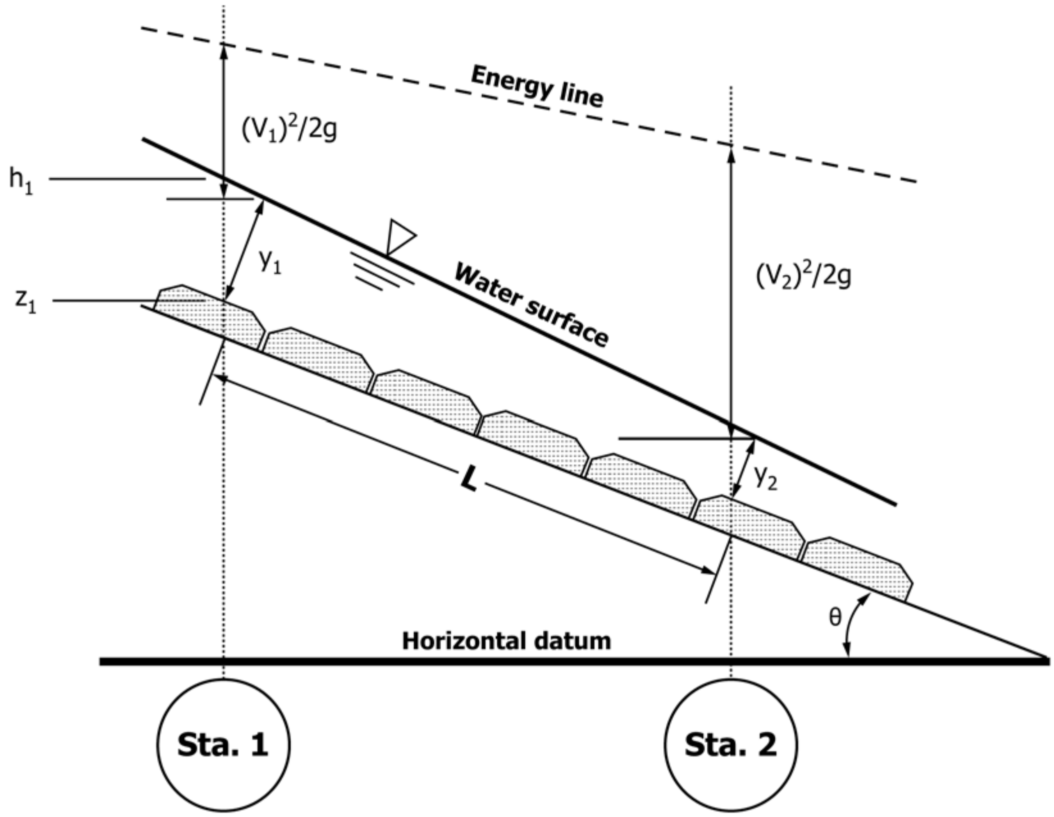


FIG. 1 Definition Sketch

6.4.1 Identifying the threshold hydraulic conditions involves the calculation of the variables described in 6.2 at the nearest point upstream from the zone of damage, where the revetment system and subsoil remained completely stable for the 4-h duration of the test.

## 7. Reporting Requirements

7.1 A summary report of the revetment testing program shall be prepared which documents, at a minimum, the following elements:

7.1.1 The names of the person(s) who performed the test.

7.1.2 The date the test was run.

7.1.3 Test bed slope angle.

7.1.4 Accuracy of discharge measurement as determined by manufacturer's data for volumetric meters or velocity meters, or by calibration records for other primary flow measurement devices such as weirs or flumes.

7.1.5 Summary of measured data and calculated hydraulic conditions for each test.

7.1.6 Plots of revetment surface, water surface, and energy grade line for each test. The stations used for the regression analysis to determine the slope of the energy grade line should also be identified on these plots.

7.1.7 Discussion of the identification (interpretation) of stability threshold location, based on either: *(a)* observed loss of intimate contact between the system and the subgrade soil at a specific location on the embankment surface during a particular test, or *(b)* system stability up to and including the maximum flow capacity of the test flume.

7.1.8 Quantification of the hydraulic conditions at the location of the stability threshold as identified above, including peak flow velocity and shear stress at the stability threshold, with supporting calculations.

7.1.9 Appendix containing the testing laboratory report including all raw data and measurements.

7.1.10 All calcualted results should be reported to at least three significant figures and shall conform to the guidelines for significant digits and rounding established in Practice D6026.

## 8. Keywords

8.1 articulating concrete blocks; channel stability; erosion; erosion control; open channel flow; overtopping; revetment

[4] Clopper, P. E., "Hydraulic Stability of Articulating Concrete Block Revetment Systems During Overtopping Flow," Final Report, Simons, Li & Associates, Inc., Fort Collins, CO. Prepared for the Federal Highway Administration, U.S. Bureau of Reclamation, Soil Conservation Service, and Tennessee Valley Authority, Report No. FHWA-RD-89-199, July, 1989.

[5] Clopper, P. E., and Chen, Y. H., "Minimizing Embankment Damage During Overtopping Flow," Final Report, Simons, Li & Associates, Inc., Fort Collins, CO. Prepared for the Federal Highway Administration and U.S. Bureau of Reclamation, Report No. FHWA-RD-88-181, November, 1988.

# APPENDIX

## X1. STEP-FOREWATER PROGRAM FOR CALCULATING SUPERCRITICAL FLOW IN OPEN CHANNELS

**(Nonmandatory Information)**

X1.1 The following example uses the standard-step method for solving the momentum equation presented in Section 6 of this standard. The method assumes that Manning's equation is valid for describing gradually varied flow in the section to be analyzed.[6] The iterative procedure used to solve the equation is the Newton-Raphson method, although many other iterative solution algorithms can be used.

X1.2 The solution procedure is as follows:

$$x^{(n+1)} = x^{(n)} - \left[\frac{f\left(x^{(n)}\right)}{f'\left(x^{(n)}\right)}\right] \tag{X1.1}$$

where the superscript $n$ denotes values obtained on the $n$th iteration, and $n$+1 indicates values to be found on the ($n$+1)th iteration.

X1.3 The function $f(x)$ is defined by rearranging the momentum equation:

$$f(x) = f(h_2) = 2g(h_2 - h_1) + g(\Delta x)\,(S_2 + S_1) + (v_2 + v_1)\,(v_2 - v_1) \tag{X1.2}$$

X1.4 The function's derivative with respect to $x$ (=$h_2$) is:

$$f'(x) = f'(h_2) = 2g - \frac{3.33g\,(\Delta x)\,(S_2)}{y_2} - \frac{2(v_2)^2}{y_2} \tag{X1.3}$$

where $h_2$, $S_2$, $y_2$ and $v_2$ are updated at each iteration, noting that $S_2$, $y_2$ and $v_2$ are all functions of $h_2$, given a constant unit discharge $q$. The above formulation is valid for any consistent set of units.

X1.5 The solution proceeds in a stepwise manner in the downstream direction given a boundary condition (water surface elevation) HBEG at the upstream-most computational station IBEG. Fig. X1.1 shows a flow chart of the overall method.

X1.6 The example described in the remainder of this section illustrates the use of the method for performing the following analyses:

X1.6.1 Obtaining the best fit Manning's $n$ to a set of observed data from a steep-slope open channel test where supercritical flow characterizes the hydraulic conditions at the nearest point upstream from the area of damage, where the ACB system remained stable for the 4-h duration of the test.

X1.6.2 Applying the optimal Manning's $n$ to calculate the theoretical water surface profile and energy grade line through the system, from which hydraulic conditions of depth, velocity, and shear stress may be determined.

X1.7 Table X1.1 provides the example input file for the step-forewater analysis. Figs. X1.2-X1.5 illustrate the output from the program, including threshold values of shear stress and velocity for the stable conditions associated with this test (actual test data has been used for this example). A standard computer analysis or software package is not available for this analysis. The user of this standard is responsible for writing and verifying any computer program.

[6] Henderson, F. M., *Open Channel Flow*, Macmillan Publishing Company, New York, NY, 1966.

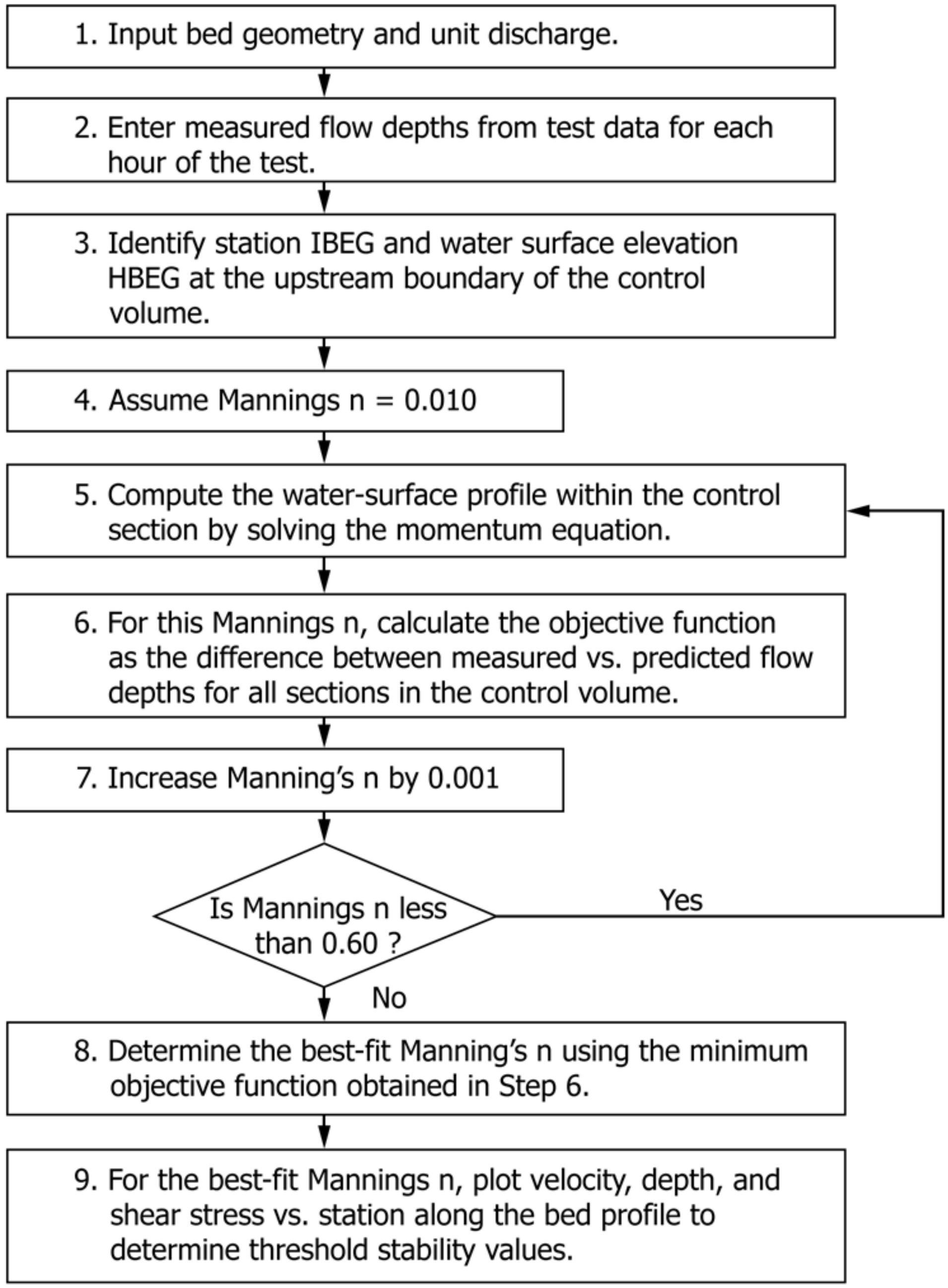


**FIG. X1.1 Flowchart of the Step-Forewater Analysis Method**

**TABLE X1.1 Example Input Data File**

| | | | | | |
|---|---|---|---|---|---|
| ACB 4.5” NON-CABLED, | 3’ OT, D/S SLOPE 33% | AUGUST 2001 | | | |
| NO. STATIONS | NO. MEAS SETS | | | | |
| 22 | 4 | | | | |
| BEG STA, | END STA, | CONTROL WSEL | | | |
| 7 | 16 | 103.17 | | | |
| X DIST | BED ELEV | WSEL MEAS 1 | WSEL MEAS 2 | WSEL MEAS 3 | WSEL MEAS 4 |
| 2.10 | 102.29 | 103.72 | 103.74 | 103.75 | 103.76 |
| 4.30 | 102.29 | 103.86 | 103.88 | 103.88 | 103.88 |
| 6.00 | 102.34 | 103.87 | 103.86 | 103.87 | 103.87 |
| 8.10 | 102.38 | 103.76 | 103.76 | 103.76 | 103.77 |
| 9.90 | 102.32 | 103.89 | 103.91 | 103.90 | 103.89 |
| 11.90 | 102.24 | 103.65 | 103.66 | 103.66 | 103.68 |
| 13.80 | 101.97 | 103.17 | 103.14 | 103.19 | 103.18 |
| 15.89 | 101.30 | 102.36 | 102.38 | 102.37 | 102.38 |
| 17.97 | 100.6,0 | 101.52 | 101.52 | 101.54 | 101.54 |
| 19.68 | 99.98 | 100.84 | 100.85 | 100.86 | 100.86 |
| 21.58 | 99.31 | 100.11 | 100.13 | 100.13 | 100.13 |
| 23.29 | 98.75 | 99.53 | 99.54 | 99.56 | 99.56 |
| 25.37 | 98.04 | 98.84 | 98.86 | 98.87 | 98.86 |
| 27.46 | 97.37 | 98.15 | 98.16 | 98.17 | 98.16 |
| 29.17 | 96.79 | 97.53 | 97.53 | 97.54 | 97.54 |
| 31.07 | 96.19 | 96.90 | 96.89 | 96.87 | 96.89 |
| 32.73 | 95.66 | 96.28 | 96.28 | 96.27 | 96.28 |
| 34.96 | 94.93 | 95.50 | 95.50 | 95.49 | 95.48 |
| 36.95 | 94.27 | 94.80 | 94.80 | 94.80 | 94.81 |
| 38.66 | 93.69 | 94.21 | 94.21 | 94.22 | 94.21 |
| 40.55 | 93.09 | 93.66 | 93.65 | 93.66 | 93.65 |
| 42.17 | 92.58 | 93.17 | 93.13 | 93.13 | 93.13 |
| UNIT Q | | | | | |
| 12.70 | | | | | |

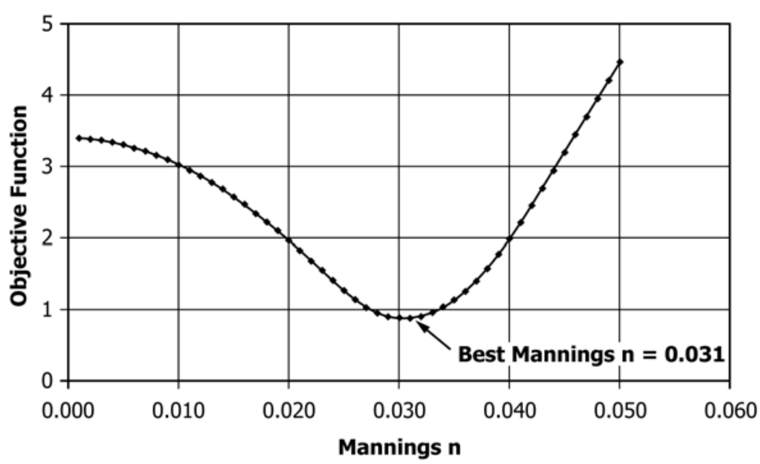


**FIG. X1.2 Objective Function versus Mannings *n* Based on Step-Forewater Analysis**

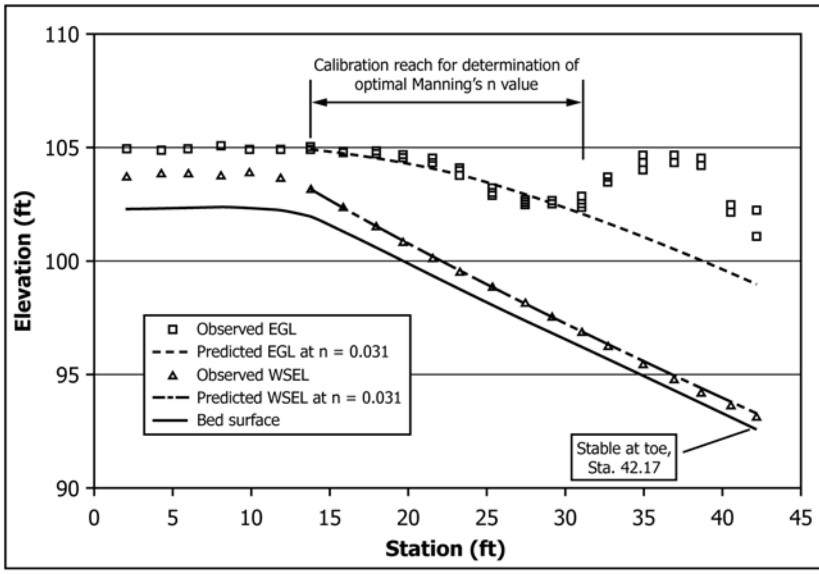


FIG. X1.3 Observed and Predicted Water and Energy Surfaces

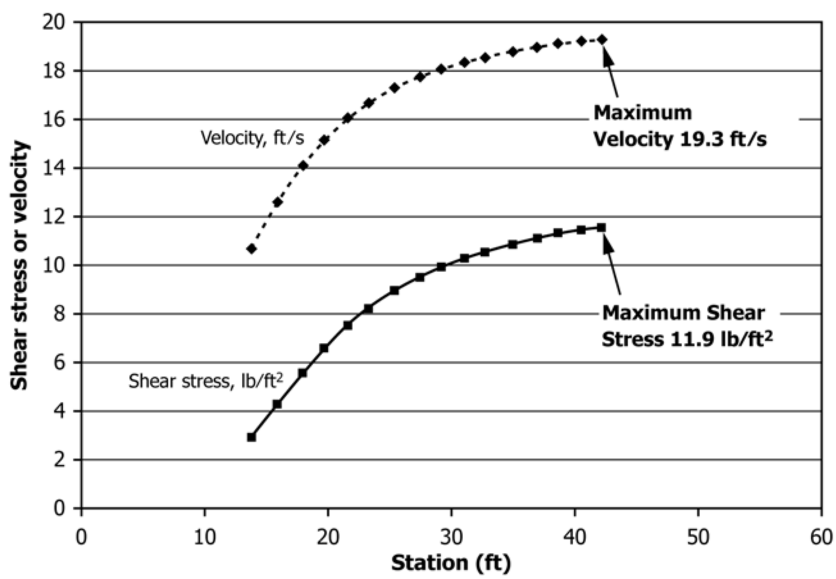


FIG. X1.4 Velocity and Shear Stress Predicted by Step-Forewater Analysis

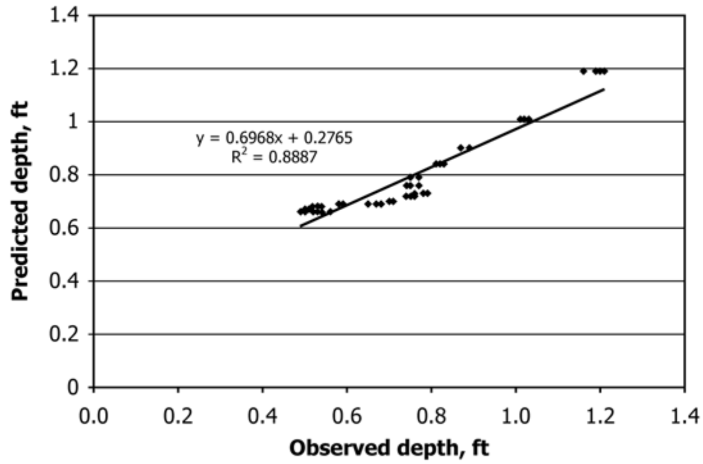


**FIG. X1.5 Observed Depth versus Depth Predicted by Step-Forewater Analysis**