RESEARCH, DEVELOPMENT, AND IMPLEMENTATION OF PERFORMANCE TESTING PROTOCOLS FOR CHANNEL EROSION RESEARCH FACILITIES (CERFS)

Paul E. Clopper, P.E.

Ayres Associates
3665 JFK Parkway, Bldg. 2, #300
Fort Collins, CO 80525

Dwight A. Cabalka, P.E.

American Excelsior Company—Earth Science Division
850 Avenue H East
Arlington, TX 76005-5067

Anthony G. Johnson

American Excelsior Company
831 Pioneer Avenue
Rice Lake, WI 54868

ABSTRACT

Scientific means to evaluate the effectiveness of erosion control Best Management Practices (BMPs) for stormwater drainage channels and other conveyance ways has become the focus of a number of activities within the erosion control industry during the past several years. This has included the efforts of leading industry associations, governmental agencies, universities and commercial laboratories. The concentrated nature of open channel flow subjects the boundary of earth-lined drainageways to much greater stresses than the overland flow associated with slope applications. Performance data on channel lining products and materials by determination of hydraulic stability thresholds is vital for the proper selection and design of materials and related installation techniques for protecting channel beds and banks.

Characterization of hydraulic conditions in open channel flow is a long and well established engineering practice; in recent years, however, it has taken on a new emphasis with the need to economically establish stable channels in urbanizing environments. A number of test facilities have been developed under widely varying conditions, each replicating “real world” conditions to one degree or another. Most performance tests have

evaluated lining material based on some measure of material loss or deformation, coupled with a soil erosion determination using channel cross-section measurements. The means for measuring channel deformation have also varied considerably, as have the statistical, engineering and scientific reliability of the reported results.

This paper summarizes an extensive effort which was used to develop comprehensive, state-of-the-art test protocols for a channel erosion research facility (CERF) located in Rice Lake, Wisconsin. Analytical techniques for discharge calibration and hydraulic computations such as flow regime (sub/supercritical), velocity, and shear stress (tractive force) are described. Channel preparation methods and documentation are discussed, including soil typing (classification), subgrade compaction, soil preparation, treatment of vegetation, and pre-test channel profiling. Data collection techniques during testing operations are identified, including measurements of depth of flow, velocity and post-flow channel profiling. Post-test analyses to determine velocity, shear stress, and soil loss are presented. Finally, evaluation of the results, using generally-accepted statistical principles, is also presented.

INTRODUCTION

Documentation of product performance has become an issue of paramount importance in the erosion and sediment control industry. End-users and designers are more frequently requesting this information to provide the basis for construction project designs, specifications, and installations. Performance data is also valuable to manufacturers so that they can provide accurate data to meet end-user, designer, and installer expectations. This information is also central to product research and development, sales and marketing activities, installation guidelines, and product certification.

Establishing carefully quantified data on erosion control product performance in open-channel environments is the fundamental purpose for American Excelsior Company's development of *The ErosionLab* Channel Erosion Research Facility (CERF). Aside from the materials themselves, related aspects of installed systems, such as soil preparation, anchor patterns, and termination details will also be evaluated. And finally, the desire to improve existing products and to innovate new materials and solutions for erosion control applications is a major objective.

The CERF shares fundamental requirements with all hydraulic erosion testing facilities: 1) the ability to simulate typical hydraulic events under controlled and documented conditions, and; 2) the ability to accurately measure boundary deformation resulting from each flow event. These two requirements must be achieved using generally accepted engineering principles, scientific procedures, analytical methods, and statistical standards.

This test protocol is limited to evaluation of non-vegetated conditions, since: 1) all Best Management Practices (BMPs) applied to channel conditions must initially perform in a non-vegetated condition to control erosion and retain seed; 2) the variables associated with performance of BMPs vary greatly depending on climatic and local agronomic conditions, and; 3) considerable time constraints are involved when attempting to evaluate vegetated conditions. By evaluating BMPs in unvegetated conditions, a conservative or "worst case scenario" is applied. Test methodologies for evaluation of vegetated BMPs in controlled conditions may be developed at a later date.

CHANNEL TESTING HISTORY

The concept of *equilibrium* forms the underlying premise behind present-day open channel design procedures (Chen and Cotton, 1986). Whether the channel is a roadside ditch, a landfill downchute, an irrigation canal, a natural creek or a major river, equilibrium is said to exist when the drainageway performs within acceptable limits of stability, both laterally and vertically. In the case of *static* equilibrium, stability is achieved when the material forming the channel boundary effectively resists the erosive forces of the design flow, thus maintaining a geometry which does not experience change during flow events. *Dynamic* equilibrium, on the other hand, requires a balance between the incoming sediment supply from upstream and the sediment transport through the reach. A system in dynamic equilibrium is expected to experience changes to the channel bed and banks, as long as these changes occur within acceptable limits.

Dynamic equilibrium techniques are usually applied to natural river systems which typically are remote from urbanization or other man-made improvements. They often involve river corridor planning and floodplain management issues which call for erosion setbacks or "buffer zones." However, for most development projects, roadway drainage designs, and other designs where infrastructure is involved, lateral or vertical migration of the drainageway cannot be tolerated. In these cases, stable channel design using static equilibrium criteria is preferred over dynamic techniques.

During the last two decades, the tremendous innovation of new products and materials for the prevention of channel erosion attests to the importance of stable channel design under conditions of static equilibrium. The growing recognition of environmental and aesthetic values afforded by drainageways has emphasized the use, where possible, of "soft armor" concepts which incorporate vegetation in the finished condition, as opposed to traditional "hard armor" philosophies that utilize riprap, cast-in-place concrete, or other materials which are difficult or impossible to revegetate.

Soft armor products can be temporary in nature, designed simply to provide protection during the vulnerable period of germination and establishment of vegetation, or they can be permanent, in which case their purpose is to provide long-lasting reinforcement (typically via the root matrix) to the vegetative component. The selection of temporary versus permanent protection depends primarily on the severity, frequency, and duration of flows, and the associated level of hydraulic stress, to which the channel boundary will be exposed. Also, the period of time necessary for vegetation to establish must be considered in the selection of erosion control materials which depend on the vegetative component to achieve ultimate performance. Therefore, in addition to material and installation costs, information necessary to the channel designer is a quantitative measure of performance of various materials in both a vegetated and unvegetated state, so that a stable channel can be designed and constructed most economically.

FACILITY DESCRIPTION

The ErosionLab CERF is located near Rice Lake, Wisconsin, and covers a site approximately 100 feet wide by 300 feet long (see Figure 1). A south-facing, sloped area was graded to provide a suitable site for excavation of 12 test channels and to simulate conditions found on typical construction projects with earthen drainageways, such as highways, landfills, mines, land developments, etc. (see Figure 2). Standard excavation, placement and compaction techniques were used to construct the channels. Six of the test channels were built at a 5 percent longitudinal

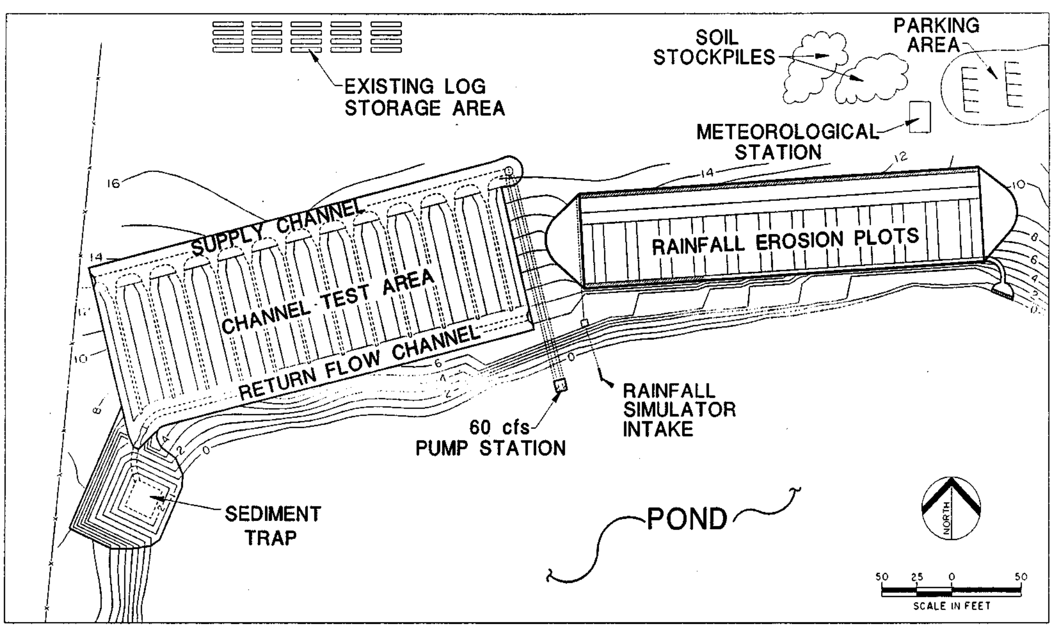

Figure 1. Overall site layout of *The ErosionLab.*

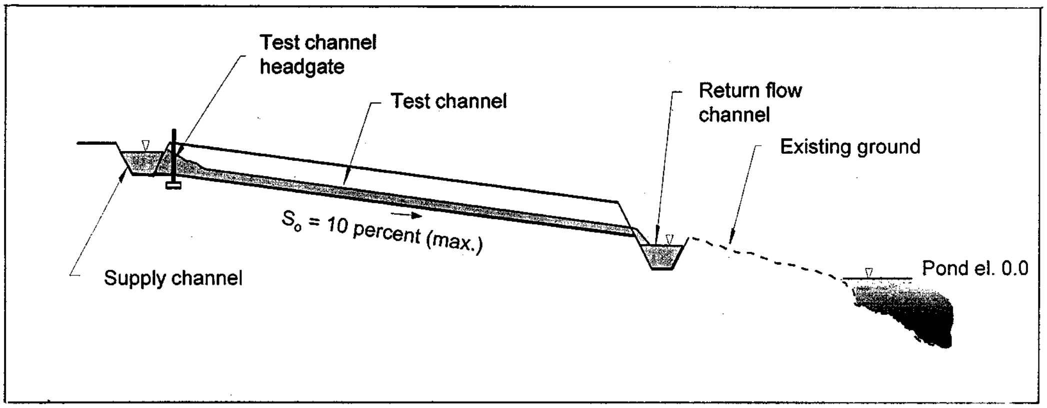

Figure 2. Profile through typical test channel.

slope, while the other six were excavated at a 10 percent slope.

The test channels, approximately 26 meters (85 feet) in length, utilize the middle 12.2 meters (40 feet) for detailed measurement and product evaluation. The sections upstream and downstream of the measurement area provide inflow and outflow transition zones.

Three different veneer soils (sand, clay, and silty loam) were placed in the test channels to a depth of approximately 46 centimeters (18 inches). To simulate "real world" conditions, the test channel cross-sections were constructed with a 2 foot bottom width and 2H:1V side slopes.

Two large vertical turbine pumps capable of a maximum combined discharge of 1.7 cubic meters per second (60 cubic feet per second) were installed on pre-cast concrete platforms and are powered by two 300 horsepower diesel engines. Water from the adjacent pond is pumped through a 36 inch diameter ductile iron pipe to the inlet control structure and into the supply channel. A series of stop log headgates were installed to direct flow into the desired test channel (see Figure 3). Once the water flows down the test channel, a tail channel routes water through a sedimentation basin and back into the pond. This closed-loop system assures a continuous supply of water and the existing land-locked pond assures minimal environmental impact from the testing activities.

KEY EQUIPMENT SELECTION

The key equipment for the CERF included pumps, precast pump station vaults, piping, inlet control structure, and headgate structures. This system was sized to create the following maximum hydraulic conditions in the test channels of approximately:

- Shear Stress: 480 Newtons per square meter (10 pounds per square foot)
  (based on a Manning's *n*-value of 0.050)
- Velocity: 4.2 meters per second (14 feet per second)
  (based on a Manning's *n*-value of 0.025).

SYSTEM START-UP AND INITIAL CALIBRATION

To assure the integrity of the discharge management system, a procedure for start-up and calibration was developed. The objectives of this procedure were: 1) initiate operation of the pumping equipment to ensure that the engines and pumps are functioning within specifications and meet design requirements; 2) measure the discharge to develop discharge versus engine speed calibration curves, and; 3) establish discharge versus hydraulic head calibration curves for the inlet control structure and for each of the 12 test channels.

The initial startup procedure assures that all the equipment is in proper operating condition before performing the initial system calibration. This includes all of the pumps, piping, inlet control structure, headgates, water conveyance channels, and sediment trap. The headgate stoplogs are emplaced in all the test channels except the channel being used, and in the supply channel immediately downstream from the test channel being used. A polyethylene or PVC geomembrane is placed down the entire length of the test channel being used, so that erosion damage is avoided. The supply channel, tail channel, discharge

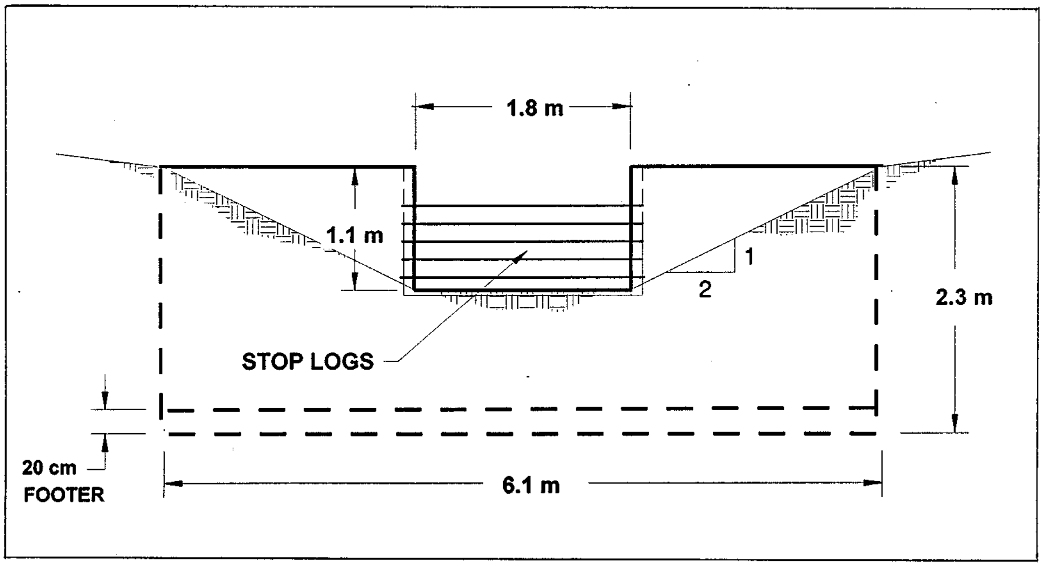

Figure 3. Stop log headgate structure.

control structure, and pump station trash racks are visually inspected and any debris or obstructions removed.

Both engines are started and increased to an idle speed of 900 rpm, at which point the clutches are engaged. As the supply channel fills, the headgate stoplogs on the test channels are examined for excessive leakage and repaired, as necessary. The sedimentation basin is visually inspected to ensure that the return flow is being properly routed through the sediment filtration structure before returning to the pond.

The purpose of the initial calibration process is to determine discharge rating curves for the pumping system. Discharge is determined by two independent methods and used to develop calibration curves relating discharge to: 1) engine speed; 2) hydraulic head at the inlet control structure weir, and; 3) hydraulic head at each test channel headgate. Calibration of the system is conducted once at the beginning of each testing season.

Discharge is determined for engine speeds of 900, 1200, 1500, 1800, and 2000 rpm (both engines running). Discharge at each target speed is calculated by the following two methods:

I. *Weir Equation*

When the discharge is steady, the elevation of the water surface inside the inlet control structure is measured, preferably on the far wall opposite the outflow weir. The difference between this elevation and that of the weir crest is the total head H above the weir crest. With free overfall conditions, the total discharge in cubic meters per second is computed as:

$$Q = 1.65(L)(H)^{1.5}$$

Where:

Q = Discharge (m^3/sec)
L = Width of weir crest (m)
H = Total head (m)

II. *Velocity-Area Equation*

With steady discharge, the velocity at three points across a cross-section of the supply channel is measured by means of a velocity probe. Either electromagnetic or spinning-cup type velocity meters may be used for this purpose. The velocity measurement is taken at six-tenths the total depth of flow (y_o) in the channel, at each of the target engine speeds. Figure 4 provides a reference sketch of the measurement locations.

With a 1.8 meter (6 foot) bottom width and 2H:1V side slopes forming the typical cross section of the supply channel, the total flow is calculated as:

$$Q = V_1A_1 + V_2A_2 + V_3A_3$$

Where:

Q = Discharge (m^3/sec)

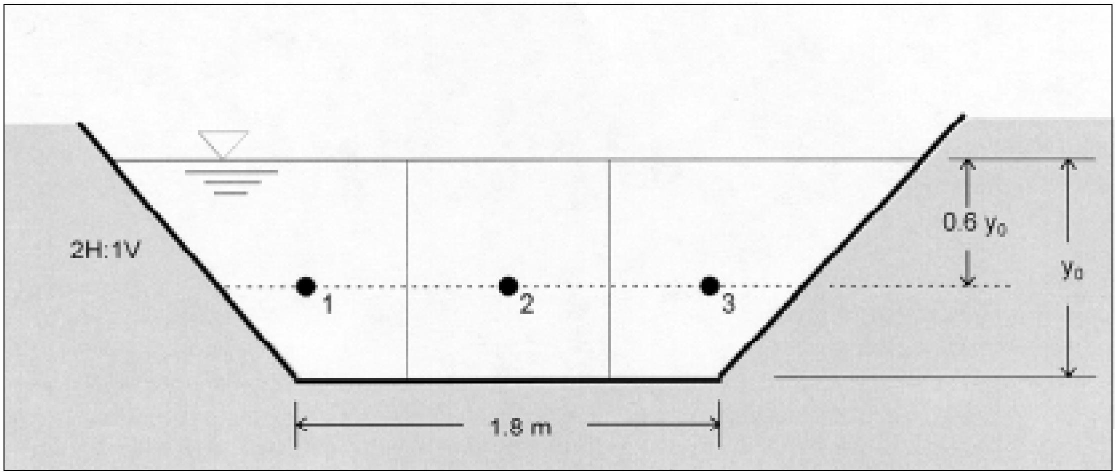

Figure 4. 3-point cross section velocity measurement (water supply channel).

V_n = Measured velocity at each location (m/sec)
A_1, A_3 = Flow area (m²) = $0.45(y_0) + (y_0)^2$
A_2 = Flow area (m²) = $0.9(y_0)$

When the discharge is steady, each of the test channels is opened in succession, while blocking off the others, and the depth of flow above the floor of each test channel headgate is recorded. An enameled staff gauge is bolted on each of the 12 headgate sidewalls to facilitate measurements. The discharges computed by Methods A and B will then be used to construct three types of calibration charts:

1. Discharge vs. engine speed (1 chart)
2. Discharge vs. hydraulic head in the control structure (1 chart)
3. Discharge vs. hydraulic head at each of the 12 test channels (12 charts)

PRE-TEST DOCUMENTATION

A test folder is maintained for each test run, including information on:

- site conditions;
- geotechnical and soil conditions;
- meteorological data, and;
- material type and description.

The site information is subjective and includes the following: general visual conditions of the plot to be tested, general meteorological information, plot treatment, photographs, and any supplemental information that is felt to be of interest to the test. The geotechnical and soils information includes: standard proctor moisture-density relationship, soil texture (USCS classification), and gradation (including hydrometer test for the P200 fraction). The meteorological information includes: all data from the on-site weather for the 30-day period prior to the test (i.e., ambient air temperature, wind movement in kilometers per day, and natural rainfall amounts). The material type and description information includes: manufacturer's name (when applicable), product name, product description, product specifications, product size, and a sample of material, if practical.

TEST SET-UP

The test set-up includes the plot preparation and material installation procedures. To obtain repeatable results, each channel is prepared in a standardized fashion prior to each test.

Any scour holes, voids, or depressions which might remain from the previous test are filled and compacted with the appropriate veneer soil from the stockpile area. Any and all obstructions or protrusions, such as roots, large stones, or other foreign material are removed. The channel surface is scarified, both on the bottom and side slopes, to a depth of 7.5 to 10 cm (3 to 4 inches) using a small rototiller. Scarification is performed on the 12.2 meter (40 feet) long measurement section, plus an additional 1.5 meters (5 feet) upstream and downstream. A vibrating plate compactor is run over the entire test channel, both on the bottom and side slopes, for three complete passes. To assure compaction on the side slopes, ropes or tow straps are used to hold and guide the compactor.

The erosion control product or material is installed according to the manufacturer's specifications or standard industry practice. Regardless of the type of product, the material is placed or applied so that it extends above the maximum flow depth. In the case of rolled erosion control products, this procedure documents such information as which side faces up, material orientation to the channel bed and side slopes, and how much overlap, if any, was provided between adjacent strips.

A schematic diagram showing the type of anchor utilized, and the anchoring pattern, complete with dimensions oriented to the channel sides and bottom, is prepared and included in the test folder. Termination details, including upstream, downstream and top of bank (lateral) trenches, are described, photographed, sketched with dimensions, and placed in the test folder. Intermediate terminations (i.e., transverse check slots), if any, are also recorded.

DATA COLLECTION

Test data includes: operator name and title, engine speed (rpm), inlet control structure flow depth, supply channel weir depth, time flow started, time flow stopped, test channel cross-section (pre-test and post-test), flow depths and velocities. Quantitative evaluation of hydraulic conditions and channel cross-section change due to erosion and/or deposition are determined from this information.

Pre- and post-test measurements are used to quantify the soil loss which occurred during the course of the test. A number of personnel are required to perform each test; as such, it is important that each person performs the same function for all measurements to minimize operator error. In other words, the same person holding the survey rod for pre-test measurements repeats that function for the post-test measurements. In addition, no personnel are allowed to enter the test channel between the pre-test and post-test measurements, so that potential channel deformation due to foot traffic is eliminated (cross channel planks are used, so that foot traffic on the test section is not necessary).

Each test channel is approximately 27.5 meters (90 feet) long from the headgate at the supply channel to the discharge pad at the tail channel. The middle section, measuring 12.2 meters (40 feet) in length, is designated as the detailed measurement reach; the sections upstream and downstream from the measurement reach are 7.6 meters (25 feet) in length and provide flow transition for inflow and outflow stabilization, respectively. The detailed measurement reach contains nine predetermined stations, at 1.5-meter (5 foot) intervals, for the measurement of channel cross section geometry, flow depth, and flow velocity. Eleven points, labeled A through K, are used to define each cross section, as shown in Figure 5.

All depth measurements, both pre- and post-flow, are made using a modified surveyor's electronic

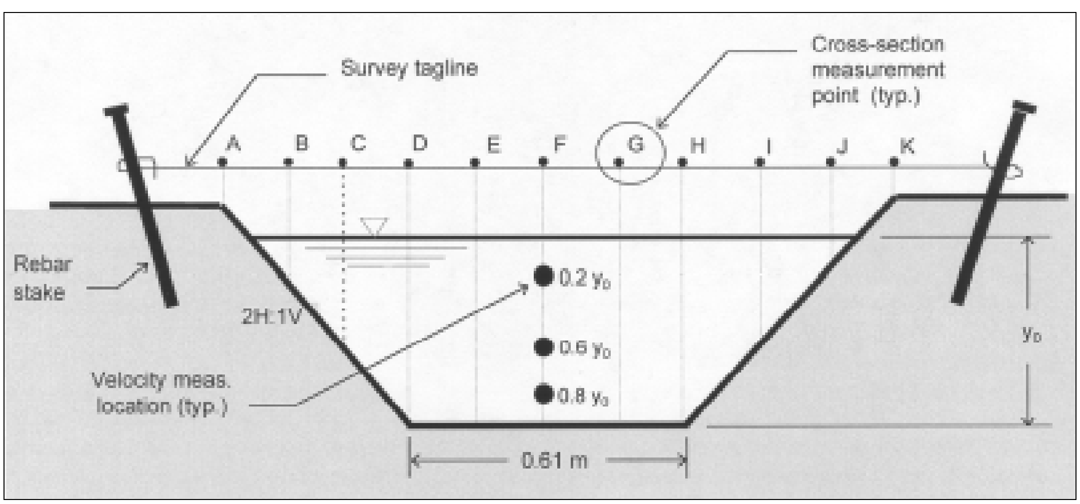

Figure 5. Typical cross-section measurement setup (test channel).

distance measuring (EDM) rod and prism outfitted with a ¼ inch diameter steel tip ("stinger") at the bottom. Cross section measurements of the channel are made before and after each test at all measurement stations by sounding the subgrade (not the top of the erosion control material) with the probe tip. Measurements are made by electronic total station (ETS) survey equipment at the predetermined points A through K on the tagline in order to determine the cross-section geometry to approximately 0.5 cm (0.02 foot) precision.

At the center point (Point F) of each of the nine cross sections, velocity measurements are made with an electromagnetic flow probe at two-tenths, six-tenths, and eight-tenths depth. If the depth of flow is less than 20 cm (8 inches), only the six-tenths depth reading is taken. At these same centerline locations, the elevation of the water surface is also measured by ETS. Measurements are made at the beginning of each test, as soon as the flow is steady and uniform.

Each test lasts for approximately 30 minutes, unless catastrophic erosion is observed, whereby the test is terminated to avoid undue damage to the facility. Thirty minutes allows ample time for a three-person data collection crew to obtain all the necessary measurements at the nine cross section stations. A set of photographs is taken before, during, and after each test and placed in the test folder. Views taken in both the upstream and downstream direction are included.

ANALYSIS AND INTERPRETATION OF DATA

Accurately quantifying the hydraulic conditions which existed during the test run is key to establishing performance thresholds. The important hydraulic variables which characterize open channel flow include total discharge, velocity, flow depth, energy slope, resistance coefficient (Manning *n*-value), and boundary shear stress.

Total discharge, Q, will be determined by use of the calibration curves established for each test channel, as described in Chapter 3 of this manual, and will also be computed at each of the nine measurement cross sections by the continuity equation:

$$Q = V_{ave}(A)$$

Where:

- V_{ave} = the average of the three centerline velocity measurements, $⅓(V_1 + V_2 + V_3)$ at any station
- A = the cross-sectional area of flow at the same station

Velocity, V, is directly measured at each of the nine measurement cross sections by use of the electromagnetic velocity probe.

Depth, y_0, is computed as the difference in the surveyed centerline water surface elevation (WSEL) and the average elevation of the channel bottom as determined at points D through H shown in Figure 5.

Energy slope, S_f, is determined by fitting a regression line through the energy grade line (EGL) elevation determined at each of the nine measurement cross sections as:

$$EGL = WSEL + (V_{ave})^2 / 2g$$

Where:

- g = gravitational constant [9.82 m/s² (32.2 ft/s²)]

The Manning resistance coefficient, n, for each test is calculated from other measured or computed variables as:

$$n = (R)^{2/3} (S_f)^{1/2} / V_{ave}$$

Where:

- R = Hydraulic radius [m (ft)], defined as cross-sectional flow area divided by the wetted perimeter

The average and maximum boundary shear stresses, τ_{ave} and τ_0, respectively, are determined from measured or calculated variables as:

$$\tau_{ave} = \gamma(R)(S_f)$$
$$\tau_0 = \gamma(y_0)(S_f)$$

Where:

- γ = Unit weight of water [1001.6 kg/m³ (62.4 lb/cf)]

Soil loss which occurred during the test is quantified by using the measured 11-point cross section survey data at all nine stations to develop pre- and post-test contour maps of the 12.2 meter (40 foot) long measurement section. The survey data is downloaded from the electronic total station into standard civil engineering earthwork software to construct contour maps. The difference between the pre- and post-test channel boundary is mapped and respective volumes quantified by average end area and triangulated irregular network (TIN) techniques. Areas of degradation (soil erosion) are quantified as "cut" and areas of aggradation (sediment deposition) as "fill."

Since one of the primary objectives in the use of erosion control materials is to protect the seed bed from disruption prior to the establishment of vegetation, only the total volume of soil quantified as degradation (or "cut") is considered in the performance assessment. This volume, quantified as cubic meters (cubic feet) of soil loss, is normalized by dividing by the total wetted area of the channel surface which occurred during the test, in square meters (square feet). The resulting value thus represents the average depth of soil loss in meters (feet); multiplying by 100 converts this figure to centimeters for purposes of plotting at a convenient scale.

Statistical Analysis: Test data and calculated performance indicators are analyzed using standard statistical methods. Both parametric and non-parametric procedures are used to analyze for differences in means between treatment and control, or between treatments. The Student "t" test will be used for the parametric procedure and the Wilcoxen rank-sum test for the non-parametric procedure.

Values from computations are rounded off to the number of decimal places justified by the data. The answer can be no more accurate than the least accurate number in the data set. Rounding is done on final calculation results only, not on interim results. All calculations and reporting of experimental results adhere to the procedures described in "Experimental Methods for Engineers" (Holman, 1984).

CONCLUSIONS

The test protocols for performance testing of erosion control products in an open-channel environment, as described here, are based on generally-accepted engineering principles, scientific procedures, analytical methods and statistical standards. This methodology provides the ability to quantify the performance capabilities of a variety of Best Management Practices, including small-to-moderate sized riprap, erosion control blankets, turf reinforcement mattings, geocellular containment systems, and gabion mattresses in a newly-installed condition. In addition, the application or installation methods of these BMPs can be evaluated to determine their effect on performance. Finally, the performance results can be compared to unprotected channel conditions to demonstrate the BMPs value in reducing soil loss, complying with regulatory requirements, improving water quality, and enhancing environmental conditions.

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EDITORIAL COMMENTS

This paper is based on *The ErosionLab* Channel Erosion Research Facility (CERF) *Procedures Manual*, dated 8/97, which was developed and published by Ayres Associates, Fort Collins, Colorado, under contract to American Excelsior Company. This document has been reviewed recently by a number of industry professionals, and may be modified to reflect their recommendations and to improve the quality of this test protocol. As an ongoing process, comments, suggestions, constructive criticism and questions regarding these testing procedures are encouraged and should be directed to American Excelsior Company, P.O. Box 1067, Arlington, TX 76005-1067, Attn: Dwight A. Cabalka, P.E., National Applications Engineer.

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