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## San Francisco Bay Regional Water Quality Control Board

*Sent via electronic email: no hard copy to follow*

October 24, 2019  
CIWQS Place ID 833044

Governor's Office of Planning & Research

**OCT 25 2019**

**STATE CLEARINGHOUSE**

San Francisquito Creek Joint Powers Authority  
615-B Menlo Avenue  
Menlo Park, CA 94025  
Attn. Mr. Len Materman  
email: [Len@sfcjpa.org](mailto:Len@sfcjpa.org)

**Subject: Comments on *Final Environmental Impact Report for the San Francisquito Creek Flood Protection, Ecosystem Restoration, and Recreation Project Upstream of Highway 101, Counties of San Mateo and Santa Clara (State Clearinghouse No. 2013062019)***

Dear Mr. Materman:

The San Francisquito Creek Joint Powers Authority (JPA) adopted the final environmental impact report (EIR) for the *San Francisquito Creek Flood Protection, Ecosystem Restoration, and Recreation Project Upstream of Highway 101*, (Project) on September 26, 2019. In our letter of June 26, 2019, we commented on aspects of the Project, as presented in the Project's draft EIR (DEIR), that may impact waters of the State. Our comments were intended to facilitate efficient project design by the JPA and our subsequent review, in part by allowing the revised EIR to include information to support the Project's future Clean Water Act section 401 water quality certification and waste discharge requirements (certification) application. The final EIR did not adequately respond to our comments. As a result, we will work with you to ensure the information can be provided during the certification process. To facilitate that, we offer the following comments for the JPA's consideration.

The EIR's preferred alternative, the Channel Widening Alternative, is likely to cause water quality impacts by smoothing the banks. This is likely to result in creek bed scour and bank erosion. In addition, the Project would remove bank vegetation that currently provides shade, refuge, nesting, and foraging habitat for aquatic life and wildlife. For a complete certification application, we will require submittal of hydraulic and geomorphic analyses sufficient to demonstrate whether the proposed bank stabilization treatments (sheet piles or soil nail walls) are necessary. The EIR indicated that the JPA used Stanford University's 2D HEC-RAS model for hydraulic analyses at Searsville Dam, Searsville Lake, and tributaries

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JIM McGRATH, CHAIR | MICHAEL MONTGOMERY, EXECUTIVE OFFICER

to the lake, but not for the Project sections from Highway 101 to Middlefield Road where the bank modifications are proposed. We understand that Stanford has a hydraulic model for the project reach and that it is available to JPA, and encourage the JPA to use it, as appropriate.

As described in the final EIR, the Project may include hard bank stabilization methods such as sheet piles and soil nail walls. Those methods are likely to impact the creek's beneficial uses, which would require appropriate mitigation. The Project has the potential to incorporate design elements, such as bioengineering techniques, that could reduce and help mitigate impacts from hard bank stabilization methods. To consider whether those measures may be appropriate for the project, an engineering model of the Project reach will be necessary to evaluate flow velocities and shear stresses. Based on the model's results, the Project design should then, as appropriate, incorporate more-environmentally-friendly bank stabilization methods. Bioengineering techniques, such as large boulders coupled with brush layering (as used in Wildcat Creek in San Pablo, Contra Costa County), or concrete soil cribwalls, are able to sustain high shear stresses and velocities in flood control channels, and are examples of such methods. The creek velocities under post-Project conditions reported in the EIR, which vary by creek reach from 6.52 to 9.21 feet per second, are well within the stability thresholds found to work for soil bioengineering bank stabilization methods (Fischenich 2001) (see Attachment). Substantial incorporation of such measures could result in the Project being considered self-mitigating.

A portion of our DEIR comments could be resolved by addressing the concerns presented above. We recognize that others remain to be resolved, and we will work with you to address them during the certification process. These include our comments on the least environmentally damaging practicable alternative for waters of the State; lack of a sufficient analysis for the Floodwalls Alternative; and a proposed Adaptive Management Plan that should be revised to adequately address the potential for the Project to exacerbate bank erosion, which could result in future impacts from additional bank stabilization. As such, this letter incorporates by reference our letter of June 26; please consider them together as you further develop the Project design and prepare an application for certification.

In conclusion, we urge the JPA to review the Project design and appropriately incorporate bioengineered bank stabilization measures. The review should use a HEC-RAS model of San Francisquito Creek (ideally, Stanford's model) from Interstate 101 to Middlefield Road, and Fischenich (2001) as a guide to the practicability of particular measures. We are available to consult with the JPA in advance of your submittal of a permit application, to help ensure we will have the information needed to support that the Project will achieve its identified goals and certify that the Project will comply with State water quality standards.

We look forward to continuing to work with you on this important project. To coordinate a meeting with us or if you have any questions on this matter, please contact Susan Glendening at [susan.glendening@waterboards.ca.gov](mailto:susan.glendening@waterboards.ca.gov) or (510) 622-2462. Please reference Place ID 833044 in any correspondence pertaining to the Project.

Sincerely,

Keith H. Lichten, Chief  
Watershed Management Division

Attachment: Fischenich, C. 2001. *Stability Thresholds for Stream Restoration Materials*. USAE Research and Development Center, Environmental Laboratory. ERDC TN-EMRRP-SR-29. Vicksburg MS. ERDC TN-EMRRP-SR-29

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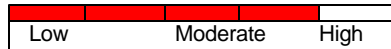
# Stability Thresholds for Stream Restoration Materials



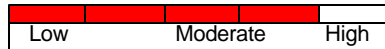
by Craig Fischenich<sup>1</sup>

May 2001

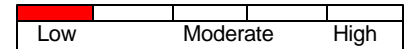
## Complexity



## Value as a Planning Tool



## Cost



## OVERVIEW

Stream restoration projects usually involve some modification to the channel or the banks. Designers of stabilization or restoration projects must ensure that the materials placed within the channel or on the banks will be stable for the full range of conditions expected during the design life of the project. Unfortunately, techniques to characterize stability thresholds are limited. Theoretical approaches do not exist and empirical data mainly consist of velocity limits, which are of limited value.

Empirical data for shear stress or stream power are generally lacking, but the existing body of information is summarized in this technical note. Whereas shear thresholds for soils found in channel beds and banks are quite low (generally < 0.25 lb/sf), those for vegetated soils (0.5 – 4 lb/sf), erosion control materials and bioengineering techniques (0.5 – 8 lb/sf), and hard armoring (< 13 lb/sf) offer options to provide stability.

## STABILITY CRITERIA

The stability of a stream refers to how it accommodates itself to the inflowing water and sediment load. In general, stable streams may adjust their boundaries but do not exhibit trends in changes to their geometric character. One form of instability occurs when a stream is unable to transport its sediment load (i.e., sediments deposited within the channel), leading to the condition referred to as aggradation.

When the ability of the stream to transport sediment exceeds the availability of sediments within the incoming flow, and stability thresholds for the material forming the boundary of the channel are exceeded, erosion occurs. This technical note deals with the latter case of instability and distinguishes the presence or absence of erosion (threshold condition) from the magnitude of erosion (volume).

Erosion occurs when the hydraulic forces in the flow exceed the resisting forces of the channel boundary. The amount of erosion is a function of the relative magnitude of these forces and the time over which they are applied. The interaction of flow with the boundary of open channels is only imperfectly understood. Adequate analytical expressions describing this interaction have not yet been developed for conditions associated with natural channels. Thus, means of characterizing erosion potential must rely heavily upon empiricism.

Traditional approaches for characterizing erosion potential can be placed in one of two categories: maximum permissible velocity, and tractive force (or critical shear stress). The former approach is advantageous in that velocity is a parameter that can be measured within the flow. Shear stress cannot be directly measured – it must be computed from other flow parameters. Shear stress is a better measure of the fluid force on the channel boundary than is velocity. Moreover, conventional guidelines, including ASTM standards, rely upon the shear stress as a

<sup>1</sup> USAE Research and Development Center, Environmental Laboratory, 3909 Halls Ferry Rd., Vicksburg MS 39180

means of assessing the stability of erosion control materials. Both approaches are presented in this paper.

### Incipient Motion (Threshold Condition)

As flow over the bed and banks of a stream increases, a condition referred to as the threshold state is reached when the forces tending to move materials on the channel boundary are in balance with those resisting motion. The forces acting on a noncohesive soil particle lying on the bed of a flowing stream include hydrodynamic lift, hydrodynamic drag, submerged weight ( $F_w - F_b$ ), and a resisting force  $F_r$ , as seen in Figure 1. The drag is in the direction of the flow and the lift and weight are normal to the flow. The resisting force depends on the geometry of the particles. At the threshold of movement, the resultant of the forces in each direction is zero. Two approaches for defining the threshold state are discussed herein, initial movement being specified in terms of either a critical velocity ( $v_{cr}$ ) or a critical shear stress ( $\tau_{cr}$ ).

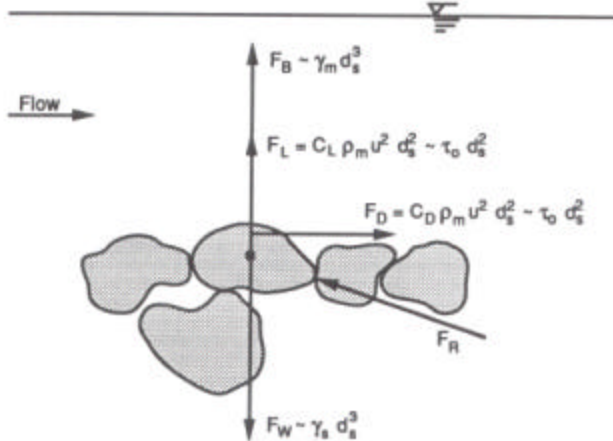


Figure 1. Forces acting on the boundary of a channel (adapted from Julien (1995)).

### Critical Velocity

Figure 1 shows that both the lift and the drag force are directly related to the velocity squared. Thus, small changes in the velocity could result in large changes in these forces. The permissible velocity is defined as the maximum velocity of the channel that will not cause erosion of the channel boundary. It is often called the critical velocity because it refers to the condition for the initiation of motion. Early works in canal design and in evaluating the stability of waterways relied

upon this method. Considerable empirical data exist relating maximum velocities to various soil and vegetation conditions.

However, this simple method for design does not consider the channel shape or flow depth. At the same mean velocity, channels of different shapes or depths may have quite different forces acting on the boundaries. Critical velocity is depth-dependent, and a correction factor for depth must be applied in this application. Despite these limitations, maximum permissible velocity can be a useful tool in evaluating the stability of various waterways. It is most frequently applied as a cursory analysis when screening alternatives.

### Critical Shear Stress

The forces shown in Figure 1 can also be expressed in terms of the shear stress. Shear stress is the force per unit area in the flow direction. Its distribution in steady, uniform, two-dimensional flow in the channel can be reasonably described. An estimate of the average boundary shear stress ( $\tau_o$ ) exerted by the fluid on the bed is:

$$\tau_o = \gamma D S_f \quad (1)$$

where  $\gamma$  is the specific weight of water,  $D$  is the flow depth ( $\sim$  hydraulic radius), and  $S_f$  is the friction slope. Derived from consideration of the conservation of linear momentum, this quantity is a spatial average and may not provide a good estimate of bed shear at a point.

Critical shear stress ( $\tau_{cr}$ ) can be defined by equating the applied forces to the resisting forces. Shields (1936) determined the threshold condition by measuring sediment transport for values of shear at least twice the critical value and then extrapolating to the point vanishing sediment transport. His laboratory experiments have since served as a basis for defining critical shear stress. For soil grains of diameter  $d$  and angle of repose  $\phi$  on a flat bed, the following relations can approximate the critical shear for various sizes of sediment:

$$\tau_{cr} = 0.5(\mathbf{I}_s - \mathbf{I}_w)d \tan \mathbf{f} \quad \text{For clays} \quad (2)$$

$$\tau_{cr} = 0.25d_*^{-0.6}(\mathbf{I}_s - \mathbf{I}_w)d \tan \mathbf{f} \quad \text{For silts and sands} \quad (3)$$

$$t_{cr} = 0.06(I_s - I_w)d \tan f \quad \text{For gravels and cobbles} \quad (4)$$

Where

$$d_* = d \left[ \frac{(G-1)g}{\nu^2} \right]^{1/3} \quad (5)$$

$\gamma_s$  = the unit weight of the sediment  
 $\gamma_w$  = the unit weight of the water/sediment mixture  
 G = the specific gravity of the sediment  
 g = gravitational acceleration  
 $\nu$  = the kinematic viscosity of the water/sediment mixture

The angle of repose  $\phi$  for noncohesive sediments is presented in Table 1 (Julien 1995), as are values for critical shear stress. The critical condition can be defined in terms of shear velocity rather than shear stress (note that shear velocity and channel velocity are different). Table 1 also provides limiting shear velocity as a function of sediment size. The  $V_{*c}$  term is the critical shear velocity and is equal to

$$V_{*c} = \sqrt{gR_h S_f} \quad (6)$$

**Table 1. Limiting Shear Stress and Velocity for Uniform Noncohesive Sediments**

<b>Class name</b>	<b><math>d_s</math> (in)</b>	<b><math>f</math> (deg)</b>	<b><math>t_c</math></b>	<b><math>t_\alpha</math> (lb/sf)</b>	<b><math>V_{*c}</math> (ft/s)</b>
<b>Boulder</b>					
<i>Very large</i>	>80	42	0.054	37.4	4.36
<i>Large</i>	>40	42	0.054	18.7	3.08
<i>Medium</i>	>20	42	0.054	9.3	2.20
<i>Small</i>	>10	42	0.054	4.7	1.54
<b>Cobble</b>					
<i>Large</i>	>5	42	0.054	2.3	1.08
<i>Small</i>	>2.5	41	0.052	1.1	0.75
<b>Gravel</b>					
<i>Very coarse</i>	>1.3	40	0.050	0.54	0.52
<i>Coarse</i>	>0.6	38	0.047	0.25	0.36
<i>Medium</i>	>0.3	36	0.044	0.12	0.24
<i>Fine</i>	>0.16	35	0.042	0.06	0.17
<i>Very fine</i>	>0.08	33	0.039	0.03	0.12
<b>Sands</b>					
<i>Very coarse</i>	>0.04	32	0.029	0.01	0.070
<i>Coarse</i>	>0.02	31	0.033	0.006	0.055
<i>Medium</i>	>0.01	30	0.048	0.004	0.045
<i>Fine</i>	>0.005	30	0.072	0.003	0.040
<i>Very fine</i>	>0.003	30	0.109	0.002	0.035
<b>Silts</b>					
<i>Coarse</i>	>0.002	30	0.165	0.001	0.030
<i>Medium</i>	>0.001	30	0.25	0.001	0.025

Table 1 provides limits best applied when evaluating idealized conditions, or the stability of sediments in the bed. Mixtures of sediments tend to behave differently from uniform sediments. Within a mixture, coarse sediments are generally entrained at lower shear stress values than presented in Table 1. Conversely, larger shear stresses than those presented in the table are required to entrain finer sediments within a mixture.

Cohesive soils, vegetation, and other armor materials can be similarly evaluated to determine empirical shear stress thresholds. Cohesive soils are usually eroded by the detachment and entrainment of soil aggregates. Motivating forces are the same as those for noncohesive banks; however, the resisting forces are primarily the result of cohesive bonds between particles. The bonding strength, and hence the soil erosion resistance, depends on the physio-chemical properties of the soil and the chemistry of the

fluids. Field and laboratory experiments show that intact, undisturbed cohesive soils are much less susceptible to flow erosion than are non-cohesive soils.

Vegetation, which has a profound effect on the stability of both cohesive and noncohesive soils, serves as an effective buffer between the water and the underlying soil. It increases the effective roughness height of the boundary, increasing flow resistance and displacing the velocity upwards away from the soil, which has the effect of reducing the forces of drag and lift acting on the soil surface. As the boundary shear stress is proportional to the square of the near-bank velocity, a reduction in this velocity produces a much greater reduction in the forces responsible for erosion.

Vegetation armors the soil surface, but the roots and rhizomes of plants also bind the soil and introduce extra cohesion over and above any intrinsic cohesion that the bank material may have. The presence of vegetation does not render underlying soils immune from erosion, but the critical condition for erosion of a vegetated bank is usually the threshold of failure of the plant stands by snapping, stem scour, or uprooting, rather than for detachment and entrainment of the soils themselves. Vegetation failure usually occurs at much higher levels of flow intensity than for soil erosion.

Both rigid and flexible armor systems can be used in waterways to protect the channel bed from erosion and to stabilize side slopes. A wide array of differing armor materials are available to accomplish this. Many manufactured products have been evaluated to determine their failure threshold. Products are frequently selected using design graphs that present the flow depth on one axis and the slope of the channel on the other axis. Thus, the design is based on the depth/slope product (i.e., the shear stress). In other cases, the thresholds are expressed explicitly in terms of shear stress. Notable among the latter group are the field performance testing results of erosion control products conducted by the TXDOT/TTI Hydraulics and Erosion Control Laboratory (TXDOT 1999).

Table 2 presents limiting values for shear stress and velocity for a number of different channel lining materials. Included are soils, various types of vegetation, and number of different commonly applied stabilization techniques. Information presented in the table was derived from a number of different sources. Ranges of values presented in the table reflect various measures presented within the literature. In the case of manufactured products, the designer should consult the manufacturer's guidelines to determine thresholds for a specific product.

### **Uncertainty and Variability**

The values presented in Table 2 generally relate to average values of shear stress or velocity. Velocity and shear stress are neither uniform nor steady in natural channels. Short-term pulses in the flow can give rise to instantaneous velocities or stresses of two to three times the average; thus, erosion may occur at stresses much lower than predicted. Because limits presented in Table 2 were developed empirically, they implicitly include some of this variability. However, natural channels typically exhibit much more variability than the flumes from which these data were developed.

Sediment load can also profoundly influence the ability of flow to erode underlying soils. Sediments in suspension have the effect of damping turbulence within the flow. Turbulence is an important factor in entraining materials from the channel boundaries. Thus, velocity and shear stress thresholds are 1.5 to 3 times that presented in the table for flows carrying high sediment loads.

In addition to variability of flow conditions, variation in the channel lining characteristics can influence erosion predictions. Natural bed material is neither spherical nor of uniform size. Larger particles may shield smaller ones from direct impact so that the latter fail to move until higher stresses are attained. For a given grain size, the true threshold criterion may vary by nearly an order of magnitude depending on the bed gradation. Variation in the installation of erosion control measures can reduce the threshold necessary to cause erosion.

**Table 2. Permissible Shear and Velocity for Selected Lining Materials<sup>1</sup>**

Boundary Category	Boundary Type	Permissible Shear Stress (lb/sq ft)	Permissible Velocity (ft/sec)	Citation(s)
<u>Soils</u>	Fine colloidal sand	0.02 - 0.03	1.5	A
	Sandy loam (noncolloidal)	0.03 - 0.04	1.75	A
	Alluvial silt (noncolloidal)	0.045 - 0.05	2	A
	Silty loam (noncolloidal)	0.045 - 0.05	1.75 – 2.25	A
	Firm loam	0.075	2.5	A
	Fine gravels	0.075	2.5	A
	Stiff clay	0.26	3 – 4.5	A, F
	Alluvial silt (colloidal)	0.26	3.75	A
	Graded loam to cobbles	0.38	3.75	A
	Graded silts to cobbles	0.43	4	A
	Shales and hardpan	0.67	6	A
	<u>Gravel/Cobble</u>	1-in.	0.33	2.5 – 5
2-in.		0.67	3 – 6	A
6-in.		2.0	4 – 7.5	A
12-in.		4.0	5.5 – 12	A
<u>Vegetation</u>	Class A turf	3.7	6 – 8	E, N
	Class B turf	2.1	4 - 7	E, N
	Class C turf	1.0	3.5	E, N
	Long native grasses	1.2 – 1.7	4 – 6	G, H, L, N
	Short native and bunch grass	0.7 - 0.95	3 – 4	G, H, L, N
	Reed plantings	0.1-0.6	N/A	E, N
<u>Temporary Degradable RECPs</u>	Hardwood tree plantings	0.41-2.5	N/A	E, N
	Jute net	0.45	1 – 2.5	E, H, M
	Straw with net	1.5 – 1.65	1 – 3	E, H, M
	Coconut fiber with net	2.25	3 – 4	E, M
	Fiberglass roving	2.00	2.5 – 7	E, H, M
<u>Non-Degradable RECPs</u>	Unvegetated	3.00	5 – 7	E, G, M
	Partially established	4.0-6.0	7.5 – 15	E, G, M
	Fully vegetated	8.00	8 – 21	F, L, M
<u>Riprap</u>	6 – in. d <sub>50</sub>	2.5	5 – 10	H
	9 – in. d <sub>50</sub>	3.8	7 – 11	H
	12 – in. d <sub>50</sub>	5.1	10 – 13	H
	18 – in. d <sub>50</sub>	7.6	12 – 16	H
	24 – in. d <sub>50</sub>	10.1	14 – 18	E
<u>Soil Bioengineering</u>	Wattles	0.2 – 1.0	3	C, I, J, N
	Reed fascine	0.6-1.25	5	E
	Coir roll	3 - 5	8	E, M, N
	Vegetated coir mat	4 - 8	9.5	E, M, N
	Live brush mattress (initial)	0.4 – 4.1	4	B, E, I
	Live brush mattress (grown)	3.90-8.2	12	B, C, E, I, N
	Brush layering (initial/grown)	0.4 – 6.25	12	E, I, N
	Live fascine	1.25-3.10	6 – 8	C, E, I, J
	Live willow stakes	2.10-3.10	3 – 10	E, N, O
	<u>Hard Surfacing</u>	Gabions	10	14 – 19
Concrete		12.5	>18	H

<sup>1</sup> Ranges of values generally reflect multiple sources of data or different testing conditions.

- |  |   |                            |
|--|---|----------------------------|
| A. Chang, H.H. (1988).                 | F. Julien, P.Y. (1995).                             | K. Sprague, C.J. (1999).   |
| B. Florineth. (1982)                   | G. Kouwen, N.; Li, R. M.; and Simons, D.B., (1980). | L. Temple, D.M. (1980).    |
| C. Gerstgraser, C. (1998).             | H. Norman, J. N. (1975).                            | M. TXDOT (1999)            |
| D. Goff, K. (1999).                    | I. Schiechl, H. M. and R. Stern. (1996).            | N. Data from Author (2001) |
| E. Gray, D.H., and Sotir, R.B. (1996). | J. Schoklitsch, A. (1937).                          | O. USACE (1997).           |



Changes in the density or vigor of vegetation can either increase or decrease erosion threshold. Even differences between the growing and dormant seasons can lead to one- to twofold changes in erosion thresholds.

To address uncertainty and variability, the designer should adjust the predicted velocity or shear stress by applying a factor of safety or by computing local and instantaneous values for these parameters. Guidance for making these adjustments is presented in the section titled "Application" below.

## EROSION MAGNITUDE

The preceding discussion dealt with the presence or absence of erosion, but did not address the extent to which erosion might occur for a given flow. If the thresholds presented in Table 2 are exceeded, erosion should be expected to occur. In reality, even when those thresholds are not exceeded, some erosion in a few select locations may occur. The extent to which this minor erosion could become a significant concern depends in large measure on the duration of the flow, and upon the ability of the stream to transport those eroded sediments.

### Flow Duration

Although not stated, limits regarding erosion potential published by manufacturers for various products are typically developed from studies using short flow durations. They do not reflect the potential for severe erosion damage that can result from moderate flow events over several hours. Studies have shown that duration of flow reduces erosion resistance of many types of erosion control products, as shown in Figures 2 - 4. A factor of safety should be applied when flow duration exceeds a couple of hours.

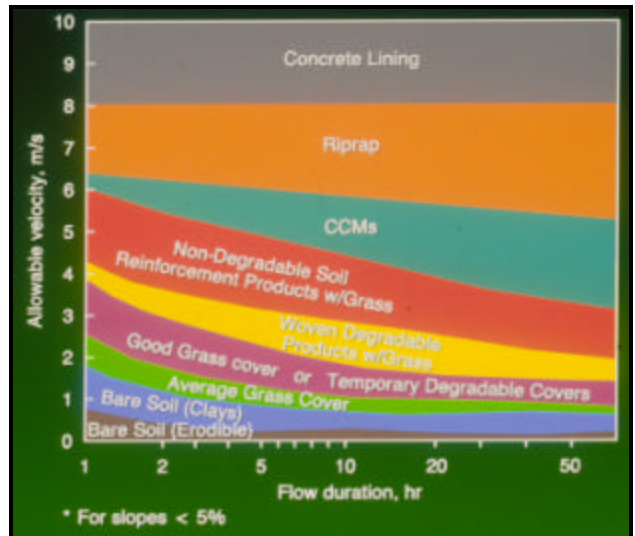


Figure 2. Erosion limits as a function of flow duration (from Fischenich and Allen (2000)).

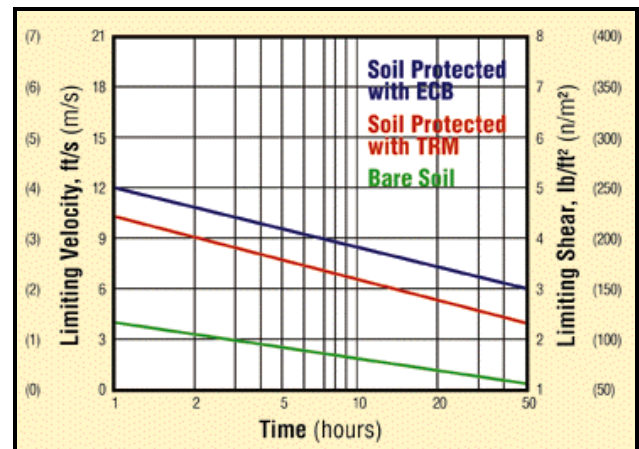


Figure 3. Limiting values for bare and TRM protected soils (from Sprague (1999))

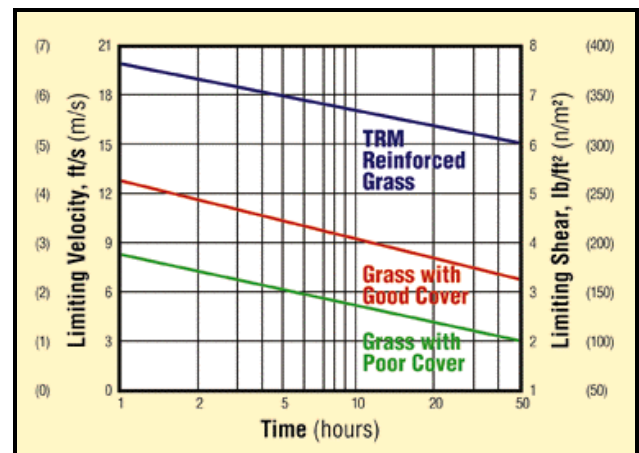


Figure 4. Limiting values for plain and TRM reinforced grass (from Sprague (1999))

Correlations between flow volume and amount of erosion tend to be poor. Multi-peaked flows may be more effective than single flows of comparable or greater magnitude because of the increased incidence of wetting. Flows with long durations often have a more significant effect on erosion than short-lived flows of higher magnitude. Sediment transport analysis can be used to gauge the magnitude of erosion potential in the channel design, but predictive capability is limited.

### Sediment Transport

A number of flow measures can be used to assess the ability of a stream to transport sediment. The unit stream power ( $P_m$ ) is one common approach, and is related to the earlier discussion in that stream power includes both velocity and shear stress as components. Sediment transport ( $Q_s$ ) increases when the unit stream power ( $P_m$ ) increases. Unit stream power in turn is controlled by both tractive stress and flow velocity:

$$P_m = v \cdot \tau = v \cdot \gamma_w \cdot D \cdot S_f \quad (7)$$

The total power ( $P_t$ ) is the product of the unit power times the channel width ( $W$ ):

$$P_t = P_m \cdot W = v \cdot W \cdot D \cdot \gamma_w \cdot S_f = v \cdot A \cdot \gamma_w \cdot S_f = Q_w \cdot \gamma_w \cdot S_f \quad (8)$$

Stream power assessments can be useful in evaluating sediment discharge within a stream channel and the deposition or erosion of sediments from the streambed. However, their utility for evaluating the stability of measures applied to prevent erosion is limited because of the lack of empirical data relating stream power to stability. The analysis of general streambank erosion is not a simple extension of the noncohesive bed case with an added downslope gravity component. Complication is added by other influencing variables, such as vegetation, whose root system can reinforce bank material and increase erosion resistance. Factors influencing bank erosion are summarized in Table 3.

**Table 3. Factors Influencing Erosion**

<b>Factor</b>	<b>Relevant characteristics</b>
<b>Flow properties</b>	Magnitude, frequency and variability of stream discharge; Magnitude and distribution of velocity and shear stress; Degree of turbulence
<b>Sediment composition</b>	Sediment size, gradation, cohesion and stratification
<b>Climate</b>	Rainfall amount, intensity and duration; Frequency and duration of freezing
<b>Subsurface conditions</b>	Seepage forces; Piping; Soil moisture levels
<b>Channel geometry</b>	Width and depth of channel; Height and angle of bank; Bend curvature
<b>Biology</b>	Vegetation type, density and root character; Burrows
<b>Anthropogenic factors</b>	Urbanization, flood control, boating, irrigation

## APPLICATION

The stability of a waterway or the suitability of various channel linings can be determined by first calculating both the mean velocity and tractive stress (by the previous equations). These values can then be compared with allowable velocity and tractive stress for a particular ground cover or lining system under consideration (e.g., existing vegetation cover, an erosion control blanket, or bioengineering treatment). Allowable tractive stresses for

various types of soil, linings, ground covers, and stabilization measures including soil bioengineering treatments, are listed in Table 2. Additionally, manufacturers' product literature can provide allowable tractive stresses or velocities for various types of erosion control products.

An iterative procedure may be required when evaluating channel stability because various linings will affect the resistance coefficient,

which in turn may change the estimated flow conditions. A general procedure for the application of information presented in this paper is outlined in the following paragraphs.

**Step 1- Estimate Mean Hydraulic Conditions.**

Flow of water in a channel is governed by the discharge, hydraulic gradient, channel geometry, and roughness coefficient. This functional relationship is most frequently evaluated using normal depth or backwater computations that take into account principles of conservation of linear momentum. The latter is preferable because it accounts for variations in momentum slope, which is directly related to shear stress. Several models are available to aid the hydraulic engineer in assessing hydraulic conditions. Notable examples include HEC-2, HEC-RAS, and WSP2. Channel cross sections, slopes, and Manning’s coefficients should be determined based upon surveyed data and observed or predicted channel boundary conditions. Output from the model should be used to compute main channel velocity and shear stress at each cross section.

**Step 2- Estimate Local/Instantaneous Flow Conditions.**

The computed values for velocity and shear stress may be adjusted to account for local variability and instantaneous values higher than mean. A number of procedures exist for this purpose. Most commonly applied are empirical methods based upon channel form and irregularity. Several references at the end of this paper present procedures to make these adjustments. Chang (1988) is a good example. For straight channels, the local maximum shear stress can be assumed from the following simple equation:

$$t_{\max} = 1.5t \tag{9}$$

for sinuous channels, the maximum shear stress should be determined as a function of the planform characteristics using Equation 10:

$$t_{\max} = 2.65 t \left( \frac{R_c}{W} \right)^{-0.5} \tag{10}$$

where  $R_c$  is the radius of curvature and  $W$  is the top width of the channel. Equations 9 and 10 adjust for the spatial distribution of shear stress; however, temporal maximums in turbulent flows can be 10 – 20 percent higher, so an adjustment to account for instantaneous maximums should be added as well. A factor of 1.15 is usually applied.

**Step 3- Determine Existing Stability.**

Existing stability should be assessed by comparing estimates of local and instantaneous shear and velocity to values presented in Table 2. Both the underlying soil and the soil/vegetation condition should be assessed. If the existing conditions are deemed stable and are in consonance with other project objectives, then no further action is required. Otherwise, proceed to step 4.

**Step 4- Select Channel Lining Material.**

If existing conditions are unstable, or if a different material is needed along the channel perimeter to meet project objectives, a lining material or stabilization measure should be selected from Table 2, using the threshold values as a guideline in the selection. Only material with a threshold exceeding the predicted value should be selected. The other project objectives can also be used at this point to help select from among the available alternatives. Fischenich and Allen (2000) characterize attributes of various protection measures to help in the selection.

**Step 5- Recompute Flow Values.**

Resistance values in the hydraulic computations should be adjusted to reflect the selected channel lining, and hydraulic condition should be recalculated for the channel. At this point, reach- or section-averaged hydraulic conditions should be adjusted to account for local and instantaneous extremes.

Table 4 presents velocity limits for various channel boundaries conditions. This table is useful in screening alternatives, or as an alternative to the shear stress analysis presented in the preceding sections.

**Table 4. Stability of Channel Linings for Given Velocity Ranges**

Lining	0 – 2 fps	2 – 4 fps	4 – 6 fps	6 – 8 fps	> 8 fps
Sandy Soils	Appropriate	Use Caution	Not Appropriate	Not Appropriate	Not Appropriate
Firm Loam	Appropriate	Use Caution	Not Appropriate	Not Appropriate	Not Appropriate
Mixed Gravel and Cobbles	Appropriate	Use Caution	Use Caution	Not Appropriate	Not Appropriate
Average Turf	Appropriate	Use Caution	Use Caution	Not Appropriate	Not Appropriate
Degradable RECPs	Appropriate	Use Caution	Use Caution	Use Caution	Not Appropriate
Stabilizing Bioengineering	Appropriate	Use Caution	Use Caution	Use Caution	Not Appropriate
Good Turf	Appropriate	Use Caution	Use Caution	Use Caution	Use Caution
Permanent RECPs	Appropriate	Appropriate	Appropriate	Appropriate	Use Caution
Armoring	Appropriate	Appropriate	Appropriate	Appropriate	Appropriate
Bioengineering	Appropriate	Appropriate	Appropriate	Appropriate	Appropriate
CCMs & Gabions	Appropriate	Appropriate	Appropriate	Appropriate	Appropriate
Riprap	Appropriate	Appropriate	Appropriate	Appropriate	Appropriate
Concrete	Appropriate	Appropriate	Appropriate	Appropriate	Appropriate

Key:

	Appropriate
	Use Caution
	Not Appropriate

**Step 6– Confirm Lining Stability.**

The stability of the proposed lining should be assessed by comparing the threshold values in Table 2 to the newly computed hydraulic conditions. These values can be adjusted to account for flow duration using Figures 2-4 as a guide. If computed values exceed thresholds, step 4 should be repeated. If the threshold is not exceeded, a factor of safety for the project should be determined from the following equations:

$$FS = \frac{t_{max}}{t_{est}} \quad \text{or} \quad FS = \frac{V_{max}}{V_{est}} \quad (11)$$

In general, factors of safety in excess of 1.2 or 1.3 should be acceptable. The preceding five steps should be conducted for every cross section used in the analysis for the project. In the event that computed hydraulic values exceed thresholds for any desirable lining or stabilization technique, measures must be undertaken to reduce the energy within the flow. Such measures might include the installation of low-head drop structures or other energy-dissipating devices along the channel. Alternatively, measures implemented within the watershed to reduce total discharge could be employed.

**APPLICABILITY AND LIMITATIONS**

Techniques described in this technical note are generally applicable to stream restoration projects that include revegetation of the riparian zone or bioengineering treatments.

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