Design for erosion control according to ISO TR 18228-8

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ABSTRACT
The recent norm ISO TR 18228-8 deals with the design of geosynthetics used for erosion control on slopes and in channels for water flow. In particular it applies to channels that are non-navigable by vessels and that sustain flow for intermittent periods and at relatively low velocities, for examples surface water and run-off control channels and spillways. The applications for erosion control geosynthetics are typically in channels with fluid velocity up to 3 m/s for sustained periods or up to 6 m/s for short periods. Allowable water velocities and sustainable periods of flow depend on the subsoil parameters and the geosynthetic product's ability to prevent the soil particles moving. Once the hydraulic parameters of the flow have been evaluated, the stability of the channel bottom and side banks against erosion can be assessed using two limit criteria: the first one takes into consideration the allowable water velocity, and the second one the allowable shear stresses. The paper presents the detailed design procedure for geosynthetics for erosion control in channels.

1. INTRODUCTION

Erosion on river and channel banks develop from the shear stresses applied by the stream. If not properly addressed, riverine erosion may cause significant issues for navigation and human activities. Moreover, uncontrolled erosion may produce the failure of dikes, with consequent flooding of surrounding areas.

The water flow in rivers and channels produces shear stresses on the bottom and side banks, which are proportional to water depth and velocity. Such shear stresses can remove soil particles and excavate progressively deeper into the channel bottom and sides, which may lead to slope failure. Channel bottom and sides can be protected by lining with different materials (concrete, riprap, geosynthetics, etc.).

The design and selection of geosynthetics for protecting river and channel banks require performance tests, in unvegetated and/or vegetated configuration, to assess the limit values of water velocity and shear stress when the bank is protected with a specific product. Two basic design concepts are used to evaluate and define a channel configuration that will perform within the accepted limits of stability. These methods are defined as the permissible velocity approach and the permissible tractive force (shear stress) approach.

2. OPEN CHANNEL FLOW CONCEPTS

2.1 Type of Flow

Open channel flow can be classified (Ven Te Chow, 1959) as:
- Steady or unsteady flow;
- Uniform flow, rapidly varied flow, gradually varied flow;
- Continuous flow, spatially varied or discontinuous flow.

In general geosynthetics for erosion control are suitable for conditions of uniform flow and gradually varied flow, while the suitability of geosynthetics for erosion control for other flow conditions needs to be checked case by case.

2.2 Flow velocity and discharge

In continuous steady flow conditions, the discharge Q at every channel section is expressed by the continuity equation:

$$Q = V \cdot A \qquad [1]$$

where: V is the average water velocity in the cross-sectional area of flow (m/s), and A is the flow cross sectional area (m^2), normal to the flow direction.

Usually, velocities in a channel are not uniformly distributed along the channel section itself, and they depend on several factors like the shape of the section, the roughness of the channel sides and the presence of bends.

2.3 Resistance to Flow

Depth of uniform flow in a channel depends on the roughness of the material lining the flow perimeter. In fluid dynamics, the Chézy formula describes the mean flow velocity of steady, turbulent open channel flow:

$$V = C \cdot \sqrt{R \cdot i} \tag{2}$$

where:
V = average velocity [m/s],
C = Chezy's roughness coefficient [$m^{½}/s$],
R = hydraulic radius (m)= A / P
A = cross-sectional area of flow (m^2)
P = wetted perimeter (m).
i = hydraulic gradient ≃ bottom slope [m/m].

The roughness coefficient C can be calculated using various formulae; the most commonly used formulae are monomial type:

- Strickler formula:

$$C = k_S \cdot R^{1/6} \tag{3}$$

where: k_s is the Strickler roughness coefficient ($m^{1/3}$ / s)

The average velocity V of flow is then given by:

$$V = k_S \cdot R^{2/3} \cdot i^{1/2} \tag{4}$$

- Manning formula:

$$C = \frac{1}{n} \cdot R^{1/6} \tag{5}$$

where: n is the Manning roughness coefficient ($s/m^{1/3}$).

The average velocity V of flow is then given by:

$$V = \frac{K_n}{n} \cdot R^{2/3} \cdot i^{1/2} \tag{6}$$

where: K_n is a conversion factor, equal to 1.486 for American customary units, and equal to 1.0 for SI units.

Tables 1 and 2 presents the values of the k_s and n coefficients for practical situations.

Note that Manning's n is the reciprocal of Strickler's k_s: n = 1 / k_s. Hence Tables 1 and 2 can be easily used for both formulas (3) and (5).

2.4 Channel bends

Flow around a bend in an open channel induces centrifugal forces because of the change in flow direction. This results in superelevation of the water surface on the external side of the bend: the water surface is higher at the outside of the bend than at the inside of the bend. Assuming that all velocities in the bend are equal to the mean velocity and that all streamlines have the same radius of curvature and the same bottom width of the channel (Fig. 1), the following formula can be used to calculate the superelevation in bends:

$$\Delta y = \frac{W \cdot V_{mean}{}^{2}}{g \cdot R_c} \tag{7}$$

where:
Δy = superelevation of water on the external side of the bend (m)
V_{mean} = mean channel velocity (m/s)
W = bottom width of the channel (m)
g = gravitational acceleration (m/s^2)
R_c = radius of curvature of the bend (m)

Table 1. Strickler's k_s coefficients for artificial watercourses

Strickler coefficients [$m^{1/3} s^{-1}$]	Max.	Norm.	Min.
(a) Earth, straight and uniform			
1. Clean, recently completed	62	56	50
2. Clean, after weathering	56	45	40
3. Gravel, uniform section, clean	45	40	33
4. With short grass, few weeds	45	37	30
(b) Earth, winding and sluggish			
1. No vegetation	43	40	33
2. Grass, some weeds	40	33	30
3. Dense weeds or aquatic plants in deep channel	33	29	25
4. Earth bottom and rubble sides	36	33	29
5. Stony bottom and weedy banks	40	29	25
6. Cobble bottom and clean sides	33	25	20
(c) Excavated or dredged channels			
1. No vegetation	40	36	30
2. Light brush on banks	29	20	17
(d) Rock cuts			
1. Smooth and uniform	40	29	25
2. Jagged and irregular	29	25	20
(e) Channels not maintained, weeds and brush uncut			
1. Dense weeds, high as flow depth	20	12	8
2. Clean bottom, brush on sides	25	20	12
3. Same, highest stage of flow	22	14	9
4. Dense brush and high stage	12	10	7

Table 2. Manning's n coefficients ($s/m^{1/3}$) for lined channels

Lining category	Lining type	Depth 0 – 0.15 m	Depth 0.15 – 0.6 m	Depth > 0.6 m
Rigid	Concrete	0.015	0.013	0.013
	Grout riprap	0.040	0.030	0.028
	Stone masonry	0.032	0.030	-
	Soil cement	0.025	0.022	0.020
	Asphalt	0.018	0.016	0.016
Unlined	Bare soil	0.023	0.020	0.020
	Rock cut	0.045	0.035	0.025
Biodegradable geosynthetics	Woven paper net	0.016	0.015	0.015
	Jute net	0.028	0.022	0.019
	Straw with net	0.033	0.025	-
	Curled wood mat	0.066	0.035	0.028
Polymeric geosynthetics	Geomat (unvegetated)	0.036	0.025	0.021
Gravel riprap	D_{50} = 25 mm	0.044	0.033	0.030
	D_{50} = 50 mm	0.066	0.041	0.034
Rock riprap	D_{50} = 150 mm	0.104	0.069	0.035
	D_{50} = 300 mm	-	0.078	0.040

Adjustments to the calculated average channel velocity that account for flow concentration around bends shall be applied. According to USDA (2007), it is possible to evaluate the maximum flow velocity on the side slopes in a bend, V_{ss}. The ratio V_{ss}/V_{avg}, where V_{avg} is the average channel velocity at the upstream end of the bend (which can be calculated with Strickler or Manning formula), has been determined to be a function of the ratio of radius of curvature, R_c, and the water surface width, W (see Fig. 1). The following formula can be used to calculate V_{ss}/V_{avg} in bends:

$$\frac{V_{ss}}{V_{avg}} = 1.74 - 0.52 \cdot Log\left(\frac{R_c}{W}\right) \qquad [8]$$

where:
V_{ss} = maximum flow velocity on the side slopes in a bend (m/s)
V_{avg} = average channel velocity at the upstream end of the bend (m/s)

Formula (8) is applicable to side slopes of 1V:1.5H or flatter. Fig. 2 (modified from USDA, 2007) illustrates this relationship for natural channels.

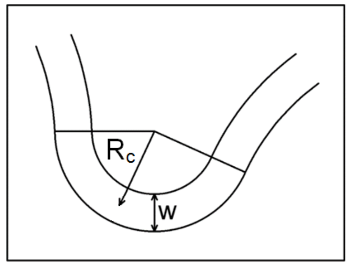


Fig. 1. Radius of curvature Rc and bottom width w in a channel bend

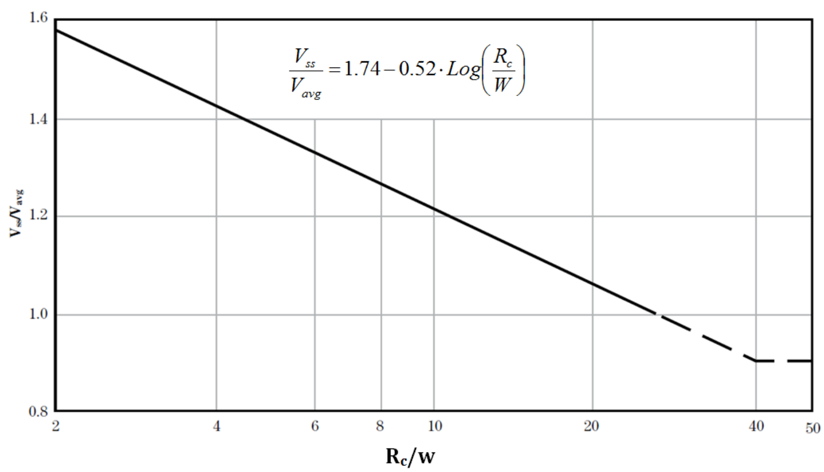


Figure 2. Design velocities in a bend for natural channels (modified from USDA, 2007)

2.5 Freeboard

The freeboard F of a channel is the vertical distance from the water surface to the top of the channel at design conditions. Usual values are: F = 0.50 ÷ 1.0 m.

Note that geosynthetics for erosion control should extend to the freeboard elevation.

3. GENERAL CRITERIA FOR DESIGN OF BANKS PROTECTION

3.1 Limit criteria

Once the hydraulic parameters of the flow have been evaluated, the stability of the channel bottom and side banks against erosion can be assessed using two limit criteria: the first one takes into consideration the allowable water velocity, and the second one the allowable shear stresses:

- velocity: $V < V_{all} / FS$ [9]
- shear stresses: $\tau < \tau_{all} / FS$ [10]

where τ_{all} and V_{all} are respectively the shear stress produced by the stream and the flow velocity of the water at which the movements of the solid particles begin, and FS is the required Factor of Safety.

3.2 Design conditions

The stability checks shall be carried out in two design conditions, which represent the two limit states, in order to take into account the vegetation development over time.

3.2.1. End of work

Just at the end of works the section is able to convey the maximum flow rate and the resistant shear stresses are minimal: this is usually the critical condition for the lining materials, hence it is the most critical situation to take into account for the bank protection check.

3.2.2. Vegetation completely grown

When vegetation is completely grown both roughness and allowable shear stresses are maximum. When the vegetation is fully developed (generally after 1 - 3 years) the resistance to erosion is higher due to the effect of the root system, but at the same time there is an increase in roughness; this is usually the critical condition for the containment of the design flow Q_d.

3.3 Method of allowable velocity

Once the water velocity V has been evaluated with Strickler or Manning formula, also considering V_{ss} in bends, it has to be compared with the allowable velocity V_{all} for the materials on the bottom and the banks of the channel: if the condition [9] is satisfied then no erosion will occur; if it is not satisfied an erosion control material needs to be lined on the wetted perimeter.

The allowable velocity V_{all} is the maximum velocity that does not cause erosion on the contour of the section. Tab. 3 provides the limit velocity V_{all} for some commonly used lining materials.

Table 3. Allowable velocities for commonly used materials (from USACE, 1991)

Material	V (m/s)
Fine sand	0.6
Coarse sand	1.2
Earth	
Sandy silt	0.6
Silt clay	1.1
Clay	1.8
Bermuda grass lined earth (slopes <5 %)	
Sandy silt	1.8
Silt clay	2.4
Kentucky blue grass lined earth (slopes <5 %)	
Sandy silt	1.5
Silt clay	2.1
Poor rock (usually sedimentary)	
Soft sandstone	2.4
Soft shale	1.1
Good rock (usually igneous or hard metamorphic)	6.1

When the bottom and banks are made up of soil, the allowable velocity depends on the particles diameter, as shown in Fig. 3, where the curve represents the V_{all} related to each particles diameter: when the water velocity is above the curve in Fig. 3, erosion would occur and lining with an erosion protection material is necessary; when the water velocity is below the curve in Fig. 3, erosion would not occur and the soil is stable, hence lining with an erosion protection material is not necessary. Fig. 4 provides the recommended limit velocity V_{all} for various erosion control materials (after Theisen, 1992).

The allowable velocities of geosynthetics for erosion control can be obtained by testing in a flume according to ASTM D6460. The typical allowable velocities of some geosynthetics for erosion control are listed in Tab. 4.

Fig. 5 shows an example, drawn from several sources, of a chart of V_{all} vs the flow duration of the flood event for a family of geomats, from testing according to ASTM D6460: the chart is divided in zones, where the lower zones refer to unvegetated geomats and the top zone refers to vegetated geomats; the top limit of each zone indicates V_{all} for reinforced geomats. These charts can be supplied by manufacturers for each specific family of products.

It is recommended, in the case of little or no vegetation coverage, that a safety factor FS of 1.3 ÷ 1.5 shall be applied both on the flood duration and the V_{all} values; in the case of fully developed vegetation, a safety factor of 1.2 ÷ 1.3 can be set. Furthermore, it is essential to ensure good adhesion between the geosynthetic and the underlying ground. This can be achieved by applying stakes according to the manufacturer's specifications.

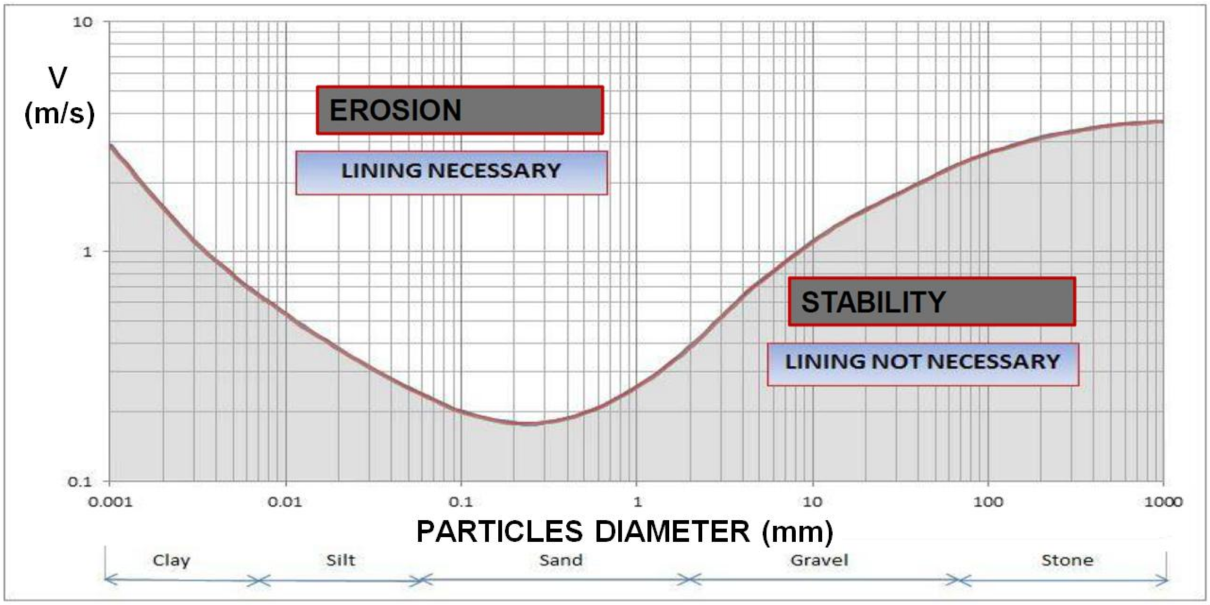
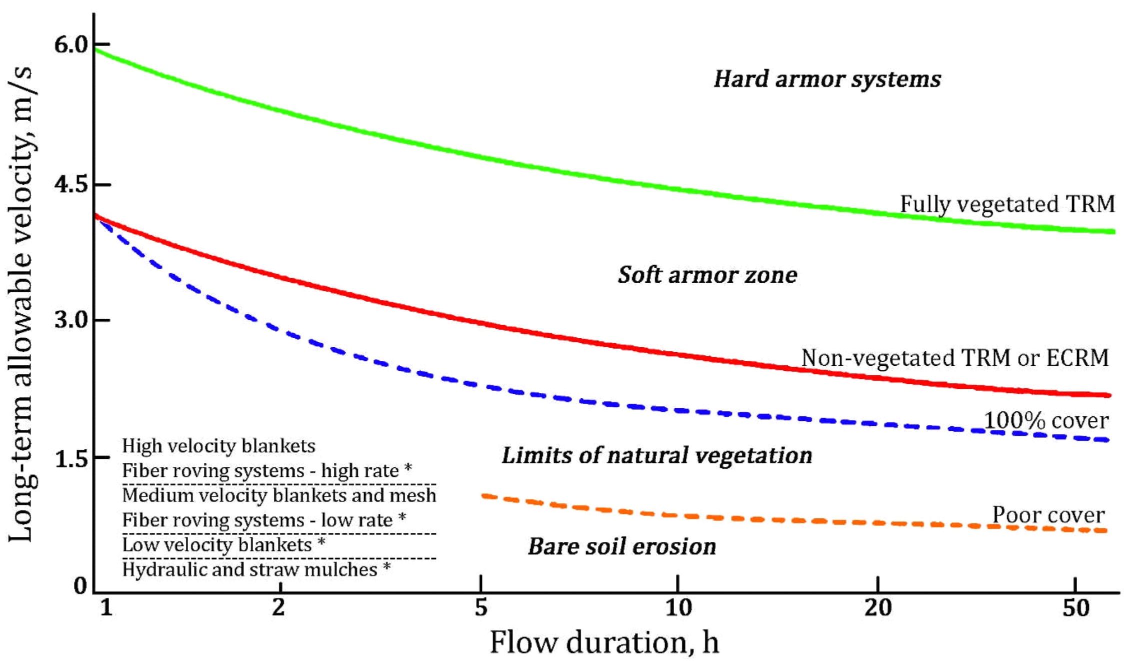


Figure 3. Limit between erosion and stability as function of particles diameter and flow velocity V (modified from Hjulström, 1935)



* no known published data for flow duration less than 0.5 h

Figure 4. Recommended maximum design velocities for various erosion control materials (modified from Theisen, 1992).

Table 4. Typical allowable velocities of geosynthetics

Lining	Thickness (mm)	Allowable velocity V_{all} (m/s)
Unvegetated Geomats	10 – 20	1.5 - 3.0
Vegetated Geomats	10 – 20	3.0 - 6.0
Unvegetated Geoblankets (natural fibres)	5 - 15	1.5 – 3.0
Vegetated Geoblankets (natural fibres)	5 - 15	3.0 – 4.6

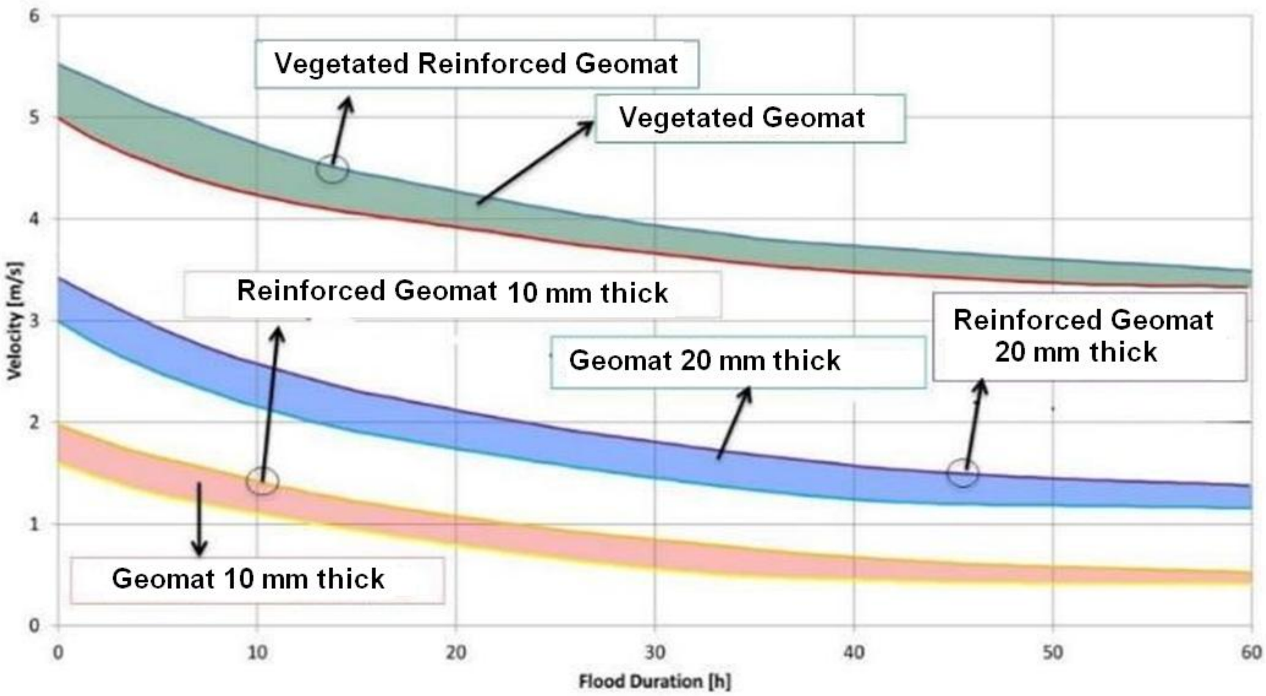


Figure 5. Example of chart of V_{all} vs flow duration for a family of geomats from testing according to ASTM D6460

3.4 Method of allowable shear stresses

By considering the shear stresses acting on the bottom or on the banks, the section of the channel is eroded if the shear stress which tends to move the particles is greater than the allowable shear stress; otherwise the material is stable against erosion.

For this method the drag shear stress has to be calculated, and then compared with the allowable shear stress, and condition (10) shall be verified.

3.4.1 Calculation of the drag shear stress

The drag shear stress on the bed of an infinitely wide channel is:

$$\tau_\infty = \gamma_w \cdot y \cdot i \qquad [11]$$

The drag shear stress τ on the wetted perimeter of the section of a real channel is given by:

$$\tau = K_1 \cdot K_2 \cdot \gamma_w \cdot y \cdot i \qquad [12]$$

where:
τ_∞ = drag shear stress on the bed of an infinitely wide channel (N/m^2)
τ = drag shear stress (N/m^2)
K_1 = bend coefficient (-)
K_2 = side slope coefficient (-)
γ_w = specific weight of water (N/m^3)

y = water depth (m)
i = longitudinal slope of the bottom of the channel (m/m)

3.4.2 Calculation of the shear stress: coefficient K_1

K_1 considers the effect of centrifugal force on dragging stresses acting on the external bank of a channel bend. K_1 is a function of the ratio between radius of curvature R and bottom width of the section W, according to the curve in Fig. 6.

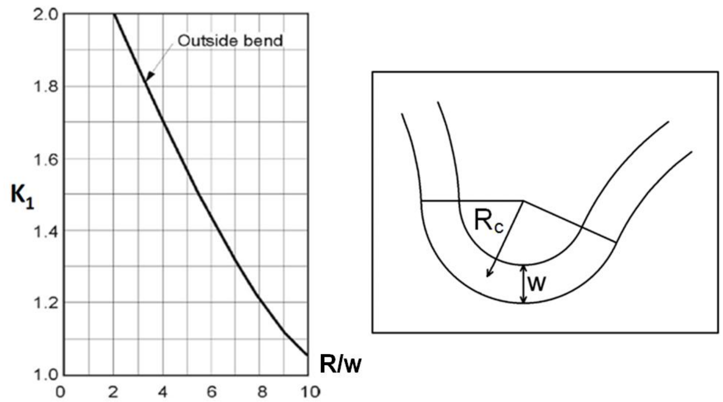


Figure 6. Coefficient K as function of the ratio between radius of curvature (R) of the bend and the bottom width of the section (W) (modified from USDA, 2007)

3.4.3 Calculation of the shear stress: coefficient K_2

The distribution of drag forces along the wetted perimeter is not uniform, like it would be on the bed of an infinitely wide channel. The coefficient K_2 is given by the ratio of the maximum channel side shear stress and of the maximum bottom shear stress of a real channel to the shear stress on the bed of an infinitely wide channel:

On the bottom: $K_2 = \tau_b / \tau_\infty$ [13]

On the side slopes: $K_2 = \tau_s / \tau_\infty$ [14]

where:
τ_b = applied shear stress on the bottom of a real channel bed (N/m^2),
τ_s = applied shear stress on the side slopes of a real channel (N/m^2).

As a conservative approximation the value of K_2 can be assumed as:

$K_2 = 1.00$ (at bottom)

$K_2 = 0.75$ (on banks)

3.4.4 Protection length downstream of channel bend

The higher water velocity on the external bank continues for a certain length downstream a channel bend, hence the protection on the external bank has to be extended to such length.

The protection length L_p downstream a channel bend can be evaluated from the chart in Fig. 7 (in US customary units) and with the following formula:

$$L_p = \alpha \cdot (R_c^{7/6} / n_b) \quad [15]$$

where:
L_p = protection length downstream a channel bend (m)
n_b = Manning roughness coefficient in the bend
α = unit conversion constant = 0.74 (SI) and 0.604 (US customary units)

When using the chart in Fig. 7, values of (L_p / R_c) in SI units can be calculated by multiplying the value obtained from the chart by 0.74 / 0.604 = 1.225.

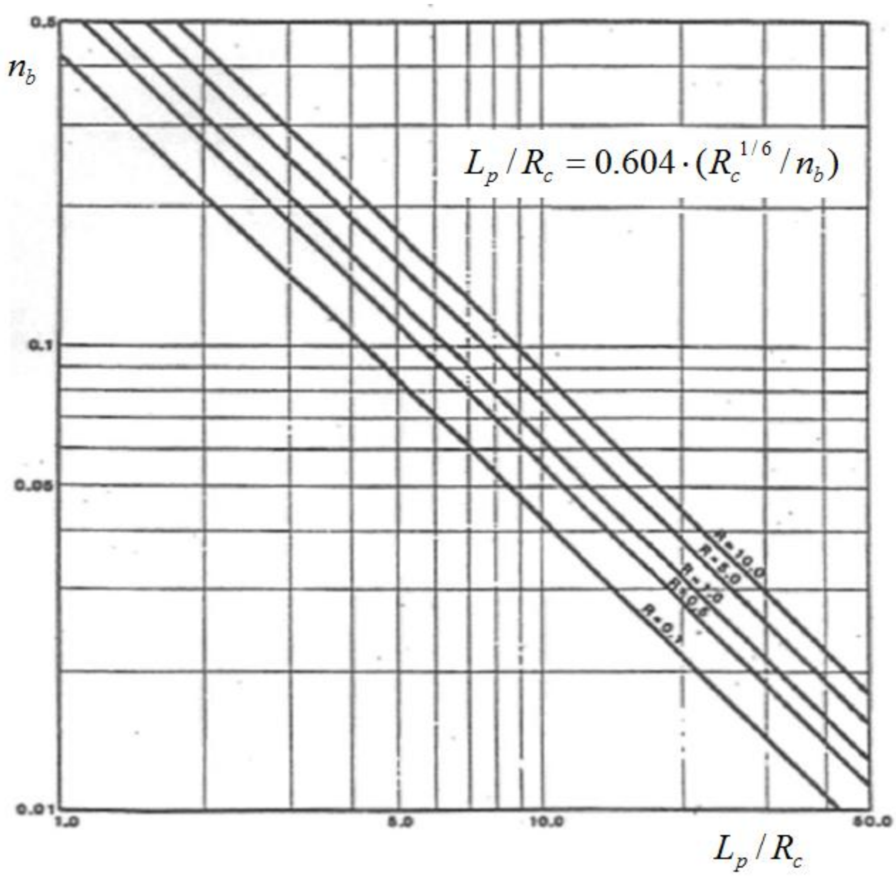


Figure 7. Protection length L_p to bend radius R ratio as function of Manning's roughness coefficient n_b in the bend, downstream of channel bend (modified from Nouh and Townsend, 1979).

3.4.5 Allowable resistant shear stress

The allowable resistant shear stress τ_{all} can be evaluated by testing in a flume according to ASTM D6460. Tests are usually performed for a maximum duration of 60 hours. The allowable resistant shear stress τ_{all} is usually recorded when 25.4 mm average erosion depth underneath the lining is reached on 50 % of the tested area.

When the bottom and banks are made up of soil, the allowable shear stress can be obtained from Fig. 8 (for non-cohesive soils) and Fig. 9 (for cohesive soils).

When the shear stress is above the curves in Figures 8 and 9, erosion would occur and lining with an erosion protection material is necessary; when the shear stress is below the curves in Figures 8 and 9, erosion would not occur and the soil is stable, hence lining with an erosion protection material is not necessary.

Typical values of the allowable resistant shear stress τ_{all} (N/m^2) for commonly used geosynthetics for erosion control are reported in Tab. 5. Specific values for each product are supplied by manufacturers.

An example (drawn from several sources) of chart of τ_{all} vs the flow duration for a family of geomats, typically obtained with tests according to ASTM D6460, is reported in Fig. 10. These charts can be supplied by manufacturers for each specific family of products.

It is recommended, in the case of little or no vegetation coverage, that a safety factor FS of 1.3 ÷ 1.5 shall be applied; in the case of fully developed vegetation, a safety factor FS of 1.2 ÷ 1.3 can be set.

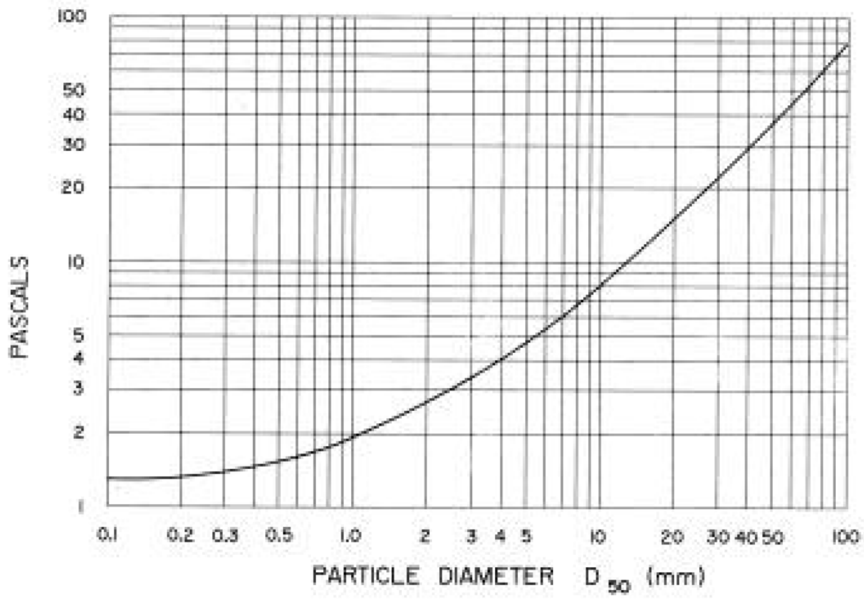
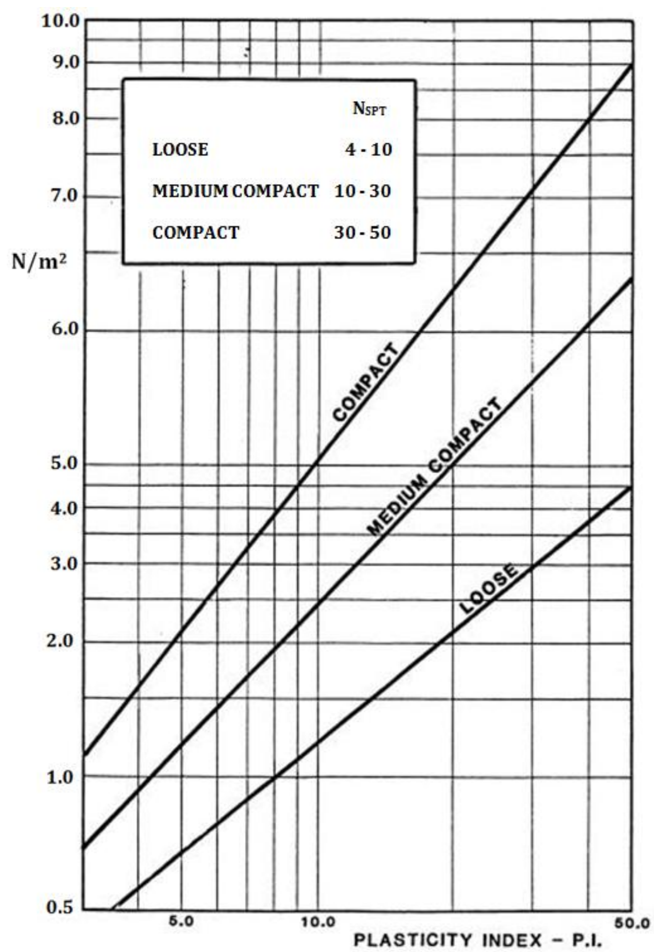


Figure 8. Allowable shear stress for non-cohesive soils (from Thibodeaux, 1982)



Key: N_{SPT} = number of blows in a Standard Penetration Test according to ISO 22476-3

Figure 9. Allowable shear stress for cohesive soils (modified from Smerdon & Beaseley, 1959)

Table 5. Typical allowable shear stress for geomats used as TRM (modified from ECTC, 2017)

Product description	Material composition	Slope application maximum gradient	Performance test unvegetated typical shear stress ASTM D6460	Performance test vegetated typical shear stress ASTM D6460
Turf reinforcement mat	A product composed of UV stabilized non-degradable synthetic fibers, filaments, nets, wire mesh and/or other elements, processed into a permanent, threedimensional matrix which may be supplemented with degradable components.	1:1 (H:V)	≥ 96 Pa	≥ 287 Pa
		1:1 (H:V)	≥ 96 Pa	≥ 383 Pa
		0.5:1 (H:V)	≥ 96 Pa	≥ 479 Pa
		0.5:1 (H:V)	≥ 96 Pa	≥ 575 Pa
		0.5:1 (H:V)	≥ 96 Pa	≥ 575 Pa
High performance turf reinforcement mat	A product composed of UV stabilized non-degradable synthetic fibers, filaments, nets, wire mesh and/or other elements, processed into a permanent, threedimensional matrix	0.5:1 (H:V)	≥ 96 Pa	≥ 670 Pa

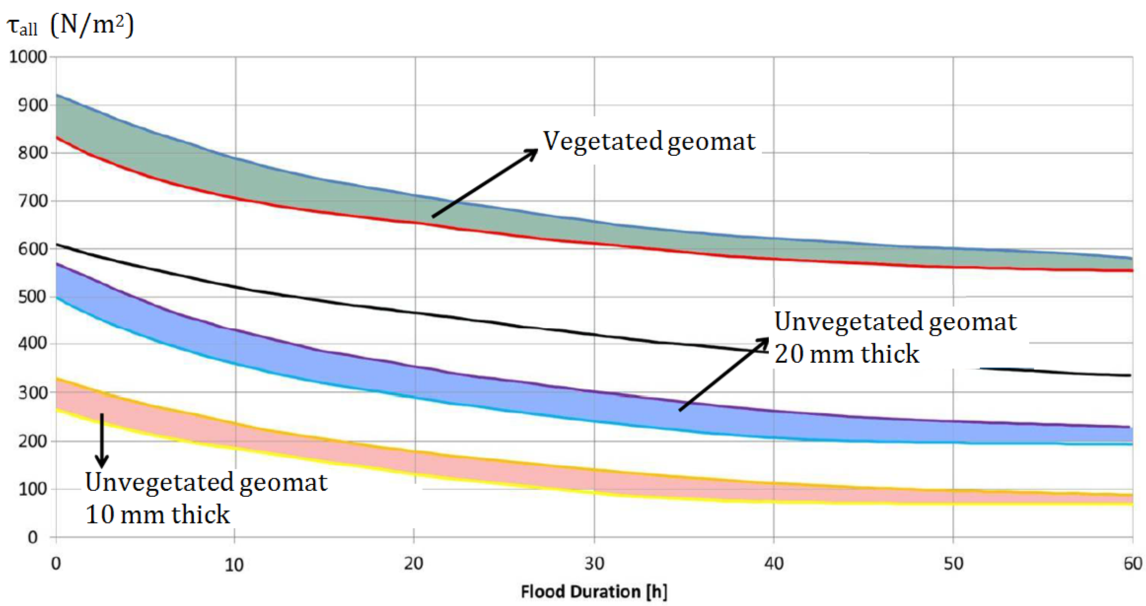


Figure 10. Example of chart of the allowable shear stresses vs flow duration for a family of geomats

4. EXAMPLE

Consider a trapezoidal channel, having bottom width w = 8 m, maximum depth y_{max} = 4.0 m, slope ratio z = 2, bottom slope i = 0.001 m/m, which carries an intermittent design discharge Q = 50 m^3/s for a flow duration of 5 hours.
The channel has a long straight segment, followed by a 45° bend with radius of curvature R_c = 50 m, followed by a long straight segment. Design the erosion protection lining of the side slopes with geomats or reinforced geomats, both in the straight segment and in the bend.

4.1 Preliminary selection of geomats

Let's select a geomat and a reinforced geomat of 10 and 20 mm thickness, and let's define the parameters using Tables 1 and 2 for n and k_s, Fig. 5 for V_{all} (for flow duration of 5 hours), and Fig. 10 for τ_{all} (for flow duration of 5 hours). The resulting parameters are listed in Tab. 6.

Table 6. Design parameters of the selected geomats

Lining type	n	k_s	V_{all} (m/s)	V_{all} / FS (m/s)	τ_{all} (N/m^2)	τ_{all} / FS (N/m^2)
Unvegetated geomat 10 mm thick	0.021	48	1.30	1.00	210	162
Unvegetated geomat 20 mm thick	0.021	48	2.50	1.92	400	308
Unvegetated reinforced geomat 10 mm thick	0.021	48	1.70	1.31	270	208
Unvegetated reinforced geomat 20 mm thick	0.021	48	2.90	2.23	480	169
Vegetated geomat 10 mm thick	0.033	30	4.50	3.46	750	370
Vegetated geomat 20 mm thick	0.033	30	4.50	3.46	750	370
Vegetated reinforced geomat 10 mm thick	0.033	30	5.20	4.00	830	638
Vegetated reinforced geomat 20 mm thick	0.033	30	5.20	4.00	830	638

4.2 Hydraulic calculations

Calculate the normal depth y_n and the water velocity V using Strickler's Eq. (3) or Manning's Eq. (5), and the shear stress τ_∞ with Eq. (11).

For calculating the actual shear stress τ with Eq. (12), let's set:

K1 = 1.90 (bend, from Fig. 6)

K2 = 0.75 (side slopes)

The water level superelevation Δy along the bend is calculated with Eq. (7) and the velocity on side slopes along the bend is calculated with Eq. (8).

Hence we get the results listed in Tab. 7.

Tab. 7. Results of hydraulic calculations

Condition	y (m)	Δy (m)	V (m/s)	τ (N/m^2)
Straight segment, short term (unvegetated)	2.41	0.00	1.65	18.1
Bend, short term (unvegetated)	2.45	0.04	2.19	34.4
Straight segment, long term (vegetated)	3.23	0.00	1.07	24.2
Bend, long term (vegetated)	3.25	0.02	1.42	46.0

It has to be noted that the vegetated condition implies a water depth that is 0.82 m higher than in the unvegetated condition: this clearly shows how much the vegetation can slow down the water flow, thus requiring a larger depth for the section to be able to carry the design discharge.

It has also to be noted that on the external bank along the bend the velocity increases of 32 % compared to the straight segment before the bend.

4.3 Design checks

Let's check the design conditions [9] and [10] both at short and long term:

From the data in Tab. 6 and Tab. 7, it results that the only product that respects all the design conditions, both at short term (unvegetated) and long term (vegetated), is the reinforced geomat 20 mm thick. In this case the most critical condition is the velocity in the bend, and not the shear stress.

As minimum, the geomat shall extend on the slopes up to the maximum water depth plus a freeboard of 0.50 m, hence the covered height h of slopes from the bottom shall be:

straight segment: $h_s = 2.41 + 0.50 = 2.91$ m

bend: $h_b = 3.25 + 0.50 = 3.75$ m

The protection length L_p downstream of the bend, where the geomat shall extend up to h_b, is calculated with Eq. (15); hence, for $n_b = 0.033$ and $R_c = 50$ m, the protection length downstream of the bend is:

$L_p = 0.74 \cdot (R_c^{7/6}) / n_b =$ 2,15 m.

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