Day 7: Design of Stable Slopes at Construction Sites

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Slope Protection Controls Listed in 95 US and International Guidance Manuals

Erosion and Sediment Control Tool	included in % of 95 reviewed US and international manuals
Erosion Control Blanket/Geotextiles	97
Temporary seeding	92
Mulching	91
Permanent Seeding	81
Temporary Slope Drain	75
Surface Roughening	64
Sodding	52
Preserving Natural Vegetation	51
Groundcover Planting	39

Slope Protection Controls Listed in 95 US and International Guidance Manuals (continued)

Erosion and Sediment Control Tool	included in % of 95 reviewed US and international manuals
Land Grading	33
Soil Binders	23
Tree Planting	20
Chemical Stabilization (PAM) land application	19

Slope Diversions


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5


Roughening Slopes while Compacting Ground

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7


Soil roughening and
compaction to protect
slopes (J. Voorhees photos)
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8

Gabions for Slope Protection Retaining Walls

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Slope Protection Using Different Materials

Rock and Asphalt for Shaded Areas

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Mechanical geowebs and other material (even old tires) for biotechnical slope protection (will be planted for slope stability, or interfiled with sand for road)

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Coir Logs with Hydromulch Binder (can also be effectively used with polymers)

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Slope Stability using Slope Benches and
Diversions to Reduce Effective Slope Length

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16

Effectiveness of Mulches at Construction Sites

	number of events X locations per treatment	TSS influent (mg/L) avg	TSS effluent (mg/L) avg	% TSS reduc	Turbidity influent (NTU) avg	Turbidity effluent (NTU) avg	% Turbidity reduc
number	10	5	5	6	7	7	7
average	4.5	6,677	1,855	78	2,990	718	74
min	3	6,537	527	50	2,279	142	41
max	6	6,770	3,320	98	3,530	1,350	96
COV		0.02	0.72	0.24	0.22	0.55	0.23

17

17

PAM Applied Directly to Soil at Construction Sites

	number of events X locations per treatment	TSS influent (mg/L) avg	TSS effluent (mg/L) avg	% TSS reduc	Turbidity influent (NTU) avg	Turbidity effluent (NTU) avg	% Turbidity reduc
number	11	9	9	9	2	2	2
average	4.5	6,589	3,265	51	2,905	2,175	23
min	3	6,537	859	19	2,279	1,950	14
max	6	6,770	5,322	87	3,530	2,400	32
COV		0.01	0.45	0.44	0.30	0.15	0.56

18

18

Effectiveness of Mulches with Polymers at Construction Sites

	number of events X locations per treatment	TSS influent (mg/L) avg	TSS effluent (mg/L) avg	% TSS reduc	Turbidity influent (NTU) avg	Turbidity effluent (NTU) avg	% Turbidity reduc
number	6	3	3	4	4	4	4
average	5	6,770	1,290	86	2,584	271	88
min	4	6,770	750	68	2,279	0	75
max	7	6,770	2,170	100	3,500	570	100
COV		0	0.60	0.15	0.24	0.93	0.12

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19

Slope Stability Applied to Erosion Control

- The basic shear stress calculations can be applied to slopes, using the flow depth of the sheetflow
- Sheetflow flow depth can be calculated using the Manning's equation:

$$y = \left(\frac{qn}{1.49 s^{0.5}} \right)^{\frac{3}{5}}$$

y is the flow depth (in feet),
q is the unit width flow rate (Q/W, the total flow rate, in ft^3/sec, divided by the slope width, in ft.)
n is the sheet flow roughness coefficient for the slope surface, and
s is the slope (as a fraction)

The basic shear stress equation can be used to calculate the maximum shear stress expected on a slope:

$$\tau_o = \gamma y S$$

20

Slope Stability Example

- Design storm peak flow rate (Q) = 2.2 ft^3/sec
- Slope width (W) = 200 ft
- Therefore the unit width peak flow = Q/W = 2.2 ft^3/sec/200 ft = 0.11 ft^2/sec
- Slope roughness (n) = 0.24 (vegetated with dense grass; would be only about 0.055 for an erosion control mat before vegetation establishment, using the established vegetation condition results in deeper water and therefore a worst case shear stress condition).

$$y = \left(\frac{(0.011)0.24}{1.49(0.25)^{0.5}} \right)^{\frac{3}{5}} = 0.033\,ft \qquad \text{(about 0.4 inches)}$$

The corresponding maximum shear stress would therefore be:

$$\tau_o = (62.4)(0.033)(0.25) = 0.51 \ \text{lb/ft}^2$$

- For an ordinary firm loam soil, the Manning's roughness is 0.020 and the allowable shear stress is 0.15 lb/ft2.
- Without a protective mat, the calculated maximum shear stress is substantially greater than the allowable shear stress for the soil.
- The effective shear stress underneath the mat would be:

$$\tau_e = \tau_o (1 - C_f) \left(\frac{n_s}{n} \right)^2 = 0.51(1-0)\left(\frac{0.020}{0.055} \right)^2 = 0.067 \ \text{lb/ft}^2$$

The safety factor would be about 1.5/0.067 = 2.2
Any mat with a Manning's n greater than about 0.037 would be adequate for this example.

Checking Erosion Yield of Protected Slope

- The final erosion control mat selection must be based on the expected erosion rate for the protected slope.

  R = 350 (Birmingham, AL conditions)

  K = 0.28

  LS for slope length of 300 ft and slope of 25% = 10.81

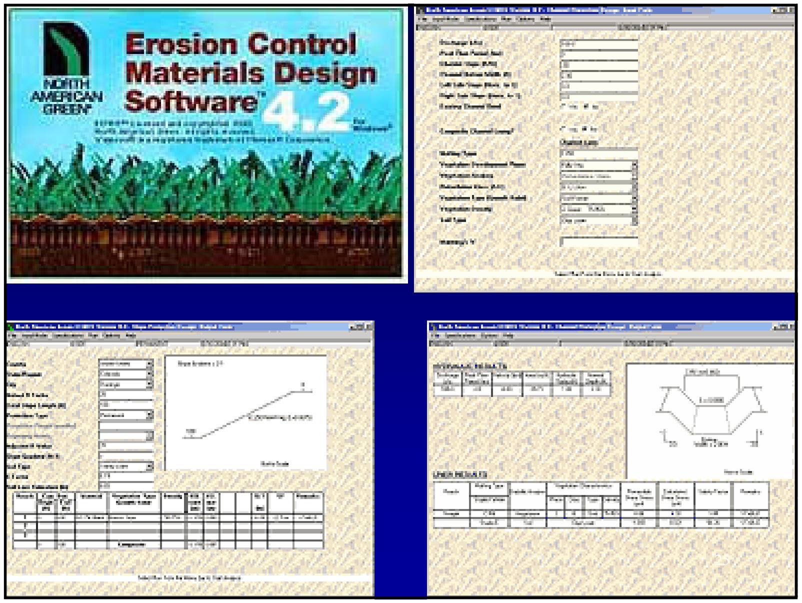
  200 ft by 300 ft slope would have an area of 1.4 acres
- For a bare slope (C = 1):

  Soil loss = (350)(0.28)(10.81)(1) = 1060 tons/acre/yr
- For a protected slope (C = 0.19, and n = 0.055 for a NAG S75 mat):

  Soil loss = (350)(0.28)(10.81)(0.19) = 201 tons/acre/yr

Checking Erosion Yield of Protected Slope (cont.)

- The unprotected bare slope would lose about 6.3 inches of soil per year, while the protected slope would lose about 1.2 inches per year.
- The USDA uses a maximum loss rate of 0.5 inches per year to allow plants to survive. Others have proposed a limit of 0.25 inches per year. This is about 42 tons/acre/year (still about 10X the typical USDA limit for agricultural operations).
- The maximum C value for this slope would therefore be about 0.039, requiring the selection of a more substantial erosion control mat.
- The minimum roughness n for this slope is 0.037, based on the previous shear stress calculations.



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North American Green Conservation Factors for Different Erosion Control Mats, for Different Slopes and Slope Lengths

Slope length and gradient	S75	S150	SC150	C125	S75BN	S150BN	CS150BN	C125BN	C350	P300
Length between 20 and 50 ft (6 to 15 m)										
S ≤ 3:1	0.11	0.06	0.51	0.04	0.11	0.010	0.005	0.003	0.02	0.04
S between 3:1 to 2:1	0.21	0.12	0.79	0.06	0.21	0.07	0.055	0.04	0.03	0.06
S≥ 2:1	0.45	0.17	0.15	0.10	0.45	0.118	0.092	0.06	0.05	0.10
Length ≥ 50 ft (15 m)										
S ≤ 3:1	0.19	0.12	0.10	0.07	0.19	0.02	0.01	0.007	0.04	0.07
S between 3:1 to 2:1	0.30	0.18	0.11	0.09	0.30	0.10	0.08	0.07	0.05	0.09
S≥ 2:1	0.66	0.22	0.19	0.11	0.66	0.15	0.12	0.07	0.06	0.11

26

26

RUSLE Cover Factors (C) for Grasses

Treatment	Mulch rate (tons/acre)	Slope (%)	<6 weeks	1.5 to 6 months	6-12 months
No mulching or seeding	--	all	1.00	1.00	1.00
Seeded grass	none	all	0.70	0.10	0.05
	1	<10	0.20	0.07	0.03
	1.5	<10	0.12	0.05	0.02
	2	<10	0.06	0.05	0.02
	2	11 – 15	0.07	0.05	0.02
	2	16 – 20	0.11	0.05	0.02
	2	22 – 25	0.14	0.05	0.02
	2	26 – 33	0.17	0.05	0.02
	2	34 – 50	0.20	0.05	0.02
Organic and synthetic blankets and composite mats	--	all	0.07	0.07	0.005
Synthetic mats	--	all	0.14	0.14	0.005

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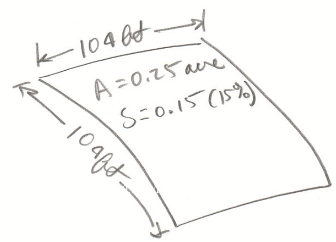
Example Slope Stability Calculation



The total critical flow rate off this hillside was previously calculated to be 1.2 ft3/sec. The Manning's n of the soil (n_s) is 0.05.

$$y = \left(\frac{qn}{1.49s^{0.5}}\right)^{\frac{3}{5}} \qquad y = \left(\frac{(0.012)(0.05)}{1.49(0.15)^{0.5}}\right)^{\frac{3}{5}} = 0.02\ ft = 0.21 in$$

$$\tau_o = \gamma y S \quad = (62.4 \text{ lb/ft2})(0.02 \text{ ft})(0.15) = 0.18 \text{ lb/ft}^2$$

28

The allowable shear stress for the soils on this hillside is only 0.11 lb/ft2, and a vegetated mat will therefore be needed.

The mat needs to have an n of at least:

$$0.18(1-0)\left(\frac{0.05}{n}\right)^2 = 0.11 lb/ft^2$$ Solving for n = 0.067

Using RUSLE:
R = 350/yr
k = 0.28
LS = 2.5 (for 104 ft slope at 15%)
R = (350)(0.28)(2.5) = 245 tons/acre/year
This corresponds to 245 (0.00595) = 1.45 inches per year.
With a maximum allowable erosion loss of 0.25 inches per year, the C factor for the mat must be: 0.25/1.45 = 0.17

29

Many mats that have this C factor for this slope condition (all except S75). In this example, the selection of a mat having an n of 0.067, or greater will be difficult. Most mats are in the range of 0.022 to 0.055. It will therefore be necessary to use filter fences, coir logs, or other methods to provide additional flow resistance to the flow on this slope. Alternatively, the slope length can be shortened with a bench and diversion.

30

Case Study: Erosion Control on Very Steep Slopes, the Millennium Pipeline Project

- The Millennium Pipeline Project consisted of the construction of 182 miles of 30 inch high pressure gas main in the southern tier of New York State just north of the Pennsylvania border.
- This linear construction project was confined to a right-of-way width of approximately 110 feet and disturbed at total area of approximately 2,400 acres. Much of the area was cleared weeks in advance of the actual excavation operations.
- On June 16, 2008 a mudslide from the work area at Peas Eddy, Town of Hancock, Delaware County, closed a town road which was reportedly covered with a mudflow 5 to 6 feet deep.
- The post mortem of the slope failure at this site stated that the mudslide was attributed to excessive spacing of the slope breakers with no exits for water to get off the site right-of-way.

31

31

- the stormwater pollution prevention plan (SWPPP) did not conform to the General Permit requirements, the environmental inspectors did not meet the standards for Qualified Inspectors, over 5 acres of disturbance at one time was occurring without DEC authorization, and the erosion and sediment control standards published by the company did not meet the New York standards and lead to a number of water quality violations.

32

- Based on these violations the project owners received the largest penalty to date for violations under the construction General Permit – approximately 8.4 million dollars.

Peas Eddy slope stabilized with slope breakers and seeding with a double layer of jute mesh over straw mulch over the entire slope face (D. Lake photo)

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33

Case History on Steep Slopes, Lake Bluff Slope Stabilization

- Lake Bluff is located on the southern shore of Lake Ontario, adjacent to Sodus Bay, halfway between Rochester and Syracuse, New York.
- At present, the edge of Lake Bluff is over 80 feet above the lake surface and has been estimated to be receding at an average rate of four feet per year.

34

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- The erosion at the toe of the bluff. A properly designed revetment system was needed to stabilize the toe.
- T he extremely steep slopes created by the toe undermining and the surface weathering had to be stabilized.
- The drumlin soils were classified by the USCS system as SM.
- The groundwater and surface water had to be controlled to prevent saturating the slope and causing sloughs or washing off the fine grained soil.

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A toe revetment was constructed that combined off-shore and on-shore components. The off-shore section was a sloping rock blanket of 3,000 pound stone with a 5 foot wide crest approximately 5 feet above mean water level. The on-shore section was built of stone weighing 2,500 to 3,000 pounds with a 4 foot wide, 4 foot thick berm just below the normal water line and running up the shoreline to an elevation 8 feet higher on the 2 to 1 constructed slope.

36

36

- A compound slope of 2 horizontal to 1 vertical for the lower half and 1.25 horizontal to 1 vertical for the upper half was designed.
- The upper half was later re-designed to a 1:1 slope due to the addition of benches for stability, access, and drainage.
- The sequencing of the construction of this slope was critical. 1) Rough grading was done first, 2) then the drainage, 3) then, from east to west on the slope, finish grading, placing and anchoring jute matting, 4) the prepared section was in-filled with seed and a compost material.

37

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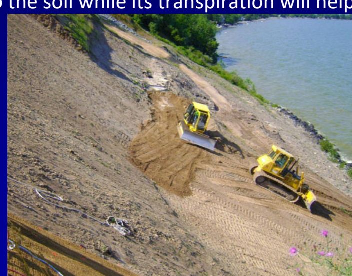
- Groundwater seeps on the face of the slope were controlled by rock slope drains tied to sub-surface outlets, while a trench drain at the top of the slope was constructed to intercept shallow groundwater and capture surface flows and divert them around the slope face to a rock lined waterway.

38

38

- Initial results were very good. The entire slope face germinated a dense seeding. However, in the spring 2010, some surface sloughing did occur as a result of snow pack melt water and additional seeps on the slope. Slope repair commenced as soon as the slope was dry enough for access. Sloughed areas were excavated and stone weep drains were installed. The linear sloughs were re-graded, seeded and mulched with anchor netting placed over the top.
- Further stabilization was provided by placing live willow stakes driven into the damp slope areas. As these root the plants will provide a reinforcement to the soil while its transpiration will help keep the slope drier.



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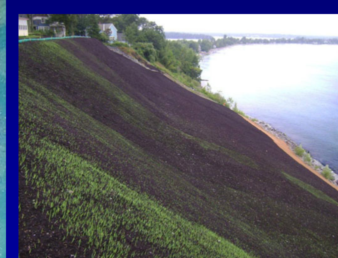
- The sequencing of the slope construction can be seen in this photo.
- Rough grading and drainage installation has been completed with some still evident at the top of the picture.
- Finish grading is occurring in the middle while below that the jute matting is being placed on the slope and anchored.
- The dark area at the bottom of the picture is the seed and compost mix that has been pumped onto the slope



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Slope drain and rill repair on Lake Bluff

Final slope stabilization of Lake Bluff

41

Winter Stabilization

- Enlarge and stabilize access points to provide for snow management and stockpiling. Snow management activities must not destroy or degrade installed erosion and sediment control practices.
- Prepare a snow management plan with adequate storage and control of meltwater, requiring cleared snow to be stored in a manner not affecting ongoing construction activities.
- A minimum 25 foot buffer shall be maintained from all perimeter controls such as silt fences.
- In areas of disturbance that drain to a waterbody within 100 feet, two rows of silt fence need to be installed on the contour.
- Drainage structures must be kept open and free of snow and ice dams.
- Sediment barriers must be installed at all appropriate perimeter and sensitive locations. Silt fence and other practices requiring earth disturbance must be installed ahead of frozen ground.

42

42

- Soil stockpiles must be protected by the use of established vegetation, anchored straw mulch, rolled erosion control product, or other durable covering. A barrier must be installed around the stockpile to prevent soil migration.
- All slopes must be stabilized as soon as practicable but in no case left unprotected for more than 3 days. Rolled erosion control blankets must be used on all slopes 3 horizontal to 1 vertical and steeper.
- If straw mulch alone is to be used for temporary stabilization, it need to be applied at double the standard rate of 2 tons per acre making the application rate 4 tons per acre. Other manufactured products should be applied at double the manufacturer's recommended rate.
- To ensure cover of disturbed soil in advance of a melt event, areas of disturbed soil must be stabilized at the end of each work
- Use stone to stabilize perimeters of building under construction and areas where construction vehicle traffic is anticipated. Stone paths should be a minimum 10 feet in width but wider as necessary to accommodate equipment.

43

43

44

44

Chemical Treatment of Exposed Soils

- Flocculation is the process where a flocculant is used to reduce the turbidity by binding suspended particles in the liquid together to form larger particles.
- The sizes of these flocs are very large, but have low densities. However, their settling rates are much greater than the individual suspended particles and therefore settle.
- Anionic PAM is a non-toxic chemical material that is the most commonly used polymer in the U.S.
- It is used for enhanced control of soil erosion and sedimentation performance on construction sites.
- PAM can be combined with conventional mulching and seeding practices, as part of coir log perimeter barriers, when added to sediment ponds, and as an enhanced soft armoring polymer on bare soil, for enhanced performance.

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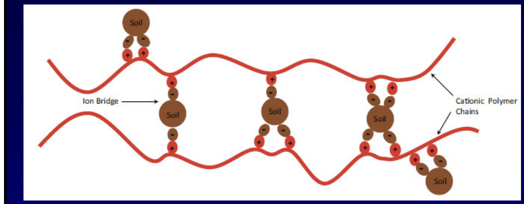
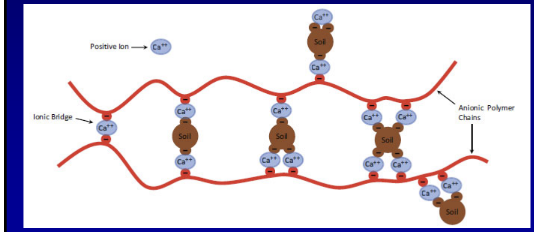


Cationic polymer flocculation (usually toxic to fish and not allowed in most areas)



Anionic polymer flocculation used with an added cation (calcium shown here) to act as bridge to soil

46

46

Examples of polymers directly added to soil, and as part of a hydromulch mixture

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47

Average Turbidities on Fescue Plots over Five Rainfall Events on 4% Slopes (McLaughlin, *et al.* 2006)

	No PAM (NTU and % reduction compared to bare soil, all no PAM)	With PAM (NTU and % reduction compared to bare soil with PAM and compared to bare soil without PAM)
Bare soil	2,279 (n/a)	1,950 (n/a, 14%)
Erosion control blanket	1,350 (41%	570 (71, 75%
Straw	763 (67%)	371 (81, 84%)
Mechanically bonded fiber matrix	349 (85%)	142 (93, 94%)

48

48

Conclusions

- It is critical that a construction site use suitable procedures to prevent erosion on site, instead of relying on sediment removal from the flowing water after erosion occurs.
- Slope protection is critical to reducing erosion at construction sites.
- These techniques must be used, in conjunction with good construction planning, to minimize the amount of land exposed to erosion, and to decrease the amount of sediment erosion produced.

49

Conclusions (continued)

- Anionic PAM is a non-toxic chemical material that is increasingly being used in the US to reduce erosion losses and enhance sediment control at construction sites.
- PAM has been combined with other practices, such as conventional mulching and seeding practices, as part of coir log perimeter barriers, and when added to sediment ponds, and as an enhanced soft armoring polymer on bare soil, for enhanced, but variable, performance.
- PAM works best in areas that contain high amounts of fine silt, clay or colloidal solids, and requires site-specific testing for to determine the optimal dosages.

50