How Steep Is Too Steep?

Design and Construction of Final Cover Systems

What’s Right for Your Site?

Thomas Maier, P.E.
Vulnerabilities of Caps

Airspace vs. Maintenance

Case Studies

- Rain Gutters (4H:1V)
- Tack-On Diversions – Soil Cap (3H:1V)
- Tack-On Diversions – Geosynthetic Cap (3H:1V)
- Cut-In Diversions – Delamination (2.75H:1V)
- Reinforced Cap (2H:1V)

Selection Guidance and Costs
Cap Failures
Remember When...
Ride The Love-Hate Rollercoaster
Airspace vs. Maintenance Costs

- Example 1 - 20 Acre Landfill
  - With 3.5:1 benched slopes, 80 ft high: 1,470,000 CY
  - With 3:1 slopes, 100 ft high: 1,740,000 CY
  - Airspace increase of about 20% (say $3 million revenue over 10 yrs)
  - Would you be willing to spend 10% to 20% of that on maintenance?
Airspace vs. Maintenance Costs

- Example 2 - 100 Acre Landfill
- With 3.5:1 benched slopes, 200 ft high: 16.3 million CY
- With 3:1 slopes, 250 ft high: 19.1 million CY
- Airspace increase of about 20% (say $28 million revenue over 40 yrs)
- Would you be willing to spend 10% to 20% of that on maintenance?

- Actual maintenance costs will vary.
- Factors: waste stream, leachate recirculation, soil type, vegetation type.
Case Study 1: Rain Gutters
Case Study 1: Rain Gutters
Case Study 1: Rain Gutters
Case Study 1: Rain Gutters

**Lessons Learned**

- A cap on 4:1 slopes is very low maintenance.
- Rain gutters are a proven stormwater management method.
Case Study 2: Soil Cap with Tack Ons

SIDE SLOPE DIVERSION BERM

DETAIL
NOT TO SCALE 6 FC1

<table>
<thead>
<tr>
<th>TYPE</th>
<th>MAXIMUM DRAINAGE AREA (AC)</th>
<th>D (FEET)</th>
<th>MINIMUM SLOPE OF FLOW LINE</th>
<th>MAXIMUM SLOPE OF FLOW LINE</th>
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</thead>
<tbody>
<tr>
<td>TYPE 1</td>
<td>1.0</td>
<td>1.5</td>
<td>3.0%</td>
<td>5.0%</td>
</tr>
<tr>
<td>TYPE 2</td>
<td>2.1</td>
<td>2.0</td>
<td>3.0%</td>
<td>5.0%</td>
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</tbody>
</table>

NOTE:
1. REFER TO DRAWING EC3 FOR HEEP/DEEP MATERIALS AND/OR DEEP IN ACCORDANCE WITH THE MANUFACTURER’S INSTRUCTIONS AND DETAIL 1/EC2. THE MORE STRINGENT REQUIREMENTS CONTROL. HM MUST EXTEND UP TO ELEVATION EQUAL TO TOP OF BERM.
2. THE SURFACE ON WHICH THE BERRYS ARE CONSTRUCTED MUST FIRST BE SCARPED TO ENSURE BONDING WITH THE BERM MATERIAL SUCH THAT A SMOOTH INTERFACE IS NOT CREATED. THIS SHOULD BE ACCOMPLISHED BY PLACING THE COMPACTED SOIL CAP BENEATH THE BERRYS TO A THICKNESS OF 24 INCHES SUCH THAT THE TOP 6 INCHES CAN BE SCARPED WITHOUT AFFECTING THE UNDERLYING 18 INCHES OF COMPACTED SOIL CAP.
3. NO PARTICLES LARGER THAN 1/4" ARE ALLOWED ON THE SURFACE OR SIDE SLOPE DIVERGENCE.
## Case Study 2: Soil Cap with Tack Ons

<table>
<thead>
<tr>
<th>Material Name</th>
<th>Color</th>
<th>Unit Weight (lbs/ft³)</th>
<th>Strength Type</th>
<th>Cohesion (psf)</th>
<th>Phi (deg)</th>
<th>Water Surface</th>
<th>Ru</th>
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</thead>
<tbody>
<tr>
<td>Cover Soil</td>
<td></td>
<td>115</td>
<td>Mohr-Coulomb</td>
<td>45</td>
<td>24</td>
<td>None</td>
<td>0</td>
</tr>
<tr>
<td>Soil Cap</td>
<td></td>
<td>115</td>
<td>Mohr-Coulomb</td>
<td>45</td>
<td>24</td>
<td>None</td>
<td>0</td>
</tr>
<tr>
<td>Waste</td>
<td></td>
<td>60</td>
<td>Mohr-Coulomb</td>
<td>500</td>
<td>30</td>
<td>None</td>
<td>0</td>
</tr>
</tbody>
</table>
Case Study 2: Soil Cap with Tack Ons
Case Study 2: Soil Cap with Tack Ons
Case Study 2: Soil Cap with Tack Ons
Case Study 2: Soil Cap with Tack Ons
Lessons Learned

- Site specific soil testing is necessary for steep-sided tack-on berms.
- With tack-on berms built of erodible soil, vegetative stabilization is of utmost importance.
Case Study 3: GM Cap with Tack Ons

MSW Landfill with 3:1 Slopes and No Benches

- Draintube

- Slope Stability
  - Veneer Stability vs. Berm Stability
  - Gas Pressure Uplift
Case Study 3: GM Cap with Tack Ons

Draintube or Geonet Drainage Composite

Distance between pipes:
- 2 m, 1 m, 1/2 m or 1/4 m

Nonwoven filter

Perforated pipe:
- Diameter of 16 mm, 20 mm or 25 mm

Capillary medium
Case Study 3: GM Cap with Tack Ons
Case Study 3: GM Cap with Tack Ons

Soil Thickness vs. Factor of Safety

- 3H:1V Slopes
- Soil Unit Weight = 110 PCF
- Interface Friction = 30 degrees
Gas Pressure vs. Factor of Safety

3H:1V Slopes
Soil Unit Weight = 110 PCF
Interface Friction = 30 degrees
Cohesive = 0 psf
No Seepage, but
LFG uplift pressure varies.
Case Study 3: GM Cap with Tack Ons

1.5:1 SLOPES
CROSS SECTION AREA = 15 FT$^2$

2.0:1 SLOPES
CROSS SECTION AREA = 30.5 FT$^2$
Case Study 3: GM Cap with Tack Ons

1.5:1 SLOPES
CROSS SECTION AREA = 15 FT²

2.5:1 SLOPES
CROSS SECTION AREA = 79.4 FT²
Case Study 3: GM Cap with Tack Ons

Flatter berm slope may reduce the factor of safety against veneer failure.

<table>
<thead>
<tr>
<th>Material Name</th>
<th>Color</th>
<th>Unit Weight (lbs/ft³)</th>
<th>Strength Type</th>
<th>Cohesion (psf)</th>
<th>Phi (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover Soil</td>
<td></td>
<td>110</td>
<td>Mohr-Coulomb</td>
<td>55</td>
<td>20</td>
</tr>
<tr>
<td>Liner</td>
<td></td>
<td>62</td>
<td>Mohr-Coulomb</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>Waste</td>
<td></td>
<td>70</td>
<td>Mohr-Coulomb</td>
<td>500</td>
<td>30</td>
</tr>
</tbody>
</table>
Lessons Learned

- For tack-on berms over a geomembrane, cohesive soil is ideal.
- The effect of some variables on slope stability is not obvious (i.e., flatter berm slopes may result in lower FS).
Progressive Delamination of Drainage Geocomposite During Cover Soil Placement


Figure 2. Placement of sand on the 2:1 slope over geocomposite.
Case Study 4: Delamination

Figure A. Typical Drainage Swale and Final Cover Slopes
Case Study 4: Delamination
Case Study 4: Delamination
Case Study 4: Delamination

- The material was tested and found to comply with specifications.
- The peel strength was 2 to 5 times greater than specified.
Case Study 4: Delamination

**Lessons Learned**

- Specifications that work for 3:1 slopes must be re-evaluated for steeper slopes.
- Drainage geocomposite specifications need to address unbonded geotextile width.
Case Study 5: Reinforced Cover

Diagram:
- 24” MIN.
- DRAINAGE GEOCOMPOSITE
- GEOGRID (AS NECESSARY)
- VEGETATIVE SOIL LAYER
- TURF REINFORCEMENT MATTING
- 40 MIL TEXTURED LLDPE GEOMEMBRANE
- PREPARED SUBGRADE

OPTION 1
Case Study 5: Reinforced Cover
Lessons Learned

- Steep cover systems are possible with the use of reinforcement.
Selection Guide

Slope Height (Feet) vs. Slope Angle (Degrees)

- NO REINFORCEMENT REQUIRED
- REINFORCEMENT REQUIRED ($\phi=32^\circ$, $\delta=30^\circ$)

3:1 and 2.6:1:

- 10 to 15
- 25 to 35
**Selection Guide**

**Graph:**
- **Y-axis (Slope Height, Feet):** 0, 100, 200, 300, 400, 500, 600
- **X-axis (Slope Angle, Degrees):** 10, 15, 20, 25, 30, 35

**Legend:**
- **Light Blue Line:** Tack-on berms feasible on slopes up to 3:1
- **Red Line:** Reinforcement required

**Notes:**
- **Slope Angle (Degrees):** (φ=32°, δ=30°)
Selection Guide

TACK-ON BERMS FEASIBLE ON SLOPES UP TO 3:1

REINFORCEMENT REQUIRED ($\phi=32^\circ$, $\delta=30^\circ$)

CUT-IN SWALES

Slope Height (Feet)

Slope Angle (Degrees)
TACK-ON BERMS FEASIBLE ON SLOPES UP TO 3:1

RAIN GUTTERS

BENCHES (3.5:1 AVG.)

CUT-IN SWALES

REINFORCEMENT REQUIRED
(\(\phi=32^\circ, \delta=30^\circ\))
## Cost Comparison

<table>
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<tr>
<th>Drainage Feature Type</th>
<th>$/LF</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Rain Gutters</td>
<td>$40 to $50</td>
<td>Pipe, Stone, Etc.</td>
</tr>
<tr>
<td>Tack-On Berms (2:1)</td>
<td>$25 to $35</td>
<td>TRM and FGM Included</td>
</tr>
<tr>
<td>Tack-On Berms (1.5:1)</td>
<td>$15 to $25</td>
<td></td>
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</tbody>
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## Cost Comparison

<table>
<thead>
<tr>
<th>Closure System Type</th>
<th>$/AC</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Rain Gutters</td>
<td>$140K - $150K</td>
<td>Costs are inside the anchor trench excluding LFG work.</td>
</tr>
<tr>
<td>Tack-On Berms (2:1)</td>
<td>$130K</td>
<td></td>
</tr>
<tr>
<td>Tack-On Berms (1.5:1)</td>
<td>$120K</td>
<td></td>
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</table>

Costs are approximate and are based on a limited number of recent projects.
Conclusion

- Remember the airspace.
- Embrace the maintenance.
- No one size fits all.
Thank You

Thomas Maier, P.E.

SMITH+GARDNER