For social and economic reasons, Landfills are becoming higher with stiffer slopes

Stability problems linked to composite barriers on slope are increasing

Geosynthetic Lining Systems are a relevant solution as Barriers to confine waste, specifically on slopes where they are easier to lay than mineral layers
Installation of a Geosynthetic Lining System (GLS) on landfill cap cover

Typical Geosynthetic Lining System (GLS) on Cap cover slope

Slope stability assessment is complex due to the multi-components of the geosynthetic liner system. Interfaces properties are required.

Geosynthetic sealing layer (GM)

Concept: ONE geotechnical function ↔ ONE geosynthetic
The stability of GLS on slope only appears to be easy...

Numerous observed failure cases demonstrate that this problem should be studied carefully.
A relevant design considers a Geosynthetic Lining System where every geosynthetic is dedicated to a **UNIQUE FUNCTION**:

- **Geomat** → Erosion control
- **Geomembrane GM** → Sealing
- **Geosynthetic of Reinforcement GTr** → Reinforcement of the veneer soil layer
- **Geospacer** → Drainage

**F-2**

Mechanism of interaction between the different components of the Geosynthetic Lining System

---

**Overall stability problem** for a Geosynthetic Liner System (GLS) on slope

- **Anchorage of geosynthetics at the top edge**
- **Tangential stress at the interfaces**
- **Veneer soil layer**

**Smooth and Textured Geomembranes (HDPE)**
Elementary case of a slopy cap liner: Veneer soil directly on the Geomembrane

- Local tensile mobilisation of the geomembrane due to the different mobilization of frictional stress between upper and lower interfaces

Shear stresses induced by soil cover

Shear Force in the Geomembrane

\[ \Delta T_{up} \]

\[ \Delta T_{down} \]

\[ \Delta T_{GM} = \Delta T_{up} - \Delta T_{down} \]

Tensile force in the Geomembrane

Tensile mobilization in the geomembrane

Limit Equilibrium of a cap cover on slope

A VERY SIMPLE MECHANISM!?}

Block 1

Block 2 (possibly)

Soil base

Tensile force in the Geomembrane

TM

Textured surface on the lower interface decreases \( T_{GM} \)

Textured surface on the upper interface increases \( T_{GM} \)

Reinforcement of the Soil Cover by a basal Geosynthetic (GTr)
To mitigate the tensile force in the Geomembrane GM → a Geotextile of Reinforcement (GTr)

- GM smooth upper interface: $T_{GGM}$ decreases
- GM textured lower interface: $T_{GGM}$ increases → $T_{GM}$ decreases

Due to

- the difficult assessment of interfaces friction
- the influence of field conditions of implementation of the GLS

It’s honest to confess that is impossible in a serviceability state to give an accurate value of the tensile forces mobilized in every geosynthetic of the GLS.

It’s only possible to give an overestimation of these tensile forces, corresponding to the ultimate limit state.

Geosynthetic GTr decreases the friction above the Geomembrane (and $T_{up}$ GM) decreasing the Friction Geomembrane / Cover

Conditions acting upon the Tensile mobilization of the GLS components

- Anchorage stiffness

GLS Anchorage Pull-out Strength
Conditions acting upon the tensile mobilization of the GLS components - Interface friction -

\( (u_{GTr} - u_{GM}) \)

Relative displacement between geosynthetics

Elasto-plastic Interface friction

GLS: Several Interfaces
Soil / Geosynthetic and Geosynthetic/Geosynthetic to test

F-3
Assessment of the interface friction
Two different devices for tests on interface friction

Shear Box
Interface 300 x 300 mm²

Inclined (or Tilting) Plane
Interface 700 x 180 mm²

The Inclined Plane test (IP) is generally preferred to the Shear Box (SB) test for this application.

Normal stress for the IP device  \( \sigma < 10 \text{kPa} \)

Inclined Plane test on multi-layers barrier

Actual thickness of cover soil + Actual GLS structure can be used in laboratory

Inclined Plane test on multi-layers barrier
Inclined plane device at LTHE laboratory

Control of β rate

Upper box

Friction test on inter fuse Geosynthetic/Geosynthetic

Parameters deduced from an IP test

The careful analysis of the IP diagrams is capable of providing far more information than the friction angle \( \beta_{50} \).

European standard \( \beta_{50} \) ≤ \( \beta_{50} \)

Gradual sliding

Correlations between data resulting of S.B. and I.P. tests should be deepened

Relation with \( \phi'_{pp} \) and \( \psi_{gg} \)?
Typical values of the interface friction angle

<table>
<thead>
<tr>
<th>Interface</th>
<th>angle de frottement en [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>geosynthétique/sol</td>
<td>23-34</td>
</tr>
<tr>
<td>géomembrane PEHD / fuseau / sol</td>
<td>18-26</td>
</tr>
<tr>
<td>PVC/fuseau</td>
<td>20-28</td>
</tr>
<tr>
<td>géotextiles non-tissés/fuseau</td>
<td>21-20</td>
</tr>
<tr>
<td>géomembrane PEHD / fuseau / angle</td>
<td>8-16</td>
</tr>
<tr>
<td>PVC/angle</td>
<td>13-20</td>
</tr>
<tr>
<td>géotextiles non-tissés/angle</td>
<td>14-22</td>
</tr>
<tr>
<td>géosynthétique géosynthétique</td>
<td>0-16</td>
</tr>
<tr>
<td>géotextiles non-tissés/PEHD</td>
<td>12-18</td>
</tr>
<tr>
<td>géomembrane PEHD / fuseau / géosynthétique</td>
<td>8-10</td>
</tr>
<tr>
<td>géotextiles non-tissés/geosynthétique</td>
<td>10-16</td>
</tr>
</tbody>
</table>

Anchorage corresponds to the max. Tensile Force in the Geosynthetics.

Anchorage of Geosynthetic Lining Systems

Anchorage of geosynthetics at the top edge

Tangential stress at the interfaces

Veneer soil layer
Anchorage trench for geosynthetic Lining System

Different shapes for the Anchorage of Geosynthetic Lining Systems

Laboratory tests about pull-out strength of the anchorage

Conventional rough design method for evaluation of the Anchor strength

Anchorage capacity

$T = T_{A1} + T_{A2} + T_{A3}$

Effect of the angles on the anchorage strength is assumed negligible:

No "Pulley" effect
Alteration of the tensile force at the Anchorage Bend - « Mechanism of Frictional Pulley »

Multi-anchorage process for GLS on slope with berms

Multiplier effect on the Tensile Force

\[ T = T' \times \tan \beta \]

Sketch of the intermediate anchorage of the GLS for long slopes

F-5 Geospacers & drainage on slope
Different kind of Geospacers

Recycled Polymers used as a Drainage Geocomposite

Improvement of collected water due to rainfall: intermediate collector pipe

Significance of a correct design of the Geosparcer
Influence of hydraulic pressure on the activating of a soil layer sliding
Correct design of the Geospacer

No hydraulic pressure in the veneer soil layer

(Unmodified: Giroud, 2006)

Influence of a partial saturation of the veneer soil layer on its stability

\[ \gamma_1 = 20 \text{ kN/m}^3 \]

(1) Interface soil/soil: \( c' = 3 \text{ kPa} \)

(2) Interface geosynthetic/soil: \( c' = 0 \)

\( \theta = 25^\circ \)

\( \gamma' = 20 \text{ kN/m}^3 \)

Slope \( \beta = 20^\circ \)

Depth of the sliding interface (Interface geosynthetic/soil): \( z = 0.8 \text{ m} \)

Two conditions of drainage are considered:

- Drainage of the run-off water (perfect drain) \( (z_w = z) \)
- Water until a depth 0.4 m (saturated drain) \( (z_w = 0.4 \text{ m}) \)

Stability Chart for Stability of Infinite Slope

GS: Geospacer

GM: Geomembrane

\[ \phi = 28^\circ \]

\[ f_{g_s} = 25^\circ \]

\[ f' = 28^\circ \]

\[ \gamma = 20 \text{ kN/m}^3 \]

\( h_{g_s} = 20 \text{ kN/m}^3 \)

(1) Interface soil/soil: \( c' = 3 \text{ kPa} \)

(2) Interface geosynthetic/soil: \( c' = 0 \)

\[ \theta = 25^\circ \]

\[ \gamma' = 20 \text{ kN/m}^3 \]

Slope \( \beta = 20^\circ \)

Depth of the sliding interface (Interface geosynthetic/soil): \( z = 0.8 \text{ m} \)

Two conditions of drainage are considered:

- Drainage of the run-off water (perfect drain) \( (z_w = z) \)
- Water until a depth 0.4 m (saturated drain) \( (z_w = 0.4 \text{ m}) \)
\[ F = \frac{c}{(g \sin b \cos b)} + [(g'/g) + (g_w z_w/g)] \cdot (\tan f / \tan b) \]

\[ z_w = 0.8 \text{ m} \rightarrow v_r = 0 \quad \text{et} \quad A = 1 \quad F = 2.04 \quad \text{(H1)} \quad 1.28 \quad \text{(H2)} \quad \text{[perfect drain-unsaturated]} \]

\[ z_w = 0.4 \text{ m} \rightarrow v_r = 0.24 \quad \text{et} \quad A = 0.75 \quad F = 1.68 \quad \text{(H1)} \quad 0.86 \quad \text{(H2)} \quad \text{[saturated drain, water table 0.4m]} \]

\[ \text{Slope at the interface soil-geosynthetic}(z_w = 0.4 \text{m}) \quad \text{excepted in case of efficient GTr} \]

**Value of the Safety Factor F from Chart**

\[ \text{(Formula)} \]

**F-6**

**Cap cover**

**Steepening of Slopes**

**Neydens'Landfill Site,**

**REINFORCED LANDFILL (Neydens'landfill)**
REINFORCED LANDFILL (Neydens'landfill)

BABYLON LANDFILL

The Hanging Gardens of Babylon

MULTIPLE REINFORCED-SOIL STRUCTURE

STEEP FACE WITH GRASS
Geogrid Reinforcement Arrangement

Babylon Landfill, New York
LANDFILL BEHIND REINFORCED-SOIL EMBANKMENT