Soil-geosynthetic interaction: Obtaining strength parameters for design

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- Importance of interface shear behaviour
- Methods of measurement
- Factors influencing interface behaviour
- Which parameters should be used in design?
- Variability of measured behaviour
- Obtaining interface shear strength parameters for design
- What are the implications of variability on design?
- Summary and the future
The presentation will not cover….

- Interaction between grids and soil
- Pull out testing
- Specific issues related to testing GCLs
- And lots of other things……
- Experience of audience?
Importance of interface shear behaviour
Interface shear strength

• Why is knowledge of interface strength important?
  ➢ Geosynthetics introduce a potential weak plane
  ➢ Overall stability is controlled by shear strength developed between geosynthetic/geosynthetic and geosynthetic/soil
  ➢ Integrity of the geosynthetic is controlled by shear strength either side
Stability and integrity

• Stability
  - Ultimate limit state
  - Complete loss of stability
  - “Large” scale movement

• Integrity
  - Serviceability limit state
  - Loss of function (e.g. overstressing, tearing, increased permeability etc.)
  - “Small” scale movement
Design issues: Stability, unconfined
Interface shear strength

- For a soil:
  \[ \tau = c' + \sigma_n' \cdot \tan \phi' \]
  where \( c' \) and \( \phi' \) are the shear strength parameters, the cohesion intercept and the friction angle

- For a geosynthetic:
  \[ \tau = \alpha' + \sigma_n' \cdot \tan \delta' \]
  where \( \alpha' \) and \( \delta' \) are the interface shear strength parameters, the cohesion intercept and the friction angle
Peak and residual shear strength

- Peak shear strength
- Residual (or large strain) shear strength
Peak and residual shear strength

Shear Stress (kPa)

Normal Stress (kPa)

Peak Shear Strength Envelope

Residual Shear Strength Envelope

\( \alpha_p \)

\( \delta_p \)

\( \delta_r \)
Methods of measurement
Factors influencing interface strength

- Material properties: Geosynthetic and soil
- Testing apparatus design and size
- Normal stress
- Shearing rate
- Geosynthetic attachment
- Moisture conditions
- Drainage conditions
- Temperature…….
Common interface shear behaviour (after Marr 2001)
Measurement: Direct shear

- Small boxes 60x60mm$^2$ and 100x100mm$^2$ (index testing and possibly acceptable for some interfaces)
- Large boxes 300x300mm$^2$ and 300x400mm$^2$ (performance testing, most commonly used)
- Full range of normal stresses (e.g. 5kPa to +400kPa)
- Granular soils and large geosynthetic samples can be accommodated
- Easy to use but limited displacements
- Wide range of designs (influences measured behaviour)
Direct shear apparatus (DSA)
Direct shear apparatus
(modified soil mechanics device: top box rotates)
Direct shear apparatus
(designed for geosynthetics: fixed top box)
Direct shear apparatus
(designed for geosynthetics: fixed top box)

Soil free to move in top box (!)

Top box fully fixed

Low normal stress system
Direct shear apparatus
(for geosynthetics: vertically moveable top box)

Top box can move vertically during shearing

Linear bearings to ensure no rotation of top box
Variation in normal stress

![Graph showing variation in normal stress and shear stress](image-url)
DSA results: Smooth geomembrane vs. geotextile

Shear stress (kPa) vs. Displacement (mm) for different pressures:
- 200 kPa
- 100 kPa
- 25 kPa
DSA results: Textured geomembrane vs. geotextile

Displacements (mm)

Shear Stress (kPa)

0 20 40 60 80 100

0 20 40 60 80 100

25 kPa

100 kPa

200 kPa
Measurement: Tilting table apparatus

- No consensus of opinion as to what size should be used (*box length is important*)
- Only peak friction angle measured
- No shear stress/displacement information
- No residual friction angle
- Limited use (low normal stresses only)
- Relevant for veneer type problems
Tilting table apparatus

(Gourc et al. 2006)
Tilting table apparatus
Tilting table results

(Gourc et al. 2006)
Ring shear apparatus (RSA)
Measurement: Ring shear apparatus

- Unlimited displacement - true residual shear strengths
- Full stress range can be accommodated
- Direction of shearing not comparable to field
- Peak shear strengths not reliable
- Cannot use granular materials or large geosynthetics
Bromhead ring shear apparatus

Rotational shear between upper and lower annular samples of geosynthetic

Matched proving rings
Residual strength measured using RSA

Shear Stress (kPa) vs. Displacement (mm)
Residual shear strength: Comparison of DSA and RSA test methods

- Peak strength
- Residual strength from DSA
- Residual strength from RSA
Factors influencing interface behaviour
Test standards

- ASTM D5321.08 - Performance testing for soil vs. geosynthetic and geosynthetic vs. geosynthetic interfaces (*comprehensive guidance*)

- BS 6906:1991 – Covers mainly index tests for sand and geosynthetic interfaces (*out of date*)

- BS EN ISO 12957-1:2005 - Index tests only for sand vs. geosynthetic (*no use for design*)

- GDA E3-8 is specifically devoted to landfill design (*only in German*)

- A comparison of specifications is provided in Dixon (2010)
Key factors influencing measured behaviour

• Design of direct shear device.

• Test set up (e.g. method of clamping/restraining the geosynthetic, gap size between top and bottom boxes, dry or submerged conditions, material in top box used to transmit normal stress to interface, shearing rate, temperature, normal stress range.)

• Variability of materials, direction of shearing, number of tests.

• SOIL MECHANICS! (density, maximum particle size, consolidation, drained or undrained shearing, pore water pressures, volume changes.)
Textured geomembrane vs. geotextile: Dry tests

![Graph comparing shear stress vs. displacement for textured geomembrane and geotextile. The graph shows a peak in shear stress as displacement increases, with different curves indicating varying levels of stress.]
Textured geomembrane vs. geotextile: Dry and Submerged Tests
Smooth geomembrane vs. geotextile: Dry tests
Smooth geomembrane vs. geotextile: Dry and submerged tests

![Graph showing shear stress vs. displacement for dry and submerged tests.](image-url)
Influence of cover soil on measured geotextile vs. drainage core shear strength

![Graph showing shear stress vs. displacement with Normal stress 51 kPa and Nylon block]
Influence of cover soil on measured geotextile vs. drainage core shear strength

Shear Stress (kPa)

Displacement (mm)

Normal stress 51 kPa

Sand

Nylon block
Influence of cover soil on measured geotextile vs. drainage core shear strength

![Graph showing the influence of cover soil on measured geotextile vs. drainage core shear strength.](image-url)
Measurement of internal interface shear strength of a geocomposite material

Cuspated rigid central core clamped to bottom box

Heat bonded geotextile glued to central core and clamped to top box
Measurement of internal interface shear strength of a geocomposite material

Loss in strength due to failure of glued connection

Displacement (mm)

Shear Stress (kPa)

$\sigma_n = 51$ kPa

$\sigma_n = 26$ kPa

$\sigma_n = 10$ kPa
Geotextile vs. glued core: Peak and residual strength envelopes

Strength parameters

Peak
\( \alpha_p = 38 \text{ kPa} \)
\( \delta_p = 14^\circ \)

Residual
\( \alpha_r = 5 \text{ kPa} \)
\( \delta_r = 23^\circ \)
Peak and residual best fit straight line failure envelopes
Peak strength best fit second order polynomial

![Graph showing peak strength fitted with a second-order polynomial. The graph plots normal stress against shear stress, with normal stress ranging from 0 to 200 kPa on the x-axis and shear stress ranging from 0 to 200 kPa on the y-axis. The graph displays two sets of data points connected by lines, one in red and the other in yellow, showing the trend of shear stress with respect to normal stress.](image-url)
Peak strength extrapolation from height to low normal stresses

Inappropriate use of tests at high normal stresses for a low normal stress problem e.g. cover design
Should adhesion ($\alpha$) values be used (1)?

The following conditions can produce an ‘adhesion’ value:

- An interface with a shear strength at zero normal stress e.g. textured geomembrane/non-woven geotextile (use the $\alpha$ value in design)

- A best fit straight line through data forming a curved failure envelope (use the $\alpha$ value in design if the tests were carried out over an appropriate normal stress range)
Should adhesion ($\alpha$) values be used (2) ?

- Incorrect measurement of shear strength resulting from the design and/or operation of the test equipment e.g. fixed top box

- Best fit straight line located through a limited number of data points with scatter about the mean value for each normal stress (use $\alpha$ values in design with care)
Which parameters should be used in design? (peak, residual or somewhere in between)
Mechanisms resulting in post-peak reductions in strength (1)

- Wear of geosynthetic/geosynthetic interfaces
  - Combing of fibres destroying Velcro® effect
  - Polishing of surfaces and reduction/removal of asperities (roughening and ploughing of the surface can result in increased interface strength)

- Soil/geosynthetic interfaces can also suffer from the above mechanisms of wear, plus the following:
  - Dilatency of soil in the shear zone
  - Realignment of clay particles parallel to the interface
Mechanisms resulting in post-peak reductions in strength (2)

- Loss of internal shear strength in geocomposites and GCL
  - Failure of needle punched fibres, stitching and glued connections
- All these mechanisms require relative shear displacement of the two materials forming the interface
- Changes that occur with no relative displacement may result in changes to both peak and residual strengths
  - Changes in soil density and moisture content
  - Extrusion of bentonite from a GCL
  - Temperature change
Mobilising post-peak strengths

- Construction related:
  - Dragging geosynthetics to position them
  - Construction plant loads during placement of veneer soil layers on slopes
  - Compaction of fine grained soils above geosynthetics
  - Improper storage and handling

- Landfill operation related:
  - Placement of waste on side slopes (same as soil veneers)
  - Settlement of waste adjacent to interface
  - Differential settlement of sub-grade
Use peak or residual strength?

The answer is site specific:

- Consider all possible mechanisms and fully justify the approach taken
- Relate the selected parameters to the factor of safety required
- Consider both stability and integrity
- Even if global instability does not occur it is possible to have large relative displacements between lining components (integrity failure) which could lead to loss of continuity and hence function (protection, drainage)
Development of post peak shear strength: Veneer slope
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Development of post peak shear strength: Veneer slope
Waste settlement generated post peak interface strengths (Jones 1999)

Back slope = 1:3
Base length = 100m
Height = 30m
Base thickness = 3m
Front width = 3m
Waste slope 1:3

Note the large interface displacement
Maximum settlement ~ 6 m

Maximum settlement ~ 6 m
Variability of measured behaviour
Uncertainty of test results!

Results from German inter laboratory comparison tests on non-woven geotextile vs. sand interface (Blumel and Stoewahse 1998)
German direct shear Inter-comparison tests

Shear Stress (kPa)

Normal Stress (kPa)

1995
1996
European inter-comparison shear tests: Sand vs. non-woven geotextile

Each test was carried out at a different laboratory (normal stress = 100 kPa)

(Gourc 1997)
European inter-comparison shear tests: Sand vs. geotextile peak strength

Each failure envelope was obtained by a different laboratory

(Gourc 1997)
Comparison of Different Shear Device Designs: Geomembrane vs. Geotextile
Peak Strength (Blumel et al. 2000)

![Graph showing the comparison of different shear device designs: Geomembrane vs. GeotextilePeak Strength (Blumel et al. 2000). The graph plots normal stress against shear stress, with various conditions such as fixed top box (LU), fixed top box (HU), normal stress controlled, and vertically free. The graph includes data points and lines representing different conditions.](image-url)
Repeatability shear tests for one DSA and operator: Geotextile vs. sand

(Stoewahse 2001)
Variability from repeatability tests

- Inter-laboratory comparison test 1995
- Inter-laboratory comparison test 1996
- Hanover University, repeatability tests
- Loughborough University, repeatability tests

Graph showing coefficient of variation [%] vs. σ [kPa] for interface geotextile vs. geomembrane.
Smooth geomembrane vs. geotextile: Repeatability tests

\( \sigma_n = 10 \text{ kPa} \)

\( \sigma_n = 20 \text{ kPa} \)

\( \sigma_n = 30 \text{ kPa} \)
Smooth geomembrane vs. geotextile: Repeatability tests

![Graph showing the relationship between normal stress and shear stress with mean and 95% confidence limit lines.](image-url)
Smooth geomembrane vs. geotextile: Repeatability tests

Possible best fit lines through three random data points
Smooth geomembrane vs. geotextile: Repeatability tests

Possible best fit lines through three random data points
Variability of gravel/non-woven geotextile interface: Data base and repeatability values
Variability of gravel/non-woven geotextile interface: Data base and repeatability values

Graph showing the relationship between Normal stress, $\sigma_n$ (kPa), and $\tau_p$ (kPa) for different gravel-NW geotextile samples (G1, G2, G3, G4). The graph includes data points from Global, Interlab, and Repeatability sources.
Significance of variability

• Mean value of shear strengths from data base and repeatability may be similar, giving similar factors of safety, BUT uncertainty and hence probability of failure is completely different

• Final design must always be based on strengths from performance tests (i.e. using site specific materials and boundary conditions)

• Only use data bases of interface shear strength to inform assessment of measured values
Obtaining interface shear strength parameters for use in design
Characteristic values for use in design

“A cautious estimate of the value affecting the occurrence of the limit state.”

Eurocode 7 (1997)
Analysis to obtain characteristic strength parameters
Statistical approach

\[ X_k = X_m - 0.5 \sigma_m \]

Where:
- \( X_k \) is characteristic value
- \( X_m \) is mean value of test results
- \( \sigma_m \) is standard deviation of test results
How many tests should be conducted?

One test at each normal stress is not enough!
Selection of characteristic values

- Generation of site specific statistical data
- Lower bound of limited repeatability data
- Method based on statistical data from published studies
Generation of site specific statistical values

Carry out a minimum of 4 No. tests at each normal stress
Are the measured strengths mean values?

Make an assessment based on experience of Engineer and personal judgement backed by published data

If in doubt, use conservative lower bound values or do more tests.
What are the implications of variability in measured values on design?
Probability of failure: LE analysis

• First order, second moment reliability based method - i.e. using mean and standard deviation of parameters (Duncan 2000)

• Two cases considered:
  - Veneer
  - Waste slope
## What is an acceptable $P_{ft}$?

<table>
<thead>
<tr>
<th>Qualitative</th>
<th>Quantitative</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HIGH</strong> (permanent base liner slopes)</td>
<td><strong>Degree of damage</strong> (Cole, 1980)</td>
</tr>
<tr>
<td><strong>LOW</strong> (cover &amp; veneer slope as infinite)</td>
<td><strong>Actual failure rates</strong> (Baecher, 1987)</td>
</tr>
<tr>
<td><strong>MODERATE</strong> (temporary base liner slope, cover &amp; veneer slope with buttress and reinforcement)</td>
<td><strong>Existing structures</strong> (Phoon et al., 1995)</td>
</tr>
<tr>
<td><strong>HIGH</strong> (permanent base liner slopes)</td>
<td><strong>Function</strong> (Koerner &amp; Koerner, 2001)</td>
</tr>
<tr>
<td><strong>LOW</strong></td>
<td><strong>Cost</strong> (Gilbert, 2001)</td>
</tr>
</tbody>
</table>

- **Target probability of failure, $P_{ft}$**

- **Qualitative**
  - Performance level (USACE, 1997)
  - Risk (Gilbert, 2001)

- **Quantitative**
  - Degree of damage (Cole, 1980)
  - Actual failure rates (Baecher, 1987)
  - Existing structures (Phoon et al., 1995)
  - Function (Koerner & Koerner, 2001)

- **Cost** (Gilbert, 2001)
What is an acceptable $P_{ft}$?

- Selection of $P_{ft}$ for veneer cover design based on minor repairs (Cole, 1980), moderate risk (Gilbert, 2001) and below to above average performance level (USACE, 1997).

$P_{ft}$ estimated in the range of $10^{-3}$ to $10^{-2}$, between mine slopes & foundations.

Assume $P_{f}=1\times10^{-2}$ (Baecher, 1987)
Implication of $P_f$ approach: Veneer

- Interface shear strength from global database yield much higher $P_f$ although the FS for both data sets are similar.

- Two methods of reaching accept. $P_{ft}=1 \times 10^{-2}$:

  1) **Reduce the variation** ($V_{strength}$) via further tests.

  2) **Increase FS**, (e.g. changing to higher interface shear strength material - increase of cost)

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### Diagram

- **GLOBAL DATABASE**
  - $\sigma_n=20\text{kPa}$
  - $V_{stress}=0.1$  
  - FS = 1.5

- **REPEATABILITY DATA**
  - $8.5 \times 10^{-11}$
  - $0.00$
  - $0.024$
  - $0.03$
  - $0.04$

- **Acceptable $P_f$ (assumed)**
  - $0.052$
  - $0.024$

- **Points**
  - $1$: FS = 1.9
  - $2$: FS = 2.2
Reliability-based design chart for target FS of 1.5 and $P_f$ of $1 \times 10^{-2}$

Note:
FS=1.5, $P_f=0.01$
H=30m, h=1m, $\phi=30^\circ$, c=0, $\gamma_d=18kN/m^3$

$V[\alpha]=10\%$, $V[\delta]$ varies
$V[\alpha]=20\%$, $V[\delta]$ varies
$V[\alpha]=40\%$, $V[\delta]$ varies

Example 6.3

Sia and Dixon (2008)
Implication of $P_f$ approach: Waste slope

Interfaces analysed
- Textured geomembrane vs. non-woven geotextile
- Non-woven geotextile vs. coarse soil

General database values used

Dixon et al. (2006)
Probability of failure vs. factor of safety for waste body stability, showing the relationship between the mean and characteristic values for factor of safety, based on combined data.

Dixon et al. (2006)
Reliability of landfill LE analysis

• Current design practice uses target Factor of Safety in LE analysis (e.g. 1.5) based on ‘conservative’ estimates of interface strengths
  - Engineering judgement - common
  - Statistical derivation – rare

• Benefits of obtaining statistical data:
  - Quantitative analysis of design reliability
  - Justification of costs for site specific testing
## Probability vs. consequences of failure

<table>
<thead>
<tr>
<th>Probability</th>
<th>0.3%</th>
<th>0.05%</th>
<th>0.01%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consequences</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Examples</td>
<td>Veneer</td>
<td>Capping</td>
<td>Waste body</td>
</tr>
<tr>
<td></td>
<td>side slope</td>
<td></td>
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</tbody>
</table>

(After Koerner & Koerner 2001)

- Waste slippage in this study $P_f >> 0.01\%$ even with Factor of Safety = 1.8
- Discussion required between regulators, owners and designers to define acceptable values of $P_f$
Probabilistic analysis of waste settlement induced stresses in liner (Sia and Dixon)
Factors included in analyses

• Statistical variability of:
  ➢ Interface shear behaviour (strength and stiffness)
  ➢ Waste engineering properties (unit weight and stiffness)
  ➢ Geosynthetic tensile elastic moduli

• Waste placed in 6 lifts, 5 metres each

• Ranges of slope angle and waste stiffness

• Short term construction condition only (i.e. no waste degradation)
Multiple FLAC analyses

- Probability distributions and ranges are assigned to input parameters (i.e. normal, uniform etc) to assess all possible measured values
- Monte Carlo simulations involve random sampling of parameters from the probability distributions to assess possible combinations of values
- Minimum of 250 FLAC analyses of staged construction for each design case
Strain in liner

Interface 3:
TGM-FINE S
Side slope

Unpublished work of Sia and Dixon

Movement of liner!
Objective of current research (Zamara, LU/Golder Associates)

Conduct site experiment to monitor a side slope lining system during and post waste placement with a range of instrumentation in order to validate current industry numerical models (Zamara et al. 2010)
Summary and future
Specification of testing

• Request information on the type of direct shear device to be used (e.g. fixity of top box, method used to apply normal stress)

• Consider the test set up in detail (e.g. geosynthetic restraint, gap size between top and bottom boxes)

• Consider in full the desired properties of the soils involved in the test (e.g. density) and likely behaviour (e.g. drained/undrained)

• Select the interface and direction of shearing, the number of tests, the normal stress range, dry or submerged and rate of shearing
Obtaining strength parameters for design

- Strength and deformability properties control stability and integrity
- At present index tests predominate but these are of limited use in design
- **Performance tests** using site specific materials and boundary conditions must be carried out to provide engineering properties for use in design
- Investigations often show that a dearth of site specific interface shear strength data contributed to failure
General good practice

• Tests should be specified and interpreted by experienced **geotechnical engineers**

• Conservative estimates (**characteristic values**) of shear strength are required (i.e. do not use measured values directly in design)

• In some cases low values are unconservative (e.g. when used to assess tensile forces in geosynthetic members)

• Design using **combined criteria** for factor of safety and probability of failure
The future....

• Improved test specifications (enforcement of existing!)
• Better awareness and skills to specify tests
• More performance testing
• Rigorous determination of characteristic, and hence design, values
• Use of reliability based approaches to support design
• Engineering interfaces for specific applications......
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