Soil nail testing

Chris Bridges
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>01</td>
</tr>
<tr>
<td>Soil nail testing</td>
<td>02</td>
</tr>
<tr>
<td>What are some of the issues with soil nail testing?</td>
<td>03</td>
</tr>
<tr>
<td>Conclusions</td>
<td>04</td>
</tr>
</tbody>
</table>
Introduction
Soil Nail – Main Components

Soil nail head plate (galvanised for corrosion protection)

HDPE Sheath (for corrosion protection)

External centraliser

Internal centraliser

Outer grout tube

Inner grout tube

Domed soil nail nut (galvanised for corrosion protection)

32mm diameter deformed soil nail bar (galvanised for corrosion protection)

Note: Other systems may use flexible facing and/or may not use grout, impermeable duct or couplers
Construction Sequence

1. Excavation of appropriate lift height
2. Drilling nail hole
3. Installation of nail, mesh and fixing assemblies
4. Application of sprayed concrete facing
5. Excavation of next lift
Applications

• construction of new slopes and retaining walls
• construction of temporary works
• upgrading existing slopes with inadequate stability
• the renovation of old retaining structures
Soil Nail Walls are not such a great idea in water charged sands and silts. (They also can’t be expected to have a 2 weeks stand up time)

Suitability

Soils that are self supporting soil for a short period, over typical excavated depths of 1.0m to 1.2m

- Stiff or better clays
- Cemented sands
- Weathered rock
- Dry
Soil nailing and ground anchors

Soil nails

Ground anchors

Passive Zone

Active Zone

Free Zone

Piled Wall

Anchor Zone

Bond length

Free length
Modes of failure

External Stability

(a) Overall Stability Failure
(b) Sliding Failure
(c) Bearing Failure

(d) Tensile Failure of Soil Nails
(e) Pullout Failure at Ground-grout Interface (or Grout-reinforcement Interface)
(f) Bending or Shear Failure of Soil Nails

Internal Stability

(g) Structural Failure and Connection Failure of Soil-nail Head
(h) Structural Failure and Connection Failure of Facing
Anchor & Soil Nail failure - internal

Ground Anchors

Soil Nails

Potential failure surface

Breakage

Pullout
Soil/grout interface
Bar/grout interface
### Wall or slope stabilisation with hard facing

#### Major components of load transfer
- Bond capacity in the resistant zone (A)
- Plate bearing capacity to transfer load from facing structure (B)
- Strength of facing structures to retain active soil (B)

#### Minor components of load transfer
- Bond capacity in the active zone (C)
- Plate bearing capacity to supplement bond capacity of the active zone

### Slope stabilisation with flexible facing

#### Major components of load transfer
- Bond capacity in the resistant zone (A)
- Bond capacity in the active zone (D)
- Surface soil retention by flexible facing (E)

#### Minor components of load transfer
- Bond capacity in the hard facing structure
Design codes and standards

AS4678-2002 Earth Retaining Structures (VicRoads)

BS8006:1995 - Strengthened/ reinforced soils and other fills (QLD TMR)

BS8006:2011-2 - Strengthened/ reinforced soils and other fills (QLD TMR)

FHWA Geotechnical Engineering Circular No. 7 – Soil nail walls (2003/2015)


Traditional FOS approach – 1.5 on global, reduction factor of bond 1.5-2
Preliminary Sizing

Typical nail spacing, walls – 1m - 2m (1 nail per 1m²-4m² of face)
Typical lifts - 1.2m
Length of Nails - 0.8 - 1.2H

It is recommended that the soil nail length outside the anticipated failure surface should not exceed 5m, and bar diameters should be greater than 20mm (CIRIA). GRP should not exceed 3m.

Note: in soils nail lengths above 15m maybe difficult to achieve due to hole collapse.
Soil nail testing
Soil nail testing

The primary method of testing soil nails *in situ* is by pulling the nail at the nail head.

There are 3 ways in which soil nails can fail due to internal stability:

- Tensile failure of the soil nail bar
- Failure between the grout and bar
- Failure between the grout and soil

The first two failure mechanisms are generally well defined but the capacity of the grout / soil interface is difficult to predict.
Soil nail testing

Factors which can affect the grout / soil capacity include:

- **Drilling technique**
- **Grouting method**
- **Ground conditions**

It is, therefore, important to get site specific information via field tests on nails that are installed in the same way as the permanent (production) nails.
Tests

Two basic types of test:

• Sacrificial nail test
• Production nail test

The procedure of the test may vary depending on what you are trying to achieve
Types of test

Sacrificial

Design / Investigation
- Carried out before design starts to investigate the ultimate bond stress
- Test load usually a function of bar strength
- Typically optional

Suitability
- Carried out either before design starts or during construction to confirm the ultimate bond stress used in design
- Test load usually based on design or working load
- Typically one per material type

Production

Acceptance
- Carried out typically on a percentage of production nails
- Confirm satisfactory performance at working load
- Test load usually based on design or working load
- Typically fully grouted

Creep Test
- Typically carried out as part of another test, but can be carried out separately
- To determine susceptibility to creep
Sacrificial Tests

Pulling out the soil nail involves some risk.
Production nail testing

Sacrificial nail testing
Testing setup

Existing slope profile

Load transfer steel frame with T32 bars as legs

Dial gauges for measuring plate movement

Test soil nail end plate

Dial gauge for measuring head displacement

1000 x 1000 x 75 mm min cast insitu concrete pad seated perpendicular to the test soil nail

Cement grout sleeve

Test soil nail

6 mm fillet weld all round

700 x 700 x 6 mm steel seating plate

Steel channel reference post

1500 mm min.
Testing setup
Figure 11.4  Preparation of bearing face for soil nail testing (adapted from Dywidag Systems International Ltd, 2003)
Testing setup

- Length of grouted zone
- Free (unbonded) length requirements
- No. of cycles
- Loading and unloading intervals
- Test load
- Period for holding load at intervals and test load
- How many tests
- Bar size (larger bar size than for production nails may be required to test full ultimate bond stress)
- Head arrangement
Specifications

Requirement

- Bedding-in load of 10%
- Load intervals equally distributed
- Minimum elongation (a percentage of the elastic deformation of unbonded length – 80-100%)
- Maximum deformation of 2mm over log time (typ. 5min/50min or 6min/60min)

Reasoning

- Alignment of equipment
- Good practice to apply the test load gradually
- To confirm the unbonded length
- If creep rate exceeds 2mm per log cycle of time additional load will lead to continuing grout body movements
## Production testing requirements

<table>
<thead>
<tr>
<th>Jurisdiction</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>QLD TMR (MRTS03)</td>
<td>• 3 Cycles, held for 60 mins, test load = 1.5 x working load</td>
</tr>
<tr>
<td></td>
<td>• Tests: 1-50 nails – 3 tests, 51-100 nails – 6 tests, &gt;100 nails – 6% of nails</td>
</tr>
<tr>
<td>VicRoads (Section683)</td>
<td>• 1 Cycle, held for 240 mins, test load = 1.5 x design load, <strong>sacrificial</strong></td>
</tr>
<tr>
<td></td>
<td>• Tests per row, largest of: 5%, 2 nails, 2 nails per soil type, 2 per installation method</td>
</tr>
<tr>
<td>NSW RMS (R64)</td>
<td>• 1 Cycle, held for 180 mins, test load = 1.5 x working load</td>
</tr>
<tr>
<td></td>
<td>• Tests: 3% of nails, 50% top row, 25% middle row, 25% bottom row</td>
</tr>
<tr>
<td>CIRIA C637</td>
<td>• 1 Cycle, held for 60 mins, test load = 1.1-1.5 x working load or = 1 x design load</td>
</tr>
<tr>
<td></td>
<td>• <strong>Tests:</strong> 1-200 nails – 3-5 tests, &gt;200 nails - 1.5%-2.5% of nails</td>
</tr>
<tr>
<td>BS8006:2011 (BS EN 14990:2010)</td>
<td>• Test as per CIRIA C637</td>
</tr>
<tr>
<td></td>
<td>• <strong>Tests:</strong> 2-3%, min 3-5 nails, 1 nails per soil type, 1 per excavation stage</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>• No test specified – <strong>non-destructive testing only</strong></td>
</tr>
<tr>
<td>*</td>
<td>* Based on risk</td>
</tr>
</tbody>
</table>
# Sacrificial testing requirements

<table>
<thead>
<tr>
<th>Jurisdiction</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>QLD TMR</td>
<td>• No test specified</td>
</tr>
<tr>
<td>VicRoads</td>
<td>• 1 Cycle, held for 240 mins, test load = 1.5 x ultimate bond stress, sacrificial</td>
</tr>
<tr>
<td></td>
<td>• 3 tests per each type of soil profile</td>
</tr>
<tr>
<td>NSW RMS</td>
<td>• 4 Cycles, held for 180 mins, test load = 2 x “design working load” or failure or 80% of the ultimate tensile strength, whichever is lower</td>
</tr>
<tr>
<td></td>
<td>• Tests: 1% of nails, min 2 nails</td>
</tr>
<tr>
<td>CIRIA C637</td>
<td>• Min. 2 Cycles, held for 60 mins, test load = 1.5-2 x design load</td>
</tr>
<tr>
<td></td>
<td>• 1-2 tests per each type of soil profile, min. 3-6 tests</td>
</tr>
<tr>
<td>BS8006:2011</td>
<td>• Test as per CIRIA C637</td>
</tr>
<tr>
<td>(BS EN 14990:2010)</td>
<td>• *Tests: min 3-5 nails, 1-2 nails per soil type</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>• 3 Cycles, held for 60 mins, test load=90% yield strength of bar</td>
</tr>
<tr>
<td></td>
<td>• Tests: 2% of nails, min 2 nails</td>
</tr>
<tr>
<td></td>
<td>• Creep test can be carried out as 2nd cycle of the pullout test or separately. Test load = 1.5 x design bond stress</td>
</tr>
</tbody>
</table>

* Based on risk
## Comparison Example

**Analysis based on BS8006:2011**

- Working load: 34 kN
- Design load: 115 kN
- Ultimate bond stress: 100 kPa
- Allowable Bar tensile capacity: 260 kN (AS2678)
- 90% yield strength: 360 kN
- 100mm grout hole

<table>
<thead>
<tr>
<th></th>
<th>QLD TMR</th>
<th>VICROADS</th>
<th>NSW RMS</th>
<th>BS8006:2011/ CIRIA C637</th>
<th>HK Geoguide 7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production test load (kN)</strong></td>
<td>51 (1.5 x working load)</td>
<td>172.5** (1.5 x design load)</td>
<td>51 (1.5 x working load)</td>
<td>38 – 51 (1.1-1.5 x working load)</td>
<td>Non-destructive testing</td>
</tr>
<tr>
<td><strong>Time load held (min)</strong></td>
<td>60</td>
<td>240</td>
<td>180</td>
<td>60</td>
<td>-</td>
</tr>
<tr>
<td><strong>Sacrificial test load (kN)</strong></td>
<td>-</td>
<td>32/m of nail (1.5 x ult. bond stress)</td>
<td>230 (2 x design load)</td>
<td>172.5 – 230 (1.5-2 x design load)</td>
<td>360 (2m bond typical)</td>
</tr>
<tr>
<td><strong>Time load held (min)</strong></td>
<td>-</td>
<td>240</td>
<td>180</td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>

*Sacrificial load tests always have an upper limit based on bar strength.

**Sacrificial test**
## Failure Criteria – sacrificial nails

<table>
<thead>
<tr>
<th>VICROADS</th>
<th>NSW RMS</th>
<th>BS8006:2011/ CIRIA C637</th>
<th>HK Geoguide 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>plot of nail head displacement with log time shall be linear or display a decreasing rate of creep</td>
<td>The creep rate is linear or decreasing, when plotted against the logarithm of time throughout Cycle 4</td>
<td>plot of nail head displacement with log time shall be display a decreasing rate of creep (creep test only)</td>
<td>plot of nail head displacement with log time shall be display a decreasing rate of creep (creep test only)</td>
</tr>
<tr>
<td>creep rate shall be less than 2 mm per log cycle of time at the test load</td>
<td>total creep movement of less than 2 mm between the 6 and 60 minutes readings is measured during Cycle 4</td>
<td>creep rate shall be less than 2 mm per log cycle of time at the test load</td>
<td>creep rate shall be less than 2 mm per log cycle of time at the test load or 0.1% of bonded length</td>
</tr>
<tr>
<td>the movement of the steel bar head under the test load shall be less than 0.2% of the bonded soil nail length</td>
<td>total creep movement of less than 1 mm between the 60 and 180 minutes readings is measured in Cycle 4</td>
<td>total creep movement of less than 1 mm between the 60 and 180 minutes readings is measured in Cycle 4</td>
<td></td>
</tr>
<tr>
<td>total nail head displacement at the design load shall not exceed 12 mm beyond the theoretical elastic deformation of the free length plus one half of the bonded length</td>
<td></td>
<td>total nail head displacement at the test load shall be not less than the theoretical elastic deformation of the free length (CIRIA is 80%)</td>
<td></td>
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<table>
<thead>
<tr>
<th>Failed test?</th>
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**Failed test?**

<table>
<thead>
<tr>
<th>Production</th>
<th>VICROADS</th>
<th>NSW RMS</th>
<th>BS8006:2011</th>
<th>CIRIA C637</th>
<th>HK Geoguide 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Review, revise and agree with Superintendent.</td>
<td>Test an additional 2 soil nails in the vicinity of the nonconforming soil nail and remove failed nail.</td>
<td>Consult designer for action to be taken and approval to continue.</td>
<td>Consult designer</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sacrificial</th>
<th>VICROADS</th>
<th>NSW RMS</th>
<th>BS8006:2011</th>
<th>CIRIA C637</th>
<th>HK Geoguide 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revise the design and shall undertake further sacrificial testing</td>
<td>Repeat on replacement nail at own cost</td>
<td>Review soil nail installation method and/or consider alternative soil nail length and layout.</td>
<td>Design/investigation test: Not applicable. Suitability test: Review the soil nail installation method, length, layout</td>
<td>Record test data</td>
<td></td>
</tr>
</tbody>
</table>

- QLD MRTS03 – not stated
- Client or contractors cost to replace and re-test?
- Failure due to ground conditions or poor workmanship?
03

What are some of the issues with soil nail testing?
Testing issues

- Different requirements in different jurisdictions
- Generally derived from ground anchor testing
- Some are generic and do not take account of the site specifics
- Magnitude of test load is a function of the design method adopted
- Do not necessarily take account of how soil nails behave
- Testing production nails can cause debonding in the active zone with detrimental effects
Soil nailing and ground anchors

Soil nails

• Soil nails are not stressed and require an amount of movement to work
• Soil nails fully encased in grout
• Installed at a higher density than ground anchors so failure of one nail is not as critical. Construction tolerances not so high as soil nails work as a mass and not individual basis. Relatively low load per nail
• Soil nails have lower head loads which can be addressed with small headplates within a shotcrete surface
• Typically less than 15m
• Usually addressing shallow failure surfaces

Ground anchors

• Typically stressed (up to its design load) to inhibit structural movement
• Only grouted over fixed anchored length
• Lower density of anchors so single anchor failure critical – low redundancy. High loads per anchor
• Anchors are usually under high load which require substantial bearing structures at the head
• Usually long (15m-45m)
• Usually suitable for deep seated failure
Wall or slope stabilisation with hard facing

<table>
<thead>
<tr>
<th>Major components of load transfer</th>
<th>Major components of load transfer</th>
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</thead>
<tbody>
<tr>
<td>• bond capacity in the resistant zone (A)</td>
<td>• bond capacity in the resistant zone (C)</td>
</tr>
<tr>
<td>• plate bearing capacity to transfer load from facing structure (B)</td>
<td>• bond capacity in the active zone (D)</td>
</tr>
<tr>
<td>• strength of facing structures to retain active soil (B)</td>
<td>• surface soil retention by flexible facing (E)</td>
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Minor components of load transfer

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<th>Minor components of load transfer</th>
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<tbody>
<tr>
<td>• bond capacity in the active zone</td>
<td>• plate bearing capacity to supplement bond capacity of the active zone</td>
</tr>
<tr>
<td>• bond capacity to the hard facing structure</td>
<td></td>
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</tbody>
</table>
• As the excavation proceeds the bond stress distribution along the soil /grout interface changes

• This means we need to make sure that testing is carried out within the active and passive zones
Nail lengths

- The bond length of sacrificial nails often shorter than production nails

Figure 26  Effect of test length and axial stiffness on measured average bond

Key

- GRP nails, $f_s = 1.19L^{-0.62}$
- Anchors, $f_s = 1.60L^{-0.57}$
- 50 mm steel bar nails, $f_s = 0.61 - 0.02L$ ($15 > L > 5$)
- 20 m steel bar nails, $f_s = 0.61 - 0.3L$ ($10 > L > 5$)

After Barley and Graham [18].

BS 8006-2:2011
Production Nails – to test or not to test?

- **BS EN 14490:2010 9.3.2.4** If load tests are conducted on production nails, consideration should be given to downgrading the capacity, and additional nails may be installed to provide sufficient resistance and long-term stability.

- **BS 8006-2:2011 6.1.1** Due to the mobilization of the strain field in a test nail subject to a pull-out test being significantly different from production nails, pull-out tests on production nails should be avoided being confined to sacrificial nails only.

- Where to test - Centrifuge modelling – lower row of nails critical
### Partial factors and factors of safety

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<td>1.35</td>
<td>1.0</td>
<td>1.0</td>
<td>1.25</td>
<td>0.8</td>
<td>1</td>
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<td>Live surcharge</td>
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<td>1.33</td>
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<tr>
<td>tan f'</td>
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<td>0.77</td>
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<td>1.0</td>
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<td>0.82</td>
<td>0.75-0.95</td>
<td>0.75-0.95</td>
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<td>c'</td>
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<td>0.61-0.67</td>
<td>0.67-0.77</td>
<td>0.63</td>
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<td>Soil nail pullout</td>
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<td>1.4-1.9</td>
<td>1.0</td>
<td>1.3</td>
<td>1.1-1.7</td>
<td>1.5-2.25</td>
<td>1.25-2.0</td>
<td>1.25-2.0</td>
<td>1.5-2.0</td>
<td>1.3-1.6</td>
<td>1.3-1.6</td>
<td>1.3-1.6</td>
<td></td>
</tr>
<tr>
<td>Overall stability</td>
<td></td>
<td>1.35</td>
<td>1.125</td>
<td>1.0</td>
<td>1.0 or 1.25</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0-1.4</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Soil nailing – code comparison

Example wall

\[ H = 7.2 \text{m} \]
\[ L = 5 \text{m} \]
\[ \text{c'} = 4 \text{ kPa} \]
\[ \phi' = 36 \text{ deg} \]
\[ \text{Ultimate bond} = 100 \text{ kPa} \]

Results

- Max. working load 34 kN
- Ave. working load 22 kN
- Max. design loads varied from 71 kN to 117 kN

So it is important that the specifying authority recommend the use of one approach to maintain consistency – establish precedent

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04
Conclusions
Testing

• Risk

• Body of data of similar soils / previous experience of the ground conditions

• Ground conditions – creep susceptible?

• Upgrade or new works / slopes or walls

• Site supervision
Table 2 — Suggested frequency of soil nail load tests based on density of nails and geotechnical structure category

<table>
<thead>
<tr>
<th>Test type</th>
<th>Suggested Minimum Frequency of Load Tests</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sacrificial nail test</td>
<td>Production nail test</td>
</tr>
<tr>
<td>Geotechnical Category 1: negligible risk to property or life.</td>
<td>Optional</td>
<td>Optional</td>
</tr>
<tr>
<td>Geotechnical Category 2: no abnormal risk to property or life.</td>
<td>If no comparable experience of soil type: a minimum of three sacrificial nails with at least one sacrificial nail per soil type. Where direct experience exists then sacrificial nail tests are optional.</td>
<td>2 %, min. three tests.</td>
</tr>
<tr>
<td>Geotechnical Category 3: all other structures not in Category 1 or 2.</td>
<td>A minimum of five sacrificial nails with at least two sacrificial nails per soil type.</td>
<td>For number of nails: 3 %, min. five tests.</td>
</tr>
</tbody>
</table>

**NOTE 1** Geotechnical Category of structure as defined in EN 1997.

**NOTE 2** Test nails should be evenly distributed throughout the structure.

**NOTE 3** The frequency of testing is a suggested minimum.

**NOTE 4** Where sacrificial nail tests are carried out the number of production nail tests can be reduced on a pro-rata basis.

**NOTE 5** For spacing, less then 0,8 m, a group test of four nails is recommended.
Problem soils

Cohesive soils

• Problematic
• Should not be installed in:
  – Organic soils
  – Consistency Index, $I_c = \frac{(LL-w)}{LL-PL} < 0.9$
  – $LL > 50%$
  – $PI > 20%$
• Saturated soft sensitive clays (undrained condition) – creep susceptible
• Insitu $Su < 50kPa$ or remoulded $Su < 25kPa$ are creep susceptible

Non-cohesive soils

• Should not be installed where:
  – SPT <10
  – Rel. Density <0.3

Other

• Corestones
• Fill
• Defects
Factor of safety isn’t everything!

Lateral Movement vs Wall Height
(Case Histories)
Production nail test results – creep?

![Graph showing production nail test results with time in minutes on the x-axis and nail extension on the y-axis.]
The effect of creep?

Wall A

Wall B

Bruce and Jewell, 1986
Durgunoglu et al, 2007a, 2007b
Clough & O'Rourke, 1990
Thompson and Miller, 1990
Stocker & Riedinger, 1990
Ho et al, 1989
Shen et al, 1981
Airport Link Project

dh/H = 0.5%
dh/H = 0.4%
dh/H = 0.2%
dh/H = 0.1%
Soil nailing an existing slope

- Full-time supervision
- High risk to life
- Issues related to cube failures and productivity
- Maintained 6% testing of production soil nails
Conclusion

When specifying testing it should be site specific based on:

- Risk
- Body of data of similar soils / previous experience of the ground conditions
- Ground conditions – creep susceptible?
- Upgrade or new works / slopes or walls
- Site supervision

Remember soil nail testing of grout/soil capacity only examines one mechanism of failure and the testing needs to be backed up by adequate ground investigation and appropriate design.