The design of soil nailed structures to AS4678

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• Introduction
• Soil Nailing in AS4678
• Design Process
Soil Nail – Main Components

HDPE Sheath (for corrosion protection)
External centraliser

Soil nail head plate (galvanised for corrosion protection)
Internal centraliser

Outer grout tube

Domed soil nail nut (galvanised for corrosion protection)

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

FIG. 1. Analogy between Soil-Nailed Excavation and Gravity Retaining Wall [after Stocker et al. (1979)]
Figure 2.13  Forces Acting on a Potential Sliding Zone for a Nailed Slope
(Phear et al., 2005)

R_N - resisting forces (nail)
R_S - resisting forces (soil)
R_D - disturbing forces

Figure 2.13  Forces Acting on a Potential Sliding Zone for a Nailed Slope
(Phear et al., 2005)
Soil nailed wall

How soil nails work

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
- bond capacity to the hard facing structure
Soil Nailing – Is it suitable?
# Advantages & Disadvantages

## Advantages
- Construction flexibility
- Cost
- Environmental/aesthetic considerations
- Complex excavation geometry
- Faster relative to other lateral support systems
- Permits top-down construction
- Can be used in situations with limited access

## Disadvantages
- Temporary conditions (cut must stand vertically)
- Groundwater
- Clay soils
- Land issues
- Corrosion
- Ground movement
- Untried for depths beyond about 25m
- Not suitable for deep seated failures
• Design Considerations – Limit States
  • Strength - Must consider all critical conditions during the excavation/nail installation process
  • Serviceability – must include movements during excavation
  • External Stability
  • Internal Stability

• Design Loads – load combinations & factors

• Design Factors – factors on material properties & uncertainty
• Structures <15m
• Face angle <90°, >70°
• “Uncomplicated”
• Informative Guidelines only
• Appendix C of AS4678
• Design principle is similar to Reinforced Soil Walls
• Appendix C refers back to Appendix B – Ground anchors
Design Process
Design Process

STEP 1 – Ground Model

STEP 2 – Input Parameters

STEP 3 – Concept

STEP 4 – Analysis

- Develop ground model, groundwater conditions, parameters, aggressivity
- Define geometry
- Determine surcharges and loads

- Determine design parameters
- Concept bar sizes and hole diameters

- Determine design bond stress
- Determine design tensile capacity of bar
- Concept nail lengths and layout

- Undertake internal and external analyses
- Design of heads and facing
- Deformation assessment

Design acceptable?

Yes

No
Design Process

No

Design acceptable?

Yes

• Complete design drawings & reporting

STEP 5 – Final Design

STEP 6 – Construction Verification

• During construction, check design against site data (pull-out tests, logging of excavated faces)
Step 2 – Input parameters
\( \phi^* = \) design angle of internal friction of soil (deg.)

\( = \tan^{-1}(\Phi_{u\phi} (\tan\phi')); \)

\( c^* = \) design value of cohesion of soil (kN/m\(^2\))

\( = c' \Phi_{uc}; \)
Bar size and hole dia.
Step 3 - Concept
Nail spacing, length and inclination

**MODEL 1**
- No soil nails
- Planar failure

**Ref.:** Zhang et al, 2001

**MODEL 6**
- Short soil nails
- \( L/H = 0.32 \)
- Block failure

**MODEL 8**
- Long, widely spaced soil nails
- \( L/H = 1 \)
- Planar failure

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FIG. 5 — Model 1 after failure.

FIG. 11 — Sketch of Model 6 after test.

FIG. 15 — Sketch of Model 8 after test.
Nail spacing, length and inclination

**TESTS 1-4**

L/H = 0.67 (incl. 0-30 deg)

Closely spaced

Two-part wedge: no difference in failure with nail inclination 0-30 deg.

**TESTS 5-7**

- L/H = 0.67 & 1.0
- Widely spaced at 0 deg inclination
- Planar failure

Ref.: Vucetic et al, 1996
Nail spacing, length and inclination

Factor of safety for different soil nail inclinations (90° wall face angle)

Factor of safety for different L/H ratios (90° wall face angle)

\[ \phi' = 36^\circ, c' = 6 \text{kPa} \]
Effect of soil nail inclination on nail force (Nail 1 is top row of nails)

Nail spacing, length and inclination
• Closer spaced nails provide greater internal stability
• Wide spacing of nails can effect internal stability
• Soil nail spacing should not exceed 1 nail per 6m² of hard facing or 1 nail per 2m² to 4m² of flexible facing otherwise the soil nailed structure will not act as a reinforced mass (CIRIA C637)
• Max. spacing – typically 1 - 2m
Nail Length

• Short nails at bottom provides less stability – likely pullout

• Shorter nails at top, longer at bottom provides “excellent” stability but shorter nails at the top will increase deformations (Shui & Chang, 2005)

• As L/H increases, deformations decrease – no additional effect when L/H>1

• Short nail lengths can effect external stability – thin gravity wall

• Length of Nails - 0.8 - 1.2H (Clouterre)

• Soil nail lengths above 15m should be avoided due to drilling difficulties and greater deformation required to mobilise tensile capacity.
Wall Height vs Nail Length
(Case Histories)

- Bruce and Jewell, 1986
- Durgunoglu et al., 2007a, 2007b
- Thompson and Miller, 1990
- Stocker & Riedinger, 1990
- Ho et al., 1989
- Shen et al., 1981
- Airport Link Project
- Gateway Upgrade Project

Graph showing the relationship between wall height (m) and nail length (m) with different case histories and lines indicating various L/H ratios.
Nail inclination between 0 and 20 deg does not appear to affect stability

>20 deg then rapid increase in wall deformation
Preliminary Sizing

The following relationships were derived by Bruce & Jewell (1987):

Length Ratio = Length of soil nail / Excavation height (L/H)

Bond Ratio = (Hole Dia. x L) / Nail Spacing

Strength Ratio = (Nail Dia.)^2 / Nail Spacing

Nail Spacing = horizontal spacing x vertical spacing (m^2)

Performance Ratio = Outward Movement = δ
                      Excavation height H

<table>
<thead>
<tr>
<th></th>
<th>Length Ratio</th>
<th>Bond Ratio</th>
<th>Strength Ratio (10^-3)</th>
<th>Performance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granular soil</td>
<td>0.5-0.80</td>
<td>0.3-0.6</td>
<td>0.4-0.8</td>
<td>0.001-0.003</td>
</tr>
<tr>
<td>Moraine / Marls</td>
<td>0.5-1.0</td>
<td>0.15-0.20</td>
<td>0.1-0.25</td>
<td>-</td>
</tr>
</tbody>
</table>

Marl – mix of calcium carbonate & clay

Moraine – glacial debris (silt thru to boulders)
Step 4 - Analyses
External Stability - Modes of Failure

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

Surcharge (Unit Weight): 32 kN/m³

Name: Stiff Clay      Unit Weight: 21 kN/m³     Cohesion: 5 kPa     Phi: 25 °
Name: Hard Clay      Unit Weight: 21 kN/m³     Cohesion: 5 kPa     Phi: 25 °
Name: VLS - LS Siltstone      Unit Weight: 22 kN/m³     Cohesion: 22.5 kPa     Phi: 30 °
Name: MS Siltstone      Unit Weight: 22 kN/m³     Cohesion: 200 kPa     Phi: 40 °

Minimum Factor of Safety = 1.65
25.7 m Behind Wall Crest
At Wall Toe
H= 16.6 m
Scale = 3 m

Soil Bound.(3) — Water
Surcharge

Date: 11-26-2009
File: South East

Elevation (mRL)
-5
0
5
10
15
20
25
30
35
40
45
50
55
60
65

Distance
0 5 10 15 20 25 30 35 40 45 50 55 60 65

South Wall
Eastern Side
Nail Tension Forces

Figure 5.1: Potential Failure Surfaces and Soil Nail Tensile Forces.
Modes of Failure

(a) Failure of Ground around Soil Nails
(b) Soil-nail Head Bearing Failure
(c) Local Failure between Soil Nails
(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
(g) Structural Failure and Connection Failure of Soil-nail Head
(h) Structural Failure and Connection Failure of Facing

Internal Stability
Soil Nailing – Internal Stability

• Soil nail pull-out (grout-ground bond)

• Nail failure (i.e. tensile failure of nail)

• Pull-out of connection to facing material
Design pull-out capacity (AS4678)

\[ T^* = \Phi_n \cdot \Phi_b \cdot \pi \cdot D \cdot L_f \cdot \tau_u \]

Where:
- \( \Phi_n \) = Structure classification design factor (Table 5.2) = 0.9-1.1;
- \( \Phi_b \) = Bond reduction factor (Table B2) = 0.7;
- \( D \) = Diameter of grout hole (m);
- \( L_f \) = Fixed length (m);
- \( \tau_u \) = Design grout/ground resistance (bond stress) (kN/m²).
• Effective stress design methods
• Pull out tests
• Empirical values
Design bond stress
(effective stress design method)

\[
\tau_u = (c^* + \sigma'_v \tan\phi^*) \text{ (kN/m}^2)\]

where:

\(\sigma'_v\) = effective vertical stress at the mid-depth of nail behind the failure surface;

\(\phi^*\) = design angle of internal friction of soil (deg.);

\(c^*\) = design value of cohesion of soil (kN/m²).
Pull-out tests

\[ \tau_u = \frac{P_{ult}}{\pi DL} \text{ (kPa)} \]

where:

- \( P_{ult} \) = pull out resistance from pullout test (kN)
- \( D \) = diameter of grout hole (m)
- \( L \) = grouted length of soil nail (m)
Pull-out tests

\[ \tau_u = \frac{P_{\text{ult}}}{\pi DL \xi \gamma_p} \quad \text{(kPa)} \]

where:

- \( P_{\text{ult}} \) = pull out resistance from pullout test (kN)
- \( D \) = diameter of grout hole (m)
- \( L \) = grouted length of soil nail (m)
- \( \xi \) = correction based on test results
- \( \gamma_p \) = partial factor (1.25 temp, 1.5 perm)

### Table 8.5
Correction factors for pullout test results to obtain characteristic values

<table>
<thead>
<tr>
<th>Number of pullout tests</th>
<th>1</th>
<th>2</th>
<th>3 or more</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \xi ) based on mean of test results</td>
<td>Not applicable</td>
<td>1.35 (^1)</td>
<td>1.30 (^1)</td>
</tr>
<tr>
<td>( \xi ) based on lowest test results</td>
<td>Not applicable</td>
<td>1.25 (^1)</td>
<td>1.10 (^1)</td>
</tr>
<tr>
<td>( \xi ) based on test result</td>
<td>1.50 (^1)</td>
<td>Not applicable</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>
Empirical Values

Apply a factor on ultimate of 0.5 - 0.66

Typical values of ultimate bond stress for various materials in the Sydney region are given below:

<table>
<thead>
<tr>
<th>Material</th>
<th>Ultimate Bond Stress (kPa)</th>
<th>Material</th>
<th>Ultimate Bond Stress (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual soil</td>
<td>50 – 75</td>
<td>Class V Sandstone</td>
<td>150</td>
</tr>
<tr>
<td>Class V Shale</td>
<td>75 – 100</td>
<td>Class IV Sandstone</td>
<td>250 – 800</td>
</tr>
<tr>
<td>Class IV Shale</td>
<td>150</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

See also:

Values should be confirmed by pull-out testing.
Design pull-out capacity

- Pull-out resistance is usually assumed to be uniform along the length of the nail.
- This is reasonable if nails are short and stiff (dia. of bar >20mm, bond length <5m)
- For more elastic nails (eg. fibre-composite nails) the ave. bond stress reduces when bond length >3m

CIRIA Report C637

Effect of Fixed Length on Bond Stress (Barley and Graham, 1997)
Nail tensile capacity

Bar strength (tension capacity) can be determined from equation B4(1) in AS4678-2002

\[ T = \Phi_k \Phi_n \Phi_t f_p A_p \quad (\text{kN}) \]

where:

\[ \Phi_k = \text{Importance category reduction factor} \]
\[ (\text{Table B1}) = 0.8 \text{ (perm.)} - 0.9 \text{ (temp)}; \]

\[ \Phi_n = \text{structure classification design factor} \]
\[ (\text{Table 5.2, AS4678}) = 0.9 - 1.1 \]

\[ \Phi_t = \text{Material reduction factor} \]
\[ (\text{Table B2}) = 0.9; \]

\[ f_p = \text{Tensile strength of nail} \quad (\text{kN/m}^2); \]

\[ A_p = \text{Cross sectional area of nail} \quad (\text{m}^2). \]
Facing can comprise:

- Individual plates or pads
- Mesh
- Shotcrete facing with steel mesh or steel fibre reinforcement
- Vegetation

Flexible facing provides similar overall stability to rigid facing, but more localised deformation

Facing type (based on case studies) –

- face angle $\geq 70^\circ$ = hard
- face angle $\leq 70^\circ$ = flexible
Vegetated Slope Works

July 2001

August 2001

September 2002

April 2003

June 2001
1. FHWA approach

2. FHWA Modified Approach (CIRIA C637)

3. Clouterre

- Shotcrete can be applied in one of two layers (a temporary layer and a permanent layer). Typical temp thickness is 75mm with a single layer of mesh

- Shotcrete thickness for a soil nailed wall is generally > 150mm (MRTS03 – 160mm)

- Shotcrete thickness for a slope 75-100mm (MRTS03 – 120mm)

- Shotcrete thickness generally governed by min. cover to steel requirements
Soil Nailing - Serviceability

Serviceability limit state of soil nailed structure is similar to RSW.

Remember – movement is required to generate resistance. Therefore beware of existing structures on top of proposed cut.

Where special concrete facings are used, any excessive deformation of the facing may constitute a serviceability limit state.
Typical settlement profile (exaggerated)

Assumed that
\[ \delta_v \approx \delta_h \]
\[ \delta_o = k(1 - \tan \phi) H \approx \delta_v / 10 \]
\[ \lambda = H (1 - \tan \alpha) k \]

Where \( \alpha = \) initial wall face angle from vertical

<table>
<thead>
<tr>
<th>Vertical or horizontal deformation</th>
<th>Weathered Rock / Stiff Soils</th>
<th>Sandy Soils</th>
<th>Clayey Soils</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta_v = \delta_h )</td>
<td>( H/1000 )</td>
<td>( 2H/1000 )</td>
<td>( 3H/1000 )</td>
</tr>
<tr>
<td>( \delta_o )</td>
<td></td>
<td>( 4H/1000 ) to ( 5H/1000 )</td>
<td></td>
</tr>
<tr>
<td>( k )</td>
<td>( 0.8 )</td>
<td>( 1.25 )</td>
<td>( 1.5 )</td>
</tr>
</tbody>
</table>
Soil Nailing - Serviceability

Lateral Movement vs Wall Height
(Case Histories)

- 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
- Gateway Upgrade Project

- dh/H = 0.5%
- dh/H = 0.2%
- dh = 4H/1000
- dh = H/1000

27 November 2017
Drainage system

Weephole

Drain

Drains

TYPICAL ARRANGEMENT
SUB-HORIZONTAL DRAINS

TYPICAL SECTION
SUB-HORIZONTAL DRAINS
Conclusion

AS 4678 – 2002 can be used for soil nailing

But:

Lack of information and guidance in the standard limits its use

Clients specify different standards

And

NOTE: The following alternative design approaches to retaining walls may be used, provided the same design considerations and performance criteria as outlined in this Standard are satisfied:

(a) For walls other than reinforced soil walls, a global (lumped) geotechnical resistance factor may be used, rather than partial material design factors. No guidance is given in this Standard for the choice of global factors.

(b) A safe design of conventional retaining structures can also be achieved by analysing limit equilibrium conditions using the worst credible soil parameters. A factor of safety just exceeding 1 would be sufficient to prevent failure. However, if the chosen safety factor is also intended to limit displacements to a tolerable maximum, the lowest credible soil strength will need to be further reduced by dividing it by a partial factor. This approach is referred to as the Direct Assessment (Worst Credible Scenario) method. No guidance for this approach is given in this Standard.
Thank you
Construction Issues
225m long wall – signs of distress during construction
Name: General Backfill  
Model: Mohr-Coulomb  
Unit Weight: 19 kN/m³  
Cohesion: 5 kPa  
Phi: 30 °

Name: Claystone  
Model: Mohr-Coulomb  
Unit Weight: 21 kN/m³  
Cohesion: 10 kPa  
Phi: 40 °

Name: Mudstone  
Model: Mohr-Coulomb  
Unit Weight: 21 kN/m³  
Cohesion: 10 kPa  
Phi: 42 °

Name: Sandstone  
Model: Mohr-Coulomb  
Unit Weight: 20 kN/m³  
Cohesion: 2 kPa  
Phi: 42 °
Revised Design

Re-analysed wall with revised ground model and design amended to incorporate same length nails for full height of wall over affected section

Name: General Backfill
Model: Mohr-Coulomb
Unit Weight: 19 kN/m³
Cohesion: 5 kPa
Phi: 30 °

Name: Claystone
Model: Mohr-Coulomb
Unit Weight: 21 kN/m³
Cohesion: 10 kPa
Phi: 40 °

Name: Mudstone
Model: Mohr-Coulomb
Unit Weight: 21 kN/m³
Cohesion: 10 kPa
Phi: 42 °

Name: Uncemented Sandstone
Model: Mohr-Coulomb
Unit Weight: 20 kN/m³
Cohesion: 0 kPa
Phi: 35 °

Name: Sandstone
Model: Mohr-Coulomb
Unit Weight: 20 kN/m³
Cohesion: 2 kPa
Phi: 42 °
But, after wall completed:

Wall still showed signs of movement

Extra nails 10m in length were recommended along 20m of the unstable section
Remediation Nail Design

Name: General Backfill
Model: Mohr-Coulomb
Unit Weight: 19 kN/m³
Cohesion: 5 kPa
Phi: 30 °

Name: Claystone
Model: Mohr-Coulomb
Unit Weight: 21 kN/m³
Cohesion: 10 kPa
Phi: 40 °

Name: Mudstone
Model: Mohr-Coulomb
Unit Weight: 21 kN/m³
Cohesion: 10 kPa
Phi: 42 °

Name: Uncemented Sandstone
Model: Mohr-Coulomb
Unit Weight: 20 kN/m³
Cohesion: 0 kPa
Phi: 35 °

Name: Sandstone
Model: Mohr-Coulomb
Unit Weight: 20 kN/m³
Cohesion: 2 kPa
Phi: 42 °
Spacers of inadequate strength

Damage to installed soil nail bars by excavator

Lack of experience of contractors staff
Soil Nail Failures

Soil nail facing failure

Grout cover cracked and peeled off from nail

Ref.: Tan. & Chow, 2004
Void within cement grout

Probed depth = 320 mm into cement grout

Probed depth = 1590 mm into cement grout

~250 mm

Cross-section
Nail with no grout

Plastic sheet

Short column of cement grout
Soil Nail Failures

Slope failure prior to soil nail heads being installed during heavy rain

Cause of failure:
- Ingress of water
- Upper row of nails too low below crest
- Wide nail spacing
- Lack of surface protection
- Poor construction of nails

Ref.: Sun & Tsui, 2005
6m³ failure in Completely Decomposed Tuff
Airport Link – Construction Issues

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)