Design of Soil Nailed Walls According to AS4678-2002

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ABSTRACT

The use of soil nails in the construction of major civil infrastructure is becoming more frequent, both for temporary and permanent works. In Australia there is no design standard for soil nailed walls, although Australian Standard *AS4678-2002 Earth-retaining structures* (Standards Australia, 2002c) provides informative guidance. Designers, therefore, use a variety of methods including traditional factor of safety approaches, including BS8006:1995 (BSI, 1995) and 2011 (BSI, 2011), CIRIA C637 (Phear *et al*, 2005) and US Federal Highway guidance (Lazarte *et al*, 2003; Lazarte *et al*, 2015). This paper discusses the guidance presented in AS4678-2002 and how it can be used to design a soil nailed wall.

1   INTRODUCTION

1.1   WHAT IS SOIL NAILING?

Soil nailing consists of reinforcing the ground using closely spaced reinforcing elements, which are designed to act in tension. Soil nails typically consist of steel or polymeric material (such as glass-reinforced plastic (GRP)) that are inserted into pre-bored holes and grouted into place (Figures 1 and 2). Driven or ballistically inserted soil nails can also be used.

It makes sense, therefore, that soil nailing requires at least two rows of nails (and preferably more) to be installed to reinforce the ground mass. Unfortunately, statements such as "Bored Piles wall with tiebacks; this method was considered, with contiguous piles being tied back using soil nail at location along each of the piles." are often seen. As the author of this text states, however, these are not soil nails but tie backs.

So, although soil nails typically consist of steel bars encased in grout in the ground, not all steel bars encased in grout in the ground are soil nails.
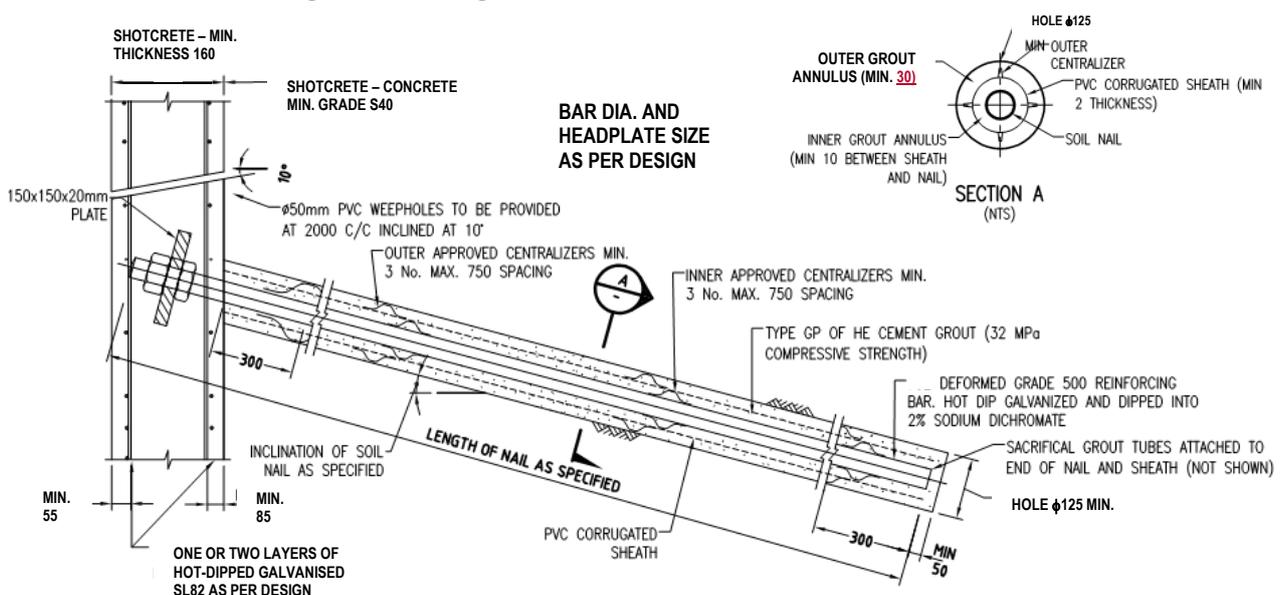
Figure 1: Typical soil nail arrangement (Department of Transport and Main Roads, 2017)
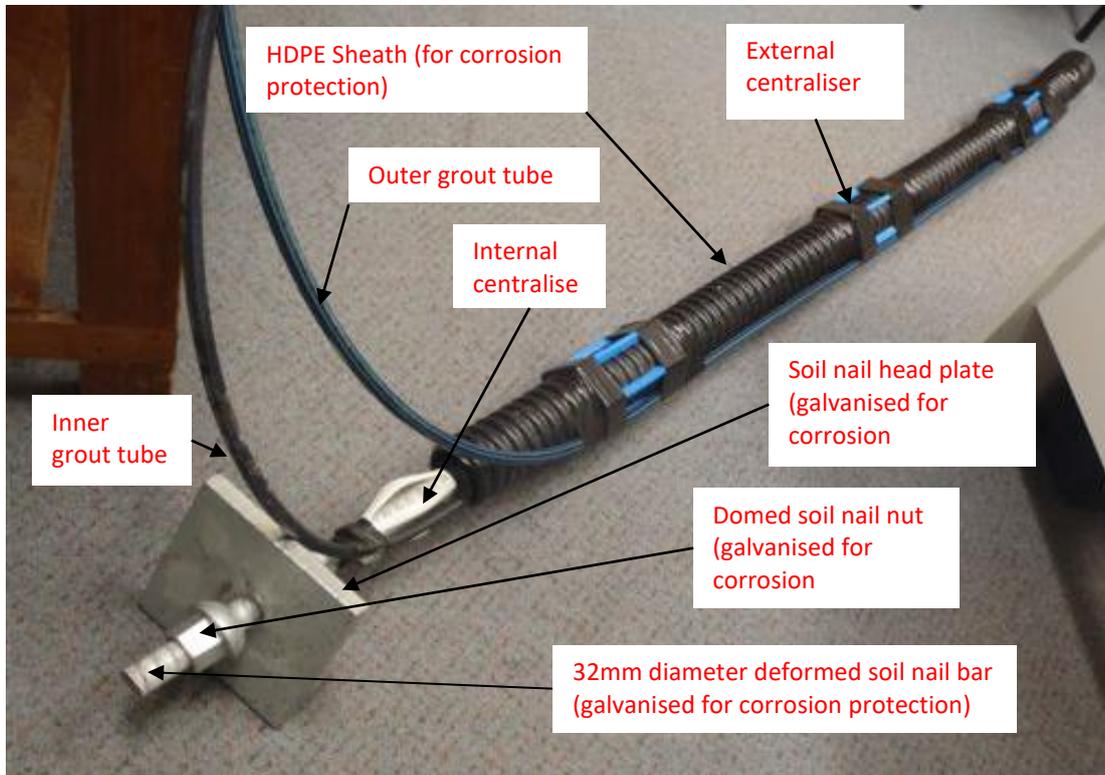

Figure 2: Soil nail components

When constructing a soil nailed wall, the excavation usually proceeds in lifts of 1.2m involving excavation, the drilling of the soil nail hole, installation and grouting in of the soil nail, and then placing of reinforcement mesh and shotcrete on the excavated face. On completion of a row of soil nails and facing, the excavation proceeds to the next row of soil nails.

2   DESIGN REQUIREMENTS OF AS4678-2002

2.1   DESIGN PRINCIPLES

AS4678-2002 (Standards Australia, 2002c) requires design to be carried out using limit state theory. Retaining walls are to be designed against two limit states:

- *Ultimate limit state* – design against collapse or major damage

- *Serviceability limit state* - design against movement or damage exceeding stated limits

For both limit states, design resistance effects, R^*, should be greater or equal to the design action effects, S^*.

This results in the need to factor material properties and loads prior to analysis, rather than trying to meet a required global factor of safety, such as 1.5 on slope stability. This also

means that a number of load cases (limit states) will have to be considered leading to more than one analysis being required.

Serviceability limit state analysis as required under the standard implies that serviceability type limits on deformation/settlement etc. should be met if the $R^* \geq S^*$. However, the serviceability limits will vary from structure to structure and additional analyses in the form of settlement or deformation assessments may need to be carried out.

2.2 DESIGN FACTORS

There are partial factors that must be applied under the standard to cover uncertainty, consequence of failure and known causes of weakness. These are as follows:

- Material strength factors – these reduce the shear strength of the soil (Tables 5.1(A) & (B) of AS4678-2002) to take account of the uncertainty of the soil properties.

- Material reduction factors – to take account of long term degradation of the materials due environmental of physical damage during installation.

- Structure classification factor – this factor takes account of the consequence of failure of the structure (Table 5.2 and Appendix A of AS4678-2002).

- Load factors – based on AS1170 with an example given in Table J1 of AS4678-2002.

There is little guidance in the standard with respect to different factors for a temporary compared to a permanent structure. The designer should, therefore, consider the effects of the variation in groundwater level, structural classification (i.e. consequence of failure) and loading condition between the temporary and permanent cases changing the factors, groundwater level and loads accordingly.
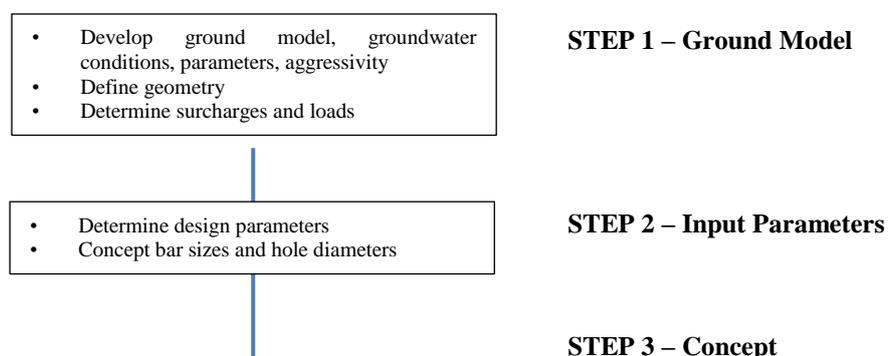
3   SOIL NAIL DESIGN

Soil nails are discussed within an Informative at the back of AS4678-2002 (Appendix C). Within that appendix the designer is often referred to Appendix B (Ground Anchors) for advice on design equations to use. The standard, however, does not provide the designer with a design process that can be used in an Australian context and makes no reference to current design standards used internationally and were available at time of publication. Designers are, therefore, forced to look overseas at published standards and guidance documents and a variety of methods and approaches are currently in use.

The author presents below an approach based on AS4678-2002 which incorporates current soil nail design philosophy.

3.1 DESIGN PROCESS

The design process can be broken down into a number of steps – for example see CIRIA C637 (Phear *et al*, 2005). The following multistep process has been adopted by the author.

• Develop ground model, groundwater conditions, parameters, aggressivity • Define geometry • Determine surcharges and loads	**STEP 1 – Ground Model**
• Determine design parameters • Concept bar sizes and hole diameters	**STEP 2 – Input Parameters**
	STEP 3 – Concept

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┌─────────────────────────────────────────┐
│  •  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
   No        acceptable?

              Yes
┌─────────────────────────────────────────┐
│  •  Complete design drawings & reporting │
└─────────────────────────────────────────┘

┌─────────────────────────────────────────┐
│  •  During construction, check design against site │
│     data (pull-out tests, logging of excavated │
│     faces)                               │
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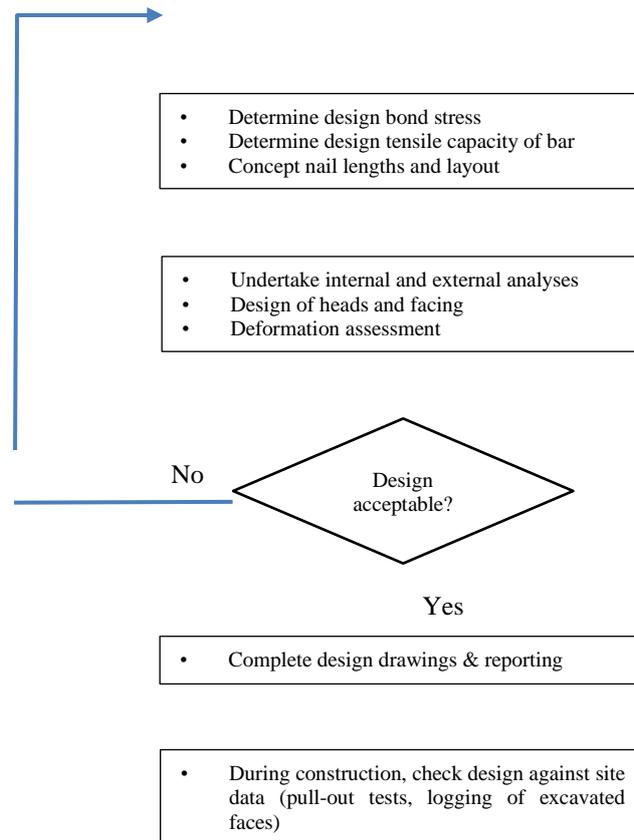
Figure 3: Design process

3.1.1 Step 1 - Development of Ground Model

This is considered as a number of steps in CIRIA C637 (Phear *et al*, 2005), but the author believe this is a single step process in development of the design. The ground model needs to be formed based on site investigation data, design requirements, existing and proposed topography etc. This should provide the wall height requirements, surcharges and other loads, geotechnical data for design (including generation of geotechnical parameters), groundwater conditions and information on site constraints including limitation on ground movements.

3.1.2 Step 2 – Design Parameters and Nail Sizes

The Australian Standard specifies factors that need to be applied to soil parameters and loads in the analyses. Section 5.2 of the standard details the relevant material factors that need to be applied the shear strength of the soil. Factors on soil density and load combinations are discussed in Appendix J and related to AS1170 (Standards Australia, 2002a, 2002b). If no surcharges are present then minimum surcharges need to be considered in design as detailed in Section 4.1 of the standard.

At this point it should be pointed out one of the main concerns with this standard. It can be clearly seen that a reduction in the values of shear strength has a direct impact on global stability. However, when considering earth pressure, we see a multiplication of factors

4

occurring as there is an indirect effect due to a reduction in shear strength – leading to an increase in the earth pressure coefficient – combined with a factored increase in the density – Appendix J. The multiplication effect is also seen with the earth pressure due to the surcharge behind the wall.

In terms of the soil nail, a bar diameter of 32mm should be adopted as a first step, reducing the bar size as necessary, within the limitations given in section 3.2. Drillhole diameters may need to be as specified by the relevant authority rather than by design. For example, Queensland Department of Transport and Main Roads (TMR) MRTS03 specifies a minimum 125mm diameter drillhole (Department of Transport and Main Roads, 2017).

The requirements for wall drainage and soil nail durability can also be determined at this stage. The need for PVC sheaths for example, should be determined at this stage as the drillhole may need to be larger to incorporate them.

3.1.3 Step 3 - Concept Wall Model

With the soil parameters and nail size determined, design bond stress and tensile capacity can be calculated. An estimate of the wall geometry (soil nail length and spacing) should then be developed based on the general guidance given in section 3.3.

3.1.4 Step 4- Wall Analysis

The wall should be analysed in accordance with the principles laid out in AS4678-2002 – which includes bearing capacity and sliding - and discussed in further detail below.

Internal stability should be checked in terms of pullout capacity and bar strength. Soil nail head and facing design should also be carried out.

External stability should be checked using limit equilibrium approaches provided by software such as SNAILZ and SLOPE/W for global stability and standard spreadsheets or hand calculations for sliding and bearing capacity.

If detailed deformation characteristics are required then finite element analysis using a program such as PLAXIS, may be required to satisfy the serviceability requirements as discussed in Section 2.1.

3.1.5 Step 5- Final Design

The design drawings should provide guidance on soil nail layout, length of nails, diameters of bars and drillhole, and drillhole inclination. Reference to relevant specifications and number and types of tests shall also be detailed. In addition, nail loads and test loads should also be provided.

The role of the designer in the verification process should be explained in the report and drawings.

3.2   REINFORCEMENT BAR LENGTH AND DIAMETER

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

Design tension capacity of steel bar,

$$T_d^* \quad \square \qquad \square_k \, \square_n \, \square_t \, f_p \, A_p \quad (kN) \qquad\qquad .....(1)$$

where f_p =   tensile strength of the bar (kPa)

A_p =   cross-section area of bar (m^2)

$\square_k$ =   importance category reduction factor (Table B1, AS4678-2002)

$\square_n$ =   structure classification design factor (Table 5.2, AS4678-2002)

$\square_t$ =   material reduction factor of the steel bar (Table B2, AS4678-2002) = 0.9

It is typical to use Grade 500N reinforcement bar, which gives a characteristic yield strength (f_y) of 500MPa. This value is often adopted as the bars tensile strength, which in reality is higher at 540MPa (1.08 x f_y (AS/NZS 4671:2001)).

However, it is not bar strength alone that is important. The stiffness of the bar should also be considered. Long bars of small diameter tend to flex during installation. Soil nails are also subject to a reduction in bond stress with length in a similar manner to ground anchors. This rate of reduction is also a factor of bar stiffness (Figure 3). 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 (Phear *et al*, 2005).

This effect is even more marked for GRP nails where this length outside the failure surface should not exceed 3m.
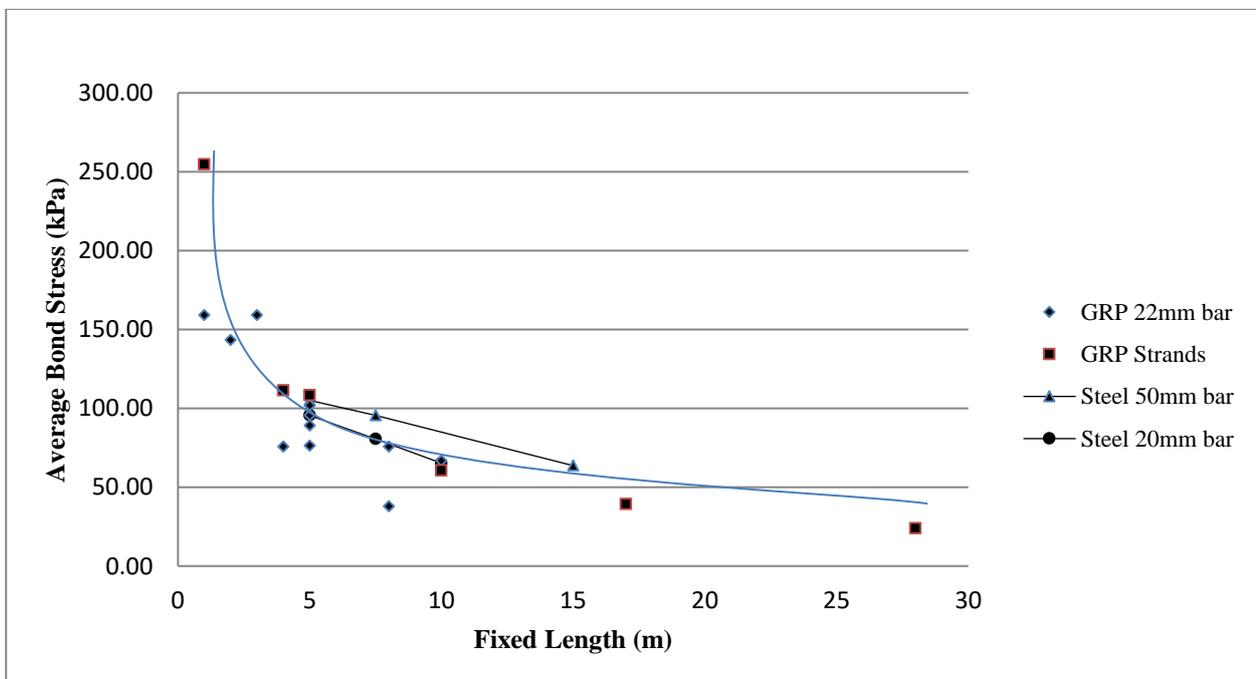

Figure 3: Effect of Fixed Length on Bond Stress (Barley and Graham, 1997)

3.3   SOIL NAIL SPACING AND LENGTH

Soil nail spacing is important as the soil nails should be close enough to provide a reinforcing of the soil and to reduce the load on individual nails. The actual spacing depends on soil type and facing angle. Typically, spacings of 1m to 2m are adopted (Phear *et al* (2005) and Lazarte *et al* (2015)) with one nail per $1m^2$ to $4m^2$ area of facing. For near vertical walls, lifts for excavations are typically 1.2m, which dictates the vertical spacing. Horizontal spacing should not exceed 2m. The top and bottom rows of nails should be less than 1m from the top and bottom of the wall, respectively.

Apart from the issues raised above in Section 3.2, soil nail lengths exceeding 15m should be avoided due to the difficulty in forming and maintaining stability of the drillhole. It is also considered that longer nails will have to deform more in order to generate their tensile capacity resulting in greater deformation of the structure (Geotechnical Engineering Office, 2008).

For soil nail walls, nail lengths are typically in the range of 0.8H to 1.2H, where H is the retained height of the wall.

Soil nails are typically inclined at 10° to 15° below the horizontal, generally in order to aid construction (particularly the flow of grout). This is fortunate as it has been found that the nail efficiency tends to decrease after the nail inclination exceeds 15° below the horizontal (Phear *et al*, 2005).

3.4   PULL-OUT CAPACITY

For an estimation of soil nail pullout capacity the designer is referred to paragraph B4.3 of the standard. The equations proposed, however, are not generally used in soil nail design as the grouted zone used is entirely different in form, and the following approach is recommended:

Design pullout capacity,

$$T^* = \Phi_n \, \Phi_b \, \pi \, D \, L_f \, \tau_u \quad (kN) \qquad\qquad .....(2)$$

where: $\quad \Phi_n \quad = \quad$ structure classification design factor (Table 5.2, AS4678-2002);

$\qquad \Phi_b \quad = \quad$ material reduction factor of the bond between grout and soil

$\qquad\qquad\qquad$ (Table B2, AS4678-2002) = 0.7;

$\qquad D \quad = \quad$ diameter of grout hole (m);

$\qquad L_f \quad = \quad$ length of soil nail behind assumed failure surface (m);

$\qquad \tau_u \quad = \quad$ ultimate grout/ground resistance (bond stress) (kN/m^2).

The ultimate bond stress can be determined from published tables and experience (see Tables 8.3 and 8.4 of Phear *et al* (2005) and Tables 4.4 to 4.6 Lazarte *et al* (2015)), pullout tests or calculations based on overburden pressure.

Where pullout test results are available then ultimate bond stress,

$$\tau_u \quad = \quad P_{ult} / p \, D \, L \quad (kPa) \quad\quad\quad .....(3)$$

where: P_{ult} = pull out resistance from pullout test (kN)

D = diameter of grout hole (m)

L = grouted length of soil nail (m)

Grouted lengths of test nails are typically kept short to 2m, with the rest of the soil nail ungrouted. However, given that the bond stress reduces with nail length, it may be useful to grout the soil nail bar to a length equivalent to the design length of soil nail behind assumed failure surface (L_f of equation (2)). Suitable test methods are described in Phear *et al* (2005) and (Geotechnical Engineering Office, 2008).

Alternatively, using overburden pressure and effective stress parameters, equation (2) becomes:

$$T^* \quad = \quad \Phi_n \, \Phi_b \, (c^* + \sigma'_v \tan\phi^*) \, \square \, D \, L_f \quad (kN) \quad\quad .....(4)$$

where: σ_v' = effective vertical stress at the mid-depth of nail behind the failure surface (kN/m²);

ϕ^* = design angle of internal friction of soil (deg.) = $\tan^{-1}(\square_{u\phi} (\tan\phi'))$;

D = diameter of grout hole (m);

L_f = grouted length of soil nail behind assumed failure surface (m);

c^* = design value of cohesion of soil (kN/m²) =c' $\square_{uc}$.

$\square_{uc}$ and $\square_{u\phi}$ are material strength factors from Table 5.1(A) of AS4678-2002.

When calculating σ_v' the density of the soil should be unfactored and surcharges should be ignored.

The grout hole diameter is typically >100mm and diameters of 125mm and 150mm are not uncommon. This allows for a significant pull-out capacity and also allows room in the grout holes for the corrugated sheathing with adequate grout cover.

3.5   GLOBAL STABILITY

Global stability is typically determined using industry standard slope stability packages such as SLOPE/W. However, for soil nail walls, specialist software such as SNAILZ are an alternative. SNAILZ takes account of the internal stability of the wall by considering the soil nail head and wall facing. Both programs have their limitations and the author often use both when designing a soil nail wall. It should be noted that all construction stages should be analysed, not just the completed structure. For the limit state approach, parameters and strengths have been already factored so the target "factor of safety" using limit equilibrium methods is 1.

3.6   WALL DRAINAGE

As with all retaining structures adequate drainage is an important issue. This is covered in the standard in Appendix G, section G6, which apart from weepholes and strip drains also recommends sub-horizontal drains. If sub-horizontal drains are installed they should be at least as long as the soil nails (Figure 4). They should be placed near the base of wall, but additional rows may be installed if there is likelihood of a perched water table higher up the wall profile.
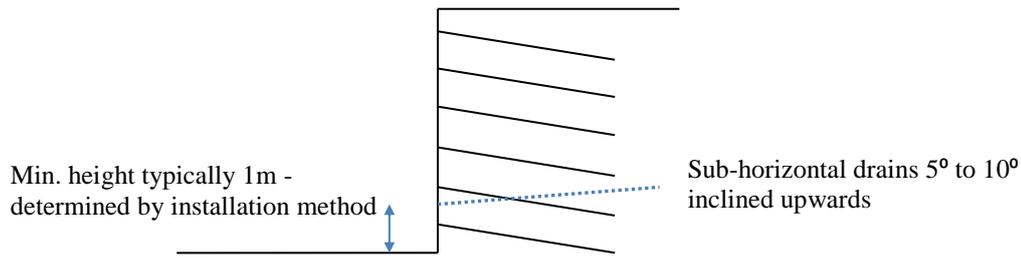
Min. height typically 1m - determined by installation method

Sub-horizontal drains 5° to 10° inclined upwards

Figure 4: Sub-horizontal drains

3.7   WALL FACING

In Queensland TMR specification MRTS03 (Department of Transport and Main Roads, 2017) a minimum shotcrete thickness of 160mm with a layer of SL82 mesh is specified. This is based on providing minimum concrete cover to reinforcement of 85mm against the soil and 55mm on the outer facing.

There is little guidance on the design of facings generally, but the most common approach is using one of the two versions of the US Federal Highway Administration (FHWA) Geotechnical Engineering Circular No. 7 (Lazarte *et al*, 2003; Lazarte *et al*, 2015). Some care must be taken when applying these approach as the overall design methodologies of these two documents are different from AS4678.

The following is an adaption of the US documents to suit the Australian Standard.

One significant difference is the US adoption of two stage shotcreting and the use of head studs which are not typical outside of the US. The following adaptation assumes a single shotcrete layer. A single layer of mesh is typical, but often additional steel reinforcement, either mesh or single bars, are added around the head, and this is also considered.

A crucial input into the facing design is the adopted nail load acting at the head. The load at the facing is not typically the maximum that occurs in the nail, so a reduction in this load is considered in the facing design. Therefore, the FHWA recommend a design load of:

$$T_o = T_{max} [0.6 + 0.2 (S_{max} - 1)] \quad (kN) \quad \ldots(5)$$

where: T_o =   Design nail head tensile force (kN);

        T_{max} =   Maximum design nail tensile force obtained from global stability analysis (kN);

        S_{max} =   Maximum soil nail spacing. Use the maximum of S_V and S_H, the vertical and horizontal nail spacing, respectively (m).

Therefore, the greater the spacing the more of the maximum nail force transferred to the head such that when the spacing reaches 3m $T_o = T_{max}$.

The shotcrete facing should be designed in accordance with AS3600 (Standards Australia, 2009).

3.8   WALL DEFORMATION

Wall deformation can be predicted using simple relations developed in France and repeated in most recent standards. However, the simplicity of this prediction method is based on the premise that the wall design has been carried out appropriately. That is, that the density (spacing) of the nails is sufficient to achieve a reinforced block of soil.

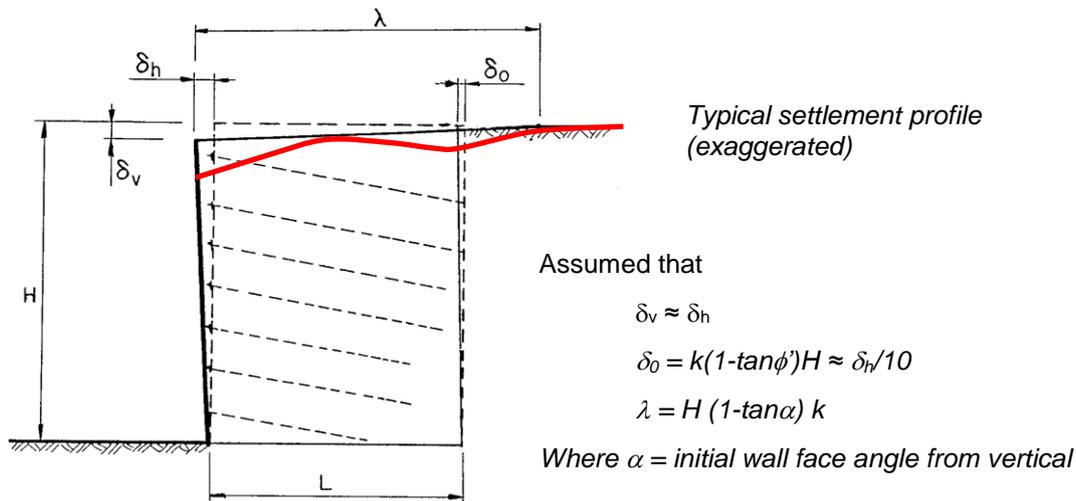A derivation of this French prediction is given below on Figure 5 and in Table 1.

Typical settlement profile (exaggerated)

Assumed that

$$\delta_v \approx \delta_h$$

$$\delta_0 = k(1-tan\phi')H \approx \delta_h/10$$

$$\lambda = H (1-tan\alpha) k$$

Where α = initial wall face angle from vertical

Figure 5: Deformation estimate (FHWA, 1993; Schlosser and Unterreiner, 1991)

Note - δ_h = lateral deflection; δ_v = vertical deflection; δ_0 = horizontal deflection at the back of the wall; H= face height; λ= distance of extent of ground deformation; k = constant; L = wall width (nail length)

Table 1   Typical movements of soil nailed structures

Vertical or horizontal deformation	Weathered Rock / Stiff Soils	Sandy Soils	Clayey Soils
$\delta_v = \delta_h$	H/1000	2H/1000	3H/1000
δ_o	4H/1000 to 5H/1000		
k	0.8	1.25	1.5

Case studies showing the relationship between wall height and lateral deformation is given on Figure 6.
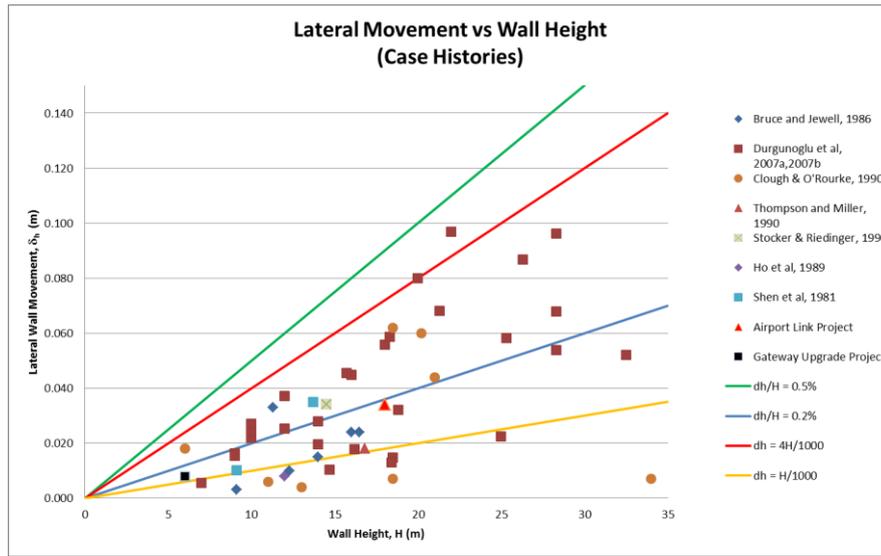
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Figure 6: Lateral movement of soil nailed walls (Bridges and Gudgin, 2014)

5   CONCLUSIONS

In practice, the author has found that AS4678-2002 approach can give similar results to traditional methods where there are a limited number of external effects. As different types of load are added the multiplication effect described in Section 3.1.2 can result in larger structures. Given that the traditional approach has been used successfully for many years, this would imply that the AS4678-2002 methodology gives an overly conservative design in some cases.

From the authors experience, the adoption of limit state design for retaining walls is generally disliked. The ability to consider a reduction in the factor of safety for particular circumstances, such as temporary works design, in a traditional factor of safety approach cannot be easily replicated. Further, there is no guidance in the literature to assist in such approach. Similarly, assessing the capacity of an existing structure can be difficult, with the pass (≥1) or fail (<1) result of limit state design.

AS4678-2002 does not cover soil nail wall design in any real detail. Instead, it directs the user to the ground anchorage Informative (Appendix B). No soil nailing references later than 1991 are contained in the document, which is a surprise given that the document was released in 2002. The authors approach given above uses a combination of design recommendations given in various design standards and guidelines to provide useable guidance that can relate back to the standard. The author accepts that there are a number of justifiable alternatives.

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