Soil Nail Design: A Malaysian Perspective

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Abstract

Soil nail is commonly used in Malaysian slopes both as stabilization measure for distressed slopes and for very steep cut slopes. The popularity of soil nail slope is due to its technical suitability as an effective slope stabilization method, ease of construction and is relatively maintenance free. As such, soil nail slope of up to more than 25m high is increasingly being used for Malaysian slopes. However, given the great height of such soil nail slopes, a proper and systematic design procedures based on sound fundamentals and confirmed by extensive research is necessary in order to ensure the soil nail slope performs satisfactorily during its service life. In this paper, review of the available design methods for soil nail slope are presented and finally, a design method is recommended to be adopted for Malaysian practice to ensure safe and economical soil nail slope design in line with international practice.

Keywords: Soil nail; Systematic design method; Two-part wedge; Log-spiral; Slip surface limiting equilibrium

1.0 INTRODUCTION

Soil nail as stabilization measure for distressed slopes and for new very steep cut slopes has the distinct advantage of strengthening the slope without excessive earthworks to provide construction access and working space associated with commonly used retaining system such as reinforced concrete wall, reinforced soil wall, etc. In addition, due to its rather straightforward construction method and is relatively maintenance free, the method has gained popularity in Malaysia for highway and also hillside development projects.

The basic concept of soil nailing is to reinforce and strengthen the existing ground by installing closely-spaced steel bars, called 'nails', into a slope as construction proceeds from 'top-down'. This process creates a reinforced section that is in itself stable and able to retain the ground behind it. The reinforcements are passive and develop their reinforcing action through nail-ground interactions as the ground deforms during and following construction.

Various international codes of practice and design manuals such as listed below are available for design of soil nail:
  a) British Standard BS8006: 1995, Code of Practice for Strengthened/Reinforced Soils and Other Fills.
  b) HA 68/94, Design Methods for the Reinforcement of Highway Slopes by Reinforced Soil and Soil Nailing Techniques.
  c) U.S. Department of Transportation, Federal Highway Administration (FHWA, 1998), Manual for Design and Construction Monitoring of Soil Nail Walls.

In this paper, a brief discussion on the various design methods are presented and subsequently, recommendations are made for design method for soil nail to be adopted for Malaysian practice to ensure safe and economical design of soil nail in line with international practice.

2.0 SOME AVAILABLE DESIGN METHODS

2.1 BS8006: 1995, Code of Practice for Strengthened/Reinforced Soils and Other Fills

The design of soil nail is covered in Section 7.5: Reinforcement of existing ground in BS8006: 1995. In BS8006, the two-part wedge method and the log-spiral method is recommended for analyzing the stability of soil nailed slopes. The use of two-part wedge and log-spiral analysis for soil nailing is illustrated in Figures 1 and 2. While either two-part wedge and log-spiral method can be used to analyze soil nailed slopes, it is highlighted in BS8006 that there is evidence from full-scale observations indicating that log-spiral approach has produced reasonable agreement with actual structures and the use of log-spiral method provides a convenient platform for calculation when shear as well as tension in the nails are to be determined.

The method outline in BS8006: 1995 is based on the limit state principles with the use of partial factors of safety. The design of soil nailing requires that the risk of attaining ultimate limit and serviceability limit states are minimized with the appropriate use of partial factors of safety on loads, materials and economic ramification of failure.

The ultimate limit states which should be considered are:
    a) external stability
        - bearing and tilt failure, see Figure 3a
        - forward sliding, see Figure 3b
        - slip failure around the reinforced soil block, see Figure 3c

    b) internal stability
        - tensile failure of the individual reinforcement elements, see Figure 4a
        - bond failure of the individual reinforcement elements, see Figure 4b

    c) compound stability
        - tensile failure of the individual reinforcement elements, see Figure 5a
        - bond failure of the individual reinforcement elements, see Figure 5b

The serviceability limit states which should be considered are:
    a) external stability
        - settlement of the slope foundation, see Figure 6a

    b) internal stability
        - post-construction strain in the reinforcement, see Figure 6b. It is to be noted however, that in soil nailing, some movement of the nailed mass of earth is expected in order to generate the tensile and shear stresses needed for stability.

Other checks required by BS8006 include face stability to prevent erosion and to ensure load transfer in the active zone. It must be noted that while BS8006 provides guidelines for the design of soil nailing, it is not as comprehensive and user-friendly compared to the design procedures outlined in HA68/94 and FHWA's manual as described in the following sections.
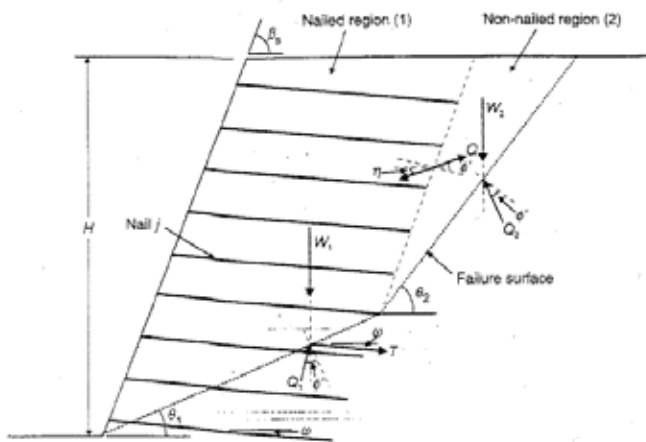
Figure 1: Use of two-part wedge analysis for soil nailing (from BS8006: 1995).
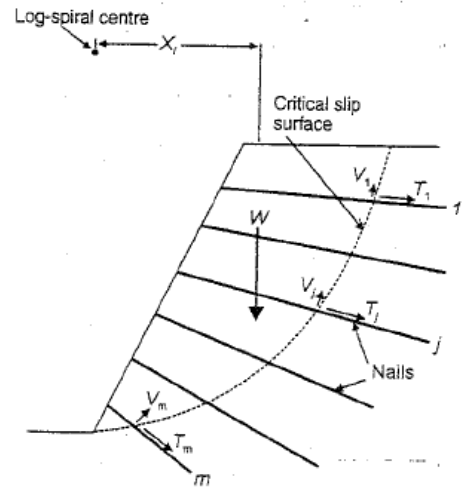

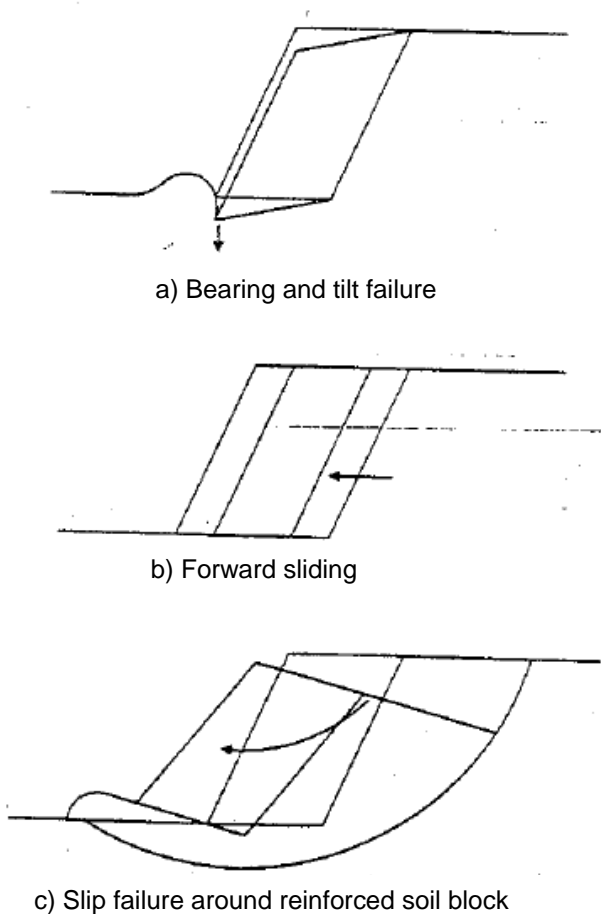Figure 2: Use of log-spiral analysis for soil nailing (from BS8006: 1995).

a) Bearing and tilt failure

b) Forward sliding

c) Slip failure around reinforced soil block

Figure 3: Ultimate limit states – external stability (from BS8006: 1995).

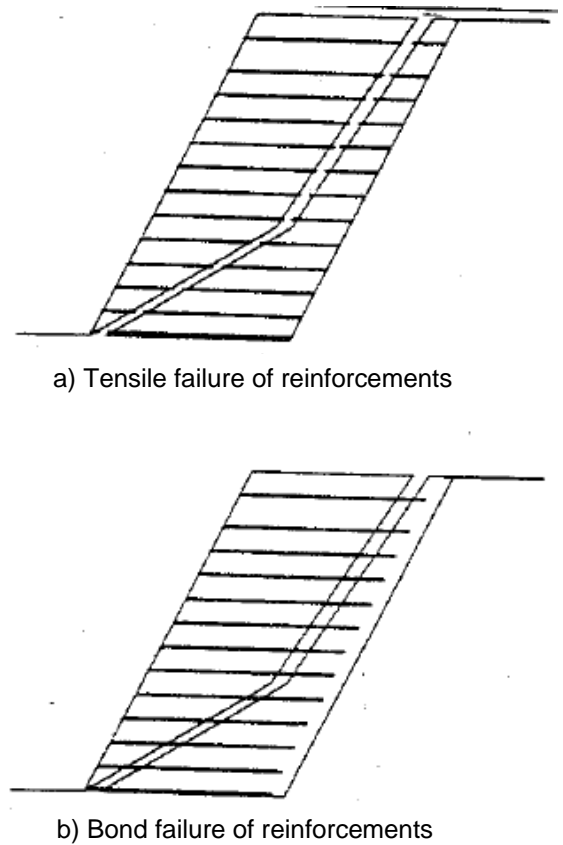a) Tensile failure of reinforcements

b) Bond failure of reinforcements

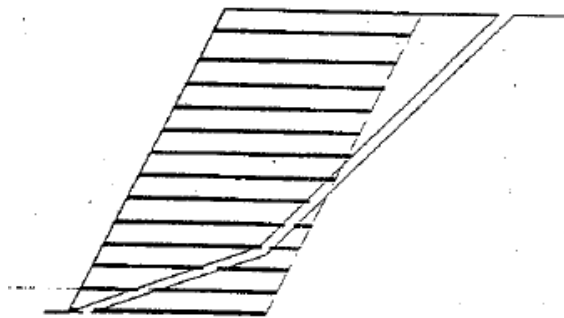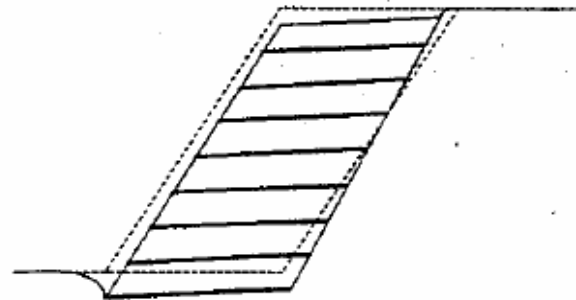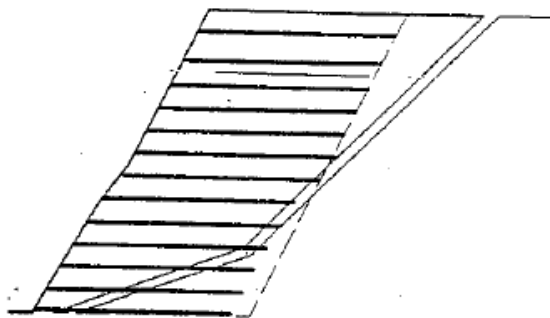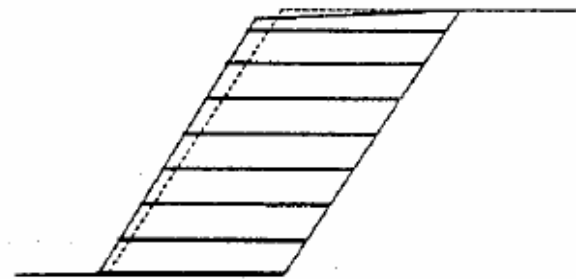Figure 4: Ultimate limit states – internal stability (from BS 8006: 1995).

a) Tensile failure of reinforcements

a) Settlement of slope foundation

b) Bond failure of reinforcements

b) Post construction strain in reinforcement

Figure 5: Ultimate limit states – compound stability (from BS8006: 1995).

Figure 6: Serviceability limit states (from BS8006: 1995).

2.2 HA 68/94, Design Methods for the Reinforcement of Highway Slopes by Reinforced Soil and Soil Nailing Techniques

The design method outlined in HA 68/94 is based on the two-part wedge mechanism which is similar to Figure 1. In HA 68/94, the two-part wedge method is preferred over the log-spiral method due to its simplicity even though it acknowledges that log-spiral is kinematically superior to the two-part wedge. The design procedures outlined in HA 68/94 is more specific compared to BS8006: 1995 such that it provides a step-by-step guidance for the design of soil nailed slope. In HA68/94, the design approach is categorized into two approaches for different applications of soil nail:

 a) Type 1: Design of cuttings into horizontal ground (Figure 7).
 b) Type 2: Cuttings into the toe of existing slopes (Figure 8).

The design procedures generally require the determination of nail length in order to satisfy two mechanisms, i.e. $\mathbf{T_{max\delta}}$ **mechanism and** $\mathbf{T_{o\delta}}$ **mechanism** as illustrated in Figure 9.

The $\mathbf{T_{max\delta}}$ **mechanism** is the critical two-part wedge mechanism which requires the greatest total horizontal reinforcement force. This critical mechanism is unique and will determine the total reinforcement force required and hence the number of reinforcement layers. The $T_{max\delta}$ mechanism also governs the length of the reinforcement zone, L_T at the tope of the slope (Figure 9b).

The $T_{o\delta}$ **mechanism** defines the length L_B required for the reinforcement at the base (Figure 9c). The key mechanism for the purposes of fixing L_B is forward sliding on the basal layer of reinforcement.

Once the number of reinforcement layers, N, length L_T and length L_B are determined, the optimum vertical spacing of the soil nail is determined to complete the design. The optimum vertical spacing of the soil nail is governed by the need to preserve geometrical similarity at all points up the slope, in order to satisfy reduced-scale T_{max} mechanisms which outcrop on the front face (Figure 10).
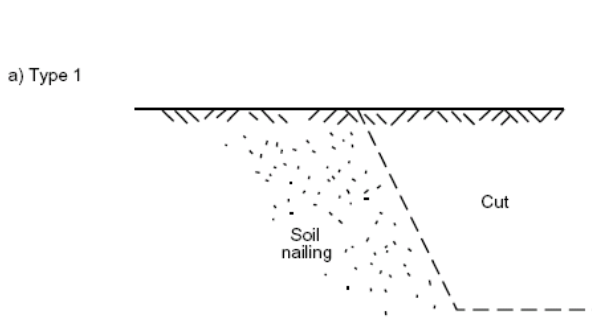

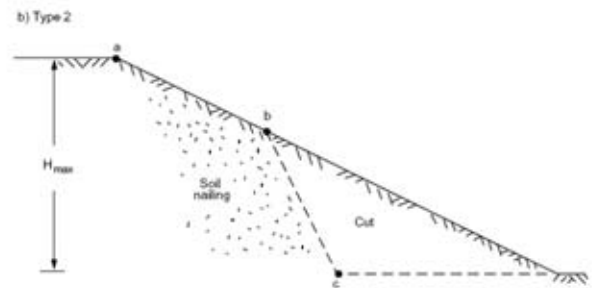Figure 7: Cuttings into horizontal ground (from HA 68/94).

Figure 8: Cuttings into the toe of existing slopes (from HA 68/94).

The design process is completed once the following checks are carried out:
   a) Check construction condition, missing out the lowest nail, but using short term soil strength parameters, (or using effective stress parameters with the value of pore water pressure parameter, r_u relevant during construction).
   b) Check intermediate mechanisms between $T_{max\delta}$ and $T_{o\delta}$ mechanisms (Figure 11).
   c) Check that L_B allows sufficient pull-out length on the bottom row of nails behind the $T_{max\delta}$ mechanism, and if not, extend L_B accordingly. (This is only likely to be critical for small values of drilled hole diameter, d_{hole} or large values of horizontal spacing, S_h.
   d) The assumption of a competent bearing material beneath the embankment slope should be reviewed and, if necessary, underlying slip mechanisms checked (Figure 12).
   e) For grouted nails the bond stress between the grouted annulus and the bar should be checked for adequacy.
   f) If no structural facing is provided then the capacity of waling plates should be checked (Figure 13). It is also likely that increased values of L_T and L_B will be required in this instance.
   g) Check that drainage measures are compatible with the pore water pressures assumed. Consider also the potential effects of water filled tension cracks.
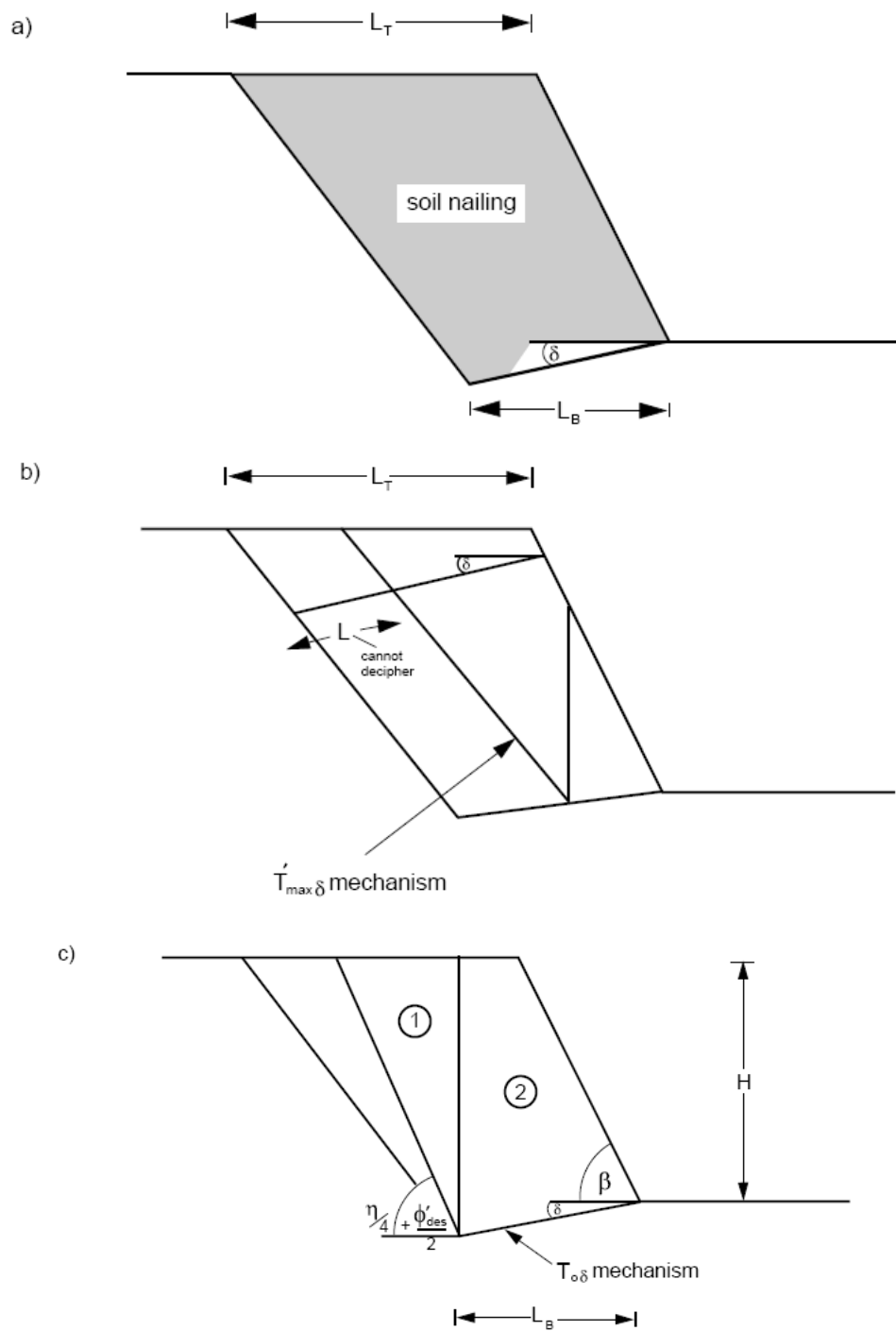   h) Check the adequacy of any front face protection provided, such as shotcrete or netting.

Figure 9: General concepts of design method for soil nail (from HA 68/94).

Figure 10: Reduced-scale T_{max} mechanisms which outcrop on the front face (from HA 68/94).

Figure 11: Intermediate two-part wedge mechanisms (from HA 68/94).

Figure 12: Underlying failure mechanisms (from HA 68/94).

Figure 13: Nail plate bearing capacity (from HA 68/94).

2.3 FHWA, Manual for Design and Construction Monitoring of Soil Nail Walls

The FHWA soil nail design method provides a complete and rational approach towards soil nail design, incorporating the following elements (FHWA, 1998):
   a) Based on slip surface limiting equilibrium concepts.
   b) Incorporates the reinforcing effect of the nails, including consideration of the strength of the nail head connection to the facing, the strength of the nail tendon itself, and the pullout resistance of the nail-ground interface.

c) Provides a rational approach for determining the nominal strength of the facing and nail/facing connection system, for both temporary shotcrete facings and permanent shotcrete or concrete facings. These strength recommendations are based on the results of both full-scale laboratory destructive tests to failure and detailed structural analysis.
d) Recommends design earth pressures for the facing and nail head system, based on soil-structure interaction considerations and monitoring of in-service structures.
e) Addresses both Service Load Design (SLD) and Load and Resistance Factor Design (LRFD) approaches.
f) For SLD, provides recommended allowable loads for the nail tendon, the nail head system and the pullout resistance, together with recommended factors of safety to be applied to the soil strength. Recommendations are separately provided for regular service loading, for seismic loading, for critical structures, and for temporary construction conditions.
g) For LRFD, provides recommended load factors and design strengths (i.e., resistance factors to be applied to the nominal or ultimate strengths) for the nail tendon, the nail head system, the nail pullout resistance, and the soil strength. Recommendations are separately provided for regular service and extreme event (seismic) loading, for critical structures, and for temporary construction conditions.
h) Recommends procedures for ensuring a proper distribution of nail steel within the reinforced block of ground to enhance stability and limit wall deformation.
i) Identifies the facing reinforcement details to be considered, together with the facing and overall soil nail serviceability checks to be performed.
j) Designs the soil nails and wall facing as a combined integrated soil-nail-wall "system".

The design approach recommended by FHWA is similar to both BS8006 and HA 68/94 in addressing the required ultimate limit and serviceability limit states requirements. The major difference between the FHWA's method and the methods of BS8006 and HA 68/94 is on the failure mechanisms assumed. As discussed earlier, both BS8006 and HA 68/94 recommends the use of two-part wedge and log-spiral failure mechanisms in the design of soil nail while FHWA recommends the "slip surface" method.

Slip surface limiting equilibrium design methods consider the global stability of zones of ground defined by potential failure surfaces. These methods have been widely used in conventional slope stability analyses of unreinforced soil and have been demonstrated to provide good correlations with actual performance in such applications. As with the corresponding slope stability models, a critical slip surface is identified as that yielding the lowest calculated factor of safety, taking into account the support provided by the installed reinforcing. The chose slip surface may be contained entirely or partially within the reinforced zone or entirely outside the reinforced zone. The most significant benefits of the slip surface limiting equilibrium approach to soil nail design are (FHWA, 1998):
a) The method considers all internal, external, and mixed potential slip surfaces for the wall and evaluates global stability for each
b) The method is more convenient and accurate for heterogeneous geometries, soil types, and surcharge loadings than other methods such as the simplified earth pressure method

It is the Authors' opinion that the FHWA method with some modifications is adopted for Malaysian practice as the method is complete and it provides a rational approach towards soil nail design inclusive of design aspects for shotcrete, soil nail head, etc. Another advantage of the FHWA method is the assumption of slip surface limiting equilibrium failure mechanism where it can be easily adopted in practical applications as various commercial slope stability analysis software are available to carry out such analysis and generally, practicing engineers are more familiar with slip surface limiting equilibrium failure mechanism as compared to two-part wedge and log-spiral failure mechanisms.

3.0 RECOMMENDED DESIGN PROCEDURES

The recommended design procedures are predominantly based on the methods outlined in FHWA's manual as it is comprehensive, systematic and can be easily adopted for Malaysian practice with some modifications. The design procedures proposed must also comply with the requirements of BS8006 and some good practices from HA 68/94 is also incorporated in order to improve its applicability for Malaysian practice. The major steps involved in the design are summarized as follows:

Step 1: Set Up Critical Design Cross-Section(s) and Select a Trial Design
This step involves selecting a trial design for the design geometry and loading conditions. The ultimate soil strength properties for the various subsurface layers and design water table location (should be below wall base) should also be determined. Table 1 provides some guidance on the required input such as the design geometry and relevant soil parameters. Subsequently, a proposed trial design nail pattern, including nail lengths, tendon sizes, and trial vertical and horizontal nail spacing, should be determined.

Table 1: Input Required for Soil Nail Design

		Remarks
Soil Properties	Bulk density, γ	-
	Ultimate friction angle, ϕ_{ult}	-
Wall Geometry	Ultimate soil cohesion, c_{ult}	-
	Wall height, H	-
	Wall inclination, α	-
	Height of upper cantilever, C	-
	Height of lower cantilever, B	-
	Backslope angle, β	$\beta \not> \phi_{ult}$
	Soil-to-wall interface friction angle, δ	Typically 2/3 ϕ_u
	Nail inclination, η	Typically 15°
	Vertical spacing of nail, S_V	Typically 1.5m to 2.5m
Nail and Shotcrete Properties	Horizontal spacing of nail, S_H	Typically 1.5m to 2.5m
	Characteristic strength of nail, F_y	Typically 460 N/mm^2
	Nail size/diameter	Minimum ϕ20mm
	Ultimate bond stress, Q_u (kN/m) Values given in Tables 2 & 3 in kN/m^2 Multiply with perimeter of grout column (π x D_{GC}) to obtain value in kN/m	Tables 2 & 3
	Shotcrete strength	-
	Thickness of shotcrete	-
	Depth / Width of steel plate	Minimum plate width 200mm
	Thickness of steel plate	Minimum plate thickness 19mm

	Reinforcement for shotcrete	Use BRC reinforcement
	Waler bars	Typically 2T12
	Concrete cover	Typically 50 – 75mm
	Diameter of grout column, D_{GC}	Typically 125mm
Factors of Safety	Soil strength	Table 6
	Nail tendon tensile strength, α_N	Table 6
	Ground-grout pullout resistance, α_Q	Table 6
	Facing flexure pressure, C_F	Table 4
	Facing shear pressure, C_s	Table 4
	Nail head strength facing flexure / punching shear, α_F	Table 5
	Nail head service load, F_F	Section 2.4.5 (FHWA, 1998) Typically 0.5
	Bearing capacity	Typically 2.5

Note: For definition of notation, refer Figure 14.

Table 2: Suggested Ultimate Bond Stress (from Tables 3.2 and 3.3, FHWA, 1998)

Construction Method	Soil Type		Suggested Unit Ultimate Bond Stress kN/m^2 (psi)
Open Hole	Cohesionless Soils	Non-plastic silt	20 – 30 (3.0 – 4.5)
		Medium dense sand and silty sand/sandy silt	50 – 75 (7.0 – 11.0)
		Dense silty sand and gravel	80 – 100 (11.5 – 14.5)
		Very dense silty sand and gravel	120 – 240 (17.5 – 34.5)
		Loess	25 – 75 (3.5 – 11.0)
	Cohesive Soils	Stiff Clay	40 – 60 (6.0 – 8.5)
		Stiff Clayey Silt	40 – 100 (6.0 – 14.5)
		Stiff Sandy Clay	100 – 200 (16.5 – 29.0)

Note: In Malaysia, the ultimate bond stress is usually obtained based on correlations with SPT "N" values and typically ranges from 3N to 5N.

In HA 68/94, the allowable bond stress, Q can be determined using the following equations:

$$Q = \sigma'_n \tan \phi'_{des} + c'_{des} \ (kN/m^2)$$

where

σ'_n = average radial effective stress

ϕ'_{des}, c'_{des} = design values for the soil shearing resistance

The average radial effective stress, σ'_n acting along the pull-out length of a soil nail may be derived from:

$$\sigma'_n = \frac{1}{2}(1 + K_L)\sigma'_v$$

where

σ'_v = average vertical effective stress, calculated mid-way along nail pull-out length

K_L = coefficient of lateral earth pressure parallel to slope

If active conditions (i.e. $\sigma'_h = K_a\sigma'_v$) are assumed to develop perpendicularly to the slope, Burd, Yu & Houlsby, 1989 has shown that:

$$K_L = \frac{1}{2}(1 + K_a)$$

where the value of K_a may be taken as $(1 - \sin\phi'_{des}) / (1 + \sin\phi'_{des})$.

Table 3: Ultimate Bond Stress – Rock (from Table 3.4, FHWA, 1998)

Construction Method	Soil Type	Unit Ultimate Bond Stress kN/m^2 (psi)
	Marl / Limestone	300 – 400 (43.5 – 58.0)
	Phillite	100 – 300 (14.5 – 43.5)
	Chalk	500 – 600 (72.0 – 86.5)
	Soft Dolomite	400 – 600 (58.0 – 86.5)
Open Hole	Fissured Dolomite	600 – 1000 (86.5 – 144.5)
	Weathered Sandstone	200 – 300 (29.0 – 43.5)
	Weathered Shale	100 – 150 (14.5 – 21.5)
	Weathered Schist	100 – 175 (14.5 – 25.5)
	Basalt	500 – 600 (72.0 – 86.5)

Table 4: Recommended Value for Design – Facing Pressure Factors (from Table 4.2, FHWA, 1998)

Nominal Facing Thickness (mm)	Temporary Facings		Permanent Facings	
	Flexure Pressure Factor, C_F	Shear Pressure Factor, C_S	Flexure Pressure Factor, C_F	Shear Pressure Factor, C_S
100	2.0	2.5	1.0	1.0
150	1.5	2.0	1.0	1.0
200	1.0	1.0	1.0	1.0

Table 5: Nail Head Strength Factors - SLD (from Table 4.4, FHWA, 1998)

Failure Mode	Nail Head Strength Factor (Group I)	Nail Head Strength Factor (Group IV)	Nail Head Strength Factor (Group VII) (Seismic)
Facing Flexure	0.67	1.25(0.67)=0.83	1.33(0.67)=0.89
Facing Punching Shear	0.67	1.25(0.67)=0.83	1.33(0.67)=0.89

Headed Stud Tensile Fracture ASTM A307 Bolt Material ASTM A325 Bolt Material	0.50 0.59	1.25(0.50)=0.63 1.25(0.59)=0.74	1.33(0.50)=0.67 1.33(0.59)=0.78

Table 6: Strength Factors and Factors of Safety (from Table 4.5, FHWA, 1998)

Element	Strength Factor (Group I) α	Strength Factor (Group IV)	Strength Factor (Group VII) (Seismic)
Nail Head Strength	α_F = Table 5	see Table 5	see Table 5
Nail Tendon Tensile Strength	$\alpha_N = 0.55$	1.25(0.55)=0.69	1.33(0.55)=0.73
Ground-Grout Pullout Resistance	$\alpha_Q = 0.50$	1.25(0.55)=0.63	1.33(0.50)=0.67
Soil	F = 1.35 (1.50*)	1.08 (1.20*)	1.01 (1.13*)
Soil-Temporary Construction Condition†	F = 1.20 (1.35*)	NA	NA

Note:

Group I: General loading conditions

Group IV: Rib shortening, shrinkage and temperature effects taken into consideration

Group VII: Earthquake (seismic) effects (Not applicable in Malaysia)

* Soil Factors of Safety for Critical Structures

† Refers to temporary condition existing following cut excavation but before nail installation. Does not refer to "temporary" versus "permanent" wall.
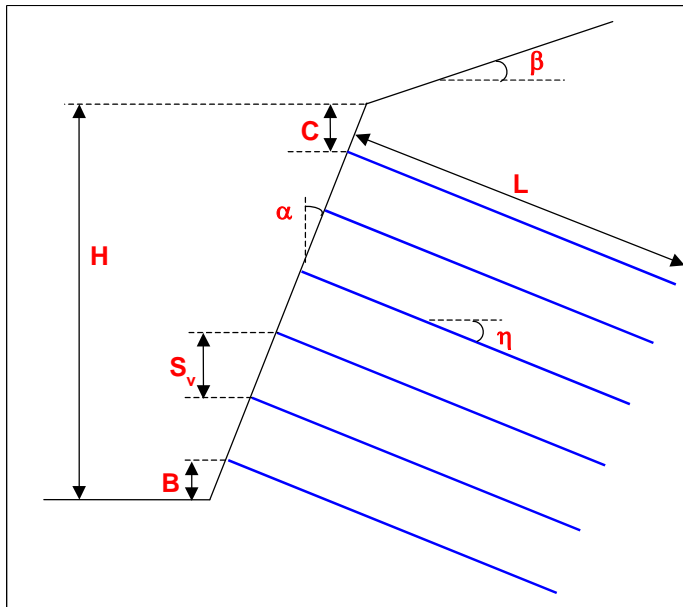

Figure 14: Definition of notation used in Table 1.

Step 2: Compute the Allowable Nail Head Load
The allowable nail head load for the trial construction facing and connector design is evaluated based on the nominal nail head strength for each potential failure mode of the facing and connection system, i.e. flexural and punching shear failure. The flexural and punching strength of the facing is evaluated as follow in accordance to the recommendations of FHWA, 1998:

Flexural strength of the facing:
Critical nominal nail head strength, T_{FN}

$$T_{FN} = C_F (m_{V,NEG} + m_{V,POS}) (8 S_H/S_V) \qquad \text{Eqn. 1}$$

$m_{V,NEG}$ = vertical unit moment resistance at the nail head
$m_{V,POS}$ = vertical unit moment resistance at mid-span locations
S_H = horizontal nail spacings
S_V = vertical nail spacings
C_F = pressure factor for facing flexure (Table 4)

Vertical nominal unit moment,

$$m_v = (A_s F_y / b) [d - (A_s F_y/1.7f'_c b)] \qquad \text{Eqn. 1A}$$

A_s = area of tension reinforcement in facing panel width 'b'
b = width of unit facing panel (equal to S_H)
d = distance from extreme compressive fiber to centroid of tension reinforcement
f'_c = concrete compressive strength
F_y = tensile yield stress of reinforcement

Punching shear strength of the facing:
Nominal internal punching shear strength of the facing, V_N

$$V_N = 0.33 (f'_c (MPa))1/2 (\pi) (D'_c) (h_c) \qquad \text{Eqn. 2}$$

$$D'c = b_{PL} + h_C$$

Nominal nail head strength, T_{FN}
$$T_{FN} = V_N [1 / 1 - C_S(A_C-A_{GC}) / (S_V S_H - A_{GC})] \qquad \text{Eqn. 3}$$

C_S = pressure factor for puching shear (Table 4)
A_C, A_{GC} – refer Figure 15

The allowable nail head load is then the lowest calculated value for the two different failure modes.
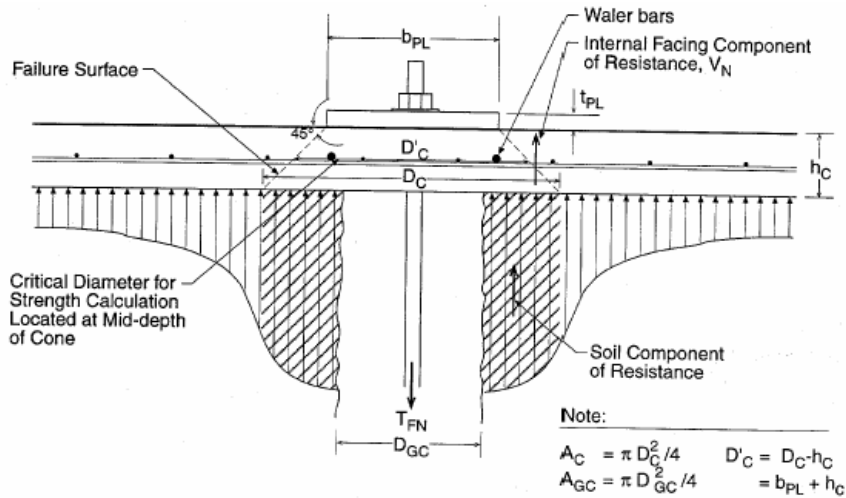
Figure 15: Bearing plate connection details (from FHWA, 1998).

Step 3: Minimum Allowable Nail Head Service Load Check
This empirical check is performed to ensure that the computed allowable nail head load exceeds the estimated nail head service load that may actually be developed as a result of soil-structure interaction. The nail head service load actually developed can be estimated by using the following empirical equation:

$$t_f = F_f \, K_A \, \gamma \, H \, S_H \, S_V \qquad\qquad \text{Eqn. 4}$$

F_f = empirical factor (= 0.5)
K_A = coefficient of active earth pressure
γ = bulk density of soil
H = height of soil nail wall
S_H = horizontal spacing of soil nails
S_V = vertical spacing of soil nails

Step 4: Define the Allowable Nail Load Support Diagrams
This step involves the determination of the allowable nail load support diagrams. The allowable nail load support diagrams are useful for subsequent limit equilibrium analysis. The allowable nail load support diagrams are governed by:

a) Allowable Pullout Resistance, Q (Ground-Grout Bond)
    $Q = \alpha_Q$ x Ultimate Pullout Resistance, Q_u
b) Allowable Nail Tendon Tensile Load, T_N
    $T_N = \alpha_N$ x Tendon Yield Strength, T_{NN}
c) Allowable Nail Head Load, T_F
    $T_F = \alpha_F$ x Nominal Nail Head Strength, T_{FN}
where
α_Q, α_N, α_F = strength factor (Table 6)

Next, the allowable nail load support diagrams shall be constructed according to Figure 16:
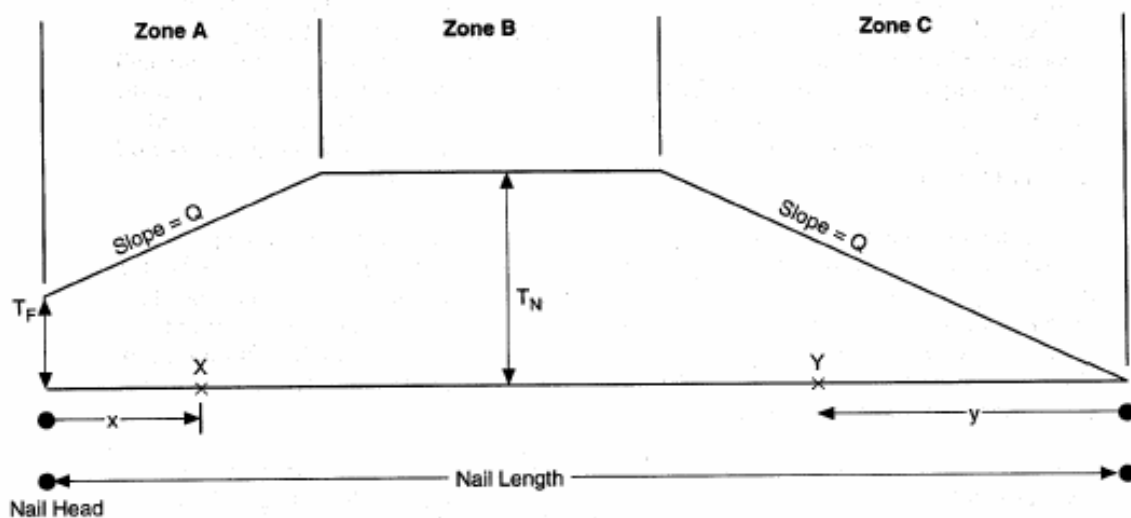
-14-

Figure 16: Allowable nail load support diagram (from FHWA, 1998).

Step 5: Select Trial Nail Spacing and Lengths

Performance monitoring results carried out by FHWA have indicated that satisfaction of the strength limit state requirements will not of itself ensure an appropriate design. Additional constraints are required to provide for an appropriate nail layout. The following empirical constraints on the design analysis nail pattern are therefore recommended for use when performing the limiting equilibrium analysis:

a) Nails with heads located in the upper half of the wall height should be of uniform length
b) Nails with heads located in the lower half of the wall height shall be considered to have a shorter length in design even though the actual soil nails installed are longer due to incompatibility of strain mobilised compared to the nails at the upper half. This precautionary measure is in accordance with the recommendations given by Figure 17. However, further refinement in the nail lengths can also be carried out if more detailed analyses are being carried out, e.g. using finite element method (FEM) to verify the actual distribution of loads within the nails.

The above provision ensures that adequate nail reinforcement (length and strength) is installed in the upper part of the wall. This is due to the fact that the top-down method of construction of soil nail walls generally results in the nails in the upper part of the wall being more significant than the nails in the lower part of the wall in developing resisting loads and controlling displacements as shown in Figure 18. If the strength limit state calculation overstates the contribution from the lower nails, then this can have the effect of indicating shorter nails and/or smaller tendon sizes in the upper part of the wall, which is undesirable since this could result in less satisfactory in-service performance. The above step is essential where movement sensitive structures are situated close to the soil nail wall. However, for stabilization works in which movement is not an important criterion, e.g. slopes where there is no nearby buildings or facilities, the above steps may be ignored.

Step 6: Define the Ultimate Soil Strengths

The representative soil strengths shall be obtained using conventional laboratory tests, empirical correlations, etc. Reference can be made to Tan & Chow, 2004a for discussions on the measurement of soil strength parameters with particular emphasis on residual soils due to the inherent complexities of residual soils. The limit equilibrium analysis shall be carried out using the representative soil strengths (NOT factored strengths).

Step 7: Calculate the Factor of Safety

The Factor of Safety (FOS) for the soil nail wall shall be determined using the "slip surface" method (e.g. Simplified Bishop method, Morgenstern-Price method, etc.). This can be carried out using commercially available software to perform the analysis. The stability analysis shall be carried out iteratively until convergence, i.e. the nail loads corresponding to the slip surface are obtained. The required factor of safety (FOS) for the soil nail wall shall be based on recommended values for conventional retaining wall or slope stability analyses (e.g. 1.4 for slopes in the high risk-to- life and economic risk as recommended by GEO, 2000).
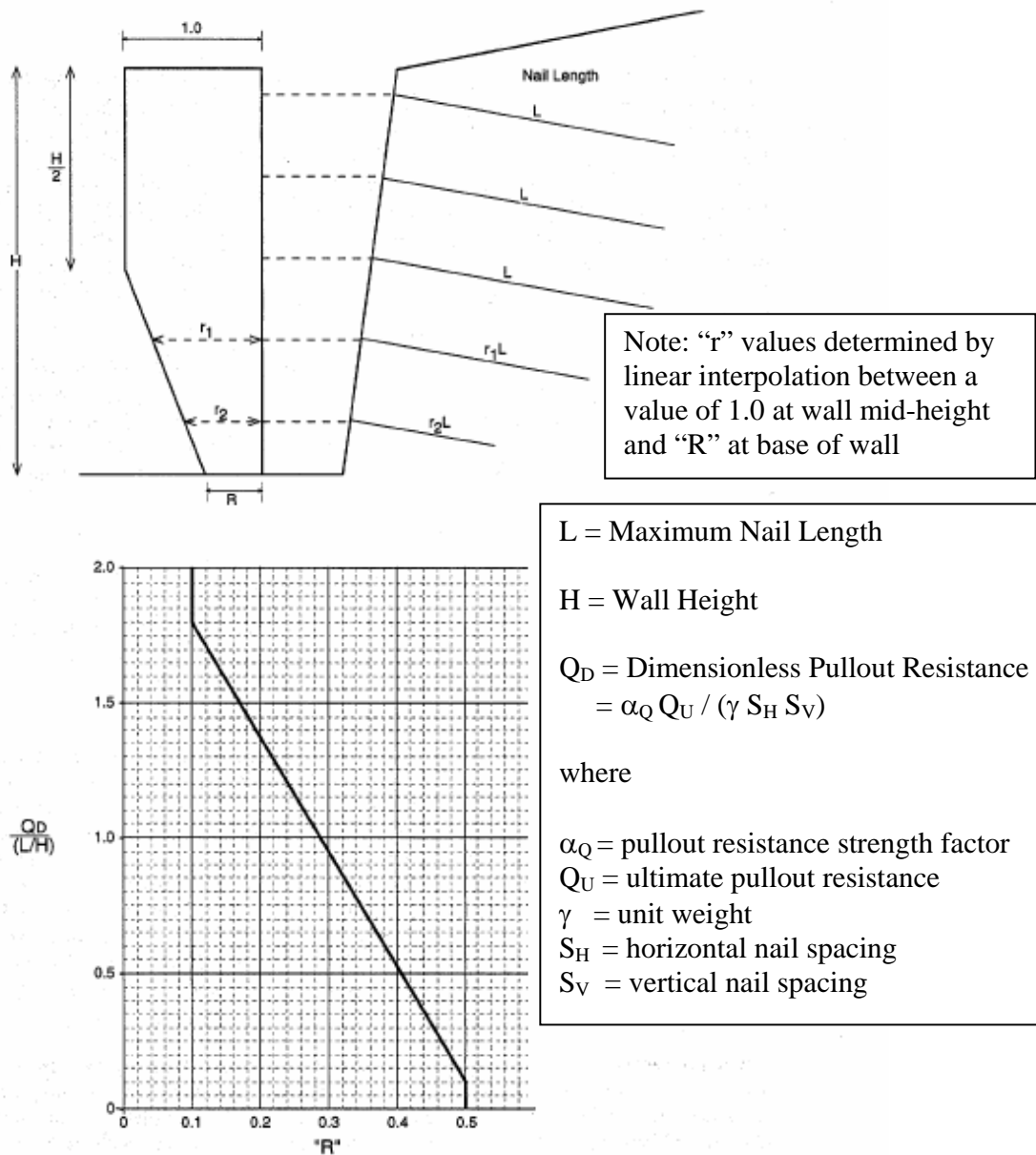

Note: "r" values determined by linear interpolation between a value of 1.0 at wall mid-height and "R" at base of wall

L = Maximum Nail Length

H = Wall Height

Q_D = Dimensionless Pullout Resistance
$\quad = \alpha_Q \, Q_U / (\gamma \, S_H \, S_V)$

where

α_Q = pullout resistance strength factor
Q_U = ultimate pullout resistance
γ = unit weight
S_H = horizontal nail spacing
S_V = vertical nail spacing

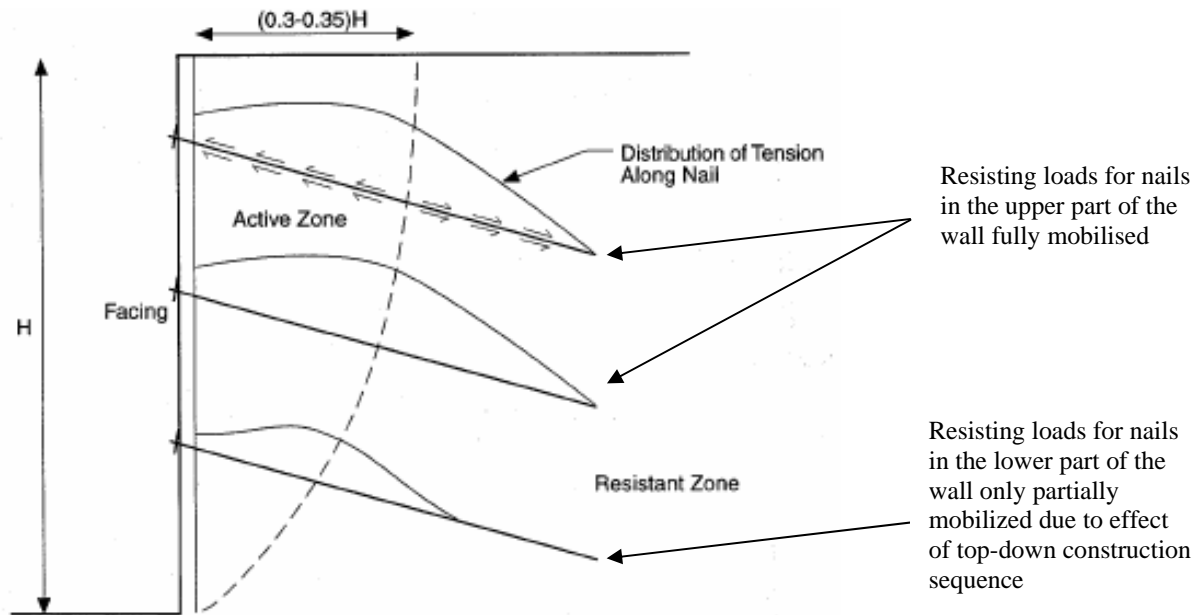Figure 17: Nail length distribution assumed for design (from FHWA, 1998).

Figure 18: Conceptual soil nail behaviour (from FHWA, 1998).

Step 8: External Stability Check

The potential failure modes that require consideration with the slip surface method include:

a) Overall slope failure external to the nailed mass (both "circular" and "sliding block" analysis are to be carried out outside the nailed mass). This is especially important for residual soil slopes which often exhibit specific slip surfaces, defined by relict structure, with shear strength characteristics that are significantly lower than those apply to the ground mass in general. Therefore, for residual soil slopes, the analyses must consider both general or non-structurally controlled slip surfaces in association with the strength of the ground mass, together with specific structurally controlled slip surfaces in association with the strength characteristics of the relict joint surfaces themselves. The soil nail reinforcement must then be configured to support the most critical condition of these two conditions.

b) Foundation bearing capacity failure beneath the laterally loaded soil nail "gravity" wall. As bearing capacity seldom controls the design, therefore, a rough bearing capacity check is adequate to ensure global stability.

Step 9: Check the Upper Cantilever

The upper cantilever section of a soil nail wall facing, above the top row of nails, will be subjected to earth pressures that arise from the self-weight of the adjacent soil and any surface loadings acting upon the adjacent soil. Because the upper cantilever is not able to redistribute load by soil arching to adjacent spans, as can the remainder of the wall facing below the top nail row, the strength limit state of the cantilever must be checked for moment and shear at its base, as described in Figure 19:

For the cantilever at the bottom of the wall, the method of construction (top-down) tends to result in minimal to zero loads on this cantilever section during construction. There is also the potential for any long-term loading at this location to arch across this portion of the facing to the base of the excavation. It is therefore recommended by FHWA, 1998 that no formal design of the facing be required for the bottom cantilever. It is also recommended, however, that the distance between the base of the wall and the bottom row of nails not exceed two-thirds of the average vertical nail spacing.
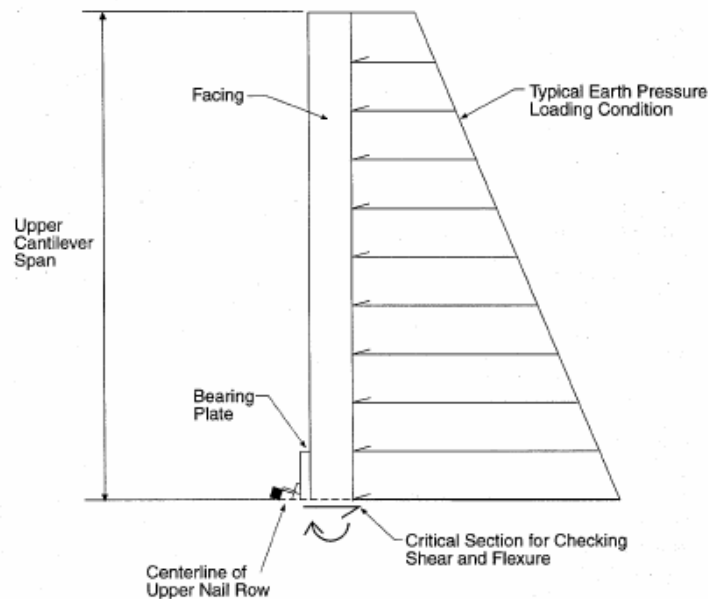
Figure 19: Upper cantilever design checks (from FHWA, 1998).

Step 10: Check the Facing Reinforcement Details

Check waler reinforcement requirements, minimum reinforcement ratios, minimum cover requirements, and reinforcement anchorage and lap length as per normal recommended procedures for structural concrete design.

It is recommended that waler reinforcement (usually 2T12) to be placed continuously along each nail row and located behind the face bearing plate at each nail head (i.e. between the face bearing plate and the back of the shotcrete facing). The main purpose of the waler reinforcement is to provide additional ductility in the event of a punching shear failure, through dowel action of the waler bars contained within the punching cone.

Step 11: Serviceability Checks

Check the wall function as related to excess deformation and cracking (i.e. check the serviceability limit states). The following issues should be considered:
a)   Service deflections and crack widths of the facing
b)   Overall displacements associated with wall construction
c)   Facing vertical expansion and contraction joints

Step 12: Construction Checks

For very high and steep slopes, the critical duration may be during the construction phase. Therefore, construction conditions shall be checked as per recommendations of HA 68/94 by missing out the lowest nail, but using short term soil strength parameters, (or using effective stress parameters with the value of r_u relevant during construction).

In addition, it is also recommended that the critical stages of works for soil nailing to be highlighted to the contractor and be included as part of the construction drawings and work specifications to ensure satisfactory performance of the soil nailed slope in the long-term and also during construction. Further reference can be made to Tan & Chow, 2004b who have discussed various construction aspects of soil nailing in relations to the assumptions made during design in order to ensure successful construction of soil nailed slopes.

4.0 SUMMARY

A systematic and rational design procedure based primarily on the recommendations of FHWA is presented for the design of soil nail. The design method is recommended as it provides a complete design method for soil nail inclusive of other design aspects such as shotcrete, soil nail head, etc. which is important to ensure satisfactory performance of soil nailed slope but is often overlooked in design.

The design procedure presented in this paper also satisfies the ultimate limit and serviceability limit states requirements of BS8006: 1995. Some good practices highlighted in HA 68/94 are also incorporated in the proposed design procedure in order to improve its applicability for Malaysian practice.

Some typical projects where the recommended design procedure has been adopted and successfully constructed are shown in Figures 20 and 21.

Figure 20: 20m high soil nailed slope in Kuala Lumpur.

Figure 21: 30m high soil nailed slope in construction in Kuala Lumpur.

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