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Appraisal of Soil Nailing Design

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Introduction

Geotechnical engineers largely prefer soil nailing as an efficient and cost effective stabilization technique for vertical cuts and slopes (Juran, 1985). Soil nail walls have been particularly well suited in applications such as roadway cut excavations, road widening under existing bridge end, repair and construction of exiting retaining structures, and temporary and permanent excavations in an urban environment (Briaud and Lim, 1997). Analysis of influence of construction factors on the behaviour of soil nail walls have been examined (Sivakumar Babu et al. 2002). As the practical application of soil nailing is increasing with time, a lot of attention is needed to be given to the analysis and design aspects. In such a scenario, appraisal of established analysis and design methods is desirable. In general, appraisal of existing analysis and design philosophies could be done based on full scale laboratory studies, close monitoring of in-situ instrumentation and numerical simulations. However, it is not always practically feasible to conduct full scale laboratory studies and / or in-situ instrumentation; numerical analyses would definitely provide an insight into behaviour of the soil nailed structures. Liew and Khoo (2006) carried out numerical simulations of 14.5 m deep soil nail stabilisation and found that finite element analyses can be successfully utilized to investigate the distresses by revealing the inherent failure mechanism and to back-calculate engineering parameters with validation by laboratory tests, analyses, and hence, optimize the proposed remedial options. In this study an attempt has been made to study the stability of the soil nail walls designed based on the conventional procedure stated in FHWA (2003) using numerical simulations.

Methodology

In order to study the stability of soil nail walls designed based on FHWA guidelines (hereafter stated as ‘conventional design procedure’), three soil nail walls supporting vertical cuts of heights 6 m, 12 m and 18 m are designed based on conventional design procedure. Table 1 presents the material properties adopted for the study. Within a set of assumptions with regard to in-situ conditions, these soil nails walls are then numerically simulated using two-dimensional finite element based computational tool Plaxis. With a view to

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ascertain the accuracy of numerical simulation several trials are carried out. Finally, various design parameters and important failure modes of soil nail wall system are compared and discussed.

Table 1. General Material Properties Adopted for the Study

Parameter	Value
Vertical height of wall, H, m	6.0, 12.0, & 18.0
Face batter, α, degrees	0.0
Slope of backfill, β, degrees	0.0
Soil type	Dense silty sand
Cohesion, c, kPa	5.0
Friction angle, φ, degrees	35.0
Unit weight, γ, kN/m^3	18.9
Modulus of elasticity of soil, E_s, MPa	20.0
Poisson's ratio, ν	0.3
Nail installation method	Rotary drilled
Nail distribution at wall face	Uniform
Grade of steel	Fe 415
Modulus of elasticity of nail, E_n, GPa	200.0
Nail spacing, S_V x S_H , m x m	1.0 x 1.0
Nail inclination (wrt horizontal), i , degrees	15.0
Drill hole diameter, D_{DH} , mm	100.0
Compressive strength of grout, f_{ck} , MPa	20.0
Ultimate bond strength, q_u , kPa	100.0
Modulus of elasticity of grout, E_g , GPa	22.0
FS for global stability, FS_G	1.35
FS for pullout, FS_P	2.00
FS for tensile strength, FS_T	1.80
FS for flexure failure, FS_{FF}	1.35
FS for punching shear, FS_{FP}	1.35

Conventional Design Procedure

A detailed design procedure as well as explanation of various terms involved in design methodology is given in FHWA (2003). This section summarises the various steps involved in conventional procedure adopted for design of soil nail walls considered in this study. It consists of two parts (a) preliminary design and (b) final design. Preliminary design is carried out using simplified design charts and tables. Following are the general steps in the preliminary design:

> For the specific project application, general parameters such as face batter α, backslope β, effective friction angle φ′, and ultimate bond strength q_u are obtained and normalised allowable pullout resistance μ is calculated using equation 1.

$$\mu = \frac{q_u D_{DH}}{FS_P \gamma S_H S_V} \tag{1}$$

> From the relevant design chart, normalised length L / H and normalised force t_{max-s} is obtained.

> Suitable correction factors to L / H ratio and t_{max-s} values obtained in previous step for drillhole diameter other than 100 mm, normalised cohesion c^* value other than 0.02 and global factor of safety other than 1.35 are evaluated and applied.

> The maximum design load in the nail T_{max-s} (kN) using the value of corrected t_{max-s} is calculated using equation 2 and the required cross-sectional area of nail bar A_t is determined from equation 3.

$$T_{max-s} = t_{max-s} \gamma H S_H S_V \tag{2}$$

$$A_t = \frac{T_{max-s} FS_T}{f_y} \tag{3}$$

> Finally, closest commercially available bar size that has a cross-sectional area at least that evaluated in the step (d) is selected.

Final design includes analysis of various failure modes (internal and external) of the soil wall, design of temporary/permanent facing and other site specific considerations. In the present study, temporary facing is only considered. Table 2 presents the summary of various design parameters for the soil nail walls designed based on conventional design procedure.

In Table 2, the maximum axial force T_{max-s} (kN) is calculated from equation 2, whereas the axial force at the nail head T_o (kN) is given by equation 4. Based on the measurements of forces in nails at the head, nail head force T_o (kN) is expressed as:

$$T_o = T_{max-s}\left[0.6 + 0.2\left(S_{max}\right) - 1\right] \tag{4}$$

where, S_{max} is the maximum soil nail spacing in meters (i.e. maximum of S_H and S_V)

Pullout capacity per unit length Q_u (kN/m) (also referred to as load transfer rate capacity) is given by equation 5.

$$Q_u = \pi q_u D_{DH} \tag{5}$$

Max. axial tensile load capacity of nail R_T (kN) is given by the equation 6.

$$R_T = A_t f_y \tag{6}$$

Table 2. Summary of Design Based on Conventional Design Procedure

Design parameter	H = 6 m	H = 12 m	H = 18 m
Nail			
Length, L_N , m	4.0	8.5	13.0
Diameter, d, mm	16.0	20.0	22.0
Maximum axial force, T_{max-s} , kN	27.0	59.0	91.5
Axial force at head, T_o , kN	16.2	35.4	55.2
Pullout capacity per unit length, Q_u , kN/m	31.42	31.42	31.42
Max. axial tensile load capacity, R_T , kN	83.0	130.0	158.0
FS against pullout, FS_P	1.03	0.99	0.98
FS against tensile strength, FS_T	3.07	1.41	0.91
Facing (for H = 6 m, 12 m and 18 m)			
Type	Temporary - Shotcrete		
Thickness, h, mm	100		
Reinforcement*	WWM – 102 x 102 – MW 9 x MW 9		
Other reinforcement	waler bars 2 nos. – 10 mm φ b / w		
Bearing plate grade	Fe 250		
Bearing plate dimensions	225 mm x 225 mm x 25 mm		
Flexure capacity, R_{FF} , kN	100		
Punching shear capacity, R_{FP} , kN	150		
FS against flexure failure, FS_{FF}	6.17	2.83	1.81
FS against punching shear, FS_{FP}	9.26	4.24	2.71

Factor of safety against nail pullout failure FS_P is calculated as the ratio of pullout capacity of nail to the maximum axial force developed in the nail, i.e.

$$FS_P = \frac{R_P}{T_{max-s}} = \frac{Q_u L_P}{T_{max-s}} \tag{7}$$

where L_p is the pullout length of the nail.

Factor of safety against nail tensile strength failure FS_T is calculated as the ratio of maximum axial tensile load capacity of nail to the maximum axial force developed in the nail, i.e.

$$FS_T = \frac{R_T}{T_{max-s}} \tag{8}$$

Factor of safety against facing flexure failure FS_{FF} is calculated as the ratio of facing flexure capacity R_{FF} to the maximum axial load at nail head T_o, i.e.

$$FS_{FF} = \frac{R_{FF}}{T_o} \tag{9}$$

Facing flexure capacity R_{FF} is taken as minimum of:

$$R_{FF}(kN) = \frac{C_F}{265}\left(a_{vn} + a_{vm}\right)\left[mm^2/m\right]\left(\frac{S_H h[m]}{S_V}\right) f_y [MPa] \tag{10a}$$

$$R_{FF}(kN) = \frac{C_F}{265}\left(a_{hn} + a_{hm}\right)\left[mm^2/m\right]\left(\frac{S_V h[m]}{S_H}\right) f_y [MPa] \tag{10b}$$

where C_F is the factor that considers the non-uniform soil pressures behind the facing and is equal to 2 for 100 mm thick temporary facing. a_{vm} and a_{vn} are the vertical reinforcement cross sectional area per unit width at midspan and at nail head respectively. Similarly, a_{hm} and a_{hn} are the horizontal reinforcement cross sectional area per unit width at midspan and at nail head respectively.

Factor of safety against facing punching shear failure FS_{FP} is calculated as the ratio of facing punching shear capacity R_{FP} to the maximum axial load at nail head T_o, i.e.

$$FS_{FP} = \frac{R_{FP}}{T_o} \tag{11}$$

For temporary facing at bearing plate connection, facing punching shear capacity R_{FP} is given by

$$R_{FP}(kN) = C_P V_F = 330\sqrt{f'_c [MPa]}\,\pi D'_C [m] h_c [m] \tag{12}$$

where C_p is a correction factor that accounts for the contribution of the support capacity of the soil (generally taken equal to 1.0 for practical purposes). V_F is the punching shear force acting through the facing section, f'_c is the concrete compressive strength, D'_c is the effective diameter of assumed conical failure surface at the center of the section (for temporary facing equal to sum of the length of bearing plate L_{BP} and facing thickness h) and h_c is the effective depth of conical surface (for temporary facing equal to facing thickness h).

Numerical Simulations

For numerical analysis using PLAXIS (2006), a plane strain state of stresses is assumed and 15 – node triangular elements with medium mesh density are used for finite element discretisation. In-situ soil is modelled as Mohr-Coulomb material, whereas nails and facing elements are simulated as elastic materials. Plate elements are used to model nails and facing. Figure 1 shows a typical finite element model of 12 m high vertical soil nail wall. Numerical simulations are conducted to assess the stability of soil nail wall system. Table 3 presents summary of some of the important results derived based on numerical simulations and these results are used to compare the corresponding parameters obtained using conventional design procedure. For the determination of factors of safety against internal failure modes (i.e. nail pullout failure and nail tensile strength failure) and facing failure modes (i.e. facing flexure failure and facing punching shear failure) the corresponding values of T_{max-s} and T_o obtained from numerical simulations are used in equations 7, 8, 9 and 11 respectively.

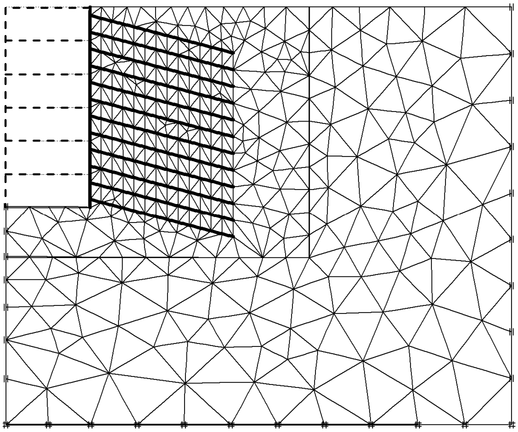

Fig. 1 Typical Finite Element Model of Soil Nail Wall (H = 12 m)

Table 3. Summary of Results of Numerical Simulations

Analysis parameter	H = 6 m	H = 12 m	H = 18 m
Soil nail wall			
FS against global stability, FS_G	1.81	1.79	1.78
Maximum horizontal displacement, %	0.11	0.21	0.29
Maximum earth pressure, kPa	30.65	88.24	131.73
Nail			
Maximum axial force, T_{max-s} , kN	12.55	34.67	61.88
Axial force at head, T_o , kN	11.23	32.17	58.26
Maximum bending moment, M_N , kNm	0.87	2.37	3.79
Maximum shear force, V_N , kN	4.13	11.79	19.22
FS against pullout, FS_P	2.23	1.69	1.45
FS against tensile strength, FS_T	6.61	3.75	2.55
Facing			
Maximum axial force, T_F , kN	17.02	90.43	223.46
Maximum shear force, V_F , kN	27.46	67.65	104.53
Maximum bending moment, M_F , kNm	9.24	14.56	29.63
FS against flexure failure, FS_{FF}	8.90	3.11	1.71
FS against punching shear failure, FS_{FP}	13.36	4.66	2.57

Results and Discussions

In the following sub-sections, some of the important parameters involved in the analysis and design of soil nail walls have been discussed. Results presented in Table 2 and Table 3 has been used for the comparative study between conventional design procedure and analysis results from numerical simulations.

Load Transfer Concept in Soil Nails

As the first stage of soil excavation is completed, the soil strength is mobilized along the uppermost critical failure surface to allow the unsupported soil wall to stand. With the inclusion of first row of nails and installation of temporary facing, some load derived from the deformation of the soil is transferred to these nails through shear stresses along the nails and gets finally translated into axial forces. With the subsequent construction stages to reach the desired excavation depth, an increment in axial forces in nails at each level occurs as the depth of excavation increases. In addition to this, the axial forces in the nails installed in preceding stages increases, however, the percent increment reduces with increasing excavation ratio (x / H, where x is the depth of excavation lift). Moreover, due to the load redistribution, percent contribution of the upper nails to the maximum axial force generated with increasing excavation stages reduces significantly.

To illustrate this aspect, development of axial force with subsequent excavation stages in second nail from top for 6 m high soil nail wall is observed. It is noticed that the maximum axial force in second nail is just 30 % of the maximum axial force developed for the entire soil nail wall system. Similarly, for soil nail walls of height 12 m and 18 m this value for the second nail from top is even lesser (about 20 %). Figure 2 shows the variation in development of axial force in second nail from top with the subsequent excavation stages.

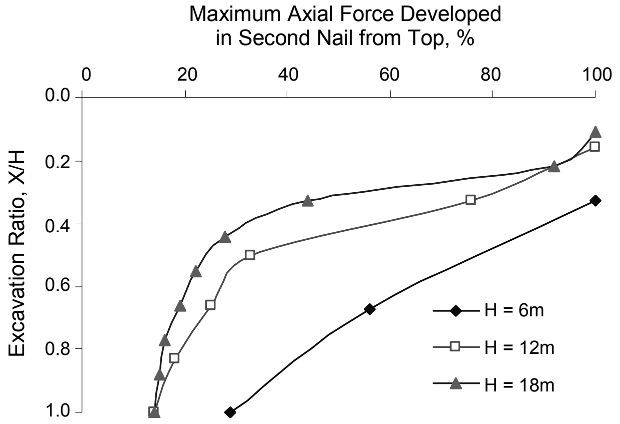

Fig. 2 Axial Force in Second Nail from Top showing Progressive Reduction as the Construction Stages Proceeds

Development of Axial Force in Nails Along their Length

A complex soil-nail interaction occurs behind the wall facing. The loads applied to the soil nails originate as reactions to the outward wall movement during excavation of the soil in front of the wall. Figure 3 shows the simplified distribution of tensile forces in a nail along its length as adopted for design purpose in conventional design procedure. It is based on the assumption that the tensile force in the nail increases at a constant slope Q_u (equal to the pullout capacity per unit length), reaches a maximum value, T_{max}, and then decreases at the rate Q_u to the value T_o at the nail head.

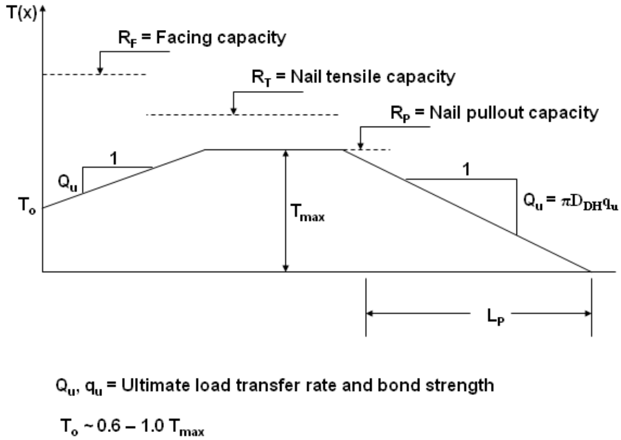

Fig. 3 Simplified Nail Force Diagram (*FHWA, 2003*)

Figure 4 7 shows the simplified nail force diagram along with the nail force distribution obtained by numerical simulation for the alternative nails from the top for a 6 m high soil nail wall. In general, for any particular nail it is

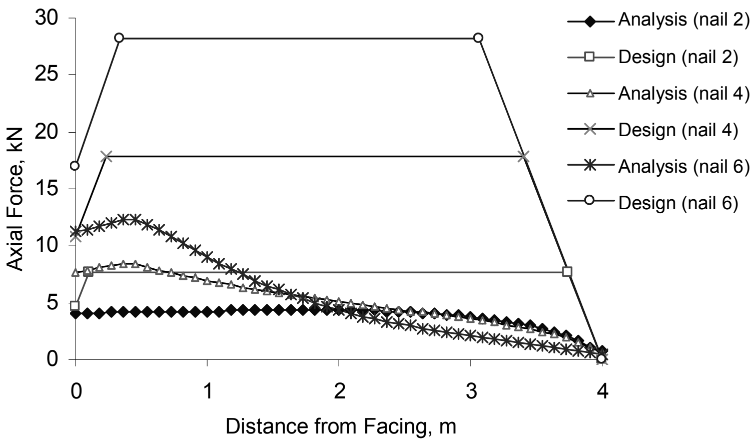

Fig. 4 Comparative Nail Force Diagrams (Alternate Nails from Top, H = 6 m)

observed that for numerical simulations nail force at head T_o is about 90 % of the maximum axial force T_{max} contrary to the evaluated theoretical value of 60 %. Also, the magnitude of maximum axial force T_{max} is also 40 to 50 % less than that calculated theoretically. The position of occurrence of maximum axial force in individual nails, is found to be in good agreement with generally expected approximate range of values of 0.3 H to 0.4 H (0.15 H to 0.2 H in the lower portion of the wall) behind the wall facing (Plumelle et al., 1990; Byrne et al, 1998). Figure 5 shows the axial force distribution in individual nails obtained from numerical simulation for 6 m high soil nail wall.

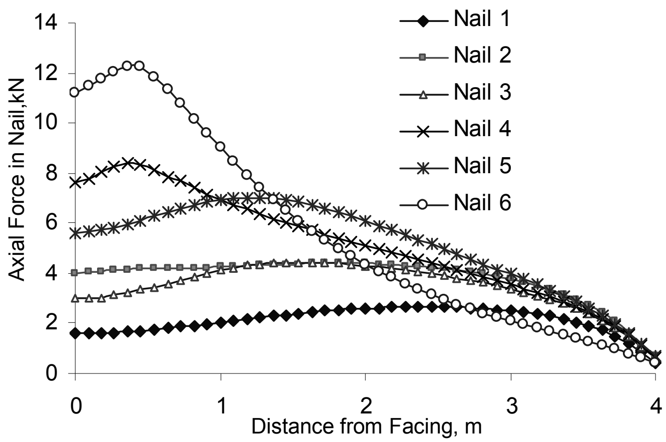

Fig. 5 Development of Axial Force along Nail Length (H = 6 m)

Development of Axial Force in Nails with Depth of Inclusion

For practical purposes, the average maximum in-service tensile force in the nails in upper two-thirds of the wall is $T_{max} = 0.75\ K_a\gamma HS_VS_H$. The tensile force in the lower portion decrease considerably to approximately 50 percent of the value in the upper part. Alternatively, Briaud and Lim (1997) suggest that the average maximum in-service tensile force in the top row of soil nails can be calculated as $T_{max} = 0.65\ K_a\gamma HS_VS_H$. For subsequent soil nail rows, Briaud and Lim (1997) also suggest that the maximum in-service tensile force is only half of the upper nails. Figure 6 shows similar trends in variation for maximum axial force in nails with the depth of inclusion. It illustrates that the average in-service nail force is smaller than that calculated by considering the full active earth lateral pressure distribution.

Maximum Displacement of Soil Nailed Walls

According to Juran (1985) the maximum lateral displacement of soil nailed walls does not generally exceeds 0.2 %. Figure 7 shows in percent the maximum lateral (horizontal) displacement of three soil nailed walls considered in this study. According to conventional design procedure, for a vertical soil nail wall with sandy soil behind, the maximum horizontal displacements at the top of the wall for heights 6 m , 12 m and 18 m are approximately 12 mm, 24 mm and 36 mm respectively (i.e. 1 / 500 of the wall height). From numerical simulation corresponding maximum displacement values are 6.80 mm, 25.03 mm and 53.08 mm respectively. The above results illustrate the efficiency of soil nail walls designed according to the conventional design procedure and also the capability of soil nailed walls to support vertical cuts.

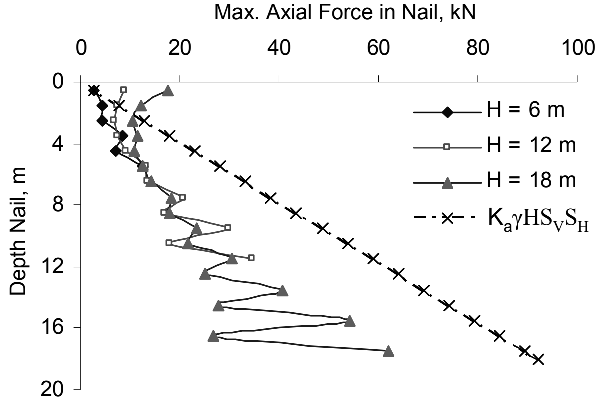

Fig. 6 Variation of Maximum Axial Force in Nails with Depth of Inclusion

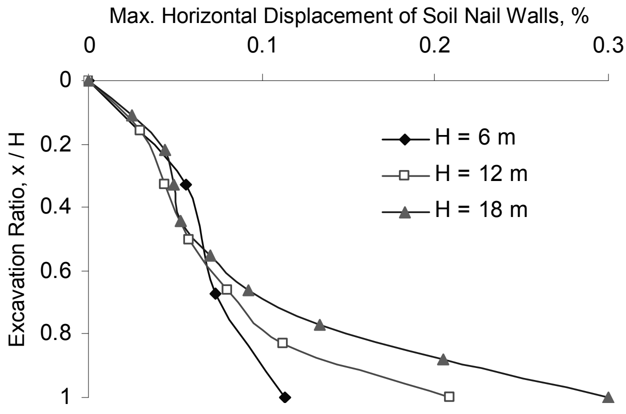

Fig. 7 Maximum Horizontal Displacement of Soil-Nail Walls

Earth Pressure Distribution Behind Soil Nail Wall

The distribution of earth pressure behind vertical face of the soil nailed walls (for H = 12 m & 18 m) is shown in Figure 8. In order to compare with theoretical distributions, earth pressure distribution curves at rest (k_o condition) and active state are also plotted. The maximum values for earth pressure obtained are 30.65 kPa, 88.24 kPa and 131.73 kPa for 6 m, 12 m and 18 m high soil nail walls respectively. It is evident from the Figure 8 that earth pressures distribution behind the vertical face of the soil nail walls lies in between the at rest and active state earth pressure distributions.

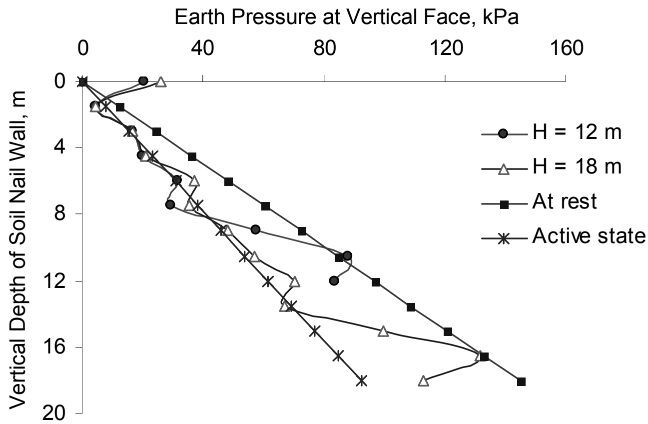

Fig. 8 Earth Pressure Distribution behind Vertical Face of Soil Nail Walls

Factor of Safety Analyses

Factor of Safety Against Global Stability, FS_G

Global factors of safety are determined using strength reduction technique (also known as phi-c Reduction technique, Matsui and San, 1992). The advantage of this method is the identification of critical failure mechanism automatically, which is normally assumed in the conventional analysis.

For each of the three soil nail walls, global factor of safety is obtained after each construction stage. Figure 9 shows the variation of global factor of safety with depth of excavation. Design charts for conventional design procedure are based on the target global factor of safety of 1.35. From numerical simulations global factor safety values 1.81, 1.79 and 1.78 are obtained for soil nail wall of heights 6 m, 12 m & 18 m respectively. This suggests that design is safe from global stability considerations.

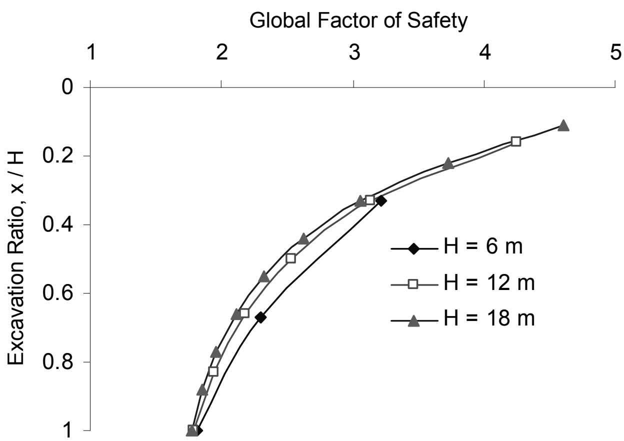

Fig. 9 Variation of Global Factor of Safety with Excavation Depth

Factor of Safety Against Nail Pullout Failure, FS_P

Nail pullout failure is a failure along the soil-grout interface due to insufficient intrinsic bond strength and / or insufficient nail length. It is the primary internal failure mode in a soil nail wall. Recommended minimum factor of safety against nail pullout failure is 2.0. Design charts in the conventional design procedure adopted are based on the criteria to achieve minimum factor of safety against pullout failure as 1.0 (based on allowable bond strength which is ½ of the ultimate pull-out capacity).

Table 2 shows that theoretically this criterion is fulfilled. Numerical simulations yields factor of safety against pullout failure FS_P values as 2.23, 1.69 and 1.45 for soil nail wall heights of 6 m, 12 m and 18 m respectively. It shows that concerned soil nail walls are safe against nail pullout failure, however, design could be revised to attain minimum recommended factor of safety against nail pullout failure.

Factor of Safety Against Nail Tensile Failure, FS_T

Nail tensile failure is another important internal failure mode in a soil nail wall. Tensile failure of a soil nail takes place when the longitudinal force along the soil nail T_{max} is greater than the nail bar tensile capacity. Recommended minimum factor of safety against nail tensile failure is 1.80. Though, numerical simulations yield factor of safety against nail tensile failure FS_T values as 6.61, 3.75 and 2.55 for soil nail wall of heights 6 m, 12 m and 18 m respectively, theoretical calculations give corresponding values as 3.07, 1.41 and 0.91 respectively. It shows that factors of safety against nail tensile strength obtained using conventional design procedure are less than 50 % of the corresponding values from numerical simulations.

Factor of Safety Against Facing Failure Modes

Flexure failure and punching shear failure are the two most potential facing failure modes influencing the stability of the soil nail walls. Flexure failure of facing takes place due to the excessive bending beyond the facing's flexure capacity. Punching shear failure occurs in the facing around the nails and is evaluated at bearing plate connection for temporary facings. Minimum recommended value of factor of safety against both facing flexure failure FS_{FF} as well as facing punching shear failure FS_{FP} is 1.35. Results presented in Table 2 and Table 3 show that the corresponding factor of safety values for facing failure modes obtained theoretically as well as from numerical simulations are significantly more than minimum recommended value.

Contribution of Shear and Bending Stiffness of Nails

The shear and bending resistances of the soil nail are mobilized only after relatively large displacements have taken place along the slip surface. Elias and Juran (1991) have found that shear and bending nail strengths contribute less than 10 percent to the overall stability of the wall. Due to this relatively modest contribution, the shear and bending strengths of the soil nails are conservatively disregarded in the conventional design procedure. From numerical simulations, the magnitude of maximum bending moment and shear force developed in the soil nails are found to be 2.46 kNm and 13.27 kN for the wall height of 18 m.

Conclusions

In this study an attempt has been made to appraise the comprehensive and most prevalently used analysis and design method for soil nail walls. Comparison of various design parameters obtained using conventional design procedure and numerical simulations, such as, lateral displacement of soil nail walls, factor of safety analyses etc. suggests that conventional design procedure adopted for this study provides a safe design. The contribution of shear and bending stiffnesses of nails appear to be of less significance as far as overall stability of soil nail wall system is considered. This aspect is evident from the results of numerical simulations and is in good agreement with previous research findings. Soil nailing is an efficient, economical and feasible option to support vertical or near vertical cuts made in soil for various slope stability applications in geotechnical engineering.

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Notations

Following notations are used in this paper.

a_{hm}	Horizontal reinforcement cross sectional area per unit width at midspan
a_{hn}	Horizontal reinforcement cross sectional area per unit width at nail head
A_t	Cross-sectional area of nail bar
a_{vm}	vertical reinforcement cross sectional area per unit width at midspan
a_{vn}	vertical reinforcement cross sectional area per unit width at nail head
c	soil cohesion
c^*	normalised cohesion = $c/\gamma H$
C_F	factor considering the non-uniform soil pressures behind the facing
C_p	correction factor for the contribution of support capacity of soil
d	diameter of the reinforcement member i.e. nail
D'_c	equivalent conical failure surface diameter at the center of facing
D_{DH}	drill hole diameter
E_g	modulus of elasticity of grout

E_n	modulus of elasticity of nail
E_s	modulus of elasticity of soil
f'_c	concrete compressive strength
f_{ck}	compressive strength of grout
FS_{FF}	factor of safety against flexure failure
FS_{FP}	factor of safety against punching shear failure
FS_G	factor of safety for global stability
FS_P	factor of safety against nail pullout failure
FS_T	factor of safety against nail tensile strength failure
f_y	yield strength of tensile reinforcement i.e. nail
H	vertical height of wall
h	thickness of facing
h_c	effective depth of conical surface
i	nail inclination (wrt horizontal)
K_a	active earth pressure coefficient
L_{BP}	length of bearing plate
L_N	length of the soil nail
L_p	pullout length of the nail
M_F	maximum bending moment in facing
q_u	ultimate bond strength
Q_u	pullout capacity per unit length
R_{FF}	facing flexural capacity
R_{FP}	facing punching shear capacity
R_T	maximum axial tensile load capacity of nail
S_{max}	maximum soil nail spacing (i.e. maximum of S_H and S_V)
S_H	horizontal nail spacing
S_V	vertical nail spacing
T_F	maximum axial force in facing
T_{max-s}	maximum axial force
t_{max-s}	normalised axial force
T_o	axial force at nail head (i.e. force in nail at facing)
V_F	punching shear force at facing
V_N	maximum shear force in nail
x	depth of excavation
α	wall face batter (wrt vertical)
β	slope of backfill (wrt horizontal)
γ	soil unit weight
μ	normalised allowable pullout resistance
ν	Poisson's ratio for soil
φ	Soil friction angle

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