Lecture 33

NPTEL Course

GROUND IMPROVEMENT

GROUND REINFORFEMENT USING SOIL NAILING

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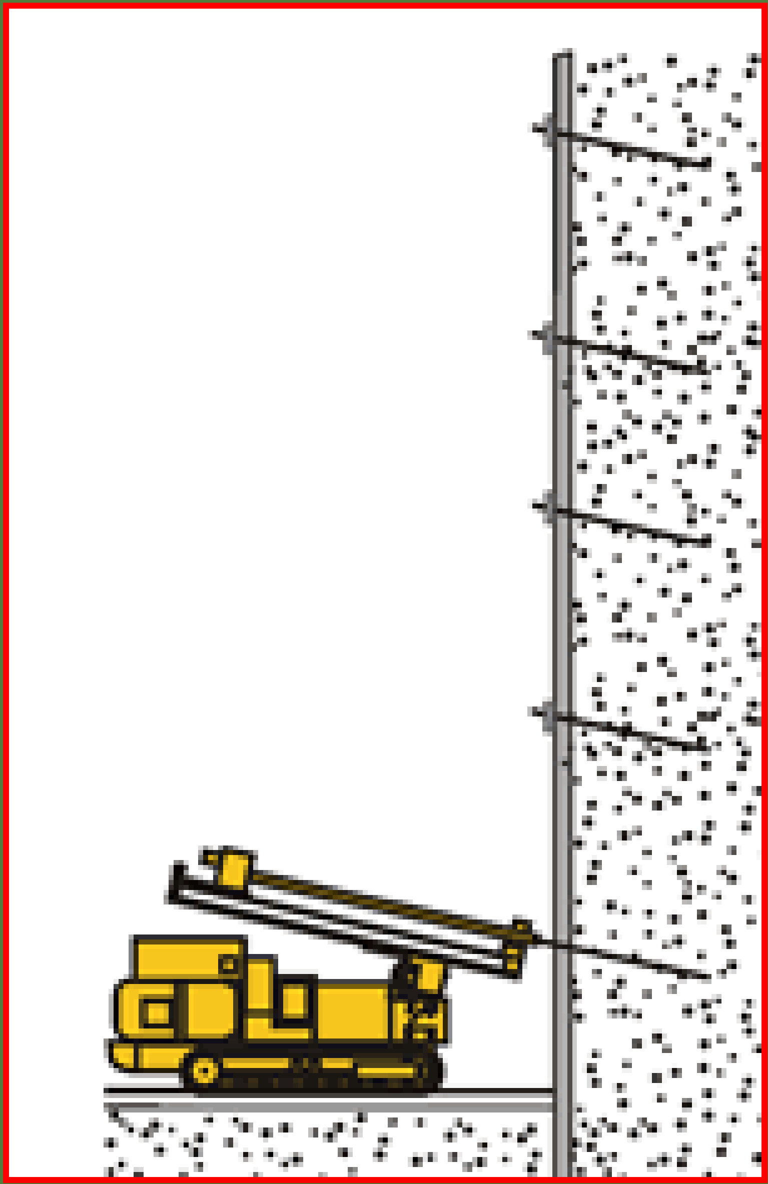
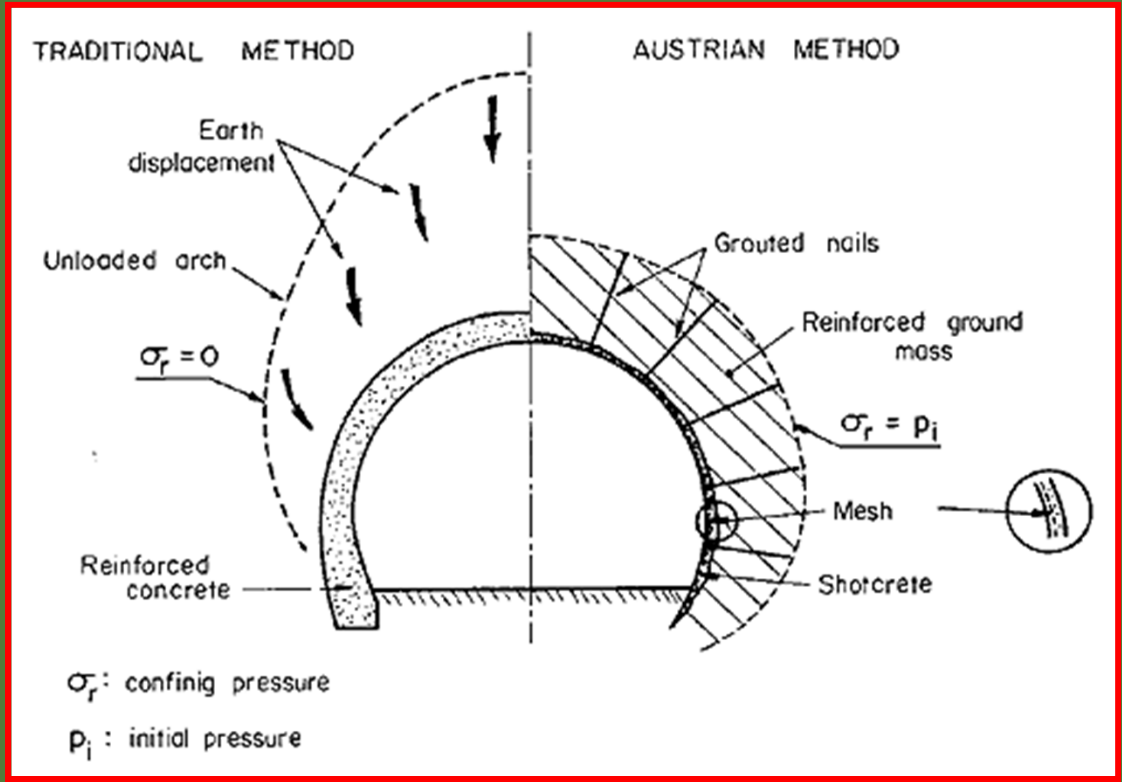
Definition

- Soil nailing consists of the passive reinforcement of existing ground by installing closely spaced steel bars (i.e., nails), which may be subsequently encased in grout.
- As construction proceeds from the top to bottom, shotcrete or concrete is also applied on the excavation face to provide continuity.
- In a soil-nailed retaining wall, the properties and material behaviour of three components—the native soil, the reinforcement (nails) and the facing element—and their mutual interactions significantly affect the performance of the structure.



Origin and Development



The origin of soil nailing can be traced to a support system for underground excavations in rock referred to as the New Austrian Tunneling Method (Rabcewicz, **1964**a, 1964b, 1965). This tunneling method consists of the installation of passive steel reinforcement in the rock (e.g., rockbolts) followed by the application of reinforced shotcrete.

- One of the first applications of soil nailing was in 1972 for a railroad widening project near Versailles, France, where an 18 m (59 ft) high cut-slope in sand was stabilized using soil nails (Rabejac and Toudic 1974). Clouterre research program, (Schlosser 1983; Clouterre 1993) is another step.
- In Germany, the first use of a soil nail wall was in 1975 (Stocker et al. 1979). The first major research program on soil nail walls was undertaken in Germany from 1975 through 1981 by the University of Karlsruhe and the construction company Bauer. (Gassler and Gudehus 1981; Schlosser and Unterreiner 1991).
- In US, the first FHWA document on soil nailing was issued through FHWA's Office of Research and Development (Elias and Juran 1991). Updated version of above FHWA soil nailing manual was made public in 2003 (Carlos et al. 2003).
- In India use of soil nailing technology is gradually increasing and guidelines have been made by IRC with the help of Indian Institute of Science, Bangalore.

Favorable (Un-) Ground Conditions

- Critical excavation depth of soil is about 1m – 2m (3 to 6 ft) high vertical or nearly vertical cut.

- All soil nails within a cross section are located above the groundwater table and if the soil nails are below the groundwater table, the groundwater does not adversely affect the face of the excavation, the bond strength of the interface between the grout and the surrounding ground, or the long-term integrity of the soil nails (e.g., the chemical characteristics of the ground do not promote corrosion).

- **Favorable Soils** : Stiff to hard fine –grained soils, Dense to very dense granular soils with some apparent cohesion, Weathered rock with no weakness planes and Glacial soils etc.

- **Unfavorable Soils** : Dry, poorly graded cohesion less soils, Soils with high groundwater, Soils with cobbles and boulders, Soft to very soft fine-grained soils, Organic soils etc.

Advantages

Requires smaller right of way.

Construction is less disruptive to traffic.

Causes less environmental impact.

Relatively fast in construction and uses typically less construction materials and hence, economic.

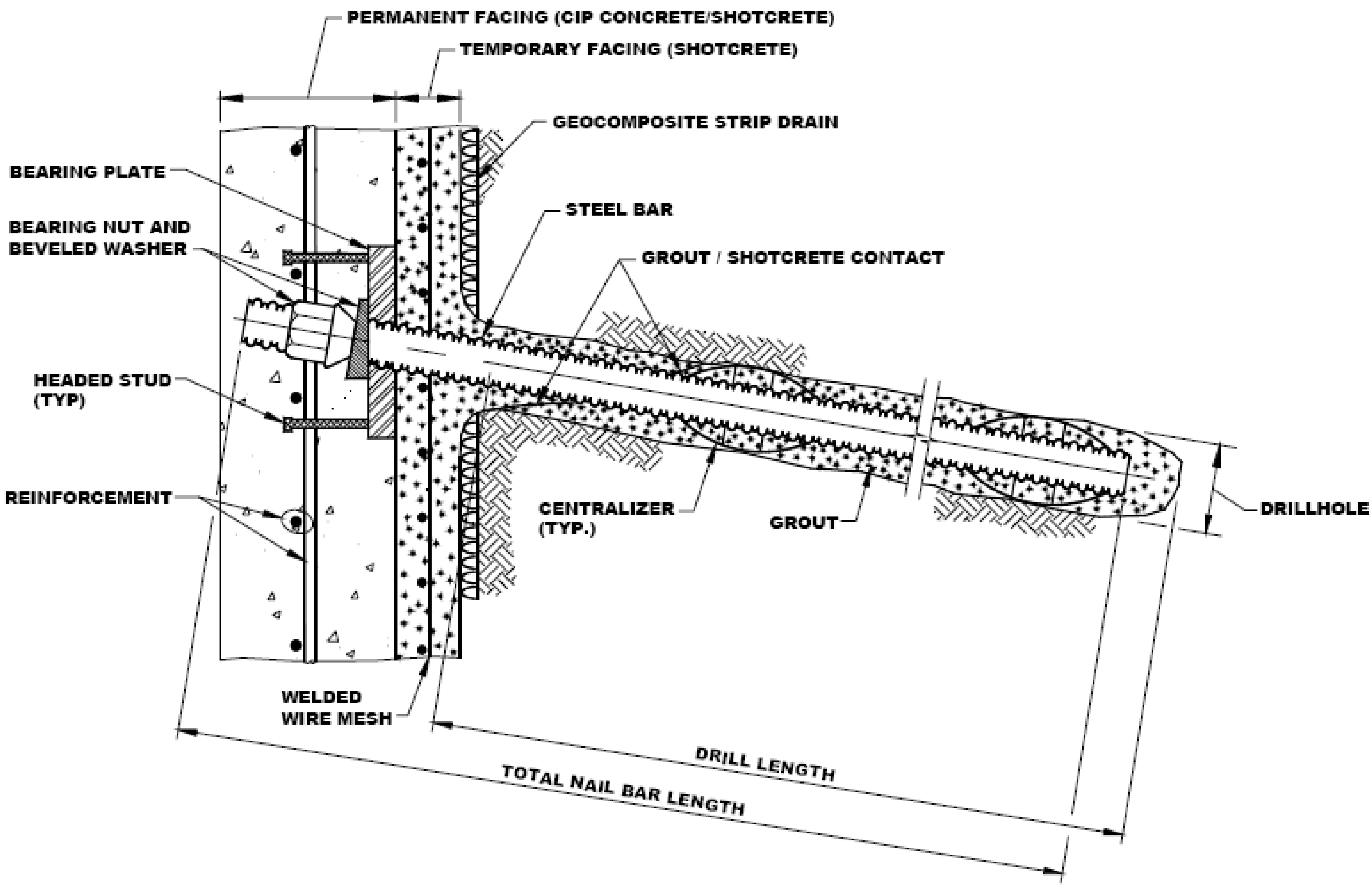
Limitations

The occurrence of utilities may place restrictions on the location, inclination, and length of soil nails (particularly in the upper rows).

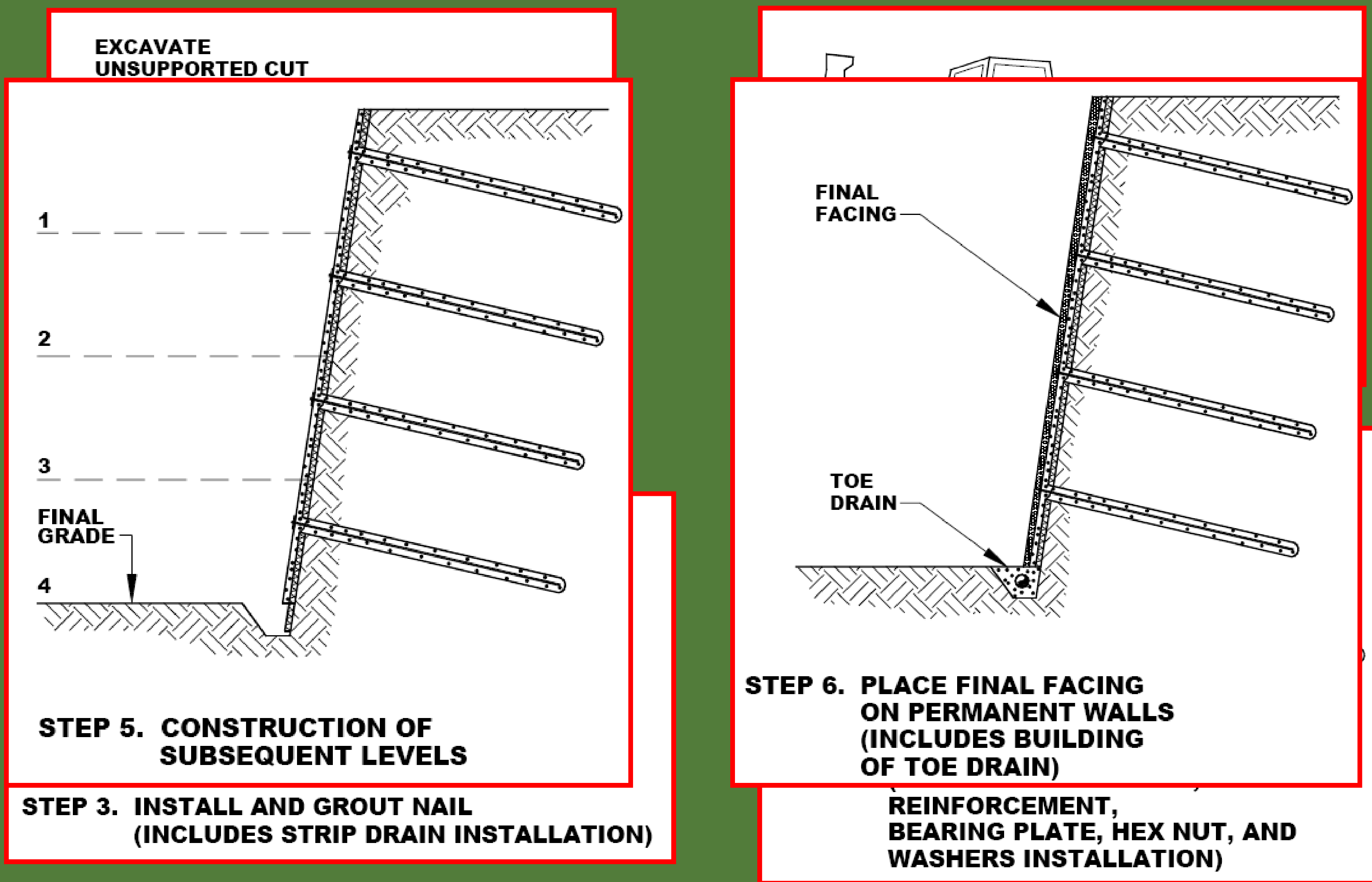
Soil nail walls are not well-suited where large amounts of groundwater seeps into the excavation because of the requirement to maintain a temporary unsupported excavation face.

Construction of soil nail walls requires specialized and experienced contractors.

Components of Soil Nail Wall



Construction Method



Applications

Applications

Small and Large Scale Field Studies

- Stocker et al. (1979)
- Shen et al. (1981a, b)
- Shen et al. (1982)
- Gassler and Gudehus (1981)
- Gassler (1988)
- Juran (1985)
- Kitamura et al. (1988)
- Plumelle et al. (1990)
- Plumelle and Schlosser (1990)
- Kakurai and Hori (1990)
- Stocker and Riedinger (1990)
- Nanda (1995)
- Kim et al. (1995)
- Kim et al. (1996)
- Yamamota et al. (2001)
- Morgan (2002)
- Menkiti and Long (2008)
- Li et al. (2008)

and many more….

Studies on Analyses and Design Aspects

Schlosser (1982)
Gassler and Gudehus (1983)
Blondeau et al. (1984)
Sano et al. (1988)
Juran and Chen (1989)
Bridle (1989)
Jewell and Pedley (1990a, b)
Juran et al. (1990a, b)
Long et al. (1990)
Jewell and Pedley (1990a-b, 1991)
Leshchinsky (1990)
Schlosser (1991)
Juran et al. (1992a, b)
Jewell and Pedley (1992)
Kirsten and Dell (1992)
Kirsten (1992)
Sabahit et al. (1995)
Bang et al. (1996)
Patra (1998)
Bang and Nyaz (2001)
Joshi (2003)
Sheahan and Ho (2003)
Patra and Basudhar (2005)
Mittal (2006)

and many more….

Studies on Soil-Nail Interaction (Pullout Behaviour)

Juran et al. (1983)
Palmeira (1987)
Tei (1993)
Bridle and Davies (1997)
Milligan and Tei (1998)
Morris (1999)
Luo et al. (2000)
Tan et al. (2000)
Luo et al. (2002)
Hong et al. (2003)

Junaideen et al. (2004)
Chu and Yin (2005a, b)
Chai and Hayashi (2005)
Yin and Su (2006)
Pradhan et al. (2006)
Su et al. (2007)
Su et al. (2008)
Tan et al. (2008)
Zhou and Yin (2008)
Yin et al. (2009)
Zhang et al. (2009)

and many more….

Studies on Numerical Analyses and Modelling

Sawicki et al. (1988)
Lee et al. (1995)
Kim et al. (1997)
Briaud and Lim (1997)
Smith and Su (1997)
Zhang et al. (1999)
Ng and Lee (2002)
Sivakumar Babu et al. (2002)
Tan et al. (2005)
Cheuk et al. (2005)
Fan and Luo (2008)

and few more….

Studies on Seismic Stability and Performance

Sabahit et al. (1996)
Tatsuoka et al. (1996)
Vucetic et al. (1998)
Tufenkjian and Vucetic (2000)
Vucetic et al. (2001)
Takahashi et al. (2001)
Hong et al. (2005)
Saran et al. (2005)

and few more….

Studies on Application Case Histories

Tan et al. (1988)
Wong et al. (1997)
Maric et al. (2001)
Murthy et al. (2002)
Turner and Jensen (2005)
Sivakumar Babu et al. (2007)
Yang (2007)
and few more….

Studies Based on Reliability Analysis

Yaun et al. (2003)

Soil Nailing International Codes and Standards

UK Codes and Standards

- BS 8006: 1995, BS 8002: 1994, BS 8081: 1989
- TRL Report 380 (1993)
- HA 68/94 (reinforced highway slopes)
- RT/CE/S/071 (2002) (design of earthworks & earthwork remediations)

Other International Codes and Standards

- Eurocode – EC7
- Euronorme – prEN 14490 (execution of special geotechnical works – soil nailing)
- France – Recommendations Clouterre (1991)
- **USA – FHWA manual for design & construction monitoring of soil nail walls (1998 and 2003)**
- Scandinavia – Nordic handbook (2002)
- Hong Kong – Watkins & Powell (1992) and many GEO publications
- Hong Kong - GEOGUIDE (2008)

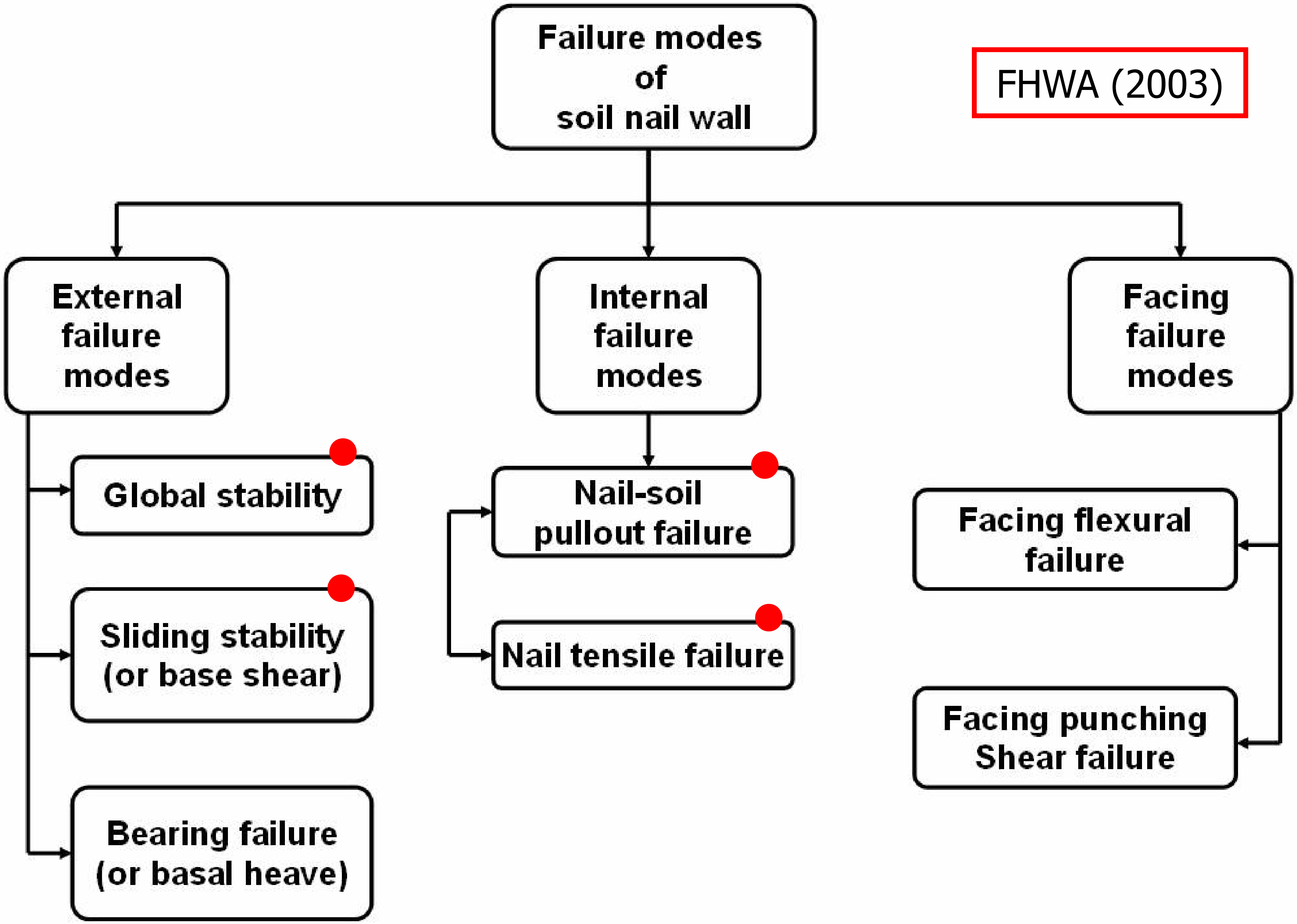
Conventional analysis and design Method

- Federal Highway Administration (FHWA) has documented comprehensive information on the analysis, design, and construction of soil nail walls in highway engineering applications in its technical manual FHWA (2003) entitled

  "Geotechnical Engineering Circular No. 7 – Soil Nail Walls".

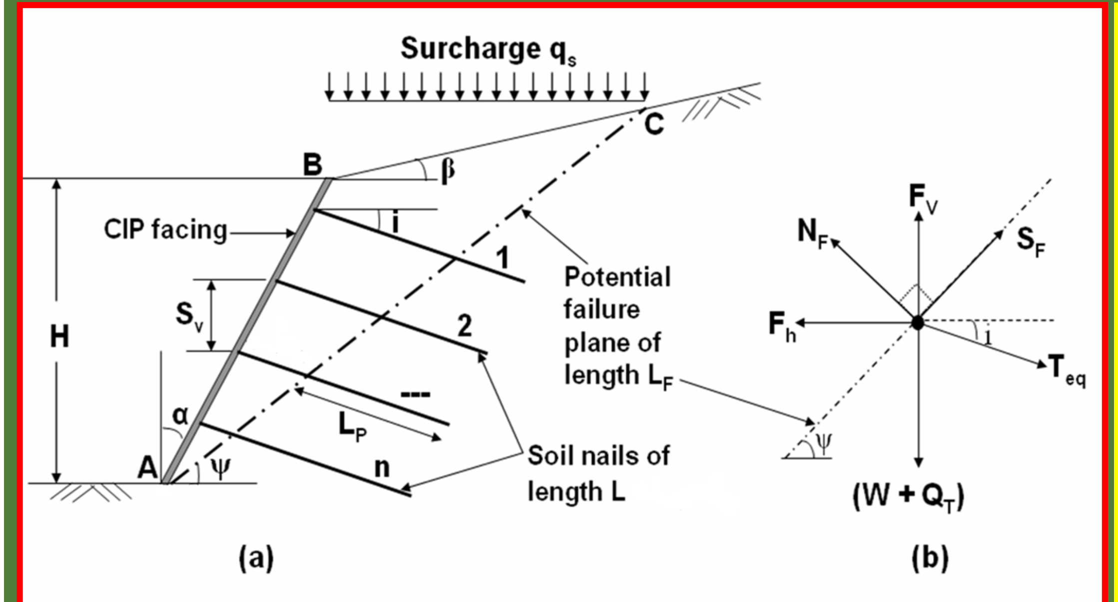
FHWA. (2003). Geotechnical engineering circular No. 7 - soil nail walls. *Report FHWA0-IF-03-017*, U. S. Department of Transportation, Federal Highway Administration, Washington D. C.

FHWA (2003)



Principal failure modes of soil nail walls

Global Stability Failure



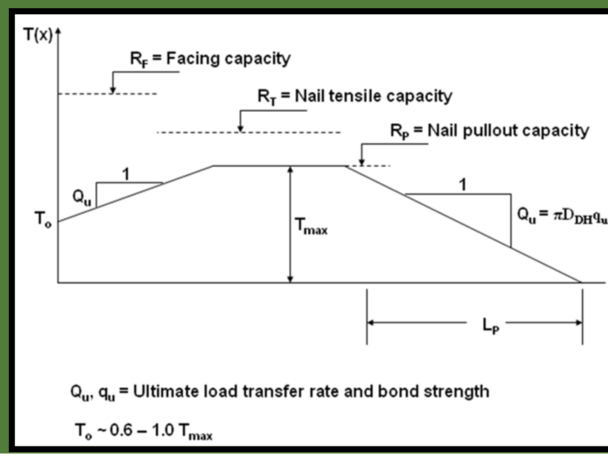
Minimum recommended factor of safety for global stability, FS_G			
Temporary walls		Permanent Walls	
Static	Seismic	Static	Seismic
1.35	1.10	1.35	1.10

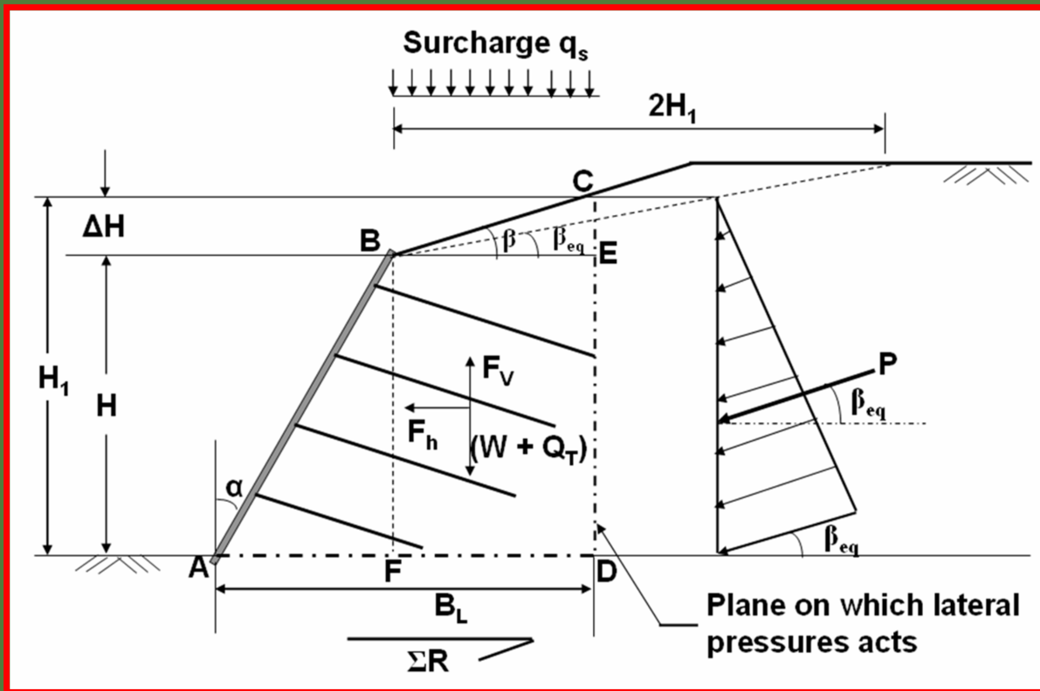
$$FS_G = \frac{\sum R}{\sum D} = \frac{cL_F + T_{eq}\cos(\psi - i) + \left[(W + Q_T - F_v)\cos\psi + T_{eq}\sin(\psi - i) - F_h \sin\psi\right]\tan\phi}{(W + Q_T - F_v)\sin\psi + F_h\cos\psi}$$

$\psi = 45 + (\phi/2)$ (Sheahan and Ho 2003; FHWA 2003)

$$T_{eq}[kN/m] = \frac{1}{S_h}\sum_{j=1}^{n}(T_{all})_j \qquad T_{all} = \min.\text{of } R_T \text{ and } R_P$$

$$(R_P)_z[kN] = (\pi D L_P q_u)/1000 \qquad (R_T)_z[kN] = (0.25\pi d^2 f_y)/1000$$





Sliding Stability Failure

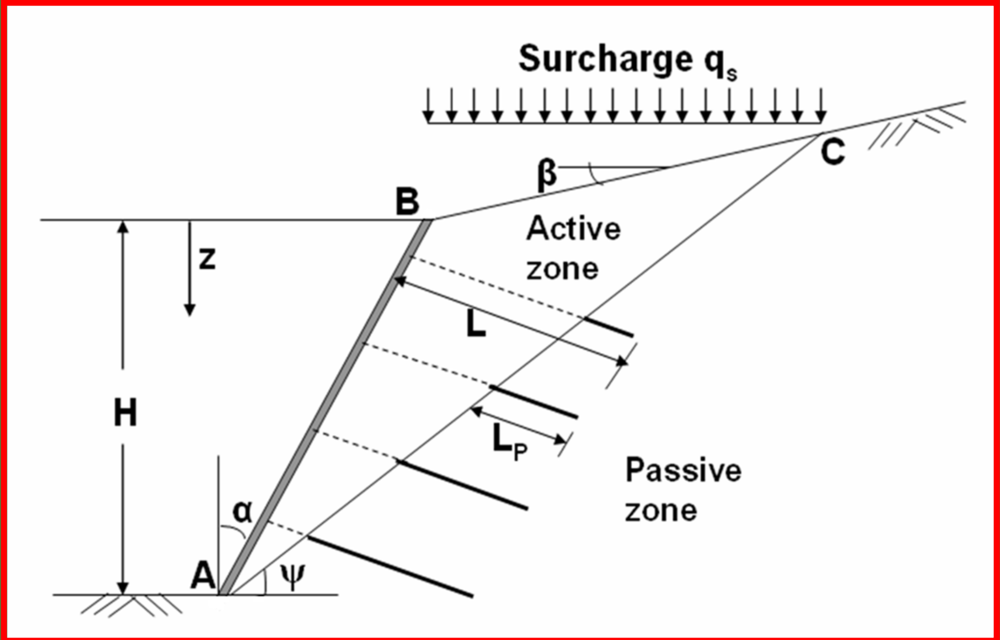
$$FS_{SL} = \frac{\sum R}{\sum D} = \frac{c_b B_L + \left(W + Q_T - F_v + P \sin \beta_{eq}\right) \tan \phi_b}{F_h + P \cos \beta_{eq}}$$

$$P = \frac{\gamma H_1^2}{2} K \left(1 - k_v\right) \left\{1 + \frac{2 q_S}{\gamma H_1} \left[\frac{\cos \alpha}{\cos\left(\beta - \alpha\right)}\right]\right\} \qquad \omega = \tan^{-1}\left(\frac{k_h}{1 - k_v}\right)$$

$$K = \frac{\cos^2\left(\phi - \alpha - \omega\right)}{\cos \omega \cos^2 \alpha \cos\left(\alpha + \beta + \omega\right) \left[1 + \sqrt{\frac{\sin(\phi + \beta) \sin(\phi - \beta - \omega)}{\cos\left(\alpha + \beta + \omega\right) \cos(\beta - \alpha)}}\right]^2}$$

Minimum recommended factor of safety for sliding stability, FS_{SL}			
Temporary walls		**Permanent Walls**	
Static	**Seismic**	**Static**	**Seismic**
1.30	**1.10**	**1.50**	**1.10**

Nail Soil Pullout Failure



$$(FS_P)_z = \frac{(R_P)_z}{(T_{max})_z} = \frac{(Q_u L_P)_z}{(T_{max})_z}$$

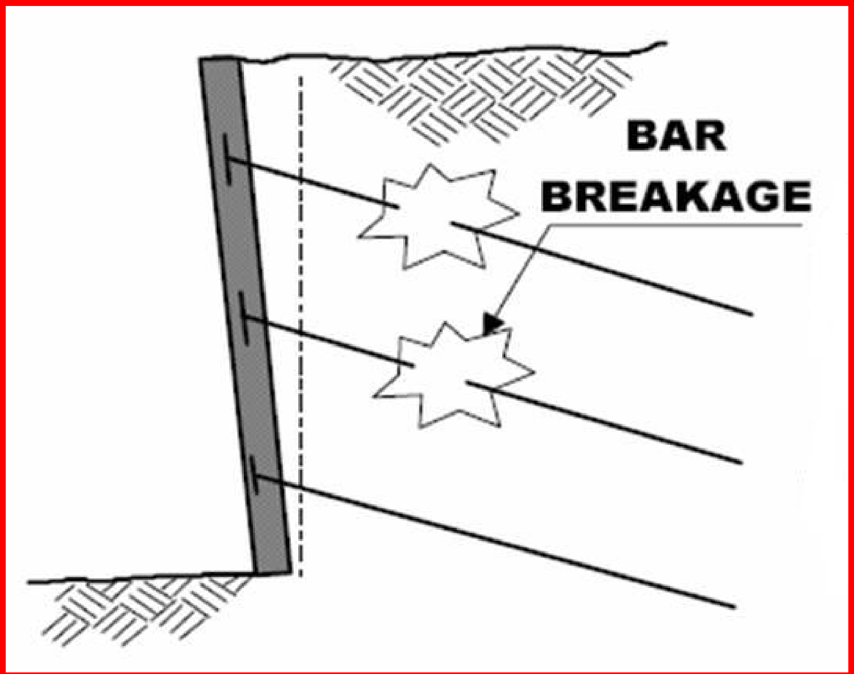
$$(T_{max})_z = K(q_s + \gamma z) S_H S_V$$

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

$$(L_P)_z [m] = L - \left[\frac{(H - z)\cos(\psi + \alpha)}{\cos\alpha \sin(\psi + i)} \right]$$

Minimum recommended factor of safety for pullout failure, FS_P			
Temporary walls		Permanent Walls	
Static	Seismic	Static	Seismic
2.00	1.50	2.00	1.50

Nail Tensile Strength Failure



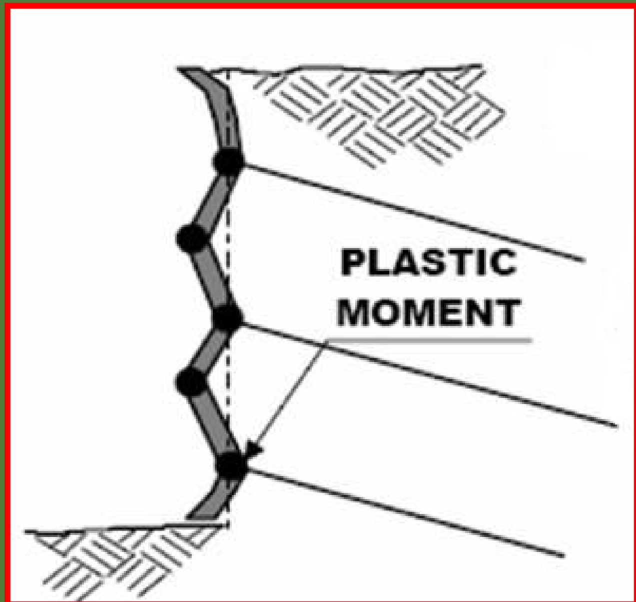
$$\left(FS_T\right)_z = \frac{\left(R_T\right)_z}{\left(T_{max}\right)_z}$$

Minimum recommended factor of safety for pullout failure, FS_T			
Temporary walls		Permanent Walls	
Static	Seismic	Static	Seismic
1.80	1.35	1.80	1.35

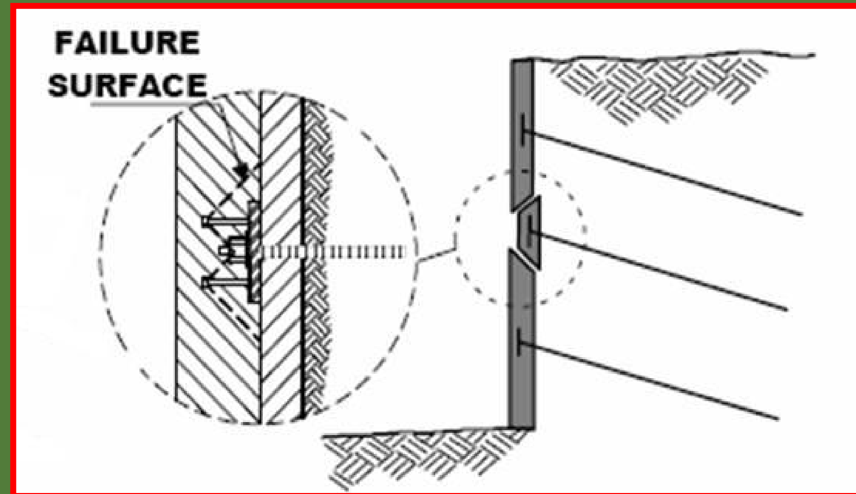
where: $R_T = A_t f_y$ = maximum axial tensile load capacity of nail

A_t = c/s area of nail

f_y = yield strength of nail



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



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

Minimum recommended factor of safety (FHWA 2003)			
Failure mode	**Static loading**		**Seismic loading**
	Temporary walls	Permanent walls	Both temporary and permanent walls
Facing flexure failure, FS_{FF}	1.35	1.50	1.10
Facing punching shear failure, FS_{FP}	1.35	1.50	1.10

DESIGN OF 7 m HIGH SOIL NAIL WALL

INITIAL CONSIDERATIONS

(a) Vertical height of wall: H = 7 m

(b) Face batter: α = 0.0 degrees; Backslope angle: β = 0.0 degrees

(c) Nailing type: Driven

(d) Soil nail spacing: $S_h = S_v = 0.5$ m

(e) Soil nail inclination: i = 25 degrees

(f) Soil nail material: Grade Fe 415; $f_y = 415$ MPa

(g) Soil properties:

Soil type: Dense to very dense sands;

Cohesion: c = 0 kPa;

Friction angle: $\varphi=28^{o}$;

Unit weight: $\gamma=17 kN/m^3$.

Ultimate bond strength (from field pullout test):

$$q_u[kPa] = \frac{Q_u}{\pi \times 0.02} = \frac{3}{\pi \times 0.02} = 47.75$$

(h) Surcharge: q_s = 0.0 kPa

PRELIMINARY DESIGN

a) Determine maximum axial force T_{max}

Maximum axial tensile force T_{max} developed is given by

$$T_{max}\left[kN\right] = K_a(q_s + \gamma H)s_h s_v$$

$$Where; K_a = \frac{1 \quad \sin\varphi}{1+\sin\varphi} = \frac{1 \quad \sin 28}{1+\sin 28} = 0.36$$

$$T\max\left[kN\right] = 0.36(0+17\times 7)0.5\times 0.5 = 10.71$$

(b) **Determine minimum nail length L and nail diameter d**

Factor of safety of against nail tensile failure

FS_T = 1.80,

The required cross-sectional area A_t of the nail bar can be determined as:

$$A_t\left[mm^2\right] = \frac{T_{max}FS_T}{f_y} = \frac{10.71 \times 1000 \times 1.80}{415} = 46.45$$

Select reinforcement bar of diameter d = 20 mm providing cross sectional area A_t = 314 mm^2 (> 46.45 mm^2).

Minimum length of soil nail L is adopted as the maximum of L_1 and L_2:

$$L_1 = \frac{(H - S_{v1})\cos\psi}{\sin(\psi + i)} + \frac{2T_1}{\pi d q_u}$$

Here: q_u = 47.75 kPa; d = 20 mm; T_1 = 0.38 kN

$$L_1 = \frac{(7 - 0.25)\cos 59}{\sin(59 + 15)} + \frac{2 \times 0.38}{\pi \times 0.02 \times 47.75} = 3.86\ \mathrm{m}$$

L_2 = 0.6 x 7 = 4.20 m

Hence, adopt nail length: L = 4.20 m

Summary: Adopt driven soil nails of 20 mm diameter and 4.20 m length

CHECK FOR IMPORTANT FAILURE MODES

Global Stability:

Determination of equivalent nail force T_{eq}

$$R_P[kN] = \pi d L_P q_u = \pi \times 0.02 \times L_P \times 47.75 = 3L_P$$

$$L_P[m] = L - \left[\frac{(H - z)\cos\psi}{\sin(\psi + i)}\right]$$

$$R_T[kN] = \frac{\pi d^2 f_y}{4 \times 1000} = \frac{\pi \times 20^2 \times 415}{4 \times 1000} = 130.37$$

Allowable axial force carrying capacity T_{all} [kN] of nail embedded at depth z is the minimum of R_P and R_T. For S_h = 0.5 m, equivalent nail force T_{eq} can be determined as:

$$T_{eq}\left[kN/m\right]=\frac{1}{S_h}\sum_{j=1}^{n}\left(T_{all}\right)_j=\frac{1}{0.5}\times 100.27=200.54$$

Here: n = 14 and is obtained from **Table 1**.

Table 1: Allowable axial force carrying capacity of nails at different levels

Nail No. j (from top)	Depth of nail z [m]	Effective pullout length L_p [m]	Nail pullout capacity R_P [kN]	Nail tensile capacity R_T [kN]	Allowable axial force carrying capacity of nail T_{all} [kN]
1	0.25	0.7	2.11	130.37	2.11
2	0.75	0.96	2.89	130.37	2.89
3	1.25	1.22	3.66	130.37	3.66
4	1.75	1.48	4.43	130.37	4.43
5	2.25	1.74	5.21	130.37	5.21
6	2.75	2.00	5.99	130.37	5.99
7	3.25	2.26	6.77	130.37	6.77
8	3.75	2.51	7.54	130.37	7.54
9	4.25	2.77	8.32	130.37	8.32
10	4.75	3.03	9.10	130.37	9.10
11	5.25	3.29	9.88	130.37	9.88
12	5.75	3.55	10.66	130.37	10.66
13	6.25	3.81	11.43	130.37	11.43
14	6.75	4.07	12.21	130.37	12.21
				$\sum_{j=1}^{14} (T_{all})_j =$	100.27

Determination of weight of failure wedge W

Weight of failure wedge can be determined as:

$$W[kN/m] = 0.5\gamma H^2 \cot\psi$$

$$W[kN/m] = 0.5 \times 17 \times 7^2 \times \cot 59 = 250.26$$

Global stability safety factor FS_G under static conditions is given by

$$FS_G = \frac{T_{eq}\cos(\psi - i) + \left[(W + Q_T)\cos\psi + T_{eq}\sin(\psi - i)\right]\tan\phi}{(W + Q_T)\sin\psi}$$

$$FS_G = \frac{200.54\cos(59-25) + \left[(250.26)\cos 59 + 200.54\sin(59-25)\right]\tan 28}{(250.26)\sin 59} = 1.37$$

Sliding stability

Factor of safety for sliding stability of soil nail wall FS_{SL} in static condition is given by:

$$FS_{SL} = \frac{c_b B_L + \left(W + Q_T + P_A \sin\beta\right)\tan\phi_b}{P_A \cos\beta}$$

For static case total active lateral earth pressure P_A can be determined as:

$$P_A\left[kN/m\right] = \frac{1}{2} K_a \gamma H^2 = \frac{0.36 \times 17 \times 7^2}{2} = 149.94$$

W [kN/m] = Unit weight x Area of sliding wedge =17 x (7 x 4.2) = 499.8

Q_T [kN/m] = Surcharge load x Length AD = q_s x B_L = 0 x 4.2 = 0

$$FS_{SL} = \frac{(0 \times 4.2) + (499.8 + 149.94 \sin 0) \tan 28}{149.94 \cos 0} = 1.77$$

Soil nail pullout failure

For any particular nail embedded at depth z, factor of safety against pullout failure FS_P can be obtained as:

$$(FS_P)_z = \left(\frac{R_P}{T}\right)_z$$

$$T[kN] = 0.36 \times (0 + 17 \times 6.75) \times 0.5 \times 0.5 = 10.33$$

$$(FS_P)_{z=6.75} = \left(\frac{12.21}{10.33}\right) = 1.18$$

Soil nail tensile strength failure

Factor of safety against nail tensile strength failure FS_T for any nail embedded at depth z can be obtained as:

$$\left(FS_T\right)_z = \left(\frac{R_T}{T}\right)_z$$

$$R_T\left[kN\right] = \frac{\pi d^2 f_y}{4 \times 1000} = \frac{\pi \times 20^2 \times 415}{4 \times 1000} = 130.37$$

$$\left(FS_T\right)_{z=6.75} = \left(\frac{130.37}{10.33}\right) = 12.59$$

Table 2: FS_P and FS_T of soil nails.

Nail No. j (from top)	Depth of nail z [m]	Factor of safety against pullout failure FS_P	Factor of safety against nail tensile strength failure FS_T
1	0.25	5.51	Very high
2	0.75	2.51	Very high
3	1.25	1.91	Very high
4	1.75	1.66	Very high
5	2.25	1.51	Very high
6	2.75	1.42	Very high
7	3.25	1.36	Very high
8	3.75	1.31	Very high
9	4.25	1.28	Very high
10	4.75	1.25	Very high
11	5.25	1.23	Very high
12	5.75	1.21	Very high
13	6.25	1.19	13.6
14	6.75	1.18	12.59

SHOTCRETE (TEMPORARY) FACING DESIGN AND CHECKS

Step 1: Calculate design nail head tensile force at the face T_o

For T_{max} = 10.71 kN; and S_{max} =0.5 m, nail head tensile force at the wall face T_o can be obtained as:

$$T_o[kN] = T_{max}\left[0.6 + 0.2(S_{max} - 1)\right] = 10.71\left[0.6 + 0.2(0.5 - 1)\right] = 5.35$$

Step 2: Adopt wall facing thickness

Temporary facing thickness h: 50 mm

- Step 3: Adopt appropriate facing materials

(a) Steel reinforcement: Grade Fe 415 with characteristic strength: f_y = 415 MPa

(b) Concrete/shotcrete: Grade M20 with characteristic compressive strength: f_{ck} = 20 MPa

(c) Welded wire mesh (temporary facing): WMM 102 x 102–MW19 x MW19

.

(d) Horizontal and vertical waler bars (temporary facing): 2 x 10 mm diameter, (f_y = 415 MPa, A_{vw} = A_{hw} = 2 x 78 = 156 mm^2) in both directions.

(e) Bearing plate (temporary facing): Grade 250 (f_y =250 MPa); Shape: Square; Length: L_{BP} = 225 mm; Thickness: t_p = 25 mm

Step 4: Checks for facing reinforcement

Determine the minimum and the maximum reinforcement ratios as:

$$\rho_{min}[\%] = 20\frac{\sqrt{f_{ck}[MPa]}}{f_y[MPa]} = 20\frac{\sqrt{20}}{415} = 0.21$$

$$\rho_{max}[\%] = 50\frac{f_{ck}[MPa]}{f_y[MPa]}\left(\frac{600}{600+f_y[MPa]}\right) = 50\frac{20}{415}\left(\frac{600}{600+415}\right) = 1.42$$

- In addition the ratio of the reinforcement in the nail head and mid-span zones should be less than 2.5 to ensure comparable ratio of flexural capacities in theses areas.

Step 5: Verify facing flexural resistance R_{FF}

Calculate facing flexural resistance R_{FF} as:

$$R_{FF}[kN] = \frac{C_F}{265} \times (a_{vn} + a_{vm})[mm^2/m] \times \left(\frac{S_h}{S_v} h[m] \right) \times f_y [MPa]$$

$$R_{FF}[kN] = \frac{2}{265} \times 472.4 \times (1 \times 0.05) \times 415 = 74$$

- Safety factor against facing flexural failure FS_{FF} is given by

$$FS_{FF} = \frac{R_{FF}}{T_o} = \frac{74}{5.35} = 13.83$$

Step 6: Verify facing punching shear resistance R_{FP}

Facing punching shear capacity R_{FP} is given by:

$$R_{FP}\left[kN\right] = 330\sqrt{f_{ck}\left[MPa\right]}\,\pi D_c^{'}\left[m\right]h_c\left[m\right]$$

Here: f_{ck} = 20 MPa;

h_c = h = 0.05 m;

$Dc^{'}$= L_{BP} + h = 225 + 50 = 275 mm = 0.275 m

$$R_{FP}\left[kN\right] = 330 \times \sqrt{20} \times \pi \times 0.275 \times 0.05 = 63.75$$

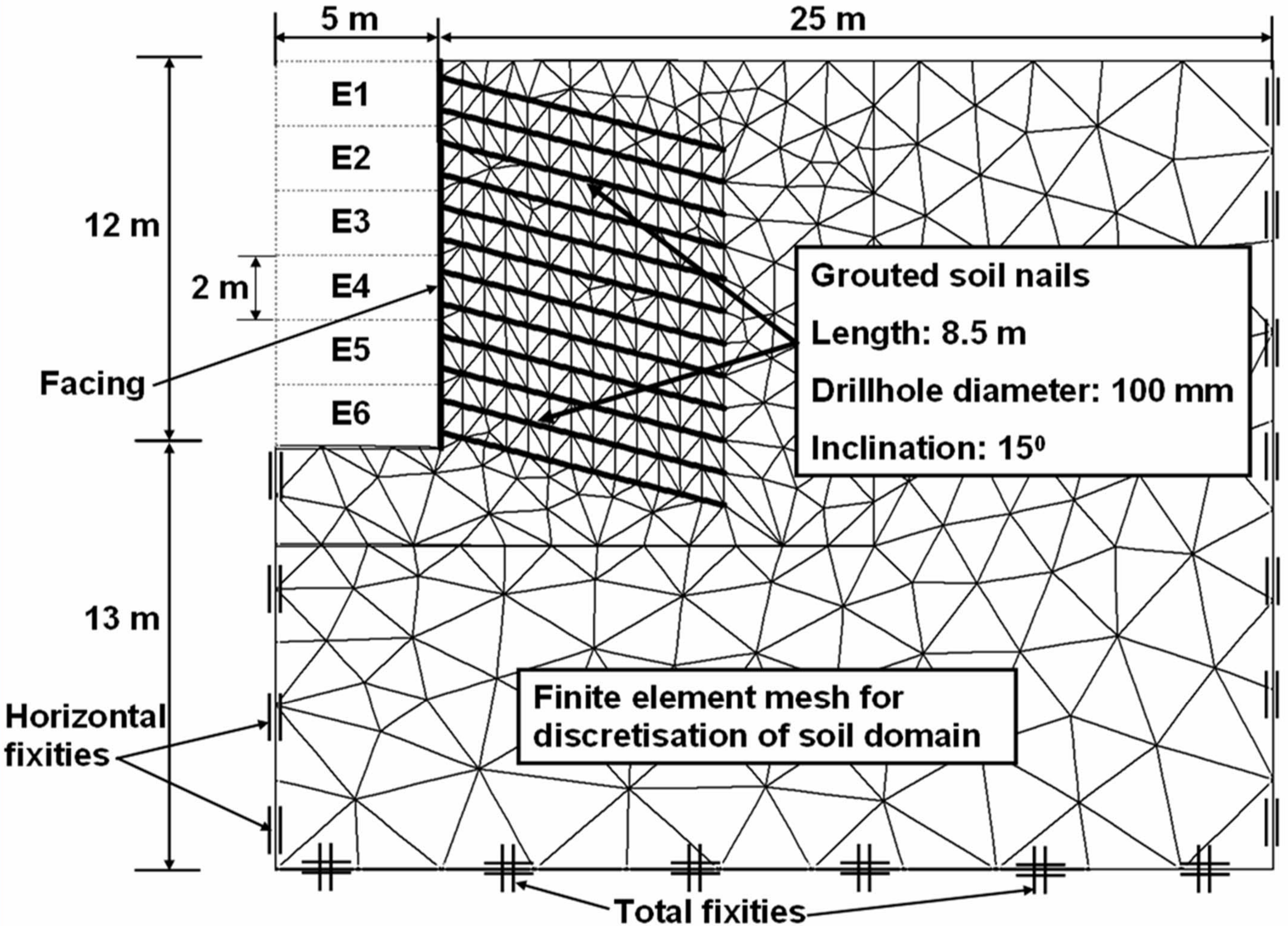
$$FS_{FP} = \frac{R_{FP}}{T_o} = \frac{63.75}{5.35} = 11.91$$

Table 3: Summary of factors of safety for various failure modes

Failure mode	Remarks	Factor of safety
Global FS_G	--	1.37
Sliding FS_{SL}	--	1.77
Pull-out resistance FS_P	Minimum	1.18 (increases to 3 if grouted nails (30 kN/m) at 1m spacing are used.
Nail bar tensile strength FS_T	Minimum	12.59
Facing flexure FS_{FF}	Temporary facing	13.83
Facing punching FS_{FP}	Temporary facing	11.91

Table 4: Summary of temporary facing design (All dimensions are in mm)

Element	Description	Temporary facing
General	Thickness h	50
	Facing type	Shotcrete
	Concrete grade	M20
Reinforcement	Type	Welded wire mesh (WWM)
	Steel grade	Fe415
	Denomination	102 x 102 – MW19 x MW19
Other reinforcement	Type	Waler bars 2 - 10 b/w
Bearing plate	Type	Square
	Steel	Fe250
	Dimensions	225 x 225 x 25

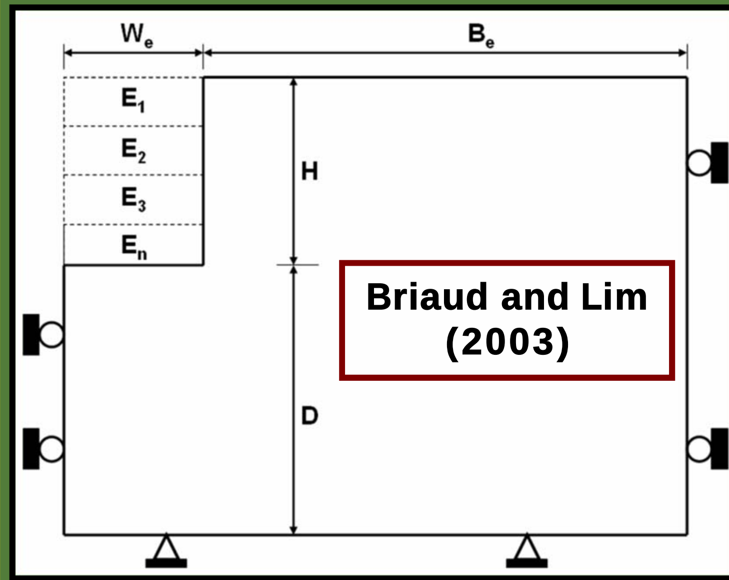

5 m
25 m
12 m
E1
E2
E3
2 m
E4
E5
E6
Facing
Grouted soil nails
Length: 8.5 m
Drillhole diameter: 100 mm
Inclination: 15⁰
13 m
Horizontal fixities
Finite element mesh for discretisation of soil domain
Total fixities

15 noded triangular elements

Coarse mesh density in general and fine to very fine in soil nail wall zone.

Elastic plate structural elements to simulate nails and facings.

Mohr-Coulomb model to simulate soil behaviour.



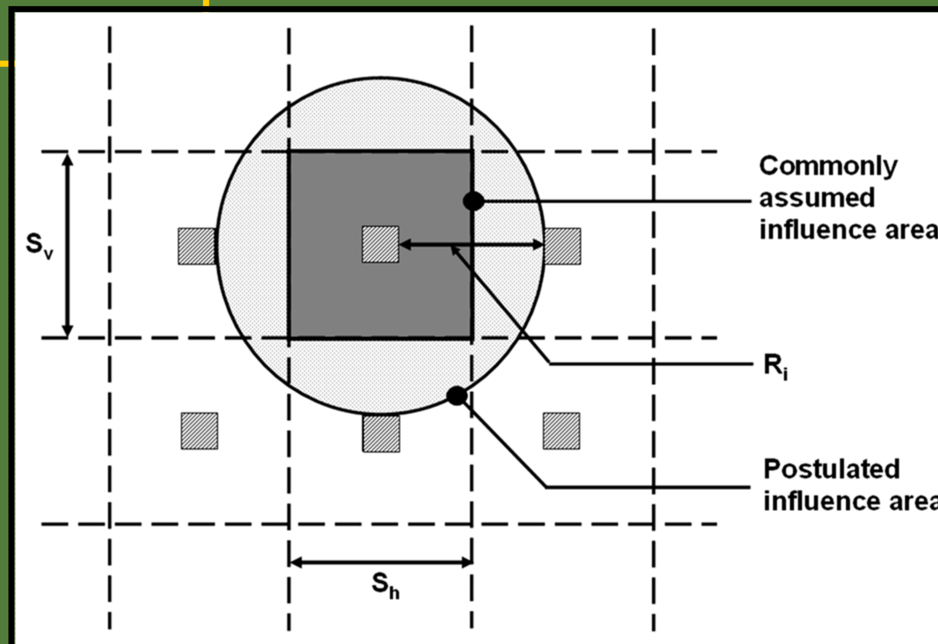
Briaud and Lim (2003)

2D ok if $R_i / S_h < 1$

3D ok if $R_i / S_h > 1$

For most soiling applications in practice, radius of the influence area R_i is approximately equal to 0.4 times the length of the nail.

$$R_i \approx 0.4L$$



Tan et al. (2005)

Influence of mesh density on finite element simulation.

Mesh density	Elements per unit volume	Global factor of safety FS_G	Max. lateral displacement (mm)	Calculation time normalised wrt medium mesh density
Very coarse	0.39	1.610	20.93	0.46
Coarse	0.60	1.598	22.31	0.61
Medium	0.98	1.592	22.86	1.00
Fine	2.08	1.553	24.79	2.24
Very fine	4.14	1.521	28.35	6.18

Note: FS_G values correspond to the fully constructed wall. If FS_G is to be determined after each construction stage, calculation time may vary even more drastically.

Influence of interface modeling on soil nail wall analysis.

R_{inter}	Maximum axial force [kN/m]	Global Stability FS_G	Maximum lateral wall displacement [mm]
0.6	107.09	1.77	25.65
0.7	105.82	1.78	25.40
0.8	94.97	1.78	22.77
0.9	103.89	1.79	24.88
1.0 (rigid)	95.34	1.78	22.32

For example:

Wang and Richwein 2002

Junaideen et al. 2004

Pradhan et al. 2006

Gosavi et al. 2008

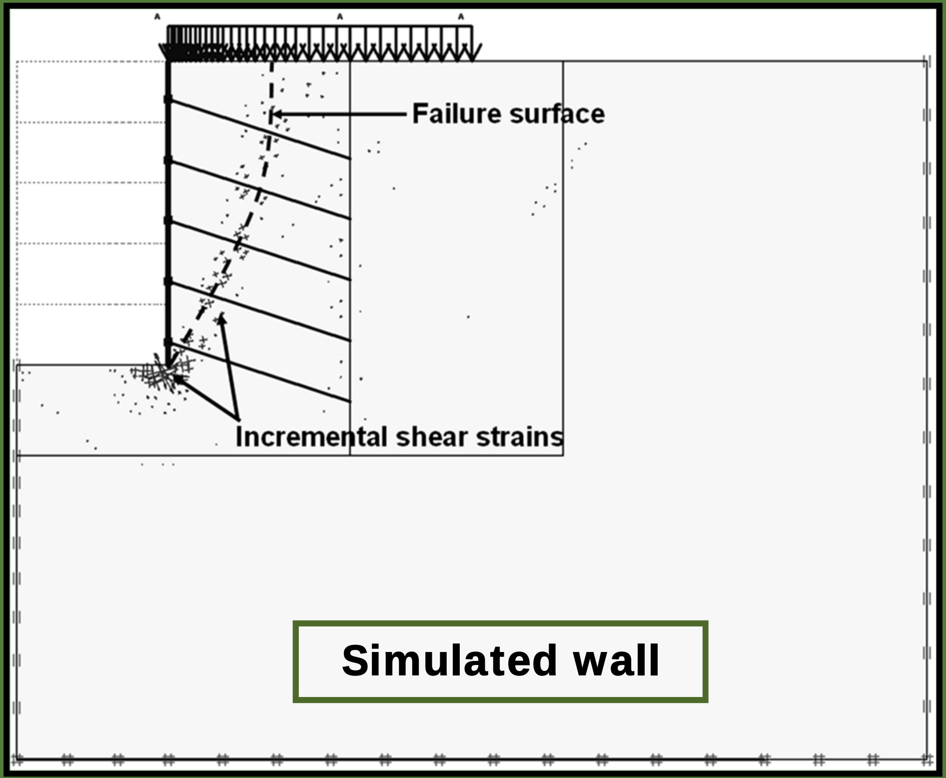
Strength Reduction Technique

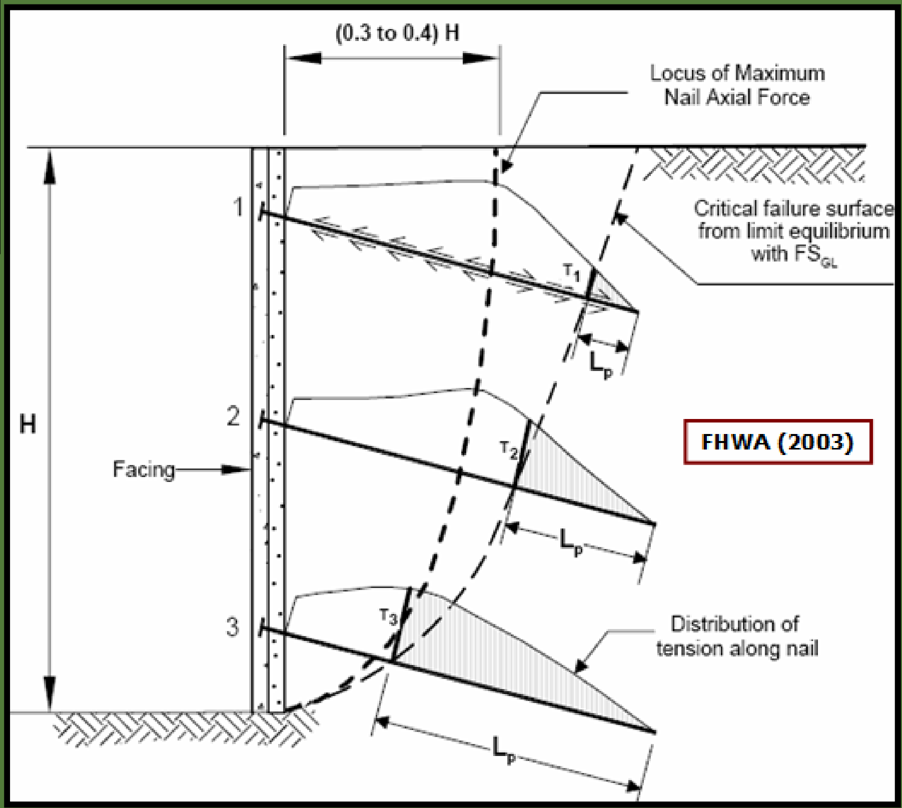
- In this method the strength parameters 'tan φ'and 'cohesion c' of the soil are successively and simultaneously reduced until failure of the structure occurs (equation 1).

- The parameters with the subscript 'input' refer to the input properties and parameters with the subscript 'reduced' refer to the reduced properties used in the analysis. This ratio is set to 1.0 at the start of a calculation to set all material strengths to their actual values. These values with subscript 'reduced' are successively reduced until failure of the structure occurs. At this point the factor of safety is given by equation 2.

$$\frac{\tan\phi_{\text{input}}}{\tan\phi_{\text{reduced}}} = \frac{c_{\text{input}}}{c_{\text{reduced}}} = 1.0 \qquad \ldots(1.)$$

$$FS = \frac{\text{available strength}}{\text{strength at failure}} \qquad \ldots(2.)$$


Failure surface
Incremental shear strains
Simulated wall


(0.3 to 0.4) H
Locus of Maximum Nail Axial Force
Critical failure surface from limit equilibrium with FS_{GL}
H
Facing
1
2
3
T_1
T_2
T_3
L_p
L_p
L_p
FHWA (2003)
Distribution of tension along nail

Study on Implications of using Advanced Soil Models

Soil nail wall geometry and other parameters.

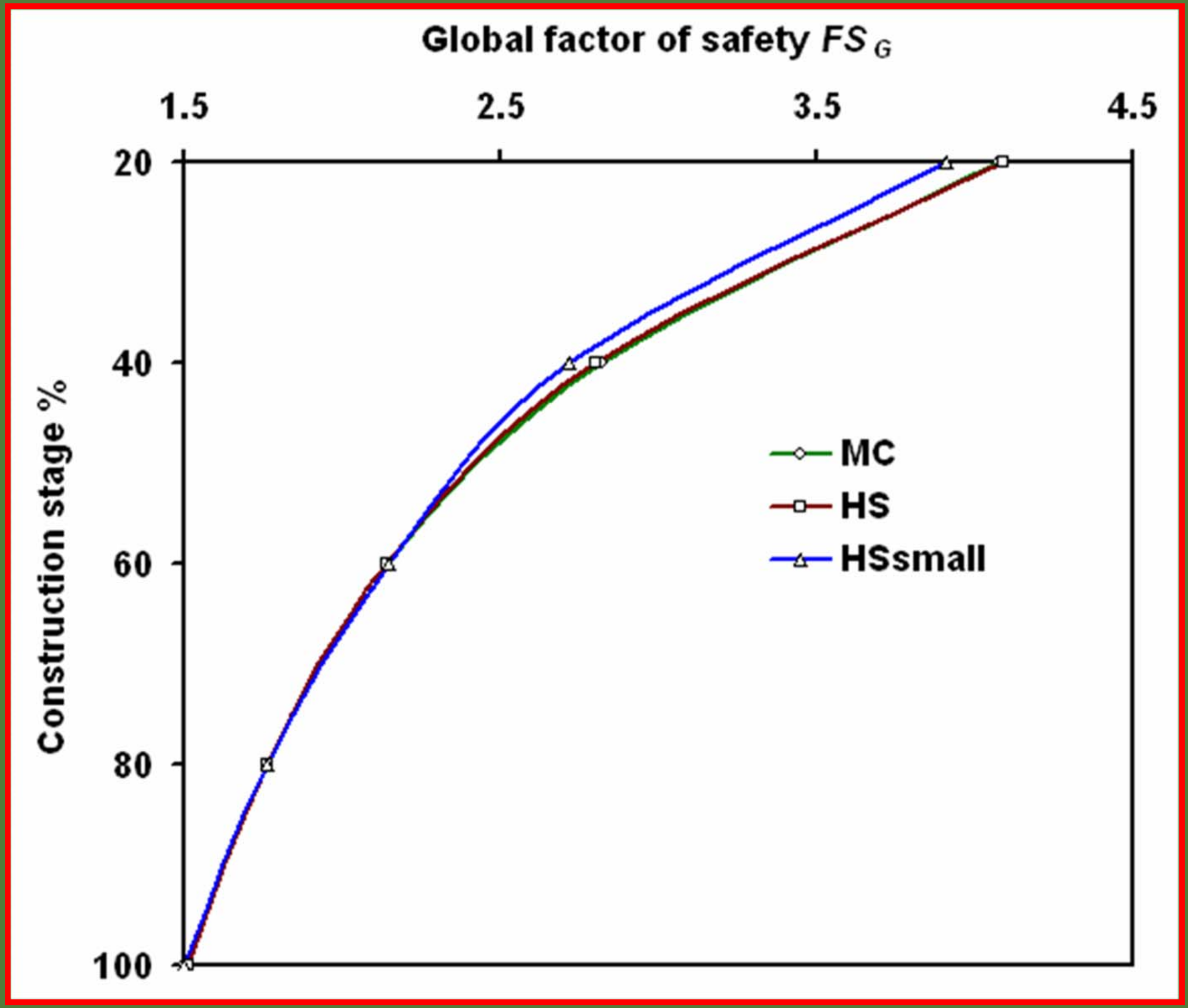
Parameter	**Value**
Vertical height of the wall H [m]	10.0
Face batter α [deg]	0.0
Backslope angle β [deg]	0.0
Nailing type	grouted
Grouted nails and facing	
Material model	elastic
Yield strength of reinforcement f_y [MPa]	415.0
Elasticity modulus of reinforcement E_n [GPa]	200.0
Elasticity modulus of grout (concrete) E_g [GPa]	22.0
Diameter of reinforcement d [mm]	20.0
Drill hole diameter D_{DH} [mm]	100.0
Length of nail L [m]	7.0
Declination wrt horizontal i [deg]	15.0
Spacing S_h x S_v [m x m]	1.0 x 1.0
Facing thickness t [mm]	200.0

Soil model parameters (Bringreve et al. 2006).

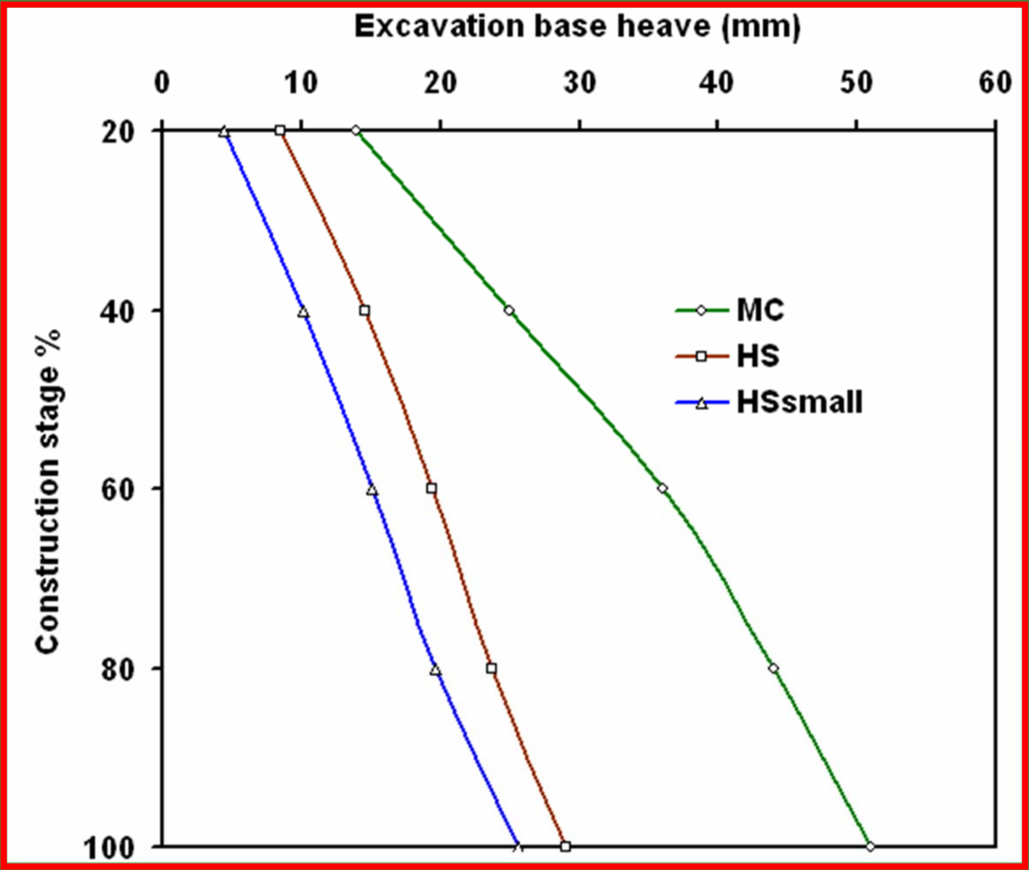
Parameter	MC	HS	HSsmall
Cohesion c [kN/m^2]	10.0	10.0	10.0
Friction angle φ [deg]	27.5	27.5	27.5
Dilatancy angle ψ [deg]	0.0	0.00.	0
Unit weight γ [kN/m^3]	19.0	19.0	19.
Modulus of elasticity of soil E [kN/m^2]	30000	-	-
Secant stiffness in standard drained triaxial test E_{50}^{ref} [kN/m^2]	-	20000	20000
Tangent stiffness for primary oedometer loading E_{oed}^{ref} [kN/m^2]	-	20000	20000
Unloading / reloading stiffness E_{ur}^{ref} [kN/m^2]	-	60000	60000
Reference shear modulus G_0^{ref}, [kN/m^2]	-	-	75000
Reference stress for stiffness p_{ref} [kN/m^2]	100.0	100.0	100.0
Shear strain at which $G_{secant} = 0.7\ G_0$, $\gamma_{0.7}$	-	-	0.0001
Poisson's ratio v	0.3	0.2	0.2
Power for stress level dependency of stiffness m	-	0.5	0.5

NOTE: For HS and HSsmall models $v = v_{ur}$ (unloading – reloading)

MC – Mohr Coulomb model
HS – Hardening soil model (Schanz et al. 1999)
HSsmall – Hardening soil with small strain stiffness (Benz 2007)



Phi/c reduction technique used in the present computational code has the limitation of accounting stress dependent stiffness and hardening behaviour of soils. Therefore, a similar response.



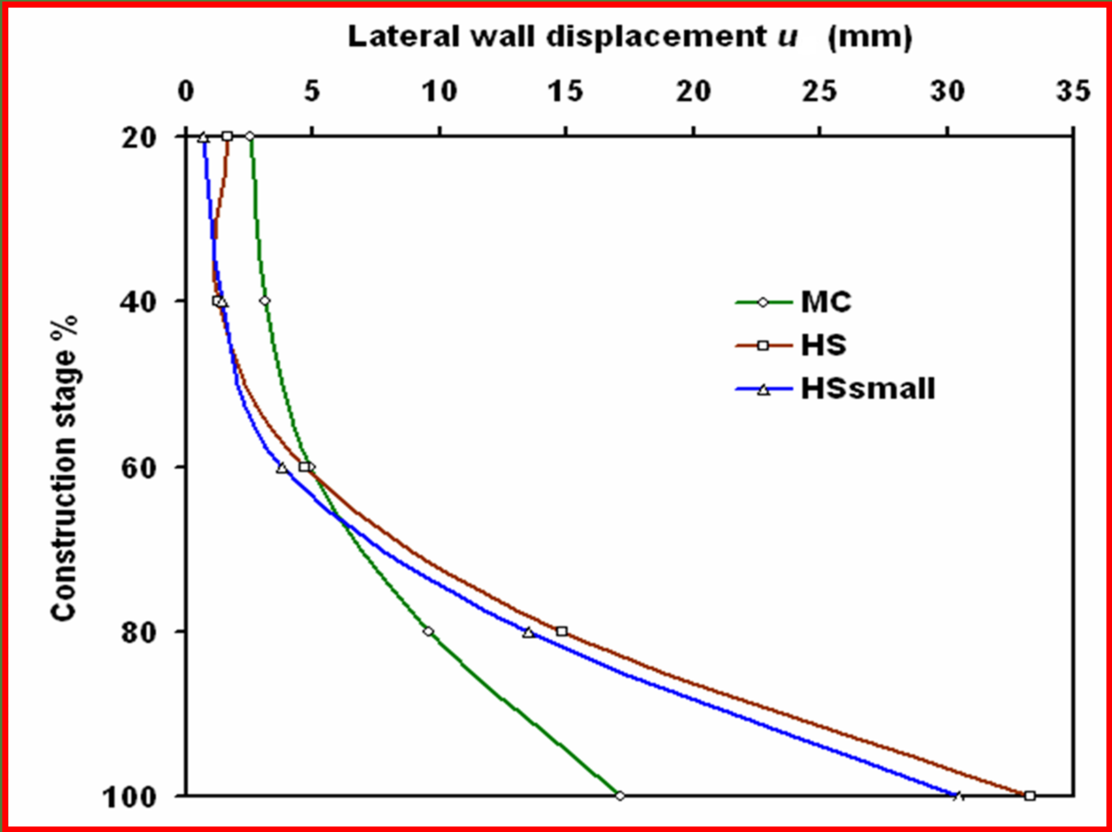
MC-model over-estimates the base heave (Brinkgreve et al. 2006; Callisto et al. 1999).

May be attributed to the consideration of linear elastic pre-failure soil behavior assumed in MC-model formulation.

Advanced soil models shall be preferred in soft soil conditions.

This aspect may be useful from the consideration of stability of soil nail walls during construction stages.

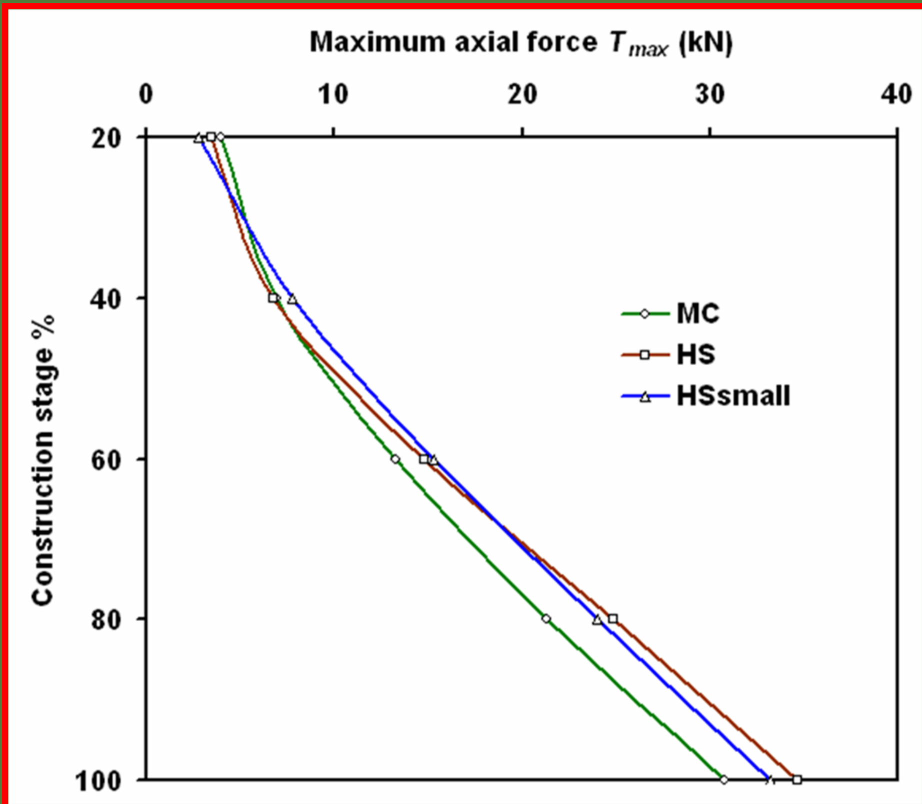
HSsmall model predicts excavation heave even lesser than HS-model attributing to the role of increased stiffness of soils at small strains (Brinkgreve 2006; Benz 2007)

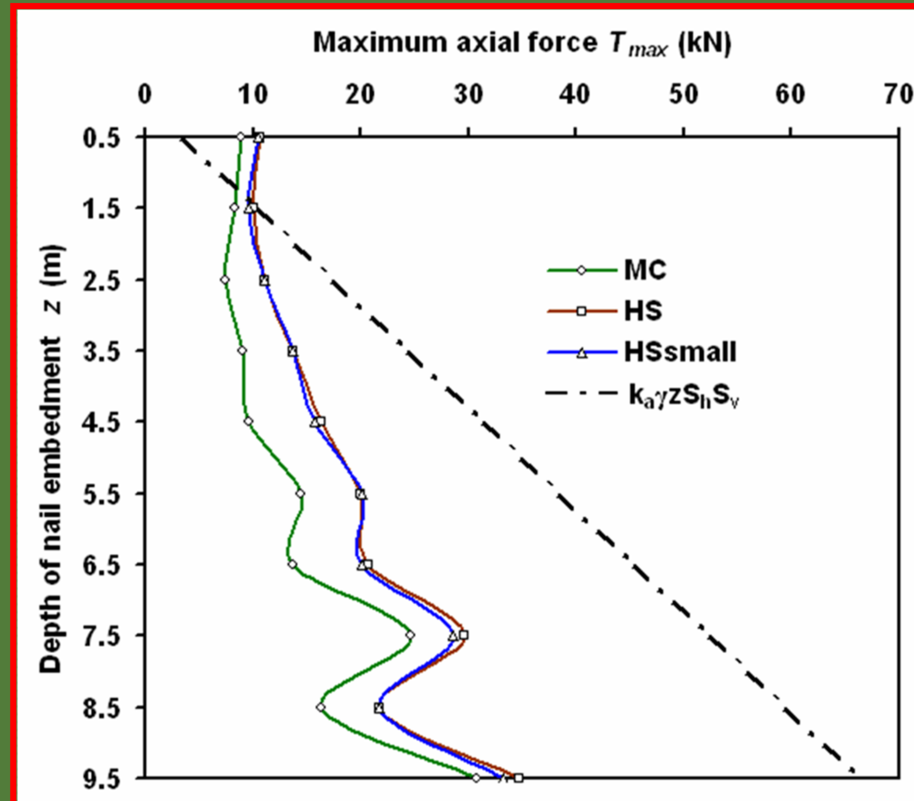


Upto 60% CS, MC > HS and HSsmall. Beyond 60% CS, HS > HSsmall > MC.

Possibly due to a hyperbolic stress-strain relationship with control of stress level dependency of soil stiffness in advanced models.

Unlike, advanced models, MC model has fixed yield surface in the principal stress space, which do not account for plastic straining due to the increasing construction stages.

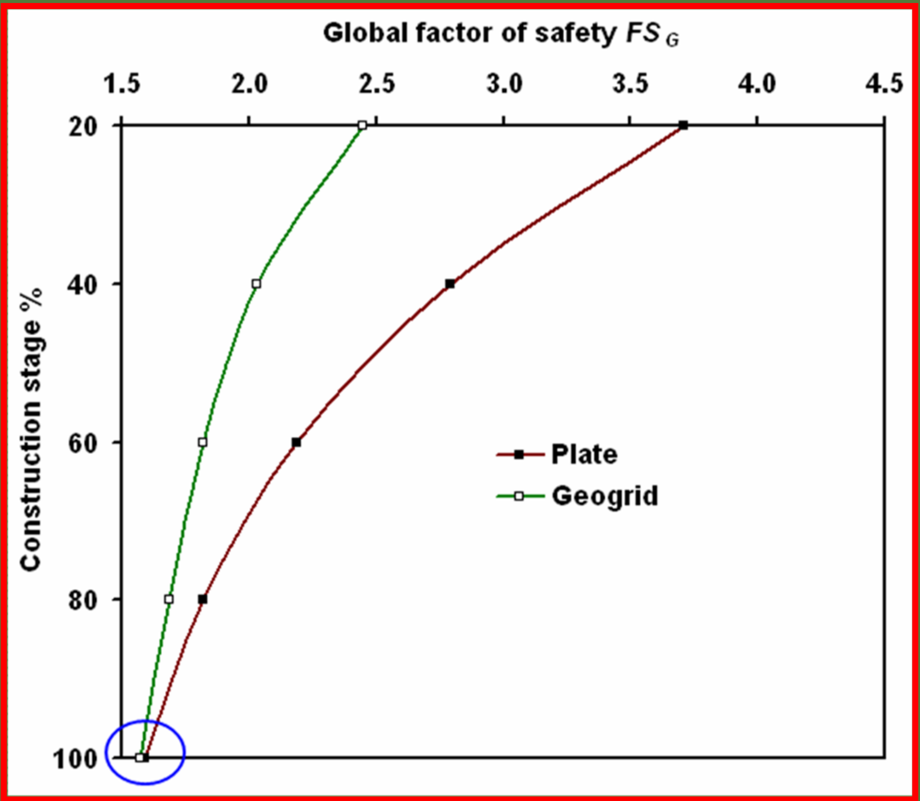




Similar response of the maximum axial force developed in soil nails.

MC-model predicts slightly conservative estimate of axial force development.

Implications of Consideration of Bending Stiffness of Soil Nails

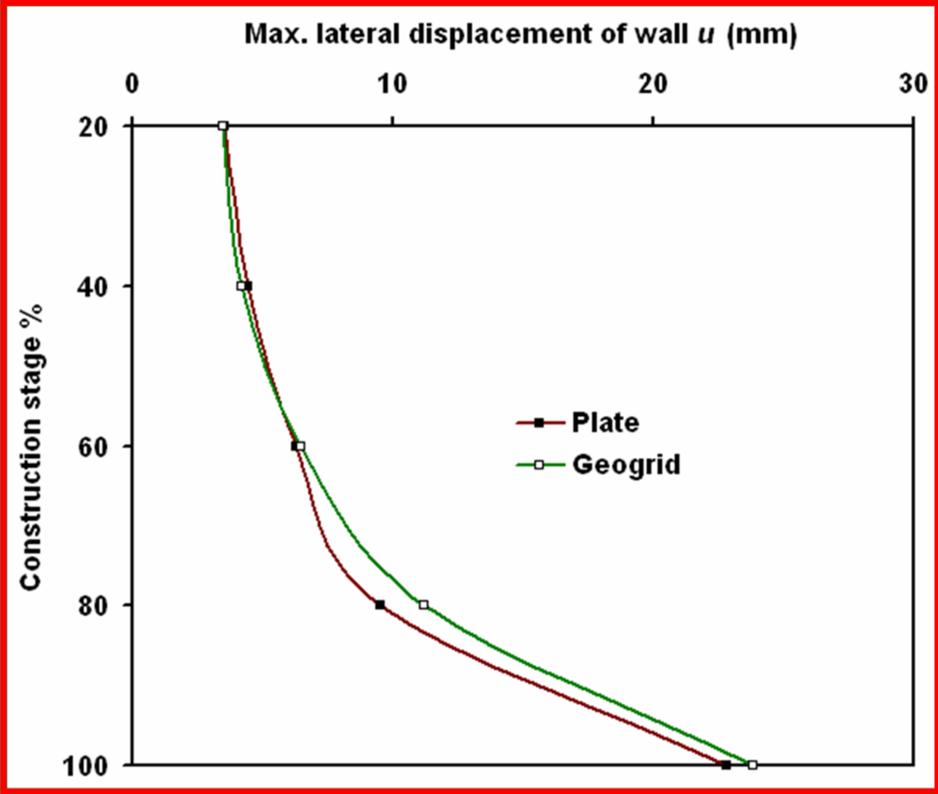


Trend of global factor of safety of soil nail wall with construction stage

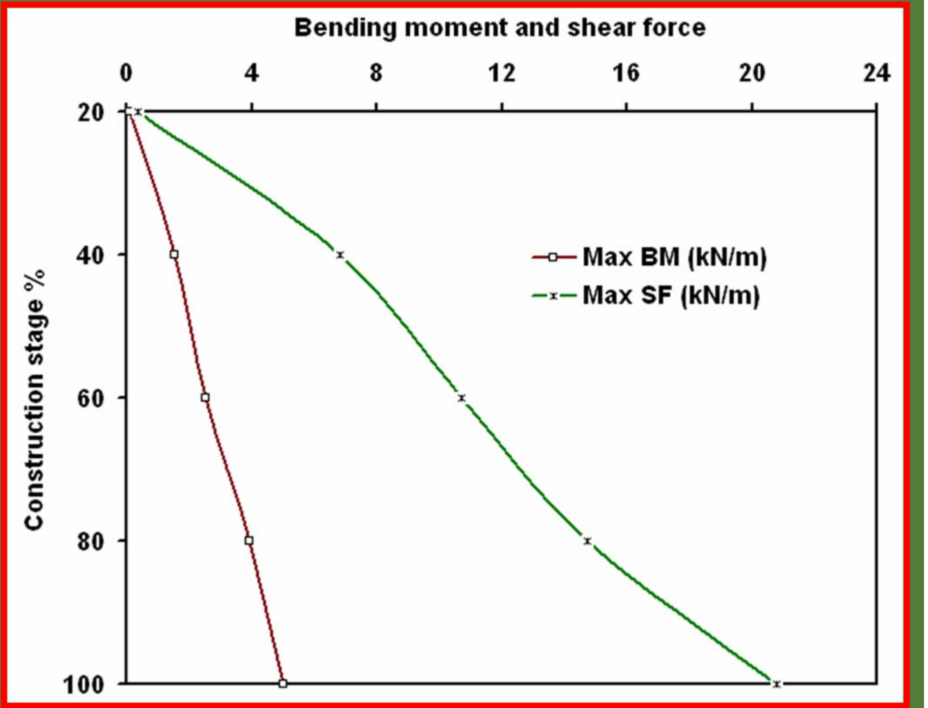
Plate structural element can be used to perform analysis of soil nail walls considering bending stiffness of soil nails as they require both axial stiffness EA and bending stiffness EI as the main material parameters.

Geogrid structural elements can be used to model soil nails with considering bending stiffness of soil nails as they require only axial stiffness EA as the main input parameter

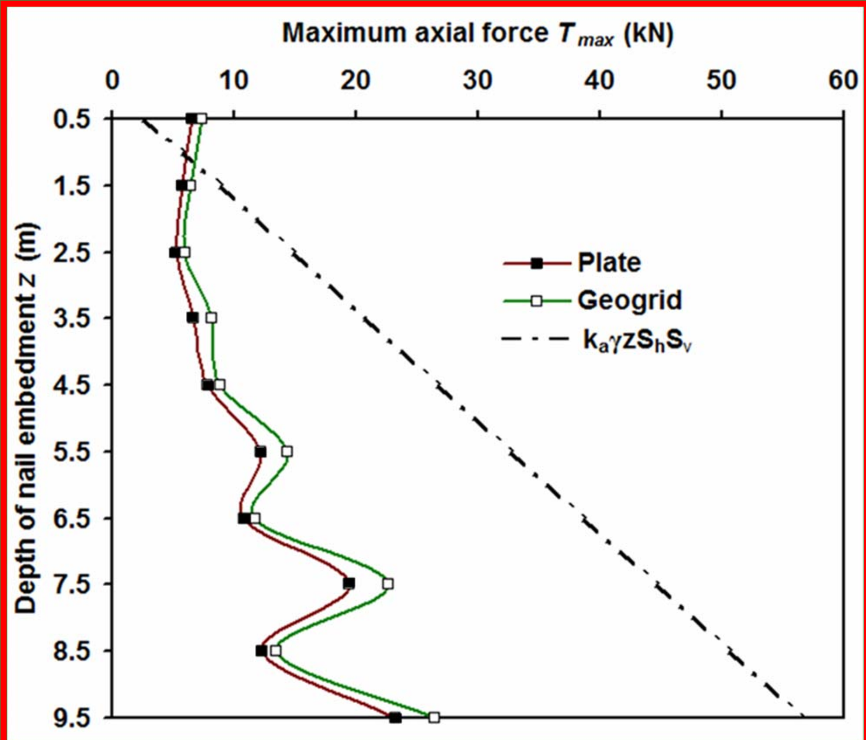
Using MC soil model

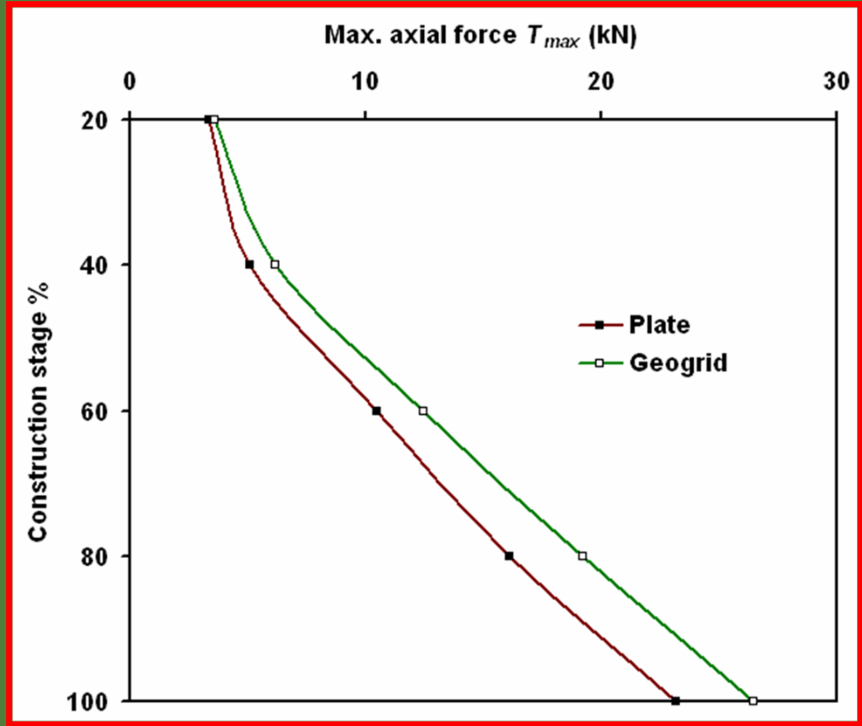


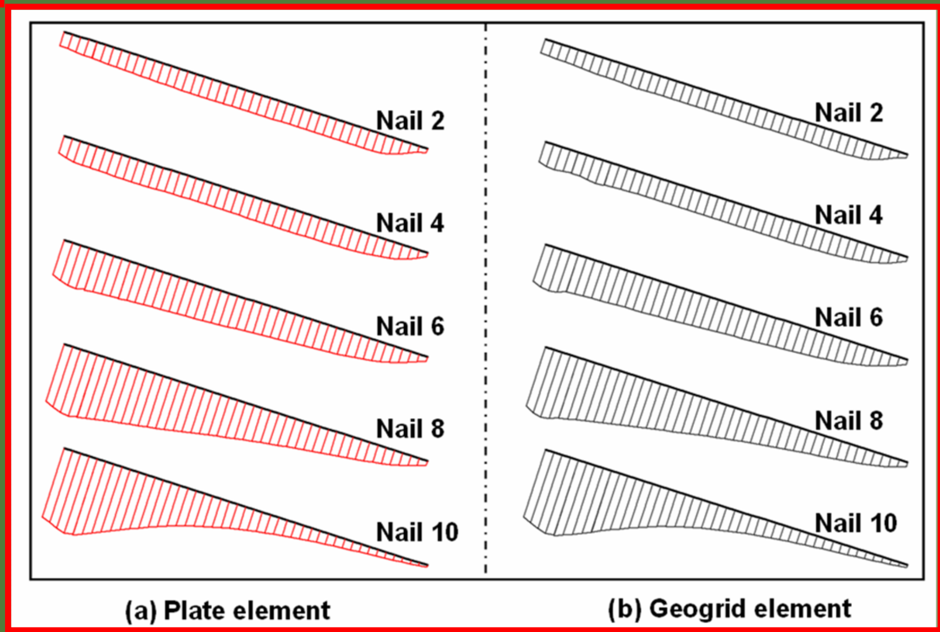
Almost same lateral displacements observed.



The bending and shear capacities of soil nail start mobilising with increasing construction stages.







T_{max} in nails simulated using geogrid elements is found to be 15% more than plate.

Very similar response

Seismic Analysis Soil Nail Walls

- Soil nail walls reported to have performed remarkably well during high intensity earthquakes (Felio et al. 1990; Vucetic et al. 1998; Tatsuoka et al. 1997; Tufenkjian 2000).
- In order to study the performance of soil nail walls in seismic conditions, a typical soil nail wall of 8 m height is conventionally designed using allowable stress design approach presented in FHWA (2003).
- Conventionally designed soil nail wall is then simulated under static and seismic (pseudo-static and time history data) conditions.

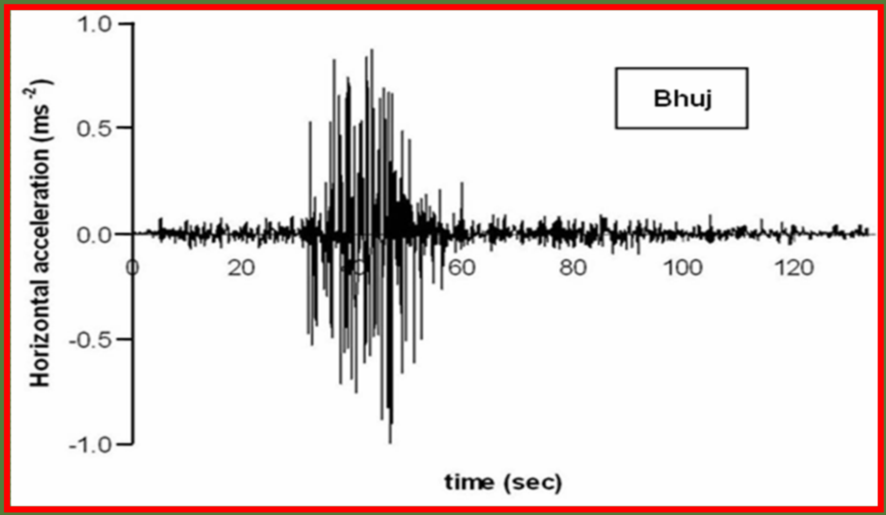
Material and geometric properties adopted for the study.

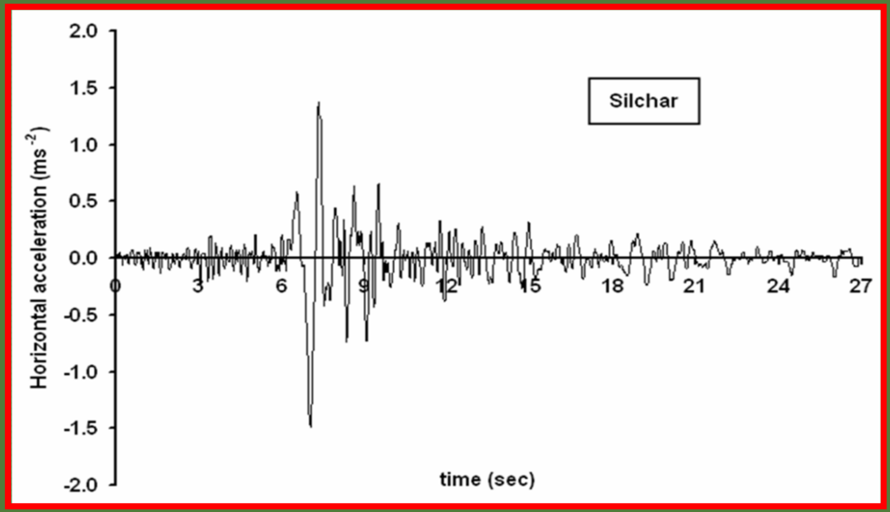
Parameter	Value
Vertical height of wall, H, m	8.0
Face batter, α, degrees	0.0
Slope of backfill, β, degrees	0.0
Cohesion, c, kPa	1.0
Friction angle, ϕ, degrees	30.0
Unit weight, γ, kN/m^3	16.0
Modulus of elasticity of soil, E_s, MPa	20.0
Yield strength of nail, f_y, MPa	415
Modulus of elasticity of nail, 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
Horizontal seismic coefficient, k_h	0.106
Vertical seismic coefficient, k_v	0.0

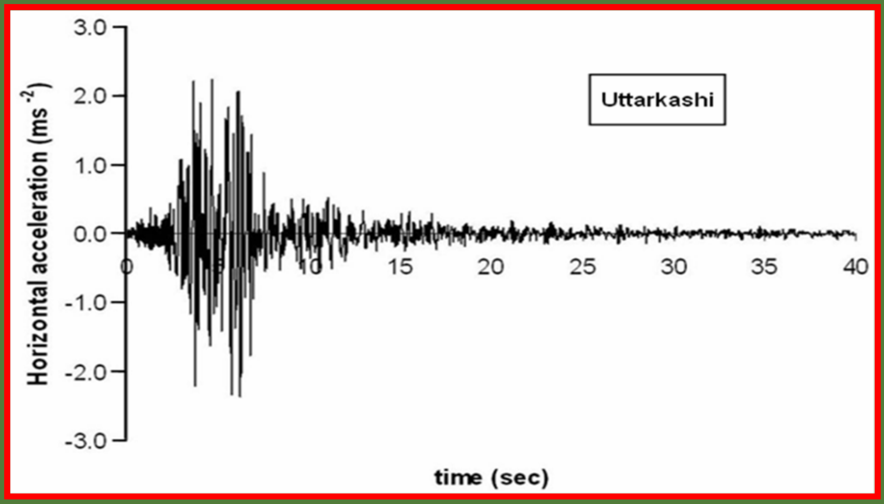
Summary of the conventional design.

Design variable	Value
Nail length, L, m	4.70
Nail tendon diameter, d, mm	16.0
Maximum axial force in nail, T_{max}, kN	40.00 (48.42)
Axial force at nail head, T_o, kN	24.00 (29.05)
Pullout capacity of nail per unit length, Q_u, kN/m	31.41
Maximum axial tensile load capacity of nail, R_T, kN	83.44
FS against pullout (on ultimate bond strength), FS_P	3.49 (2.88)
FS against nail tensile strength, FS_T	2.09 (1.72)
FS against global stability, FS_G	2.70 (2.48)
FS against sliding stability, FS_{SL}	1.99 (1.26)

Note: Figures in bracket indicates corresponding values from seismic considerations (k_h = 0.106, k_v = 0.0)







Ground acceleration time histories for three earthquakes

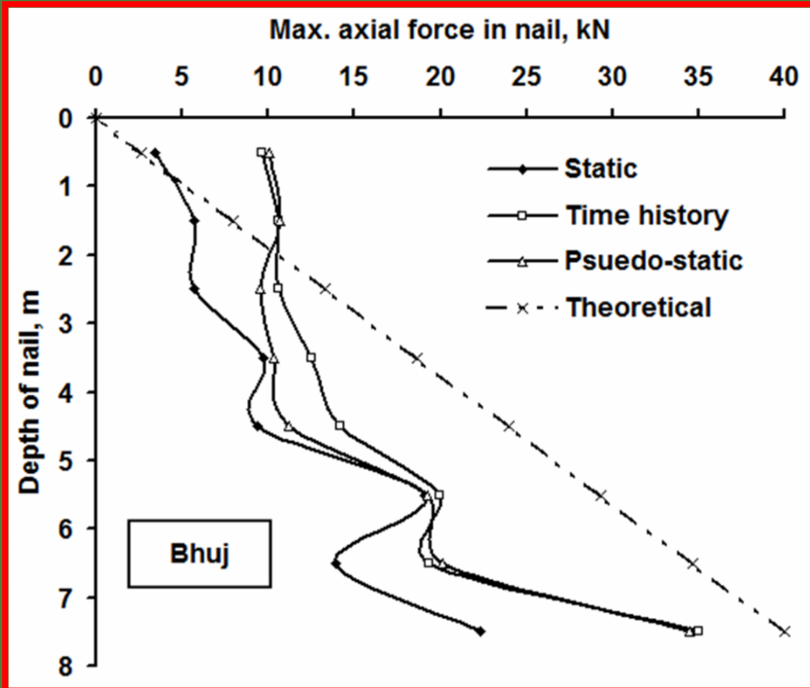
Summary of strong motion records (Shrikhande 2001).

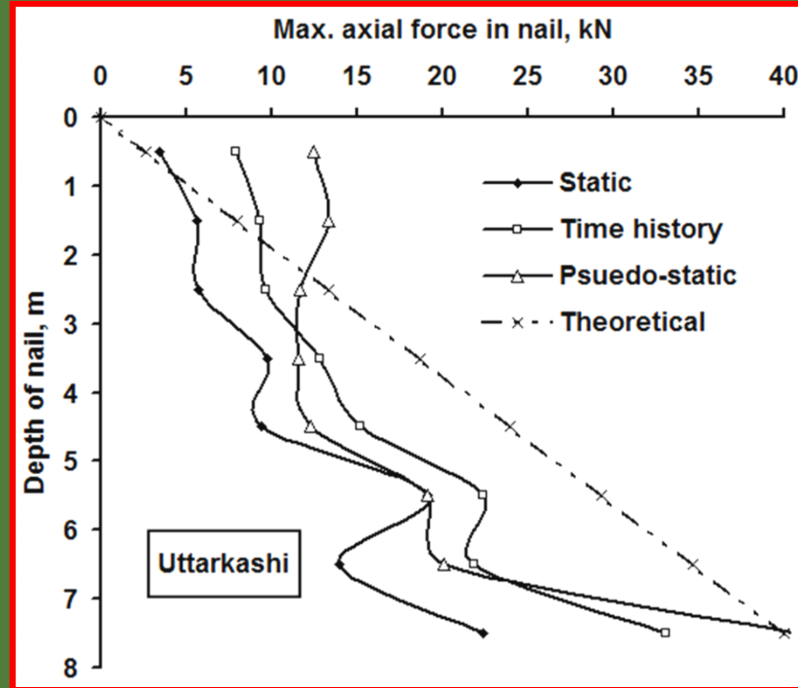
Parameter	Bhuj earthquake	Silchar earthquake*	Uttarkashi earthquake
Date of occurrence	January 26, 2001	May 08, 1997	October 20, 1991
Seismograph station	Ahemdabad	Silchar	Uttarkashi
Body wave magnitude	$m_b = 7.0$	$m_b = 5.7$	$m_b = 6.5$
Frequency (Hz)	2.91	3.44	5.56
Peak acceleration (m/s^2)	-1.0382	-1.4882	-2.3700
Peak velocity (m/s)	0.1113	-0.2058	0.1700
Peak displacement (mm)	-88.21	52.01	-21.10
Strong motion duration (sec)	≈ 25 sec	≈ 10 sec	≈ 8 sec

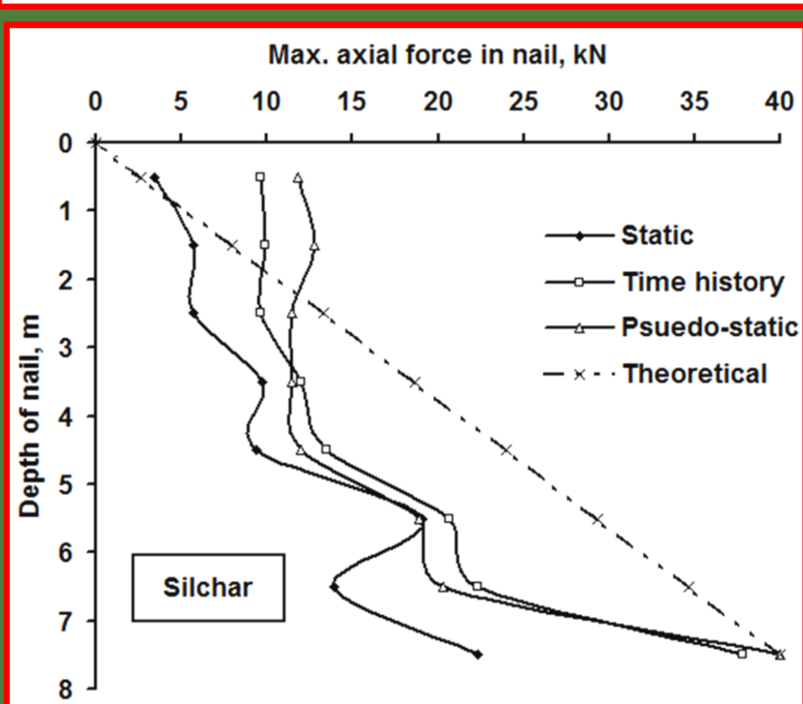
* - Silchar earthquake is the India-Burma border earthquake occurred in north-east India.

Summary of results from numerical simulations.

Analysis parameter	Static	Seismic: pseudo-Static			Seismic: time history data		
		Bhuj	Silchar	Uttarkashi	Bhuj	Silchar	Uttarkashi
Horizontal seismic coefficient, k_h	--	0.106	0.152	0.241	--	--	--
Vertical seismic coefficient, k_v	--	0.00	0.00	0.00	--	--	--
Maximum axial force in nail, T_{max-s}, kN	22.34	34.50	40.04	40.73	34.98	37.79	33.06
Maximum axial force at nail head, T_o, kN	19.96	27.80	31.68	32.46	29.17	33.47	28.86
Maximum horizontal displacement, % of H	0.61	3.29	4.78	5.24	1.13	1.54	0.82
FS against global stability, FS_G	1.23	0.95	0.84	0.81	1.10	1.03	1.17
FS against nail pullout failure, FS_P	1.78	1.15	0.98	0.98	1.14	1.07	1.21
FS against nail tensile strength failure, FS_T	3.73	2.42	2.08	2.05	2.38	2.21	2.52



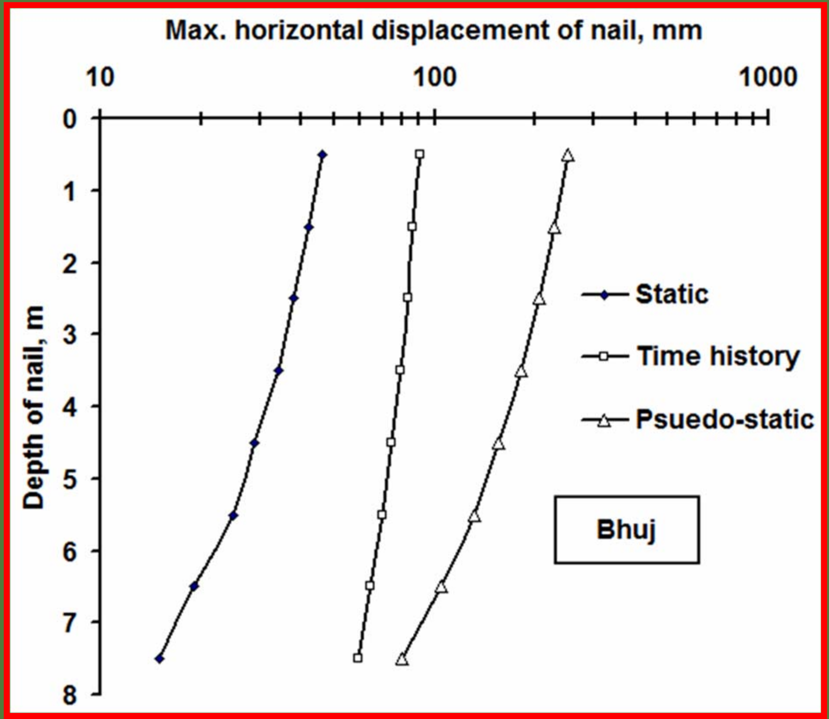


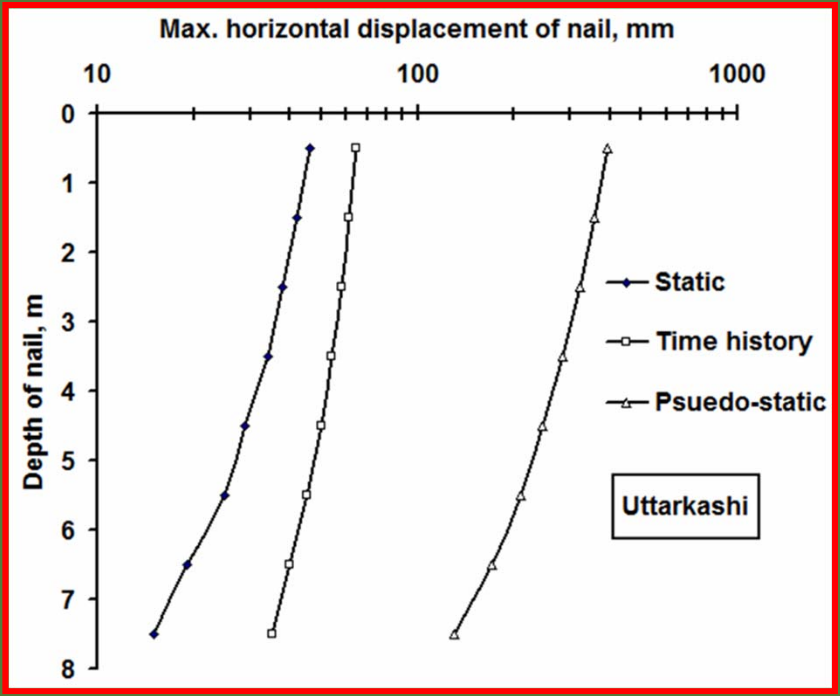


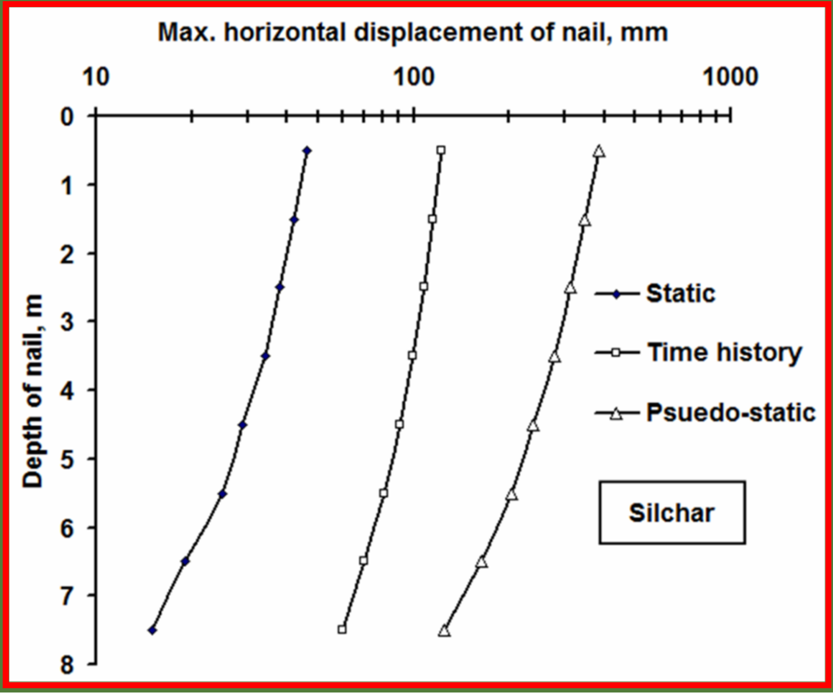
In general a very similar response

Upper nails (top two or three): more for the pseudo-static

Lower nails: very close for both pseudo-static and time history data







In general a very similar response

Very conservative for the pseudo-static

Tolerable seismically induced displacement corresponds to 0.63-1.25% of H (FHWA 2003)

Results of numerical simulations using revised nail length of 6 m. **Original L = 4.70 m**

Analysis parameter	Numerical simulation type				
	Static		Seismic		
	Actual	FHWA (2003)	Uttarkashi earthquake (pseudo-static)	Silchar earthquake (time history data)	FHWA (2003)
Maximum axial force in nail, T_{max-s}, kN	25.59	--	32.38	32.13	--
Maximum axial force at nail head, T_o, kN	20.94	(0.6~1.0) T_{max-s}	28.72	29.59	(0.6~1.0) T_{max-s}
Maximum horizontal displacement, % of H	0.26	0.20-0.30	2.22	1.13	0.63-1.25
FS against global stability, FS_G	1.40	1.35-1.50	0.84	1.11	1.10
FS against nail pullout failure, FS_P	2.08	2.00	1.65	1.66	1.50
FS against nail tensile strength failure, FS_T	3.26	1.80	2.57	2.59	1.35

Conclusions

- Conventional design procedure using FHWA (2003) provides a safe but conservative design.
- Provision of facing results in the significant improvement of the stability and performance of soil nail walls.
- Intermittent facing with a small offset in each construction stage is found to be more effective in reducing the lateral deformation of soil nail walls than regular continuous vertical facing.
- For soil nail walls with rigid facing the axial force developed at the head (i.e. at facing end) of a given soil nail is generally 80-90% of the maximum axial force developed in it.
- In addition to the peak seismic acceleration, the overall stability (i.e. external as well as internal) and performance of the soil nail walls is dependant on the other spectral properties (e.g., strong motion duration and peak displacement) of the time history data of an earthquake.
- Pseudo-static analyses is found to provide conservative estimate of displacements and factor of safety values.

Thank You