



# Parametric Optimization and Multi-regression Analysis for Soil Nailing Using Numerical Approaches

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**Abstract** Soil nailing as a construction practice has turned into a prime earth retention and slope stabilization technique. Present study undertakes potential parametric optimization in soil nailing by considering soil nail interaction and back analysis of the pull-out strength of nail using Finite Element Analysis using PLAXIS 2D. Results suggested pull-out strength as a function of depth, thereby providing a potential scope for optimization of soil nail length pattern. The observed trend of results has been further validated using Limit Equilibrium Analysis. Further, dynamic analysis was undertaken to ensure the seismic stability considering the reduced nail length pattern using FHWA guidelines and the numerical approaches like finite element and limit equilibrium methods. Results suggest that the observed trend with reduced nail length patterns caused mild increment in the serviceability conditions like horizontal deformation, but the results were observed to be within permissible limits in the ultimate limit state. Furtherance to the numerical analyses, a numerical regression analysis was

undertaken to develop a correlation between the geotechnical parameters, nail length patterns and the limit conditions.

**Keywords** Soil nailing · Parametric optimization · Pull-out strength · Numerical analyses · Finite element analysis · Limit equilibrium analysis · Regression analysis

## 1 Introduction

Soil nailing is a slope stabilization and earth retention technique which has over time gained its applications in several construction works such as slope stabilization, steep cuts for widening or construction of highways and railways, construction of tunnel portals, temporary and permanent earth retention structures, repair of several existing retaining walls and base-ments etc. The standard design guidelines are principally based on the classical earth pressure theories and scale models (Tei et al. 1998), yet considering the field practice experiences, there still remains a scope for a systematic study for its optimization. Federal Highway Administration (FHWA) in its manual for design and construction of soil nail walls (FHWA Manual 2015), details load and resisting mechanisms and limit states such as strength limit state, service limit state and global safety to be considered for design of soil

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nail walls. Amongst the important internal stability criteria for geotechnical strength limit state are nail pull-out resistance and lateral stability. For both the criteria, the pull-out strength of the soil–nail interaction and the nail length and pattern are vital. FHWA Design and Construction manual has transitioned from Allowable Stress Design (ASD) approach to the Load and Resistance Factor Design Approach (LRFD) for assessment of the governing limit states for design of soil nail walls. LRFD approach enable us to account the inherent uncertainties associated with load and resistances (NCHRP Report 507 2004). The results for pull-out strength resistances are back calibrated for LRFD approach from the Allowable Strength Design (ASD) approach. FHWA Manual, for simplicity, considers uniform nail length distribution patterns along the height of the wall, but recommends consideration of shorter nail length in the lower half of the wall depending upon the geometry and ground conditions. Current study undertakes an analytical design approach considering the LRFD approach along with numerical models towards potential parametric optimization of the technique. Results from numerical approaches such as Finite Element Analysis (Babu and Singh 2009a, b) and Limit Equilibrium Analysis (Shaw-Shong 2005) have been undertaken in static and dynamic conditions to study potential optimization of parameters such as pull-out strength and nail length patterns. Observed set of results are compared with standard design practices like theoretical results prior field practices and model tests. Further relevant checks for limit strength and global stability in static and dynamic conditions have been undertaken to validate the optimized parameters like pull-out resistance and nail length patterns. The obtained and validated set of parameters are further correlated to relevant limit strength conditions using regression analysis.

## 2 Design Approach

Standard practices for design of soil nail walls are well encased in several manuals detailing guidelines for design of soil nail walls. The guidelines are primarily based on full scale laboratory test results and classic earth pressure theories. The FHWA Manual for Design and Construction of Soil Nail Walls details and considers the design of soil nail walls using

Allowable Stress Design approach (ASD) be checked and verified using Load and Resistance Factor Design Approach (LRFD) for assessment of limit states such as strength limit state, serviceability limit state and global safety conditions. LRFD approach enables incorporation of inherent design bound uncertainties over wider range of parameters associated with loads and resistances of the soil nail wall like geotechnical and structural strength limit states and serviceability limit states (Paikowsky 2004; FHWA Manual 2015).

For the current study, the design procedure and checks were undertaken considering the Limit Resistance Factor Design (LRFD) approach as presented in FHWA guidelines. Preliminary analysis was undertaken initially to consider aspects like slope layout, nail spacing, nail length and ground properties, which was followed by the final design verification and checks using standard charts and graphs. The considered preliminary parameters including the geometrical and geotechnical parameters are detailed in Table 1. For initial design considerations, uniform nail length pattern was considered for analysis. Strength limit and Service limit checks and verifications for internal and external failure modes considering the LRFD approach like nail tensile resistance, pull-out resistance, sliding check, face bending and global stability were considered for ensuring the relevance of the considered parameters and subsequent design. Considering the design procedures, the material properties and parameters were adjusted, defined and established as detailed in Table 1.

Considering the above mentioned ground and nail parameters, the soil nail slope was found to satisfy the criteria for internal and external (Global) stability. Further numerical analyses were undertaken for validation and potential parametric optimization.

## 3 Numerical Analyses

In order to validate the undertaken design procedure for soil nailing and to further analyse the results for its potential parametric optimization, numerical analyses were undertaken using finite element and limit equilibrium techniques. Commercially available software PLAXIS 2D and GEO5 were used for Finite Element Analysis (FEA) and Limit Equilibrium Analysis (LEA) respectively. For slope stability or earth retention analyses, the worst case condition generally

**Table 1** Initial design parameters considered

Parameters	Symbol	Value	Unit
<i>Geometrical and geotechnical properties</i>			
Height	$H$	8	m
Dead load surcharge	$Q_{sd}$	10	kN/m <sup>2</sup>
Live load surcharge	$Q_{st}$	20	kN/m <sup>2</sup>
Face batter	$A$	5	°
Cohesion	$c'$	3	kN/m <sup>2</sup>
Friction angle	$\phi'$	30	°
Unit weight	$\gamma$	20	kN/m <sup>3</sup>
Modulus of elasticity of soil	$E_{soil}$	2E+04	kN/m <sup>2</sup>
<i>Nail properties</i>			
Yield strength of nail	$f_y$	415	N/mm <sup>2</sup>
Modulus of elasticity	$E_{nail}$	2E+08	kN/m <sup>2</sup>
Nail spacing, horizontal $\times$ vertical	$S_h \times S_v$	1.5 $\times$ 1.5	m
Nail inclination	$I$	15	°
Drill hole diameter	$D_{dh}$	0.11	m
Ultimate bond strength	$q_u$	125	kN/m <sup>2</sup>
Modulus of elasticity	$E_{grout}$	2E+06	kN/m <sup>2</sup>
Thickness of facing	$t_{facing}$	0.2	m

corresponds to the effective stress condition or drained condition (CIRIA C580 2003), hence for numerical analyses using both the numerical techniques, effective stress condition or drained parameters were considered. For Global stability considerations, safety factors determined from the numerical analyses were considered while for serviceability conditions, the horizontal displacements were considered.

### 3.1 Finite Element Analysis

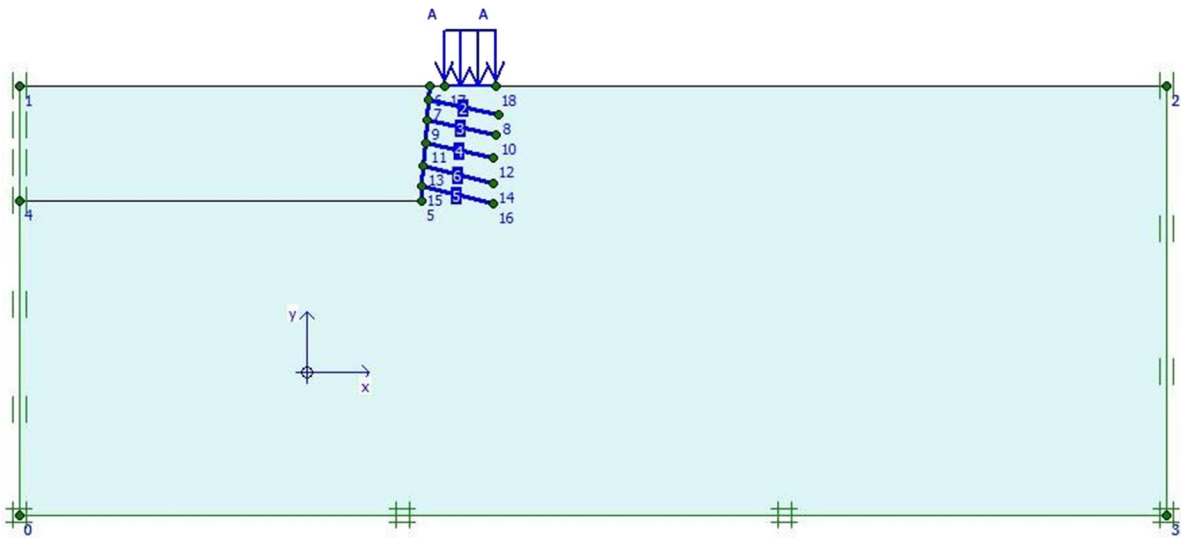
FEA was undertaken using PLAXIS 2D. The geometrical, soil and nail parameters considered for FEA are detailed in Tables 1 and 2 respectively. Finite element analysis has made significant developments recently,

**Table 2** Parameters considered for finite element analysis

Parameters	Symbol	Value	Unit
Nail length	$L$	4.8	m
Nail diameter	$D$	0.025	m
Nail axial stiffness	$EI_{nail}$	2.32E+05	kN/m
Nail bending stiffness	$EA_{nail}$	1.75E+02	kNm <sup>2</sup> /m
Facing axial stiffness	$EI_{facing}$	2.0E+06	kN/m
Facing bending stiffness	$EA_{facing}$	1.66E+03	kNm <sup>2</sup> /m

owing to its degree of precision and relative ease for modelling (Babu and Singh 2009a, b; Sharma et al. 2019b, c). 15 node Plain Strain model of 8 m height was considered for the model analysis. Medium size mesh was considered for the analysis. The soil was modelled using Hardening soil model, which is relatively preferable over other soil models such as Mohr–Coulomb model for simulating excavation sequences due to its accountancy of stress dependent stiffness modulus (Tjie-Liong 2014; Ardakani et al. 2014). Figure 1 depicts the finite element model considered for the analysis.

The nails and the facing of the soil nail wall were modelled using plate element. Their stiffness was derived considering the grouted nails and are detailed in Table 2. To simulate relatively larger area, the end boundary conditions were considered to be at roller condition on the sides ( $U_x = 0$ ) and fixed at the bottom ( $U_x = U_y = 0$ ) (Babu and Singh 2009a, b). Top-down construction sequence was simulated in calculation stage using the staged construction technique (Liu et al. 2015) available in PLAXIS 2D. The safety factor for the simulation was calculated using the strength reduction technique i.e. phi-reduction technique in PLAXIS 2D, which in iterative steps (Eq. 1) reduces the soil shear strength parameters until the soil body fails (PLAXIS Reference Manual 2002). Axial forces



**Fig. 1** Finite element model for soil nailing

on the nails and horizontal displacement of facing were amongst the observed parameters from the numerical analyses.

$$\Sigma Msf = \frac{\tan(\tan \phi_{input})}{\tan(\tan \phi_{reduced})} = \frac{c_{input}}{c_{reduced}} \quad (1)$$

where  $\phi_{input}$  = input value of angle of internal friction ( $^{\circ}$ ),  $\phi_{reduced}$  = reduced value of angle of internal friction at failure ( $^{\circ}$ ),  $c_{input}$  = input value of cohesion (kPa),  $c_{reduced}$  = reduced value of cohesion (kPa) at failure.

#### 4 Parametric Optimization

Based on the simulations undertaken and subsequent results obtained using finite element analysis, potential parametric optimization was considered to be undertaken using soil–nail interaction and Load and Resistance Factor Design (LRFD) approach. Several studies have been undertaken detailing the effect of parametric variation such as nail lengths, nail inclinations, grouting pressure etc. on the stability of nail slopes (Zhou et al. 2011; Hong et al. 2017). Julusic and Zlender (2013), presented soil nailing optimization using non-linear programming approach for predicting the safety factor using parameters such as slope angle, inclination of nail, length of nails etc. Further, Joon et al. (2014), considered optimization of soil nailing using three variable design parameters; bonded length

of nails, number of nails and pre-stress. Considering the above, pull-out strength and nail length patterns were considered as the parameters for potential optimization for the current study.

##### 4.1 Pull-Out Strength Using Soil Nail Interaction

Considering the design and subsequent numerical analysis using FEA, it can be evidently established that the parameters considered for the design and analysis carry high importance. Amongst the considered parameters for the design practice, pull-out strength or pull-out resistance of a soil nail is a vitally important parameter (Sharma et al. 2019a). Pull-out strength or pull-out resistance in simple terms can be defined as a measure of resistance of soil–grout–nail interaction to the axial pull-out force. Pull-out strength can be characterised as a function of various soil and nail parameters such as soil type, texture, surface roughness, overburden pressure, grouting pressure, nail inclination, acting axial forces etc. (Hong et al. 2017; Seo et al. 2017; Yin et al. 2009). Pradhan et al. (2006) conducted laboratory tests and showed that pull-out strength is a function of soil parameters and further developed a numerical model for interpretation of pull-out strength. For standard design practices using standard codes and charts, a conservative value considering the soil type is recommended. Federal Highway Administration (FHWA) design and construction practice manual recommends pull out

strengths for different types of soil for different nail types (FHWA Manual 2015). Standard manuals such as Construction Industry Research and Information Association and French National Research Project on Soil Nailing also suggests use of conservative values, semi-empirical equations and field tests as methods for consideration of pull-out strength (Phear et al. 2005; CLOUTERRE 1991). For the present study, the pull-out strength or pull-out resistance of soil nail has been estimated and compared from the back calculation of the results of FEA using the soil–nail interaction and Load and Resistance Factor Design (LFRD) approach recommended by FHWA, using the Eq. 2. In order to consider the worst-case condition and to simulate the effect of pull-out, the axial forces were considered at failure. Capacity-to-Demand Ratio (CDR) is conservatively considered as a minimum value of 1.

$$CDR = \frac{\phi_{po} \times \pi \times D_{dh}}{\gamma_{EV} \times T_{max}} \quad (2)$$

where  $q_u$  = Estimated Pull out Strength,  $\gamma_{EV}$  = Load Factor = 1.35,  $T_{max}$  = Maximum Axial Force (kN/m),  $\phi_{po}$  = Resistance Factor = 0.65,  $D_{dh}$  = Drill Hole Diameter (m),  $CDR$  = Capacity to Demand Ratio.

Axial forces are the critical forces acting on a soil nail and as it is evident from the above mentioned equation, pull-out strength or pull-out resistance is a function of the maximum axial force acting over the length of the nail. Isaka et al. (2016), based on an experimental and numerical investigation for analysis of pull-out strength in lateritic soil concluded that pull-out strength is in direct correlation with the overburden pressure and in inverse correlation with the degree of saturation. The pull-out strength increased with increase in overburden pressure and reduced with increase in degree of saturation. Figure 2 illustrates akin set of results of the ratio of theoretical estimates of pull-out strength from back-calculation of the finite element analysis in drained conditions to the conventionally assumed value of pull-out strength for the conventional design practice with respect to the elevation.

Evident from the Fig. 2, it can be established from the results that the observed trend of values obtained from the finite element results are comparable and relatively upper bound to the assumed/considered value for pull out strength. The ratio of pull out strength obtained from the back analysis of finite

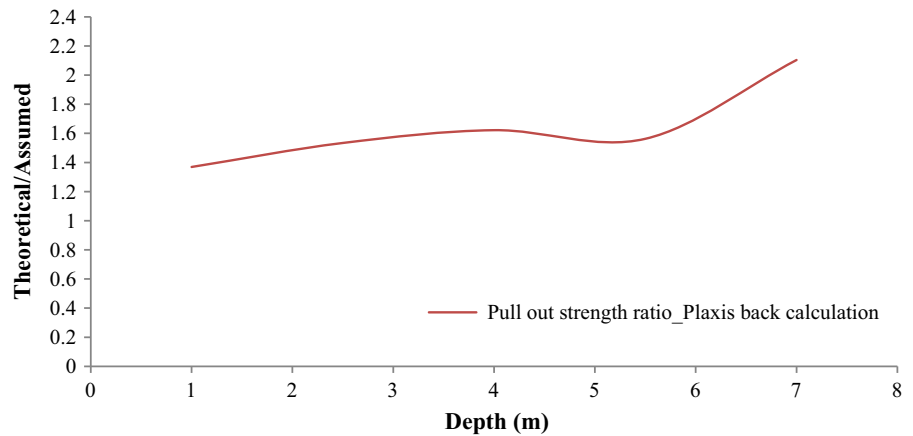
element results suggests an observed to assumed pull-out strength ratio of 1 to 2. It is also evident and worth noting from Fig. 2 that the observed set of results validate the fact that the pull-out resistance of soil nail is a function of overburden or effective pressure, as it varies with depth. It can be hence established from the observed trend of results that the pull-out strength considered for the design analysis is relatively conservative and can be potentially optimized.

A collective review for suggested approaches for estimation of pull-out strength was carried out by the Geotechnical Engineering Office, Hong Kong and published in Geo Report 264 (2009). They shortlisted the applicable approaches to four practical methods; Empirical Correlations, Field Pull-Out test method, Undrained Shear Strength and Effective Stress method. The results from considered methodologies were compared to the observed field test results. The study concluded that the field pull-out strength results yield relatively higher values than the theoretical estimated or conventionally considered values. Another study conducted by Pradhan et al. (2006) concluded that the pull-out strength of soil nail is directly proportional to the overburden acting over it. Gursaud et al. (2011), in an experimental study for estimation of pull-out strength in unsaturated conditions concluded that the pull-out capacity estimated using the conventional methods are relatively conservative. Results of the current study concur with the findings of above stated experimental and numerical studies and are further tabulated in Table 3.

#### 4.2 Nail Length Pattern

An implication of consideration of non-uniform pull-out resistance can potentially enable us to optimize the nail length pattern. Earlier studies for optimization of nail length pattern includes studies by Patra and Basudhar (2005) whereby a new approach for optimized design of soil nailing was suggested by using limit equilibrium techniques and considered parameters such as nail length, diameter, spacing and orientation as critical parameters. Lin et al. (2013) studied the effect of nail length on the slip circle pattern and concluded that the safety factor increases linearly with nail length until it reaches the effective reinforcement length from where onwards the safety factor reaches the maximum value. For the current study, in order to study the possible optimization of

**Fig. 2** Comparison between pull-out strength obtained from analytical back calculation and assumed value



**Table 3** Comparison of theoretical/estimated pull-out ratios

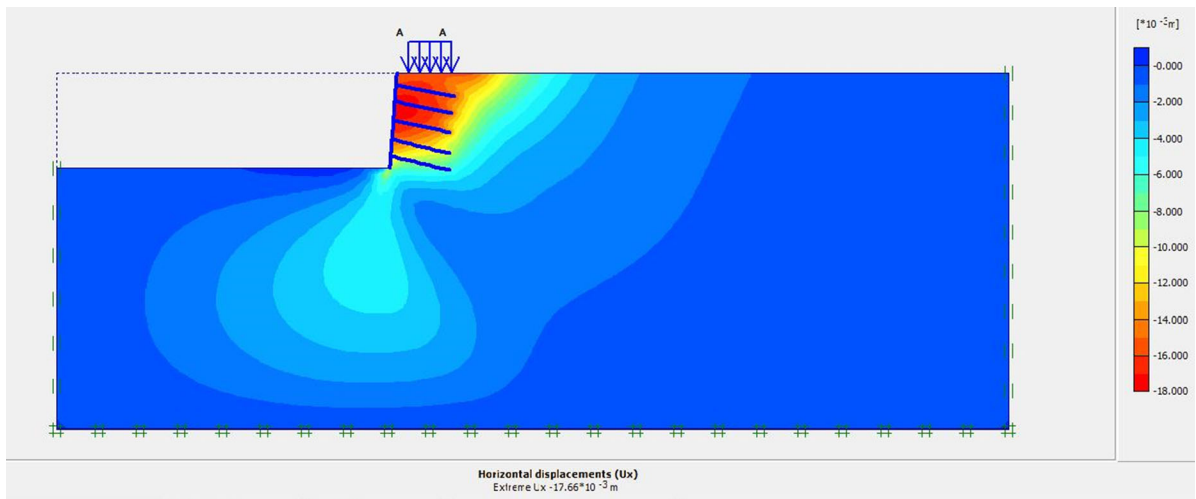
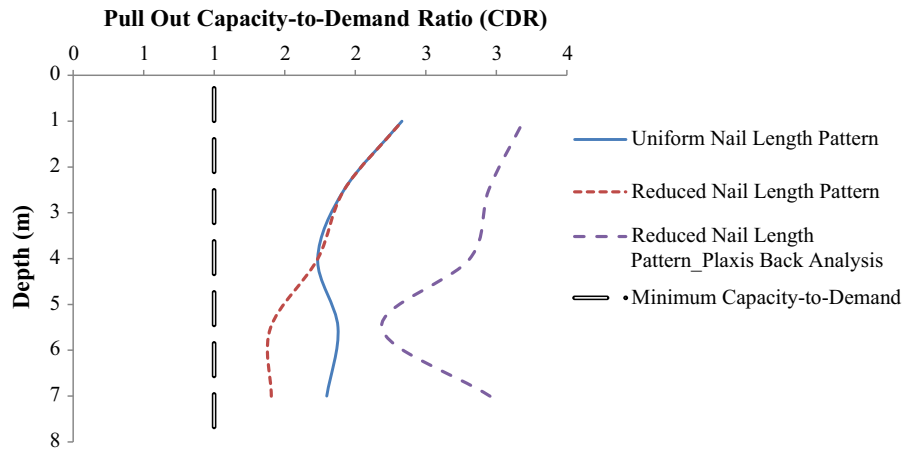
Sl. no	Pull out	Type of study	Theoretical/assumed pull-out ratio
1	Current study	Numerical study	1–2
2	Cheung & Shum (2012)	Field tests (approx 1000)	5.7–7.6
3	Isaka et al. (2016)	Numerical study	2–2.7
4	Lin et al. (2015)	113 field tests	3.0–3.7

nail length pattern, the conventional design and subsequent finite element analysis using reduced nail length patterns were undertaken. Checks for failure modes such as internal (tensile and pull-out strength checks) and external failure modes were undertaken with and without the optimized pull-out strengths for the reduced nail length patterns to ensure the stability in respective failure modes. Further analysis considering the reduced nail length patterns were undertaken for Global Safety using finite element software PLAXIS 2D. The results of finite element analysis for the serviceability suggested that the upper one-third and the middle one-third portion are found to have relatively profound impact on the pull-out failure, as the horizontal displacements observed were relatively greater and were observed till relatively larger portions behind the slope. While the nails in the upper-third and mid-third are prone to relatively greater horizontal displacements, they also experience relatively lower axial forces as compared to the nails in the lower third portion of the slope, where the nails are exposed to relatively larger magnitude of axial forces and relatively smaller magnitude of displacements (Zhang and Lu 2015). Considering that, the

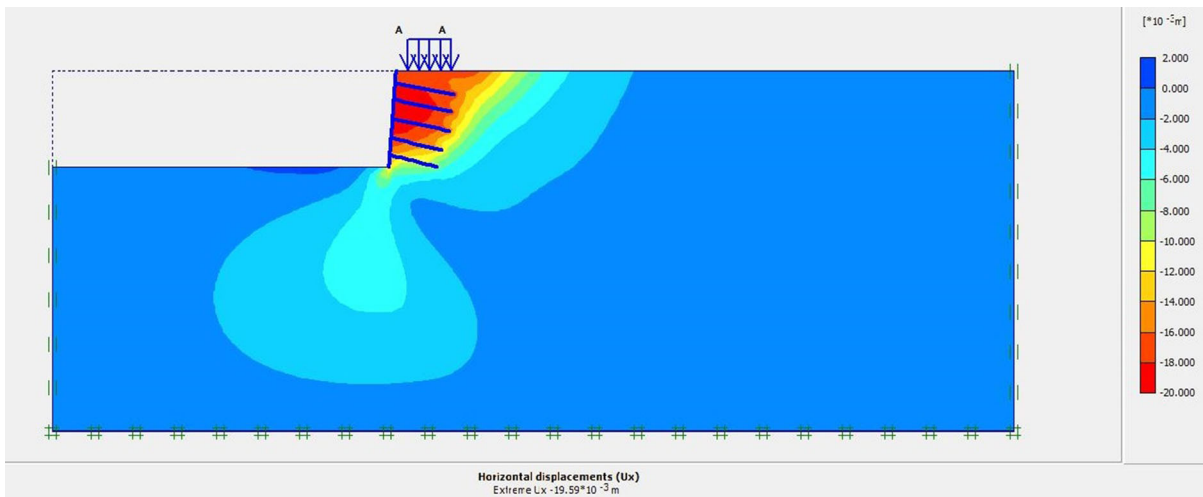
potential zone for optimization (10–20% reduced nail length) was considered as the lower third portion. The results for the internal failure checks like the pull-out check with and without considering the optimized pull-out strength and nail length patterns are depicted in Fig. 3.

The considered reduced nail length patterns were further checked for Global Stability using PLAXIS 2D. Figures 4 and 5 depicts the trend of shear failure plane in uniform and reduced nail length patterns respectively. Figure 6 shows the comparison of observed trends of global safety factor with respect to construction stage in uniform nail length pattern and considered reduced nail length patterns. Based on the observed set of results, it can be inferred that the nail length in the lower third portion of the slope can be reduced considerably by 10–20% of the nail length. Further reduction in nail length in the lower third portion beyond the above mentioned criteria (10–20% nail length) were found to be just within the permissible limits in the pull-out criteria, but failed to satisfy the global safety factor. Although the maximum displacements for reduced nail length pattern was found to be relatively higher than the uniform nail

**Fig. 3** Comparison of pull-out capacity-to-demand ratio with reduced nail length pattern

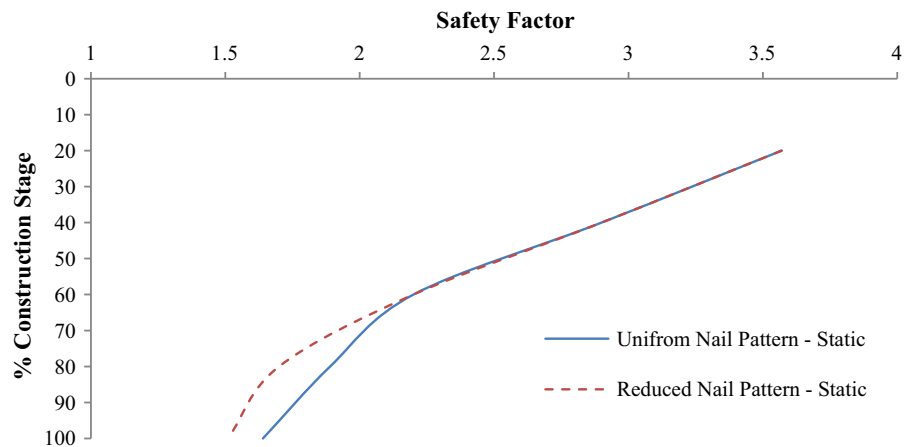


**Fig. 4** Horizontal displacements and shear failure plane for uniform nail length pattern



**Fig. 5** Horizontal displacements and shear failure plane for reduced nail length pattern

**Fig. 6** Safety factor for uniform and reduced nail length pattern with respect to construction stage using finite element method



pattern displacements, they were found to be within the permissible range and comparable with the theoretical values.

Figures 4 and 5 shows the observed trend of shear failure plane pattern and horizontal displacements in uniform and reduced nail length patterns. Evidently it can be stated that the reduction in nail length pattern causes minimal deviation in the shear failure patterns and displacement trends. Figure 6 further depicts the construction-stage wise global factor of safety as obtained for uniform and reduced nail length patterns using phi-c reduction technique in PLAXIS 2D. The results of numerical analyses show that a relatively lower factor of safety for global stability is obtained for the reduced nail length pattern and to be within permissible limits. Geotechnical Engineering Office, Hong Kong conducted a detailed numerical study on effect of nail length pattern on deformation on soil nail walls using numerical FLAC software and are detailed in the GEO Report 197 (2005). The results of the study concur with the findings of the current study.

Figure 7 shows the observed trend of horizontal displacement for uniform and reduced nail length patterns. It is also to be noted that the observed trend of horizontal displacements on facing were found to correspond to the observed trend and horizontal displacement in nails at the corresponding elevation. The displacement values obtained are in good agreement with the empirical correlation for assessment of deformation as suggested in FHWA Manual—Equation 5.65. Maximum theoretical or semi-empirical assessment of horizontal deformation of a soil nail wall can be considered as  $(\delta h/H)_I \times H$ , where  $(\delta h/H)_I = 1/333$  which is roughly 22–24 mm. Considering

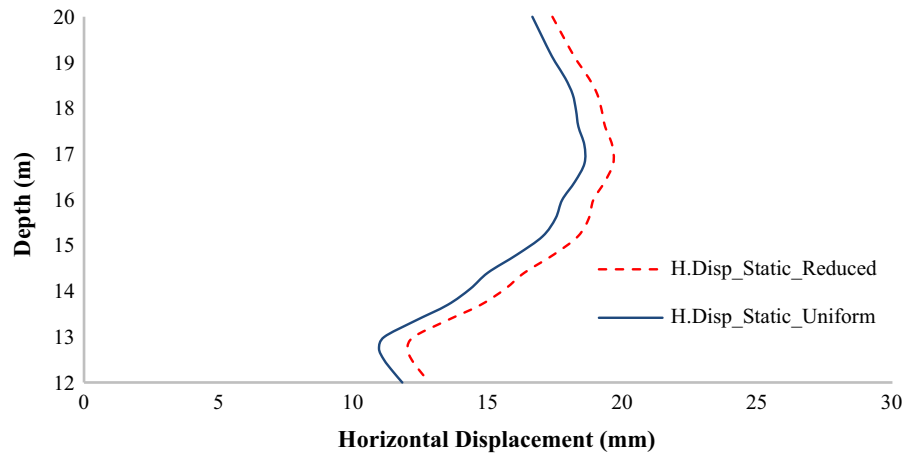
the slope batter, the results can be considered as marginally on the conservative side. In a numerical and experimental study detailed in GEO Report 197 (2005), conducted by Geotechnical Engineering Office, Govt. of Hong Kong about behaviour of nailed structures using PLAXIS, FLAC and laboratory results, variation of the nail patterns was considered as one of the varying parameter and the results suggested similar trends as observed in the current study. The observed deformations in the above study was found to concur with the findings of the present study. The middle third portion which is more susceptible to pull-out failure was found to undergo maximum displacements and with a reduced nail length pattern, mild increment in deformation was observed in the affected zone. Considering the same, the results observed from finite element analysis in uniform and in reduced nail length patterns stand validated i.e. effect of reduced nail length pattern marginally increases the horizontal displacements as observed, yet can be considered within tolerable limits.

#### 4.3 Limit Equilibrium Analysis

The observed results for safety factors as obtained from the FEA were further validated using the LEA (Ramkrishnan et al. 2018a, b) using commercially available software, GEO5. The software enables analysis of nailed walls in varying conditions and allows to study corresponding effects (GEO5 Reference Manual 2015). The parameters along with the loading conditions as tabulated in Tables 1 and 2



**Fig. 7** Horizontal displacements for uniform and reduced nail length pattern with respect to depth using finite element method



which were considered in the preliminary design analysis and FEA were further considered for LEA.

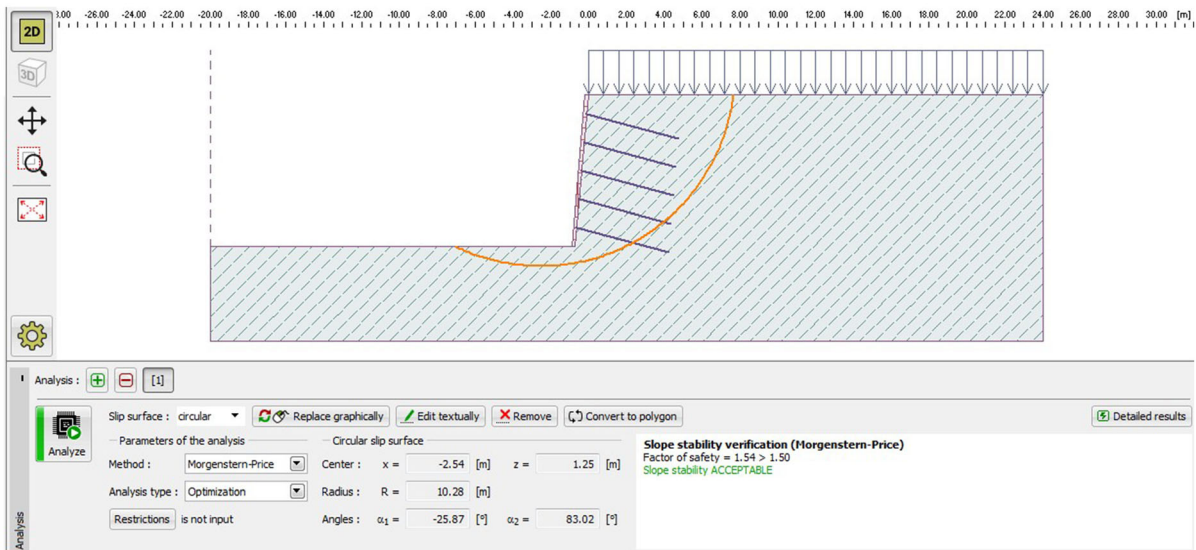
Figures 8 and 9 shows the safety factor obtained from the limit equilibrium analysis using GEO5. Figures 8 and 9 depicts the safety factors obtained from uniform nail lengths and reduced nail lengths respectively. The observed results are in good agreement with the results of conventional design approach and FEA.

As depicted in Figs. 8 and 9, the observed safety factors for the final construction stage in uniform and reduced nail length patterns using limit equilibrium technique (Morgenstern-Price method) are found to be within permissible limits and comparable with the

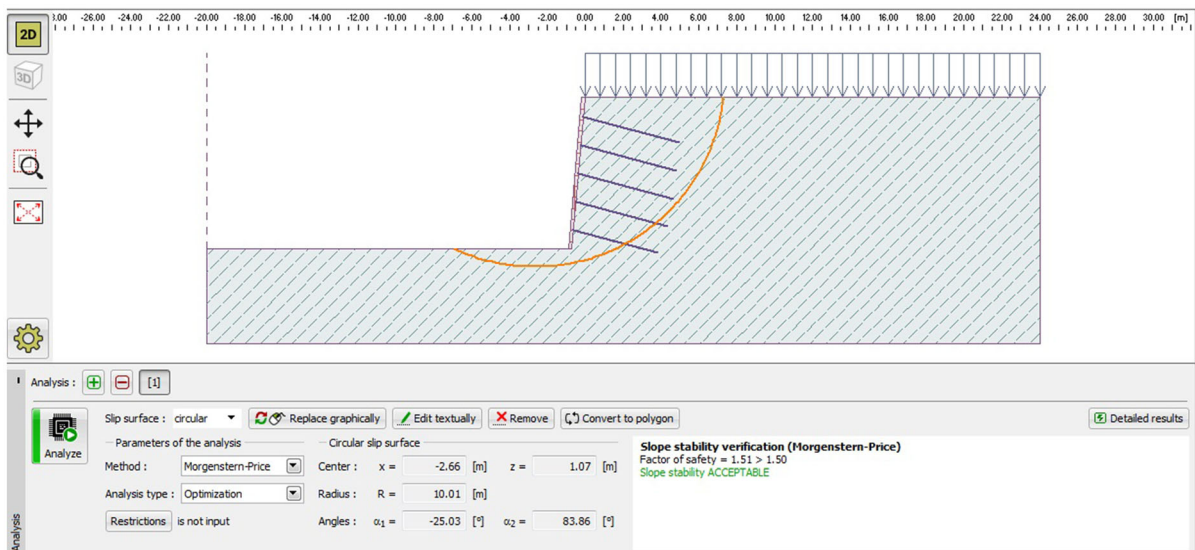
results of conventional design and FEA. Results further depicts similar trends and variations as compared to the other methods for slope stability as considered in earlier studies (Dong-ping et al. 2017).

### 5 Seismic Analysis

Furtherance to the above static analyses considering reduced nail lengths, design and FEA under seismic loading conditions were undertaken in order to study the effect of the reduction in nail lengths under dynamic loads. Design considerations for seismic analysis were undertaken using the standard



**Fig. 8** Global safety factor using limit equilibrium method in uniform nail length pattern



**Fig. 9** Global safety factor using limit equilibrium method in reduced nail length pattern

guidelines as defined in FHWA manual. Seismic parameters considered for seismic analysis using LRFD approach are further presented in Table 4.

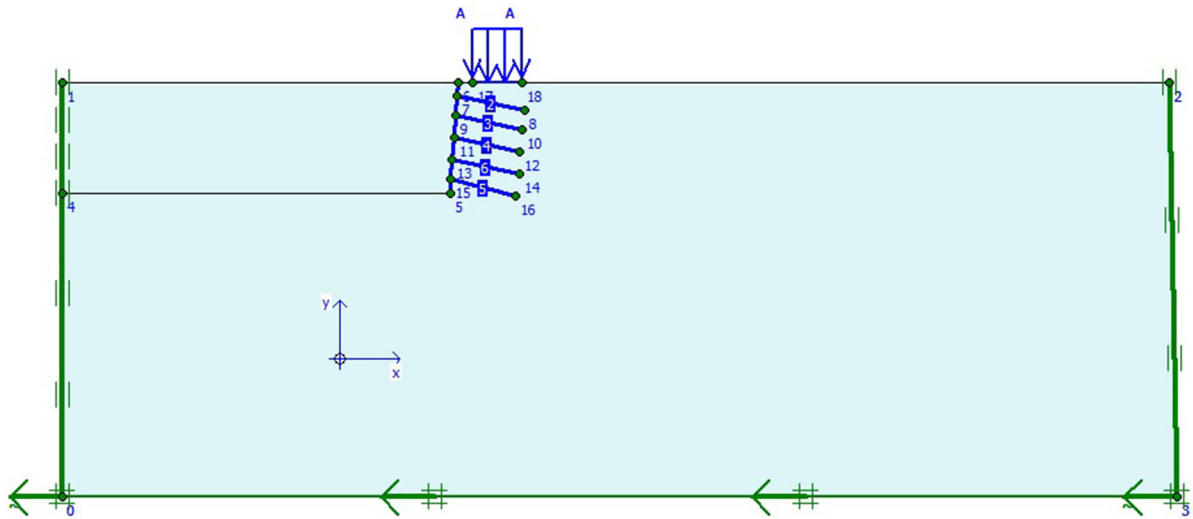
Geometric and geotechnical parameters were considered the same as for static analysis and are detailed in Table 1. Limit state checks in seismic conditions for geotechnical and structural strength, serviceability and global safety were undertaken considering the Load and Resistance Factor Design (LRFD) approach (considering seismic resistance factors) and were found to be in permissible limits for seismic condition. Considering the parameters, the global safety factor considering the LRFD approach (considering seismic resistance factors) was found to be around 1.3.

Seismic analysis for reduced nail length pattern was undertaken using Finite Element Software PLAXIS

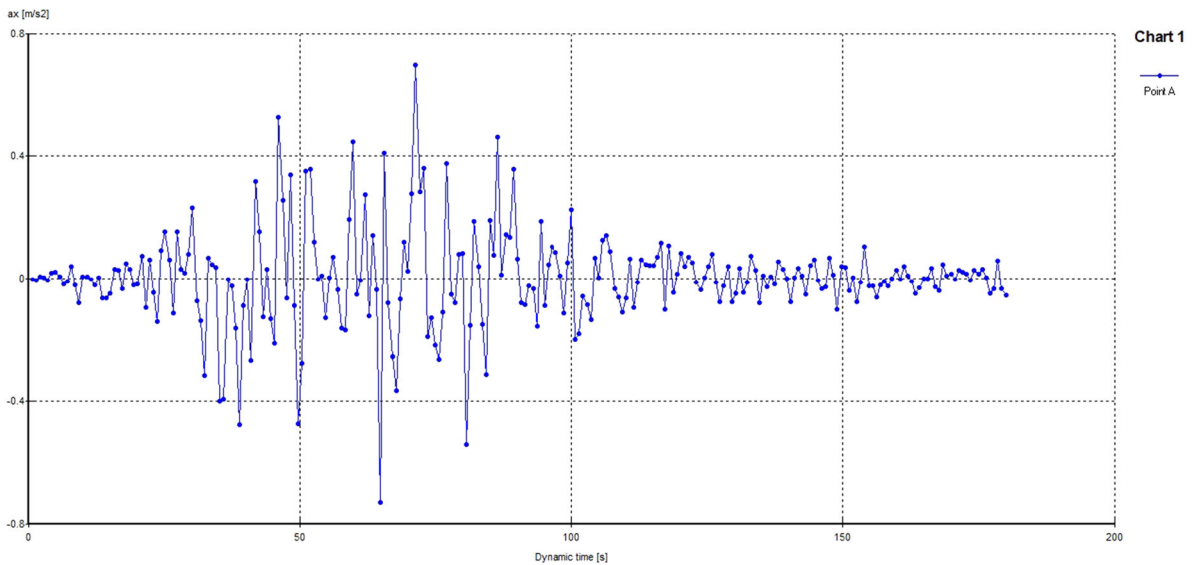
2D. Dynamic analysis/dynamic calculations available in PLAXIS 2D was considered to carry out the seismic analysis to assess the corresponding effects in global and serviceability states in dynamic conditions. The finite element model and parameters considered for static analysis were further considered for seismic analysis. In order to ensure the effect, large boundary was considered for seismic analysis (Aryal et al. 2006). Figure 10 depicts the considered geometry for the analysis. Effect of earthquake in PLAXIS 2D was simulated using prescribed dynamic displacements at the bottom boundary conditions (Barar Pirooz and Qing Liu 2010). Absorbent boundary conditions on sides and bottom were considered in order to absorb the effect of outgoing waves during the simulation (PLAXIS Dynamic Reference Manual). Acceleration-time histories of an actual earthquake, the Andaman Islands [Port Blair, August 2009 made available through website (pesmos.in)] earthquake of moment magnitude,  $M_w$  7.5 were considered for modelling and simulation of earthquake loading (Kumar et al. 2012) on a nailed slope with uniform and reduced nail length patterns. The considered acceleration-time history is presented in Fig. 11. Since the effect on reduced nail length pattern was to be assessed, the high magnitude earthquake event was considered for the analysis. PLAXIS dynamic manual recommends consideration of Rayleigh damping coefficients ( $\alpha$  and  $\beta$ ) associated with small damping ratio to simulate physical

**Table 4** Seismic parameters for design consideration

Parameters	Symbol	Value	Unit
Horizontal seismic coefficient	$kh$	0.048	
Vertical seismic coefficient	$kv$	0.024	
Site class		C	
Average shear wave velocity	$V_{s,30}$	350–800	m/s
Average SPT $N_{60}$	$N_{60}$	50	Bpf
Average $c_u$		100	kPa
PGA		1.569	$m/s^2$



**Fig. 10** PLAXIS 2D model for dynamic analysis

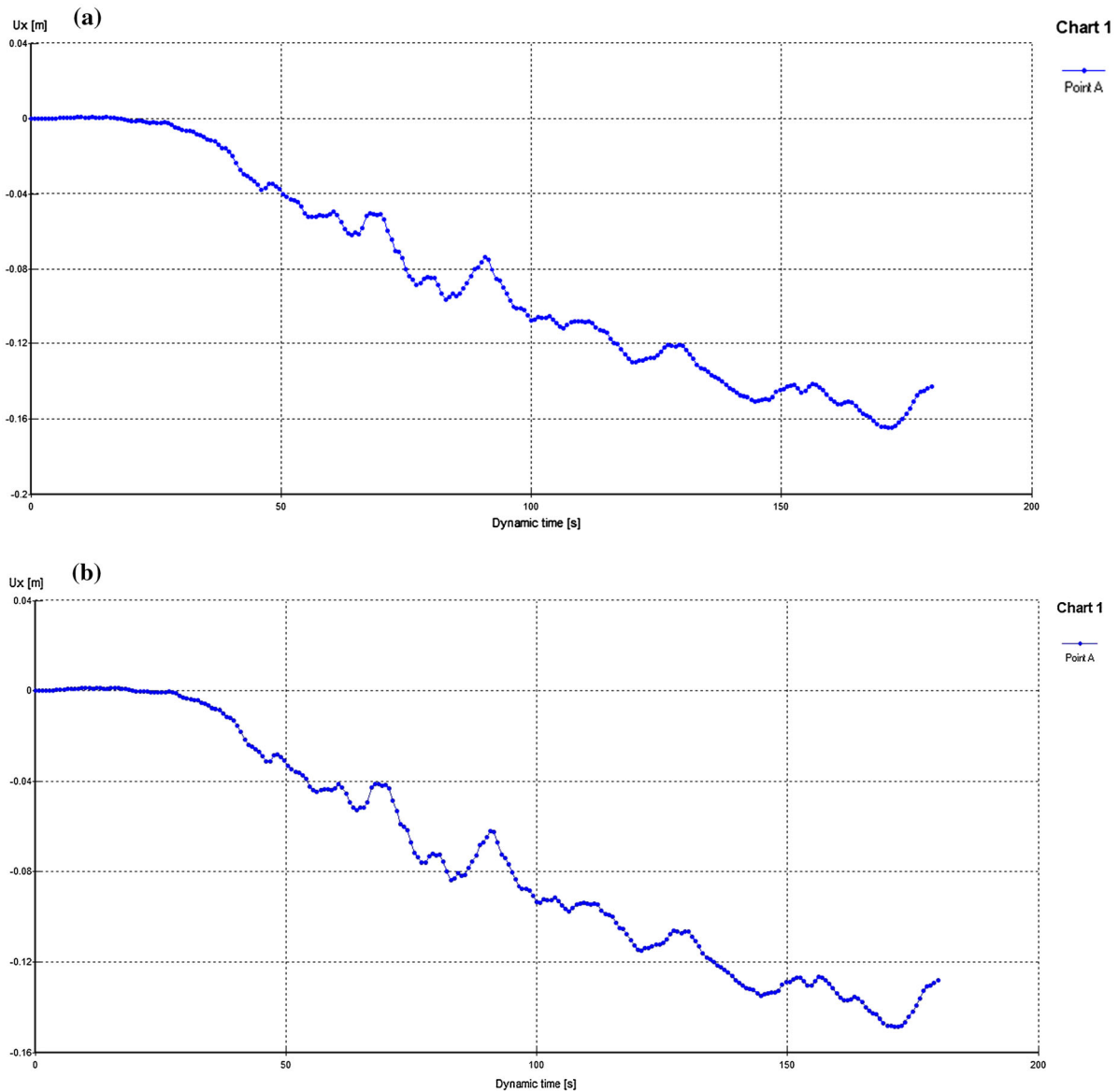


**Fig. 11** Acceleration–time history considered for the PLAXIS 2D analysis

damping in soil. Considering that the coefficients were considered as 0.01 and 0.01 respectively for the soil models.

Effects of ground motion on global safety of soil nailed wall was studied and compared for the uniform nail length pattern and reduced nail length pattern as considered in the previous sections. Parameters considered for the dynamic analyses using FEA were considered as same as that of the static analyses. Observed results from FEA suggested a safety factor

ranging from 1.10 to 1.13, whereas the safety factor considering the LRFD technique using conventional design procedure was found to be relatively conservative i.e. 1.3; which in all the cases, were found as permissible. The safety factors as obtained are found to concur with the design charts suggested by Rawat and Chatterjee (2018). Effect of ground motion on serviceability were also considered using finite element analysis. Figure 12 depicts the observed trend of



**Fig. 12** Comparative trend of dynamic horizontal displacements for **a** uniform nail pattern, **b** reduced nail length pattern with respect to dynamic time

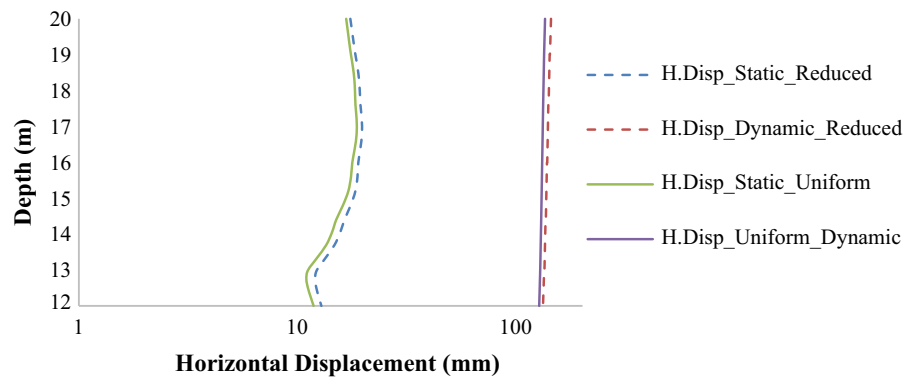
horizontal displacement on soil nailed slopes, considering the effect of the considered earthquake.

The observed trends of results were subsequently compared to the theoretical horizontal seismic deformations. FHWA (2003) recommends consideration of 0.67–1.25% times the height of wall or slope as permissible seismic horizontal deformation which almost corresponds to the observed trend of results from dynamic analysis using Finite Element Analysis. Results in seismic conditions were compared to the

results of static analyses as detailed in previous sections and consequently, the effect of earthquakes on horizontal displacements (Zaki et al. 2015) of nail length patterns were compared and a comparative trend generated is represented in Fig. 13.

From the results and subsequent comparisons, it is quite evident that, in both the cases, uniform and reduced nail length patterns, the effect of earthquake increases the impact on nails and facing as considerable increment in horizontal displacements of nails

**Fig. 13** Comparative trend of horizontal displacements under static and dynamic conditions using finite element analysis



and facing was observed. The observed horizontal displacements with reduced nail length patterns were found to be relatively greater than the case of uniform nail length pattern which happens to be in line with the observed trend in static condition. It is also to be noted that safety factors in case of reduced nail length patterns were found to be just within permissible limits in both static and dynamic conditions.

To validate the observations considering the FEA in dynamic condition of soil nailed slopes, further dynamic analysis using the limit equilibrium method was undertaken. Figure 14 represents the observed results from the dynamic analysis using LEA using GEO5 software.

Same set of soil, nail and dynamic parameters used in previous sections were considered for dynamic analysis using limit equilibrium techniques using GEO5. The obtained results were found comparable with the results obtained using FEA as the safety factors were obtained in the range of 1.10 to 1.11. The observed trend for uniform and reduced nail length pattern were observed to be in line with the one obtained in the static case.

### 6 Regression Analysis

Based on the observed trend of results, it was clear that upon considering the reduced nail length pattern, the horizontal deformation increased. Hence an inverse correlation can be ascertained between the nail length pattern and the horizontal deformations. Estimation of horizontal deformations is a vitally important criterion i.e. serviceability for design of soil nail walls/slopes and is directly correlated to the global safety factor. FHWA Manual recommends an empirical correlation

for estimation of horizontal deformations which has been reproduced in Eq. 3.

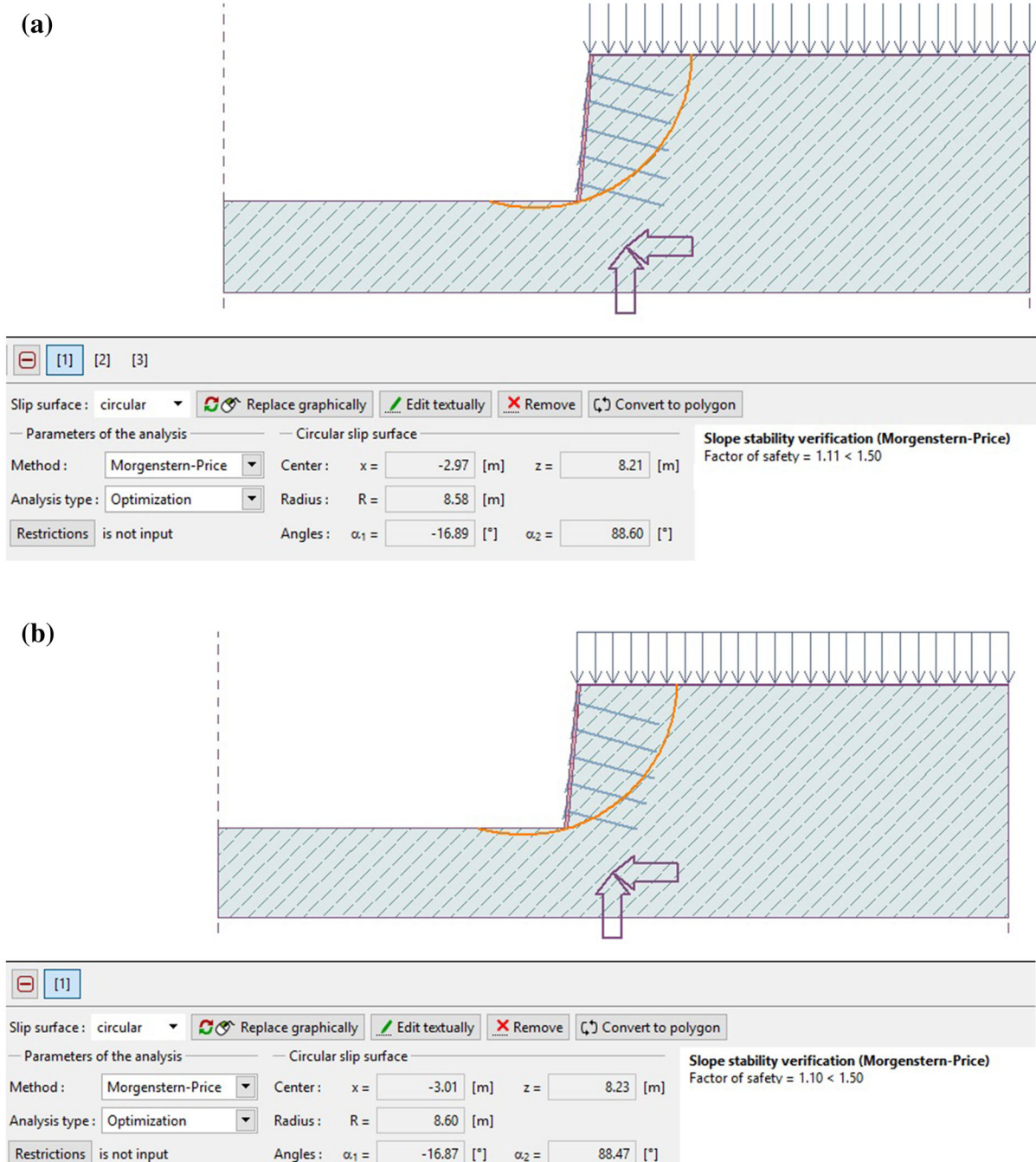
$$\delta_h = (\delta_h/H)_i \times H \tag{3}$$

where  $(\delta_h/H)_i = 1/500$  and  $1/333$  for coarse and fine grained soils respectively;  $\delta_h$  = horizontal displacement (m);  $H$  = height of the retained fill (m)

Empirical equation shown in Eq. 3 considers the geometrical and geotechnical parameters. Several other numerical and field studies such as those carried out by Ma et al. (2011), suggests that the horizontal deformation varies with other parameters such as nail inclination, stiffness, spacing etc. Another parametric numerical study by Abdallah (2010) concluded that parameters like nail inclination, stiffness, spacing and soil properties affected the horizontal displacement of nailed wall/slope. A parametric study undertaken by the Govt. of Hong Kong in 2006, concluded that the nail length pattern, inclination of nails and the bending stiffness have an impact on the horizontal displacement and eventually on the safety factors the of nailed slopes. Based on the presently undertaken Finite Element Analyses and several earlier studies as mentioned above, it can be established that the horizontal deformations of nailed slopes/walls can be considered as a function of following:

- Geometrical Parameters such as: Height, Slope angle of wall
- Geotechnical parameters like; Type of soil and shear strength parameters like cohesion and friction
- Nail Parameters; Nail length, horizontal and vertical spacing of nails, nail inclination etc.

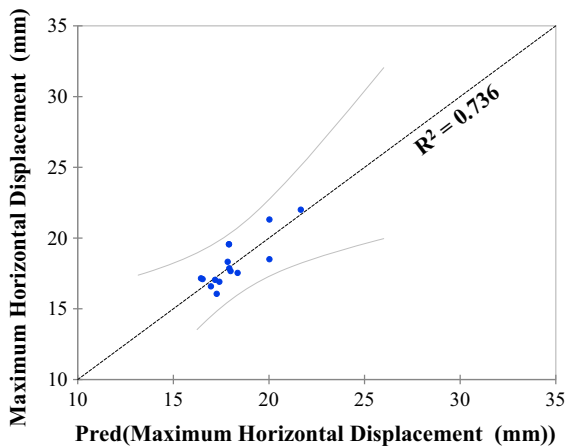
For the current analysis, the above parameters were considered for establishing correlation between the



**Fig. 14** a Dynamic analyses for uniform and, b reduced nail length patterns using limit equilibrium technique

above-mentioned parameters and the horizontal displacement of wall/slope. In order to ascertain a correlation, Finite Element Analyses were undertaken considering varying geometrical, geotechnical and nail parameters. Further in order to establish the

correlation of above-mentioned parameters on horizontal displacement and the safety factors, a multi-regression analysis was undertaken. The horizontal displacement of slope/wall as obtained from numerical simulations using Finite Element Analysis with



**Fig. 15** Comparison of horizontal displacements of soil nail wall/slope

different nail length patterns were considered to establish a correlation between horizontal displacements with the soil nail length (Hitha et al. 2019). For the considered multi-regression analyses, parameters considered were geotechnical and nail parameters, while parameters like height of slope/nail, vertical spacing and horizontal spacing were implicitly considered by considering the nail length per section height per m nail length wall/slope as a parameter. Although parameters like nail inclination and slope angle of facing were found to have an impact on the horizontal displacements of wall/slope facing, they were not considered for analysis assuming 10°–15° of inclination as optimum and assuming the slope angle as conservative (Fan and Luo 2008; Rotte Veerabhadra and Vishwanadham 2013; Rawat and Gupta 2016; Dewedree and Jusoh 2019).

Equation 4 represents the obtained correlation for considering the above mentioned parameters with an observed R<sup>2</sup> value of 0.73.

$$H_x = 23.105 + (0.505 \cdot NL) - (0.149 \cdot c') - (9.76 \cdot \tan\phi') \tag{4}$$

where *NL* = Total Nail Length per m section height per m length of wall/slope (m), *H<sub>x</sub>* = Horizontal displacement (mm), *c'* = Effective cohesion (kPa), *φ'* = Angle of internal friction (°).

Figure 15 depicts the observed comparison of predicted horizontal displacements as obtained from the above equation which was obtained from

regression analysis based on the data obtained from current numerical analyses, case studies and previous literatures. The predicted results are found to be comparable with the observed results as depicted in Fig. 15 with the dotted line representing the best fit. The obtained equation was further compared with the obtained results from previous literatures detailing the results for horizontal displacements from numerical analyses and field test results. Table 4 further compares the estimated horizontal deformations based on considered parameters as per Eq. 4. Evidently from the represented comparisons, the results are found to be comparable with each other (Table 5).

It is evident from the obtained results that the horizontal displacement values obtained from regression analyses concur with the simulation results from various results obtained from field observations and numerical results in cited literatures. The results cited can be further correlated with the safety factors considering the horizontal displacements as obtained using the following correlation in Eq. 5 by Babu and Singh (2008).

$$FS_G = 2.7346 (h_{sx})^{-0.2013} \tag{5}$$

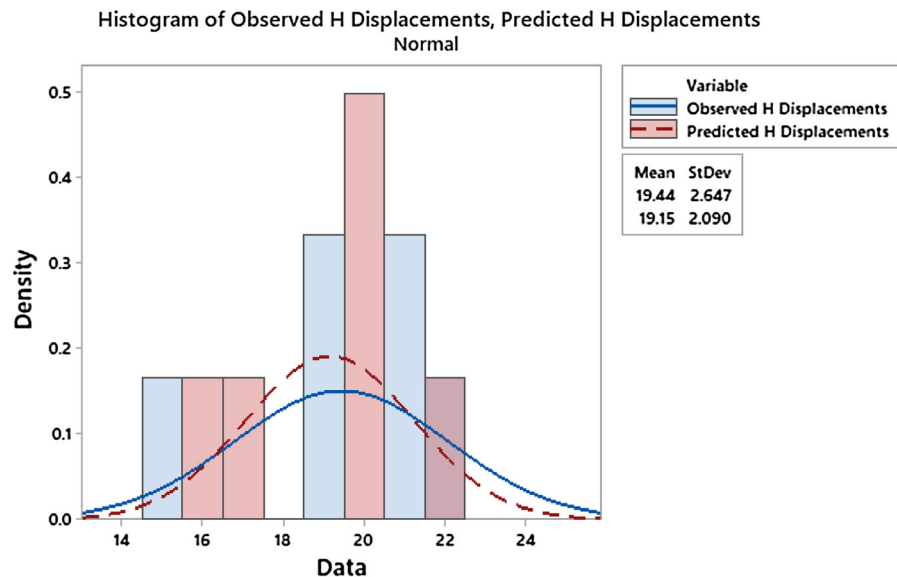
where *FS<sub>G</sub>* = Global stability factor, *h<sub>sx</sub>* = horizontal displacement (mm)

The tabulated results validate the correlation between soil deformations, soil shear strength parameters and nail length.

In order to further verify and validate the recommended equation to obtain horizontal displacement considering shear and nail parameters, statistical hypothetical tests were undertaken to draw statistical inference. The statistical inference tests/hypothesis tests were undertaken using Minitab (*t* Test) and MS-Excel Analysis of Variance (ANOVA). The horizontal displacements as obtained from several literatures (field results and numerical analyses) along with results from Finite Element Analyses using PLAXIS 2D were considered for comparison with the predicted horizontal displacements for the same shear and nail parameters. For testing the hypothesis, 95% confidence intervals were considered. Null hypothesis was considered to be true if the mean or variance of the observed results are relatively equal to the mean or variance of the predicted results. Accordingly, the alternate hypothesis was considered to be true if mean or variance of the predicted results were significantly

**Table 5** Comparison of the results of multiple linear regressions

Referred literature	Effective cohesion $c'$ (kPa)	Angle of friction $\phi'$ (°)	Nail length per section height per m wall/slope length (m)	Average horizontal displacement in literature (mm)	Predicted horizontal displacement (mm)
Babu and Singh (2008)	4	31.5	7.0	21.31	20.05
Singh and Babu (2010)	10	27.5	7.0	18.50	20.06
Manjularani et al. (2014)	10	20.0	7.0	22.00	20.05
Moniuddin et al. (2016)	4	31.5	7.0	21.31	21.59
Lima et al. (2003)	10	32	2.8	15.00	16.92
Shiu & Chang (2006)	5	39	3.5	18.50	16.24

**Fig. 16** Comparative histogram of observed and predicted horizontal displacements

different to the mean of observed set of results. Figure 16 further represents the comparative histogram i.e. value with respect to density (weighted frequency) of observed set of results and predicted results as obtained using Minitab. The plot also indicates the comparative mean and standard deviation.

Based on the obtained results of the hypothesis tests (t-Test and ANOVA) undertaken using MS-Excel and Minitab, it was observed that all criteria to test the hypothesis failed to reject the null hypothesis. The P-Values obtained which represent the probability of getting extreme result as the observed one were 0.685 and 0.513 from Minitab and ANOVA respectively.



Classic Method:  $t_{stat} < \text{critical value}$ ; failed to reject null hypothesis

$p$ -Value Method:  $p > \text{confidence interval}$ ; failed to reject null hypothesis

The Hypothesis Tests undertaken further infers that the mean or variances of both the sets of results for horizontal displacements i.e. observed results and predicted results are relatively in the same range.

## 7 Conclusions

Current study primarily underlines potential for parametric optimization considering the soil nail interaction and finite element approach. The pull-out strength estimated considering back analysis of the results obtained from finite element analysis in effective stress conditions suggest that the pull-out strengths of soil–nail were found to be a function of depth and were relatively upper bound to the conservatively suggested values by standard references by a factor of 1–2. The obtained results were found to concur with the results of various laboratory and field studies. An application of consideration of non-uniform pull out strength would enable optimization of considered nail length patterns and hence ultimately the nail length. Stability of the nailed slopes were then assessed considering the reduced nail length patterns. Internal and external failure modes were checked using limit states in strength and global safety using LRFD approach, finite element method and limit equilibrium methods. Strength limit state analysis suggested that the nails in the lower third portion were more susceptible to tensile failure than pull-out failure. From global safety and serviceability aspects, mild decrement in safety factors and mild increment in horizontal displacements were observed on considering the reduced nail length pattern. Based on the analysis and observed set of results, it can be established that the nail length for the lower-third portion could considerably be reduced by 10–20% of their lengths than in the upper-third and middle-third portion of the wall. Further analyses were undertaken considering the dynamic conditions. Seismic analysis was undertaken using the LRFD approach suggested by FHWA, finite element analysis and limit equilibrium methods. Limit state checks for strength and global safety for uniform nail length pattern were undertaken using the LRFD approach.

Impact in limit strength states, serviceability and global safety considering reduced nail length pattern were further studied using Finite Element Approach. High magnitude was considered to study the effect on reduced nail length pattern and hence time acceleration history of the high magnitude Andaman earthquake was considered for simulation of seismic analysis. Results again suggested that upon considering the reduced nail length pattern, the observed global safety factors and serviceability limits were marginally within permissible limits. In order to develop a correlation between the ground parameters and the nail length patterns, regression analysis was undertaken by considering a variation of nail length patterns and ground parameters and subsequently observed horizontal displacement of soil nail slopes. The trend of variation of horizontal displacements showed that it is inversely proportional to cohesion angle of internal friction and nail length. The obtained correlation was then further tested using hypothesis tests for drawing statistical inferences whereby it was found to adhere to accept the null hypothesis. The correlation can enable us to address the limit strength states such as serviceability and global safety and at the same time enable optimization of the nail length patterns considering the ground parameters.

## 8 Limitations of the Study

Load and Resistance Factor Design (LRFD) approach has been considered for the current study which is based on resistance factors calibrated based on equivalent minimum factor of safety considering Allowable Stress Design (ASD) approach. Notwithstanding the same, the resistance factors are valid as long as bond strength is verified by field load test conducted with minimum frequency. Furthermore, current study mainly considers the effective stress condition or drained condition of just soil parameters (not rock parameters) which is generally the governing/extreme case. However, considering the ground conditions, design considerations should undertake both i.e. effective and total stress parameters/conditions under consideration to assess the governing criteria.

The application of suggested equation for determination of horizontal displacement for drilled nails in soils based on shear and nail parameters. Applicability of equation is limited to steep slopes with  $0^{\circ}$ – $15^{\circ}$  face

batter and nail inclination of  $10^{\circ}$ – $15^{\circ}$  from horizontal. Further, the equation is considered to be valid for cases verifying the internal and external strength limit states only.

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