Static and Dynamic Analysis of Nailed Slope

Padmavathi M[1], Srinivas Ch[2]

[1, 2]Jawaharlal Nehru Technological University, College of Engineering, Hyderabad-500085, India

Abstract: ***This paper presents the stability analysis for a nailed slope with 50º slope angle and 20m height under both static and seismic condition. The analysis is carried out by both 2D limit equilibrium and Finite element methods using a geotechnical modeling software GeoStudio. A parametric study is carried out to analyse the effect of nail inclination, nail spacing and nail length on the stability of nailed slope. The soil slope attained stability with factor of safety of 1.628 by the inclusion of nails into the slope. The behavior of optimum nailed slope during an earthquake of PGA 0.15g is analysed with the help of finite element analysis in QUAKE/w module of GeoStudio. The response of the nailed slope during the earthquake is analysed in terms of its factor of safety, displacements and shear stresses at nodal points which are selected in the cross section. The nailed slope is critical at 7th second of earthquake with factor of safety of 1.35 for an average acceleration 0.124m/s². The nailed slope is also analysed to verify its stability against an earthquake record of Uttar Kashi with PGA of 0.31g lapsed for 40sec.***

Keywords: soil nailing, finite element analysis, numerical analysis, dynamic analysis.

1. Introduction

Slope stability is an essential consideration in the design and construction of various geotechnical structures like embankments, earth dams and excavations. The failure of slopes leads to heavy damages in terms of both life and property. The failures of soil slopes are observed mainly due to static loading, dynamic loading and rapid drawdown conditions. Hence it is necessary to study the stability of soil slopes before construction. A technique which is being practiced globally to stabilize soil slopes, retaining walls and excavations is by passively reinforcing with slender elements or normally steel reinforcing bars called soil nails. The unstable soil slopes can now be improved and made stable by the insertion of nails into the slope. Slope stability analysis procedures have been developed to evaluate the global stability of the soil nailed mass and the surrounding ground by considering the tension or pull-out resistance of the nails crossing the potential failure surface.

Generally, the stability of nailed slopes is analysed by conventional limit equilibrium methods. Many researchers developed the limit equilibrium methods to analyse the stability of nailed slopes [1]-[3]. The stability of nailed slope is mainly depends on nail pullout and tensile strengths. The laboratory model tests and field tests are proposed to determine the nails pullout strength and stability of the nailed slope [4]-[6]. Numerical modeling with limit equilibrium methods and finite element methods (FEM) are used to analyse the stability of nailed slope, failure zone, soil nonlinearity and the staged construction effect to predict the actual site conditions [7]-[10]. Numerical modeling of reinforced soil slope by finite element methods has proved very useful in prediction of slope deformations, stresses. The effect of nail length, nail spacing, nail inclination on stability of the nailed soil slope is also analysed by the numerical models. Mohamed developed the design charts for nailed walls with different nail lengths, nail spacing's and nail inclinations for different soils [11]. However the soil slopes are more prone to failure when they are subjected to earthquake loading. So the researchers proposed new methods to analyse the stability of slopes against dynamic loading. The conventional seismic stability of soil slopes is based on Pseudo-static method [12]. Though it is very simple method but its applicability in seismic analysis is very limited. It considers only earthquake forces and neglects amplification of waves through the soil stratum. Pseudo-dynamic (Steedman & Zeng, 1990) method is the concept which imports amplification of vibrations into the analysis [13]. Numerical methods are used to study the nailed slope failure pattern, deformations and stresses during earthquake by dynamic analysis [14].

2. Methodology

A soil slope of 50º slope angle and 20m height is considered in this study for the purpose of illustration and better understanding. The stability analysis is carried out for both static and seismic conditions. The static analysis is carried out by limit equilibrium methods. The seismic analysis is carried out by both limit equilibrium and finite element methods using a geotechnical modeling software GeoStudio. In limit equilibrium analysis, Bishop's simplified method of slices is used to find the stability of nailed slope by SLOPE/w module of GeoStudio. QUAKE/w module of GeoStudio is used to carry out the seismic analysis by finite element method.

3. Numerical Modeling

3.1 SLOPE/w modeling for static analysis

SLOPE/w is one of the modules of software tool, GeoStudio. In this study, SLOPE/w module is used to analyse the stability of slope with and without nails. SLOPE/W module allows construction of the soil slope by drawing the slope regions. Slope dimensions are scaled down to incorporate into the SLOPE/w to create the numerical model. The slope is modeled at different slope angles and heights by coordinate system present in the SLOPE/w. Materials of slope are defined and assigned to regions, once the slope regions have been determined. The soil properties used in the analysis are summarized in Table 1 [15]. The numerical model of the slope is presented in Fig. 1.

Table 1: Soil properties used in the analysis

Property	*Symbol*	*Values*
Unit weight (kN/m^3)	γ	18 kN/m^3
Cohesion (kN/m^2)	c	20 kN/m^2
Friction angle (^{0})	ϕ	28°
Coefficient of permeability (m/s)	k	1.16*10^{-8} m/s
Poison's ratio	μ	0.35
Young's modulus (kPa)	E	37000kPa

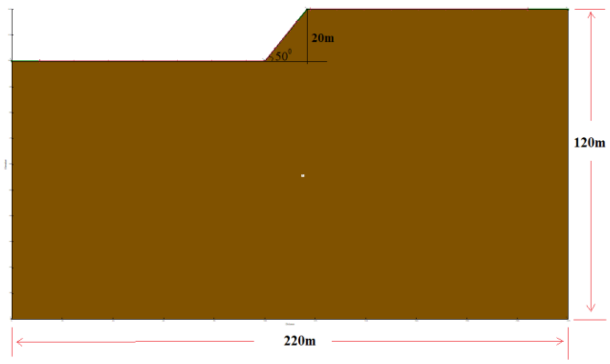

Figure 1: Numerical model of slope

SLOPE/w module provides the option to input reinforcement in the form of anchors, nails, piles and geosynthetics. Nail element option is used in this analysis. The nail properties used in the analysis are summarized in Table 2. The slip surface is simulated by providing the range of the slip surface along the ground surface. In the present study, entry-exit option is used to simulate the range of slip surface. SLOPE/w provides different limit equilibrium methods to analyze the problem. Bishop's simplified method is considered to analyse the stability.

Table 2: Optimum nail details used in the analysis

Property	*Symbol*	*Values*
Yield strength	f_y	415 N/mm^2
Nail diameter	D	25mm
Nail length	*L*	0.6H
Nail inclination	Λ	15°
Horizontal spacing	S_h	1m
Vertical spacing	S_v	1m

3.2 SLOPE/w modeling for Pseudo-static analysis

The slope is further analysed to find the stability against an earthquake of given PGA. Pseudo- static analysis considers seismic loading in terms of horizontal and vertical seismic coefficients of earthquake. The slope modeling and assigning materials in pseudo-static analysis are similar to static analysis. The magnitudes of both horizontal and vertical seismic coefficients of earthquake are given as input once the modeling of slope is done. In the present study, seismic coefficients of k_h =0.15 and k_v=0.075 is considered for the analysis. The failure slip circle and Factor of Safety (FOS) are the major results from the pseudo- static analysis.

3.3 QUAKE/w modeling for dynamic analysis

The dynamic analysis is carried out to analyse the stability of the slope during the period of earthquake. The acceleration-time history of the earthquake is taken in to consideration to analyse the behavior of the slope during earthquake. In the present study, the optimum nailed slope obtained in static and pseudo static analysis is considered for dynamic analysis.

In the present study, the dynamic analysis is carried out in 4 phases. The first and second phases are carried out in QUAKE/W and third and fourth phases are carried out in SLOPE/W to find the FOS by considering the first two phases as parent analysis. In first stage initial static stresses are calculated in QUAKE/W. The construction of slope regions by coordinate system and assigning materials to the regions is similar to the process in SLOPE/W. QUAKE/W provides an option to input slope boundaries to the model. History nodes have been selected where the results are required to retrieve after the analysis.

The static stresses obtained in first phase are considered as input in second stage. The dynamic analysis is carried out by equivalent dynamic method in the present study. The acceleration – time history of the earthquake is given as an input in the second phase. An earthquake of 0.15g PGA is considered for the dynamic analysis. Fig. 2 shows the acceleration –time history used in the analysis. The complete slope model is divided into elements to generate the finite element mesh. Slope deformation and stresses distribution during the earthquake are the primary results in the dynamic analysis.

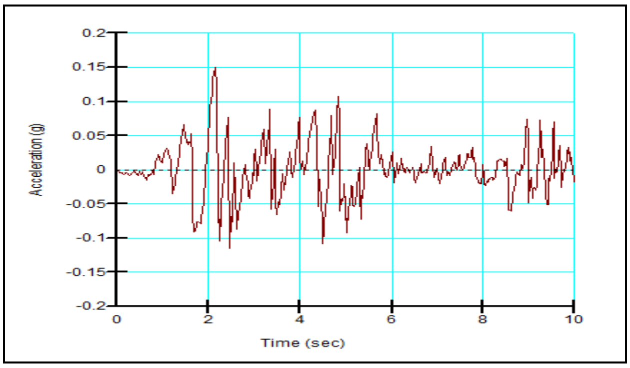

Figure 2: Earthquake acceleration-time history

The variation of stresses and displacements during the earthquake are stored from the above two phases. These stresses are incorporated into SLOPE/W to find FOS. In third phase, initial static stresses are considered as parent analysis. The range of slip surface is once again specified in this phase like in static condition. The factor of safety before earthquake is obtained in this phase as an output. In final phase, Equivalent linear dynamic analysis is considered as parent analysis. This analysis is performed to find Factor of safety during the earthquake by Newmark's deformation method in SLOPE/W. The nailed slope with history nodes is presented in Fig. 3

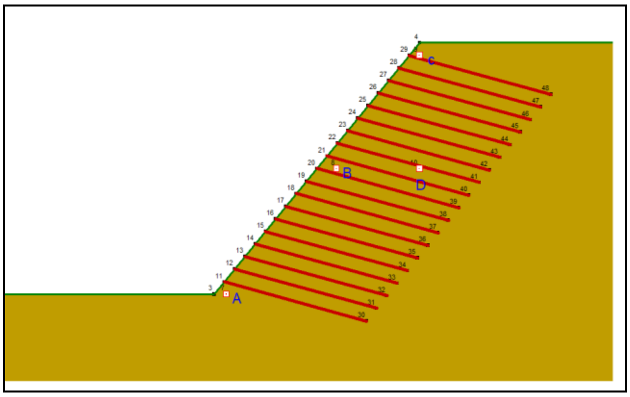

Figure 3: Nailed slope with history nodes A, B, C and D

4. Results and Discussion

4.1 Results of static analysis

The factor of safety of slope without nails in static condition is found to be 1.116 which is far below the safe value of FOS of 1.5 as shown in Fig. 4 [2].

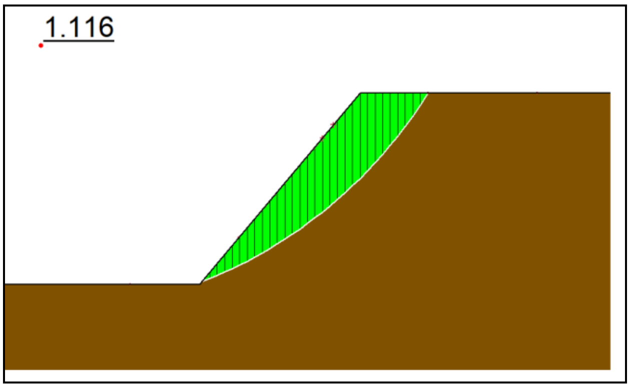

Figure 4: Critical slip surface of slope without nails in static condition (H = 20m, θ = 50º)

Soil nailing technique is employed to stabilize the slope. The nailed slope design is optimized with the optimum values of nail length, nail spacing and nail inclinations. To find the optimum design, the numerical model of nailed slope is analyzed for different combinations of nail lengths from 0.5H to 0.75H, nail inclinations from 10^0 to 25^0 and nail spacing from 1m to 2m in both directions.

4.1.1 Effect of nail inclination

Initially, the nailed slope is analyzed for stability at different nail inclinations of 10^0, 15^0, 20^0 and 25^0. The length and spacing of nails are kept constant with 0.7H and 1.5m respectively to find the optimum nail inclination. Fig. 5 depicts the variation of FOS with nail inclination.

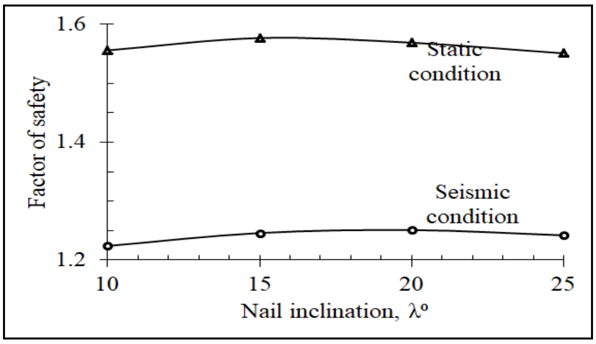

Figure 5: Influence of nail inclination on factor of safety (H = 20m, θ = 50º, *l* = 0.7H = 14m, S_h=S_v=1.5m)

From the Fig. 5, it is observed that the nailed slope with 15º nail inclination attains maximum FOS of 1.577 which is more than minimum recommended value of FOS of 1.5 [2]. Hence nail inclination of 15º is considered as optimum nail inclination for the study.

4.1.2 Effect of nail length

The nailed slope is further analyzed for stability at different nail lengths of 0.5H, 0.55H, 0.6H, 0.65H, 0.7H, 0.75H and 0.8H. The nail inclination and spacing are kept constant at 15º and 1m to study the effect of nail length on stability. The results are presented in Fig. 6.

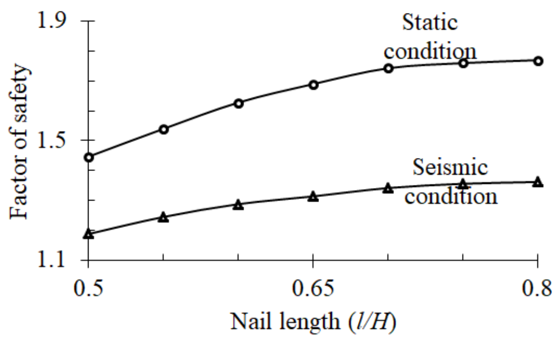

Figure 6: Influence of nail length on Factor of Safety (H=20m, θ =50^0, λ=15^0, S_h=S_v=1m)

The factor of safety increases with increase in nail length from 0.5H to 0.7H and then shows an asymptotic variation. Based on the results presented in Fig. 5 and Fig. 6, the nailed slope with 12m (0.6H) length nails at 15º inclination and 1m spacing in both directions is considered as optimum with FOS of 1.628 which is more than minimum recommended value of FOS of 1.5. The critical slip circle of nailed slope is with optimum parameters are given in Fig. 7.

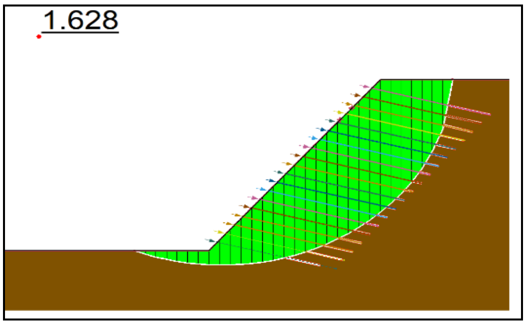

Figure 7: Nailed slope with critical slip surface (*l*= 0.6H, S_h = S_v = 1m, λ= 15^0)

4.2 Results of pseudo-static analysis

The stability of the nailed slope against an earthquake of 0.15g PGA is analyzed with the help of numerical model in SLOPE/W module. The horizontal seismic coefficient, k_h = 0.15 and vertical seismic coefficient, $k_v = 0.5k_h = 0.075$ are used to import the seismic loading into the analysis. Table 3 presents the different values of FOS obtained in the pseudo static analysis.

Table 3: Results of static & pseudo-static analysis

Slope	*Minimum recommended FOS [2]*		*Obtained FOS*	
	Static analysis	Seismic analysis	Static analysis	Pseudo static analysis
Without nails	1.5	1.1	1.116	0.881
With nails	1.5	1.1	1.628	1.288

4.3 Results of dynamic analysis

The dynamic analysis helps to analyse the behavior of slope during earthquake. The variation of FOS, stresses distribution and displacements at history nodes during the earthquake of 0.15g PGA are studied in the dynamic analysis.

4.3.1 Shear stress variation during earthquake

Variation of the maximum shear stresses developed at history nodes during the earthquake of PGA 0.15g in the slope without and with nails are presented in Fig. 8 and Fig. 9 respectively.

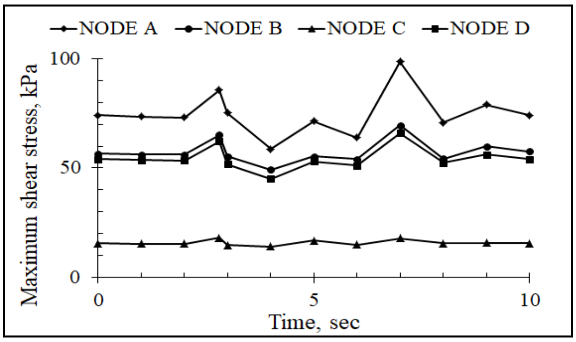

Figure 8: Variation of shear stresses at history nodes in the slope without nails

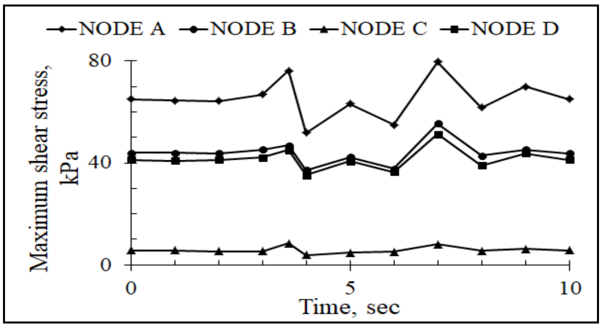

Figure 9: Variation of shear stresses at history nodes of nailed slope

The maximum shear stress is found at NODE A which is located at bottom of the slope for both the cases of slope with and without nails. It deceases from 98.69kPa to 79kPa by the inclusion of nails into the slope. The minimum shear stress is found at the top of the slope at NODE C with a value of about 10kN in the nailed slope.

4.3.2 Nail axial force

The distribution of nail axial force along the length in both bottom and top nail row is depicted in Fig. 10. The maximum nail axial force is developed in bottom nail row.

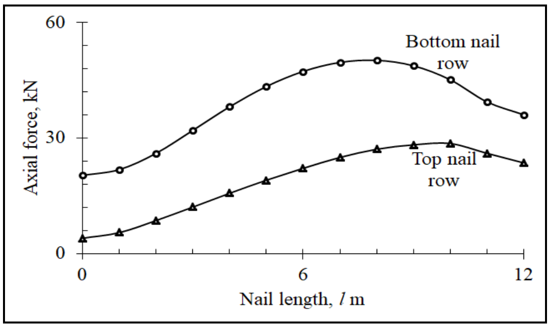

Figure 10: Variation of nail axial force along the length

Maximum nail axial forces in top and bottom nail rows are 24.44kN and 50.38kN respectively. Nail axial force increases along nail length. It attains maximum in between the lengths of 0.6L (7.2m) to 0.9L (10.8m) from nail head and then decreases towards nail tip. Location of maximum nail force is presented in Fig. 11.

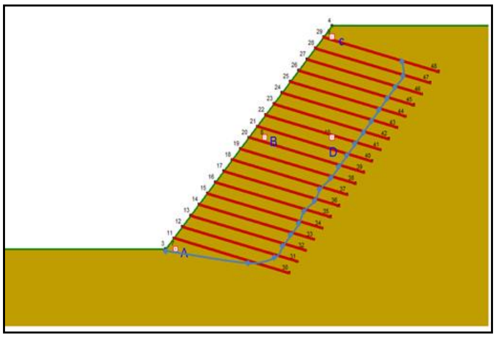

Figure 11: Location of maximum nail axial force

4.3.3 Displacements

The variation of horizontal and vertical displacements of nailed slope at history nodes during the earthquake of 0.15g PGA are presented in Fig. 12 and Fig. 13 respectively.

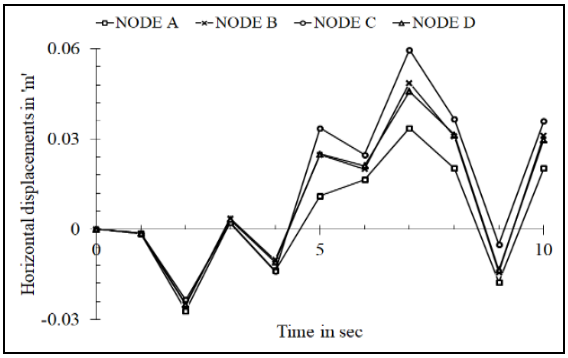

Figure 12: variation of horizontal displacements in nailed slope (H= 20m, θ =50^0, l = 0.6H = 12m, λ=15^0, S_h=S_v=1m)

Nailed slope experiences maximum horizontal displacement of 60mm at NODE C which is at the top of the slope. It experiences minimum horizontal displacement of 28mm at the bottom of the slope at NODE A.

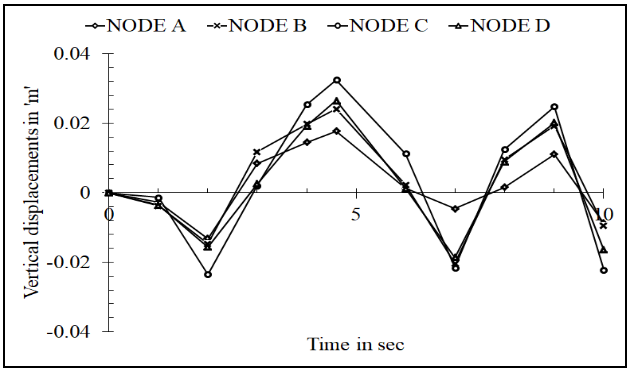

Figure 13: Vertical displacements of nailed slope (H= 20m, $\theta = 50^0$, $l = 0.6H = 12m$, $\lambda = 15^0$, $S_h = S_v = 1m$)

The nailed slope experiences maximum and minimum vertical displacements of 32mm and 17mm at the top (NODE C) and bottom (NODE A) of the slope respectively.

4.4 Results of Newmark's deformation analysis

The study is carried out in SLOPE/w by considering stresses developed in QUAKE/w analysis. FOS obtained during the earthquake ground motion is clearly studied in the analysis and results reported in Fig. 14 and Fig. 15.

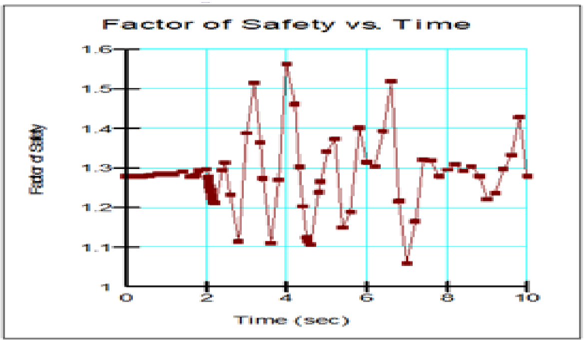

Figure 14: Variation of FOS with time in slope without nails

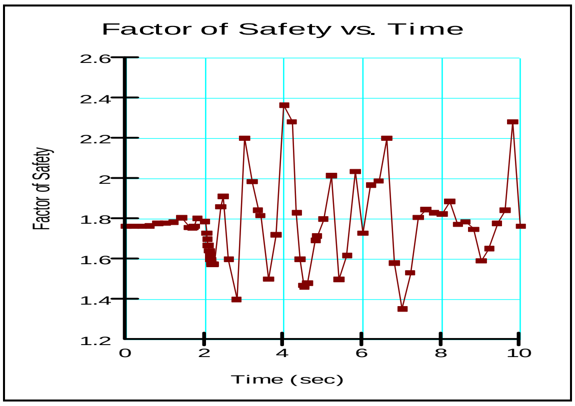

Figure 15: Variation of FOS with time in naile slope

The slope without nails attains minimum FOS of 1.05 (less than the recomonded FOS of 1.1) at 7th second of ground acceleration. The slope attains safe FOS of 1.288 at 7th second of ground acceleration by the inclision of nails. Hence the slope with nails of length, 12m inserted at 15^0 inclination and 1m spacing is stable even during earthquake of PGA 0.15g.

4.5 Influence of nail spacing on stability of slope

The analysis is carried out in SLOPE/W for different nail spacing from 1m to 2m and the results are presented in Fig. 16. Square nail pattern ($S_h = S_v$) is used to analyse the effect of nail spacing on slope stability.

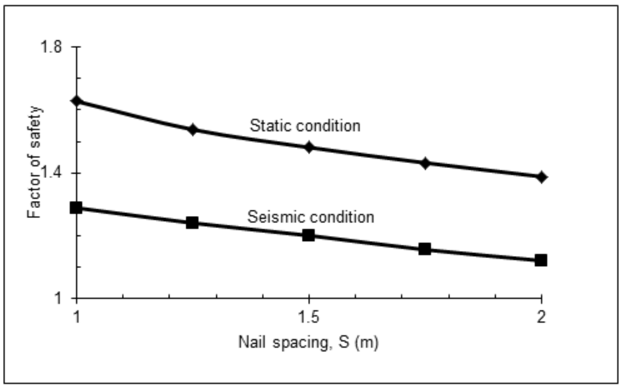

Figure 16: Influence of nail spacing on factor of safety

The FOS decreases with increase in nail spacing due to decreasing the resisting force developed by nails at failure surface. The slope with 1.25m spaced nails also attains FOS of 1.538 (FS>1.5) but leads to facing failure. Hence nails pattern with 1m spacing is preferred for design.

4.6 Analysis for uttara kashi earthquake

Stability analysis is also carried out on nailed slope to analyse the response of the nailed slope against an earthquake of Uttar Kashi occurred in the year 1991. Uttar Kashi earthquake is one of the major earthquakes occurred in India. The earthquake occurred on 20th October 1991 with a magnitude of 6.8 and PGA of 0.31g. The input Earthquake record used in the analysis is shown in Fig. 17.

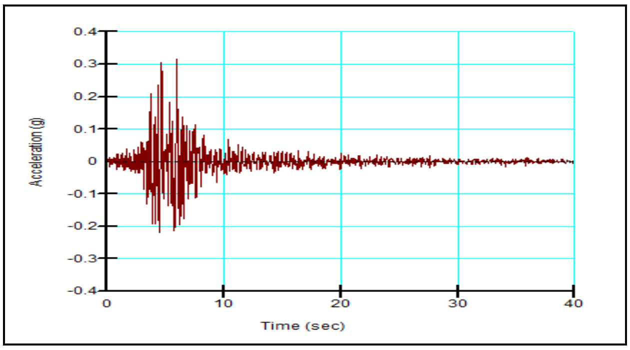

Figure 17: Uttar Kashi earthquake record

4.6.1 Shear stress variation during the earthquake

Shear stress variation during the earthquake for the slope without and with nails is presented in Fig. 18 and Fig. 19.

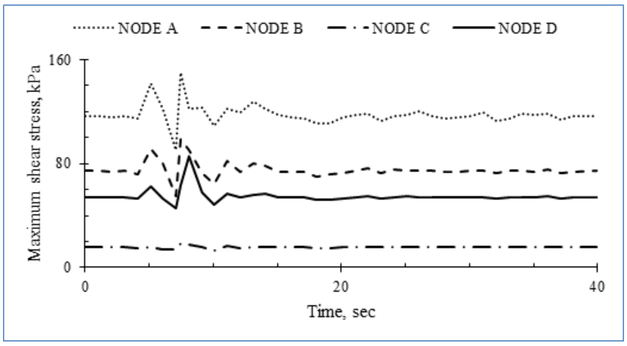

Figure 18: Shear stress variation during the earthquake in slope without nails

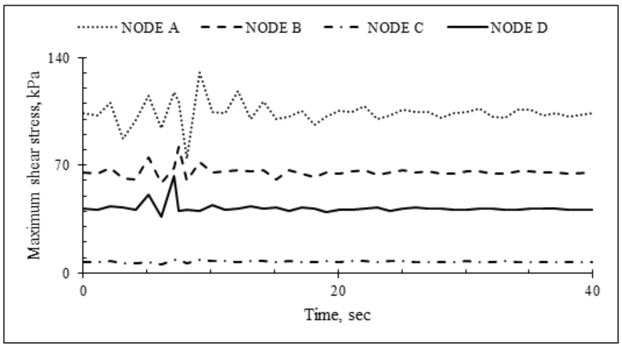

Figure 19: Shear stress variation during the earthquake in nailed slope

Maximum shear stresses found in slope without nails and with nails is 150kN and 130kN respectively at NODE A (bottom of the slope). The percentage of decrease in shear stress is about 14%, 18%, 50% and 26% at nodes A, B, C and D respectively within the reinforced area. The shear stress increases from top to the bottom of the slope.

4.6.2 Horizontal displacements

The variation of horizontal displacements in nailed slope during the earthquake (Uttar Kashi) is presented in Fig. 20. The nailed slope experiences maximum horizontal displacement of 121mm at Node C (near top of the slope) and minimum displacement of 80mm at Node A (at bottom of the slope).

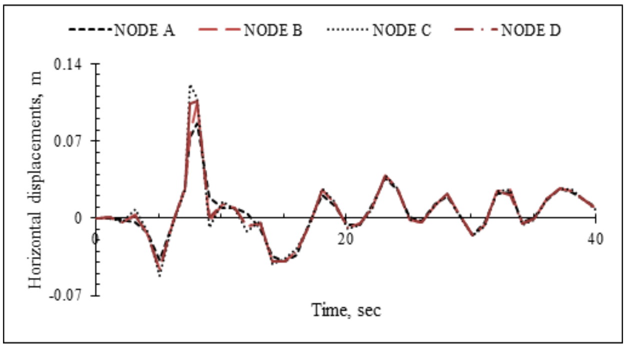

Figure 20: Horizontal displacements at nodes

The slope experiences maximum horizontal displacements of 120mm at node C (near top of the slope). The slope experiences minimum displacements of 80mm at node A (at bottom of the slope). Displacements are decreases from top to bottom of the slope.

4.6.3 Nail axial force

Axial forces in bottom nail row during the earthquake are presented in Fig.21. The maximum axial force occurred in bottom nail row is 106.53kN at 8.56m. Axial forces in nails are increasing from nail head to some extent and then decreases. It attains maximum between 0.6L to 0.9L from nail head and then decreases towards nail tip.

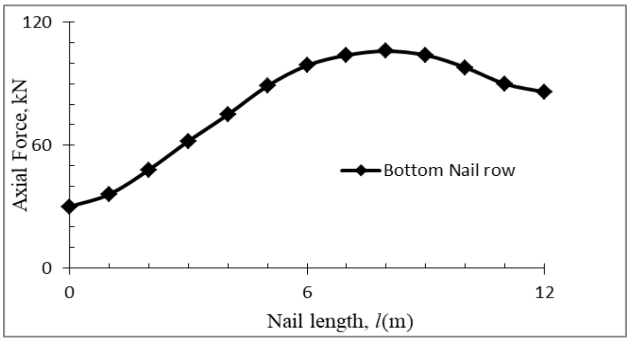

Figure 21: Nail axial force during uttar kashi earthquake

4.6.4 Results of Newmark's deformation analysis

Variation of FOS during the Uttar Kashi earthquake is presented in Fig. 22.

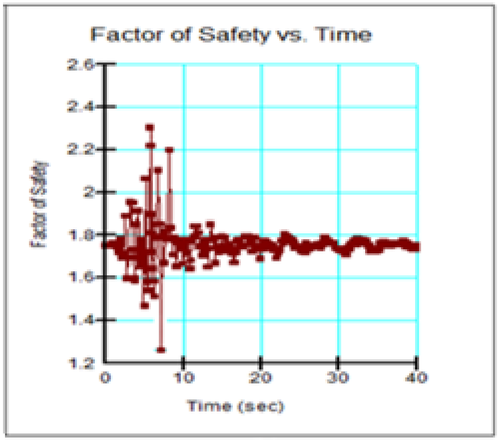

Figure 22: Variation of FOS with time in naile slope

The FOS of nailed slope before earthquake is 1.75, which is more than the safe recommended FOS. The nailed slope is critical with minimum FOS of 1.22 (more than recommended FOS 1.1) during uttar kashi earthquake. Hence the nailed slope is safe against earthquakes like uttar kashi earthquake.

5. Conclusions

Following conclusions are made based on the results obtained from the study.

1) The slope is stabilized by the inclusion of nails of length 12m at 15^0 inclination and 1m spacing in both directions. The FOS increases from 1.116 to 1.628 after nailing.
2) From dynamic analysis, the horizontal and vertical displacements of nailed slope decreases from top to the bottom of the slope. The slope experiences displacement of 60mm and 33mm in both horizontal and vertical directions both at the top of the slope. The inclusion of 12m nails with 15^0 inclinations at 1m spacing into the slope leads to 20% reduction in shear stress.
3) The nailed slope is safe against an earthquake of PGA,

0.15g with FOS of 1.288 and 1.35 in both pseudo-static and dynamic analyses respectively.

4) The FOS for slope reinforced with 12m nails discussed in the study is 1.22 by Newmark's method against Uttar Kashi earthquake record. Hence the nailed slope is stable for this case and may fail in case of an earthquake with intensity more than that of Uttar Kashi's earthquake with PGA of 0.31g.

References

[1] Amit prasanth, Mousumi Mukherjee, "Soil nailing for stabilization of steep slopes near railway tracks", pp. 1-203.

[2] Federal Highway Administration, FHWA. Reference manual, 7th Edition, U.S.A. 2015, FHWA-NHI-14-007.

[3] P.K. Basundhar, Anubhav, M.R. Lakshminatayana, "Three-dimensional limit-equilibrium stability analyses of slopes and effect of inclusion of soil nails", International Journal of Geo-mechanics, XVII (9), pp. 1-11, 2017.

[4] I.H. Wong, B.K. Low, P.Y. Pang, G.V.R. Raju, "Field performance of nailed soil wall in residual soils", Journal of Performance of Constructed Facilities, XI (3), pp. 105-112, 1997.

[5] Lok Man Chu, Jain-Hua Yin, "Comparison of interface shear strength of soil nails by both direct shear box tests and pull-out tests, Journal of Geotechnical and Geo Environmental Engineering, CXXXI (9), pp. 1097-1107, 2005.

[6] H.J. Seo, Lee, P. Loizos, "Net load displacement estimation in soil nail pullout tests", Geotechnical Engineering, CLXX, pp. 534-547, 2017.

[7] Chia Cheng Fan, Jiun Hung Luo, "Numerical study on the optimum layout of soil nailed slopes", Computers and Geotechnics, XXXV, pp. 585-599, 2008.

[8] G.L. Shivakumar babu, Vikas prathap singh, "2D numerical simulations of soil nail walls", Geotechnical and Geological Engineering, XXVIII, pp. 299-309, 2009.

[9] S. Sahoo, B. Munna, K. G. Sharma, "Stability analysis of un-reinforced and reinforced soil slopes", Geo-China, CCLVII, pp. 74-81, 2016.

[10] S. Rawat, A.K. Gupta, "Analysis of nailed soil slope using limit equilibrium and finite element methods, International Journal of Geo-synthetics and Ground Engineering, II(34), pp. 1-23, 2016.

[11] Ahmed Mohamed, "Design charts for soil nailing", Research Gate, pp. 1-221.

[12] D. Jonatan, T. Thaleia, "Pseudo static slope stability procedure", 5th International Conference of Earthquake Geotechnical Engineering, I, pp. 10-13, 2011.

[13] S.L. Kramer, Chapter 10, Seismic slope stability, Geotechnical Earthquake Engineering. Pearson Education, Singapore, 2018.

[14] P.Rawath, K. Chatterjee, "Seismic stability analysis of soil slopes using soil nails", Geotechnical Earthquake Engineering and Soil Dynamics, CCXCIII, pp. 79-87, 2018.

[15] S. Shrestha, N. Ravichandran, M. Raveendra, J.A. Attenhofer, "Design and analysis of retaining wall backfilled with shredded tire and subjected to earthquake shaking. Soil Dynamics and Earthquake Engineering, XC, pp. 227-239, 2016.

Author Profile

Padmavathi M is presently working as Associate Professor of Civil Engineering JNTUHCEH. Her Administrative positions includes Co-ordinator, Academic and Planning, JNTUH and Deputy Warden for Girls Hostels of JNTUH College of Engineering, Hyderabad. She obtained B.Tech (Civil Eng.) from K L College of Engineering, Nagarjuna University, Guntur, M.E. from College of Engineering, Guindy Campus, Anna University, Chennai, Tamilnadu and Ph D. from JNTU, Hyderabad. She is the member of Indian Geotechnical Society, IGS and International Society for Soil Mechanics and Geotechnical Engineering, ISSMGE.

Srinivas Ch received the B.E in Civil Engineering from Chaitanya Bharathi Institute of technology in 2015 and M.Tech in Geoechnical Engineering from Jawaharlal Nehru College of Engineering in 2019.