Static and Dynamic Analysis of Nailed Slope

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Abstract. In the present study, slope stability analysis is carried out for a nailed slope with 50^0 slope angle and 20 m height. Analysis is carried out by both 2D limit equilibrium and Finite element methods using a geotechnical modeling software GeoStudio. Sections of slope without and with nails are analysed for stability with respect to static, pseudo- static and dynamic conditions. Dynamic response of nailed slope is analysed against an earthquake with PGA of 0.15g by Finite element method. The acceleration-time history is used as an input to simulate the earthquake in the numerical model. 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 variation of factors of safety, shear stresses and displacements during earthquake are also analysed by finite element method using Geo-slope. From the analysis, it is found that the slope is unstable without nails with factor of safety 1.116 in static condition. And the factor of safety increases to about 1.628 by soil nailing. The slope with optimum nail inclination and spacing is analyzed for dynamic response. The nailed slope is critical at 7th second of earthquake with factor of safety of 1.35 for an average acceleration $0.124 m/s^2$. Horizontal displacement of 60mm is obtained at the top of the nailed slope due to earthquake. The displacements decrease from top to the bottom of the slope.

Keywords: Soil Nailing, GeoStudio, Dynamic Analysis.

1 Introduction

Soil nailing is a technique of in-situ ground reinforcement which is widely used in the natural slopes, excavations and retaining structures.The unstable slopes can be improved and made stable by the insertion of nails into the slope. Soil nailing system has many special advantages like high flexibility, light structure, simple construction process, fast construction speed, economic benefits and little effect on the environment.

Soil nailing system is effective to reinforce the slope. Therefore, many scholars have studied on it. They have developed the limit equilibrium methods to analyse the stability of nailed slopes [1]-[3]. The stability of nailed slope is mainly depends on nail pull-out strength and nail tensile strength. The laboratory model tests and field tests are proposed to determine the pull-out strength and stability of the nailed slope [4]-[6]. Numerical modelling, 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 modellingof reinforced 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 slope is also analysed by the numerical models. Mohamed proposed design charts for nailed walls with different nail lengths, nail spacing's and nail inclinations for different soils [11]. However the 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 slopes is based on Pseudo-static method [12]. Though it is very simple approach but its applicability in seismic condition is very limited. It considers only the earthquake forces and neglects amplification of waves into 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

For the purpose of illustration and better understanding, a slope with 50^0 slope angle and 20m height is considered for the study. The stability analysis is carried out for static, pseudo-static and dynamic conditions. Pseudo-static and dynamic conditions refer to seismic condition in limit equilibrium and finite element analysis respectively. The analysis is carried out by both 2D 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 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 the present study, stability analysis for a slope with 20m height and 50^0 slope angle is carried with and without nails. SLOPE/W module enables to construct the soil slope by drawing the slope regions. The dimensions of soil slope are scaled down to incorporate into the SLOPE/W to create the numerical model. The slope is modeled at different slope angles 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	Value
Unit weight (kN/m^3)	γ	18kN/m^3
Cohesion (kn/m^2)	c	20kN/m^2
Friction angle ( )	ϕ	28
Coefficient of permeability (m/s)	k	$1.16*10^{-8}$ m/s
Poisson's ratio	μ	0.35
Young's modulus	E	37,000 kPa

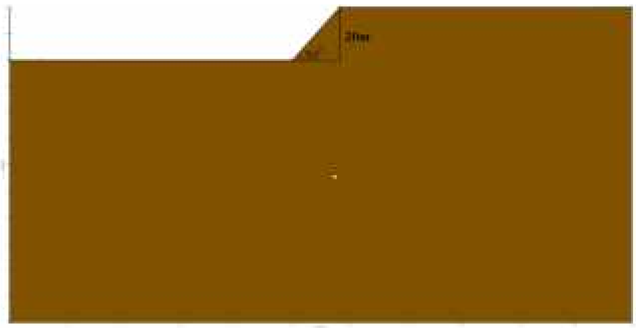

Fig.1. Slope without nails

SLOPE/W module provides the option to input reinforcement in the form of anchors, nails, piles and geosynthetics. Nail element option is used to model reinforcement in the nailed slope. 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 in the present analysis.

Table 2. Optimum nails details used in the analysis.

Nail property	Symbol	Value
Yield strength	f_y	415MPa
Nail diameter	d	25mm
Nail length	*l*	0.6H (12m)
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 analyzed 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.

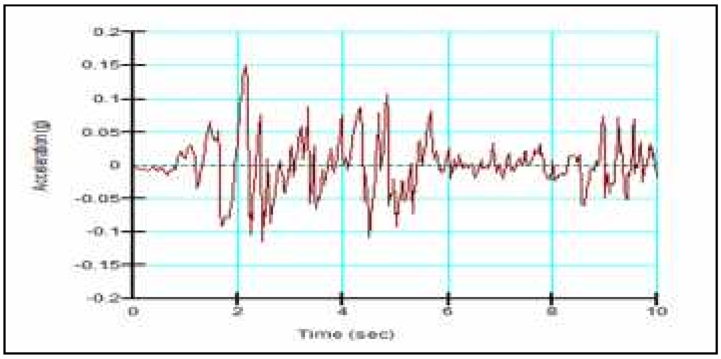

Fig.2. Earthquake acceleration-time history

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.

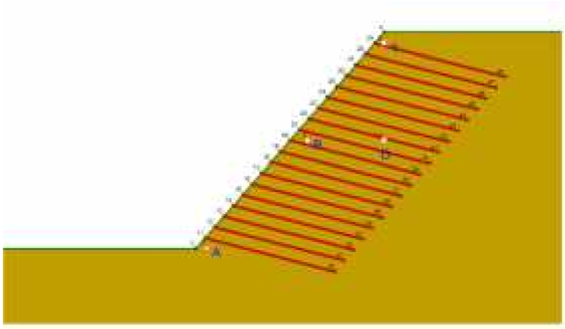

Fig.3. Nailed slope with history nodes A, B, C and D

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].

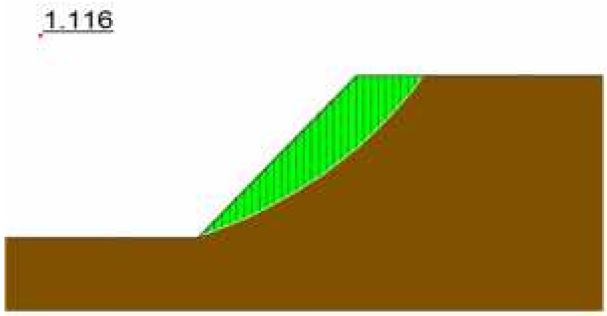

Fig.4. Critical slip surface of slope without nails in static condition (H =20m, θ= 50)

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.

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.

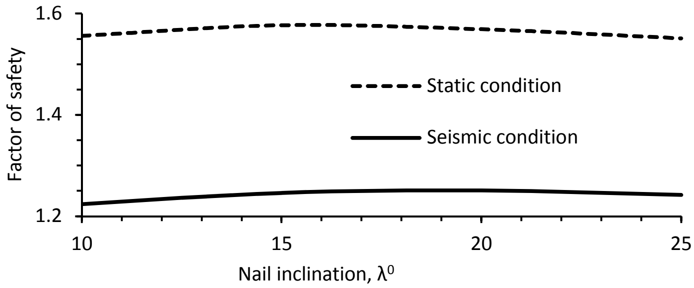

Fig.5. Influence of nail inclination on factor of safety (H = 20m, θ = 50 , l = 0.7H = 14m, S_h=S_v=1.5m)

From the Fig. 5, it is observed that the nailed slope with 15^0 nail inclination attains maximum FOS of 1.577 which is more than minimum value of FOS of 1.5 [2]. Hence nail inclination of 15^0 is considered as optimum nail inclination for the study.

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 15^0 and 1m to study the effect of nail length on stability. The results are presented in Fig. 6.

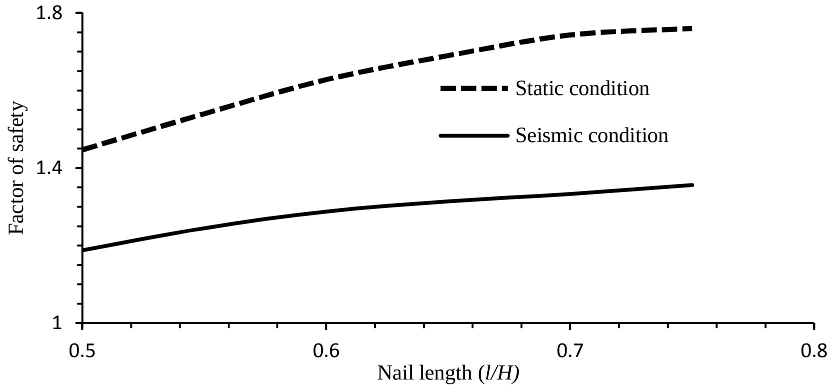

Fig. 6. Influence of nail length on Factor of Safety (H= 20m, θ =50^0, λ=15^0, S_h=S_v=1m)

The factor of safety increases with increase in nail length from up to about 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 15^0 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.

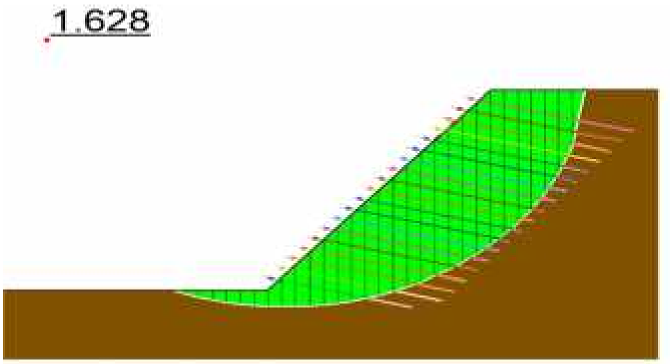

Fig. 7. Nailed slope with critical slip surface (*l*= 0.6H, $S_h = S_v$ = 1m, λ= 15^0)

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. The FOS obtained from numerical analysis by Geoslope is verified analytically by Bishop's simplified method of slices[1]. The results from both methods are almost same. The results that are presented in Table 3 are belongs to slope before and after nailing with 12m length nails at 15^o nail inclination with 1m spacing in both directions.

Table 3. Results of static & Pseudo-static analysis

Slope	Minimum recommended FOS [2]		Obtained FOS			
	Static condition	Seismic condition	Static analysis		Pseudo static analysis	
			Geoslope	Analytical method	Geoslope	Analytical method
Without nails	1.5	1.1	1.116	1.081	0.881	0.87
Nailed slope	1.5	1.1	1.628	1.601	1.288	1.268

4.3 Results of Dynamic Analysis

The dynamic analysis helps to analyze 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.

Shear stress variation

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.

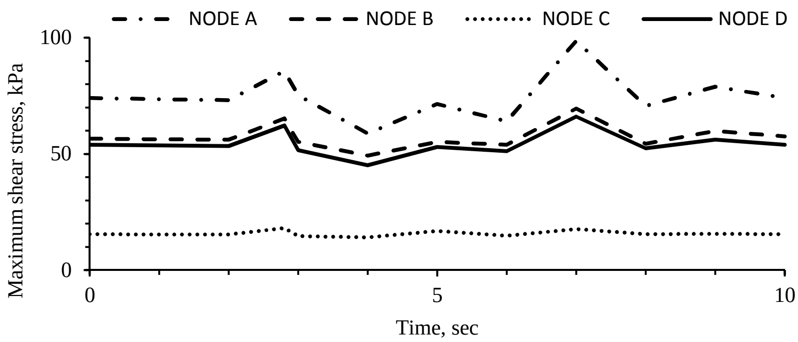

Fig. 8. Variation of shear stresses at history nodes in the slope without nails

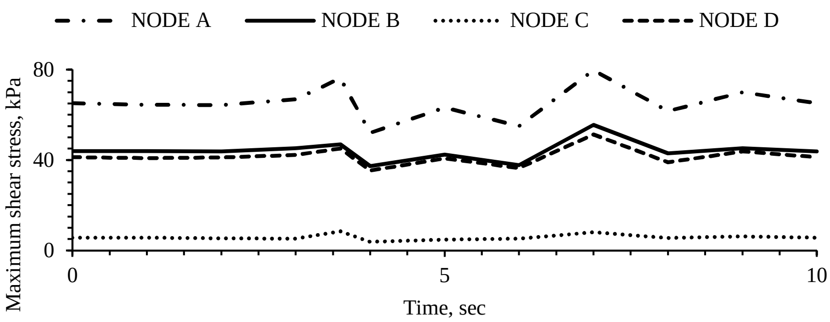

Fig. 9. Variation of shear stresses at history nodes in nailed slope

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.

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.

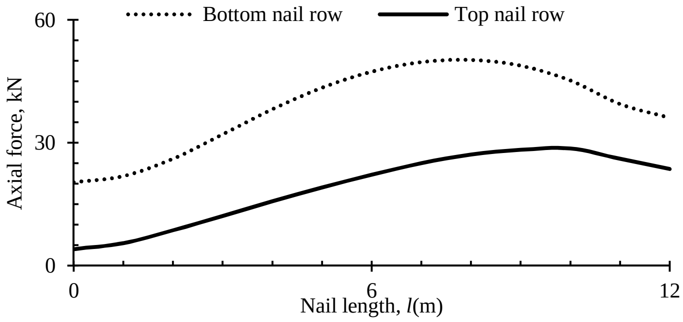

Fig. 10. Variation of nail axial force along the length

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.

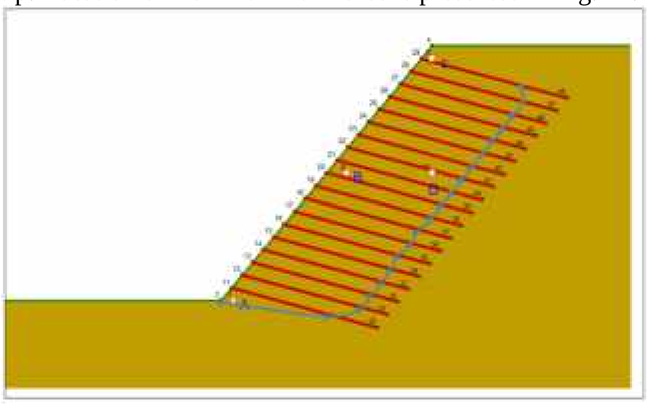

Fig. 11. Location of maximum nail axial force

Horizontal Displacements

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

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.

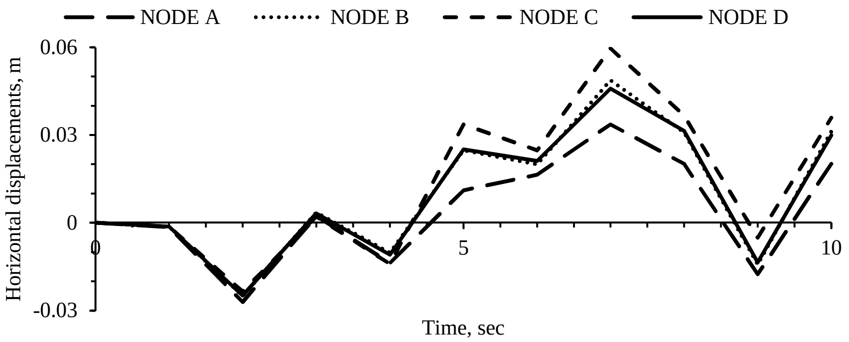

Fig.12. Variation of horizontal displacements in nailed slope (H= 20m, θ =50^0, *l* = 0.6H = 12m, λ=15^0, S_h=S_v=1m)

Results of Newmark's Deformation Analysis

The variation of FOS during the total period of the earthquake (PGA of 0.15g) is presented in Fig. 13.The nailed slope attains minimum FOS of 1.352 at 7^{th} second of ground motion which is more than the safe FOS of 1.1 [2]. 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.

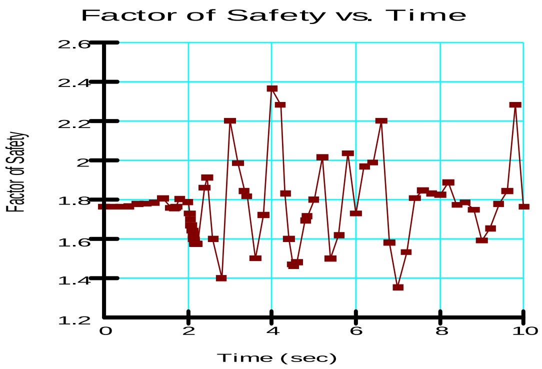

Fig.13. Variation of FOS with time in nailed slope

Influence of Nail Spacing on Stability of Slope

The analysis is carried out in SLOPE/W for different nail spacing's like 1m, 1.25m 1.5m, 1.75m and 2m in both static and pseudo static condition. The remaining all parameters are kept constant and the results are presented in Fig. 14. Square nail pattern (S_h=S_v) is used to analyse the effect of nail spacing on slope stability.

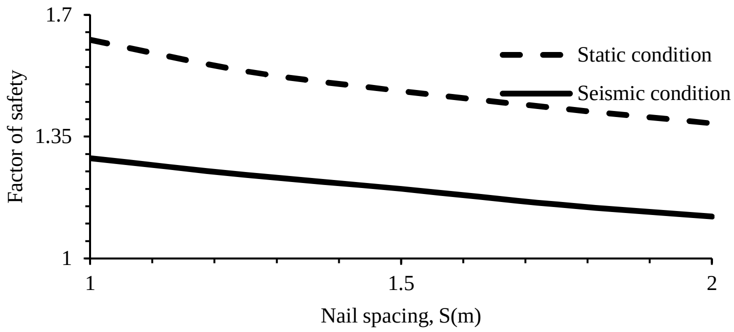

Fig.14. influence of nail spacing on factor of safety(H= 20m, θ =50^0, *l* = 0.6H = 12m, λ=15^0)

The Factor of safety 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 factor of safety of 1.538 (FS>1.5) but leads to facing failure. Hence nails pattern with 1m spacing is preferred for design.

Influence of Earthquake PGA on Stability of Slope

The analysis is carriedout to find the effectof earthquake on slope stability by considering different PGA. A graph is drawn and presented as Fig. 16 between PGA and FOS to show the variation of FOS against different earthquake PGA.

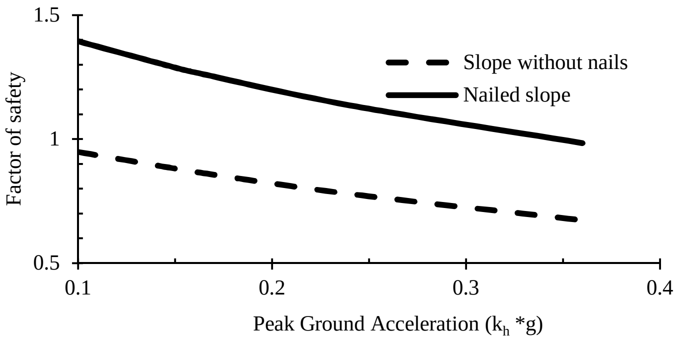

Fig. 15 Influence of PGA on factorof safety

The Factor of safety decreases with increase in PGA due to increase in driving force at critical failure surface.

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 displacements of nailed slope decreases from top to the bottom of the slope. The slope experiences displacement of 60mm in horizontal direction 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 soil slope considered in the analysis is safe with the inclusion of 12m length nails at 15^o slope angle and 1m spacing in both directions for seismic conditionsup to a PGA of 0.3 with a factor of safety of 1.1.

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