Seismic Stability of Nailed Slopes for Un-drained and Drained Conditions

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Abstract. The Slopes are the inclined mass of soil that is subjected to numerous types of loading in nature. It becomes necessary to analyze the slopes such that service requirement is satisfied without any compromise in safety criterion. In the present study Mohr-Coulomb slope profile model has been developed using Plaxis-3D, a finite element based software. Numerical investigations varying intensity of seismic loads have been performed to predict the behavioral characteristics of slope under un-drained and drained soil conditions. Furthermore, soil nailing technique has been incorporated in the study to observe the changes in factor of safety characteristics in the soil slope when subjected to seismic loading under un-drained and drained conditions. It was observed that there has been significant increase in factor of safety values on installation of nails in slopes and pore water pressure plays an important role in safety and deformation characteristics of slope.

Keywords: Slope stability, Cohesive soil, Pore pressure, Soil Nailing, Seismic loads.

Introduction

Slopes are the unsupported inclined soil mass. Slopes can occur naturally or they are engineered by humans for various reasons like space constriction, economy etc. Gravity is principle force causing the movement of soil mass down the slope. As its effect is experienced all over Earth's surface, it tends to exhibit the force towards center of the Earth. Numerous factors have been known which have impact on the stability of slope like composition of soil, angle of slope, water pressure, and subjugation of static and dynamic loads [1]. Various methodologies have been designated to appraise slope stability by means of analytical as well as experimental approaches. Evaluation of slope stability has received wide range of acceptance under the effect of static loads. Conventionally, Pseudo-static approach is adopted to assess the dynamic stability of slopes. Which employs displacement based methods [2] or linear equivalent linear methods. When the prime frequency of the input motion surpasses the natural frequency of the mass the sliding block procedure appears to be conservative [3]. The performance of soils in association with slope response has been described comprehensively by experimental approaches. Kokusho & Ishizaw [4] suggested an energy balance method taking an inclined plane with rigid block supporting over it. Stability of slopes has always been a governing factor for carrying out a construction on slopes. Both static and dynamic loads can cause failure to a slope yet there are considerate methods to determine the bearing capacity and factor of safety for slopes under static loads while as dynamic loads specifically seismic loads are generally unpredictable. Different constraints are involved in many aspects of slope stability assessments that include Geological uncertainties, spatial variability of ground materials, lack of sufficient data, unpredictable failure mechanisms, simplified geotechnical simulation techniques, human errors in characterization of ground materials, and the modeling process of slope. Commonly used deterministic methods are not able to address the influence of these uncertainties on the overall Factor of Safety (FS). FS is calculated as the ratio of resisting forces to driving forces. These methods may result in either over-designed or under-designed slopes. Theoretically, a FS of over one represents stability conditions but because of the above-mentioned uncertainties, a range of 1.3–1.5 is often used in practice [5,6]. Two slopes with the same FS may have significantly different likelihoods of instability because of the different levels of uncertainty in their input geotechnical properties. Soil nailing technique is one way of protecting slopes especially steep slopes against a catastrophic failure during earthquake. However, Seismic resistance and the failure mechanism of nailed soil slope during an earthquake event are not clearly understood and need to be investigated properly[7–9] . Surface displacements, settlement of the crest and the acceleration responses along with the behavior of the facing wall were examined by[9, 10]. The stability of soil nailed vertical excavation is found to decrease with increase in seismic horizontal and vertical earthquake forces [11, 12]. Pseudo-static analysis within the limit equilibrium framework was incorporated to obtain the slip surface with an acceptable stress field within the surface [13]**.** Cohesive slopes were analyzed under dynamic loading condition and examined for relations between different parameters such as slope geometry, yield acceleration, and displacement [14]. Seismic excitation was also applied to slopes at various angles. Additionally, nailed slopes exhibited characteristics of ductility under strong excitation. The angle of the nails influences the deformation of the slope but only slightly affects seismic resistance. An increase in the length of the nails increased the seismic resistance of the slope and reduced the displacement of the facing only when subjected to strong excitation [15]. Length of nails and size of nails have been devised by Micholowski method [16]**.**PLAXIS is a finite element method (FEM) based software package that has been programmed explicitly for the evaluation of deformation and stability in geo-tech based engineering assignments. With easy input technique used by Plaxis as in the form of graphical input the process of generation of complex finite element models has hastened, and the improved output facilities have been found of providing in depth exhibition of calculated results. Earthquakes are considered as natural source of vibration. Dynamic analysis is set to be carried out when the frequency of vibration exceeds the natural frequency of the system. Vibrations with lower frequency values are computed by pseudo-static approach. While exhibiting the response of dynamic loads on a soil structure, the inertia and time dependence of load on sub-soil are also taken into consideration while carrying out the analysis. It involves the incorporation of absorbent boundaries for earthquake loads[17] **.**This paper checks effect of installation of driven nails in soil slopes under drained and un-drained conditions [18] . This study was primarily carried out using PLAXIS software with strong motion CD-ROM (SMC) file of WNW OF FERNDALE, CA on 10th March 2014. It was carried out on a 3- dimensional Finite Element based model. The model was scaled as 15 x 10 x 10 m with slope angle of 75^0 and a model footing of .5x 1 x 10 m which was loaded suitably [19]. Installation of nails was kept as horizontal. FS of safety values were determined on installation of nails in slope under un-drained and drained conditions.

Properties of Materials used

Properties of Soil

The properties of soil used in the study are assumed to be predetermined and have been referred from the studies carried out by[20] . The soil modeled for the analysis is supposed to be the clay of low plasticity and with certain percentage of silt as well. The detailed classification of properties of soil is given below as in **Table 1**.

Table 1 Properties of soil

Soil Properties	Value
Specific Gravity (G)	2.65
Silt %	12
Clay	88
Liquid limit (%)	45
Plastic Limit (%)	22
Shrinkage Limit (%)	16
Cohesion,C	14.0 kPa
Angle of Friction ,ϕ	24^0
Unit weight, ϒ	18 kN/m^3
Modulus of Elasticty, E	25 N/mm^2
Poisson's Ratio, µ	0.33

Properties of Nails

All the nailed slope models are reinforced with 99 number of grouted aluminum nails. The spacing of nails is governed by the principles of Michlowski's method where topmost nail is spaced at .5m depth from the top of slope and further progressed at 1m distance between the nails. A horizontal spacing of 1m between the nails is provided in the model. The length of nails has been sufficiently provided as 5 times the width of footing from the edge of the footing. The properties of soil nails have been acquired from a study carried by [10] and these properties are listed below in the **Table 2.**

Table 2 properties of Soil-Nails

Properties of reinforcement	**Value**
Elastic modulus, E (at 2% strain)	134800 GPa
Yield strength, Ty	5640 N/m2
Compressive strength, Tc	0
Cross section area, A	201.1428 mm2
Shear bond stiffness, Kbond	4.215 MPa
Density, ρ	2550 kg/m3

Properties of footing

A model strip footing of size .5 x 1 x 10 m is provided on the slope model and placed at a distance of 2m from the edge of slope (2 times width of the footing). the loading imposed was assumed to be uniformly distributed load with intensitynof 100kN/m^2 The interation of footing and slope has been taken as 0.5. Properties of the model footing are given in the **Table 3**

Table 3 Properties of Footing

Properties	**Value**
Young’s Modulus of Elasticty, E	25000MPa
Poisson’s Ratio, µ	0.15
Unit Weight, Υ_c	2500kg/m^3
Depth of footing, d	.143m

Smc File characteristics

The Strong motion file (SMC File) of earthquake used during the analysis was of WNW of Ferndale, California Earthquake that occurred on 10/03/2014, 05:18 UTC (09/03/2014, 21:18 PM PDT) [21]**.** Its magnitude was 6.80 recorded on Richter scale. Earthquake was recorded at 73.20 km from epicenter with maximum frequency of 200Hz. It recorded motion is given in **Fig.1.**

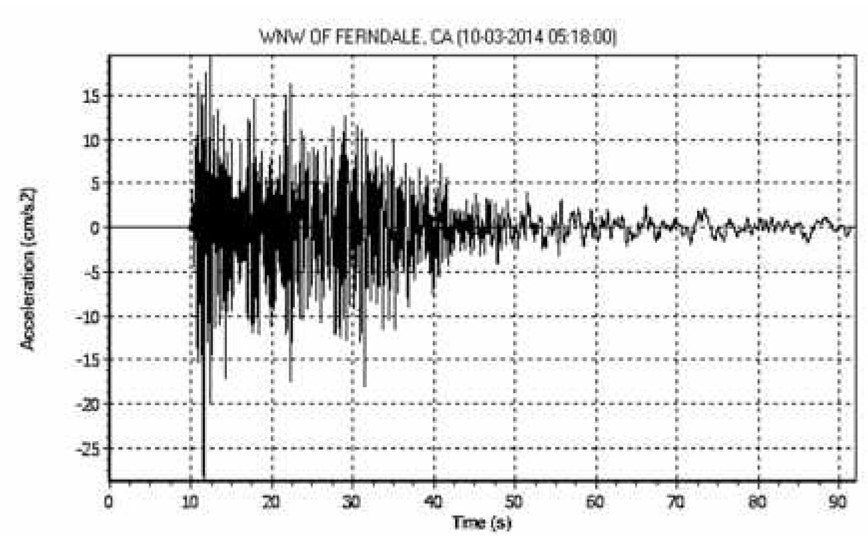

Fig. 1. SMC File characteristics of Ferndale earthquake

2. Mesh model

Finite element mdelling has been used to generate the mesh of the model of slope. 15 noded triangular elements with 12 guassian stress points have been incorporated to predict the simulation results of modeled slope. **Fig.2** represents the noded elemental view of the model with embedded footing. **Fig. 3** represents the node and stress point location in the model. The embedding of nails in slope with imposed oad on footing as been represented in **Fig 4**. Incorporation of earthquake absorbent boundaries and generation of refined mesh is depicted in **Fig 5**. For saturated and undrained condition of model representation of saturated model has been depicted in **Fig .6.**

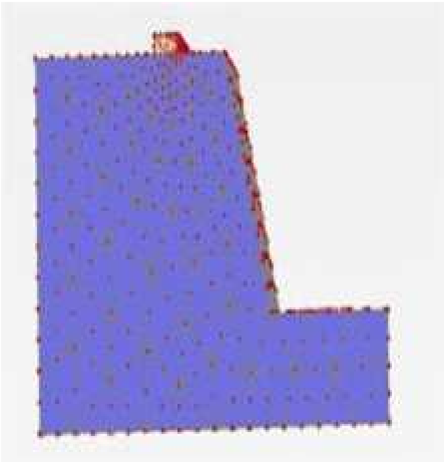

Fig. 2. Noded Element model of Slope.

Fig.3. Stress Point and Noded Element model of slope

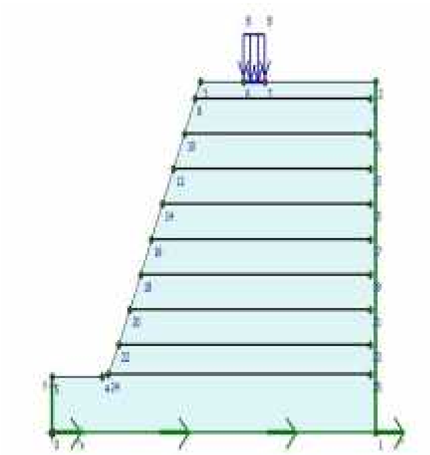

Fig.4. Nailed soil model with footing and absorbent boundary

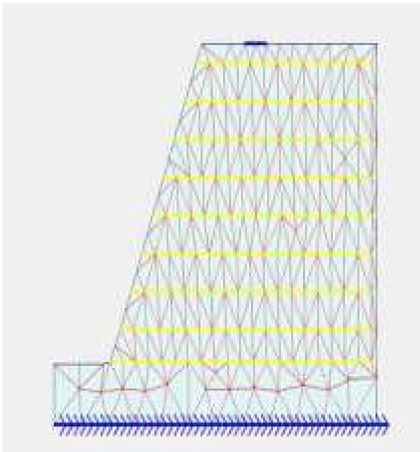

Figure 5 Mesh model of nailed slope

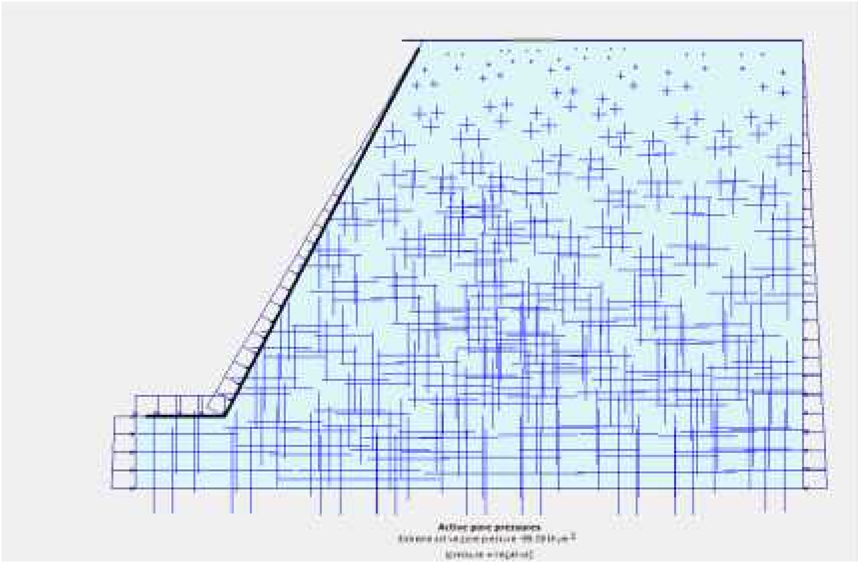

Fig. 6. Un-Drained nailed slope model

3. Results

3.1 Effect of loading on un-drained and drained virgin soil condition

Non-reinforced or virgin soils when subjected to eqarthquake loads proved to cause large deformation. It was further observed that when the model was subjected to earthquake loads under saturated condition larger deformations were observed. **Fig.7** and **Fig. 8** represents the deformation pattern in mesh and induced displacement pattern on virgin soil respectively. Typical displacement based factor of safety pattern can be observed from the **Fig 9.** That clearly depicts the sudden failure in soil after attainment of definite displacement.

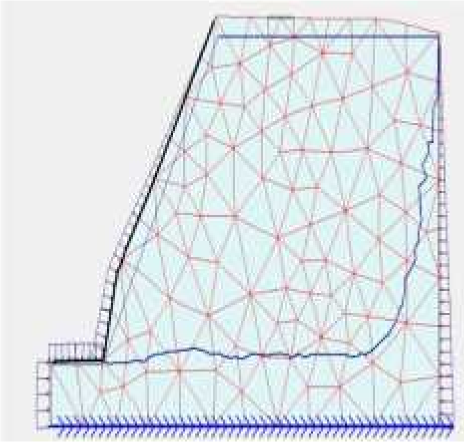

Fig. 7. Un-Drained deformed mesh

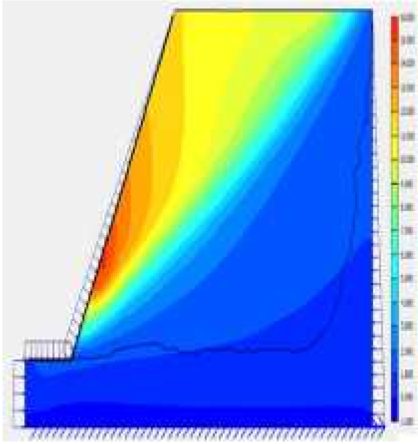

Fig.8. Displament profile of Un-Drained slope.

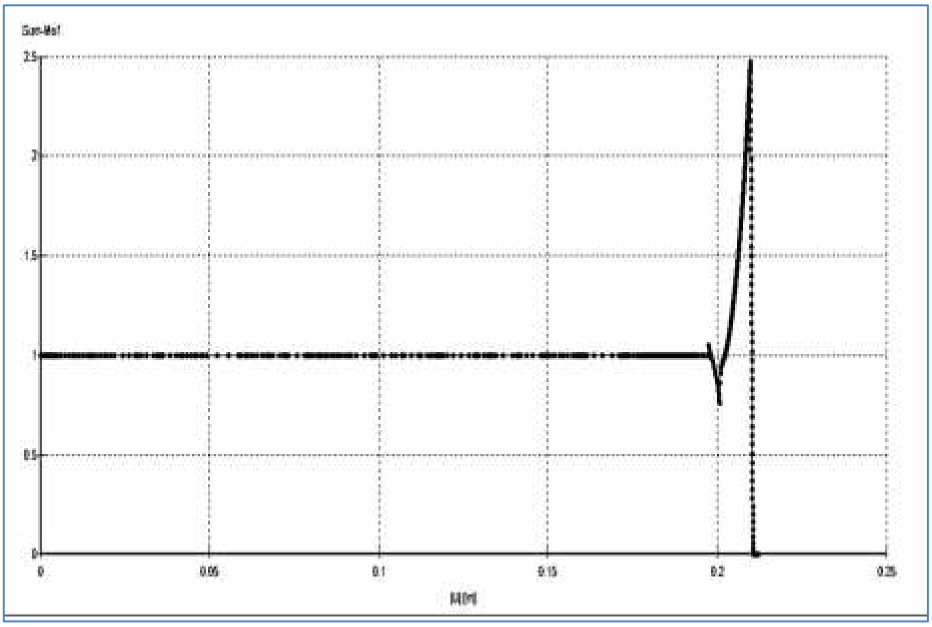

Figure 9 Typical Saftey Factor of undrained soil

Factor of safety calculation

During the analysis of dynamic factor of safety values it was observed that intially soil behaves well when subjected to dynamic loading but as soon as it passes a certain dispacement region which is as 21cm in undrained and 24.9 cm in drained condition. The factor of saftey starts receeeding and soil being brittle in nature fails abruptly. A small reserved strength was also observed in undrained soils which may be possibly due to dissipation of pore water pressure. The values of factor of saftey for drained and undrained conditions without were observed as 1.25 and 1.20 respectively and sudden failure was observed in the slope. The factor of safety values for virgin or untreated soils is given in **Fig. 10.**Factor of safety values were also determined for the slopes with footing installed over it. It was observed that slope collapsed at a given condition under the seismic load. Upto a certain dispacement value 10 to 15 cm the factor of safety values observed as 1 and later a sudden collapse was observed.

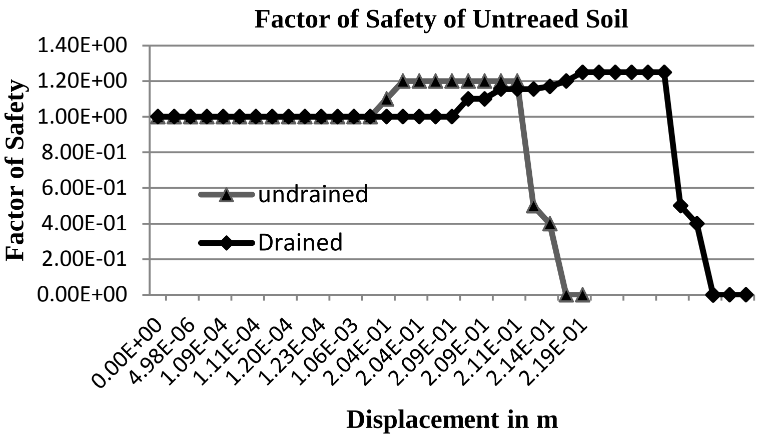

Figure 10 factor of safety values for Untreated Soil without footing.

Effect of loading on drained and un-drained nailed soils

On installation of reinforcement in soils it was observed that installation of reinforcement in soils enhances the seismic bearing capacity values of soil. It can be inffered from the numerical results that apart from imparting strength nails improve the distribution of stresses in soils, Thus transeferring the stresses over larger area and increasing the strength of soils. **Fig. 11** represents the displacement behaviour of nailed slopes under drained condition**.**

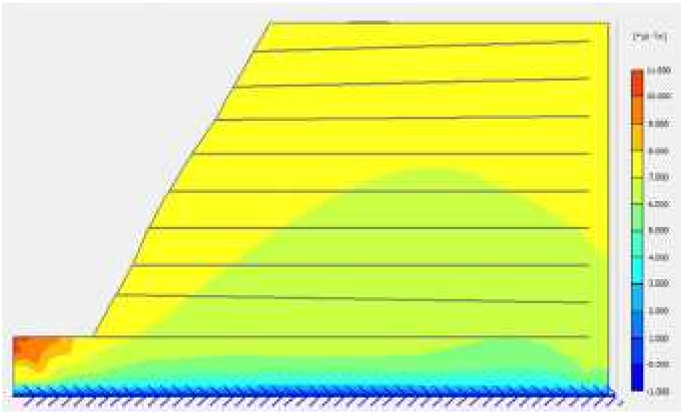

Figure 11 Displacement profile of Nailed slope under Drained condition

Factor of safety relation

It was observed that factor of safety of reinforced slopes was better as compared to un-reinforced slopes under seismic loads. It mainly aids to the fact that uniform distribution of stress increases the factor of safety of slopes. It was also observed that installation of reinforcement under undrained condition also increases the seismic bearing capacity of slope but proper dissipiation of pore water pressure method must be adopted to avoid the excess stress generation method in slopes. It was observed that Factor of safety values have increased in nailed slopes for both un-drained and drained condition and the peak values achieved were about 3.2 and 3.6 respectively. The graphical representation of factor of safety values is given in the **Fig.12.**

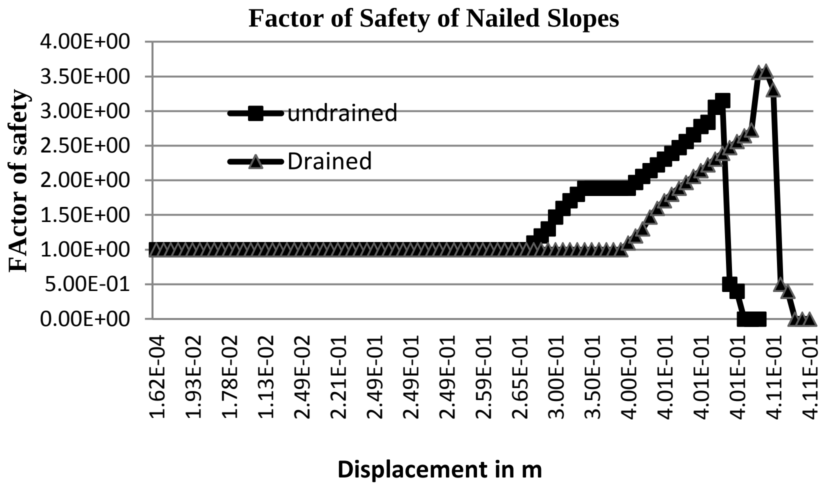

Figure 12 Factor Of Safety Of Naile Slope Under Drained And Un-Drained Condition

Conclusion

Soi-nail modelling is found to play an important role in enhancing the factor of safety of slope when subjected to seismic loading. It can be further concluded that the lower portion of the slope gets severly affected due to earthquake loading and this region is highly susceptible of failure. Overburden pressure on the nails is found to have large varitional effects in drained and un-drained conditions under seismic loads. The water pressure exhibited in undrained conditions has proven to aggravate the chances of slope failure under seismic loads. It can be also inferred from the results that factor of safety values for both undrained and drained conditions varied from 1.25 and 1.20 respectively in untrested slopes. A prominent enhanced effect in factor of safety was also observed due to installation of nails, the enhanced values were 3.2 and 3.6 from 1.20 and 1.25 under undrained and drained conditions respectively. Results have also depicted that dissipation of pore water pressure may lead to the greater stability of the slope. During the study it was observed that installation of reinforcement in soils helps in proper distribution of stress and soil starts behaving as one unit.

References

1. Chavan, D., Mondal, G., Prashant, A.: Seismic analysis of nailed soil slope considering interface effects. Soil Dyn. Earthq. Eng. 100, 480–491 (2017). https://doi.org/10.1016/j.soildyn.2017.06.024.
2. Newmark, N.M.: Effects of Earthquakes on Dams and Embankments. Géotechnique.

15, 139–160 (2009). https://doi.org/10.1680/geot.1965.15.2.139.
3. BELYTSCHKO, T.: The Finite Element Method: Linear Static and Dynamic Finite Element Analysis: Thomas J. R. Hughes. Comput. Civ. Infrastruct. Eng. 4, 245–246 (2008). https://doi.org/10.1111/j.1467-8667.1989.tb00025.x.
4. Kokusho, T., Ishizawa, T.: Energy approach for earthquake induced slope failure evaluation. Soil Dyn. Earthq. Eng. 26, 221–230 (2006). https://doi.org/10.1016/j.soildyn.2004.11.026.
5. Sahoo, S., Manna, B., Sharma, K.G.: Seismic stability of a steep nailed soil slope-Shaking table testing and numerical analysis. 2195–2198 (2005).
6. Belal, A.M., George, K.P.: Finite Element Analysis of Reinforced Soil Retaining Walls Subjected To Seismic Loading. 12Wcee. 1–8 (2000).
7. Arbor, A.: To R Einforced S Lopes S Ubjected. J. Geotech. Geoenvironmental Eng. ASCE. 126, 685–694 (2000).
8. Ghazavi, M., Karbor, L., Hashemolhoseini, H.: A New Pseudo-Dynamic Alysis Of Soil Nailied Walls. 13 th World Conf. Earthq. Eng. (2004).
9. Sivakumar Babu, G.L., Singh, V.P.: Numerical analysis of performance of soil nail walls in seismic conditions. ISET J. Earthq. Technol. 45, 31–40 (2008).
10. Sengupta, A.: Behavior of nailed steep slopes in laboratory shake table tests. 721302, 1–7 (2010).
11. Sarangi, P., Ghosh, P.: Seismic analysis of nailed vertical excavation using pseudo-dynamic approach. Earthq. Eng. Eng. Vib. 15, 621–631 (2016). https://doi.org/10.1007/s11803-016-0353-x.
12. Joyner, W.B., Chen, A.T.F.: Calculation of nonlinear ground response in earthquakes. Bull. Seismol. Soc. Am. 65, 1315–1336 (1975).
13. Tan, D.: SEISMIC SLOPE SAFETY - DETERMINATION OF CRITICAL SLIP SURFACE USING ACCEPTABILITY CRITERIA A thesis submitted to the University of London in partial fulfillment for the degree of Doctor of Philosophy and Diploma of Imperial College London by University of. (2006).
14. Sil, A., Dey, A.K.: Dynamic performance of cohesive slope under seismic loading. 5, 1–14 (2014). https://doi.org/10.6088/ijcser.2014050001.
15. Hong, Y.-S., Chen, R.-H., Wu, C.-S., Chen, J.-R.: Shaking table tests and stability analysis of steep nailed slopes. Can. Geotech. J. 42, 1264–1279 (2005). https://doi.org/10.1139/t05-055.
16. Michalowski, R.L.: Soil reinforcement for seismic design of geotechnical structures. Comput. Geotech. 23, 1–17 (1998). https://doi.org/10.1016/S0266-352X(98)00016-0.
17. Kouroussis, G., Verlinden, O., Conti, C.: Finite-Dynamic Model for Infinite Media: Corrected Solution of Viscous Boundary Efficiency. J. Eng. Mech. 137, 509–511 (2011). https://doi.org/10.1061/(ASCE)EM.1943-7889.0000250.
18. Department of Transportation Administration Federal Highway: Soil Nail Walls-Reference Manual. 425 (2015).
19. Code of practice for strengthened / reinforced soils BS:8006 Part 2 : Soil nail design. (2011).
20. Tests, S., Suitability, S., Support, F., Index, T.P.: Properties of Soils.
21. Seismic Data: WNW Ferndale C.A USA, https://escweb.wr.usgs.gov/nsmp-data/data_sets/20140310_0518.html.