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Influence of Soil Properties on the Performance of Soil Nail System

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Abstract. Soil Nailing is a system used for forming or stabilizing vertical or nearly vertical slopes by installing the grouted nails closely into the soil in a progressive manner from top to bottom while excavation proceeds. This technique has been increasing in popularity among the engineers, as it is a cost effective earth retaining structure for a variety of ground conditions. This paper focuses on the effect of various soil properties on the behavior and mechanism of soil-nail system. The soil properties considered for the study are cohesion, angle of friction, dilatancy angle and unit weight of soil. In addition, the effects of surcharge intensity and surcharge inclination are also considered. By varying these properties, the changes in axial force and displacement at wall face are studied and thus the variations in factors of safety for internal and external stability are found. Two dimensional Finite Element software PLAXIS is used with soil idealized byMohr Coulomb model. From the present study, it has been inferred that with theincrease in cohesion, it is observed that the axial force tends to decrease till cer- tain stage, beyond which there is no appreciable change in axial force, With in- crease in friction angle, axial force and displacement at wall face reduce till cer-tain stage, beyond which variations are minimal and with increase in unit weight,the axial force increases linearly. Further, apart from heavily over-consolidated layers, clays tend to show little dilatancy and in sands dilatancydepends on fric- tion angle. Surcharge intensity and surcharge inclination decrease the factors of safety and at some point, the system fails. In order to avoid this failure, load in- tensity must be kept away from the wall face.

Keywords: Soil Nails, Soil Properties, Cohesion, Friction angle, dilatancy, Unit weight.

1 Introduction

Soil Nailing application for stabilization of vertical cuts or nearly vertical slopes has become one of the popular methods of deep excavation and ground improvement techniques. Soil nails are constructed in ‘top-down’ construction sequence, and are suitable and cost effective for various ground conditions. The stability of earth-resisting systems is the main criteria achieved through soil nails which act as tension members due to the deformation of retained soil or weathered rock mass. The tensile stresses are transferred to the surrounding soil through bond stresses along grout-ground interface and ensure long-term performance of the system. The behavior and performance of the soil nails system are influenced by many factors (ShivakumaraBabu et al 2002). Some researchers have done a detailed study of the reinforced earth structures for only load transfer mechanism between soil and nail. The soil strength is mobilized along the uppermost critical failure surface to allow unsupported soil wall to stand (ShivakumaraBabu and VikasPratap Singh et al 2009).The nails shall be fixed to the facing such a way it provides total or horizontal fixity to ensure minimum horizontal displacement (Krupa H R and Prasad S K, et al IJERT 2020). Also, keeping the excavation phase at minimum for each nail, say 1m also ensures less axial force on the nails and thus the higher performance (Krupa H R and Prasad S K, et al IGC 2020). Juran (1985) describes briefly the different mechanisms of soil-reinforcement interaction in reinforced earth and in nailed soil structures. The contribution of soil on the performance of soil nail system is very less discussed. In this paper, efforts are made to report different soil parameters on the performance of the entire system. PLAXIS 2D is used for numerical simulation and analysis. Elias and Juran (1991) have observed that shear and bending nail strength contribution is less than 10% to the overall stability of the wall. Figure 1 shows typical cross section of the soil nail system.

2 Numerical Simulation

2.1 Conventional Design

The manual design procedure (FHWA (2003)) consists of two parts in the design, a preliminary design and the final design. The final design includes analysis of external failure modes (global stability and sliding stability), analysis of internal failure modes (nail pullout failure and nail tensile strength failure), design of permanent facing and verification of important facing failure modes (facing flexure failure and facing punching shear failure), and influence of other site-specific considerations, such as seismic loading. The model and material parameters are as mentioned in Table 1. In the present study, only the important internal failure modes and facing failure modes are considered to assess and to compare the performance of (conventionally designed) soil nail wall. Table 2 comprises of conventional design details. It is observed that the factors of safety are greater than the target assumed thus making the design procedure dependable.

2.2 Numerical Simulation

In order to study the behavior of soil nail system and for its stability analysis, numerical simulations were made using PLAXIS 2D. For preliminary design, input data was obtained from reference manual (FHWA (2003)). A two dimensional plane strain 15-noded finite element model was idealizedfor a 10m vertical cut for soil nailing with grouted nails installed at an inclination of 15degrees and spaced at 1m both vertically and horizontally. The initial facing is provided at the face of the wall simultaneously at each excavation stage and the nails are installed using centralizers. The angle of 15 degrees inclination helps in easy installation of the nail and easy flow of the grout into the drilled hole. The finite element model is as shown in Fig 2. The results from numerical simulation are as shown in Table 3.

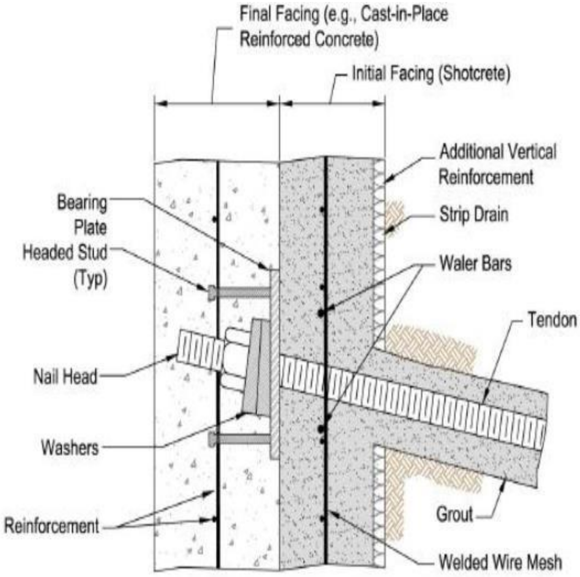

Fig.1. Typical Cross Section of Soil-Nail System, FHWA (2003)

Table 1. Model/Material Parameters.

Parameter	Value
Vertical height of wall, H, m	10m
Soil type	Dense silty sand
Cohesion, c, kPa	5
Friction angle, φ, degrees	31.5
Unit weight, γ, kN/m^3	17
Modulus of elasticity of soil, Es, MPa	20
Poisson's ratio, ν	0.3
Nail installation method	Rotary Drilled and grouted
Grade of steel	Fe415
Modulus of elasticity of nail, En, GPa	200
Nail spacing, S_V x S_H , m x m	1x1
Nail inclination (with horizontal), i, degrees	15
Drill hole diameter, D_{DH}, mm	100
Nail diameter, D_{DH}, mm	20
Compressive strength of grout, f_{ck} , MPa	20
Ultimate bond strength, qu , kPa	100
Modulus of elasticity of grout, E_g , GPa	22

Table 2. Conventional Design Summary

Description	Symbol (unit)	Formulae	Value
Normalized Bond Resistance	μ	$(q_u D_{DH})/(FS_{PO}\gamma_s S_H S_V)$	0.29
Normalized SN length	L/H	from the charts of FHWA(2003)	0.65
Normalized T_{max}	t_{max}		0.29
Corrected Length factor	L/H *	C1*C2*C3*L/H	0.63
Corrected Tmax factor	t_{max*}	T1*T2*T_{max}	0.28
Length of the Nail	L (m)	rounded up	**7.00**
Maximum tension in the Nail	T_{max} (kN)	$\gamma_s S_H S_V t_{max*}$	**47.60**
Tension at face	T_o (kN)	$T_{max*}(0.6+0.2(S_{max}-1)$	**28.56**

Table 3. Results from Numerical Simulation

Parameter	Symbol	Value
Horizontal Displacement of the System	H (mm)	21.52
Maximum tension in the Nail	T_{max}(kN)	56.21
Error from Theoretical Value	%	+15.32
Tension at face	T_o (kN)	51.41
Maximum Shear Force	Q (kN)	19.63
Maximum Bending moment	M (kN-m)	2.74
Pullout length	Lp (m)	6.53
FS for pullout of Nail	FS_{PO}	**3.65**
FS for tensile strength of Nail	FS_T	**2.31**
FS against flexure failure of face (R_{FF}=157.91kN/m^2)	FS_{FF}	**3.07**
FS against punching shear of face (R_{FP}=204.62kN/m^2)	FS_{FP}	**3.98**

For better understanding of the Soil Nail system, it is necessary to study the influence of each soil parameter on the overall behavior of the system. This paper presents the finite element analysis results of a parametric study conducted on various soil properties to evaluate their effect on the performance of the soil-nailed wall. The performance was evaluated in terms of factor of safety and horizontal displacement of the wall. The various soil properties considered are as mentioned below.

a. Cohesion of the Soil
b. Angle of Friction

c. Dilatancy angle
d. Unit Density of the Soil
e. Surcharge intensity and inclination

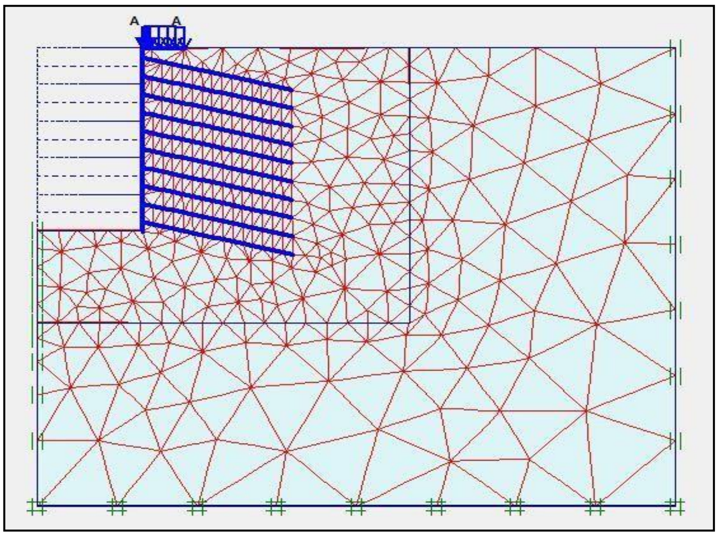

Fig. 2. Typical Finite Element Model of Soil Nail System

3 Results and Discussion

3.1 Cohesion of the Soil (c)

The undrained shear strength parameters of the fine-grained soils should be considered for short term stability of the wall during excavation. In Mohr- Coulomb model, the cohesion parameter is used in combination with friction angle. Whether it is drained or un-drained conditions, the software considers only the effective stress analysis.

3.2 Angle of Friction (ϕ)

As discussed before the shear strength parameters of the soil have an unavoidable effect on the behavior of the system. Fig. 6 shows the variation of tensile forces (both T_{max} and T_o), Fig. 7 shows the decrease in the Horizontal displacements and Fig. 8 gives the variation of factors of safety with increase in friction angle. During the numerical simulations, it was observed that for friction angle values ranging from 0 to 15 degrees, the system fails at early stages of excavation. However, with angle of friction from and above 20 degrees, a decrease in the tensile forces and decrease in the horizontal displacement of the system was found in turn increasing the factors of safety against various conditions.

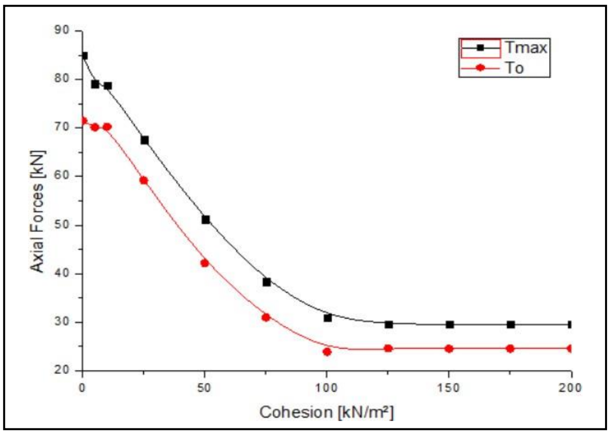

Fig. 3. Variations in$T_{max}$and T_o for various values of Cohesion

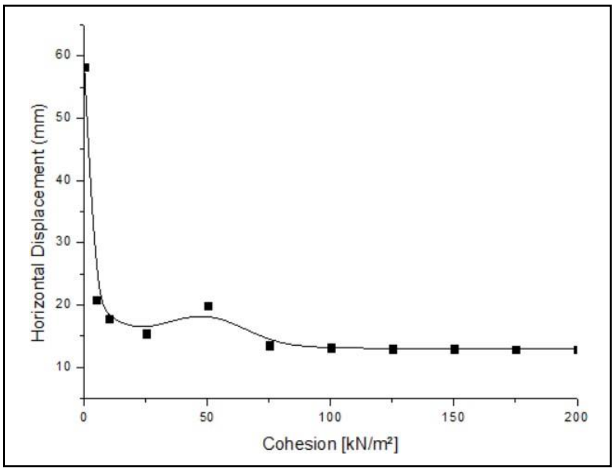

Fig. 4. Variation of Horizontal Displacement with increase in Cohesion of soil

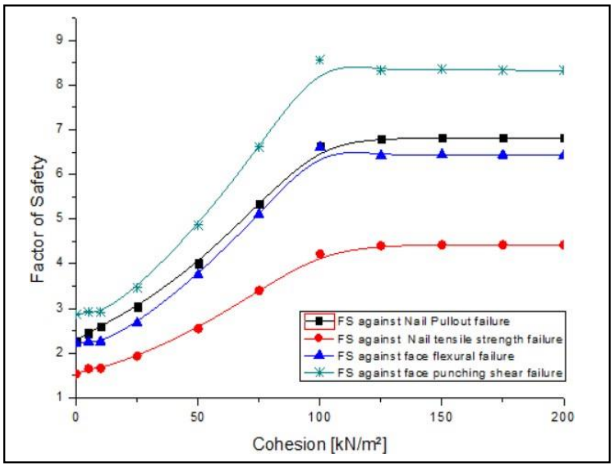

Fig. 5. Variation in Factors of safety with increase in Cohesion of soil

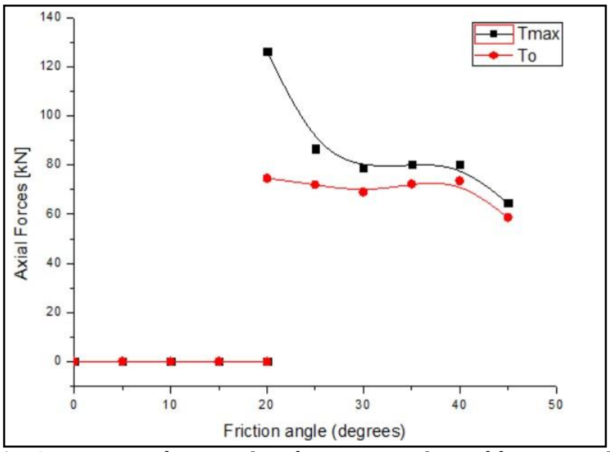

Fig. 6. Variation of T_{max} and T_o for various values of friction angle

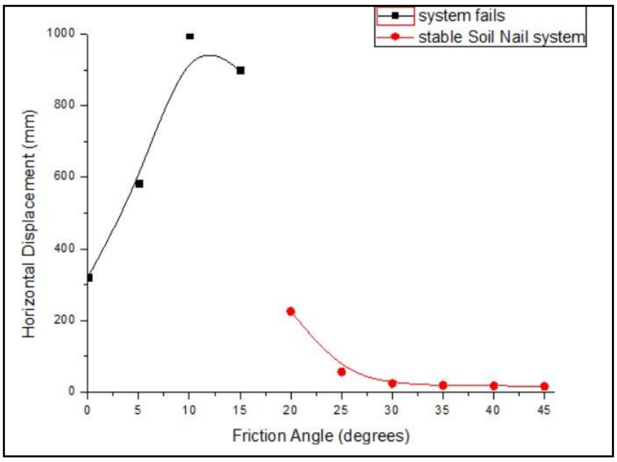

Fig. 7.Variation in Horizontal Displacement for different values of friction angle

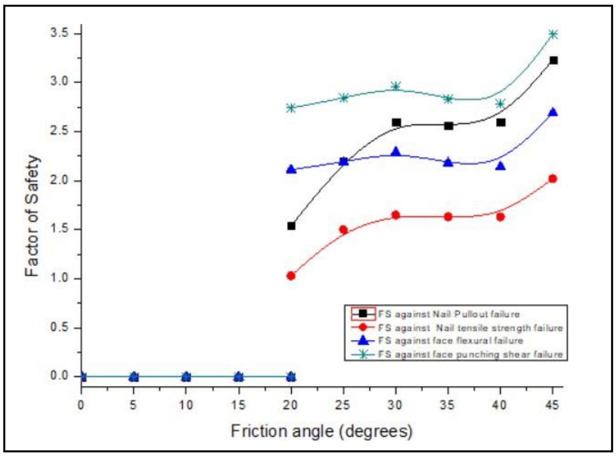

Fig. 7.Variation in Factors of safety with increase in friction angle

3.3 Dilatancy Angle (Ψ)

Apart from heavily over consolidated layers, clays tend to show a little dilatancy ($\Psi \approx 0$) and for sands, it depends on the friction angle and dilatancy. In general, the dilatancy angle for friction angles below 30 degrees is considered as zero and above 30degrees, it is considered as (ϕ-30) degrees. Due to this variation, efforts have been made in this section to study the effect of dilatancy angle on the performance of the soil-nail system.

Fig. 8, Fig. 9 and Fig. 10 provide the graphs for the variations of tensile forces, horizontal displacements and factors of safety respectively for different dilatancy angles. It is observed that the tensile forces vary suddenly between the angles 0 to 1.5 degrees and tend to increase very slowly after 1.5 degrees. Also the horizontal displacement shows less variation similar to that of factors of safety. The factors of safety tends to decrease gradually after 1.5degrees. Thus, we can conclude that dilatancy angle has a very less effect on the performance of the soil nail and obeys the formula (Φ-30°).

3.4 Unit weight of the Soil (γs)

The unit weight of the soil is used in stability analysis and calculations of the soil nail wall design, proving the need to study its effect on system. Fig. 11, Fig. 12 and Fig. 13 show the variations of tensile forces, Horizontal displacements and Factors of safety respectively. It is observed that the tensile forces increase linearly with increase in the unit weight of the soil and so is the horizontal displacement in turn decreasing the factors of safety. So, we can say that the soil nail system works well for a soil with less unit weight.

3.5 Surcharge Intensity and Inclination (q & β)

The surcharge intensity is considered as a strip footing of 4m resting on the back slope area of the soil-nail system 1m behind the excavation cut or the wall line. In this section, efforts have been made to study its effect on the system.

It is observed from Fig. 14 that the tensile forces increase with increase in the surcharge intensity and the maximum forces move up towards the surcharge load and the system eventually fails at an load intensity of 500kN/m^2 at the footing level. The displacements also increase with increase in the load intensity (Fig.15), reducing the factors of safety (Fig. 16). Surcharge inclination yields similar results as that of surcharge intensity, thus ignored in this paper. The stability of the overburden soil slope can be improvised with the help of geo-textiles and other stabilization means the effect of back slope inclination on the soil nail performance can be considerably reduced.

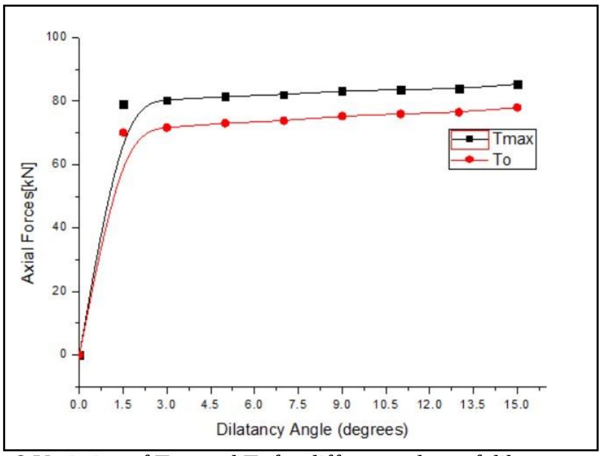

Fig. 8. Variation of T_{max} and T_o for different values of dilatancy angle

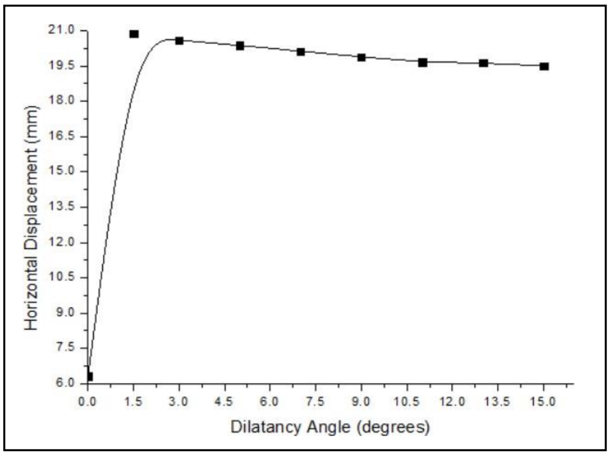

Fig. 9.Variation in Horizontal displacement for different dilatancy angles

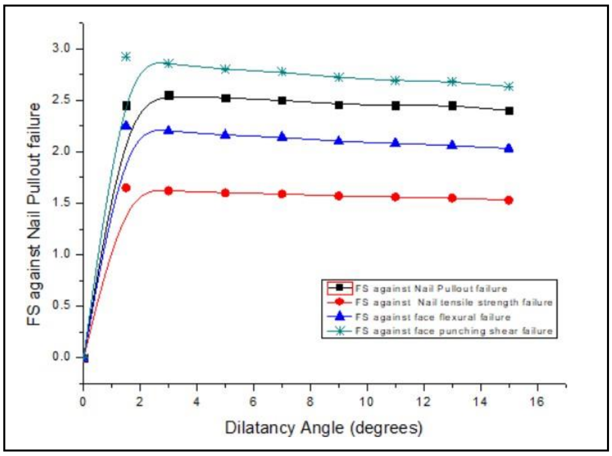

Fig. 10. Variation in factors of safety for different dilatancy angles

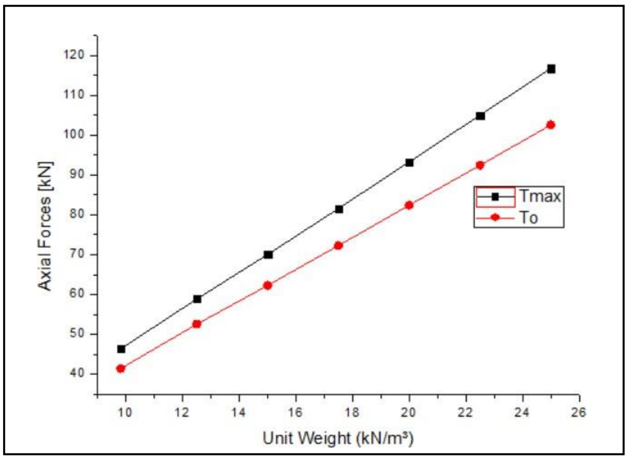

Fig. 11. Variation of T_{max} and T_o for different Unit weights of the soil

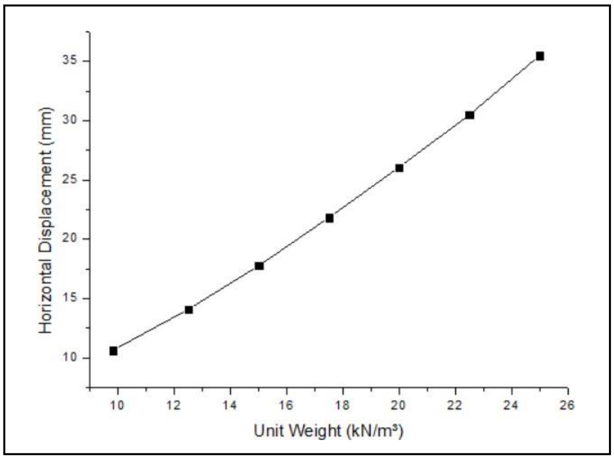

Fig. 12. Variation in Horizontal Displacement for various Unit weights of Soil

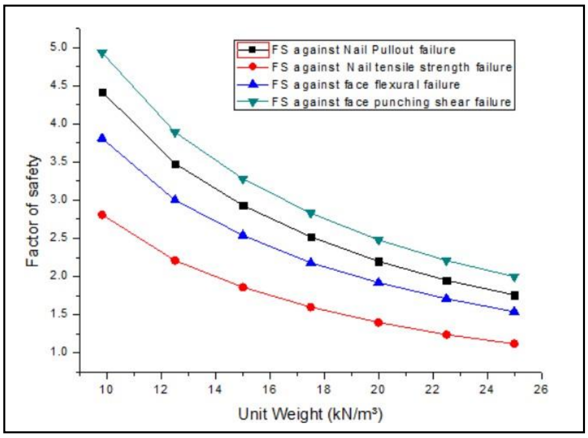

Fig. 13. Variation in Factors of safety for various Unit weights of Soil

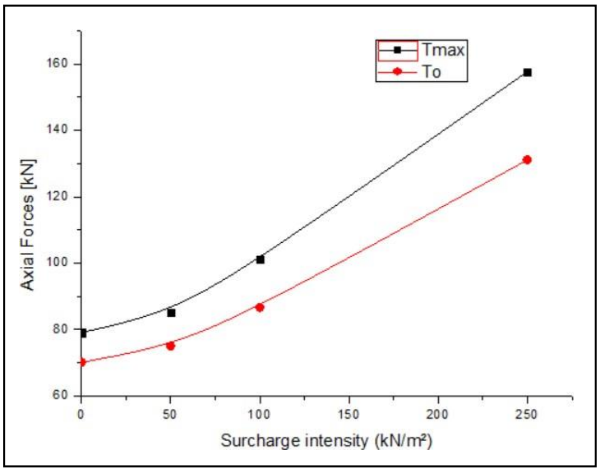

Fig. 14. Variation of Tmax and To for increase in Surcharge intensity

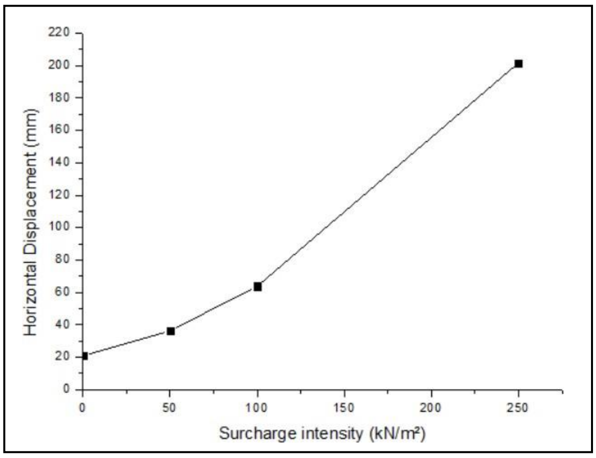

Fig. 15.Variation inHorizontal Displacement for increase in Surcharge intensity

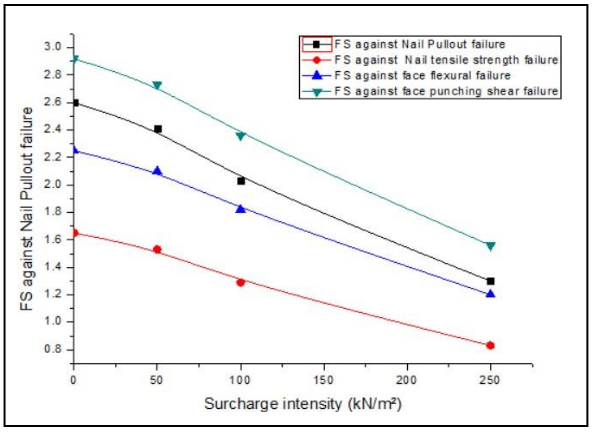

Fig. 15. Variation in Factors of safety for increase in Surcharge intensity

Conclusion

The following are a few important inferences on the effects of different soil properties drawn from the present study.

1. With increase in cohesion of the soil, the soil nail system shows decreased displacement and increased factor of safety.
2. Friction angle shows its effect only after 20 degrees and the displacement of the wall decreases with further increase in the angle of friction. This also implies that the factors of safety increase with increase in friction angle. Also the dilatancy angle has less effect of the performance of the soil nail system and obeys the rule of (Φ-30) degrees.
3. The unit weight of the soil has a linear effect on the performance of the soil nail system. With increase in the unit weight of the soil, a decrease in the factors of safety and an increase in displacement of the wall are observed. Thus for soils with higher unit weight, the redesign of the system is to be considered.
4. Surcharge intensity and surcharge inclination have a similar effect on the performance of the soil nail system. Increase in the intensity or the inclination decreases the factors of safety and at some point, the system fails. In order to avoid this, the load intensity may be kept away from the wall. Also, inclined surcharges shall be analyzed for slope stability and suitable methods shall be adopted to decrease the effect on the performance of the underneath soil nail.

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