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Bearing Capacity of Reinforced CNS Soil Bed on Clay Soil with Inclined Reinforcement Considering Kinematics

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Abstract. Usually geosynthetic reinforcement in reinforced foundation beds is aligned in horizontal layers but transversal to the application of gravity stresses to restrain the tensile strains developed in the soil through interfacial bond resistance limited by its tensile strength. Geosynthetic soil structures can accommodate large deformations before failure. Subgrade soil generally exhibits non-linear behavior at large deformations. Present work analyses non-linear response of Cohesive Non-swelling (CNS) soil bed reinforced with geotextile reinforcement placed inclined from the edge of the footing towards the free end at an inclination varying between 0 to 20° and evaluated normalized bearing capacity values and compared with horizontally placed geotextile reinforcement considering kinematics and nonlinearity of soil bed. The variation of normalised bearing capacity with the angle of shearing resistance of soil, interface friction angle, stiffness of soil bed, relative fill stiffness factor, transverse displacement is studied in addition to the effect of inclination of reinforcement. Improvement in normalised bearing capacity ratios with inclined reinforcement considering non-linear soil bed is significant over and above the effect of transverse resistance of horizontal reinforcement.

Keywords: Geosynthetic, Normalised bearing capacity, Non-linear kinematic analysis, Stiffness of soil bed, Relative fill stiffness factor, Transverse displacement, Inclined reinforcement

1 Introduction

Soil reinforcement for foundation beds is usually placed in horizontal layers to restrain tensile strains in the soil and increases the overall resistance of the composite medium through interfacial bond resistance. In many of the studies available related to the analysis and stability of reinforced soil structures, only bond resistance mobilized due to (Jewell,1992) axial pull is considered. Whereas in the reinforced soil structures, critical plane intersects the reinforcement layer obliquely thus the reinforcement deforms transversely under the action of oblique force/displacement. The soil beneath the reinforcement develops additional normal stress along with the soil reinforcement interface resulting in additional bond resistance. Rowe (1992) considered a force in the reinforcement to act along the direction between the alignment of reinforcement and tangent to the slip surface. Reinforced soil structure has been studied by Madhav and Umashankar (2003) considering kinematics and showed that reinforcement is subjected to transverse pull in addition to axial pull. Kumar and Madhav (2011) presented an analysis for analyzing the reinforced earth wall with geosynthetic reinforcement inclined and established that factor of safety against pullout is enhanced due to mobilized normal stress acting on the bottom of reinforcement. It is noticed that geosynthetic reinforced structures accommodate large deformations before failure and at large deformation soil exhibit non-linear behavior. In this paper, it is proposed to study the bearing capacity of nonlinear response of CNS soil bed reinforced with inclined reinforcement over in-situ clay layer considering the transverse displacement of reinforcement.

2. Methodology

2.1 General

A strip footing having width B is resting on Cohesive Non-Swelling soil stratum of thickness, H with unit weight, γ and angle of internal friction (ϕ), relative fill stiffness factor (β) overlying soft clay with geotextile reinforcement with length L_r is placed in the soil bed at a depth of u from the bottom of footing with an inclination of $\boldsymbol{\alpha}$. ϕ_r is the interface bond resistance between soil and reinforcement. Fig. 1 shows deformation of the soil column and geotextile reinforcement due to punching shear failure of footing. The initial position of inclined reinforcement is represented by line PQRS, and it gets deformed to the new position defined by PQQ'R'RS. Full mobilization of shear resistance along with reinforcement-soil interface and non-linear stress displacement response of soil bed is assumed.

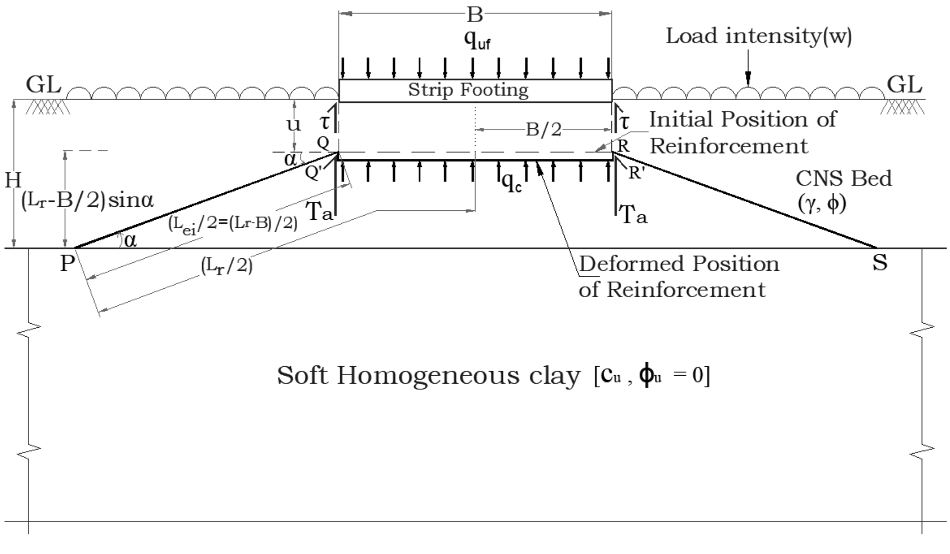

Fig. 1. Definition Sketc

2.2 Bearing capacity of Cohesive Non-Swelling soil bed on clay soil

The bearing capacity of footing resting on thin dense sand bed overlying soft clay considering punching mode of failure presented by Meyerhof (1974) is

$$q_{cns} = cN_c + \frac{\gamma H^2}{B} k_s(1 + 2(\frac{D}{H})\tan\phi + \gamma D \leq 0.5\gamma B N_r \qquad (1$$

N_c, N_r= Bearing capacity factors γ = unit weight of soil. ϕ = angle of shearing resistance of soil, K_s can be had from the Figure given by Meyerhof & Hanna (1978)

2.3 Bond resistance of geotextile reinforcement placed inclined in CNS soil bed

Axial Pull. Strip footing along with CNS soil column below the footing moves down due to punching effect resulting in mobilization of shear stresses on both sides of the soil column and bond resistance will be mobilized at the soil reinforcement interface

Tangential stress, q_t offers direct resistance against pullout of reinforcement, and due to normal stress, q_n resistance $q_n \tan\phi_r$ is mobilized as shown in Fig.2.
Bearing capacity of soil bed with inclined reinforcement resting on soft clay considering axial pullout force mobilized in the reinforcement as

$$q_{uir} = cN_c + \frac{\gamma H^2}{B} K_s \tan\phi + 4\left\{\gamma\left(\frac{u}{B} + \frac{1}{2}\left[\left(\frac{Lr}{2B} - \frac{1}{2}\right) sin\alpha\right]\right) + \frac{w}{B}\right\}\left(\frac{Lr}{2B} - \frac{1}{2}\right)(tan\phi_r\ cos\alpha + sin\alpha) \qquad (2)$$

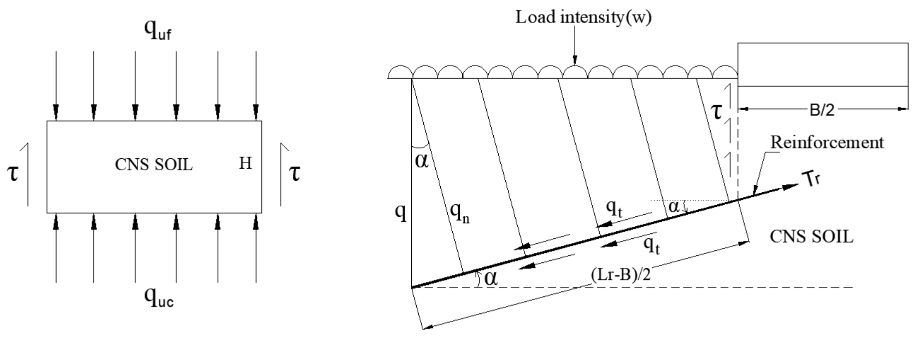

Fig.2. Stress on soil column and inclined reinforcement

Normalizing the above equation with *c*

$$q_{uir}{}^* = N_c + (\frac{\gamma B}{c})(\frac{H}{B})^2 K_s tan\phi + 4\{\frac{\gamma B}{c}(\frac{u}{B} + \frac{1}{2}\ [(\frac{Lr}{2B} - \frac{1}{2})sin\alpha]) + \frac{w}{c}\}\left(\frac{L_r}{2B} - \frac{1}{2}\right)(tan\phi_r\ cos\alpha + sin\alpha) \qquad (3\ )$$

Transverse pull. For the estimation of bearing capacity of the double layered soil considering the kinematics punching shear failure is considered. The analysis is ca out assuming the response of the soil to the transverse displacement is nonlinear a shown in Fig.3.

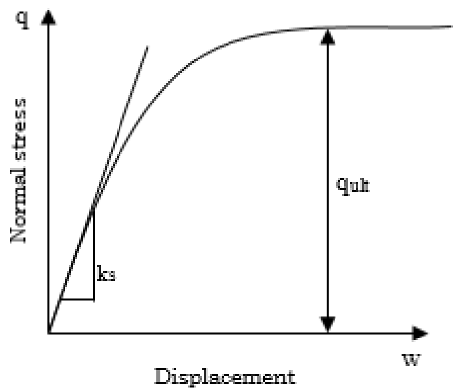

Fig. 3. Normal stress-displacement response of soil

Madhav and Umashankar (2003) developed a method to estimate the mobilized additional bond resistance for the analysis of sheet reinforcement subjected to transverse force/displacement. A transverse displacement, (w_L) of the reinforcement layer at the face of the footing is considered to estimate additional mobilized bond resistance. Because of transverse displacement, w_L of the reinforcement, upward resisting force P gets developed. Pullout force in the reinforcement increases due to this transverse displacement,
Tension mobilized in the reinforcement due to additional normal force, P as

$$T = 2\gamma u_{avg} L_{ei} tan\phi_r + P \sec\alpha \, tan\phi_r \quad (4)$$

Where P is the transverse force in geotextile reinforcement layer mobilized due to transverse displacement (w_L) at the edge of footing, P is calculated as follows.

$$P = \gamma u_{avg} L_{ei} P^* \quad (5)$$

Where P* is the normalized transverse force in geotextile reinforcement obtained from Umashankar and Madhav (2003). In soil bed with relative stiffness, $\mu\left(\frac{k_s L}{\gamma H}\right)$, relative fill stiffness factor $\beta\left(\frac{k_s L}{q_{ult}}\right)$, the variation of normalised transverse force P* with normalised displacement $\left(\frac{w_L}{L}\right)$ is shown in Fig. 4 for ϕ=30°.

A parametric study has been carried out for W_L=0.001 to 0.01, ϕ_r=22.5° to 30°, γ= 15 to 20 kN/m^3, μ=500 to 10000, L_r=2m to 10m, β = 50 to 3000 and q_{ult}=300 to 1000 kN/m^2. The bearing capacity of nonlinear CNS bed with reinforcement inclined overlying soft clay soil is the sum of bearing capacity of clay layer, shear resistance developed in CNS bed, axial resistance of inclined reinforcement and additional resistance mobilized due to kinematics.

$$q_{uirkn} = cN_c + \frac{\gamma H^2}{B} K_s \tan\phi + 4\left\{\gamma\left(\frac{u}{B} + \frac{1}{2}\left[\left(\frac{Lr}{2B} - \frac{1}{2}\right)\sin\alpha\right]\right) + \frac{w}{B}\right\}\left(\frac{Lr}{2B} - \frac{1}{2}\right)(\tan\phi_r \cos\alpha + \sin\alpha)(1 + T^* + P^*) \quad (6)$$

Normalizing the above equation with c

$$q_{uirkn}{}^* = N_c + \left(\frac{\gamma B}{c}\right)\left(\frac{H}{B}\right)^2 K_s \tan\phi + 4\left\{\frac{\gamma B}{c}\left(\frac{u}{B} + \frac{1}{2}\left[\left(\frac{Lr}{2B} - \frac{1}{2}\right)\sin\alpha\right]\right) + \frac{w}{c}\right\}\left(\frac{L_r}{2B} - \frac{1}{2}\right)(\tan\phi_r \cos\alpha + \sin\alpha)(1 + T^* + P^*) \quad (7)$$

$q_{uir}*$ is the ratio of bearing capacity of geotextile reinforced CNS bed with reinforcement placed inclinedly considering axial tension in inclined reinforcement to that of undrained shear strength of underlying clay.

$q_{uhrkn}*$ is the ratio of bearing capacity CNS bed with nonlinear response and reinforcement placed horizontal considering the effect of the transverse force in addition to axial tension mobilized in horizontal reinforcement to that of undrained shear strength of in-situ clay.

$q_{uirkn}*$ is the ratio of bearing capacity CNS bed with nonlinear response and reinforcement placed inclined considering the effect of the transverse force in addition to axial tension mobilized in inclined reinforcement to that of undrained shear strength of in-situ clay.

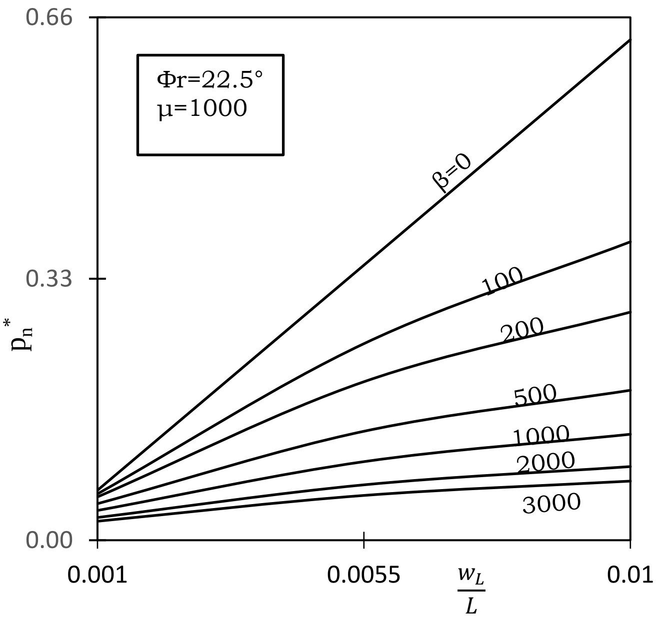

Fig. 4. Variation of normalised transverse force, P* with normalised displacement, (w_L/L)-Effect of relative fill stiffness factor

3 Results and Discussions

To illustrate the effect of the nonlinearity of CNS soil bed and transverse deformation of inclined reinforcement on normalized bearing capacity of strip footing supporting on CNS soil bed over clay for a wide range of following non-dimensional parameters are presented. $\gamma B/c$ = 1.8, Lr/B= 2.5 to 3.5, H/B = 0.5, w_L = 0.001 to 0.01, β=0 to 3000 computations are made for $\frac{\phi_r}{\phi}$= 0.75, ϕ= 30°, w/c = 0 in addition to that α = 0 to 20° are studied. For various values of α, the effect of these parameters on normalized bearing capacity is quantified and compared with the normalized bearing capacity of nonlinear soil bed reinforced horizontally.

3.1. Effect of relative stiffness of soil bed (μ)

The variation of q_{urikn}* with α for different values of μ, for u/B =0.15, H/B =0.5, L_r/B =3, ϕ_r/ϕ = 0.75, ϕ= 30°, β= 500, w/c= 0, $\gamma B/c$= 1.8, w_L/L= 0.01 is presented in Fig. 5. q_{urikn} * increases from 6.98 to 10.03 an increase of 43.7% with increase in α from 0 to 20°due to inclination of reinforcement due to mobilization of additional normal force exerted on reinforcement and additional bond resistance mobilised due to transverse deformation of reinforcement for μ=2000. q_{uirkn} * increases from 7.98 to 9.5 an increase of 19%

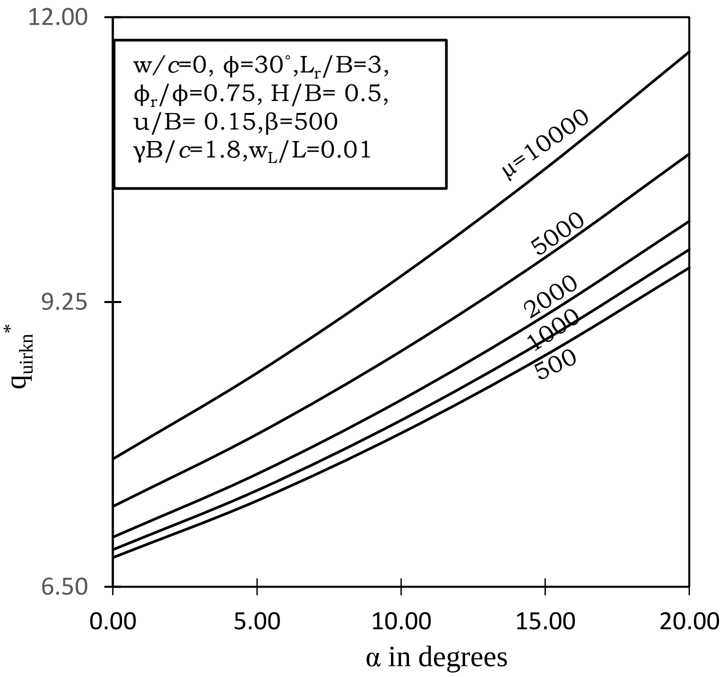

Fig. 5. Variation of normalised bearing capacity with inclination of reinforcement(α)-Effect of relative stiffness

For the inclination of reinforcement, α= 10 ° with an increase in μ from 500 to 10000 due to increasing in relative stiffness the transverse force required to mobilize transverse displacement increases, hence increase in bearing capacity. Effect of α on the increase of bearing capacity is significant whereas effect of μ on normalized bearing capacity is considerable

3.2. Effect of transverse displacement (W_L)

Variation of q_{urikn}* with α for different values of w_L/L for L_r/B =3, H/B =0.5, u/B =0.15, ϕ_r/ϕ= 0.75, μ=1000, β=500, w/c=0, γB/c=1.8, is depicted in Fig. 6. q_{urikn}* increases from 6.79 to 9.6 an increase of 41.4% with an increase in α from 0 to 20° for w_L/L=0.0055 due to inclination of reinforcement resulting in mobilization of additional normal stress on reinforcement and also due to transverse deformation of reinforcement, additional bond resistance developed between the bottom of reinforcement and soil due to upward normal stress acting on bottom of reinforcement. q_{urikn}* increases from 7.79 to 8.11 an increase of 4.1% for α=10° with increase in transverse displacement from 0.001 to 0.01 due to upward normal stress acting on the bottom face of the reinforcement consequently additional bond resistance acting on the interface and thus additional tension mobilised in the reinforcement leading to increase in bearing capacity.

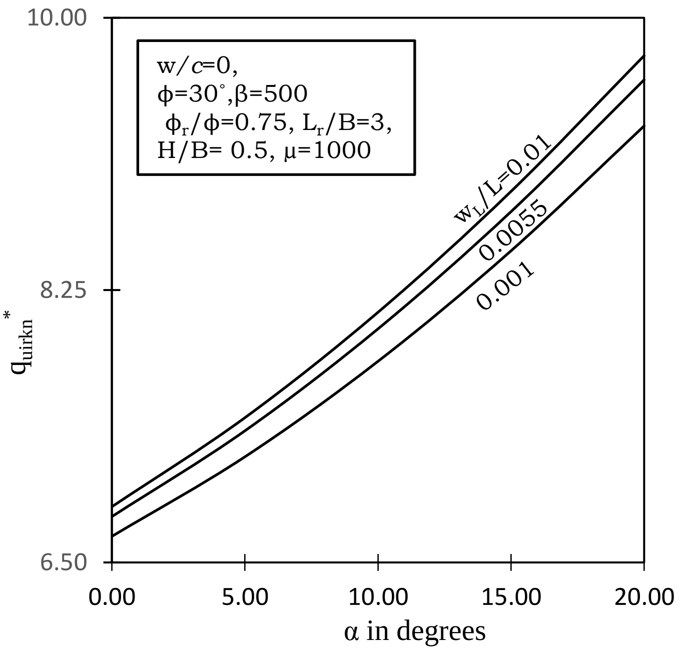

Fig. 6. Variation of normalised bearing capacity with inclination of reinforcement(α)-Effect of transverse displacement

3.3.Effect of relative fill stiffness factor (β)

Variation of q_{uirkn} * with α for various values of β, for H/B= 0.5, u/B = 0.15, $L_{r/}$B= 3, ϕ=30° $ϕ_{r/}$ϕ= 0.75, μ=1000, γB/c= 1.8, = 0.01, α=20°, w/c= 0 is represented in Fig 8. q_{uirkn}* increases from 6.86 to 9.76 an increase of 42.3% with increase in α from 0 to 20° due to combined effect of additionally mobilized frictional resistance due to increase in normal stress component, q_n and additional bond resistance mobilized due to transverse deformation of reinforcement for β= 200. q_{uirkn}* increases from 7.89 to 8.87 an increase of 12.42% for a decrease in β from 3000 to 0, due to stronger soil bed (more q_{ult}) there by transverse displacement is localized near the failure surface.

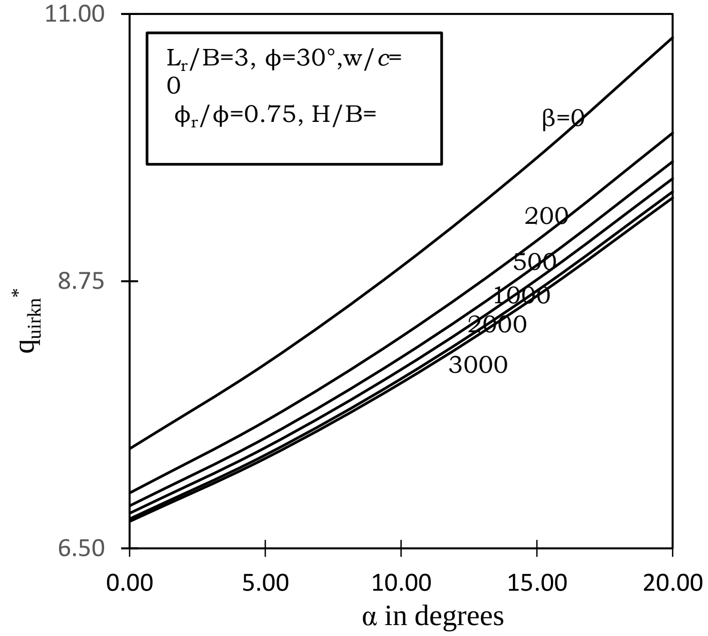

Fig. 7. Variation of normalised bearing capacity with α inclination of reinforcement-Effect of relative fill stiffness factor

3.4. Effect of Various improvement techniques

Variation of normalized bearing capacities q_{uhr}*or q_{uir}*or q_{uhrn}* or q_{urikn} * with α for various improvement techniques, for L_r/B, for u/B =0.15, ϕ=30° $ϕ_{r/}$ϕ = 0.75, H/B= 0.5, μ=1000, γB/c= 1.8, $w_{L/}$L= 0.01, w/c= 0 are illustrated in Fig.9. q_{urikn} * increases 42.3% when compared with q_{uhrn}* for 20° of inclination of reinforcement due to combined effect of increase in normal stress acting on reinforcement and additional bond resistance mobilized along bottom of reinforcement due to upward force acting normally on reinforcement caused due to transverse deformation of reinforcement. q_{uir}* increases 20% when compared with q_{uhr}* due to inclination of reinforcement resulting additional normal stress acting on reinforcement there by mobilization of additional bond stress along reinforcement.

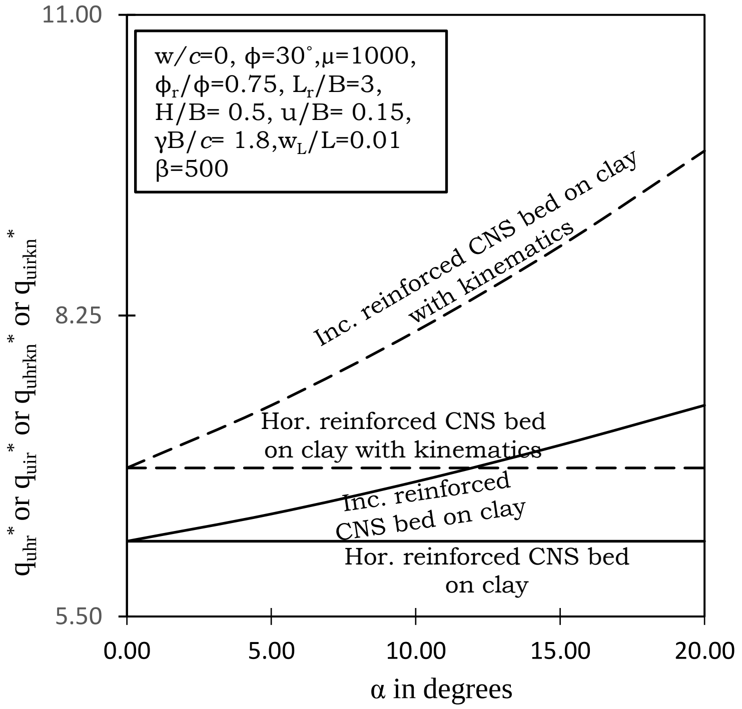

Fig. 8. Variation of Normalised bearing capacities versus α -Effect of various Improvement techniques

4 Validation of Results

Table 1. Comparison of normalized bearing capacity of present study with available literature

S. No	Author	Normalized bearing capacity	Results of Present Study for corresponding properties
1	Rajyalakshmi et al., (2011)	1.33(Analy.)	1.69

As shown in Table 1, the predicted normalized bearing capacity value is more than the value of other author corroborating that the present approach is giving better results than the existing approach.

5 Conclusions

Bearing capacity analysis of strip footing resting on CNS soil stratum with geotextile reinforcement placed inclined overlying clay subjected to transverse displacement/pull is proposed by considering nonlinear shear stress displacement relation with horizontal reiforced CNS soil bed. Meyerhof`s punching shear failure model for thin dense sand bed on clay is extended to include the axial tension in inclined reinforcement and mobilised additional bond resistance due to transverse deformation of inclined reinforcement theory proposed by Umashankar and Madhav (2003) has been used.

Normalised bearing capacity, q_{urikn} *increases 19% with increase in stiffness of soil, μ from 500 to 10000, for normalized displacement of 0.01 due to increase in stiffness of soil bed. As the reinforcement deforms transversely, the soil beneath the reinforcement mobilizes additional normal stresses resulting in mobilization of larger shear stresses for inclination of reinforcement, α=10°.

Normalised bearing capacity, q_{urikn}* increases 4.1% with increase in transverse deformation from 0.001 to 0.01, for α=10°. Soil beneath the reinforcement mobilizes additional normal and therefore shear stresses increases the bearing capacity.

Normalised bearing capacity, q_{urikn} * decreases from 8.87 to 7.89 a decrease of 12.4 % with an increase in β from 0 to 3000 for α= 10° due to weaker soil bed (less q_{ult}). The deformations become more uniform and normal stresses are distributed over greater length of reinforcement, therefore less mobilization of bond resistance and pull out.

Normalised bearing capacity, q_{urikn}* is 31%,20.5%,18.2% more when compared with q_{uhr}*, q_{uir}*, q_{uhrkn}* due to increase in normal stress on reinforcement and additional upward normal stress acting on reinforcement due to transverse deformation of reinforcement, additional bond resistance developed along the bottom of reinforcement due to transverse deformation of reinforcement and increase in normal stress acting on reinforcement due to inclination of reinforcement.

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