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APPENDIX 1

Theoretical calculation of ultimate bearing capacity of sandy soil

For surface foundations on **medium dense dry sand**, the ultimate bearing capacity, $q_U$can be represented by the conventional relationship (Vesic, 1973) as below-

For square footing

$$q_U = 0.5\,\gamma N_\gamma B s_\gamma$$

where, $q_U =$ ultimate bearing capacity of unreinforced sand bed, γ = unit weight of soil, N_γ =bearing capacity factor, shape factor, s_γ = 0.8 (IS 6403 1981)

Since as per Vesic's bearing capacity factor, $N_\gamma = 2\left(N_q + 1\right)\tan(\varphi)$

where, N_q= bearing capacity factor

$$N_q = e^{\pi tan\varphi}(\frac{1+sin\varphi}{1-sin\varphi})$$

$$\because \varphi_{ps} = 40.5^0 \text{ for medium dense sand (Chapter 3, Table 3.1)}$$

After Lade and Lee (1976)

$$\varphi_{ps} = 1.5\varphi_{tr} - 17 \quad (\varphi_{tr} > 34^0)$$

$$\therefore \quad \varphi_{tr} = \frac{(\varphi_{ps}+17)}{1.5} = \frac{(40.5+17)}{1.5} = 38.3^0$$

$$\therefore \quad \varphi_{tr} = 38.3^0$$

$$\therefore N_q = e^{\pi tan38.3}(\frac{1+sin38.3}{1-sin38.3}) = e^{2.48} \times 4.26 = 50.87$$

$$\therefore N_\gamma = 2 \times (50.87 + 1) \times \tan 38.3 = 82.0$$

Thus, q_U= 0.4 × 16.23 × 82.0 × 0.15 = 79.85 kPa ≈ 80.0 kPa

Similarly, rectangular footing

$$q_U = \frac{1}{2}\gamma N_\gamma B\ [1 - 0.4\left(\frac{B}{L}\right)]$$

where shape factor, s_γ = $[1 - 0.4\left(\frac{B}{L}\right)]$ (IS 6403 1981)

Thus, q_U = 0.5 × 16.23 ×82.0 × 0.15× 0.70 = 69.87 kPa ≈ 70 kPa

and strip footing

$\because \varphi_{ps} = 40.5^0$ for medium dense sand (Chapter 3, Table 3.1)

$\therefore N_q = e^{\pi tan40.5}(\frac{1+sin40.5}{1-sin40.5}) = e^{2.683} \times 4.70 = 68.75$

$\therefore N_\gamma = 2 \times (68.75 + 1) \times \tan 40.5 = 119.1$

$q_U = \frac{1}{2}\gamma N_\gamma B s_\gamma$

Thus, q_U = 0.5 × 16.23 ×119.1 × 0.15

$\therefore q_U$ = 0.5 ×16.23 ×119.1 × 0.15 =144.97 kPa ≈ 145 kPa

Similarly, for surface foundations on **loose dense dry sand**,

$\because \varphi_{ps} = 38.8^0$ for loose dense sand (Chapter 3, Table 3.1)

After Lade and Lee (1976)

$$\varphi_{ps} = 1.5\varphi_{tr} - 17 \quad (\varphi_{tr} > 34^0)$$

$$\therefore \quad \varphi_{tr} = \frac{(\varphi_{ps}+17)}{1.5} = \frac{(38.8+17)}{1.5} = 37.2^0$$

$$\therefore \quad \varphi_{tr} = 37.2^0$$

$\therefore N_q = e^{\pi tan37.2}(\frac{1+sin37.2}{1-sin37.2}) = e^{2.38} \times 4.058 = 43.84$

$\therefore N_\gamma = 2 \times (43.84 + 1) \times \tan 37.2 = 68.08$

Thus, q_U= 0.4 × 15.79 ×68.08 × 0.15= 64.5 kPa ≈ 64.5 kPa

and for surface foundations on **very dense dry sand**,

$\because \varphi_{ps} = 41.5^0$ for very dense sand (Chapter 3, Table 3.1)

After Lade and Lee (1976)

$$\varphi_{ps} = 1.5\varphi_{tr} - 17 \quad (\varphi_{tr} > 34^0)$$

$$\therefore \quad \varphi_{tr} = \frac{(\varphi_{ps}+17)}{1.5} = \frac{(41.5+17)}{1.5} = 39^0$$

$$\therefore \quad \varphi_{tr} = 39^0$$

$\therefore N_q = e^{\pi tan39}(\frac{1+sin39}{1-sin39}) = e^{2.54} \times 4.395 = 55.73$

$\therefore N_\gamma = 2 \times (55.73 + 1) \times \tan 39 = 91.88 \approx 92.0$

Thus, q_U= 0.4 ×16.7 × 92 × 0.15= 92.0 kPa ≈ 92.0 kPa

APPENDIX 2

Calculation of shape factor of footing

The first shape factor proposed by Meyerhof (1963) is a semi-empirical one and is given as below-

$$s_\gamma = 1 + 0.1\, tan^2(45 + \frac{\varphi}{2})\frac{B}{L}$$

where, *B* = width of footing, *L* = Length of footing and *φ* = friction angle of soil
For square footing, rectangular footing and strip footing, $\frac{B}{L} is\ \frac{150}{150} = 1, \frac{150}{200} = 0.75$ & $\frac{150}{980} = 0.15$, respectively.

Furthermore, $\varphi_{tr} = 38.3^0$ is used for square and rectangular footing, whereas, $\varphi_{ps} = 40.5^0$ is used for strip footing.

Therefore, $s_{\gamma(sq)} = 1 + 0.1\, tan^2\left(45 + \frac{38.3}{2}\right) \times 1 = 1 + 0.1\ \times 4.26\ \times 1 = 1.43$

Similarly, $s_{\gamma(rec)} = 1 + 0.1\, tan^2\left(45 + \frac{38.3}{2}\right) \times 0.75 = 1 + 0.1\ \times 4.26\ \times 0.75 = 1.32$

and $s_{\gamma(st)} = 1 + 0.1\, tan^2\left(45 + \frac{40.5}{2}\right) \times 0.15 = 1 + 0.1\ \times 4.705\ \times 0.15 = 1.07$

Another is a semi-empirical one given by De Beer (1970) based on his 1g small scale model tests -

$$s_\gamma = 1 - 0.4(\frac{B}{L})$$

Therefore, $s_{\gamma(sq)} = 1 - 0.4\ \times 1 = 0.6$

Similarly, $s_{\gamma(rec)} = 1 - 0.4\ \times 0.75 = 0.7$

and $s_{\gamma(st)} = 1 -\ 0.4\ \times 0.15\ = 0.94$

For the present study, the shape factor for square, rectangular and strip footing is calculated as shown below-

For square footing rested on surface of sand bed

$$q_U = \frac{1}{2}\gamma N_\gamma B s_\gamma$$

where, $q_U =$ ultimate bearing capacity of unreinforced sand bed, γ = unit weight of soil, N_γ =bearing capacity factor, shape factor, s_γ = 0.8 (IS 6403 1981).

Since as per Vesic's bearing capacity factor, $N_\gamma = 2\left(N_q + 1\right)\tan(\varphi)$

where, N_q= bearing capacity factor

$$N_q = e^{\pi tan\varphi}(\frac{1+sin\varphi}{1-sin\varphi})$$

$\because \varphi_{ps} = 40.5^0$ for medium dense sand (Chapter 3, Table 3.1)

After Lade and Lee (1976)

$$\varphi_{ps} = 1.5\varphi_{tr} - 17 \quad (\varphi_{tr} > 34^0)$$

$$\therefore \quad \varphi_{tr} = \frac{(\varphi_{ps}+17)}{1.5} = \frac{(40.5+17)}{1.5} = 38.3^0$$

$$\therefore N_q = e^{\pi tan 38.3}(\frac{1+sin38.3}{1-sin38.3}) = e^{2.48} \times 4.26 = 50.87$$

$$\therefore N_\gamma = 2 \times (50.87 + 1) \times \tan 38.3 = 82.0$$

Thus, $91 = 0.5 \times 16.23 \times 82 \times 0.15\, s_\gamma$

$\therefore s_\gamma = 0.911$

Similarly, rectangular footing rested on surface of sand bed

$$q_U = \frac{1}{2}\gamma N_\gamma B s_\gamma$$

Thus, $105 = 0.5 \times 16.23 \times 82 \times 0.15\, s_\gamma$, $\quad \therefore s_\gamma = 1.05$

and strip footing rested on surface of sand bed

$\because \varphi_{ps} = 40.5^0$ for medium dense sand (Chapter 3, Table 3.1)

$$\therefore N_q = e^{\pi tan 40.5}(\frac{1+sin40.5}{1-sin40.5}) = e^{2.683} \times 4.70 = 68.75$$

$$\therefore N_\gamma = 2 \times (68.75 + 1) \times \tan 40.5 = 119.1$$

$$q_U = \frac{1}{2}\gamma N_\gamma B s_\gamma$$

Thus, $145 = 0.5 \times 16.23 \times 119.1 \times 0.15\, s_\gamma$

$\therefore s_\gamma = 1.00$

APPENDIX 3

Theoretical calculation of ultimate bearing capacity of geocell-reinforced sand beds

Part-1

The ultimate bearing capacity (q_R) of geocell-reinforced soil can be calculated by the relationship, Koerner, 2005 as below-

$$q_R = 2\tau + cN_c s_c + qN_q s_q + 0.5\,\gamma B N_\gamma s_\gamma$$

where, $q_R =$ ultimate bearing capacity of geocell-reinforced sand

c = cohesion = 0 (for the present study)

q = surcharge load = $\gamma_q h_q$

γ_q = unit weight of soil within the geocell

h_q = depth of geocell

B = width of applied pressure (footing)

γ = unit weight of soil in failure zone

$N_c = N_q = N_\gamma$ = bearing capacity factors

$s_c = s_q$ = shape factors = $[1 + 0.2\left(\frac{B}{L}\right)]$ = 1.2 (IS 6403 1981)

s_γ = shape factor = 0.8 (IS 6403 1981)

τ = shear strength between geocell wall and soil = σ_n tanδ

σ_n= average horizontal force within the geocell ≈ P K_a

P = applied vertical pressure,

K_a = coefficient active pressure, and

δ = angle of shearing resistance between infill soil and geocell wall

Since as per Vesic's bearing capacity factor, $N_\gamma = 2(N_q + 1)\tan(\varphi)$ [Vesic, 1973]

where, N_q= bearing capacity factor

$$N_q = e^{\pi tan\varphi}(\frac{1+sin\varphi}{1-sin\varphi})$$

$\because \varphi_{ps} = 38.8^0$ for loose dense sand (Chapter 3, Table 3.1)

After Lade and Lee (1976)

$$\varphi_{ps} = 1.5\varphi_{tr} - 17 \quad (\varphi_{tr} > 34^0)$$

$$\therefore \quad \varphi_{tr} = \frac{(\varphi_{ps}+17)}{1.5} = \frac{(38.8+17)}{1.5} = 37.2^0$$

$$\therefore \quad \varphi_{tr} = 37.2^0$$

$$\therefore N_q = e^{\pi tan37.2}(\frac{1+sin37.2}{1-sin37.2}) = e^{2.38} \times 4.058 = 43.84$$

$$\therefore N_\gamma = 2 \times (43.84 + 1) \times \tan 37.2 = 68.1$$

and $N_c = (N_q - 1) \times \cot\varphi = (43.84 - 1) \times cot37.2 = 42.84 \times 1.31 = 56.4$

Similarly, $\varphi_{ps} = 40.5^0$ for medium dense sand (Chapter 3, Table 3.1)

After Lade and Lee (1976)

$$\varphi_{ps} = 1.5\varphi_{tr} - 17 \quad (\varphi_{tr} > 34^0)$$

$$\therefore \quad \varphi_{tr} = \frac{(\varphi_{ps}+17)}{1.5} = \frac{(40.5+17)}{1.5} = 38.3^0$$

$$\therefore \quad \varphi_{tr} = 38.3^0$$

$$\therefore N_q = e^{\pi tan38.3}(\frac{1+sin38.3}{1-sin38.3}) = e^{2.48} \times 4.26 = 50.87$$

$$\therefore N_\gamma = 2 \times (50.87 + 1) \times \tan 38.3 = 82.0$$

& $N_c = (N_q - 1) \times \cot\varphi = (50.87 - 1) \times cot38.3 = 49.87 \times 1.266 = 63.15$

and $\varphi_{ps} = 41.5^0$ for very dense sand (Chapter 3, Table 3.1)

After Lade and Lee (1976)

$$\varphi_{ps} = 1.5\varphi_{tr} - 17 \quad (\varphi_{tr} > 34^0)$$

$$\therefore \quad \varphi_{tr} = \frac{(\varphi_{ps}+17)}{1.5} = \frac{(41.5+17)}{1.5} = 39^0$$

$$\therefore \quad \varphi_{tr} = 39^0$$

$$\therefore N_q = e^{\pi tan39}(\frac{1+sin39}{1-sin39}) = e^{2.54} \times 4.395 = 55.73$$

$$\therefore N_\gamma = 2 \times (55.73 + 1) \times \tan 39 = 91.88 \approx 92.0$$

& $N_c = (N_q - 1) \times \cot\varphi = (55.73 - 1) \times cot39 = 49.87 \times 1.266 = 67.6$

***Case1*: For loose dense dry sand**

c = 0

γ_q = 16.23 kN/m^3

h_q = depth of geocell = 0.115 [depth of geocell = height of geocell + depth of geocell layer from bottom of footing = 0.1+0.015 = 0.115 m]

q = surcharge load = $\gamma_q h_q$ = 16.23 × 0.115 = 1.866 kN/m^2

B = width of applied pressure (footing) = 0.15 m

γ = unit weight of soil in failure zone = 15.79 kN/m^3

$N_c = 56.4, N_q = 43.84, N_\gamma = 68.1$

$s_c = s_q$ = shape factors $= [1 + 0.2\left(\frac{B}{L}\right)]$ = 1.2 (IS 6403 1981)

s_γ = shape factor = 0.8 (IS 6403 1981)

τ = shear strength between geocell wall and soil = σ_n tanδ

σ_n= average horizontal force within the geocell ≈ P K_a

P = 58 kPa, δ = 38.0^0

$K_a = \frac{1-sin\delta}{1+sin\delta} = \frac{0.384}{1.615} = 0.238$

$\therefore \sigma_n$ = 58 × 0.238 = 13.8 kPa

$\therefore q_R = 2 \times 13.8 + 0 \times 56.54 \times 1.2 + 1.866 \times 43.84 \times 1.2 + 0.5 \times 15.79 \times 0.15 \times 68.1 \times 0.8$

$\therefore q_R = 27.6 + 98.2 + 64.5$ = 190.3 kPa

***Case2*: For Medium dense dry sand**

c = 0

γ_q = 16.23 kN/m^3

h_q = depth of geocell = 0.115 [depth of geocell = height of geocell + depth of geocell layer from bottom of footing = 0.1+0.015 = 0.115 m]

q = surcharge load = $\gamma_q h_q$ = 16.23 × 0.115 = 1.866 kN/m^2

B = width of applied pressure (footing) = 0.15 m

γ = unit weight of soil in failure zone = 16.23 kN/m^3

$N_c = 63.15, N_q = 50.87, N_\gamma = 82.0$

$s_c = s_q$ = shape factors $= [1 + 0.2\left(\frac{B}{L}\right)]$ = 1.2 (IS 6403 1981)

s_γ = shape factor = 0.8 (IS 6403 1981)

τ = shear strength between geocell wall and soil = σ_n tanδ

σ_n= average horizontal force within the geocell ≈ P K_a

P = 91 kPa, δ = 38.8^0

$K_a = \frac{1-sin\delta}{1+sin\delta} = \frac{0.373}{1.626} = 0.229$

$\therefore \sigma_n$ = 91 × 0.229 = 20.8 kPa

$\therefore q_R = 2 \times 20.8 + 0 \times 63.2 \times 1.2 + 1.866 \times 50.87 \times 1.2 + 0.5 \times 16.23 \times 0.15 \times 82 \times 0.8$

$\therefore q_R = 41.6 + 113.9 + 79.85$ = 235.3 kPa

***Case3*: For Very dense dry sand**

c = 0

γ_q = 16.23 kN/m^3

h_q = depth of geocell = 0.115 [depth of geocell = height of geocell + depth of geocell layer from bottom of footing = 0.1+0.015 = 0.115 m]

q = surcharge load = $\gamma_q h_q$ = 16.23 × 0.115 = 1.866 kN/m^2

B = width of applied pressure (footing) = 0.15 m

γ = unit weight of soil in failure zone = 16.7 kN/m^3

$N_c = 67.6, N_q = 55.7, N_\gamma = 92$

$s_c = s_q$ = shape factors $= [1 + 0.2\left(\frac{B}{L}\right)]$ = 1.2 (IS 6403 1981)

s_γ = shape factor = 0.8 (IS 6403 1981)

τ = shear strength between geocell wall and soil = σ_n tanδ

σ_n= average horizontal force within the geocell ≈ P K$_a$

P = 28.3 kPa, δ = 41.4^0

K$_a$ = $\frac{1-sin\delta}{1+sin\delta} = \frac{0.338}{1.66} = 0.20$

$\therefore \sigma_n$ = 128.3 × 0.20 = 26.1 kPa

$\therefore q_R = 2 \times 26.1 + 0 \times 67.6 \times 1.2 + 1.866 \times 55.7 \times 1.2 + 0.5 \times 16.7 \times 0.15 \times 92 \times 0.8$

$\therefore q_R = 52.2 + 124.7 + 92.18$ = 269.1 kPa

Part-2

The ultimate bearing capacity (q_R) of geocell-reinforced soil using Neto et al., 2013

$$q_R = p_u + 4\frac{h}{d} + K_0 pe\ tan\delta + (1-e)p$$

where, p_u = ultimate bearing capacity of unreinforced sand

p = load at the top of geocell mattress

γ_q = unit weight of soil within the geocell

h = height of geocell

d = pocket size of geocell

K_0 = coefficient of lateral earth pressure at rest = $1 - sin\delta$

δ = angle of shearing resistance between infill soil and geocell wall

$e = \frac{BL}{(B+2d)(L+2d)}$

B = width of footing

L = length of footing

Since h = depth of geocell = 0.1m; d = pocket size of geocell = 0.075m

$B \times L$ = 0.15 × 0.15 = 0.0225 sqm.

***Case1*: For loose dense dry sand**

$p_u = 58$ kPa, δ = 38.0 & $p = 202$ kPa

$K_0 =$ 1- sin38.0 = 0.384

$tan38$ = 0.781

$e = \frac{0.0225}{0.6}$ = 0.0375

$\therefore q_R = 58 + 4 \times 1.33 \times 0.384 \times 202 \times 0.0375 \times 0.781 + (1 - 0.0375) \times 202$

$\therefore q_R = 58 + 12.1 + 194.4$ = 264.5 kPa

***Case2*: For Medium dense dry sand**

$p_u = 91$ kPa, δ = 38.8 & $p = 214$ kPa

$K_0 =$ 1- sin38.8 = 0.373

$tan38.8$ = 0.80

$e = \frac{0.0225}{0.6}$ = 0.0375

$\therefore q_R = 91 + 4 \times 1.33 \times 0.373 \times 214 \times 0.0375 \times 0.8 + (1 - 0.0375) \times 214$

$\therefore q_R = 91 + 12.7 + 206$ = 309.7 kPa

***Case3*: For Very dense dry sand**

$p_u = 128.3$ kPa, δ = 41.4 & $p = 239$ kPa

$K_0 =$ 1- sin41.4 = 0.338

$tan41.4$ = 0.88

$e = \frac{0.0225}{0.6}$ = 0.0375

$\therefore q_R = 128.3 + 4 \times 1.33 \times 0.338 \times 239 \times 0.0375 \times 0.88 + (1 - 0.0375) \times 239$

$\therefore q_R = 128.3 + 14.2 + 230$ = 372.5 kPa

LIST OF PUBLICATIONS

Considerable part of the work is published in international peer-reviewed journals and conference (national and international) proceedings. Remaining part will be submitted for possible publication in journals. Publications on the part of this work are listed as follows:

Journals:

1. Doley, C., Das, U.K. and Shukla, S.K (2022). Development of a multiple regression equation for prediction of bearing capacity of geocell-reinforced sand beds based on experimental study, *Arabian Journal of Geosciences*, 15 (16) https://doi.org/10.1007/s12517-022-10652-y
2. Doley, C., Das, U.K. and Shukla, S.K (2022). Load-settlement behaviour of geotextile-based geocell reinforced sand bed. *Geotechnical Engineering journal of SEAGS & AGSSEA*, Vol. 53 No. 1 March 2022 ISSN 0046-5828.
3. Doley, C., Das, U.K. and Shukla, S.K (2021). Response of square footing on geocell-reinforced sand bed under static and repeated loads. *International Journal of Geosynthetics and Ground Engineering* 7, 90 https://doi.org/10.1007/s40891-021-00336-0

Book chapters:

1. Doley, C., Das, U. Kr., Shukla, S.Kr. (2019). Effect of cell height and infill density on the performance of geocell-reinforced beds of Brahmaputra river sand. *Sustainable Civil Engineering Practices*, Select Proceedings of ICSCEP 2019 (Kanwar, V.S., Shukla, S.K. (eds.)) pp. 173-183.

Papers in conferences proceedings:

1. Doley, C., Das, U. Kr. (2018). Effect of geocell geometry on the performance of model square footing resting on reinforced sand bed under static loading. *National Conference on Advances in Civil and Infrastructure Engineering-2018 (ACIE18), February 16-17 2018.*