Geocell Reinforced Soil/Subgrade: Comparative Study of Bearing Capacity Evaluation Methods

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Abstract

At present, rapid urbanization results in enormous infrastructure growth, which led engineers to face construction challenges over soft soil or weak subgrade. Many soil stabilization approaches have been established as a viable way to overcome this hindrance. Among all the ground improvement techniques, geocell, being a three-dimensional form of geosynthetics, is often used to enhance the bearing capacity of soft soils. This paper discusses analytical methods developed by researchers Presto (2008) [1], Koerner (2012) [2], Avesani Neto et al. (2013) [3], and Sitharam and Hedge (2013) [4] to evaluate the bearing capacity of soil reinforced with geocell. The paper also compares the results of these methods with those of laboratory experiments conducted by Dash et al. (2003b) [5] and Emersleben and Meyer (2008) [6].

Researcher Dash et al. used cohesive soil in foundation, while Emersleben and Meyer used c-ϕ soil in foundation. The comparisons show that researchers Koerner and Presto underestimate the bearing capacity when compared with experimental results of both Dash et al. and Emersleben and Meyer. Whereas authors Avesani Neto et al. and Sitharam and Hegde offer the best fit with experimental results of Dash et al. But, with Emersleben and Meyer's experimental results, Avesani Neto et al. gives the overestimated results, while Sitharam and Hegde partially agree for lower geocell aspect ratios beyond settlement equal to 35% of footing diameter.

Keywords: Soft soil, Weak subgrade, Bearing capacity, Geocell reinforced soil/subgrade, Geocell aspect ratios

1. Geocell Reinforced Soil

Worldwide rapid urbanization leads to excessive demand for good quality land for the construction of civil engineering structures. As suitable land available for construction is limited, geotechnical engineers and designers are forced to design and construct the structures over available unsuitable land or soft soil. Since soft soil has a limited load-bearing capacity, soft soil stabilization has been prioritized in order for the structure to withstand the load without failing. Several ground improvement techniques have been evolved in the recent past, such as soil removal and replacement, preloading with sand and vertical drain, dynamic compaction, stone columns, geosynthetics, etc. Among these, geosynthetics have arisen as an exciting engineering material in many applications- transportation, geotechnical, environmental, coastal, mining, and hydraulics due to their ease of construction, cost-benefit, sustainability, and efficacy (Koerner 2012) [2]. Geosynthetics provide the proper solution to design and construction problems despite climatic, geographical, or technological differences [7]. The US Army Corps of Engineers developed Geocell, three-dimensional nature of geosynthetics, for military applications in the early 1970s [8]. Due to its 3D confinement system, Geocell is used in geotechnical engineering applications like foundation, pavement and embankment, slope stabilization, retaining wall, etc.

To demonstrate the efficacy of geocell in soft soil, numerous laboratory experiments were conducted. The load-deformation action of geoweb-reinforced (ultrasonically welded nonperforated plastic strips), geocell-reinforced (made of geogrid strips), and unreinforced gravel bases were contrasted by Bathurst and Jarrett [9]. By performing plate load studies, authors Mhaiskar and Mandal [10] investigated the efficacy of geocells over the soft saturated marine clay subgrade, taking into account geocell geometry and relative density of backfilled sand. The effect of geocell geometry with and without the planar geogrid reinforcement at the base of the geocell sheet, changing the size and shape of footing, variations in infill materials, different patterns to create geocell (diamond and chevron), and subgrade stiffness, among other parameters, were studied in small-scale laboratory model tests by researcher Dash. [11–15]

Zhou and Wen [16] used a static plate load test to compare the bearing capacity enhancement of geocell, and geogrid reinforced sand cushions versus unreinforced sand cushions. Madhavi Latha et al. [17] demonstrated the benefits of geocell reinforced earthen embankments built over weak foundation soil using geocell made of geogrid of varying tensile through lab-scale model tests strength. Pokharel et al. [18] carried out static as well as cyclic laboratory plate load tests. The introduction of geocell reinforcement enhanced the bearing capacity of the soil in both of these studies. Tafreshi and Dawson used lab-scale model experiments on strip footings resting on geocell and planar reinforced sand beds, accounting for variables including the depth of geocell layer underneath the footing bases, reinforcing thickness, and the amount of geotextile planar layers. According to the findings of laboratory experiments, the geocell reinforced base system outperforms the equivalent planar reinforced base system (geotextiles) in terms of load-carrying capacities.

Field output of geocell reinforced embankments and geocell reinforced road sections has also been documented by some researchers, demonstrating the beneficial potential of geocell. [4], [20]–[25]. Triaxial compression tests of soil encased with geocell were conducted by some researchers [26]–[28], and it was discovered that geocell containment increased the apparent cohesive strength in soil. Aside from numerous experimental tests, there are only a few analytical methods for calculating the bearing potential of a subgrade reinforced with geocell. The intend of this paper is to study and compare these approaches to experimental studies that have been published in the literature.

1. REINFORCEMENT MECHANISM OF GEOCELL

Soil behaves good in compression but weak in tension; vice versa, geocells are good in tension but weak in compression. Thus, a combination of soil and geocells forms a good stability composite structure. The geocell-reinforced base can offer lateral and vertical confinement, a tensioned membrane effect, and a larger stress distribution as compared to the unreinforced base. Bending resistance, tensile strength, and shear strength are all demonstrated by geocell-reinforced bases, which frequently meet the failure planes from the subgrade.

1.1 Lateral retrain or confinement effect:

Whenever foundation bases are subjected to vertical loading, the material within the foundation bases tends to move outward. Thus, the magnitude of loading can be concentrated over the soft subgrade soil, resulting in shear failure of the underlying soft subgrade soil, which eventually causes bearing capacity failure. When a geocell is mounted, interlayer contact between the geocell wall and the filler material prevents the infill material from spreading laterally, causing shear stresses to be mobilized inside the foundation bases. The shear stress that has been mobilized will act upward and resist vertical loading to a certain degree, as shown in figure 1.

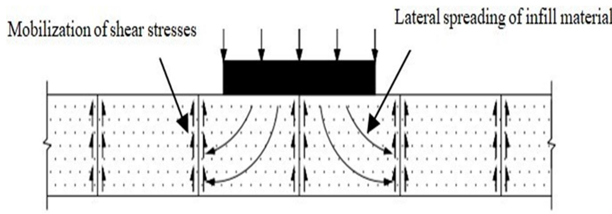

Fig. 1. Reinforcement mechanism of geocell: Confinement effect

1.2 Wider stress dispersion area:

3-dimensional geocell mattress forms the flexible raft foundation upon spreading. This flexible raft distributes the stresses over the wider area, as shown in figure 2. The failure mode is not circular arc. Possibly plastic failure occurs. Geocell reinforcement contributes to the wider stress distribution, reducing tension at the junction of the base and the subgrade, and increasing the subgrade's bearing potential.

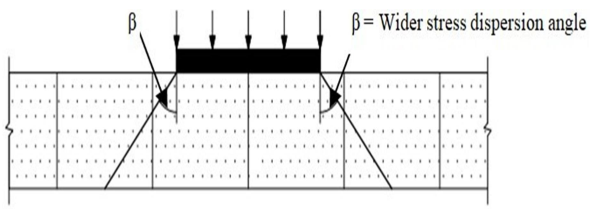

Fig. 2. Reinforcement mechanism of geocell: Wider stress dispersion area

1.3 Tension membrane effect:

The vertical load is resisted by the stress caused in the curved geocell-reinforced cushion is referred to as the tensioned membrane or beam effect [12], [16], [28]. The structure should bend sufficiently [29], [30] to mobilize the tensioned membrane effect, as shown in figure 3a. The bent portion of the geocell-reinforced layer applies forces upward and lower down forces acting over the subgrade. Separation is achieved by placing basal reinforcement (geogrid/geotextile) underneath the geocell. As shown in figure 3b, this basal reinforcement often has a tension membrane effect when a significant settlement occurs.

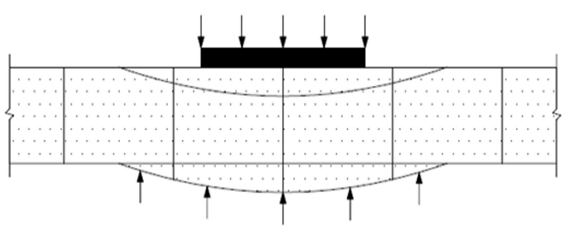

Fig. 3. a) Reinforcement mechanism of geocell: Tension membrane effect

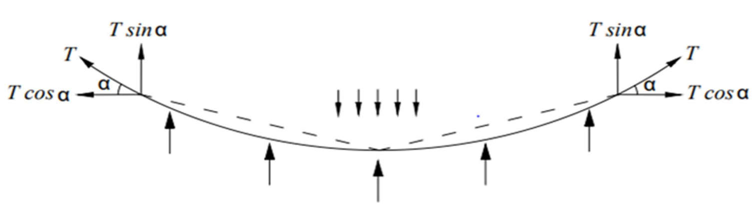

Fig 3. b) Reinforcement mechanism of basal reinforcement (geogrid/geotextile): Tension membrane effect

2. Methods to evaluate the bearing capacity of geocell-reinforced soil/subgrade

2.1 Presto (2008)

Based on experimentally derived design approaches for unpaved roads over weak soils, (Presto 2008) established a theoretical bearing capacity approach for geocell-reinforced soil [1]. This method only considers the confinement effect generated due to geocell reinforcement. The decrease in stresses at the foot of the reinforcement layer is calculated based on the Boussinesq equation. The proposed equation is

$$Q_r = Q_u + I \quad (1)$$

$$Q_r = s.N_c + 2.(h/d).k_a.\sigma_{avg}.tan(\delta) \quad (2)$$

$$Q_u = s.N_c \quad (3)$$

$$I = 2.(h/d).k_a.\sigma_{avg}.tan(\delta) \quad (4)$$

Where Q_r = Geocell improved soil bearing capacity,
Q_u = Bearing capacity of the soil (unreinforced),
Q = Vertically applied load,
I = Improvement in bearing capacity of soil due to geocell reinforcement,
s = Cohesion of soil,
h = Height of geocell,
d = Diameter of geocell,
k_a = Active earth pressure coefficient,
N_c = Bearing capacity factor
σ_{avg} = Vertical stresses averaged throughout the geocell's top and bottom.
Presto recommended values of δ/ϕ *as* 0.71, 0.88, and 0.9 for smooth wall, textured wall, and textured-perforated wall, respectively.
Based on U.S. Forest Service guidelines, Presto suggested the value of N_c = 2.8 for high traffic-low rutting and 3.3 for low traffic-high rutting.

2.2 Koerner (2012)

Based on Terzaghi's bearing capacity principle, (Koerner 2012) came up with an equation to measure the bearing capacity of soil reinforced with geocell [2]. In this equation, Koerner does not consider the geometry of geocell. Terzaghi's bearing capacity equation is enhanced by adding the confinement effect of geocell reinforcement, as shown below

$$Q_r = Q_u + I \quad (5)$$

$$Q_r = s.\ N_c.\ S_c + q.\ N_q.\ S_q + ½.\ \gamma.\ B.\ N_\gamma.S_\gamma + 2.\ \tau \quad (6)$$

$$Q_u = s.\ N_c.\ S_c + q.\ N_q.\ S_q + ½.\ \gamma.\ B.\ N_\gamma.\ S_\gamma \quad (7)$$

$$I = 2.\ \tau = 2.\ k_a.\ Q.\ tan(\delta) \quad (8)$$

Where τ = Shear strength between geocell wall and soil,
s = Cohesion of soil,
γ = Unit weight of soil,
B = Width or diameter of footing plate,
k_a = Active earth pressure coefficient,
δ = Interface shear angle between the cell wall and the filling soil, (Koerner recommended this value between 15^0 to 20^0 for sand and HDPE)
N_c, N_q, N_γ = Terzaghi's bearing capacity factors,
S_c, S_q, S_γ = Shape factors (square/ rectangular/ circular).

2.3 Avesani Neto et al. (2013)

The bearing capacity of geocell reinforced soil is determined using this approach by adding the bearing capacity of unreinforced soil to the increased bearing capacity of soil due to the geocell-reinforcement mechanism (confinement effect and stress dispersion effect) [3]. The equation proposed by the (Avesani Neto et al. 2013) is

$$Q_r = Q_u + I \tag{9}$$

$$Q_r = s.\ N_c.\ S_c + ½.\ γ.\ B.\ N_γ.\ S_γ + 4.\ h/d.\ k_o.\ Q.\ e.\ tan(δ) + (1- e).\ Q \tag{10}$$

$$Q_u = s.\ N_c.\ S_c + ½.\ γ.\ B.\ Nγ.\ Sγ \tag{11}$$

$$I = 4.\ h/d.\ k_o.\ Q.\ e.tan(δ) + (1- e).Q \tag{12}$$

Where h/d = Aspect ratio of geocell
k_o = At rest earth pressure coefficient,
e = Stress redistribution effect = $\frac{BL}{(B+2d)(L+2d)}$
B = Width of footing plate,
L = Length of footing plate,
δ = Interface shear angle between the cell wall and the filling soil (2/3rd of the filling material friction angle),
s = Subgrade soil cohesion,
N_c, N_γ = Terzaghi's bearing capacity factors,
S_c, S_γ = Shape factors (square/ rectangular/ circular).

2.4 Sitharam and Hegde (2013)

The method of (Sitharam and Hegde 2013) is founded on the assumption that geocell is responsible for the lateral resistance and vertical stress distribution processes, whereas basal reinforcement is responsible for the membrane effect (geotextile or geogrid) [4]. The proposed equation is

$$Q_r = Q_u + I \tag{13}$$

$$Q_u = s.\ N_c.\ S_c + ½.\ γ.\ B.\ Nγ.\ Sγ \tag{14}$$

$$I = Q_i + Q_{ii} + Q_{iii} \tag{15}$$

Q_i is an improvement in soil's bearing capacity due to the confinement effect and is calculated using the Koerner (2012) method.

$$Q_i = 2.\ τ \tag{16}$$

$$τ = 2.\ k_a.\ Q.\ tan(δ), \tag{17}$$

Q_{ii} is an improvement due to the stress spreading effect of geocell and is calculated as

$$Q_{ii} = Q\ (1- \frac{B}{B+2.h.tan(\beta)}) \tag{18}$$

Q_{iii} is an improvement owing to the tension membrane effect contributed by basal geogrid. The vertical portion of the mobilized tensile strength of the planar reinforcement, if given, contributes to the tension membrane effect. The rise in the load-carrying capacity due to the tension membrane effect (Q_{iii}) is given by

$$Q_{iii} = \frac{2.T\sin(\alpha)}{B} \tag{19}$$

$$\sin(\alpha) = (\frac{2.S_f}{B_g}) \tag{20}$$

Where k_a = Active earth pressure coefficient,
δ = Interface shear angle between the cell wall and the infill soil, (Koerner recommended this value between15^o to 20^o for sand and HDPE),

B = Width or diameter of footing plate,
B_g = Width of basal reinforcement,
h = Height of geocell,
β = Stress dispersion angle (30° to 45°),
T = Tensile strength of basal reinforcement material,
α = Horizontal angle of tension force T,
S_f = Footing settlement measures at the top surface.

3. Comparative study

The methods are compared through the laboratory bearing capacity experiments on geocell reinforced soil/subgrade performed by Dash et al. (2003b) and Emersleben and Meyer (2008). The variables associated with the laboratory experimental work are tabulated in Table 1,

Table 1. Summary of laboratory experiment work.

Variables	**Researchers**	
	(Dash et al. 2003b)	**(Emersleben and Meyer 2008)**
Subgrade Soil	Cohesive soil Cohesion = 3 kPa Friction angle = 0°	c- ϕ soil Cohesion = 15 kPa Friction angle = 8°
Infill material (sand)	Friction angle = 41°	Friction angle = 38.9°
Geocell Material	High-Density Polyethylene (HDPE)	High-Density Polyethylene (HDPE)
Geocell aspect ratios	0.53, 1.05, 1.58	0.43, 0.65, 0.87
Geocell Pocket Diameter	120 mm	230 mm
Basal reinforcement of Geogrid	Tensile Strength = 20.5 kN/m	Tensile Strength = 20.7 kN/m
Diameter of the Loading plate	150 mm	300 mm
Ratio of geocell diameter to Loading plate diameter (*d/B*)	0.8	0.7

Figures 4-6 show the comparison of the experimental results of researcher Dash et al. with the analytical methods discussed in the above section. As Koerner only considers the confinement effect mechanism of geocell, it shows the same underestimation with the experimental results for all three aspect ratios. Presto considers the geocell geometry and calculates the stress reduction directly underneath the loaded area's center due to stress transfer to the geoweb cell walls, and observes the increasing stress distribution for high aspect ratio values. However, Presto's approach, which relies solely on the confinement effect, underestimates the bearing potential of geocell reinforced soil and offers an unstable approximation to experimental test results. The approaches of Avesani Neto et al. and Sitharam and Hegde best fit the experimental results for all three aspect ratios. This may be due to, Sitharam and Hegde consider the confinement effect and stress spreading effect mechanism of geocell reinforcement and the mobilized tension membrane effect of basal geogrid in their bearing capacity evaluation method. Whereas Avesani Neto et al. do not consider the tension membrane mechanism mobilized due to basal geogrid but still matching well with experimental results. This may be because Avesani Neto et al. use stress spreading on both sides of the load at a distance equal to the diameter of one pocket (d). According to conventional soil mechanics and foundation conceptions, this stress spreading overcomes a comparatively wider angle.

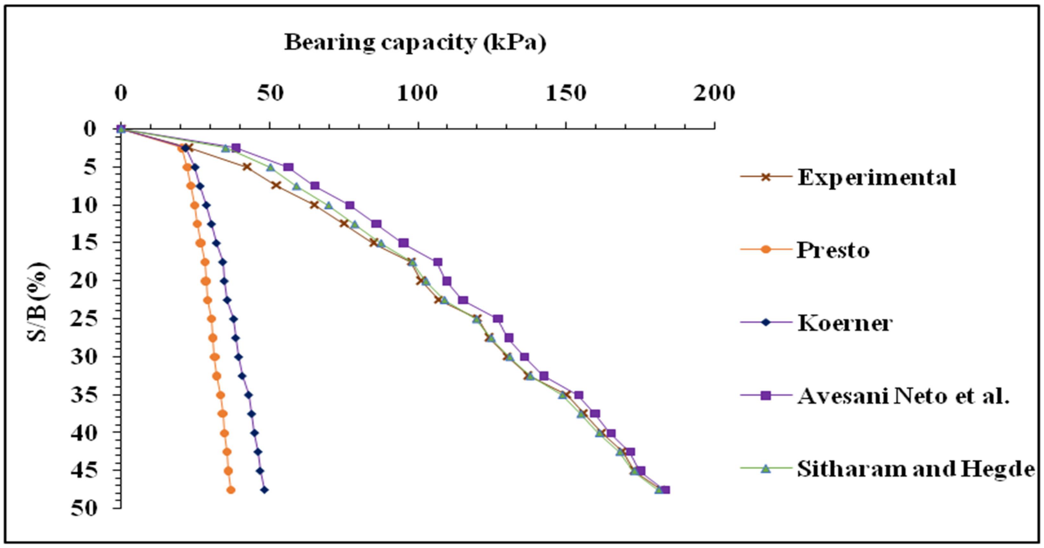

Fig. 4. Comparison between experimental (Dash et al. 2003b) and analytical bearing capacities for *h/d*=0.53

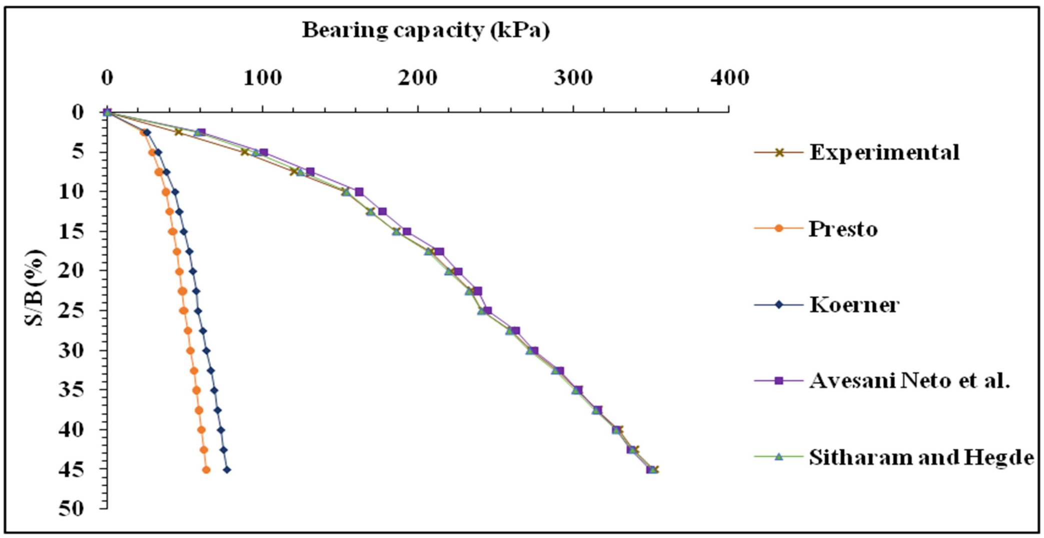

Fig. 5. Comparison between experimental (Dash et al. 2003b) and analytical bearing capacities for *h/d*=1.05

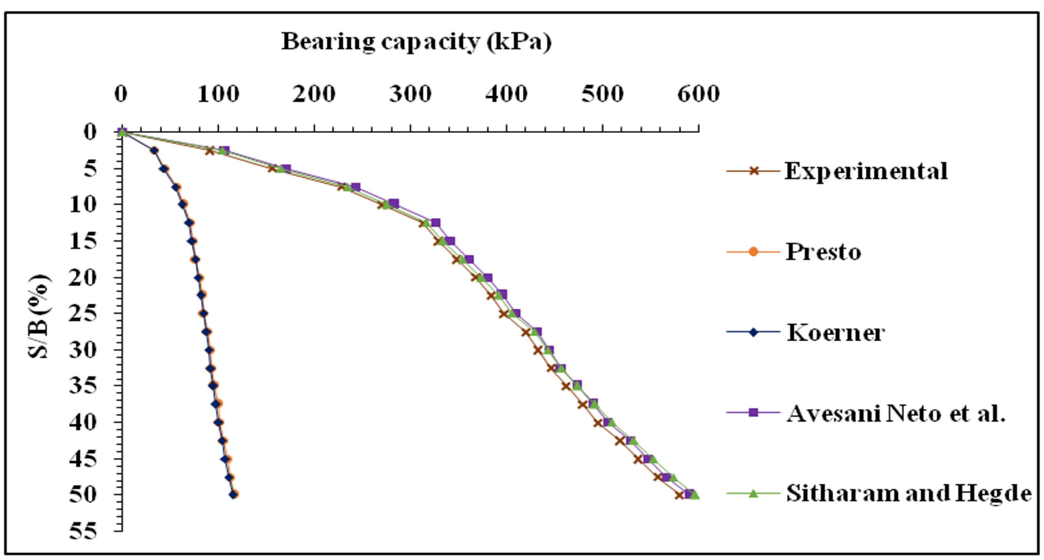

Fig. 6. Comparison between experimental (Dash et al. 2003b) and analytical bearing capacities for *h/d*=1.58

Figures 7-9 demonstrate the comparison of experimental results of researchers Emersleben and Meyer with the analytical methods discussed in the above section. Here, it is observed that the experimental result shows inconsistent behavior with all analytical methods among three different aspect ratios. As compared to experimental findings, Koerner's approach ignores both the stress distribution effect and the geocell geometry, resulting in significantly underestimated results. Presto's system, though taking into account the aspect ratio, does not account for other factors, resulting in underestimation. For the aspect ratio of geocell (0.0.43 and 0.0.65), the method proposed by Sitharam and Hegde shows partial approximation with experimental results after significant settlement. But for a higher geocell aspect ratio of 0.87, this method overestimates the experimental results. Simultaneously, Avesani Neto's method overestimates the experimental results for all three aspect ratios. This may be due to the available stiff subgrade below the geocell reinforced bases. The stable subgrade may restrict the optimum mobilization of the reinforcement mechanism of geocell, which leads to the sparse approximation between this analytical method and the experimental results.

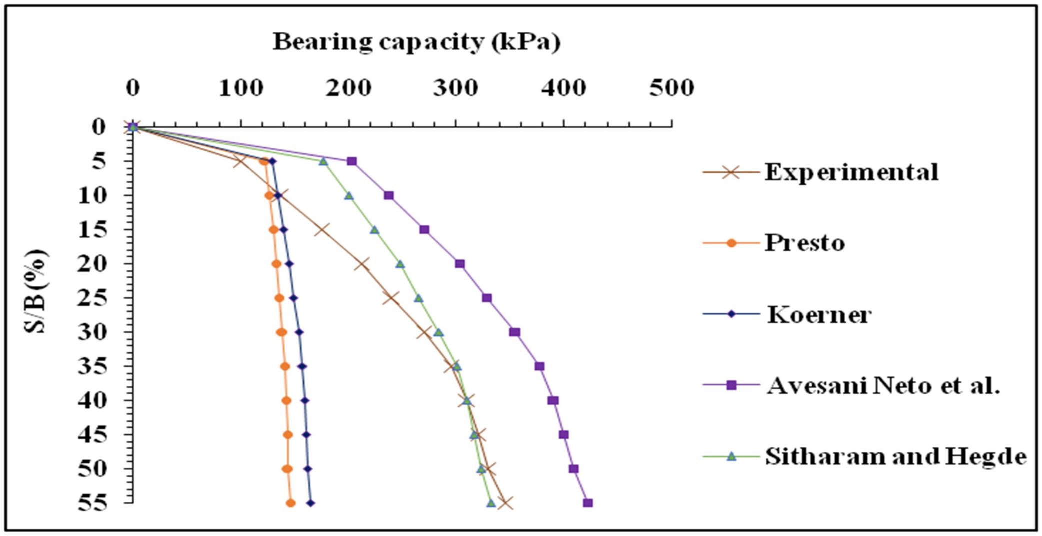

Fig. 7. Comparison between experimental (Emersleben and Meyer 2008) and analytical bearing capacities for *h/d*=0.43

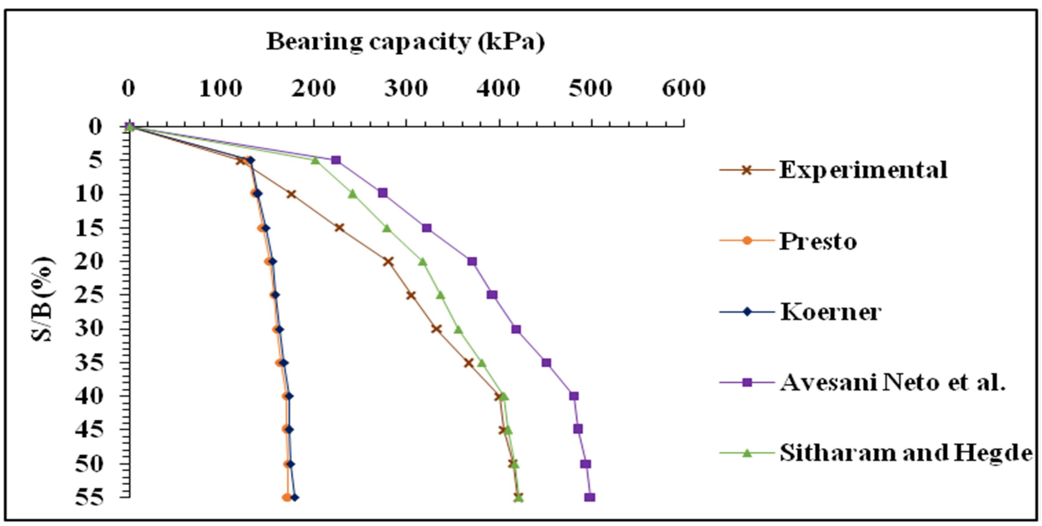

Fig. 8. Comparison between experimental (Emersleben and Meyer 2008) and analytical bearing capacities for *h/d*=0.65

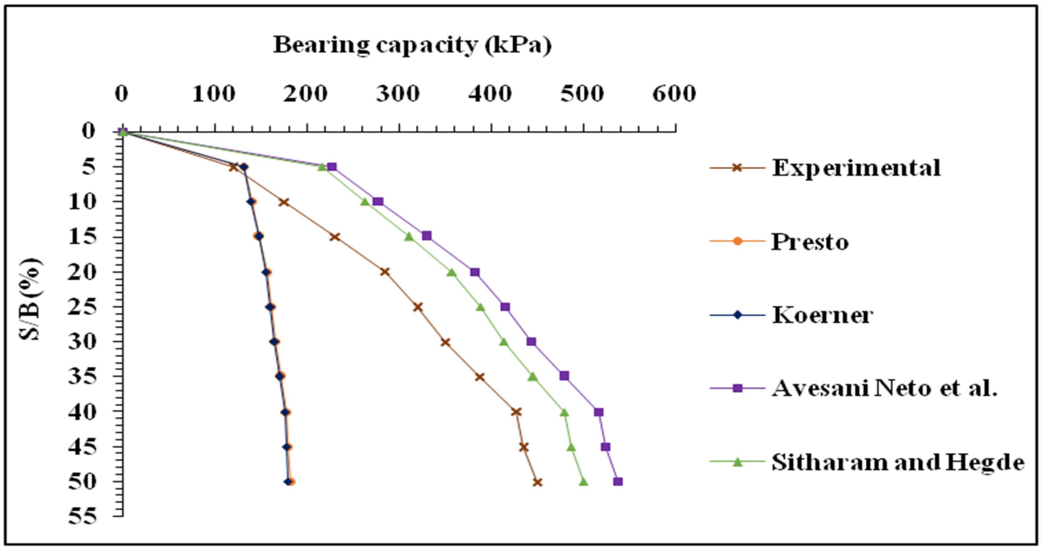

Fig. 9. Comparison between experimental (Emersleben and Meyer 2008) and analytical bearing capacities for *h/d*=0.87

4. Conclusions

This paper compared the experimental data of researchers (Dash et al. 2003b) and (Emersleben and Meyer 2008) with the four analytical methods predicting the bearing capacity of geocell reinforced foundation bases. Based on the observation following conclusions can be drawn.

1. Bearing capacity evaluation methods proposed by researchers Avesani Neto et al. (2013) and Sitharam and Hegde (2013) show good harmonizing results for cohesive subgrade.

2. In case of subgrade of c-ϕ soil, Koerner and Presto significantly underestimate, while Avesani Neto et al. overestimates the bearing capacity.

3. For c-ϕ soil, the method proposed by authors Sitharam and Hegde partially agrees with experimental results for lower aspect ratios beyond the settlement of 35% of the footing diameter. For settlement less than 35 % of the footing diameter, this method overestimates the bearing capacity.

4. As Avesani Neto et al.'s method considers a large stress dispersion area compared to Sitharam and Hegde's method, showing increase in the bearing capacity prediction for c-ϕ soil subgrade than that of Sitharam and Hegde's method.

5. Koerner's and presto's methods very much underestimate the bearing capacity prediction for both cohesive and c-ϕ soil as these methods do not incorporate total reinforcement mechanisms of geocell and basal reinforcement (geogrid/geotextile).

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List of Symbols

s	Cohesion of soil
Q_r	Geocell improved soil bearing capacity
Q_u	Bearing capacity of unreinforced soil
Q	Vertically applied load
I	Improvement in bearing capacity of soil due to geocell reinforcement
τ	Shear strength between geocell wall and soil
γ	Unit weight of soil
B	Width or diameter of footing plate
L	Length of footing plate
B_g	Width of basal reinforcement
k_a	Active earth pressure coefficient
k_o	At rest earth pressure coefficient
δ	Interface shear angle
N_c, N_q, N_γ	Terzaghi's Bearing capacity factors
S_c, S_q, S_γ	Shape factors
h	Height of geocell
d	Diameter of geocell
σ_{avg}	Average of vertical stresses calculated at the top and bottom of geocell.
e	Stress redistribution effect
β	Stress dispersion angle (30^o to 45^o),
T	Tensile strength of basal reinforcement material,
S_f	Footing settlement measures at the top surface,
α	Horizontal angle of tension force T,
S/B	Settlement to footing width or diameter ratio.