



Influence of Aspect Ratio on the Performance of Geocell-Reinforced Footings in Sandy Soils

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Highlights

- 3D-FE analyses were used to evaluate the effect of L/B on geocell-reinforced footing in sandy soils.
- Improvement factors ranged from 1.12 to 2.56, with maximum values observed for square footings.
- Shape factor values were strongly governed by footing aspect ratio and soil relative density.
- Geocell reinforcement shifted the maximum shape factor from L/B=2 to L/B=1.

Article Info

Received: 16 Dec 2025

Accepted: 26 Mar 2026

Keywords

Geocell
Geosynthetic
Aspect ratio
Shape factor
Finite element analysis

Abstract

The aspect ratio of the shallow footing is a key parameter affecting the bearing capacity performances. However, the recommendations of previous studies exhibit notable inconsistencies among themselves for the unreinforced condition, and no numerical study in the literature has investigated the effect of aspect ratio under geocell-reinforced condition. This pioneer study investigates the influence of footing aspect ratio and soil relative density on the ultimate bearing capacity, shape factor, improvement factor, and failure mechanism of unreinforced and geocell-reinforced footings resting on sandy soils. A total of 36 rigorous three-dimensional finite element analyses were performed and validated against physical model tests. The analyses considered footings with aspect ratios ranging from 1 to 10 placed on loose and dense sands. The results showed that geocell reinforcement substantially improves footing performance by increasing bearing pressures, ultimate bearing capacities, stiffness of the footing pressure versus footing settlement ratio curves and shape factor values. Improvement factors were observed to lie between 1.12 and 2.56, with square footings showing the maximum improvement, and the magnitude of improvement increasing as the relative density increased. Furthermore, for unreinforced footings, the maximum shape factor occurred at aspect ratio of 2, whereas in geocell-reinforced conditions, the peak shifted to aspect ratio of 1. The shape factor values also increased with increasing relative density. Moreover, it was observed that the aspect ratio influences both the failure surface geometry and reinforcement mechanism of geocell.

1. INTRODUCTION

The footing system serves as the primary element through which superstructure loads are transmitted to the supporting soil. Therefore, accurately determining the ultimate bearing capacity (q_{ult}), defined as the highest footing pressure the soil can sustain without undergoing shear failure or collapse, is vital for ensuring the safety and economic efficiency of shallow footing designs. Prandtl [1] studied the plastic deformation of materials under compression, laying the analytical foundation for ultimate bearing capacity and soil failure mechanisms, despite not being developed specifically for soils. Reissner [2] and Fellenius [3] extended Prandtl's work, and their contributions directly influenced subsequent formulations of the q_{ult} equation. The earliest formulation of the q_{ult} was presented by Terzaghi [4] for strip footing or embankment under plane strain condition. This formulation incorporates the bearing capacity factors (N_c , N_q , N_γ)—representing cohesion, surcharge and, effective unit weight components—which are functions of the internal friction angle (ϕ) of the soil below the shallow footing. In the following years, Terzaghi's equation was further refined by introducing correction factors to address the geometric shape of the footing (S_c , S_q , S_γ), inclination of load (i_c , i_q , i_γ), depth of embedment (d_c , d_q , d_γ), slope inclination (g_c , g_q , g_γ) and base inclination (b_c , b_q ,

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b_f), resulting in a more general and widely applicable. This paper focuses on the influence of the footing aspect ratio—expressed as the length-to-width ratio (L/B)—on the behavior of unreinforced and geocell-reinforced surface shallow footings on cohesionless soil under central loading. Under the assumed conditions, N_c and N_q are taken as zero and factors for load inclination, depth, slope inclination and base inclination are set to 1; the q_{ult} is calculated using Equation (1). The S_γ values are then obtained by normalizing the q_{ult} of a given footing with respect to that of a strip footing, as described in Equation (2), wherein the S_γ value for the strip footing is taken as 1

$$q_{ult} = 0.5B\gamma N_\gamma S_\gamma \quad (1)$$

$$S_\gamma = \frac{q_{ult(r)}}{q_{ult(s)}} \quad (2)$$

where B denotes width of the shallow footing, γ is effective unit weight of the soil beneath the shallow footing, $q_{ult(r)}$ represents the ultimate bearing capacity of the rectangular shallow footing, $q_{ult(s)}$ corresponds to the ultimate bearing capacity of the strip shallow footing.

The earliest S_γ value was proposed by Terzaghi [4] as a constant of 0.8 for footings with an L/B ratio of 1, based on tests for unreinforced footings. In the subsequent years, several researchers [5-8] empirically suggested S_γ values for different L/B ratios, but these recommendations exhibit notable inconsistencies with each other. Some studies indicated that the S_γ value is independent of the soil's internal friction [7, 8], whereas Hansen [5] reported a decrease in the S_γ with increasing internal friction, and Meyerhof [6] suggested the opposite trend. Additionally, Meyerhof [6] proposed that the S_γ value increases as the L/B ratio decreases, in contrast to the findings of other researchers [5, 7, 8] reported the contrary. To address these discrepancies, many researchers have carried out three-dimensional (3D) numerical analyses to investigate the q_{ult} and the S_γ performance of unreinforced footings with varying L/B ratios. Several researchers [9-14] reported for unreinforced footings on cohesionless soil that the maximum S_γ value occurs between square and strip footings, within an L/B ratio range of 1 to 2.5, based on rigorous 3D finite difference (FD) and finite element (FE) analyses. This behavior is attributed to the dilative characteristics of cohesionless soil, the three-dimensional geometry of the failure surface, and footing–soil interaction. Furthermore, numerical analyses [9-17] indicate that the S_γ value increases with increasing soil internal friction angle, implying that higher friction enhances soil shear strength, thereby increasing resistance to deformation and expanding the failure surface. Mohapatra and Kumar [13] and Osman [17] noted that both q_{ult} and S_γ decrease with decrease in roughness of the footing. Detailed information about the S_γ value for unreinforced shallow footings can be found in the state-of-the-art review study by Ref. [18].

Geocell reinforcement, a three-dimensional geosynthetic system manufactured from polyethylene (PE), polypropylene (PP), polyester (PET), or other advanced polymeric materials, has emerged as a sustainable and effective technology within geotechnical and geosynthetic engineering. Owing to its cost-effectiveness, ease of installation, environmentally friendly characteristics, and substantial improvement in soil bearing performance compared with conventional planar geosynthetic materials, geocell technology has become a promising alternative reinforcement option for shallow foundations, load transfer platforms for piles, paved and unpaved roadways, railways, retaining structures, anchor systems, and slope stabilization works, as well as protection of buried pipes [19-24]. Geocell reinforcement improves soil performance increases footing bearing pressures and reduces footing settlements by activating three dominant mechanisms: stress dispersion, membrane and lateral confinement. The three-dimensional matrix of the geocell material prevents the lateral soil displacements under footing pressure, producing confining pressure along the geocell walls and generating apparent cohesion within the confined cohesionless soil. Consequently, the reinforced soil zone behaves as a relatively stiff layer—similar to a semi-rigid plate—that distributes the applied pressure across a larger region; this process is referred to as the stress dispersion mechanism. Tensile forces are created at the underside of the geocell pockets as a result of the applied load deforming the geocell layer into a concave shape. A phenomenon known as the membrane mechanism occurs when the upward component of these tensile forces lessens the stress that is delivered to the soil beneath the geocell mattress. Additionally, the interface friction between the surrounding soil and geocell walls enhances bearing performance via a mechanism termed lateral confinement.

Over the past twenty years, a substantial body of experimental [19, 24-37] and numerical [31, 34, 38-42] research has been devoted to understanding the improvement performance and reinforcement mechanisms of geocell reinforcement systems. These studies have examined a wide range of design parameters, including geocell stiffness and strength, embedment depth, height, pocket and laying width, and the number of geocell layers beneath footings, as well as various soil conditions, loading configurations, interference effects, and composite systems that incorporate geocells with other geosynthetics. Moreover, recent developments in geocell reinforcement and its practical field applications have been thoroughly reviewed by numerous researchers [43-46]. Despite the breadth of studies in the literature, the majority of existing studies in the literature have concentrated on square, circular, or strip shallow footings. The performance of geocell-reinforced and unreinforced footings to explore the effects of aspect ratios (L/B) of 1, 3, and 10 on loose and dense sand was only examined in one laboratory model test research, carried out by Ref. [37]. Gurbuz et al. [37] have reported that soil reinforcement with geocells resulted in an augmentation of both the q_{ult} and S_y values. Furthermore, most analytical and semi-empirical approaches [47-49] developed for geocell-reinforced footings are applicable only for embankments or strip footings under plane-strain condition. Aside from the study by Demirdogen et al. [50]—which suggested extending Terzaghi's [4] S_y values for square footing under unreinforced conditions to geocell-reinforced cases—no recommendations [51, 52] have been proposed regarding the S_y values for geocell-reinforced rectangular footings. In addition, the limited methods proposed for geocell-reinforced rectangular footings have not been validated through either experimental or numerical studies.

In this pioneer research, 36 comprehensive three-dimensional (3D) finite element (FE) simulations were conducted using PLAXIS 3D (Version 20) to investigate how the footing aspect ratio (L/B) and the relative density (D_r) of soil influence the S_y values, improvement performance, and failure mechanisms. No assessments in the current literature compare experimental or in-situ tests with numerical studies of geocell-reinforced footings having various L/B ratios. Therefore, in the first stage of this study, the physical model tests conducted by Gurbuz et al. [37] were numerically simulated to validate the footing pressure (q) versus settlement ratio (s/B) responses for both unreinforced and reinforced conditions. However, the experimental investigation included only three aspect ratios ($L/B=1, 3$, and 10), which is not adequate to comprehensively understand the influence of the L/B ratio on the behavior of geocell-reinforced footings. To address this limitation, the second stage of the FE study employed rectangular footings with six additional aspect ratios ($L/B=2, 4, 5, 6, 7$ and 8) to provide a more comprehensive understanding of L/B ratio effects. The failure mechanism of the unreinforced footings was evaluated using incremental deviatoric strain contours, whereas the failure mechanism of the geocell-reinforced footings was interpreted using a combination of incremental deviatoric strain contours, soil vertical stress contours, and the tensile force distribution along the geocell walls. Furthermore, the obtained S_y values for unreinforced footings were compared with existing semi-empirical and numerical recommendations, whereas the corresponding values for geocell-reinforced footings were benchmarked against the findings of Ref. [37]. Overall, this study extends current knowledge on geocell-reinforced footings across a wide range of L/B ratios and relative densities, providing valuable insights for the broader field of civil engineering.

2. DESCRIPTION OF THE PHYSICAL LABORATORY MODEL TEST

The physical laboratory model tests conducted by Ref. [37] on unreinforced and geocell-reinforced footings with varying L/B ratios were employed to validate the finite element analyses and to facilitate comprehensive parametric studies using rigorous 3D finite element modeling. The experimental investigations were carried out in a rigid steel container with internal dimensions of $1000 \text{ mm} \times 1000 \text{ mm} \times 700 \text{ mm}$ (length $\times$ width $\times$ height), which is sufficiently large to prevent the failure surface from contacting the tank border. The loading system consisted of an I-section loading frame and two U-section reaction columns and loading was applied using an automatic hydraulic press equipped with a piston supported by the frame. Three linear variable displacement transducers (*LVD*Ts), a load cell, and a data acquisition gauge were used in the model tests. Three different rough-based steel footings, measuring $100 \times 100 \text{ mm}$, $100 \times 300 \text{ mm}$, and $100 \times 996 \text{ mm}$ with a uniform thickness of 20 mm , were utilized in the physical laboratory model tests to investigate the influence of the L/B ratio on S_y values and improvement performance. In the model tests, shallow footings with L/B ratios of 1 and 3 were employed to represent

square and rectangular configurations, respectively, whereas a footing with an L/B ratio of 10 was utilized to simulate a strip footing.

Dry, poorly graded (SP) silica sand at 35% and 75% relative densities (D_r) was employed in the physical laboratory model tests to evaluate the effect of the soil's internal friction angle on the performance of unreinforced and geocell-reinforced footings with various L/B ratios. The researchers conducted direct shear tests at D_r values of 35% and 75%, obtaining peak internal friction angles of 32° and 36° , respectively. Small-scale laboratory model tests are not perfectly simulating prototype structures due to having low mean confining pressures and scale effects [21, 22, 28], although these tests have several advantages over full-scale or field tests, including cost-effectiveness, time-saving, repeatability, and allowing the different test configurations. Demirdogen et al. [31] reported that small-scale tests using unscaled geocells yielded higher improvement factor (I_f) values, whereas experiments conducted with scaled geocells produced results more consistent with full-scale and field observations. Moreover, Demirdogen et al. [31] noted that the pressure-settlement responses derived from the scaled 3D-printed geocell were well aligned with prototype field conditions obtained in three-dimensional finite element analysis. Gurbuz et al. [37] observed through a series of tensile tests that 3D-printed geocells manufactured using TPU filament with a 5% infill rate exhibited tensile force-strain curves similar to those of a traditional prototype geocell made from HDPE, which was scaled down to 1/3 of its geometric dimensions and 1/9 of its tensile stiffness and tensile strength. Thus, researchers [37] utilized the scale of 3 (N) in accordance with the scale law recommended by Iai [53] to simulate real-world geocell-reinforced footing conditions (Table 1). Moreover, a rectangular geocell geometry was preferred in the model tests, instead of a honeycomb configuration, owing to its ease of fabrication. In all model tests, the geocell pocket width and length ratio (b_g/B and l_g/B), laying width and length ratio (b/B and l/B), height ratio (h/B), embedment depth ratio (u/B), and tensile properties were kept constant, determined by the averaging optimum values that produced the maximum performance reported by previous studies [24-27, 29, 40, 43-46]. Figure 1 presents a schematic illustration and photo of the physical laboratory model test setup and Table 2 summarizes the material properties utilized in the experiments. A detailed account of the laboratory testing procedures is available in the study by Ref. [37].

Table 1. Scale factors used in the physical laboratory model test [37]

Parameter	Scale factor (model to prototype)	Scale factor utilized in this study (model to prototype)
Unit weight of soil	1	1
Elastic modulus of soil	$1/N$	$1/3$
Dimension of footing	$1/N$	$1/3$
Dimension of geocell	$1/N$	$1/3$
Embedment depth of geocell	$1/N$	$1/3$
Tensile strength and stiffness of geocell	$1/N^2$	$1/9$

3. FINITE ELEMENT ANALYSIS

In this study, unreinforced and geocell-reinforced footings with L/B ratios ranging from 1 to 10 were simulated on sandy soils with relative densities of 35% and 75% using PLAXIS 3D commercial FE software to determine the improvement factors (I_f), the ultimate bearing capacities (q_{ult}), the shape factors (S_γ) and to interpret the reinforcement mechanism of the geocell. Because in two-dimensional (2D) numerical analyses the soil-geocell composite structure is typically modeled as a distinct layer with artificially increased modulus and strength—an approach known as the equivalent composite approach (ECA)—this method often leads to overestimated performance predictions for geocell-reinforced footings and does not capture the tensile force values in the geocell layer [54]. Furthermore, PLAXIS 3D software has been extensively preferred by numerous researchers [31, 34, 38-41] for analyzing geocell-reinforced footings due to its comprehensive range of soil constitutive models, structural modeling capabilities, sensitivity analysis options, and its strong agreement with laboratory and field test results.

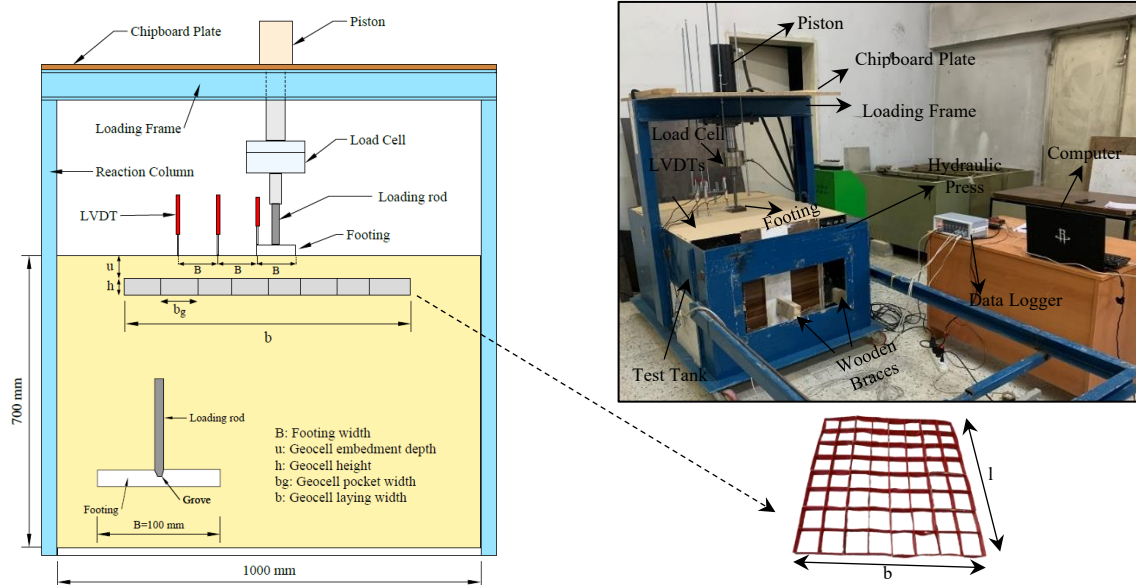


Figure 1. Schematic illustration and photo of physical laboratory model test setup [37]

Table 2. Properties of the material used in the physical laboratory model test [37]

Soil				3D-printed geocell			
Description	Symbol	Unit	Value	Description	Symbol	Unit	Value
Soil classification	SP	-	-	Height	h	mm	33
Specific gravity	G_s	-	2.63	Width	b	mm	560
Maximum dry unit weight	$\gamma_{dry(max)}$	kN/m ³	16.41	Length	l	mm	656
Minimum dry unit weight	$\gamma_{dry(max)}$	kN/m ³	14.03	Pocket width	b_g	mm	70
Coefficient of uniformity	C_u	-	1.57	Pocket length	l_g	mm	82
Coefficient of curvature	C_c	-	1.02	Tensile strength	T_{ult}	kN/m	1.61
Fine content	F	%	0	Tensile stiffness at 2% strain	J	kN/m	50
Average particle size	D_{50}	mm	0.41	Footing			
Peak internal friction angle at D_r of 35%	ϕ	°	32	Description	Symbol	Unit	Value
Peak internal friction angle at D_r of 75%	ϕ	°	36	Width	B	mm	100
Dilatancy angle D_r of 35%	ψ	°	0	Length	L	mm	100, 300, 996
Dilatancy angle D_r of 75%	ψ	°	6	Thickness	d	mm	20

3.1. Properties of the Materials

In the 3D-FE analyses, the soil was represented through the Hardening Soil (HS) constitutive model, which adeptly reflects the stress-dependent and nonlinear characteristics of cohesionless soils by using three different stiffness parameters: secant modulus, unloading-reloading modulus, and oedometer modulus. This methodology provides enhanced realism in comparison to traditional elastic-perfectly plastic models, which operate under the assumption of a constant Young's modulus. Moreover, the HS model also outperforms the Duncan-Chang hyperbolic model by integrating advanced plasticity mechanism, including a yield cap, a tension cut-off, dilatancy effects, that collectively enable realistic simulation of complex soil responses [14, 55]. A more advanced constitutive model that hardens soil with small strain stiffness (HSsmall) may add additional accuracy for problems dominated by very small strains. However, footing plate tests primarily focus on the bearing capacity, failure mechanism and large deformation behavior of geosynthetic reinforced footings, where strain levels exceed the small-strain levels. Furthermore, several researchers [31, 38, 41] have indicated that the prediction of the footing and soil surface settlement, footing pressure, pressure distribution and bearing capacity is more accurate using the HS model compared to the traditional Mohr-Coulomb model for geocell-reinforced footings. The HS model parameters for loose and dense sandy soils were derived through calibration using data obtained from the laboratory model tests

conducted by Ref. [37] for using Plaxis Soil test module inside the PLAXIS 3D software. Moreover, in the present study, a very low cohesion value ($c = 0.1$ kPa) was assigned in the soil model to avoid convergence errors and prevent early yielding [9, 31, 39, 41, 56–58]. Table 3 provides properties of the sandy soil incorporated in the 3D-FE analyses.

Table 3. Material properties used for the 3D-FE finite element analyses

Parameters	Symbol	Unit	Values	
Sandy soil			Loose sand ($D_r=35\%$)	Dense sand ($D_r=75\%$)
Material model	-	-	HS model	HS model
Drainage type	-	-	Drained	Drained
Unit weight	γ	kN/m ³	14.8	15.8
Reference secant modulus	E_{50}^{ref}	kPa	3500	30000
Reference oedometer modulus	E_{oed}^{ref}	kPa	3500	30000
Reference unloading-reloading modulus	E_{ur}^{ref}	kPa	10500	90000
Reference confining pressure	p_{ref}	kPa	100	100
Peak internal friction angle	ϕ	°	32	36
Dilatancy angle	ψ	°	0	6
Cohesion	c	kPa	0.1	0.1
Poisson's ratio for unloading-reloading	ν_{ur}	-	0.2	0.2
Exponential power	m	-	0.5	0.5
Failure ratio	R_f	-	0.9	0.9
Footing			Steel plate	
Material model			Linear elastic	
Young's modulus	E	kPa	210×10^6	
Unit weight	γ	kN/m ³	77	
Poisson's ratio	ν	-	0.29	
Geocell			3D-printed	
Material model	-	-	Geogrid	
Axial stiffness	EA	kN/m	50	
Strength reduction factor	R_{int}	-	0.8	

The footings were modeled as linear elastic plate structural elements to efficiently simulate the footing's bending behavior, load transfer, and soil–structure interaction without requiring complex volumetric modeling. Typical engineering properties of steel were selected to define the material characteristics of the footing in the 3D finite element analyses, as summarized in Table 3. The geocell layer was assigned as a geogrid structural element, an isotropic linear elastic material characterized by axial stiffness (EA) without bending stiffness (EI). In addition, several researchers [31, 38, 39, 41, 59] have recommended modeling the geocell using geogrid structural elements to achieve a more realistic representation of its mechanical behavior. In these 3D-FE analyses, the EA values of the geogrid structural element were derived from the stiffness of the TPU material at a 2% strain level, as reported by Gurbuz et al. [37], since several researchers [26, 29, 33–35, 60] have observed that the maximum tensile strain measured on the surface of the geocell material is typically less than 2%. Furthermore, researchers [37] have reported that the tensile force-strain curve behaves approximately linearly up to a strain level of 2%. During the footing loading, the friction forces occur between the soil particles and geocell walls, resulting in an interface friction angle (ϕ_{int}) that is typically lower than the internal friction angle of the surrounding soil [40]. Therefore, the strength reduction factor (R_{int}) was utilized in finite element analyses to simulate geocell walls-infill sandy soil interaction (Equation (3)). In the present study, R_{int} value was selected as 0.8, which is consistent with the

recommendation of several researchers [31, 34, 38-41]. The material properties of the geocell utilized in this 3D-FE analysis are presented in Table 3.

$$\tan\phi_{int} = R_{int}\tan\phi \quad (3)$$

3.2. Modelling of the Problem

The geometry of the 3D-FE model utilized in this study is depicted in Figure 2, including the soil volume, footing, geocell, interface, and uniform footing pressure. The soil volume was generated in accordance with the model container dimensions reported by Gurbuz et al. [37]. The footing with a width of 100 mm was modeled as a plate element with varying L/B ratios ranging from 1 to 10 and was centrally positioned on the surface of the soil domain. The shape and dimensions of the 3D-printed geocell used in the model tests were created using AutoCAD drawing program and imported into PLAXIS 3D environment, where extrusion in the vertical direction was applied to generate the 3D geocell geometry.

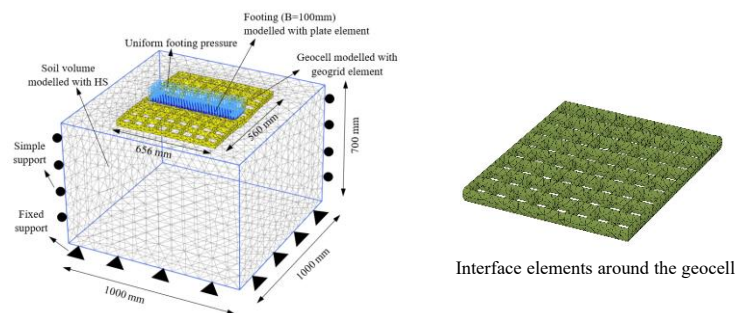


Figure 2. The geometry and boundary conditions of finite element analyses

In the rigorous 3D-FE analyses, fixed support boundary was implemented at the base of the soil domain to limit soil displacement in both vertical and horizontal directions. Meanwhile, a simple support boundary, which inhibits horizontal soil movement while allowing vertical displacement, was specified for the sides of the soil domain. Groundwater effects were not considered in this study. Ten-node tetrahedral elements, each incorporating four Gauss integration points, were used to mesh the soil domain, while the footing plate was modeled using six-node triangular elements with three Gauss points. Additionally, 12-node interface elements with six Gauss points were employed to simulate the interactions between the geocell material and sandy soil. The 3D-FE simulation was performed in two phases. In the first phase, the initial stress field condition was generated utilizing the at-rest soil (K_0) procedure based on the traditional Jaky [61] equation (Equation (4)). In the second phase, the plastic analysis, which is recommended for undrained and drained conditions and does not consider consolidation, was selected as the calculation type instead of the at-rest soil procedure. The footing, geocell, and interface elements were activated, and a predefined uniform surface pressure was incrementally applied to the shallow footing until collapse occurred. Furthermore, mesh sensitivity analyses were conducted through trial and error to determine the optimum element size that achieved high accuracy with minimal analysis time, resulting in an average element size of 0.078 m.

$$K_0 = 1 - \sin\phi \quad (4)$$

where K_0 is the at-rest horizontal earth pressure coefficient.

3.3. Determining the Ultimate Bearing Capacity

The footing pressure (q) versus footing settlement ratio (s/B) curves are preferred to determine the q_{ult} for experimental and numerical studies [14]. There is currently no universally accepted approach in the geosynthetic literature for determining the q_{ult} value of geocell-reinforced footings from pressure–settlement ratio curves, although several techniques—such as the tangent intersection, minimum slope, limited settlement, and log–log methods—have been commonly preferred to estimate the q_{ult} value of unreinforced footings. Demirdogen et al. [32] reported that traditional bearing capacity prediction

approaches for unreinforced footings cannot accurately capture the q_{ult} of geocell-reinforced footings, with the discrepancy being most pronounced in loose soil conditions. To address this limitation, Demirdogen et al. [32] proposed a new interpretation method, termed the semi-log method, which involves plotting the footing pressure–settlement curve on a semi-logarithmic scale consisting of linear, transitional, and final regions. The q_{ult} is then identified at the point where the curved segment intersects with the straight line connecting the transitional and final regions. Thus, in this study, the semi-log method was preferred to interpret the q_{ult} in the 3D-FE analyses for the unreinforced and geocell-reinforced cases, as illustrated in Figure 3.

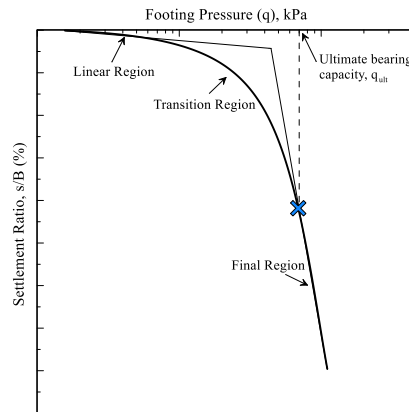


Figure 3. Graphical representation of the prediction of ultimate bearing capacity from the footing pressure–settlement ratio curve using the semi-log method

3.4. Program of the Three-Dimensional Finite Element Analysis

A total of 36 comprehensive 3D-FE analyses were conducted to investigate the effect of L/B ratio and D_r on the S_y values, failure mechanisms, and improvement performance of geocell. The analyses encompassed footing L/B ratios ranging from 1 to 10 in loose and dense sands for unreinforced and geocell-reinforced scenarios. The overall FE analysis program is summarized in Table 4. Firstly, by modelling the laboratory physical laboratory model tests conducted by Gurbuz et al. [37] in Series A and B, were simulated to verify the pressure–settlement ratio responses. Secondly, in Series C and D, additional parametric analyses were carried out to comprehensively evaluate the effect of L/B ratio on both unreinforced and reinforced footings by incorporating L/B ratios that were not examined in the physical laboratory model tests. In all series, footing width was set to 100 mm and in Series B and D, geocell parameters were maintained constant, as utilized in the laboratory model tests conducted by Ref. [37].

Table 4. The 3D-FE finite element analysis program

Series	Condition	Variable Parameters	Constant Parameters
A	Unreinforced	$L/B=1, 3$ and 10 $D_r=35\%$ and 75%	$B=100$ mm
B	Geocell-reinforced	$L/B=1, 3$ and 10 $D_r=35\%$ and 75%	$B=100$ mm, $b_g/B=0.7$, $l_g/B=0.82$, $b/B=5.6$, $l/B=6.4$, $h/B=0.33$, $u/B=0.1$, $EA=50$ kN/m
C	Unreinforced	$L/B=2, 4, 5, 6, 7$ and 8 $D_r=35\%$ and 75%	$B=100$ mm
D	Geocell-reinforced	$L/B=2, 4, 5, 6, 7$ and 8 $D_r=35\%$ and 75%	$B=100$ mm, $b_g/B=0.7$, $l_g/B=0.82$, $b/B=5.6$, $l/B=6.4$, $h/B=0.33$, $u/B=0.1$, $EA=50$ kN/m

4. RESULTS AND DISCUSSION

4.1. Verification of the Three-Dimensional Finite Element Analyses

Verifying experimental or field studies through FE analyses is essential for ensuring the reliability and accuracy of numerical simulations. Thus, in this study, 12 laboratory model tests performed by Gurbuz et al. [37] were simulated using PLAXIS 3D software. The footing pressure (q) versus settlement ratios (s/B) responses reported from the experimental study were compared with those generated by the 3D-FE analyses (Figure 4). The results indicate that the footing q - s/B curves obtained from the 3D-FE analyses for the unreinforced and geocell-reinforced conditions exhibited good agreement with the physical laboratory model test results. However, owing to the limitations inherent in the HS model, the 3D-FE model could not capture the post-failure softening behavior observed in the pressure–settlement ratio curves of unreinforced footings on dense soil in the laboratory model tests.

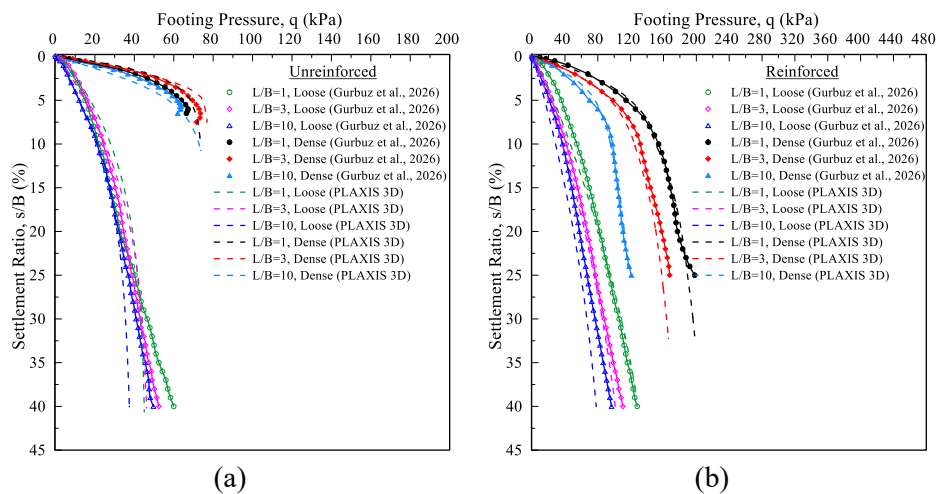


Figure 4. Comparison of the 3D-FE analysis results with laboratory model test results: (a) unreinforced and (b) geocell-reinforced cases

The results of this 3D-FE study demonstrated that geocell substantially enhanced footing behavior by improving the stiffness of the q - s/B response and increasing the q_{ult} when compared with the unreinforced footing, owing to the reinforcement mechanism of the geocell. Furthermore, it was observed that for unreinforced footings on dense sand, a sudden pronounced soil failure occurred at lower settlement ratios (s/B), indicating a general shear failure mechanism. In contrast, for geocell-reinforced footing on dense sandy soil, the failure mode transitioned to local failure characterized by an extension of the transition and hardening regions of the pressure–settlement ratio curve. This behavior is attributed to the 3D geocell architecture, which limits dilation of cohesionless soil within the geocell mattress while simultaneously providing lateral confinement through the confining pressures mobilized along the geocell walls. Additionally, for unreinforced and geocell-reinforced shallow footings on loose sand, a conventional punching shear failure mode was observed with the q - s/B responses exhibiting an approximately linear trend up to a s/B of 40%.

4.2. Improvement Factor Values

The improvement in bearing pressure due to geocell reinforcement was assessed using the improvement factor (I_f), which is the ratio of the footing pressure under reinforced (q_r) to unreinforced conditions (q_u) at a specified s/B ratio (Equation (5)). Furthermore, numerous researchers [25–32, 38, 42] have demonstrated that improvement factors are effective parameters for systematically comparing and interpreting results from laboratory, in-situ, and numerical studies

$$I_f = \frac{q_r}{q_u} \quad (5)$$

The I_f values obtained from 3D-FE analyses for footings with various L/B ratios on loose and dense soils, up to an s/B ratio of 24%, are displayed in Figures 5a and 5b, respectively. In the present study, the I_f values were restricted to this range to emphasize realistic and serviceable settlement levels. The results of the comprehensive 3D-FE analyses revealed that I_f values ranged from 1.12 to 2.56, which are in close agreement with those reported in field studies as well as in large-scale and small-scale tests where the geocells were appropriately scaled [28, 29, 62]. In contrast, laboratory studies that employed unscaled or geogrid-based geocells with relatively higher stiffness have reported improvement factor values reaching up to 9 [31].

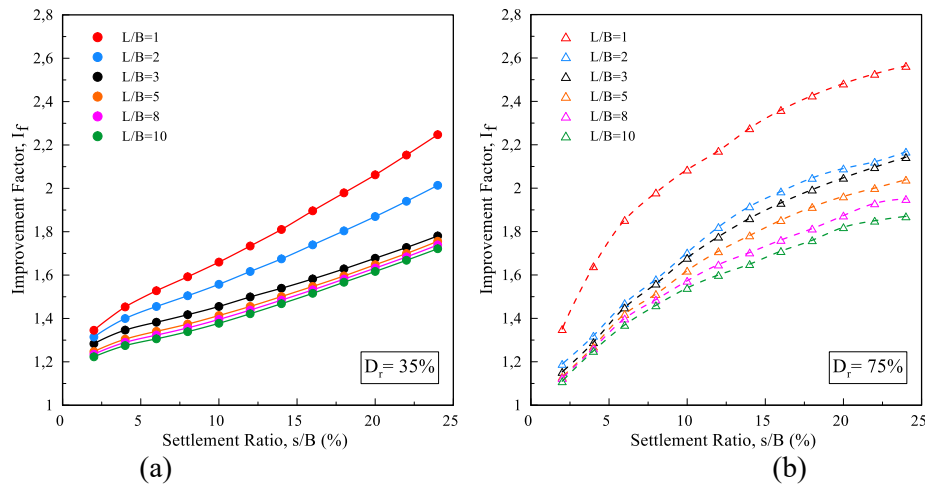


Figure 5. Improvement factor values obtained from 3D-FE analyses for footing with various aspect ratios: (a) loose sand (b) dense sand

The results demonstrated that at lower settlement ratios (i.e., $s/B \leq 6\%$), the difference between I_f values of loose and dense sandy soil for footings with the same L/B ratio were relatively similar. However, the difference of I_f values between loose and dense sandy soil exhibits an increasing trend with a rise in the D_r of the soil at higher s/B ratios, consistent with the findings of previous studies [25, 26, 29, 31, 32]. As can be seen in Figure 5, I_f values exhibit a decreasing trend with increasing L/B ratio of the shallow footing. The maximum I_f values were observed in square footing on both loose and dense sands for all s/B ratios. Similar behavior has been documented in previous studies [63–66] that examined planar geotextile and geogrid-reinforced footings across a range of L/B ratios. Furthermore, a comprehensive review of 84 laboratory and field tests conducted by 23 researchers, as compiled by Demirdogen et al. [50] revealed that geocell-reinforced square and circular footings exhibited significantly higher improvement factor values than geocell-reinforced strip footings. Even at an s/B ratio of 2%, the I_f values reached 1.34 and 1.35 for square shallow footings on soil at D_r values of 35% and 75%, respectively. In contrast, when the L/B ratio was 10, the improvement factors remained below 1.2 at the same s/B level. This indicates that the L/B ratio, alongside relative density, plays a critical role in governing the improvement performance of geocell-reinforced footings.

4.3. Ultimate Bearing Capacities and Shape Factor Values

The obtained q_{ult} values from the comprehensive 3D FE analyses for both unreinforced and geocell-reinforced footing on loose and dense sandy soil is presented in Table 5. The Table 5 demonstrated that q_{ult} values increased with increase in relative density of the soil because of increase particle interlocking, internal friction angle and dilative behavior. For geocell-reinforced footings, as relative density increases, the confining pressure around the geocell and interface friction forces on the geocell walls increases, causing an increase in the contribution of geocell reinforcement mechanisms to the improvement of bearing capacities. Moreover, it was observed that q_{ult} values of reinforced footings increase with a decrease in aspect ratio, ranging from 1.42 to 2.25 times for both loose and dense sandy soil.

The S_y values for unreinforced shallow footings, derived from 3D rigorous FE analyses conducted in Series A and C, correspond to rectangular footings with aspect ratios ranging from $L/B=1$ to 8 and a strip footing

($L/B=10$) under D_r of 35% and 75%, as shown in Figure 6. These values were compared with existing recommendations [4-13, 15-17], which were developed using semi-empirical formulations, numerical analyses, and Eurocode 7 [67] design provisions, as well as with the experimental results reported by Ref. [37]. It was observed that the S_y values obtained from the PLAXIS 3D analyses ranged between 1.00 and 1.23, showing strong agreement with the experimental findings of Gurbuz et al. [37] and closely matching the trends reported by Meyerhof [6], Antao et al. [12], and Mohapatra and Kumar [13].

Table 5. Ultimate bearing capacity of unreinforced and geocell-reinforced footings

Aspect Ratio (L/B)	Ultimate Bearing Capacity (q_{ult}), kPa			
	Unreinforced		Reinforced	
	Loose Sand	Dense Sand	Loose Sand	Dense Sand
1	37.8	66.7	76.4	150.1
2	40.5	75.5	69.8	137.2
3	39.0	73.5	63.9	125.3
4	37.6	69.8	60.3	116.5
5	36.6	66.8	58.2	110.4
6	35.9	65.1	55.3	104.0
7	35.6	63.9	53.2	100.8
8	35.5	63.2	52.0	95.7
10	35.1	62.6	50.2	88.9

The results of 3D-FE analyses for the unreinforced case demonstrated that, for both loose and dense sands, the S_y values reached their minimum for the strip footing ($L/B=10$) and their maximum at an L/B ratio of 2. Similarly, numerous recent studies [9-14] for unreinforced footings on cohesionless soil have indicated that S_y values initially increase as the L/B ratio rises from 1, reaching a local peak between $L/B=1$ and 2.5 and beyond this range, the S_y values gradually decrease as the L/B ratio continues to increase toward that of a strip footing. However, the results of the present numerical investigation, along with recent studies, contradict conventional semi-empirical methods [5, 7, 8] and Eurocode 7 [67], which propose that the S_y increases with the L/B ratio. Furthermore, as shown in Figure 6, the S_y values were found to rise with the D_r of the soil, consistent with recent recommendations and the findings of Meyerhof [6]. This trend, however, contrasts with earlier studies [4, 5, 7, 8] and the Eurocode 7 [67] provisions, which assert that the S_y value remains unaffected by the internal friction angle of the sandy soil below unreinforced shallow footing.

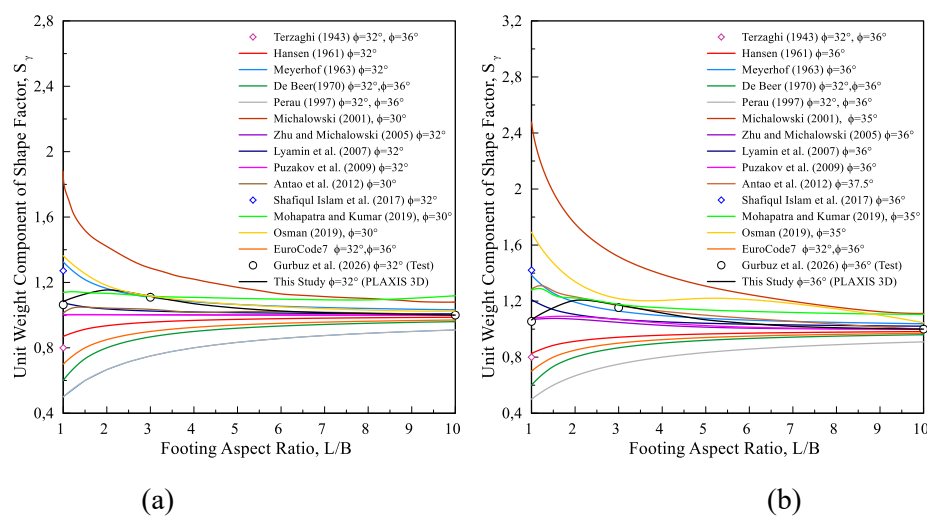


Figure 6. Comparison of the shape factor values across various aspect ratios obtained in this study with the recommendations reported in previous studies: (a) loose sand (b) dense sand

The S_y values derived from the 3D-FE analyses for geocell-reinforced footings in Series B and D, covering rectangular footings with varying aspect ratios ($L/B=1-8$) and a strip footing ($L/B=10$) on sandy soils with D_r values of 35% and 75%, are presented in Figure 7. In addition, S_y values obtained from the experimental

study carried out by Ref. [37] for geocell-reinforced footings with L/B ratios of 1, 3, and 10 were incorporated into the same figure for comparison. The application of geocell reinforcement led to an increase in S_γ values by a factor of 1.00 to 1.41 in loose sand and 1.00 to 1.57 in dense sand, compared to the unreinforced condition, depending on the footing aspect ratio. Moreover, the 3D-FE analysis results showed good agreement with the physical laboratory model test findings reported in Ref. [37]. It was found that similar to the unreinforced condition, an increase in the D_r of the sandy soil below the shallow footing leads to increase S_γ values for geocell-reinforced cases due to the dilative characteristic of the cohesionless soil and reinforcement mechanism of the geocell. The 3D-FE analyses result also demonstrated that geocell reinforcement caused the aspect ratio corresponding to the maximum S_γ to shift from $L/B=2$ to $L/B=1$ in loose sand and dense sand, aligning with observations reported in Refs. [63–66] for planar geosynthetic-reinforced footing. Moreover, as the L/B ratio increased, the S_γ values decreased, and for the strip footing ($L/B=10$), the S_γ value was equal to 1 for loose and dense sandy soils. However, existing geocell-reinforced bearing capacity prediction methods [47-52] have either been recommended only for strip footings or embankments under plane strain condition or have suggested using S_γ values derived for unreinforced footings in the design of geocell-reinforced footings.

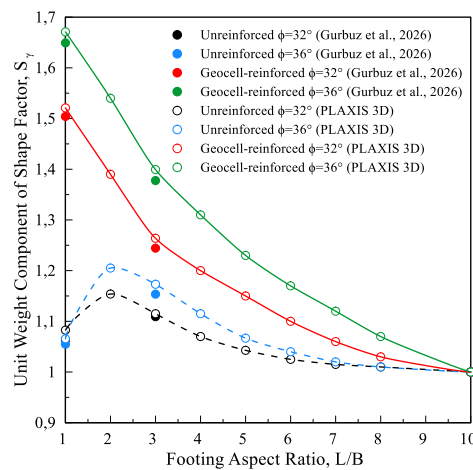


Figure 7. The variation of the shape factor values for unreinforced and geocell-reinforced condition on loose and dense sand across various aspect ratios

4.4. Failure Mechanism

The correlation between S_γ , L/B ratio, and the cohesionless soil's internal friction angle exhibits a complex nature due to the influence of three-dimensional interaction between footing and soil. This interaction affects both the geometry and confinement of the incremental deviatoric strain contours that define the failure surface within the infill soil in the unreinforced condition. Thus, in the present FE analyses, incremental deviatoric strains obtained from PLAXIS 3D software were examined to elucidate the failure mechanisms for both unreinforced and reinforced cases.

Three-dimensional incremental deviatoric strain contours for unreinforced footings with L/B ratios of 1, 2, and 10 in loose and dense soils are illustrated in Figure 8. The 3D-FE results indicate that higher incremental deviatoric strains are concentrated directly beneath the footing and along its edges. Moreover, the extent of the incremental deviatoric strain zone expanded into a wider volume with a more inclined geometry as the relative density increased, consistent with previous findings [9, 10, 13, 14]. As a result of these situations, the S_γ values increase with increasing D_r of the sandy soil. The geometry of the incremental deviatoric strain contours, except for the case of $L/B=10$, exhibited four distinct elliptical zones extending outward from the edges of the footing when viewed from above. In contrast, for footings with $L/B=10$ or strip footings, the contours adopted a more rectangular geometry due to the confinement of the failure surface along the footing's longitudinal direction, reflecting a plane strain condition. Furthermore, in accordance with the results obtained from FE analyses, the three-dimensional extent of the incremental deviatoric strain contour reached its maximum at an L/B ratio of 2 for loose and dense sands, in comparison to other L/B ratios. With an increase in L/B ratio beyond 2, the three-dimensional boundaries of the incremental deviatoric strain

contour became more confined. This behavior indicates that the three-dimensional interaction and the geometry of the deviatoric strain contours influence the mobilization of passive forces within the failure surface, thereby affecting the ultimate q_{ult} and S_y values. Additionally, Zhu and Michalowski [9] and Yunkul et al. [14] noted that the reason for the changing S_y values depending on the L/B ratio is intrinsically linked to the ratio of the volume of the deviatoric strain contours to the footing area, denoted as volumetric failure ratio (r_v), as a greater failure volume enhances the mobilized shear resistance.

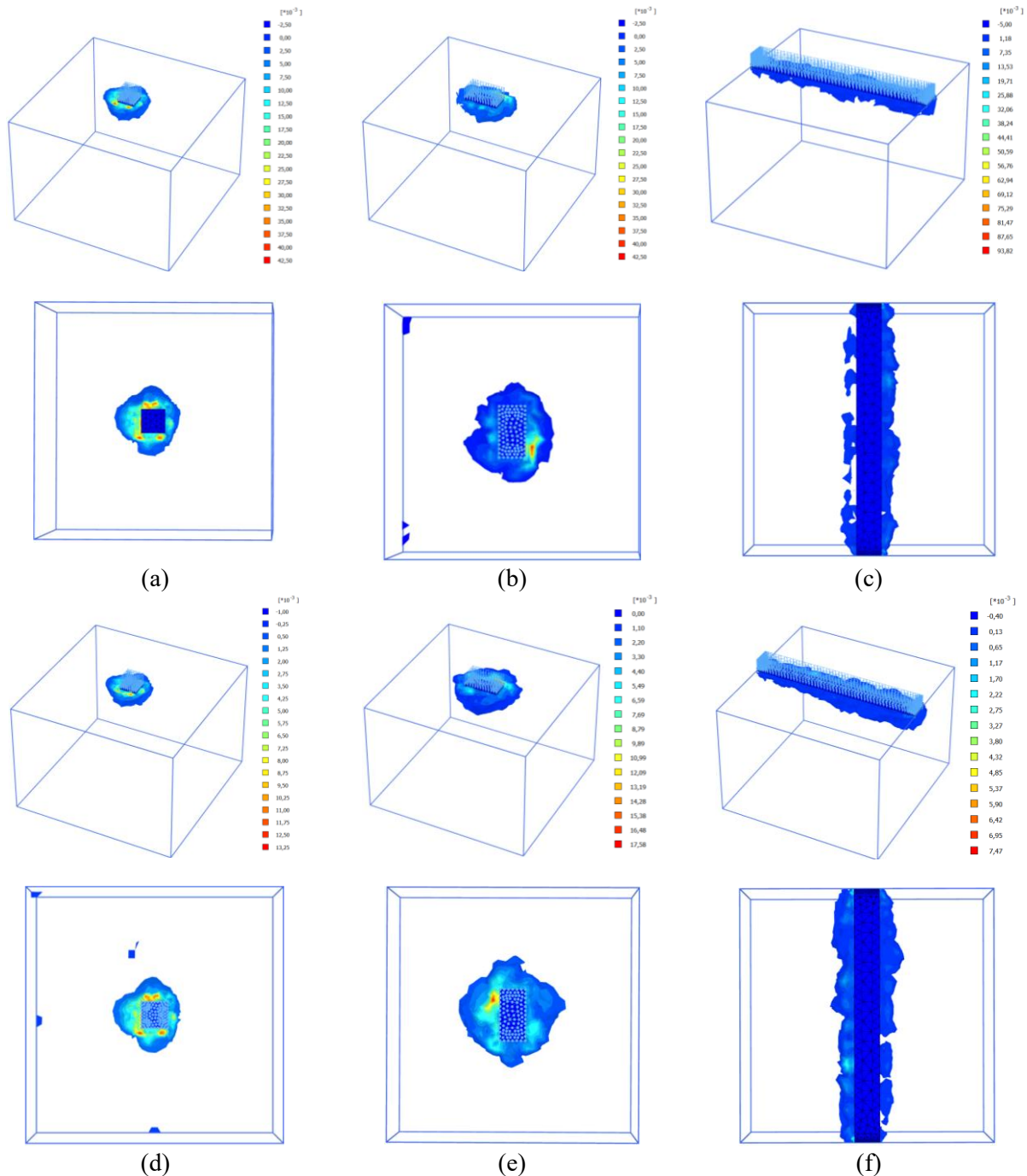


Figure 8. Incremental deviatoric strain contours for unreinforced footings: (a) $L/B=1$ on loose soil, (b) $L/B=2$ on loose soil, (c) $L/B=10$ on loose soil, (d) $L/B=1$ on dense soil, (e) $L/B=2$ on dense soil and (f) $L/B=10$ on dense soil

In the 3D-FE analyses, the vertical stress beneath the shallow footing spread over a wider region, as the soil surrounded by geocell eventually acted as a semi-rigid plate, consistent with the findings of many

researchers [24-27, 31, 36, 40, 41, 59] due to the stress dispersion mechanism of geocell material. Consequently, the vertical stress intensity in the sandy soil decreases notably, leading to an increase in ultimate bearing capacities. To more clearly elucidate the influence of L/B ratio on the geocell-reinforced footing, vertical stress dispersion patterns were investigated on loose and dense sandy soil and are given at the point of finite element failure in Figure 9. As the L/B ratio of the shallow footing decreased and the D_r of sandy soil increased, the intensity of vertical stresses within the soil volume along footing length and width directions decreased. Furthermore, the depth of the stress bulbs was also reduced. These results indicated that the L/B ratio of the footing and D_r of the cohesionless soil are key parameters for stress dispersion mechanisms in geocell-reinforced footings.

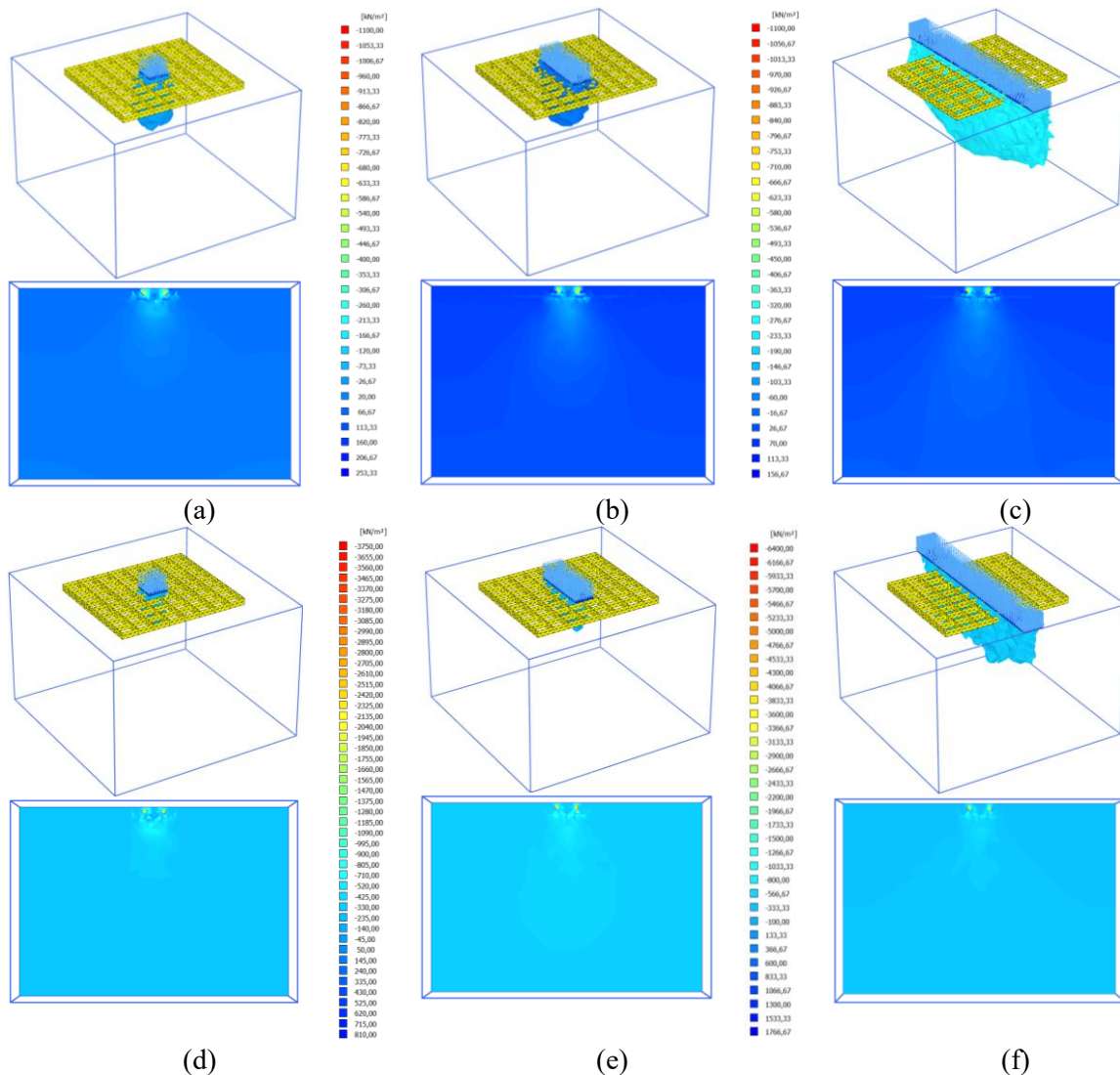


Figure 9. Vertical stress contours for geocell-reinforced footings: (a) $L/B=1$ on loose soil, (b) $L/B=3$ on loose soil, (c) $L/B=10$ on loose soil, (d) $L/B=1$ on dense soil, (e) $L/B=3$ on dense soil, (f) $L/B=10$ on dense soil

The applied footing pressures induce deflection in the geocell reinforcement, leading to the development of tensile forces along the underside of the geocell mattress—a phenomenon known as the membrane reinforcement mechanism. The upward-directed component of the tensile forces helps to reduce pressures on the sandy soil, thereby improving the bearing pressures and q_{ult} . Therefore, in this numerical study, the tensile forces developed within the geocell layer were analyzed with respect to the D_r of the sands and the footing's aspect ratio. The distribution of horizontal tensile forces on the geocell layer walls with deformation geometry for three aspect ratios ($L/B=1, 3$ and 10) at the time of FE failure in loose and dense sands is presented in Figure 10. The observation revealed that the tensile force contours predominantly

concentrated in the lower portion of the geocell layer, particularly under the loaded area of the footing and progressively diminished toward the edges. As illustrated in Figure 10, the maximum tensile forces on the geocell walls were generally observed for strip footings, whereas the minimum tensile forces occurred for square footings in both loose and dense sands. The distribution of tensile forces along the footing's length and width was found to vary with changes in the L/B ratio of the footing. In the case of strip footing, tensile forces occurred in the geocell only in the direction of footing width. However, as the L/B ratio decreased, tensile forces began to develop in the geocell walls oriented along the footing length and in the case of the square footing, these forces were nearly equivalent to those mobilized in the walls aligned with the footing width. Thus, it is considered that the tensile force distribution within the geocell mattress is a decisive factor for improvement performance and ultimate bearing capacity.

The variations in tensile force distribution are attributed to the deformation geometry of the geocell material, which changes with the footing's L/B ratio. Figure 10 shows that the geocell layer exhibited bending only along the footing width, forming a concave deformation pattern when L/B ratio was 10. As L/B ratio decreased, deformation in the geocell layer became more pronounced and progressively extended along the footing length, while the deformation across the footing width diminished. For square footings, the geocell layer developed a fully symmetrical concave deformation profile. Furthermore, the geocell layers in loose soil had approximately 1.5 times lower tensile force compared to dense soil due to lower friction resistance of the geocell wall and loose soil particle and lower confining pressure around the geocell pockets, findings that are consistent with several researchers [26, 28, 29, 35]. This behavior indicates that with increasing D_r of the soil, the membrane effect becomes more dominant in contributing to the improvement of the I_f , q_{ult} and S_y values.

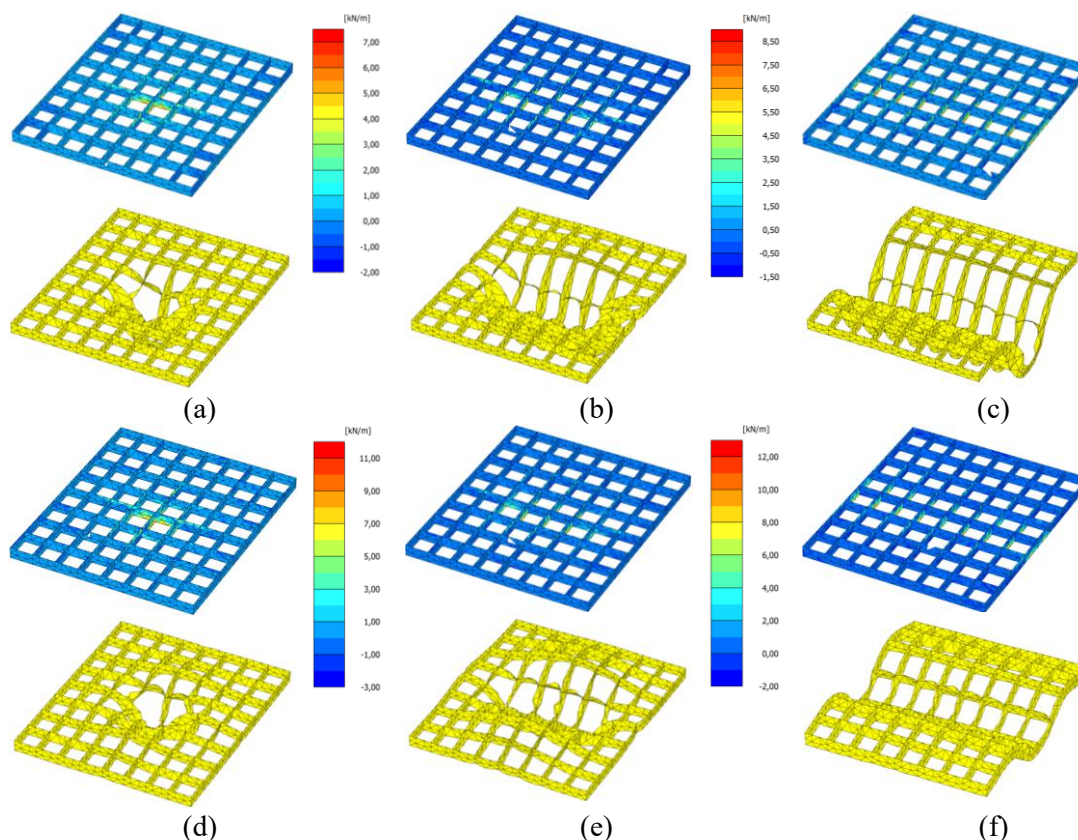


Figure 10. The distribution of tensile forces and deformation geometry of geocell layers for different L/B ratio: (a) $L/B=1$ on loose soil, (b) $L/B=3$ on loose soil, (c) $L/B=10$ on loose soil, (d) $L/B=1$ on dense soil, (e) $L/B=3$ on dense soil, (f) $L/B=10$ on dense soil

The soil particles move more freely as the L/B ratio increases for the geocell-reinforced condition, which is attributed to the reduced efficiency of the lateral confinement mechanism caused by lower tensile forces on the geocell walls along the footing length and diminished stress dispersion. Accordingly, S_y of geocell-

reinforced footing showed an increasing tendency from strip footing to square footing. Consequently, the border of the incremental deviatoric strain contours expanded with an increase in the L/B ratio (Figure 11), contrasting with the behavior observed in the unreinforced case. The maximum deviatoric strains were seen at the edges of the geocell-reinforced square footings. Furthermore, the geometry of the three-dimensional failure surface was observed to differ between loose and dense sands, a variation attributed to the enhanced lateral confinement offered by the geocell pockets in dense sand relative to loose sand.

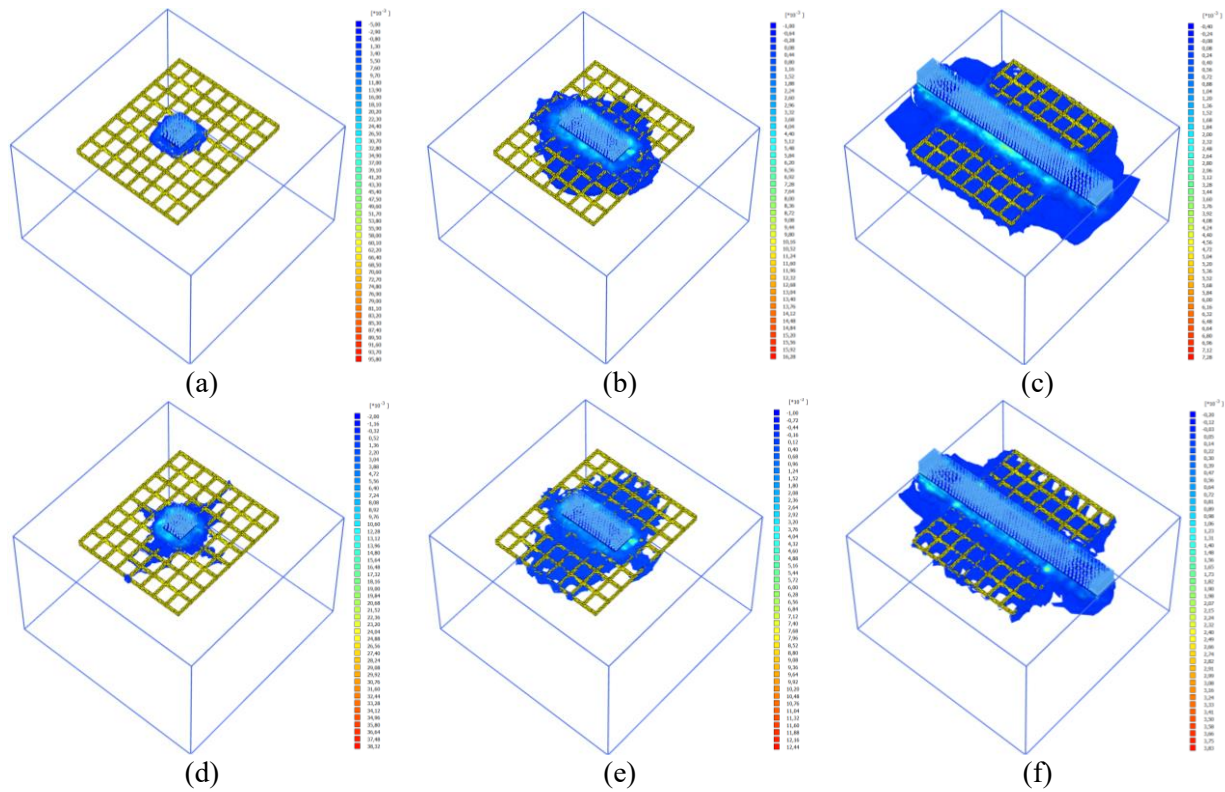


Figure 11. Incremental deviatoric strain contours for geocell-reinforced footings: (a) $L/B=1$ on loose soil, (b) $L/B=3$ on loose soil, (c) $L/B=10$ on loose soil, (d) $L/B=1$ on dense soil, (e) $L/B=3$ on dense soil, (f) $L/B=10$ on dense soil

4.5. Limitations of Three-Dimensional Finite Element Analyses

The limitations of the current three-dimensional finite element analyses concerning the influence of footing aspect ratio and soil relative density on the ultimate bearing capacity, shape factor, improvement factor, and failure mechanism of unreinforced and geocell-reinforced footings resting on sandy soils are summarized as follows:

- Loose and dense sandy soil parameters were used, which were calibrated from the laboratory model tests conducted by Ref. [37].
- The width of the footings was selected as 100 mm and modeled as a fully rough condition.
- Nine different footing aspect ratios (L/B), ranging from 1 to 10, were utilized.
- The geocell pocket width and length ratio (b_g/B and l_g/B), laying width and length ratio (b/B and l/B), height ratio (h/B), embedment depth ratio (u/B), and axial stiffness (EA) were kept constant as 0.7, 0.8, 5.6, 6.4, 0.33, 0.1, and 50 kN/m.
- Rectangular geocell geometry was preferred.

5. CONCLUSIONS

This study carried out a series of comprehensive 3D-FE analyses to investigate the influence of shallow footing aspect ratio (L/B) and soil relative density (D_r) on the ultimate bearing capacity (q_{ult}), shape factor (S_f), improvement factor (I_f), and failure mechanisms under both unreinforced and geocell-reinforced

conditions. A total of 36 numerical simulations were performed using PLAXIS 3D commercial finite element software, encompassing configurations with and without geocell reinforcement on loose sand ($D_r=35\%$) and dense sand ($D_r=75\%$), across nine footing aspect ratios ranging from $L/B=1$ to $L/B=10$. Based on the results of these analyses, the following conclusions can be drawn:

- The footing pressure (q) versus footing settlement ratio (s/B) curves generated using the Hardening Soil (HS) constitutive model showed good agreement with the results of physical laboratory tests for unreinforced and geocell-reinforced conditions. However, the 3D-FE simulations did not accurately reproduce the post-peak softening response of unreinforced footings on dense sand, due to the inherent limitations of the HS model in representing the strain-softening response of dense granular soils.
- Improvement factor values were found to increase with decreasing footing L/B ratio, reaching maximum values in square footing for geocell-reinforced condition on loose and dense sands. For square footing, these values were approximately 1.10-1.38 times higher than those for footing with an aspect ratio of 10 or strip footing, depending on the s/B of footing and D_r value of the sandy soil. Additionally, at lower settlement ratios (i.e., $s/B \leq 6\%$), the improvement factors for loose and dense sands were comparable, whereas the disparity between them became more pronounced with increasing s/B value.
- The findings of the 3D-FE analyses revealed that S_y values initially increased as the L/B ratio rose from 1 to 2, after which gradually decreased with further increases in L/B for unreinforced footings. This trend is attributed to the three-dimensional interaction between the footing and the surrounding soil, as well as the geometry and volume of the incremental strain contours. S_y values were found to rise with increasing D_r of sandy soil, owing to the greater expansion and more inclined geometry of the incremental strain contours.
- The geocell reinforcement resulted in increased S_y values and caused the L/B ratio corresponding to maximum S_y to shift from $L/B=2$ to $L/B=1$. S_y values exhibited a consistent decreasing trend with further increases in the L/B ratio. This behavior can be attributed to the reinforcement mechanism of the geocell material. The 3D-FE analyses demonstrated that as the L/B ratio decreased and the soil D_r value increased, the three-dimensional stress dispersion within the soil improved, contributing to an enhanced bearing capacity. A decrease in the L/B ratio reduced the disparity between the tensile forces developed in the geocell mattress along the footing length and width, resulting in an almost symmetrical tensile force distribution along the geocell walls of the square footing. Additionally, the tensile forces developed within the geocell mattress were observed to be lower in loose sand compared to dense sand due to lower confining pressure acting on the geocell walls and reduced interfacial friction.
- The proposed bearing capacity equations developed for geocell-reinforced footings [47-52] did not propose S_y values or S_x values for unreinforced footings. Moreover, these equations do not adequately capture the relationship between the D_r and the L/B . This situation may lead to an underestimation of the q_{ult} of geocell-rectangular footings, potentially increasing in construction costs. Therefore, it is recommended that generalized S_y equations for geocell-reinforced footings should be included in design codes based on the findings of this study and the outcomes of future research.

DECLARATION OF ARTIFICIAL INTELLIGENCE (AI) USE

When drafting the manuscript, neither generative AI agents nor large language models (LLMs) were used in any aspect of the study.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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