The International Maritime Transport and Logistics (MARLOG 15) - ISSN 2974-3141
http://dx.doi.org/10.21622/MARLOG.2026.15.1.29
Smart & Resilient Logistics Corridors Future Gateway to the Green Trade

Enhancing Port Yard Infrastructure Using Geocell Technology a Sustainable Approach for Heavy-Duty Ground Reinforcement

Ahmed M. Ebid *(1), Ashraf Sabry (2), Laila A. Elkadi (3), Karim Sherif Mostafa (4), Norbaya Sidek (5), and Mohamed A. Hafez (3,6)

(1) Future University in Egypt, Cairo, Egypt, Corresponding author email: ahmed.abdelkhaleq@fue.edu.eg

(2) LSF consultant, Cairo, a.sabry@lsf-egyp.com

(3) Faculty of Engineering and Quantity Surveying INTI-IU, Universi, Nilai-Malaysia, lklailaanwar@gmail.com

(4) Civil Engineering Discipline, School of Engineering, Monash University, Malaysia, karim.mostafa@monash.edu.my

(5) Faculty of Civil Engineering, Universiti Teknologi MARA (UiTM), Selangor, Malaysia, norbayasidek@uitm.edu.my

(6) Faculty of Management, Shinawatra University, Pathum Thani Thailand, mohdahmed.hafez@newinti.edu.mv

Keywords: Geocell; container yards; sustainability

ABSTRACT

Port logistics areas are increasingly exposed to heavier loads and higher traffic due to the expansion of containerized trade and intermodal transport systems. Traditional pavement structures in storage yards often suffer from rapid deterioration, settlement, and excessive maintenance costs, especially when constructed on weak subgrades or exposed to repetitive dynamic loads. This research investigates the application of geocell reinforcement as an innovative solution for strengthening port yard foundations, aiming to enhance durability, load distribution, and sustainability. Geocells, as a three-dimensional cellular confinement system, improve the mechanical behaviour of soil layers by restricting lateral displacement, thereby increasing bearing capacity and reducing rutting. Their use in port yards offers significant potential for reducing construction material requirements, lowering life-cycle costs, and minimizing environmental impact. The paper discusses the geotechnical principles of geocell-reinforced pavements, design considerations specific to heavy-duty port operations, and the role of geocells in supporting sustainable infrastructure development. The study also explores the broader Implications of integrating such technologies in modern port resilient infrastructure, where resilience, cost-effectiveness, and environmental responsibility are becoming strategic priorities. By adopting geocell solutions in yard pavement construction, ports can achieve higher operational efficiency, extend service life, and align with global sustainability goals.

1. INTRODUCTION

The relentless expansion of global trade and containerized shipping has precipitated a surge in the scale and capacity of maritime port facilities worldwide. This growth necessitates the development of larger, more robust storage yards adjacent to quays to handle the increasing volume of containers and the heavier loads imposed by modern stacking equipment and intermodal transport systems [1]. These yards, often constructed on marginal or reclaimed lands with weak, compressible subsoils, are subjected to extreme static loads from multi-tiered container stacks and repetitive dynamic loads from heavy machinery like rubber-tired gantry (RTG) cranes and straddle carriers. The combination of poor subgrade conditions and intense operational loading frequently leads to rapid pavement deterioration, manifested as excessive rutting, differential settlement, and structural failure, resulting in escalated maintenance costs and operational disruptions.

Conventional soil improvement techniques for such demanding environments typically involve the removal and replacement of weak soils or the construction of excessively thick base courses using high-quality imported aggregates. While effective, these methods are often materially intensive, economically costly, and environmentally unsustainable due to the high carbon footprint associated with quarrying and transporting vast quantities of fill material [2]. Alternative ground improvement methods, such as vibro-compaction or the use of planar geosynthetics (geogrids, geotextiles), offer partial solutions but can be limited in their ability to provide comprehensive three-dimensional confinement and significant reduction in aggregate layer thickness.

In this context, geocell reinforcement has emerged as an innovative and efficient technique to enhance the performance of soil structures. Geocells are three-dimensional, honeycomb-like cellular structures made from novel polymeric alloys, which are expanded on-site and infilled with soil or aggregate. The primary mechanism of improvement is derived from lateral confinement of the infill material. Upon vertical loading, the tensile resistance of the cell walls mobilizes passive earth resistance within the confined zone, creating a stiffened mattress that distributes the imposed loads over a wider area of the weak subgrade [3] as shown in Fig. 1a-1c.

Geotechnical engineers primarily rely on numerical modelling, actual tests, and theoretical calculations to comprehend how a structure responds to the soil. To solve engineering-related problems, various numerical methods, including the Finite-Difference Method (FDM), Finite-Element Method (FEM), Discrete Element Method (DEM), and Boundary Element Method (BEM), were created by various scholars. The most used continuum numerical method for tackling geotechnical engineering issues is FEM. To quantitatively assess the performance of geocell-reinforced soil under the heavy loads characteristic of port storage yards, a comprehensive finite element method (FEM) parametric study was undertaken.[16]

The role of geocell confinement in enhancing the mechanical behavior of granular soils was first highlighted by Rajagopal, Krishnaswamy, and Latha [4]. Through a series of triaxial compression tests on soils encased within single and multiple geocells fabricated from different geotextiles, they demonstrated that geocell confinement markedly increases the apparent cohesion and stiffness of granular soils. The degree of improvement was found to depend on the material characteristics of the geosynthetics, and a simplified approach was proposed to estimate the apparent cohesion based on the geometry and material properties of the geocell (see Fig. 1d). These mechanisms significantly increase the composite layer's bearing capacity and stiffness while reducing permanent deformations and rutting [5].

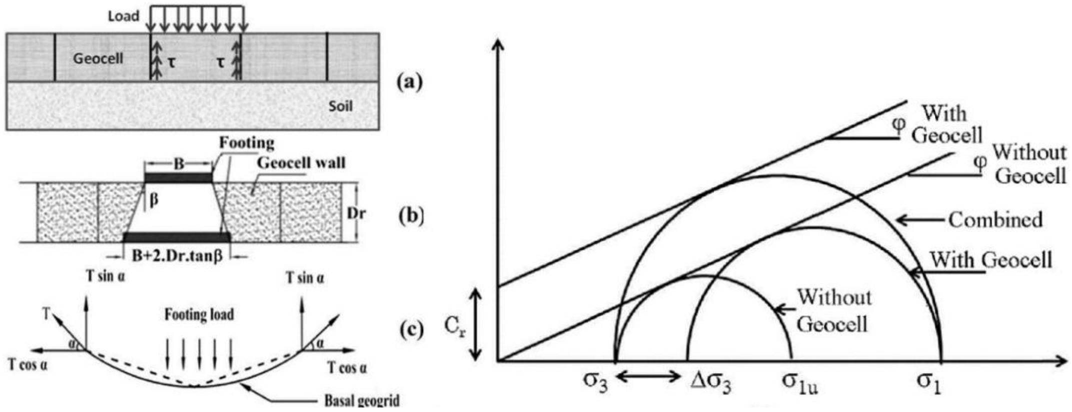


Figure 1: Load transfer mechanisms and failure envelope of confined soil in geocell [6]. a) Lateral resistance, b) vertical dissipation, c) membrane action, and d) failure envelope

A growing body of literature and case studies substantiates the efficacy of geocells in port-like applications. Full-scale field tests and numerical modeling have demonstrated that geocell-reinforced bases can reduce vertical stress on the subgrade by up to 30% and decrease rut depth by over 50% compared to unreinforced sections under similar loading conditions [7]. Case studies from port expansion projects, particularly those on soft reclaimed lands, report successful implementation where geocells enabled a reduction in aggregate base thickness by up to 50%, translating to substantial cost savings and minimized environmental impact [8].

Field-scale applications have further reinforced the benefits of geocell foundations. Hegde and Sitharam [9] reported the successful design and construction of a geocell-supported foundation for a 3 m high embankment over soft red mud, a challenging byproduct of the aluminum ndustry. Their study emphasized the geotechnical difficulties of the site and demonstrated that a combined geocell–geogrid system significantly outperforms geocell reinforcement alone in terms of load-carrying capacity. The implemented foundation system in Lanjigharh, Orissa, proved durable, with the embankment maintaining stability through multiple monsoon seasons.

Advancements in geocell modeling have been presented by Hegde [10], who addressed the complexities of realistically simulating geocells' honeycomb structures in numerical analyses. By employing FLAC3D with geogrid and interface elements, a more accurate three-dimensional model was developed. The study confirmed that geocells substantially improve load distribution within reinforced foundation beds, with performance strongly influenced by geocell modulus, height, pocket size, and surface texture. The validated numerical results showed excellent agreement with experimental findings.

More recently, Demirdöğen, Gürbüz, and Yünkül [11] investigated eccentrically loaded strip footings on geocell-reinforced sand through laboratory model tests. Their work evaluated pressure- settlement behavior, surface displacement, failure modes, and ultimate bearing capacity while varying load eccentricity, geocell height, material stiffness, and soil density. Results indicated up to a 6.5-fold improvement in bearing capacity compared to unreinforced soils. They further proposed a design chart for predicting failure mechanisms and a novel method for estimating ultimate capacity. It was found that higher relative density and stiffer geocell materials enhanced performance, whereas geocell height had only a minor effect.

Collectively, these studies demonstrate the significant contribution of geocell foundations to the performance of structures on weak soils. However, the procedure for proper geocell solution design still not well defined yet due to the many affecting parameters such as the thickness of the geocell layer, the proprieties of the infilling materials, the cell dimensions and material properties.

This paper explores the impact of each one of these parameters on the behavior of containers footings rested on geocell layer for constructing cost-effective storage yards in modern port infrastructure.

2. METHODOLOGY

To quantitatively assess the performance of geocell-reinforced soil under the heavy loads characteristic of port storage yards, a comprehensive finite element method (FEM) parametric study was undertaken. The numerical modeling approach is well-established for simulating the complex soil-structure interaction inherent in geosynthetic-reinforced systems [12, 13]. This study utilized PLAXIS 2D, a commercially available and widely validated FEM software package, ideal for modeling geotechnical problems under plane strain conditions.

In the model, the geocell-reinforced layer was simulated using an equivalent composite approach, a method frequently employed to simplify the modeling of cellular confinement systems while capturing their fundamental mechanical behavior [14]. This approach represents the geocell-reinforced zone as a single, homogenous layer with enhanced mechanical properties derived from the confinement effect. The primary enhancement is a significant increase in the apparent cohesion (c) of the infill material, accounting for the confining effect of the cell walls, and an increase in the elastic modulus (E), representing the increased stiffness of the confined composite [15,16]. The Mohr-Coulomb constitutive model was selected for all soil layers due to its suitability for modeling granular materials and its widespread use in geotechnical practice. Eq. 1 to 3 present correlations between geocell and infilling material characteristics and equivalent properties of strengthen soil [14, 15].

$$\sigma_3 = \frac{2M}{D}\frac{1-\sqrt{1-\varepsilon_a}}{1-\varepsilon_a} \quad (1)$$

$$c = \frac{\sigma_3\sqrt{K_p}}{2} \quad (2)$$

$$E = 4(\sigma_3)^{0.7}\,(K_u + 200M^{0.16}) \quad (3)$$

Where, D is the initial diameter of the geocell and M is the secant modulus of the geocell material, Kp is the coefficient of passive earth pressure and Ku is the dimensionless modulus parameter of the unreinforced soil. In this study, M, Ku and ε_a values are considered 280 kN/m, 500 and 2.5% respectively.

A parametric study was designed to investigate the influence of three key variables: the magnitude of confining stress provided by the geocell (σ3), the geocell thickness to foot width (H/B), and the internal friction angle (φ) of the infill material. The 2D model geometry consisted of a 20.0 m wide by 10.0 m deep of loose sand. A 1.0 m width surface distributed load is used to simulate the stresses under a typical strip footing supported a stack of containers. The model boundaries were vertically fixed at the bottom and fixed horizontally on the vertical sides as shown in Fig 2. Fig 3 presents the considered methodology. The parameters were varied systematically as follows:

- Confining stress (σ_3): The selected values were 0, 15, 21, and 32 kPa to simulate the unreinforced soil and soil confined using geocell (45x52 cm), (34x36 cm), and (21x24 cm), respectively.
- Geocell thickness to foot width (H/B): The thickness of the geocell-reinforced layer (H) was set to 0.0, 0.2, 0.4, and 0.6 m to simulate unreinforced soil and soil

reinforced with one, two, and three layers of geocell. The foot and geocell widths are kept 1.0 and 3.0 m.

- Internal friction angle of infill material: Three types of infill were considered:
  - Pure Sand (γ = 18 kN/m^3, φ = 30°, E = 10 MPa, μ = 0.3, ψ = 0°).
  - Sand and crushed stone (1:1) mixture (γ = 20 kN/m^3, φ = 38°, E = 50 MPa, μ = 0.3, ψ = 8°).
  - Pure crushed stone (γ = 22 kN/m^3, φ = 45°, E = 100 MPa, μ = 0.3, ψ = 15°).

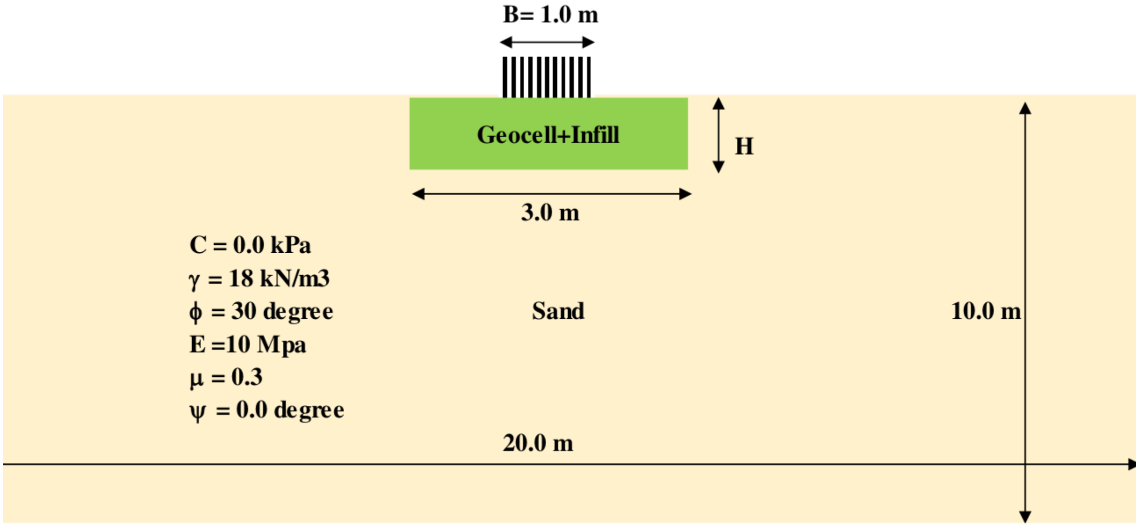


Figure 2: The considered FEM model

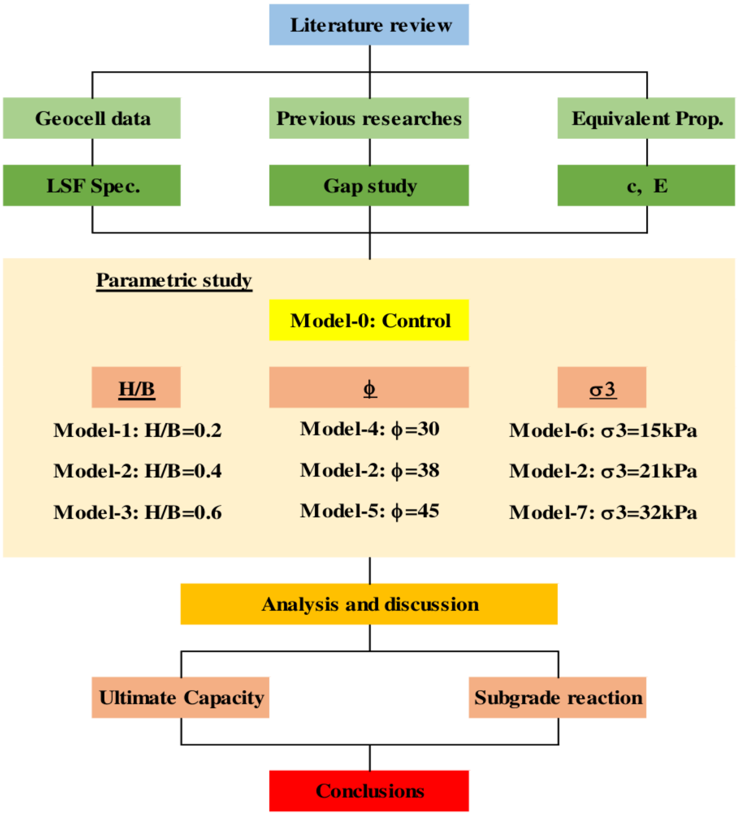


Figure 3: The considered methodology

The developed control FEM model was verified against the reported results by Loukidis et al , 2009 [17]. They presented a detailed investigation about modeling strip and circular footings on sand using FEM. The parameters of the control model of this research matched one of their models, and hence, their results was used to verify it. Their ultimate bearing capacity and settlement values were 110 kN and 35mm comparing with 99 kN and 27mm in the current study.

For each combination of parameters, the model was run to failure. The performance of each scenario was assessed based on three critical output metrics: (1) the ultimate bearing stress (Wu) (2) the ultimate settlement below the center (Δu), and (3) the subgrade reaction at stress of 100 kPa (K100) which is (100/Δ100) where Δ100 is the settlement corresponding to a stress of 100 kPa. The results from this systematic analysis provide a robust framework for evaluating the effectiveness of different geocell configurations in mitigating settlement and protecting weak subgrades.

3. RESULTS AND DISCUSSION

This section presents the numerical results obtained from the finite element models developed to investigate the effect of geocell reinforcement on the behavior of strip footings resting on loose sand. The analysis considers the influence of geocell thickness, type of infill material, and confining stress. The performance of the footing was evaluated in terms of ultimate bearing capacity, settlement at failure, stiffness characteristics, and subgrade reaction modulus. Table 1 summarized the results of this study.

Table 1: The study results

Group	Model ID	H/B	φ (degree)	σ_3 (kPa)	c (kPa)	E (MPa)	Wu (kPa)	Δu (mm)	Δ100 (mm)	K100 (kN/m^3)
Control	**0**	0	30	0	0	10	99	31	27	3704
H/B	**1**	0.2	38	21	21	33	124	42	25	4000
H/B	**2**	0.4	38	21	21	33	273	153	21	4762
H/B	**3**	0.6	38	21	21	33	331	173	20	5000
φ	**4**	0.4	30	21	18	33	198	88	22	4545
φ	**2**	0.4	38	21	21	33	273	153	21	4762
φ	**5**	0.4	45	21	25	33	295	159	21	4762
σ_3	**6**	0.4	38	15	15	26	258	137	22	4545
σ_3	**2**	0.4	38	21	21	33	273	153	21	4762
σ_3	**7**	0.4	38	32	33	45	279	146	20	5000

Notes: H/B = geocell thickness / foot width; c = equivalent cohesion strength; E = equivalent elastic modulus; Wu = ultimate capacity; Δu = ultimate settlement; Δ100 = settlement at stress of 100 kPa; K100 = subgrade reaction at stress of 100 kPa.

3.1. Load-settlement behavior

Fig. 4 compares the load-settlement curves of all models. Reinforced cases consistently demonstrated stiffer initial response than the untreated soil, as evidenced by higher subgrade reaction modulus. For example, Model 0 had K100 = 3704 kN/m^3, while reinforced cases reached K100 = 4000 to 5000 kN/m^3. The improvement in stiffness is particularly pronounced for thicker geocell layers and high-strength infills. Nevertheless, the ultimate settlement at failure tended to increase in reinforced cases, especially for thick layers and high-capacity infills. This can be attributed to the higher mobilization of load transfer mechanisms before failure, allowing larger deformations. From a design perspective, this implies that while geocell reinforcement improves capacity, settlement criteria must be carefully evaluated depending on serviceability requirements.

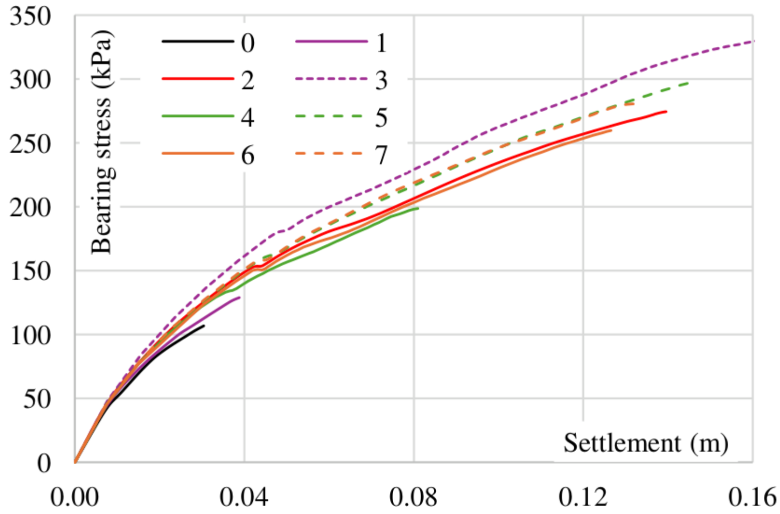


Figure 4: Load-settlement curves for all models

The control model with the untreated soil (Model 0), consisting of loose sand with a friction angle of 30°, served as the reference case. The footing exhibited an ultimate bearing capacity of 99 kPa with corresponding ultimate settlement of 31 mm. The subgrade reaction modulus was calculated as 3704 kN/m^3, the lowest among all cases. Fig. 3 illustrates the load-settlement response, which shows a soft initial stiffness. These results underscore the limited load-carrying capacity of unreinforced loose sand and the need for ground improvement.

3.2. Influence of geocell thickness to foot width (Models 1, 2, and 3)

The effect of geocell layer thickness to foot width was examined by varying it from 0.2 to 0.6 while keeping the infill type (sand-crushed stone mixture, φ = 38°) and confining stress (σ_3 = 21 kPa) constant. Model 1 (H/B=0.2): The ultimate stress increased to 124 kPa, representing a 125% of the untreated case. Settlement at failure increased to 42 mm (135%). (Model 2 (H/B=0.4): A significant improvement was observed with an ultimate capacity of 273 kPa (276%) and settlement of 153 mm (494%). This corresponds to an improvement ratio of approximately 2.8 compared to the baseline. Model 3 (H/B=0.6): The maximum improvement was achieved with a capacity of 331 kPa (334%) and settlement of 173 mm (558%). Fig. 5 compares the load-settlement curves, demonstrating that increasing geocell thickness not only improves ultimate capacity but also enhances the initial stiffness.

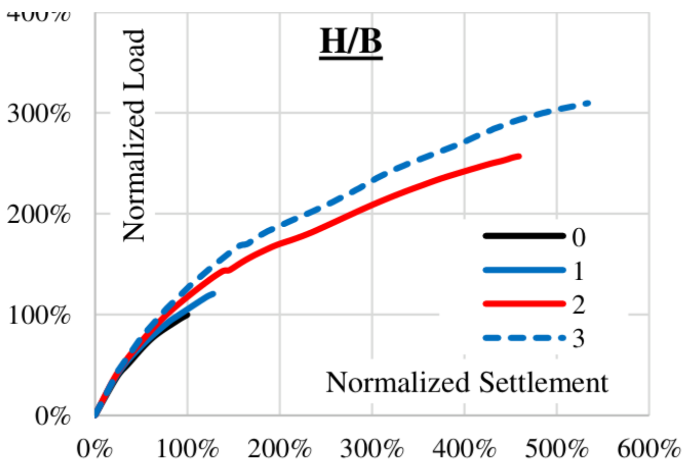


Figure 5: Influence of geocell thickness / foot width (H/B)

3.3. Influence of infill material (Models 2, 4, and 5)

The type of material used to fill the geocell pockets strongly influenced footing performance. For a constant thickness of 0.4 m and confinement stress of 21 kPa, three infill types were compared: Sand infill (Model 4, φ = 30°): Ultimate stress increased to 198 kPa, nearly doubling the control model capacity (200%). Settlement at failure was 88 mm (284%). Sand-crushed stone mixture (Model 2, φ = 38°): Provided higher capacity of 273 kPa (276%) with settlement of 153 mm (494%). Crushed stone infill (Model 5, φ = 45°): Yielded the highest capacity of 295 kPa (298%), with settlement of 159 mm (513%). The comparison (Fig. 6) shows a clear trend: higher friction angle infills result in higher capacity. Crushed stone, with the highest strength and stiffness, produced the best performance. Interestingly, increasing the internal friction angle of the infilling material increases only the apparent cohesion (c) while the equivalent elastic modulus (E) still the same, that improves the bearing capacity but not the subgrade reaction.

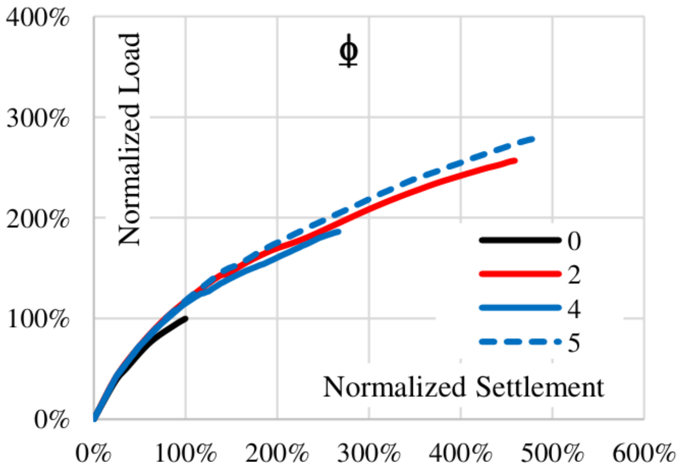


Figure 6: Influence of infilling friction angle

3.4. Influence of confining stress (Models 2, 6 and 7)

The effect of lateral confinement on footing response was examined for geocell layers of 0.4 m thickness filled with a sand-stone mixture. Low confinement (σ_3 = 15 kPa, Model 6): Ultimate capacity dropped to 258 kPa (261%), with settlement of 137 mm

(442%). Medium confinement (σ_3 = 21 kPa, Model 2): Produced an ultimate capacity of 273 kPa (276%) and settlement of 153 mm (494%). high confinement (σ_3 = 33 kPa, Model 7): Capacity improved slightly to 279 kPa (282%) with a settlement of 146 mm (471%). The results (Fig. 7) indicate that confinement enhances the mobilization of geocell–soil interaction. However, beyond a certain threshold, the improvement in capacity diminishes. The optimum confining stress appears to lie between 21–33 kPa, above which the gains are marginal.

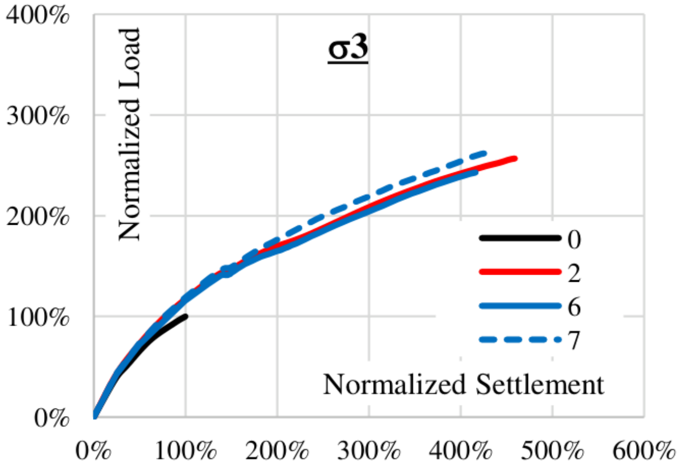


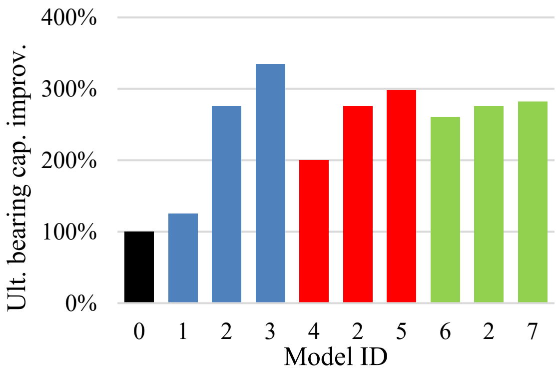
Figure 7: Influence of confining stress

3.5. Comparative performance and design implications

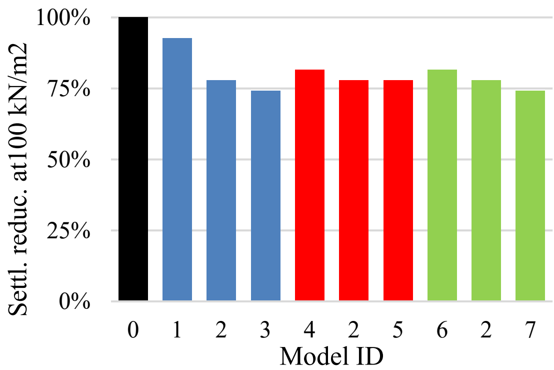
Fig. 8 presents a comparison of improvement ratios in bearing capacity and settlement across all models. The results highlight that Geocell thickness is the most influential parameter, with a nearly linear improvement in capacity up to 0.6 m.

- Infill material strongly affects performance. Crushed stone provides maximum strength improvement, while sand infill offers lower settlement.
- Confining stress has a secondary role, with diminishing returns beyond σ_3 = 21 kPa.

These findings are consistent with previously reported laboratory studies, which emphasize the combined role of confinement and infill strength in geocell-reinforced systems. The FEM results confirm that geocell reinforcement redistributes stresses more effectively and restricts lateral soil movement, thereby enhancing footing stability.

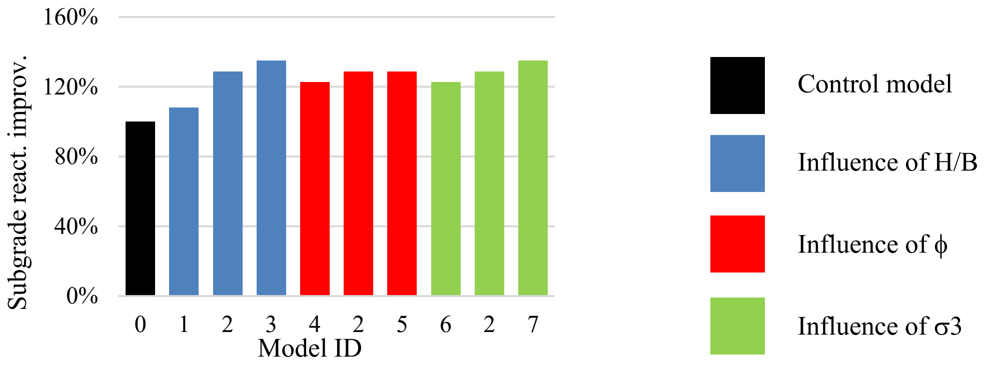


a) Ultimate bearing capacity



b) Settlement at stress of 100 kPa

http://dx.doi.org/10.21622/MARLOG.2026.15.1.29



c) Subgrade reaction at stress of 100 kPa

Figure 8: Comparing the impact of inputs (H/B, φ, σ_3) on a) ultimate bearing capacity, b) settlement at stress of 100 kPa, and c) subgrade reaction at stress of 100 kPa

A key practical implication emerging from these results is the strength–settlement trade-off associated with increasing geocell thickness. While ultimate bearing capacity rises markedly with larger H/B ratios, the corresponding increase in ultimate settlement becomes substantial and may challenge serviceability requirements in operational ports. For example, at H/B = 0.6 the ultimate settlement reached up to 5.6 times the control model, reflecting significantly greater vertical deformation prior to failure. In real container yards, however, serviceability limits and pavement performance criteria are typically governed not by ultimate failure conditions, but by allowable settlements that maintain level surfaces for crane rails, stacking equipment, and container stability. Excessive deformation can disrupt drainage, reduce operational efficiency, and require costly maintenance interventions.

Therefore, designers must balance the gains in load capacity with acceptable deformation targets when specifying geocell layer thickness. For many port applications, the results suggest that intermediate values of H/B (≈0.2–0.4) may offer an optimum range: they deliver large gains in ultimate capacity and improved subgrade stiffness while limiting settlement growth to levels more consistent with serviceability thresholds. Beyond this range, the marginal benefits in bearing strength may not justify the associated increase in deformation. To refine this balance for a specific site, practitioners should evaluate allowable settlements based on operational tolerances, incorporate elastic settlement predictions rather than only ultimate values, and consider pairing geocells with higher-modulus infills or surface pavement layers capable of distributing load more efficiently.

This trade-off highlights the importance of linking numerical design to performance-based criteria. The geocell configuration should be selected not solely for maximum strength enhancement, but for optimal yard performance under working loads—maintaining stability, service lifespan, and operational smoothness without exceeding acceptable differential settlement limits. Future port-specific design guidelines may therefore benefit from establishing recommended H/B limits tied to settlement performance, offering engineers a clearer pathway to balance capacity enhancement with practical serviceability control.

Although the sustainability advantages of geocell reinforcement are described qualitatively in this paper, the approach also offers quantifiable environmental and material-saving benefits that strengthen its contribution to sustainable port engineering. Published field applications have reported that geocell-reinforced bases can reduce granular base thickness by up to 50% compared with conventional unreinforced sections, translating into significant reductions in quarried aggregate and associated transportation demands [18]. In port yard projects, where pavement areas extend over tens to hundreds of thousands of square meters, even a 20–30% reduction in imported aggregate could result in thousands of tons of material saved, accompanied by meaningful decreases in fuel use, carbon emissions, and construction time [19].

In addition, the improved load distribution demonstrated in this study—where bearing capacity increased by factors ranging from 1.25 to 3.34 depending on H/B—suggests that geocells may enable thinner pavement structures or longer operational life cycles under the same loading conditions [20]. These outcomes are directly linked to sustainability indicators, including life cycle cost reduction, minimized maintenance interventions, and decreased operational disruptions [21].

4. CONCLUSIONS

This study undertook a systematic numerical investigation to evaluate the efficacy of geocell reinforcement for improving the load-bearing capacity and settlement response of soil foundations in port storage yards, which are increasingly subjected to extreme loads. Utilizing Finite Element Method (FEM) modeling in PLAXIS 2D, a parametric study was conducted to isolate and quantify the influence of key design variables—geocell thickness to foot width, magnitude of confining stress, and infill material type—on 1.0 m width strip footing. The principal outcomes of this research are summarized as follows:

- The inclusion of geocell reinforcement markedly improved the ultimate bearing capacity of strip footings on loose sand. Compared with the untreated case (Model 0), the capacity increased by factors ranging from 1.25 (H/B=0.2) to 3.34 (H/B=0.6), confirming the efficiency of geocells in enhancing load resistance.
- Geocell thickness emerged as the dominant parameter: capacity improved nearly linearly with thickness up to B/H=0.6, while settlements at ultimate load also increased, reaching up to 5.6 times the control model settlement. This highlights a trade-off between strength gain and deformation control.
- The infill type strongly influenced performance. Sand infill (φ=30o) doubled the control model capacity (2.0×), while sand-stone mixture (φ=38o) and crushed stone (φ=45o) achieved 2.76× and 2.98× improvements, respectively. However, higher-strength infills were associated with larger ultimate settlements because increasing the (φ) has no impact on the equivalent elastic modulus (E).
- Confining stress enhanced performance but showed diminishing returns. Reducing confinement to 15 kPa lowered capacity to 2.61× the baseline, while increasing it to 33 kPa yielded only a modest rise to 2.82×, suggesting that an optimum value exists around 21 kPa.
- Geocell reinforcement improved stiffness characteristics: the subgrade reaction modulus by 1.35 times compared to untreated soil. These enhancements confirm the ability of geocells to redistribute stresses and restrict lateral soil displacement, thereby improving both strength and deformational behavior.

A primary limitation of this study is the use of an equivalent composite model to represent the geocell layer. While computationally efficient, this approach simplifies the complex three-dimensional soil-geosynthetic interaction and does not explicitly model the individual cell walls and their interface with the infill material. Furthermore, the model considered a static load under plane-strain conditions. Future studies should build upon this work by employing more advanced 3D modeling techniques that can explicitly represent the geocell geometry to provide deeper insight into the micromechanics of confinement. Subsequent research should also incorporate cyclic loading analysis to simulate the long-term effects of repetitive traffic and investigate the potential for fatigue or degradation. Finally, full-scale field validation studies within an operational port environment are essential to calibrate numerical models and confirm the long-term economic and performance benefits predicted herein.

5. ACKNOWLEDGMENTS

The authors would like to thank LSF Co. and NECB consultancy for their valuable assistance in preparing this study.

6. DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

During the preparation of this work, the authors used Chat GPT 4.0 in order to improve the language. After using this tool/service, the authors reviewed and edited the content as necessary and take full responsibility for the content of the publication

7. REFERENCES

[1] Notteboom, Theo E., and Jean-Paul Rodrigue. "Port regionalization: towards a new phase in port development." Maritime Policy & Management 32, no. 3 (2005): 297-313. https://doi.org/10.1080/03088830500139885

[2] Ebid, Ahmed M., Kennedy C. Onyelowe, Mohamed Salah, and Edward I. Adah. "Using FEM-AI technique to predict the behavior of strip footing rested on undrained clay layer improved with replacement and geo-grid." Civ. Eng. J 9, no. 05 (2023). http://dx.doi.org/10.28991/CEJ-2023-09-05-014.

[3] Han, Jie. Principles and practice of ground improvement. John Wiley & Sons, 2015. ISBN: 978-1-118-42130-7

[4] Rajagopal, K., Krishnaswamy, N. R., & Latha, G. M. (1999). Behaviour of sand confined with single and multiple geocells. Geotextiles and Geomembranes, 17(3), 171-184. https://doi.org/10.1016/S0266-1144(98)00034-X

[5] Pokharel, Sanat K., Jie Han, Dov Leshchinsky, Robert L. Parsons, and Izhar Halahmi. "Investigation of factors influencing behavior of single geocell-reinforced bases under static loading." Geotextiles and Geomembranes 28, no. 6 (2010): 570-578. https://doi.org/10.1016/j.geotexmem.2010.06.002

[6] Ebid, Ahmed M., Nada M. Abdelhamid, Amr H. Zaher, and Dina M. Ors. "Improving the punching capacity of footings using geocell, geogrid and granular soil replacement." Scientific Reports 15, no. 1 (2025): 11148. https://doi.org/10.1038/s41598-024-81251-y

[7] Yang, Xiaoming, Jie Han, Sanat K. Pokharel, Chandra Manandhar, Robert L. Parsons, Dov Leshchinsky, and Izhar Halahmi. "Accelerated pavement testing of unpaved roads with geocell-reinforced sand bases." Geotextiles and Geomembranes 32 (2012): 95-103. https://doi.org/10.1016/j.geotexmem.2011.10.004

[8] Biswas, A., A. Murali Krishna, and S. K. Dash. "Influence of subgrade strength on the performance of geocell-reinforced foundation systems." Geosynthetics International 20, no. 6 (2013): 376-388. https://doi.org/10.1680/gein.13.00025

[9] Hegde, A., and T. G. Sitharam. "3-Dimensional numerical modelling of geocell reinforced sand beds." Geotextiles and Geomembranes 43, no. 2 (2015): 171-181. https://doi.org/10.1016/j.geotexmem.2014.11.009

[10] Hegde, A. "Geocell reinforced foundation beds-past findings, present trends and future prospects: a state-of-the-art review." Construction and Building Materials 154 (2017): 658-674. https://doi.org/10.1016/j.conbuildmat.2017.07.230

[11] Demirdöğen, Sarper, Ayhan Gürbüz, and Kaan Yünkül. "Performance of eccentrically loaded strip footings on geocell-reinforced soil." Geotextiles and Geomembranes 52, no. 4 (2024): 421-434. https://doi.org/10.1016/j.geotexmem.2023.12.007

[12] Bathurst, Richard J., and Mark A. Knight. "Analysis of geocell reinforced-soil covers over large span conduits." Computers and Geotechnics 22, no. 3-4 (1998): 205-219. https://doi.org/10.1016/S0266-352X(98)00008-1

[13] Leshchinsky, Ben, and Hoe I. Ling. "Numerical modeling of behavior of railway ballasted structure with geocell confinement." Geotextiles and Geomembranes 36 (2013): 33-43. https://doi.org/10.1016/j.geotexmem.2012.10.006

[14] Madhavi Latha, G., and K. Rajagopal. "Parametric finite element analyses of geocell-supported embankments." Canadian Geotechnical Journal 44, no. 8 (2007): 917-927. https://doi.org/10.1139/T07-039

[15] Vibhoosha, M. P., Anjana Bhasi, and Sitaram Nayak. "A review on the design, applications and numerical modeling of geocell reinforced soil." Geotechnical and Geological Engineering 39, no. 6 (2021): 4035-4057. https://doi.org/10.1007/s10706-021-01774-3

[16] Engr Hamza Ahmad Qureshi, Muhammad Safdar, Md. Munir Hayet Khan, Lateral capacity of group helical piles in sand: an experimental and numerical study for sustainable infrastructures, International Journal of Geotechnical Engineering, Volume 18, 2024 - Issue 7-10

[17] Loukidis, D., & Salgado, R. (2009). Bearing capacity of strip and circular footings in sand using finite elements. Computers and Geotechnics, 36(5), 871-879.

[18] Yang, X., Han, J., Pokharel, S. K., Manandhar, C., Parsons, R. L., Leshchinsky, D., & Halahmi, I. (2012). Accelerated pavement testing of unpaved roads with geocell-reinforced sand bases. Geotextiles and Geomembranes, 32, 95-103.

[19] Saleh, R. M., & Abdelmaguid, T. F. (2025). Comparative Analysis of Dedicated and Randomized Storage Policies in Warehouse Efficiency Optimization. Eng, 6(6), 119..

[20] Pokharel, S. K., Han, J., Leshchinsky, D., Parsons, R. L., & Halahmi, I. (2010). Investigation of factors influencing behavior of single geocell-reinforced bases under static loading. Geotextiles and Geomembranes, 28(6), 570-578.

[21] Hegde, A. (2017). Geocell reinforced foundation beds-past findings, present trends and future prospects: a state-of-the-art review. Construction and Building Materials, 154, 658-674.