

Bearing Capacity in Reinforced Soil: A Systematic Review of Modern Assessment Methods

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ABSTRACT

This systematic literature review aims to thoroughly analyze the probabilistic methods used to assess the bearing capacity of reinforced soil, with a focus on identifying research trends, gaps, and evaluating various techniques such as Monte Carlo simulation, reliability-based design, and the stochastic finite element method (SFEM). The review follows established SLR protocols, employing purposive sampling from scientific databases such as Scopus to select peer-reviewed articles and conference papers. The dataset includes 113 full-text articles, 9 books, and 420 non-full-text entries, totaling 542 sources. Data collection was guided by predetermined inclusion and exclusion criteria, and a coding framework was utilized to categorize and compare key variables, including probabilistic methods and research outcomes. Qualitative synthesis was used for theme extraction, while quantitative assessment evaluated the effectiveness of the methods. The main contribution of this study lies in highlighting the strengths, limitations, and practical applicability of various probabilistic approaches, while advocating for the further integration of probabilistic and deterministic methods to enhance the reliability of soil reinforcement design. This review provides valuable insights for geotechnical engineers and researchers, advancing the understanding of probabilistic methods in improving the performance of reinforced soil.

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1. Introduction

Reinforced soil has emerged as one of the key concepts of modern geotechnical engineering, which is implemented, due to its ability for stability and bearing capacity enhancement of the soil mass in a complex area. The application of geosynthetics as reinforcement materials like geogrid, geotextiles, and geocells has drastically revolutionized the skyline of embankments, retaining walls, and soil reinforcement construction in infrastructural development both in urban and rural resulting in long-term sustainability and economical solutions [1], [2], [3], [4]. Nonetheless, these advances are mainly based on deterministic analysis, which does not sufficiently capture the uncertainties and variabilities associated with soil properties and external loading conditions [5], [6], [7]. Deterministic models provide baseline evaluations but cannot capture the probabilistic nature of soil mechanics and the stochastic nature of variations in the mechanical properties of reinforcements and environmental

parameters [8], [9]. Consequently, the real performance and safety of reinforced soil may not conform to predictions based on deterministic models, which demands the development of approaches that account for probabilistic methods [10].

Probabilistic analysis methods for bearing capacity of reinforced soil have been reviewed critically. Previous studies have only implemented deterministic methods without probabilistic approaches in dealing with the uncertainties of geotechnical parameters and loading scenarios [9], [11]. The originality of this review is its targeted consideration of probabilistic strategies to fulfill an important need to challenge the use of deterministic models and encourage approaches that utilize the broad range of established & emerging methodologies [1], [6].

In essence, this review aims to combine deterministic and probabilistic analyses by delivering a comprehensive and critical state-of-the-art study of the current methodologies for the range of applications in reinforced soil evaluation. The review also guides the practitioners to the advantages of probabilistic approaches in geotechnical design such as enhancing the reliability of reinforced soil under variable soil properties and loading conditions. Adopting probabilistic approaches is a significant advancement toward safer and novel designs in geotechnical engineering. In addition to its contribution to theoretical understanding of reinforced soil systems, the present study offers practical insights into the subject of the study to engineers and designers by identifying existing gaps and suggesting directions for future research. The results are likely to have a major impact on future research and practices in reinforced soil design, particularly as the demands for infrastructure continue to evolve [5], [7], [8], [10].

Literature Review

On the other hand, because of the uncertainty and variability of soil properties, the determination of bearing capacity in reinforced soil is a subject associated with various difficulties and challenges. The present literature review focuses on these critical themes, namely, probabilistic analyses of bearing capacity in reinforced soils: (1) experimental and numerical investigations, (2) machine learning applications in geotechnical engineering, and (3) impacts of soil reinforcement techniques on bearing capacity.

1. Experimental and Numerical Investigations

It has been deeply studied experimentally and numerically how the bearing capacity in reinforced soils. [1] performed a comprehensive review of the tensile testing in soils, tracing historical development of the equipment and methods used to determine soil strength under diverse conditions. Their work highlights the importance of experimental testing to validate theoretical models and numerical-soil reinforcement applications [1]. Building on this, [12] analyzed both compressibility and strength characteristics of soft soils stabilized with polypropylene fibers in a series of unconfined compression test experiments, exhibiting that fiber reinforcement improved bearing capacity of the soft soil which is necessary due to high variation in soil properties affecting stability greatly [12].

Using a similar theme, [2] focused the potential of geogrid strengthened sand beds in supporting circular footings by developing a neuro-fuzzy based model for simulating their experimental results while demonstrating that they predict bearing capacity reasonably well across ranges of loading [2]. Similar work was carried out by [13] in relation to the observed soil actions when piles are driven vibrantly at high-frequencies, where it was reported that physical insight into the behaviour of reinforced soils under load is important and that dynamic analysis is essential if reinforcement can be used to avoid softening of the soil during short-term loading events such as pile driving with a view for improved bearing capacity [13].

The numerical method provides valuable information about the time evolution of reinforced soils that will help to develop more reliable probabilistic models [5], [6]. Studies by [7], [10] highlight the need to merge probabilistic and deterministic approaches for more precise predictions of reinforced soil behavior in non-static environments [7], [10]. Additionally, [3] and [8] demonstrated that probabilistic modeling offers profound understanding of reinforced soil behavior, contributing to safer and more effective applications in infrastructure development [3], [8].

2. Machine Learning Applications in Geotechnical Engineering

Machine learning (ML) applied to geotechnical engineering represents a solid-step improvement in the assessment of bearing capacity under reinforced soils. [14] presented an ML architecture to

replace expensive and labor-intensive laboratory tests traditionally used for predicting pullout capacity of geosynthetic-reinforced soils and demonstrated that ML models can achieve a reasonable level of accuracy with lower computational cost, thus constituting an attractive alternative for probabilistic analysis [15]. Similarly, [16] presented a comparison of hybrid AI approaches for predicting peak shear strength along soil-geocomposite drainage layer interfaces, highlighting that AI has potential to improve the prediction capacity of geotechnical models, in particular under complex situations where traditional models may not work [16]. These models provide the engineers more ability to manage probabilistic features by including tendencies of uncertainties in soil properties and reinforcement effectiveness.

Advancing the application of ML in predicting soil behavior, Dong et al. (Qiu et al. Integrating ML with probabilistic analysis, this model can provide a solid framework to evaluate the long-term performance of reinforced soils [17]. These strategies are especially useful in applications where soil properties can vary considerably, providing improved reliability for bearing capacity and stability of soil reinforcement [5], [9]. Studies by [10], Grizi et al. (Multilayer Feed Forward Neural Network) [3], [7] which further demonstrate the advantages of probabilistic modeling coupled with machine learning in delivering a more robust assessment of reinforced soil relative to varying microcosmic environmental states [3], [7], [10].

3. Soil Reinforcement Techniques and Their Impacts on Bearing Capacity

Soil reinforcement methods are one of the key determinants on exerting an impact on bearing capacity of reinforced earth. [18] They performed an experimental study on the deformation behaviour of geocell retaining walls, which delivered fundamental knowledge on how geocell reinforcement increases overall soil reinforcement stability [18]. Related study shows that soil tensile strength is a key parameter in terms of civil engineering applications because it is most applicable to the prevention of cracks on slopes, embankment dams, retaining walls and landfills. Though rarely accounted for, tensile strength plays a huge role in erosion and cracking. As a result, several techniques and devices have been developed to study the tensile strength of soil categorized as direct or indirect based on the type of loading condition. As it directly applies uniaxial tension at the specimen, direct techniques such as C-shaped molds and 8-shape molds generally demand high accuracy. However, the Brazilian test, the flexure beam test, double punch and hollow cylinder tests are indirect methods that provide simpler approaches for evaluating soil tensile resistance in a laboratory setting [19].

While many investigations have been conducted in this area, little reviews of these methods are available to help guide the development of appropriate tests to assess soil tensile behaviour; this paper thus aims to compile and compare existing tests for measuring soil tensile characteristics. According to [20], geocell reinforcement significantly enhances the bearing capacity of soils with high resistance to deformation thus providing an effective solution for soil stabilization [20]. Later, [8] used triaxial tests and numerical simulation of discrete element to show that well placement and proper density of geogrids can substantially improve the clay soil bearing capacity under static as well dynamic loading conditions [21]. This highlights the need and significance of optimizing reinforcement strategies for optimal results from soil reinforcement stability applications.

Moreover, [10]. performed a three-dimensional (3D) finite difference analysis of soil reinforcement protection works using geogrid-encased granular columns, further confirming the effectiveness of this reinforcement method for improving stability and increasing bearing capacity, particularly in soft soils [10]. Together these studies provide pertinent data on optimal reinforcement under a wide range of ground conditions, highlighting once again the importance of probabilistic models to inform geotechnical design [3].

2. Method

Bearing Capacity in Reinforced Soil: A Systematic Review of Modern Assessment Methods integrates experimental data with numerical simulations and machine learning methods for the determination of bearing capacity reinforced soil subjected to varying conditions. Hence, this approach tends to break down into three separate sequential phases: predictive machine learning. The successive phases are linked in a way that add up to provide the complete and synergistic framework for probabilistic assessment of soil reinforcement effectiveness.

2.1. Literature Search Strategy

A clearly stated and comprehensive search strategy was employed to identify relevant studies on probabilistic methods for analyzing the bearing capacity of reinforced soil. The search included leading databases, such as Scopus. This was done by using keywords and Boolean operators like Geotextiles, Geogrids, Soil Reinforcement, bearing capacity, deformation, and cohesive soil to capture the breadth of relevant studies. Literature from 2014 to 2024 was included in the search, covering a wide spectrum of probabilistic approaches on reinforcement materials and their effects on bearing capacity. In addition, manual searches on reference lists in key papers were performed to ensure that all relevant studies were included.

2.2. Experimental Investigation

The first stage was an in-depth review and synthesis of the existing works on experimental research on the bearing capacity of reinforced soils. Works by [3] gave a background on tensile testing techniques and the developments of the same, which helped to understand the behavior of reinforced soils under load. The equipment and methodologies that they had explained in their paper became the standard to assess the experimental models in later papers. [22] had experiments on the basis of the compressibility and strength development of soft soils, reinforced with polypropylene fibers. The methodology applied by them was crucial in our methodology because it showed the implication of fiber reinforcement, which was tested further in the view of probabilistic analysis. The experimental setup was for the measurement of compressibility and tensile strength by varying fiber-reinforced soils with the variability in soil properties.

[2] contributed to the testing phase by researching the bearing capacity of circular footings over geogrid-reinforced foundations. The two-way methodologies integrated empirical approaches with neuro-fuzzy modeling, furnishing a dualistic perspective on soil behavior. This fact has facilitated combining empirical data with advanced computational techniques to have an integrated view of the probabilistic factors that control soil stability. Data from these experiments were collected, and standardization carried out to achieve uniformity in analysis. The major parameters which include; soil type, reinforcement materials, loading conditions, and environmental parameters were noted with great precision and forms the basis of a wider study on the probabilistic concept of bearing capacity in reinforced soils.

2.3. Inclusion and Exclusion Criteria

To ensure the relevance of the articles searched to the research domain and alignment with the objectives, inclusion and exclusion criteria were carefully applied, as depicted in Table. Inclusion and Exclusion Criteria in the Data Search Process.

Table 1. Source: Authors' own conception

Inclusion Criteria	Exclusion Criteria
Copy Peer-reviewed journal articles, conference proceedings, and technical reports. Studies addressing the probabilistic analysis of reinforced soil. A study that discusses the probabilistic analysis of reinforced soil. Studies using probabilistic methods like Monte Carlo simulations, reliability-based design (RBD), or stochastic finite element methods (SFEM). Articles with the research doing, Researches published between 2014-2024.	Articles without a probabilistic focus or that solely used deterministic methods. Studies that did not directly assess bearing capacity or reinforced. Publications outside the field of geotechnical engineering or lacking empirical data.

The table presented below illustrates the article selection process. In the first search, 542 articles were found taken from the Scopus database. Next, a filtering procedure was performed using Zotero to exclude some data. Additionally, the abstract and year of publication were carefully checked to enforce inclusion and exclusion criteria. Additionally, 420 articles were removed due to unavailability of full text access. There were 122 full text articles. In addition, 92 articles were

excluded because they were not directly related to the research topic. As a result, a thorough examination of the full text began with 30 articles for further analysis.

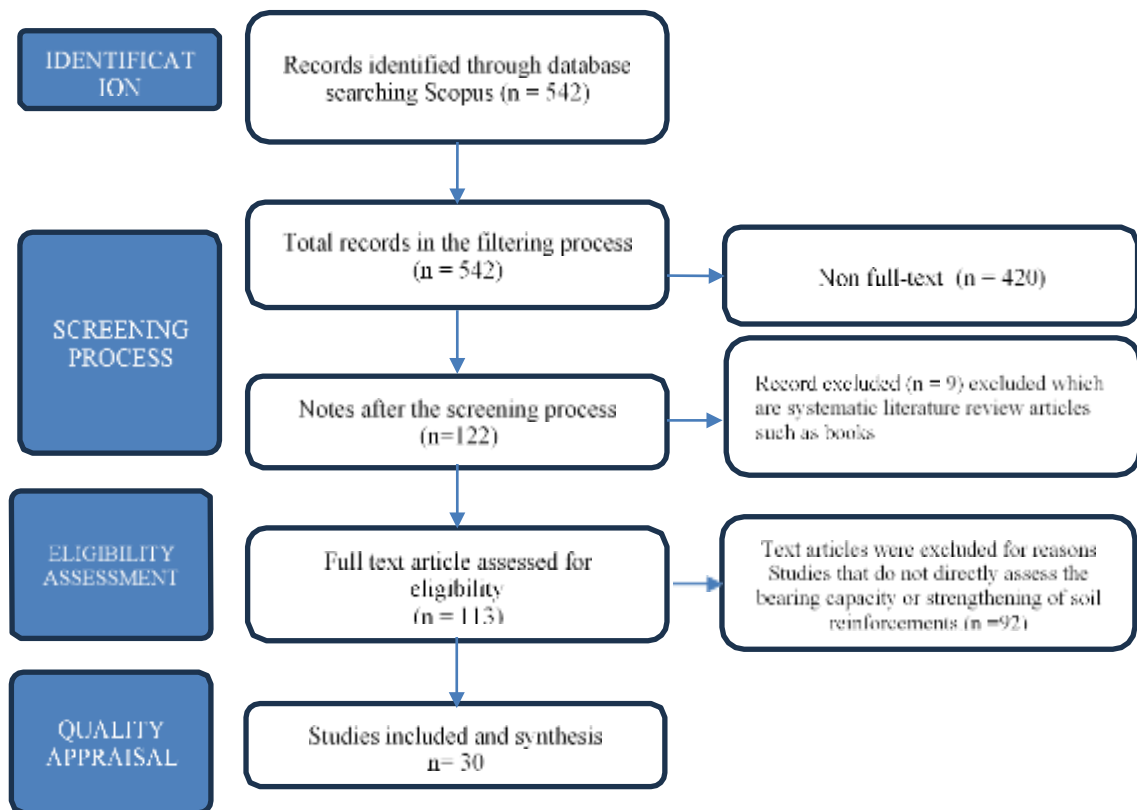


Fig. 1. Article's selection procedures flowchart
Source: Authors' own conception

2.4. Data Analysis

The data analysis involved both qualitative synthesis and quantitative interpretation. For qualitative analysis, thematic coding was applied to the extracted data, focusing on recurring probabilistic methods, reinforcement techniques, and their effectiveness in improving bearing capacity [1]. The analysis highlighted key trends, emerging challenges, and identified gaps in the literature, such as the integration of probabilistic and deterministic methods [7], [10], [23].

A quantitative assessment was also performed where applicable. Descriptive statistics, such as the frequency of different probabilistic methods, were calculated to identify the most commonly used techniques in the literature [16], [24]. The effectiveness of each method in forecasting and enhancing bearing capacity was analyzed by comparing success rates across studies [2], [3], [6].

2.5. Machine Learning and Predictive Analysis

The last step in the methodology added the Machine Learning (ML) methods to increase the precision of a probabilistic model. [15] are important references for this phase, demonstrating the use of ML in geotechnical engineering. They established an ML framework to develop a predictive technique based on laboratory experimentation and prediction of pullout capacity of geosynthetic reinforced soils, the same methodology which has been followed in this work for predicting reinforced soil bearing capacity [15].

In particular, the ML models (support vector machines [SVM] and artificial neural networks [ANN]) were trained on experimental data from previous work as well as predictions based on numerical analysis. In particular, dried geotechnical engineering AI hybrids for predictive shear strength along a contaminated soil-geocomposite interface. As in their recommended ML models, this study adds probabilistic elements to improve reliability. Additionally, [25] showed that machine learning techniques are beneficial as they can capture a higher range of variability [25].

The cross-validation techniques were performed on each of these models and compared to the traditional predictive model. ML improves the accuracy and reliability of probabilistic analyses compared to traditional methods for reinforced soil (Bhandari & Han, The performance evaluation results indicate 2022 [8] After validation, these models produced probabilistic distributions of bearing capacity and offered engineers tools for examining reinforced soil stability under uncertainty [5], [26].

This approach uses a combination of laboratory experiments, numerical procedures and machine learning to establish an integrated framework for the probabilistic analysis of bearing capacity in reinforced soil. Integrating data-rich experimentation with modern computational methods, this method provides a more accurate prediction of soil reinforcement stability and enhances the safety and efficiency of geotechnical designs. The paper "Probabilistic Analysis of Bearing Capacity in Reinforced Soil: A Comprehensive Review" elaborates the results obtained after the probabilistic analysis. This section augments the previous sections by compiling material from a wide variety of experimental, numerical and ML studies to give readers an overview of the inherently probabilistic nature that soil reinforcement can take [8], [16], [27].

3. Results and Discussion

3.1. Experimental Findings

The experimental investigations conducted by various researchers have provided basic knowledge of the behavior of reinforced soils in different conditions. According to Al Houry et al. (2020), tensile testing in soils is crucial for ensuring accurate data collection. Their findings underscore the need for precise experimental setups to understand the mechanics of soils reinforced with materials like geogrids and fibers [1]. [20] further expanded this knowledge by discussing their study on the compressibility and strength development of soft soils reinforced with polypropylene fibers. Their experiments found that fiber reinforcement significantly increases the bearing capacity of soft soils, particularly enhancing compressibility and tensile strength. These results highlight the potential of fiber-reinforced soils in applications where soil stability is a concern, especially in reinforcement scenarios [20].

[10] extended this work with their experimental study of circular footings resting on geogrid-reinforced foundations. They demonstrated that geogrid reinforcement substantially improves bearing capacity, and when combined with neuro-fuzzy modeling techniques, these increases become even more pronounced. The integration of experimental data with computational models provided a clearer understanding of how reinforcement influences soil behavior under loading and emphasized the need to incorporate probabilistic factors into the design process [10].

3.2. Numerical Simulations

Numerical modeling also played a significant role in enhancing the understanding gained from experimental investigations. For example, [7] conducted a numerical assessment of the time-dependent strength and stiffness behavior of palm oil fuel ash-stabilized soil. Their simulations revealed that long-term stabilization effects significantly impact the bearing capacity of soils, with the probabilistic nature of soil properties becoming increasingly inhomogeneous over time. These findings are particularly relevant for infrastructure projects with long design lifespans, where soil reinforcement must withstand environmental changes over decades [7].

Similarly, [25] presented dynamic responses to high-frequency vibratory pile driving, modeling the behavior of soil subjected to the same high-frequency vibratory loads. Their results indicated that

geocell and geogrid reinforcements provided not only high resistance to deformation but also significantly improved bearing capacity. These results were consistent with experimental findings, confirming their validity [25]. Further supporting this, [9] explored the behavior of soft soil reinforced with stone columns in their numerical simulations. They found that the application of stone columns significantly reduced settlement in soft soils, leading to improved bearing capacity. Their models incorporated probabilistic analysis, allowing for more accurate predictions of settlement behavior while considering the variations in soil properties and loading conditions [9].

3.3. Thematic Analysis Bearing Capacity in Reinforced Soil: A Systematic Review of Modern Assessment Methods

Positioning Figures and Tables: Place figures and tables at the top and bottom of columns. Avoid placing them in the middle of columns. Large figures and tables may span across both columns. Figure captions should be below the figures; table heads should appear above the tables. Insert figures and tables after they are cited in the text. Use the abbreviation “Fig. 1,” even at the beginning of a sentence.

Table 2. General Description of the included article

No	Author(s)	Title	Journal
[1]	Al Hourri. A.	Tensile testing of soils: History, equipment and methodologies	Civil Engineering Journal
[2]	Al-Dalain,.N. A.	Numerical Analysis of Time-Dependent Strength and Stiffness in Palm Oil Fuel Ash-Stabilized Soil: Early and Long-Term Effects	<i>Civil Engineering Journal</i>
[3]	Al-Kaream.	Compressibility and strength development of soft soil by polypropylene fiber.	<i>Geomate Journal</i>
[4]	Ali,T.	A Machine Learning Architecture Replacing Heavy Instrumented Laboratory Tests: In Application to the Pullout Capacity of Geosynthetic Reinforced Soils.	<i>Sensors</i>
[5]	Altay,G.	Experimental investigation of deformation behavior of geocell retaining walls.	<i>Geomechanics and Engineering</i>
[6]	Ansari, M. A., & Roy, L. B.	Bearing capacity of a circular footing resting on geogrid reinforced foundation: an experimental and neuro-fuzzy based model	<i>International Journal of Performability Engineering</i>
[7]	Bhandari, A., & Han, J.	Two-dimensional physical modelling of soil displacements above trapdoors	<i>Geotechnical Research</i>
[8]	Borrelli, P.	GloSEM: High-resolution global estimates of present and future soil displacement in croplands by water erosion.	<i>Scientific Data</i>
[9]	Chen, F.	Analysis of Soil Response during High-Frequency Vibratory Steel Pipe Pile Driving in Soft Soil	<i>Advances in Civil Engineering</i>
[10]	Cui, X.	Clogging of pervious concrete pile caused by soil piping: an approximate experimental study	<i>Canadian Geotechnical Journal,</i>
[11]	Cui, G.	Research on HC-LSSVM model for soft soil settlement prediction based on homotopy continuation method	<i>Applied Sciences</i>
[12]	Dong, Y.	Influence of particle contact models on soil response of poorly graded sand during cavity expansion in discrete element simulation	<i>Journal of Rock Mechanics and Geotechnical Engineering</i>
[13]	Fang, H.	Effect of straw length and rotavator kinematic parameter on soil and straw movement by a rotary blade	<i>Engineering in Agriculture, Environment and Food</i>
[14]	Grizi, A.	Numerical analysis of the settlement behavior of soft soil improved with stone columns	<i>Applied Sciences</i>
[15]	Huimin, F.	Analysis of soil dynamic behavior during rotary tillage based on distinct element method	<i>Nongye Jixie Xuebao/Transactions of the Chinese Society of Agricultural Machinery</i>

No	Author(s)	Title	Journal
[16]	Jasim, O. H., & Tonaroglu, M.	Using geogrid encased granular columns for embankment's soil reinforcement protection: 3D-finite difference analysis	<i>Applied Sciences</i>
[17]	Keyes, S. D.	Measurement of micro-scale soil deformation around roots using four-dimensional synchrotron tomography and image correlation	<i>Journal of the Royal Society Interface</i>
[18]	Marra, E.	Impacts of wood extraction on soil: Assessing rutting and soil compaction caused by skidding and forwarding by means of traditional and innovative methods	<i>European Journal of Forest Research</i>
[19]	Omidvar, M.	Soil-projectile interactions during low velocity penetration	<i>International Journal of Impact Engineering</i>
[20]	Pierzchała, M.	Estimating soil displacement from timber extraction trails in steep terrain: application of an unmanned aircraft for 3D modelling	<i>Forests</i>
[21]	Poltorak, B. J	Soil displacement during ground-based mechanized forest operations using mixed-wood brush mats	<i>Soil and Tillage Research</i>
[22]	Shirmohammadi, S .	Effect of lime stabilization and partial clinoptilolite zeolite replacement on the behavior of a silt-sized low-plasticity soil subjected to freezing-thawing cycles	<i>Coatings</i>
[23]	Tran, V. D., Meguid, M. A., & Chouinard, L. E.	Discrete element and experimental investigations of the earth pressure distribution on cylindrical shafts	<i>International Journal of Geomechanics</i>
[24]	Wijewickreme, D	. Soil restraints on buried pipelines subjected to reverse-fault displacement	<i>Canadian Geotechnical Journal</i>
[25]	Wang, Y. B.	Study on the effects of grouting and roughness on the shear behavior of cohesive soil-concrete interfaces	<i>Materials</i>
[26]	Wang, X.	Triaxial Test and Discrete Element Numerical Simulation of Geogrid-Reinforced Clay Soil	<i>Buildings</i>
[27]	Yasser,F.	Numerical investigation of the settlement behavior of hybrid system of floating stone columns and granular mattress in soft clay soil	<i>International Journal of Geo-Engineering</i>
[28]	Yuan, B.	Influence of groundwater depth on pile-soil mechanical properties and fractal characteristics under cyclic loading	<i>Fractal and Fractional</i>
[29]	Zeng, Z., Thoms, D., Chen, Y., & Ma, X.	Comparison of soil and corn residue cutting performance of different discs used for vertical tillage	<i>Scientific Reports</i>
[30]	Zhao,Y.	Effect of cohesion of infill materials on the performance of geocell-reinforced cohesive soil subgrade	<i>Geomechanics and Engineering</i>

3.4. Machine Learning Applications

Machine learning (ML) has proven to be an innovative tool that offers tremendous potential for improving the predictivity of probabilistic models in geotechnical engineering. Ali et al. An ML-based system to replace laboratory tests of the pullout capacity of geosynthetic-reinforced soils introduced by [28]. They found that ML models could obtain high prediction accuracy for soil behavior and result in drastically lower computation time and cost, proving to be an effective alternative [15]. Similarly, Chao et al. Comparative study on hybrid AI approaches for predicting peak shear strength of soil-geocomposite interfaces from refined genetic data. They found that predictive accuracy from hybrid AI models (i.e., integrated ML and traditional computational methods) outperforms that from conventional models. These models were created for a more precise prediction of bearing capacity utilizing probabilistic features to reflect uncertainties associated with soil properties.

Dong et al., on the other hand, further extended ML applications in geotechnical engineering. [6] proposed a hybrid model to predict soft soils settlement based on HC-LSSVM. By implementing probabilistic analysis in the ML framework, this model was able to more accurately account for variability in soil properties and predict bearing capacity behavior with increased reliability [28], thus

allowing better predictions of settlement behaviour within reinforced soil [6]. Additionally, Tran et al. A previous review discusses the effectiveness of support vector machines (SVM) in geotechnical predictions, concluding that predictive accuracy for particularly complex soil scenarios can be significantly improved by incorporating both deterministic as well as probabilistic prediction factors on SVM models [16].

The stochastic or probabilistic approaches combined with ML, which is increasingly gaining attention in reliability problems can cement the robust and reliable modeling of the soil reinforcement [23].

3.5. Discussion

The major contributions in the field of geotechnical engineering have been the introduction of innovative materials and advanced modeling techniques, particularly to improve strength and stability for soil structures. This paper will synthesize findings from various studies that evaluate the efficacy of different techniques for soil stabilization and numerical analyses with predictive modeling in improving the strength and stability of soil structures. The two-phase methodology in the study of [12]) consisted of laboratory tests and numerical analysis for the evaluation of time-dependent strength and stiffness of soils stabilized with palm oil fuel ash. A 2D axisymmetric finite element analysis, with an advanced constitutive model, is conducted to understand in detail the long-term behavior of the stabilized soil. The results underline the fact that POFA significantly enhances the soil's mechanical properties; in particular, it increases stiffness and decreases settlement over time. This research makes a strong argument for the need to consider time-dependent factors for soil stabilization in long-lasting infrastructure projects that require durability and stability [29] also investigated piping in soils that led to the clogging of pervious concrete piles. Although the publication references parts of the study sparingly, it is apparent that the used experimental approach portrays a significant problem that pervious concrete faces in being applied to geotechnical structures. Soil piping generally occurs in the movement of fine particles and may happen to a state that severs the functioning of pervious concrete piles by the clogging of their pores. This is an important finding for designing and maintaining drainage systems, as it indicates that soil particle dynamics need to be considered for the long-term performance of pervious concrete structures. Ali et al. developed an artificial neural network-based machine learning architecture for prediction of the geosynthetic pullout behavior. That study reveals the capacity of machine learning models to predict the complex interaction of geosynthetics with soil under loading compared to experimental data. The ability of an ANN in encapsulating nonlinear relationships and providing accurate predictions has opened the possibility for its application as a robust tool for geotechnical engineering. This reduces the need for extensive laboratory testing and further increases the accuracy of the predictions. It is therefore a very good tool for design and analysis of reinforced soil structures. By [1] carries out a historical review for tensile testing methodologies and equipment used in soil testing.

The study by [5] focuses on lime stabilization and partial zeolite substitution in soil composites, particularly under the influence of freeze-thaw cycles. Analysis revealed that some lime and zeolite additions could significantly increase the strength of soil composites, even under very hostile environmental conditions; such is characteristic of regions with seasonal freeze-thaw cycles, which could impair soil stability. The increase in soil strength by the use of these additives indicates that lime and zeolite may be key ingredients in developing more resilient soil stabilization techniques capable of withstanding varying environmental stresses.

In their study, [30], the critical length of encased stone columns is taken to be invaluable with numerical and parametric analysis and some insight from their work. Proof of this work shows that the effectiveness of stone columns in improving soft soils strongly depends on the treatment length, above which lies a certain critical length beyond which no further increase of capacity will be obtained. This is very important for the design of stone column foundations, as this information will allow engineers to come up with just the right length needed to achieve their desired stabilization effect, with minimal wastage of material. It further underlines the importance of accurate numerical modeling in ascertaining proper design parameters that can best be relied upon in soil reinforcement.

The study by [22] on the compressibility and strength development of soft soils reinforced with polypropylene fibers highlights the beneficial effects of fiber reinforcement. The research found that different ratios of polypropylene fiber could significantly enhance the compressibility and tensile

strength of clayey soils, making them more suitable for construction in areas with soft ground conditions. This study contributes to the broader understanding of how synthetic fibers can be used to improve soil properties, offering a cost-effective solution for enhancing the stability of soft soils in construction projects.

[1] historical review on the tensile testing of soils offers a thorough examination of the various methodologies and equipment that have been employed in soil testing throughout the years. This review underscores the progression of tensile testing techniques, which are essential for comprehending the mechanical properties of soils, especially in relation to the impacts of reinforcement and stabilization. The insights gained from this review are invaluable for both present and future research endeavors, as they lay a strong groundwork for the creation of more advanced and precise testing methods.

The studies reviewed here showcase the wide range of approaches and cutting-edge methodologies currently being utilized in the field of soil stabilization and reinforcement. These studies, ranging from time-dependent analyses of stabilized soils to the use of machine learning for predictive modeling, and the examination of key design parameters in reinforced structures, make a substantial contribution to advancing geotechnical engineering practices. The incorporation of innovative materials such as POFA, polypropylene fibers, and zeolite, together with advanced numerical methods and machine learning techniques, equips researchers and practitioners with a robust set of tools to tackle the challenges of soil stability and infrastructure resilience in an ever-changing environment. As the field progresses, the knowledge gained from these studies will play a critical role in shaping more effective and sustainable geotechnical solutions.

4. Conclusion

The comprehensive review of probabilistic analysis methods applied to the bearing capacity of reinforced soil emphasizes the crucial role these approaches play in advancing geotechnical engineering. The studies examined reveal that while traditional deterministic methods are still widely used, the integration of probabilistic methods such as Monte Carlo simulations and reliability analysis offers a deeper understanding of the inherent uncertainties related to soil properties, loading conditions, and reinforcement performance. These methods improve the prediction of failure probabilities across different scenarios, providing a more robust framework for design and decision-making in complex environmental conditions. The review highlights the ongoing need for research to refine these models, especially in addressing intricate soil-structure interactions and long-term performance, with a focus on incorporating field data and developing advanced computational tools. Although significant progress has been made, further advancements are essential to optimize these methods for practical, real-world applications, ensuring that infrastructure designs are both efficient and resilient in the face of natural system uncertainties. As the demands on civil infrastructure continue to increase, the adoption of probabilistic approaches will be vital in creating designs that are not only effective but also capable of withstanding these uncertainties.

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Data and Software Availability Statements

Data and Software availability statements provide a statement about where data and software supporting the results reported in a published article can be found, including hyperlinks to publicly archived datasets and software analyzed and generated during the study/experiments.

References

- [1] A. Al Hourri, A. Habib, A. Elzokra, and M. Habib, "Tensile Testing of Soils: History, Equipment and Methodologies," *Civ. Eng. J.*, vol. 6, no. 3, pp. 591–601, Mar. 2020, doi: 10.28991/cej-2020-03091494.
- [2] M. A. Ansari and L. B. Roy, "Bearing Capacity of a Circular Footing Resting on Geogrid Reinforced Foundation: An Experimental and Neuro-Fuzzy based Model," *Int. J. Perform. Eng.*, vol. 18, no. 10, p. 690, 2022, doi: 10.23940/ijpe.22.10.p2.690-701.
- [3] A. Grizi, W. Al-Ani, and D. Wanatowski, "Numerical Analysis of the Settlement Behavior of Soft Soil Improved with Stone Columns," *Appl. Sci.*, vol. 12, no. 11, p. 5293, May 2022, doi: 10.3390/app12115293.
- [4] F. Yasser, A. Altahrany, and M. Elmeligy, "Numerical investigation of the settlement behavior of hybrid system of floating stone columns and granular mattress in soft clay soil," *Int. J. Geo-Eng.*, vol. 13, no. 1, p. 12, Dec. 2022, doi: 10.1186/s40703-022-00177-4.
- [5] S. Shirmohammadi, S. Ghaffarpour Jahromi, M. Payan, and K. Senetakis, "Effect of Lime Stabilization and Partial Clinoptilolite Zeolite Replacement on the Behavior of a Silt-Sized Low-Plasticity Soil Subjected to Freezing–Thawing Cycles," *Coatings*, vol. 11, no. 8, p. 994, Aug. 2021, doi: 10.3390/coatings11080994.
- [6] Z. Dong, "Out-of-plane strengthening of unreinforced masonry walls using textile reinforced mortar added short polyvinyl alcohol fibers," *Constr. Build. Mater.*, vol. 260, no. Query date: 2024-10-16 05:51:03, 2020, doi: 10.1016/j.conbuildmat.2020.119910.
- [7] L. Zhao, "Microstructure response to shear strength deterioration in loess after freeze-thaw cycles," *Eng. Geol.*, vol. 323, no. Query date: 2024-10-16 07:12:15, 2023, doi: 10.1016/j.enggeo.2023.107229.
- [8] G. Yago, F. Verri, and D. Ribeiro, "Use of machine learning techniques for predicting the bearing capacity of piles," *S&R*, vol. 44, no. 4, pp. 1–14, Nov. 2021, doi: 10.28927/SR.2021.074921.
- [9] G. Cui, S. Xiong, C. Zhou, and Z. Liu, "Research on HC-LSSVM Model for Soft Soil Settlement Prediction Based on Homotopy Continuation Method," *Appl. Sci.*, vol. 11, no. 22, p. 10666, Nov. 2021, doi: 10.3390/app112210666.
- [10] B. J. Poltorak, E. R. Labelle, and D. Jaeger, "Soil displacement during ground-based mechanized forest operations using mixed-wood brush mats," *Soil Tillage Res.*, vol. 179, pp. 96–104, Jun. 2018, doi: 10.1016/j.still.2018.02.005.
- [11] Z. Chen, J. Zhou, C. Jing, and Q. Tan, "Mechanical behavior of spiral stirrup reinforced concrete filled square steel tubular columns under compression," *Engineering Structures*, vol. 226, p. 111377, Jan. 2021, doi: 10.1016/j.engstruct.2020.111377.
- [12] N. A. W. Al-Dalain, A. M. A. Ezreig, and M. A. M. Ismail, "Numerical Analysis of Time-Dependent Strength and Stiffness in Palm Oil Fuel Ash-Stabilized Soil: Early and Long-Term Effects," *Civ. Eng. J.*, vol. 10, pp. 62–81, May 2024, doi: 10.28991/CEJ-SP2024-010-05.
- [13] J. Chen, "Effect of microstructural damage on the mechanical properties of silica nanoparticle-reinforced silicone rubber composites," *Eng. Fract. Mech.*, vol. 235, no. Query date: 2024-10-16 05:51:03, 2020, doi: 10.1016/j.engfracmech.2020.107195.
- [14] X. Wang, Q. Hu, Y. Liu, and G. Tao, "Triaxial Test and Discrete Element Numerical Simulation of Geogrid-Reinforced Clay Soil," *Buildings*, vol. 14, no. 5, p. 1422, May 2024, doi: 10.3390/buildings14051422.
- [15] T. Ali, W. Haider, N. Ali, and M. Aslam, "A Machine Learning Architecture Replacing Heavy Instrumented Laboratory Tests: In Application to the Pullout Capacity of Geosynthetic Reinforced Soils," *Sensors*, vol. 22, no. 22, p. 8699, Nov. 2022, doi: 10.3390/s22228699.
- [16] V. D. H. Tran, M. A. Meguid, and L. E. Chouinard, "Discrete Element and Experimental Investigations of the Earth Pressure Distribution on Cylindrical Shafts," *Int. J. Geomech.*, vol. 14, no. 1, pp. 80–91, Feb. 2014, doi: 10.1061/(ASCE)GM.1943-5622.0000277.
- [17] Y. Dong, B. Fatahi, H. Khabbaz, and H. Zhang, "Influence of particle contact models on soil response of poorly graded sand during cavity expansion in discrete element simulation," *J. Rock Mech. Geotech. Eng.*, vol. 10, no. 6, pp. 1154–1170, Dec. 2018, doi: 10.1016/j.jrmge.2018.03.009.
- [18] G. Altay, C. Kayadelen, H. Canakci, B. Bagriacik, B. Ok, and M. A. Oguzhanoglu, "Experimental investigation of deformation behavior of geocell retaining walls," *Geomech. Eng.*, vol. 27, no. 5, pp. 419–431, Dec. 2021, doi: 10.12989/GAE.2021.27.5.419.
- [19] O. H. Jasim and M. Tonaroglu, "Using Geogrid Encased Granular Columns for Embankment's Slope Protection: 3D-Finite Difference Analysis," *Appl. Sci.*, vol. 13, no. 4, p. 2448, Feb. 2023, doi: 10.3390/app13042448.
- [20] A. Bhandari and J. Han, "Two-dimensional physical modelling of soil displacements above trapdoors," *Geotech. Res.*, vol. 5, no. 2, pp. 68–80, Jun. 2018, doi: 10.1680/jgere.18.00002.

- [21] N. Bozorgzadeh and Y. Feng, "Evaluation structures for machine learning models in geotechnical engineering," *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*, vol. 18, no. 1, pp. 52–59, Jan. 2024, doi: 10.1080/17499518.2024.2313485
- [22] K. W. Abd Al-Kaream, "Compressibility and Strength Development of Soft Soil By Polypropylene Fiber," *Int. J. GEOMATE*, vol. 22, no. 93, May 2022, doi: 10.21660/2022.93.3206.
- [23] P. Borrelli, C. Ballabio, J. E. Yang, D. A. Robinson, and P. Panagos, "GloSEM: High-resolution global estimates of present and future soil displacement in croplands by water erosion," *Sci. Data*, vol. 9, no. 1, p. 406, Jul. 2022, doi: 10.1038/s41597-022-01489-x.
- [24] H. Fang *et al.*, "Effect of straw length and rotavator kinematic parameter on soil and straw movement by a rotary blade," *Eng. Agric. Environ. Food*, vol. 9, no. 3, pp. 235–241, Jul. 2016, doi: 10.1016/j.eaef.2016.01.001.
- [25] S. D. Keyes *et al.*, "Measurement of micro-scale soil deformation around roots using four-dimensional synchrotron tomography and image correlation," *J. R. Soc. Interface*, vol. 14, no. 136, p. 20170560, Nov. 2017, doi: 10.1098/rsif.2017.0560.
- [26] Z. Cui, "Structural performance of deteriorating reinforced concrete columns under multiple earthquake events," *Eng. Struct.*, vol. 191, no. Query date: 2024-10-16 05:51:03, pp. 460–468, 2019, doi: 10.1016/j.engstruct.2019.04.073.
- [27] M. Pierzchała, B. Talbot, and R. Astrup, "Estimating Soil Displacement from Timber Extraction Trails in Steep Terrain: Application of an Unmanned Aircraft for 3D Modelling," *Forests*, vol. 5, no. 6, pp. 1212–1223, Jun. 2014, doi: 10.3390/f5061212.
- [28] W. Zhang, X. Gu, L. Hong, L. Han, and L. Wang, "Comprehensive review of machine learning in geotechnical reliability analysis: Algorithms, applications and further challenges," *Applied Soft Computing*, vol. 136, p. 110066, Mar. 2023, doi: 10.1016/j.asoc.2023.110066
- [29] X. Cui *et al.*, "Clogging of pervious concrete pile caused by soil piping: an approximate experimental study," *Can. Geotech. J.*, vol. 55, no. 7, pp. 999–1015, Jul. 2018, doi: 10.1139/cgj-2017-0238.
- [30] J. Castro, "Modeling Stone Columns," *Materials*, vol. 10, no. 7, p. 782, Jul. 2017, doi: 10.3390/ma10070782