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Optimization of Bearing Capacity of Sandy Soil Using Geosynthetic: An Experimental Study on Sand Types and Reinforcement Material Variations

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ABSTRACT

Sand is commonly used as a base material in construction; however, its non-cohesive nature and high deformability make it less ideal for directly supporting structural loads. One of the solutions developed to address this limitation is the use of geosynthetic materials for soil reinforcement. This study aims to analyze the influence of sand gradation (coarse, medium, fine) and types of geosynthetics (woven geotextile, non-woven geotextile, and geogrid) on the bearing capacity of sand, with geosynthetics placed at a fixed depth of 5 cm. The testing was conducted using a plate load test within a small-scale laboratory model box. Results indicate that the combination of coarse sand and geogrid produced the highest bearing capacity, increasing from 161.46 kg (unreinforced) to 261.63 kg. Woven and non-woven geotextiles also improved bearing capacity, albeit with lower effectiveness. The stress–strain graph shows that the use of geosynthetics enhances soil stiffness and reduces deformation. The ultimate bearing capacity versus settlement graph confirms that geogrid and woven geotextile are effective in maintaining structural performance up to a 1-inch settlement. Overall, geosynthetics proved to be effective, particularly in coarse sand, with a bearing capacity increase of up to 61.33%.

1. INTRODUCTION

Sandy soil is one of the most commonly found soil types across various regions, including Indonesia. Its primary characteristics—coarse particles, non-cohesive behavior, and high porosity—result in low bearing capacity and high susceptibility to deformation, particularly under saturated conditions [1-4]. These conditions present significant challenges in infrastructure development, especially for shallow foundation construction, which requires adequate soil strength and stability [5].

To address these challenges, various soil reinforcement methods have been developed. One effective approach involves the use of geosynthetic materials, such as geotextiles, geogrids, and geocells. These materials function as reinforcement elements that enhance soil stiffness and stability while facilitating more uniform load distribution [6, 7].

However, most geosynthetics are made from synthetic polymers like polypropylene (PP), polyester (PET), and polyethylene (PE), which are manufactured through chemical processes. These processes can have environmental impacts, including fossil fuel consumption, greenhouse gas emissions, and industrial waste generation [8, 9]. Therefore, it is important to consider sustainability aspects in the application of geosynthetics, such as the use of bio-based polymers, recycled products, or other eco-friendly technologies that align with sustainable development principles [10, 11].

The application of geosynthetic materials such as woven geotextiles, non-woven geotextiles, and geogrids has expanded rapidly as a soil reinforcement solution [12]. Geosynthetics are synthetic materials specifically designed for geotechnical engineering purposes to improve soil performance. Each type—geotextile, geogrid, and geocell—has distinct characteristics and applications [6, 12, 13]. Their use in sandy soil reinforcement has been shown to significantly enhance bearing capacity and reduce deformation, as evidenced by numerous experimental and numerical studies. The reinforcement mechanism involves increasing mechanical interaction between the soil and the reinforcement elements through frictional resistance, interlocking effects, and restriction of lateral deformation [7, 14]. This technology not only improves soil shear strength but also effectively reduces settlement and enhances the stability of subsoil layers [8].

Several experimental studies have shown that the effectiveness of geosynthetics depends heavily on soil characteristics and the type of geosynthetic material used. Thakur and Sharma [10] demonstrated that applying geogrids to high-density sand significantly increases its bearing capacity compared to unreinforced conditions. Meanwhile, Lafifi et al. [11] and Panigrahi and Pradhan [15] highlighted that non-woven geotextiles are more effective in fine sand due to their high permeability and flexibility, which allow better adaptation to ground contours.

Selecting the appropriate type of geosynthetic requires careful consideration of soil physical properties, such as particle size, grain shape, gradation, and moisture content. Coarse-grained soils with angular particles, such as coarse sand, tend to form strong interlocking with geogrids, thereby significantly increasing bearing capacity [16]. Conversely, for fine-grained or uniformly graded sand, non-woven geotextiles are more recommended due to their porous structure, which facilitates water drainage and retains fine soil particles, improving stability and reducing deformation risks [17]. High moisture content is another critical factor, necessitating geosynthetics with good drainage capabilities to prevent excess pore water pressure that could weaken soil shear strength [18].

Geosynthetic application in sandy soil reinforcement has been a central topic in geotechnical research over the past few decades. Zamani et al. [8] revealed that geotextiles treated with additives such as lime can increase foundation bearing capacity by up to 75% compared to untreated geotextiles. This finding highlights the importance of surface treatment in enhancing geotextile-soil interaction. On the other hand, Liu et al. [1] investigated the interface behavior between geogrids and gravelly soil through tensile tests and found that factors such as normal stress, pull-out speed, particle shape, and moisture content significantly affect maximum tensile strength.

Buragadda et al. [17] evaluated the influence of geosynthetic geometric parameters on the bearing capacity of sandy soil. Their findings indicate that geogrids with specific aperture sizes and stiffness levels can substantially improve soil performance. This emphasizes the importance of selecting geosynthetics based on soil characteristics and specific design requirements.

Sandy soil characteristics vary depending on geological origins and processes, directly influencing the interaction between the soil and reinforcement materials. Zamani et al. [8] concluded that both the type of sand and geotextile treatment affect the bearing capacity of foundations. Likewise, Liu et al. [1] found that particle shape and size distribution significantly impact the tensile interaction between geogrids and soil.

Similarly, the choice of reinforcement material plays a crucial role in system performance. Buragadda et al. [17] emphasized that selecting geosynthetics with optimal geometric parameters can considerably enhance sandy soil bearing capacity. These studies underscore the urgency of using soil-specific and technically sound design approaches.

Numerous experimental studies have been conducted to assess the effectiveness of geosynthetics in reinforcing sandy soil. Zamani et al. [8], using plate load tests, demonstrated increased bearing capacity and reduced deformation. Liu et al. [1], through tensile testing, evaluated geogrid-soil interactions and reported that normal stress, pull-out speed, and moisture content significantly influence tensile strength. Buragadda et al. [17] also employed plate load tests and found that aperture size and material stiffness greatly affect reinforcement performance.

Despite the proven effectiveness of geosynthetics, further systematic research is still required. The wide variability in sand properties and reinforcement types calls for a more structured approach to comprehensively understand their interaction. Moreover, experimental studies that simulate real field conditions and consider relevant design parameters will offer more practical insights. However, there remains a limited number of studies that explicitly compare the effects of various geosynthetic types on sands with different gradations at fixed installation depths such as 5 cm, which points to a clear research gap.

Systematic laboratory testing is necessary to map geosynthetic performance across a range of soil gradations, thereby supporting more precise and adaptive engineering designs. Such evaluations are increasingly relevant within the framework of performance-based subgrade design approaches that emphasize the compatibility between soil characteristics and reinforcement materials [1, 2].

To address this research gap, integrated testing methods such as plate load tests and geosynthetic tensile tests are essential. Plate load tests are used to directly assess soil bearing capacity and deformation behavior under controlled loads, providing realistic insights into field performance. Meanwhile, tensile tests determine the maximum tensile strength of geosynthetic materials, including the influence of surface texture or structural modifications on their interaction with soil particles [4, 12 ,14].

Moreover, the placement of geosynthetics at a depth of 5 cm below the ground surface has been widely studied and shown considerable potential in improving the stability of shallow soil layers. However, the effectiveness of this configuration still requires quantitative and comparative analysis based on soil type and geosynthetic material to determine the optimal depth and refine design parameters [6, 7].

Through an integrated experimental approach, the outcomes of this research are expected to contribute meaningfully to the formulation of technical guidelines for soil reinforcement based on local conditions and to support the implementation of sustainable and data-driven infrastructure design.

Based on the above background, this study aims to evaluate the effectiveness of various geosynthetic types in enhancing the bearing capacity of sandy soil using an experimental approach. The research considers variations in sand types and reinforcement materials to understand their interaction under controlled laboratory conditions. Three sand types are used: coarse, medium, and fine, along with three geosynthetics: woven geotextile, non-woven geotextile, and geogrid. All reinforcements are installed at a fixed depth of 5 cm. The findings are expected to contribute significantly to the development of more effective, efficient, and adaptable soil reinforcement designs for field applications.

2. MATERIAL

The primary soil material used in this study is uniformly graded, loose sand (non-cohesive soil) that is free from clay and organic matter. To ensure these criteria, a grain size distribution analysis was conducted using sieve analysis in accordance with ASTM D422 to identify particle size distribution and confirm the absence of particles passing through the No. 200 sieve (0.075 mm), which typically indicates the presence of clay or silt fractions [1]. In addition, a loss on ignition (LOI) test following ASTM D2974 was used to detect organic content. The very low LOI value (<1%) confirmed that the sand samples contained no significant organic matter [2], thereby representing ideal conditions for reinforcement studies using geosynthetics. This type of sand was selected due to its homogeneous composition, chemical stability, and high sensitivity to reinforcement variations, making it a suitable medium for observing the interaction between soil and geosynthetic materials.

In this study, three particle size gradations were used, as illustrated in Figures 1, 2, and 3. Coarse sand particles range from 2 mm to 4.75 mm, medium sand from 0.42 mm to 2 mm, and fine sand was sourced from the Lambung Bukik River, with grains passing through the No. 40 sieve (0.42 mm opening) and retained on the No. 100 sieve (0.15 mm opening). These three gradations represent commonly encountered coarse, medium, and fine sands in the field.

Figure 1. Coarse sand

Figure 2. Medium sand

Figure 3. Fine sand

The geotechnical characteristics of each sand type, including maximum dry density, optimum moisture content, internal friction angle, and specific gravity, are presented in detail in Table 1. Meanwhile, the particle size distribution for each sand variation used in the laboratory tests is shown in Figure 4. This information aims to provide a comprehensive overview of the physical and mechanical properties of the soil used, thereby enabling a more accurate and practical interpretation of the interaction between soil and geosynthetic materials in geotechnical engineering applications.

Table 1. Geotechnical properties of sandy soil

Description	Coarse Sand	Medium Sand	Fine Sand
Gravel (%)	0	0	0
Sand (%)	100	100	100
Clay (%)	0	0	0
% Retained #200 (0.075mm)	100	100	100
% Pass # No.4 (4.74mm)	100	100	100
D_{10} (mm)	2.091	0.483	0.108
D_{30} (mm)	2.453	0.638	0.153
D_{60} (mm)	3.084	1.230	0.214
Coefficient of Uniformity (C_u)	1.475	2.547	1.981
Coefficient of Gradation (C_c)	0.933	0.685	1.031
Group Symbol	SP	SP	SP
Maximum Dry Bulk Weight $\gamma_{dry(min)}$ (gr/cm^3)	1.516	1.60	2.172
Relatif Density, Dr (%)	29.74	46.64	66.43
Consistency	loose	loose	loose
Cohesi,C (kN/m^2)	0.066	0.061	0.056
Internal Friction Angle, φ (^{0})	42.376	37.668	35.061

The geosynthetic materials used in this experiment consist of three main types: woven geotextile, non-woven geotextile, and geogrid. The woven geotextile applied in this study is the GlobalTEX GTW 150 type, while the non-woven geotextile used is the GlobalTEX GTW 151G. The type of geogrid employed is PET Geogrid. All geosynthetic materials were manufactured by PT. Geoforce Indonesia and were selected based on their commercial availability and the compatibility of their technical characteristics with the reinforcement requirements of sandy soils in this study.

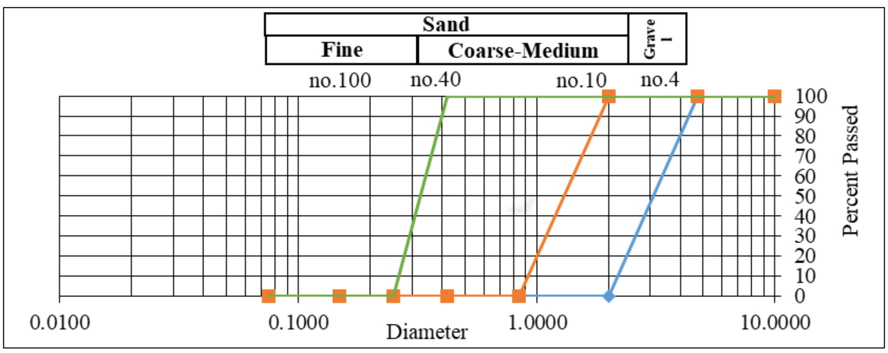

Figure 4. Grain size distribution curves of coarse sand, medium sand, and fine sand

The selection of these three geosynthetic types aims to evaluate the performance differences among material types in enhancing the bearing capacity of sandy soils with varying gradations. Woven geotextile (Figure 5), characterized by its stiff woven structure and high tensile strength, is ideal for soil reinforcement through interlocking mechanisms and the restriction of lateral deformation. Non-woven geotextile (Figure 6), with its randomly arranged fibers and high permeability, is suitable for fine-grained or uniformly graded soils. Geogrid (Figure 7), which features a mesh-like structure, is designed to improve the stiffness of the soil system through mechanical interlocking between soil particles and the geogrid apertures.

By utilizing these three types of geosynthetics, this study is expected to provide a more comprehensive understanding of the effectiveness of each material in reinforcing sandy soils, as well as their contribution to improving bearing capacity and reducing soil deformation under controlled laboratory conditions.

Figure 5. Woven geosynthetic

Figure 6. Non-woven geosynthetic

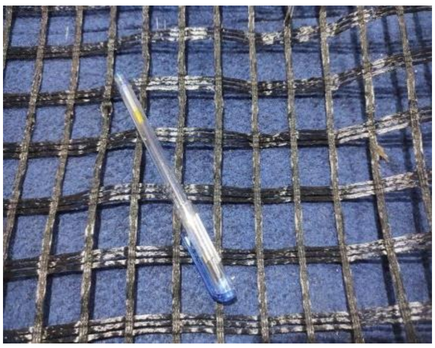

Figure 7. Geogrid

3. EXPERIMENTAL SETUP AND PROCEDURES

3.1 Experimental setup

In this study, the experimental testing was conducted using a small-scale physical model in a controlled laboratory setting. The test setup utilized a rectangular model box made of transparent glass on all four sides to facilitate visual observation during the loading and deformation process. The dimensions of the model box were 80 cm in length, 40 cm in width, and 30 cm in height, with 10 mm thick glass panels that were structurally rigid enough to withstand vertical loading without deformation.

The tests were performed on sandy soils with three particle size gradations: coarse sand, medium sand, and fine sand. Each sand type was tested under two conditions: unreinforced (natural soil) and reinforced with three different types of geosynthetic materials—namely, woven geotextile, non-woven geotextile, and geogrid.

Vertical loading was applied using a manual hydraulic jack system capable of delivering loads up to 50 kN, with a measurement accuracy of ±0.5% of the maximum reading. Settlement (vertical deformation) was measured using an analog dial gauge with a capacity of 25 mm and a precision of 0.01 mm, positioned directly above the center point of the circular steel loading plate with a diameter of 10 cm. The entire testing system was placed on a flat, rigid steel testing table to ensure overall stability during the experiment.

This experimental design was intended to evaluate the effects of geosynthetics on the bearing capacity and vertical deformation of sandy soils with different gradations under controlled laboratory conditions. The use of transparent model materials, appropriate box dimensions, and high-precision loading and measuring devices allowed for optimal observation and data collection, thereby enhancing the validity and replicability of the testing procedure.

3.2 Sample preparation

The sandy soil was placed into the model box in stages using a layered filling method, with each layer of sand dropped from a constant height of 5 cm. This height was selected based on standard laboratory practice guidelines for loose soil filling, aiming to minimize particle segregation and ensure uniform energy distribution during the filling process [1]. The fixed drop height method was intended to allow natural grain arrangement through gravitational force, resulting in a uniform density without the need for additional mechanical compaction.

Each layer was 5 cm thick, and the filling process was repeated until the total height reached 40 cm, resulting in a total of eight layers. After each layer was deposited, the surface was manually leveled using a flat metal plate to ensure consistent layer thickness and to prevent local variations in density. This approach was adopted to maintain homogeneous particle distribution throughout the entire volume of the model.

Relative density was estimated by comparing the actual dry unit weight of the soil to the maximum and minimum values in accordance with ASTM D4253 (Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table) and ASTM D4254 (Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density) [2, 3].

The geosynthetic material was installed horizontally at the mid-height of the model, specifically at a depth of 35 cm from the base of the box, which corresponds to 5 cm below the loading plate. The geosynthetic was placed after the underlying sand layers had been filled and leveled. Sheets of woven geotextile, non-woven geotextile, or geogrid were cut to match the dimensions of the model box and laid flat without folds or wrinkles. Once the geosynthetic layer was in place, the remaining three layers of sand (each 5 cm thick) were added to reach the final model height.

Loading was applied through a square-shaped steel plate measuring 100 mm × 95 mm, positioned directly on the soil surface and centered within the model area. The geosynthetic placement depth of 5 cm (equivalent to ½B, where B is the width of the loading plate) was selected to reflect the critical depth commonly used in soil reinforcement studies, ensuring optimal interaction between the geosynthetic layer and the zone of maximum stress induced by vertical loading.

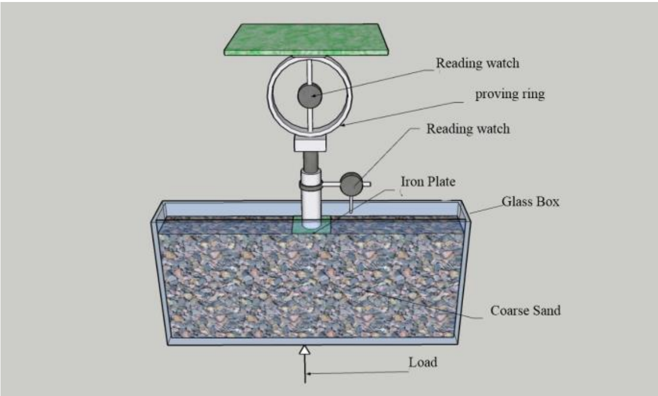

Figure 8. Experimental model design without geosynthetic layer

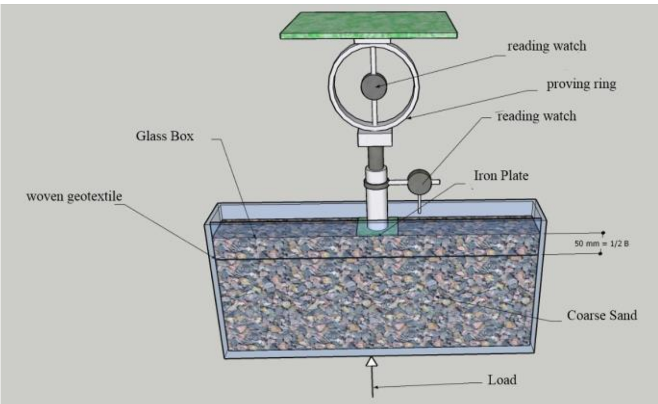

Figure 9. Geosynthetic variation model at 50 mm or ½B depth in coarse sand

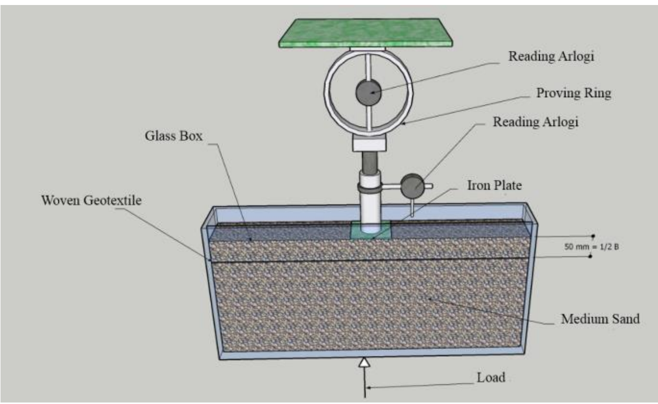

Figure 10. Geosynthetic variation model at 50 mm or ½B depth in medium sand

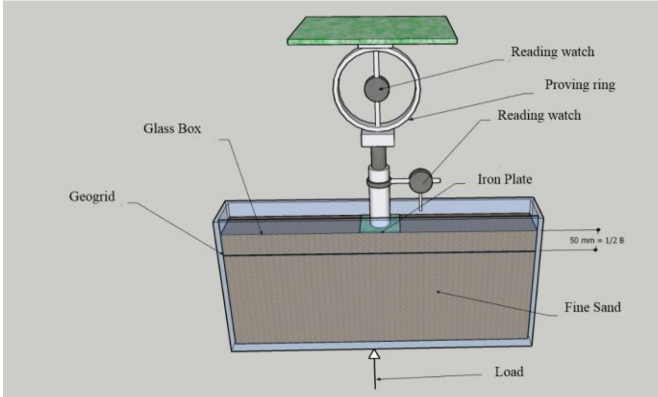

Figure 11. Geosynthetic variation model at 50 mm or ½B depth in fine sand

Figure 8 presents an illustration of the experimental model design for the condition without geosynthetic layers across three sand gradations: coarse sand, medium sand, and fine sand. Meanwhile, Figures 9, 10, and 11 respectively depict the test models for coarse, medium, and fine sand reinforced with geosynthetic layers. These three figures represent the testing scenarios involving different types of geosynthetics—namely, woven geotextile, non-woven geotextile, and geogrid—installed at a fixed depth of 50 mm, equivalent to ½B from the base of the loading plate.

This experimental setup was designed to comprehensively evaluate the influence of sand grain size gradation and geosynthetic type on the bearing capacity of sandy soil under controlled laboratory conditions.

3.3 Loading process

The model testing procedure was carried out by applying vertical loads incrementally using a mechanical loading apparatus equipped with a pressure gauge to measure the applied load and a dial gauge to monitor the foundation settlement. The experimental setup is illustrated in Figures 8, 9, 10, and 11. The loading was applied at a controlled settlement rate of approximately 1 mm per minute to ensure gradual and uniform deformation.

During the loading process, the magnitude of the applied load was recorded at every settlement interval of 2.52 mm, which corresponds to 1 inch. The loading continued until the total settlement reached 25.2 mm or until the specimen exhibited signs of failure. This procedure was repeated for each variation in sand gradation, namely coarse sand, medium sand, and fine sand, under two conditions: without geosynthetic reinforcement and with the application of three different geosynthetic types—woven geotextile, non-woven geotextile, and geogrid.

All geosynthetic materials were placed horizontally at a consistent depth of 5 cm from the base of the loading plate, corresponding to ½B, to ensure uniform testing conditions and allow for meaningful comparison of performance across different configurations.

3.4 Data acquisition

Based on the test results, load–settlement curves were generated to determine the ultimate load (P) of the shallow foundation. In addition, the modeling results enabled further analysis of the relationships between load, stress, strain, settlement, and the ultimate bearing capacity of the soil (Qu) for each experimental configuration.

All tests were conducted under controlled laboratory conditions to minimize external variables and ensure data consistency. The loading plate used was made of rigid steel, measuring 100 mm × 95 mm, and was placed symmetrically on the soil surface to simulate a shallow foundation condition. The load was applied uniformly to ensure symmetrical stress distribution, which is essential for accurately capturing the behavior of both reinforced and unreinforced sandy soils under vertical loading.

During the testing process, observations focused on the load–settlement behavior, with key parameters such as maximum bearing capacity and deformation characteristics carefully recorded. The data obtained from each test scenario were analyzed to assess the influence of sand gradation and geosynthetic type on soil performance. A comparative analysis between unreinforced and reinforced models was conducted to evaluate the effectiveness of each geosynthetic type in enhancing bearing capacity and reducing soil settlement.

Particular attention was also given to the interface condition between the geosynthetic material and the surrounding soil, as this interaction plays a critical role in the reinforcement mechanism. The geosynthetic layer was consistently placed at a fixed depth of 5 cm below the loading plate, a depth commonly used in subgrade reinforcement studies, which corresponds to the critical zone where maximum stress transfer typically occurs.

This testing procedure provides a comprehensive framework for understanding the mechanical response of sandy soils with varying gradations and reinforcement types. The findings from this experimental study serve as a basis for evaluating geosynthetic performance and its practical implications in improving the stability and ultimate bearing capacity of granular soils in geotechnical engineering applications.

4. RESULTS AND DISCUSSION

4.1 Results of sand characterization tests

The variations in the physical and mechanical properties of the three sand types—coarse, medium, and fine—demonstrate a significant influence on the performance of soil–geosynthetic interaction in the context of soil reinforcement. All three samples are classified as SP (poorly graded sand) according to the Unified Soil Classification System (USCS), indicating a narrow particle size distribution without substantial diversity in their gradation curves. However, the values of the uniformity coefficient (C_u) and the coefficient of curvature (C_c) reveal different potentials for interparticle interlocking [19]. Coarse sand has a C_u of 1.475 and a C_c of 0.933, which are lower than those of medium sand (C_u = 2.547; C_p = 0.685) and fine sand (C_u = 1.981; C_c = 1.031). The low C_u value in coarse sand indicates a more uniform material, which may reduce its inherent structural stability, though this can be compensated by the effective use of geosynthetics [1].

Regarding the maximum dry density ($\gamma_a$dry), a clear increasing trend is observed from coarse sand (1.516 g/cm^3) to medium (1.600 g/cm^3) and fine sand (2.172 g/cm^3). This can be attributed to the efficient packing ability of finer grains, which fill pore spaces more effectively [8]. Fine sand also exhibits the highest relative density (Dr) at 66.43%, indicating it is naturally denser compared to coarse sand, which has a Dr of only 29.74%. Relative density is a crucial factor in terms of deformation and surface settlement. Higher Dr values suggest better soil stability under load, especially when reinforced with suitable geosynthetics [17].

In terms of mechanical behavior, all sand types are categorized as non-cohesive, as evidenced by cohesion (c) values approaching zero. However, a clear difference appears in the internal friction angle (φ), which decreases with finer grain sizes: coarse sand (42.38°), medium sand (37.67°), and fine sand (35.06°). The internal friction angle is a key indicator of soil's resistance to shear before plastic deformation occurs. The higher friction angle in coarse sand can be attributed to strong mechanical interlocking among larger particles, which greatly supports the performance of geogrid-based geosynthetic applications through enhanced interlocking between structural elements and sand grains [1].

Although fine sand has a lower internal friction angle, it still has the potential to provide adequate bearing capacity when reinforced with systems such as geotextiles or geocells, which help restrain lateral movement and improve bearing capacity by creating confinement layers that enhance stress redistribution. The performance of geosynthetics in fine sand is highly dependent on the type and configuration of the reinforcement material. Zamani et al. [8] reported that multilayer geotextiles with chemical treatment can improve cohesion and interface friction, significantly enhancing performance in fine-grained soils.

The grain size distribution curves shown in Figure 1 illustrate the gradation differences among the three sand types—coarse, medium, and fine—based on sieve analysis data. All curves exhibit a steep, nearly vertical slope, indicating that all three sands fall into the category of poorly graded sand (SP). This classification is supported by low uniformity coefficient (C_u) values ranging from 1.475 to 2.547 and curvature coefficient (Cc) values outside the optimal range (approximately 1.0). Poorly graded soils tend to have low interlocking potential and high porosity [18].

Coarse sand (the curve on the right of the graph) is dominated by larger particles (D_{10} = 2.091 mm), resulting in a high internal friction angle (φ) of 42.38°. However, due to its narrow gradation, the natural interparticle interaction is relatively weak in terms of mechanical interlocking. Medium sand displays a curve position between fine and coarse sands, with a relatively better gradation (C_u = 2.547), although it is still classified as SP. This makes it theoretically the most stable in terms of settlement behavior, particularly when reinforced with multi-layer geosynthetics. A study by Buragadda et al. [17] emphasized that using two layers of geogrid on medium-grained sand resulted in the most significant improvement in bearing capacity compared to other configurations.

4.2 Analysis of the relationship between applied load and settlement in the model

The graph illustrating the relationship between vertical load (kg) and settlement (mm) for various sandy soil configurations—both unreinforced and reinforced with geosynthetics—is presented in Figure 2. This graph is used to evaluate the effectiveness of each type of geosynthetic (woven, non-woven, and geogrid) in enhancing the soil's resistance to vertical deformation. A settlement of approximately 1 inch (25.4 mm) is used as the structural serviceability limit, in accordance with shallow foundation design standards. This data serves as a primary reference for assessing the performance improvement of soil due to reinforcement interventions.

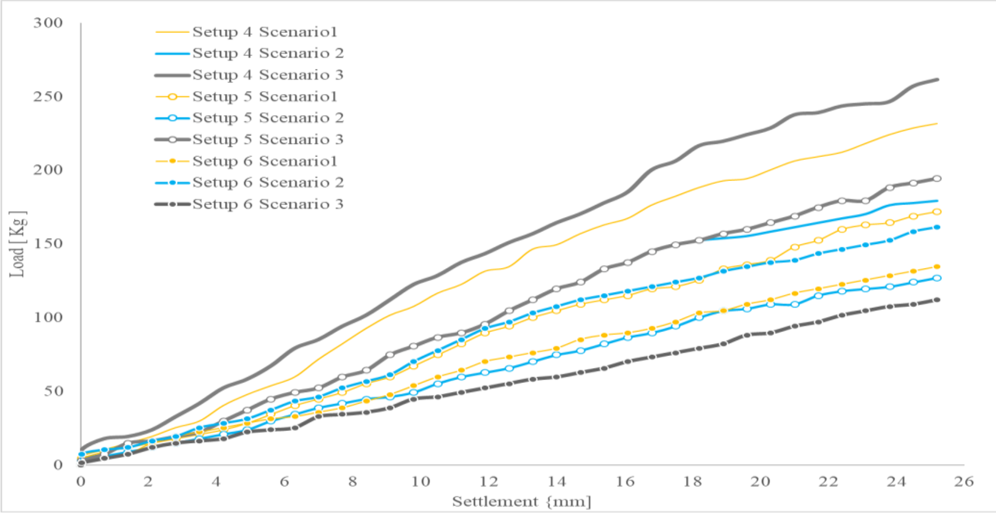

Figure 12. Load–settlement curve of the model

Based on the load–settlement graph (Figure 12), which presents various configurations of sand types and geosynthetics, it is evident that the unreinforced configuration (Configuration 1: coarse sand) could only sustain a maximum load of approximately 123.975 kg at a settlement of around 26 mm, which technically corresponds to 1 inch (25.4 mm). This value serves as a baseline for comparing the effectiveness of each reinforcement type. In soil mechanics, a settlement of 1 inch is often used as the serviceability limit in load tests, representing a threshold of significant deformation without total failure, as emphasized in shallow foundation load–settlement test procedures [18].

When geosynthetics are introduced, the bearing capacity increases significantly. Configuration 4, Scenario 3 (coarse sand with geogrid), achieved a load capacity of up to 261.625 kg at a settlement near 25 mm. This indicates that the geogrid layer effectively enhances the subgrade stiffness and reduces vertical settlement. Configuration 4, Scenario 1 (coarse sand with woven geotextile) and Scenario 2 (coarse sand with non-woven geotextile) showed maximum loads of approximately 232.725 kg and 179.4 kg, respectively—still substantially higher than the unreinforced condition. These patterns suggest that the interaction between coarse sand particles and geosynthetic materials with high tensile strength and strong interlocking potential (especially geogrid and woven geotextiles) results in an effective reinforcement mechanism by distributing load laterally [18].

In medium sand (Configuration 5), the maximum load at a settlement close to 1 inch dropped to around 194.350 kg for the geogrid scenario, and further decreased with woven geotextile (171.925 kg) and non-woven geotextile (127.075 kg). This indicates that reinforcement effectiveness tends to diminish in soils with intermediate density and internal friction, such as medium sand. In contrast, for fine sand (Configuration 6), the best performance was observed with non-woven geotextile, supporting a maximum load of approximately 161.460 kg, followed by woven geotextile (134.550 kg) and geogrid (112.5125 kg). Although these values indicate an improvement compared to the unreinforced condition, they remain lower than those observed in coarse sand. This aligns with the theory that fine particles have limited ability to interlock with open-structure geosynthetics, thus reducing load transfer efficiency [20].

From a loading theory perspective, as vertical load increases, soil particles deform, and lateral forces intensify. In unreinforced conditions, these lateral forces lead to uncontrolled load dispersion, resulting in large settlements. However, when geosynthetics are applied, these forces are redirected laterally and resisted by the tensile strength of the geosynthetic material, thereby reducing overall vertical deformation. This creates an interactive system between soil and geosynthetics that enhances stiffness modulus and improves load distribution [19]. This mechanism works optimally when the geosynthetic is placed horizontally beneath the foundation, as in square footing model load tests, which also serve to evaluate ultimate bearing capacity at the 1-inch settlement criterion.

The most significant increase in bearing capacity was observed in coarse sand reinforced with geogrid, nearly doubling the load capacity compared to the unreinforced condition. A 1-inch settlement is a critical parameter for assessing reinforcement performance, as it represents the serviceability limit for foundation structures. The interaction between soil particles and geosynthetic type plays a vital role in resisting loads, with the general effectiveness ranking as Geogrid > Woven > NonWoven. This study supports the theory that reinforcement materials with high stiffness and tensile strength significantly reduce deformation and enhance load distribution.

Across all configurations, the use of woven geotextile in coarse sand (Configuration 4, Scenario 1) achieved the highest bearing capacity, demonstrating that both geosynthetic type and soil gradation have a substantial influence on bearing performance. Geogrids tend to deliver consistent results across all sand types—coarse, medium, and fine—while non-woven geotextiles consistently showed the lowest performance. These findings align with soil–geosynthetic interaction theory, which states that woven geotextiles and geogrids, due to their high stiffness and tensile strength, are more effective in limiting lateral deformation and improving load distribution [21]. Additionally, the open structure of geogrids allows for effective interlocking with sand particles, enhancing soil–reinforcement bonding [21].

4.3 Analysis of the relationship between bearing capacity and settlement in the model

Figure 13 presents the relationship between the soil's ultimate bearing capacity (*qultim*, in N/cm²) and settlement (mm) for various combinations of sand types and geosynthetic materials. This graph is used to assess the effectiveness of reinforcement materials in enhancing soil bearing capacity up to a specific settlement limit. The analysis focuses on performance at the 1-inch settlement benchmark (25.2 mm), which is widely adopted in shallow foundation design. Through this graph, the contribution of each geosynthetic type in increasing ultimate bearing capacity and maintaining vertical deformation stability under critical conditions can be clearly observed

Based on Figure 13, which illustrates the relationship between the ultimate bearing capacity of the soil (*qultim*, in N/cm²) and settlement (in mm) across various sand and geosynthetic configurations, it is evident that the use of geosynthetics significantly enhances the bearing capacity of sandy soils compared to unreinforced conditions. This graph highlights the effectiveness of soil–geosynthetic interaction in modifying the vertical deformation response under loading, with particular focus on the 1-inch settlement threshold (approximately 25.4 mm), which is commonly used as a serviceability limit in foundation design [18].

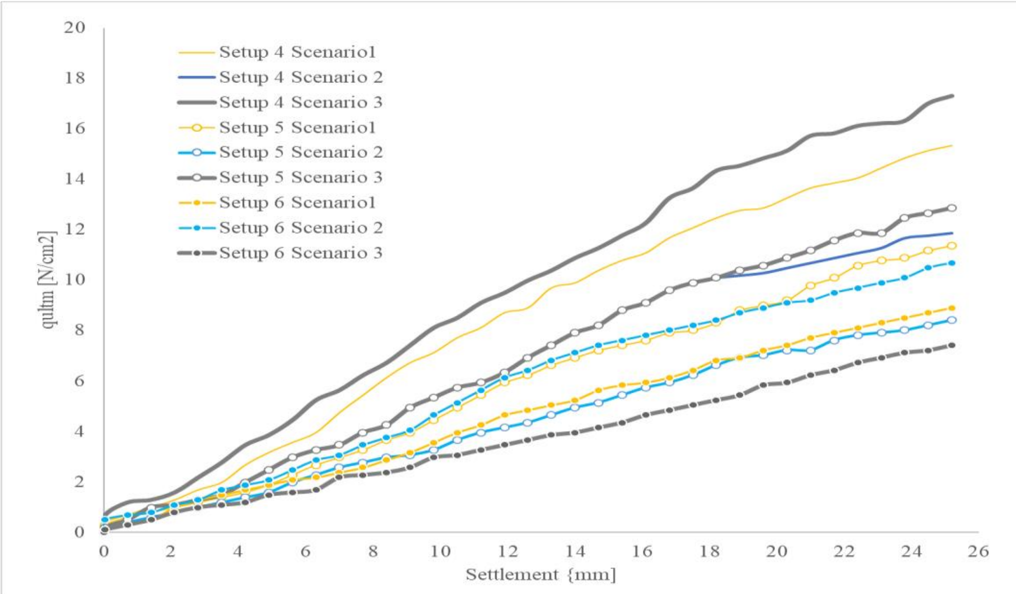

Figure 13. Curve of the relationship between bearing capacity of sand and settlement in the model

In Configuration 1 (coarse sand without reinforcement), the maximum ultimate bearing capacity reached approximately 10.983 N/cm² at a settlement near 26 mm. This value serves as the baseline for evaluating the effectiveness of other configurations. When geosynthetic layers were applied to coarse sand, a substantial increase was observed. Configuration 4, Scenario 3 (with geogrid) achieved the highest bearing capacity of around 17.311 N/cm² at a similar settlement, followed by Configuration 4, Scenario 1 (woven geotextile) at 15.332 N/cm², and Scenario 2 (non-woven geotextile) at 11.870 N/cm². These results indicate that geogrid is the most effective in enhancing the bearing capacity of coarse sand, followed by woven and non-woven geotextiles. This aligns with Koerner's [20] theory, which states that geosynthetics with high tensile modulus and structural stiffness provide better resistance to lateral strain and thus enhance vertical load-bearing capacity.

In medium sand (Configuration 5), the bearing capacity values were lower than those in coarse sand. Geogrid (Scenario 3) provided the highest value at 12.859 N/cm², followed by woven geotextile (11.375 N/cm²) and non-woven geotextile (8.408 N/cm²). Although the difference between woven and geogrid was relatively small, the trend suggests that medium-grained sand can still interact effectively with open-structured geosynthetics.

In contrast, fine sand (Configuration 6) exhibited a significant decrease in performance across all configurations. The maximum bearing capacities reached only 10.683 N/cm² for non-woven geotextile, 8.903 N/cm² for woven geotextile, and 7.419 N/cm² for geogrid. This phenomenon can be attributed to the limited interlocking capability between fine particles and the open structure of geosynthetics, reducing the reinforcement's contribution to lateral stress distribution [19].

A 1-inch (25.4 mm) settlement is recognized as a critical limit in evaluating the serviceability of shallow foundations, as defined in standard foundation design codes [22]. At this settlement level, most configurations showed significant variations in *qultim*, underscoring the importance of reinforcement type and soil gradation in service-level structural performance. Reinforcement systems capable of sustaining higher stress without substantial deformation are considered structurally more reliable.

The application of geosynthetics in sandy soils—particularly coarse sand—has proven effective in increasing ultimate bearing capacity. The optimal configuration was found to be coarse sand reinforced with geogrid, which demonstrated an improvement of up to 61.33% compared to the unreinforced condition. On the other hand, performance in fine sand was notably lower, emphasizing the importance of selecting reinforcement materials based on soil gradation. These findings support the theory that geosynthetics perform most effectively in granular soils with high mechanical interlocking potential, and that a 1-inch settlement serves as an appropriate indicator for evaluating the performance of reinforced systems.

5. CONCLUSIONS

The results of the study demonstrate that the use of geosynthetics significantly improves the performance of sandy soil in resisting applied loads. In the load–settlement graph, unreinforced coarse sand was only able to sustain approximately 161.46 kg, whereas the use of geogrid increased the bearing capacity to 261.625 kg. Woven and non-woven geotextiles also contributed to load enhancement, though with relatively lower effectiveness. In the stress–strain graph, the application of geosynthetics increased soil stiffness, with maximum stress rising from 10.683 N/cm² (unreinforced) to 17.331 N/cm² (with geosynthetics). This indicates that the soil–geosynthetic system is more capable of withstanding deformation with controlled strain. The ultimate bearing capacity versus settlement graph further confirms that woven geotextiles and geogrids are effective in maintaining structural performance up to the 1-inch settlement limit, which is a common design threshold in shallow foundation engineering.

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