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Numerical Investigation of the Influence of Geogrid Reinforcement on the Bearing Capacity of Shallow Strip Foundations on Sandy Soils

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Abstract

Geogrids are widely utilized geosynthetic materials designed to reinforce soil structures and enhance their mechanical performance. While cohesionless soils exhibit minimal tensile strength and are prone to shear failure under loading, geogrids possess high tensile strength, enabling them to redistribute stresses across a wider zone within the soil mass through interlocking and membrane mechanisms. This paper presents a numerical investigation into the bearing capacity of a shallow strip foundation on geogrid-reinforced sandy soil. A parametric study was conducted using finite element analysis to evaluate the influence of reinforcement layout parameters, specifically focusing on the normalized geogrid depth ((u/B)) and normalized geogrid width ((b/B)). The vertical spacing of the first geogrid layer relative to the foundation width ((u/B)) was varied between (0.25) and (1.0), while the normalized geogrid width ((b/B)) was investigated in the range of (1.0) to (15.0). The reinforcement efficiency was quantified using the non-dimensional Bearing Capacity Ratio ((BCR)), defined as the ratio of the ultimate bearing capacity of the reinforced soil to that of the unreinforced counterpart. The numerical results demonstrate that the installation of geogrid layers significantly enhances the bearing capacity of the sandy soil. However, the improvement rate diminishes asymptotically beyond certain threshold limits. The optimum reinforcement width was determined to be approximately (1.75) to (2.0) times the foundation width ((b/B \approx 1.75)–(2.0)). Beyond this optimal geometry, further increasing the width yields negligible increases in the ultimate bearing capacity. Similarly, the effectiveness of the reinforcement decreases as the depth of the first layer ((u/B)) increases beyond the critical threshold.

Keywords: *Geogrid reinforcement; Bearing capacity; Strip foundation; Sandy soil; Finite element analysis (FEA); ABAQUS.*

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1. Introduction

The bearing capacity of shallow foundations is a fundamental criterion in geotechnical design. In cases where the underlying soil exhibits insufficient strength or is subjected to significant loading, soil improvement techniques become essential. Over the past few decades, the integration of geosynthetics, particularly geogrids, has emerged as a highly effective and economical solution for reinforcing sandy soils [1, 7]. Geogrids, characterized by their high tensile strength and open aperture structure, enhance the soil's performance through lateral confinement and the "interlocking" mechanism between the soil particles and the grid ribs [8].

Extensive research has been conducted to quantify the benefits of geogrid reinforcement under various conditions. Previous studies have utilized both experimental and numerical approaches to identify the optimum configuration of reinforcement layers. For instance, Arafar and Abrishami [9] and Parsai Moghadam and Rad [10, 11] investigated the influence of geogrid layers and width on the static and dynamic response of foundations, noting that increasing the number of layers and optimizing the width (typically (b = 3B)) significantly enhances bearing capacity while reducing settlement. Similarly, investigations by Biniaz et al. [12] and Astaneh et al. [13] emphasized the role of stiffness and placement depth in improving the subgrade’s plastic modulus and ultimate capacity. Furthermore, seminal works by Das [14], Khing et al. [15], and Shin et al. [16] have established critical ratios for the depth of the first layer ((u/B)) and the total number of layers ((N)) required for maximum efficiency.

Despite these advancements, the complex interaction between geogrid geometry, embedment depth, and foundation type necessitates further localized and detailed numerical analysis to optimize design parameters for specific soil conditions. Given the logistical constraints and costs associated with large-scale laboratory testing, numerical modeling offers a robust alternative for parametric studies.

The primary objective of this study is to perform a comprehensive numerical investigation using Abaqus finite element software to evaluate the influence of geogrid reinforcement on the bearing capacity of shallow strip foundations on sandy soil. The research systematically examines key variables, including the number of geogrid layers, spacing between layers ((h)), distance of the first layer from the foundation base ((u)), and foundation embedment depth ((D_f)). Finally, the numerical findings are validated against experimental data to ensure the reliability of the proposed model.

2. Research Significance

The application of tensile elements such as metallic strips, geotextiles, or geogrids has revolutionized soil reinforcement practices over the past forty years. Despite the widespread construction of reinforced earth structures globally, translating academic findings into standardized design guidelines remains challenging. This challenge stems from persistent ambiguities regarding the simulation of geosynthetic-soil interfaces and the exact interaction mechanisms under varied confining pressures.

Many existing studies rely heavily on empirical relations that ignore the micro-mechanical interlocking behavior of geogrid apertures. Furthermore, the operational efficiency of geogrids depends on critical spatial limits (e.g., determining the exact threshold where adding more layers or increasing width yields diminishing returns).

By establishing a robust, validated numerical framework in Abaqus, this research addresses these critical gaps. It provides design engineers with verified parametric thresholds ((u/B), (b/B), (h/B)) that prevent conservative over-design and structural underperformance, thereby optimizing the economic and safety profiles of shallow foundations on sandy soils.

3. Materials and Methods

3.1. Numerical Modeling Approach

To investigate the bearing capacity and deformation behavior of a shallow strip footing resting on reinforced sandy soil, a series of three-dimensional (3D) finite element analyses were performed using ABAQUS. To simulate a rigid and rough footing under displacement-controlled loading (equivalent to plane strain conditions in terms of failure mechanism), a uniform downward velocity boundary condition was applied to the nodes representing the footing. The sand was modeled using an elastoplastic constitutive model governed by the Mohr-Coulomb failure criterion. The geogrid reinforcement was modeled as an elastic-perfectly plastic material. To systematically analyze the influence of reinforcement configuration, key dimensionless geometric parameters were defined: the normalized embedment depth of the first geogrid layer (u/B), the normalized spacing between geogrid layers (h/B), and the normalized width of the geogrid (b/B). The reinforcing efficiency was quantified using the Bearing Capacity Ratio (BCR), defined as:

$$\mathrm{BCR} = \frac{q_u\ (\text{reinforced})}{q_u\ (\text{unreinforced})}$$

where $q_u$represents the ultimate bearing capacity of the footing.

3.2. Finite Element Model Configuration

The geometric configuration of the soil-foundation-reinforcement system is illustrated in Figures 1 and 2. The boundary dimensions of the soil domain were set to $2.0\ \mathrm{m} \times 2.0\ \mathrm{m}$to eliminate boundary zone effects. The strip footing has a width (B) of $0.1\ \mathrm{m}$($10\ \mathrm{cm}$). The geogrid layer of width $b$is embedded at a depth $u$below the bottom of the footing.

To conduct a parametric study, the normalized parameters were varied within realistic ranges:

- The normalized geogrid width (b/B) ranged from $5$to 15.
- The normalized depth of the first layer (u/B) varied from $0.25$to 1.75.

3.3. Material Properties

The physical and mechanical properties of the sand used in the numerical model are summarized in Table 1, defined by the Mohr-Coulomb plastic parameters (friction angle ϕ, dilation angle ψ, and cohesion c). Table 2 lists the elastic properties, tensile capacity, and geometric specifications of the geogrid reinforcement.

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Table 1. Soil characteristics

Density (kg / m3)	Modulus of elasticity (Mpa)	Poisson's ratio	Friction coefficient	Expansion coefficient	Final adhesion stress
1920	182	0.2	46	4	1000

Table 2. Geogrid specifications

Thickness (mm)	Hole size (mm)	Density (kg / m3)	Modulus of elasticity (Mpa)
1	4	1800	46.2

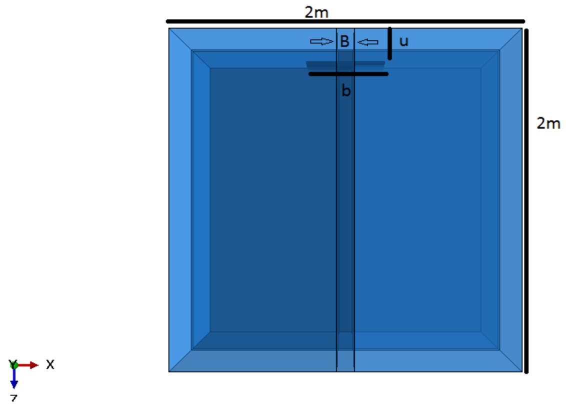

Figure 1. Dimensions and elements defined in software

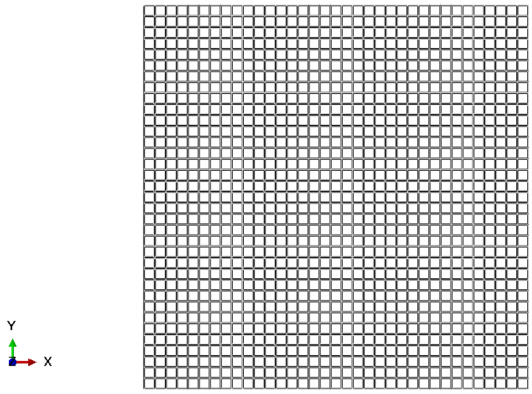

Figure 2. Simulated geogrid with dimensions of 1.75 * 1.75 cm^2

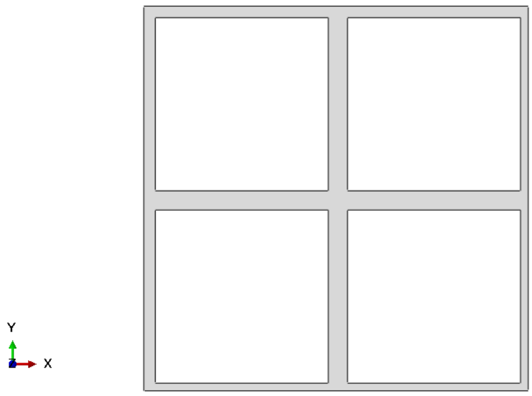

Figure 3. Simulated geogrid with dimensions of 0.1 * 0.1 m^2

3.4. Boundary Conditions and Loading

The boundary conditions of the numerical model are depicted in Figure 4. The bottom boundary of the soil domain was fully fixed against translation in all directions, while the lateral boundaries were constrained against horizontal displacement (lateral rollers). Loading was applied under displacement control at a constant downward velocity of 5.7×10^{-6} m/sto ensure quasi-static loading conditions and prevent dynamic effects. Geostatic stress initialization was performed to establish the initial in-situ effective stress field under self-weight.

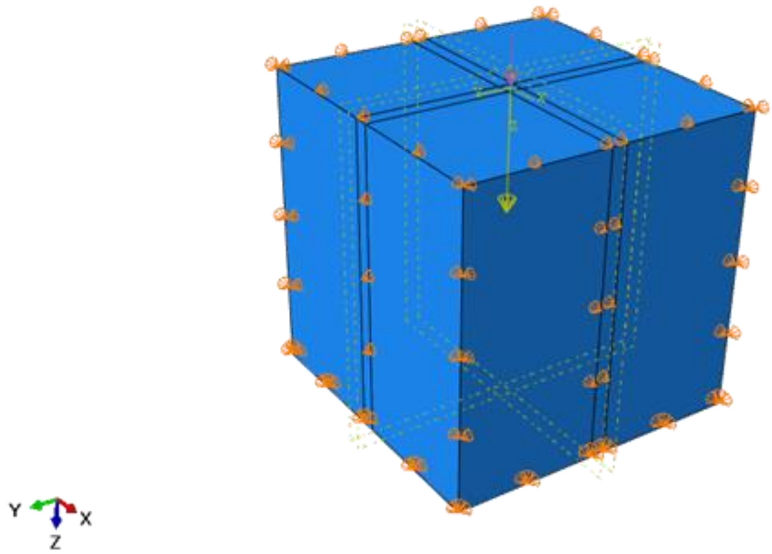

Figure 4. Border conditions and force applied

3.5. Finite Element Meshing

The mesh discretization for the soil and geogrid domains is shown in Figures 5 and 6, respectively. The soil was discretized using 8-node linear brick elements with reduced integration and hourglass control (C3D8R). The geogrid was modeled as a sheet using 4-node doubly curved shell elements with reduced integration (S4R). An embedment constraint was utilized to model the soil-geogrid interaction, assuming perfect displacement continuity between the soil matrix and the reinforcement apertures.

3.6. Influence of Geogrid Depth (u/B)

The effect of the depth of the first geogrid layer was analyzed by varying u/Bwhile keeping the geogrid dimensions constant. Figures 7 to 9 show the plastic strain contours for geogrid lengths of 0.5 m, 1.0 m, and 1.5 mat an embedment depth of 20 cm. Figure 10 compares the bearing capacity ratio (BCR) as a function of the normalized depth (u/B). The results indicate that while the introduction of the geogrid significantly enhances the bearing capacity, the reinforcement efficiency diminishes when the depth of the first layer exceeds a critical threshold, determined to be approximately $u/B = 1.75$.

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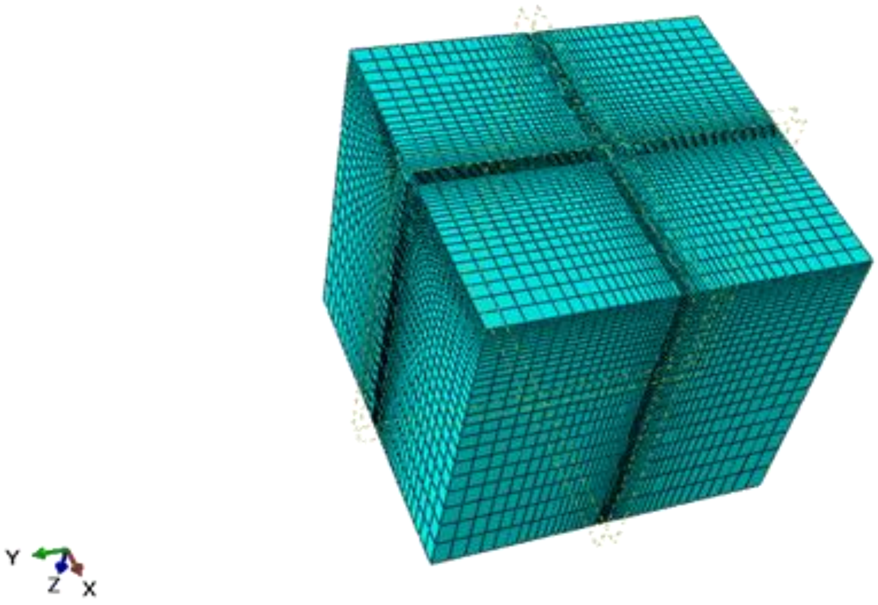

Figure 5. Soil networking

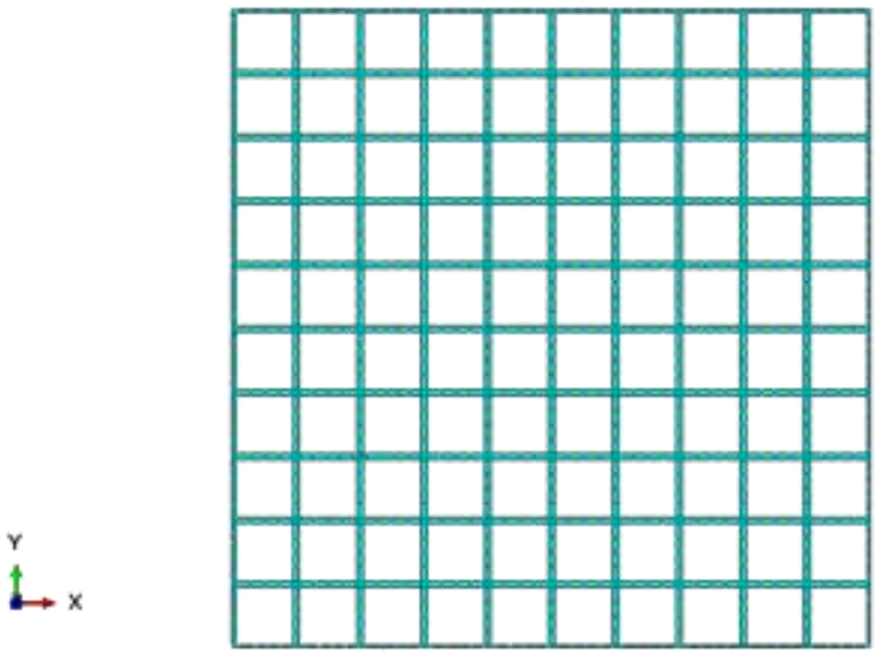

Figure 6. Geogrid networking

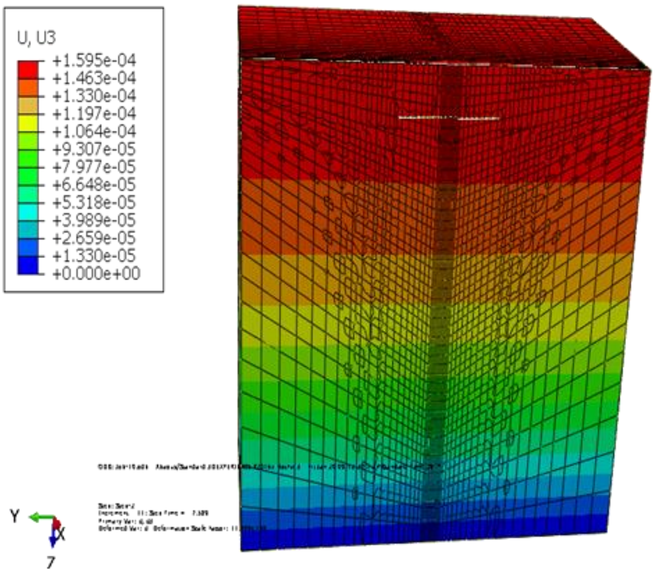

Figure 7. Distance from soil surface 20 cm and length of geogrid 50 cm

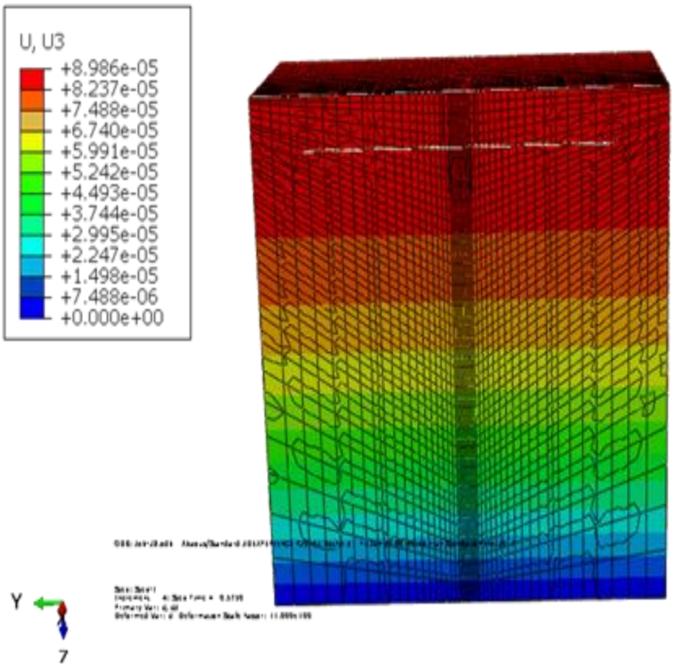

Figure 8. Distance from soil surface 20 cm and length of geogrid 100 cm

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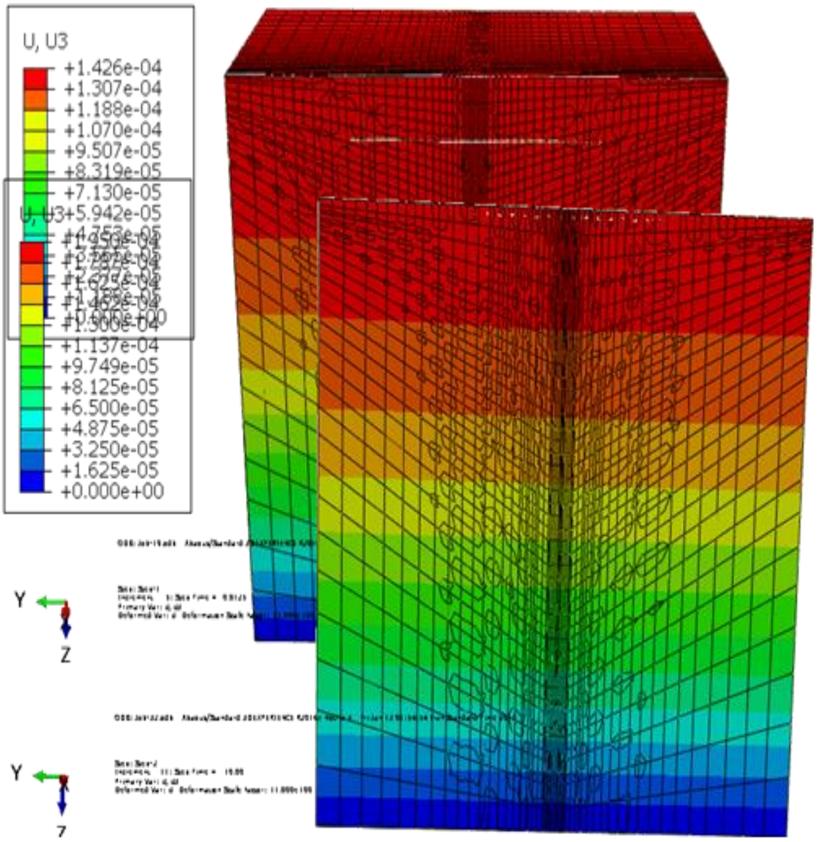

Figure 9. Distance from soil surface 20 cm and geogrid length 150 cm

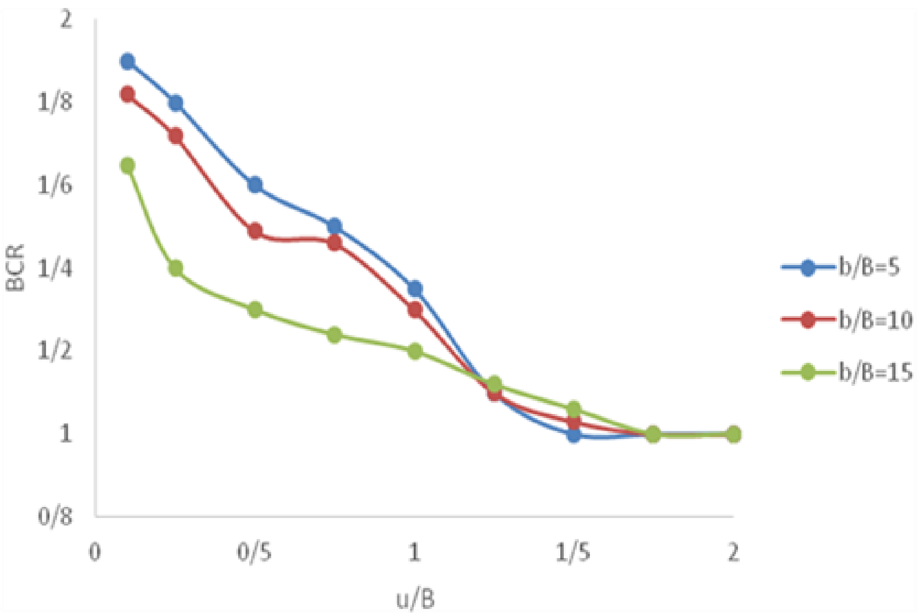

Figure 10. Comparison of soil load ratio at different distances from soil surface in 3 different dimensions

3.7. Influence of Geogrid Width (b/B)

To evaluate the influence of geogrid width on the bearing capacity, the width ratio (b/B) was varied under different embedment depths. Figures 11 to 13 present the failure mechanisms at a geogrid depth of 75 cmfor geogrid widths of 2.5 cm, 5 cm, and 10 cm. Figure 14 illustrates the variation of BCR with respect to b/B. The analysis demonstrates that bearing capacity increases with geogrid width up to an optimum ratio of $b/B \approx 15$, beyond which further increases in width yield negligible improvements in footing performance.

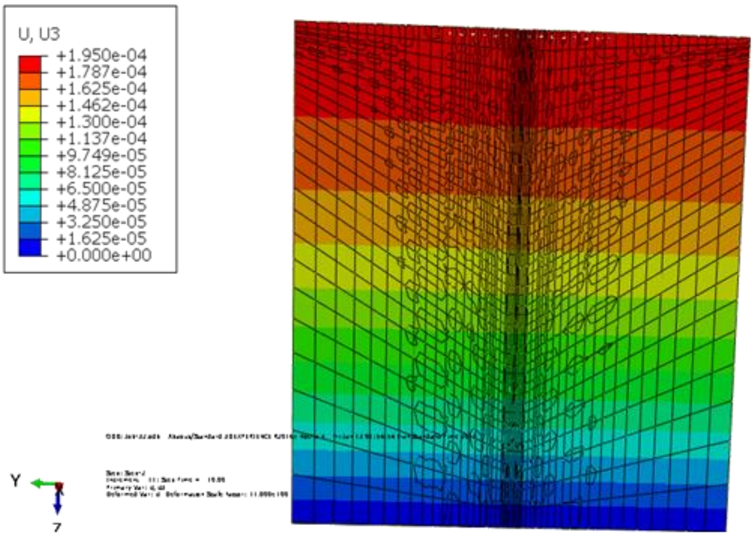

Figure 11. Distance from soil surface 2.5 cm and geogrid length 75 cm

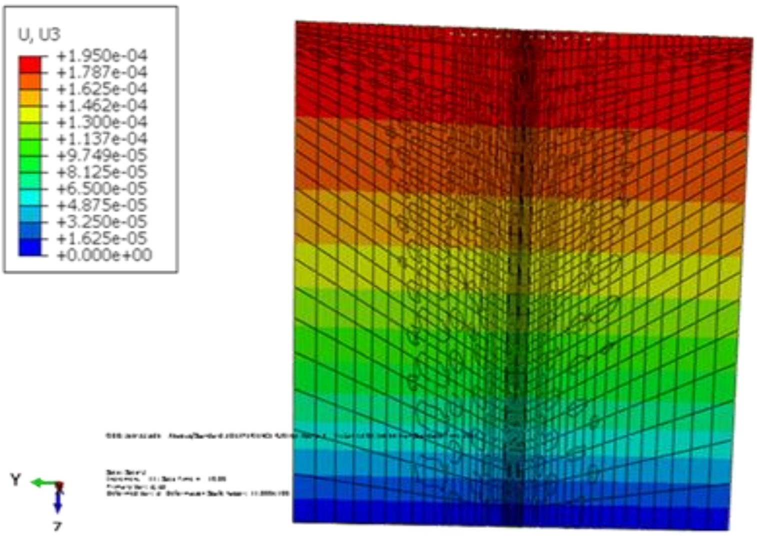

Figure 12. Distance from soil surface 5 cm and length of geogrid 75 cm

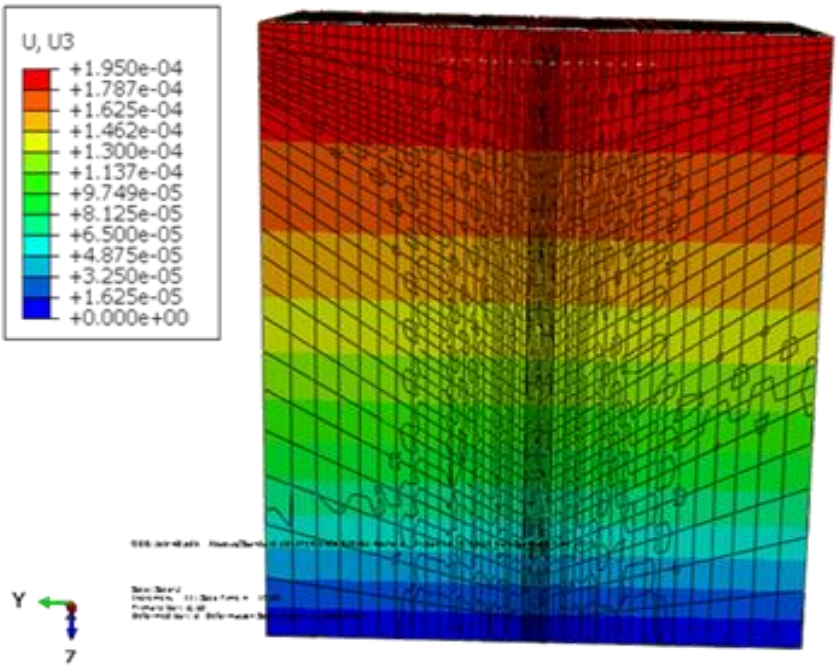

Figure 13. Distance from soil surface 10 cm and geogrid length 75 cm

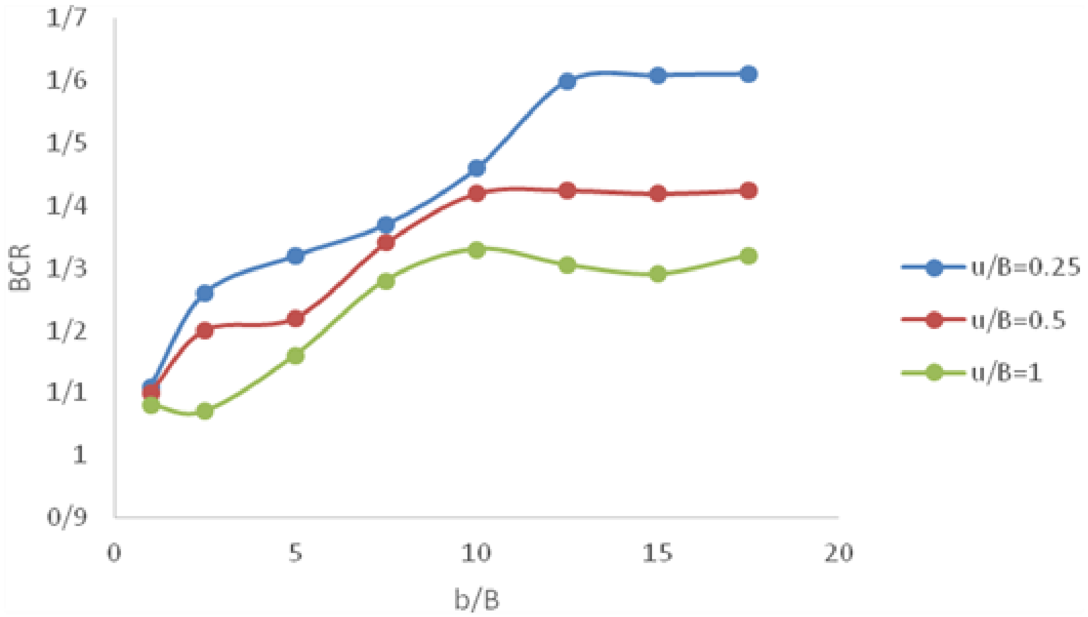

Figure 14. Comparison of soil load ratio in different geogrid dimensions at different geogrid distances from the soil surface

4. Conclusion

In this study, a comprehensive three-dimensional finite element analysis was conducted using ABAQUS to evaluate the influence of geogrid reinforcement on the bearing capacity and settlement behavior of shallow strip footings resting on sandy soil. The numerical model was validated using experimental database parameters. Based on the parametric analysis, the following conclusions can be drawn:

- **Effect of First Layer Depth (u/B):** The embedment depth of the first geogrid layer plays a critical role in the reinforcement efficiency. The ultimate bearing capacity ratio (BCR) increases as the geogrid is placed closer to the footing. However, an optimum depth ratio of $(u/B)_{\mathrm{cr}} \approx 1.75$ was identified. Placing the first layer beyond this depth yields negligible improvements in the bearing capacity, as the reinforcement falls outside the primary shear failure zone of the soil.
- **Effect of Geogrid Width (b/B):** Increasing the width of the geogrid reinforcement enhances the confinement effect and increases the BCR. The results indicate that the optimum normalized geogrid width is $b/B \approx 15$. Increasing the width beyond this limit does not contribute to further bearing capacity mobilization, as the failure envelope is already fully contained within the reinforced zone.
- **Failure Mechanism:** The presence of geogrid layers effectively redistributes the applied contact pressure over a wider area, forcing the shear failure surface to propagate deeper and wider into the sandy bed, which significantly controls plastic deformation and footing settlement.

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