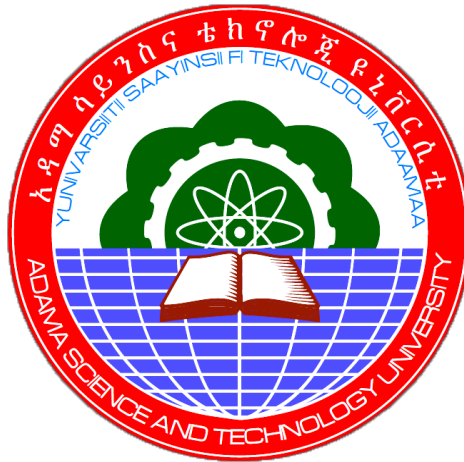


# Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils



Bereket Bogale Beyi

A Thesis Submitted to the Department of Civil Engineering,

School of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree  
of Master's in Civil Engineering

(Specialization in Geotechnical Engineering)

Office of Graduate Studies

Adama Science and Technology University

November, 2024

Adama, Ethiopia

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Main Advisor: - Argaw Asha Ashango (Ph.D.)

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Adama, Ethiopia

**DECLARATION**

I hereby declare that this Master Thesis entitled “**Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils**” is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All materials used for this thesis have been duly acknowledged through citation.

Bereket Bogale Beyi

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I/we, the advisor(s) of this thesis, hereby certify that I/we have read the revised version of the thesis entitled “**Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils**” prepared under my/our guidance by **Bereket Bogale Beyi** submitted in partial fulfillment of the requirements for the degree of Masters of Science in Civil Engineering. Therefore, I/we recommend submitting the revised version of the thesis to the department following the applicable procedures.

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**APPROVAL PAGE**

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**ACRONYMS, ABBREVIATIONS, AND SYMBOLS**

|                |                                                                    |
|----------------|--------------------------------------------------------------------|
| AASHTO         | American Association of State Highway and Transportation Officials |
| AAU            | Addis Ababa University                                             |
| ASTU           | Adama Science and Technology University                            |
| ASCE           | American Society of Civil Engineers                                |
| ASTM           | American Society of Testing Materials                              |
| BC             | Bearing Capacity                                                   |
| BCR            | Bearing Capacity Ratio                                             |
| BEM            | Boundary Element Method                                            |
| CBR            | California Bearing Ratio                                           |
| CEC            | Cation Exchange Capacity                                           |
| DGC            | Department Graduate Council                                        |
| EBCS           | Ethiopian Building Code Standard                                   |
| FEA            | Finite Element Analysis                                            |
| FEM            | Finite Element Methods                                             |
| GI             | Group Index                                                        |
| LL             | Liquid Limit                                                       |
| MC             | Mohr-Coulomb                                                       |
| MDD            | Maximum Dry Density                                                |
| OMC            | Optimum Moisture Content                                           |
| OPGS           | Office of Postgraduate Studies                                     |
| PI             | Plasticity Index                                                   |
| PL             | Plastic Limit                                                      |
| RSF            | Reinforced Soil Foundation                                         |
| SGC            | School Graduate Committee                                          |
| SL             | Shrinkage Limit                                                    |
| UCS            | Unconfined Compressive Strength                                    |
| USCS           | Unified Soil Classification System                                 |
| A              | Activity of Clay                                                   |
| C <sub>c</sub> | Coefficient of Curvature                                           |
| K              | Permeability Coefficient                                           |
| C <sub>u</sub> | Coefficient of Uniformity                                          |
| C              | Clay                                                               |

## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

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|                |                            |
|----------------|----------------------------|
| G              | Gravel                     |
| eo             | Initial void ratio         |
| NP             | Non – Plastic Materials    |
| O              | Organic Soil               |
| S              | Sand                       |
| M              | Silt                       |
| Cr             | Swelling Index             |
| Su             | Undrained Shear Strength   |
| e              | Void ratio                 |
| Vk             | Volume of soil in kerosene |
| Vw             | Volume of Soil in water    |
| GGI            | Geogrid Type I             |
| GGII           | Geogrid Type II            |
| GGIII          | Geogrid Type III           |
| GGV            | Geogrid Type V             |
| 2D             | Two – Dimensional          |
| 3D             | Three – Dimensional        |
| XRD            | X-ray diffraction          |
| $\gamma$       | Bulk unit weight           |
| $\gamma_{sat}$ | Saturated Unit Weight      |
| $\nu$          | Poisson's ratio            |
| $\phi$         | Angle of internal Friction |
| $\Psi$         | Angle of dilatancy         |
| E              | Youngs Modulus             |

## ***ABSTRACT***

*This study delineates a quantitative analysis of the efficacy of square and rectangular footings situated on geogrid-reinforced expansive soil. The investigation scrutinizes the impact of several pivotal parameters on the load-bearing capacity and settlement of distinct foundation geometries and dimensions, specifically a square footing measuring 2m x 2m and rectangular footings of dimensions 2m x 3m, 2m x 4m, and 3m x 4m. The parameters examined encompass the tensile modulus of the geogrid reinforcement, the vertical spacing between layers of reinforcement, the number of reinforcement layers, the embedment depth of the initial geogrid layer relative to the base of the footing, and the extension length of the reinforcement beyond the peripheries of the footing. The results reveal that an elevation in the tensile modulus of the reinforcement corresponds with a proportional enhancement in bearing capacity and reduces the rate of settlement. Furthermore, the bearing capacity demonstrates an increase with vertical spacing up to 1.5m, beyond which a decline is observed conversely the settlement of square and rectangular footing significantly decreases up to 1.5m and then rises. Regarding the embedment depth of the inaugural geogrid layer, the optimal values were identified as 0.5B for both square and 2m x 3m and 2m x 4m rectangular footings, and 0.33B for the 3m x 4m rectangular footing for bearing capacity increment and settlement reduction; surpassing these depths led to a reduction in bearing capacity but increase in the rate of settlement. Additionally, the investigation illustrates that augmenting the number of reinforcement layers enhances bearing capacity and reduces settlement up to four layers, beyond which additional enhancement confers minimal advantages. These numerical findings are corroborated by pre-existing experimental studies, revealing a significant degree of correlation and dependability. The research contributes essential insights for the design and optimization of geogrid-reinforced foundations under expansive soil conditions, intending to improve the load-bearing capacity and settlement both square and rectangular footing.*

**Key Words:** Settlement, Bearing Capacity, Geogrid-reinforced, Square and Rectangular Footing, Expansive Soils, Numerical Investigation.

## **CHAPTER ONE**

### **INTRODUCTION**

#### **1.1. Background**

Expansive soils are predominantly located in regions characterized by arid and semi-arid climates, arising from inadequate drainage and suboptimal climatic conditions; their coloration ranges from gray to deep black, with rare occurrences of reddish or yellowish types, and their thickness can vary significantly from 30 centimeters to 15 meters (Ashango and Patra 2014; Rao, 2000). Expansive soils, commonly known as black cotton soil, cover around 20% of the land area in the Indian subcontinent. These soils, characterized by their high shrink-swell potential, are not confined to this region alone. They are also found across various parts of the world, including Africa, Australia, and Ethiopia. Additionally, expansive soils are prevalent in countries such as Israel, Jordan, and the United States, posing similar geotechnical challenges (Ashango and Patra, 2014; Rao, 2000). In the African continent, expansive soil is found in South Africa, Ethiopia, Kenya, Mozambique, Morocco, Ghana, and Nigeria, among others (Teferra and Mesfin, 1999).

Expansive soils are characterized by their substantial volumetric alterations in response to variations in moisture content. The interaction of expansive soils with moisture can generate considerable forces on structures erected above them, resulting in significant structural damage. Expansive soils and bedrock constitute the substratum beneath more than one-third of the terrestrial land surface. Annually, the extent of damage incurred on buildings, roadways, pipelines, and other infrastructures due to expansive soils exceeds the cumulative damage inflicted by floods, hurricanes, tornadoes, and seismic activities. The consequences of such damages encompass severe structural impairments, fissured driveways, sidewalks, and basement flooring, uplift of roadways and highway infrastructures, structural failures of buildings, as well as interruptions to pipelines and sewer systems (Das and Sabat, 2008). The total estimated annual damages attributed to expansive soils on civil engineering infrastructures amount to approximately one billion dollars in the United States and 450 million dollars in the United Kingdom (Ashango and Patra 2014; Sabat and Nanda, 2011; Gourley et al., 1993).

Expansive soils are problematic for geotechnical engineering applications. Expansive soils contain mainly montmorillonite clay minerals they have weak Vander Wall's bonds which give greater affinity to absorb more water and expand, causing volume change of the soil

mass. Volume change in expansive due to moisture variation can cause significant damage to lightweight structures such as cracks in the walls of a building, which may cause structural failure of a building, distortion of highway pavement, and pipelines constructed on them (Canakci et. al., 2015).

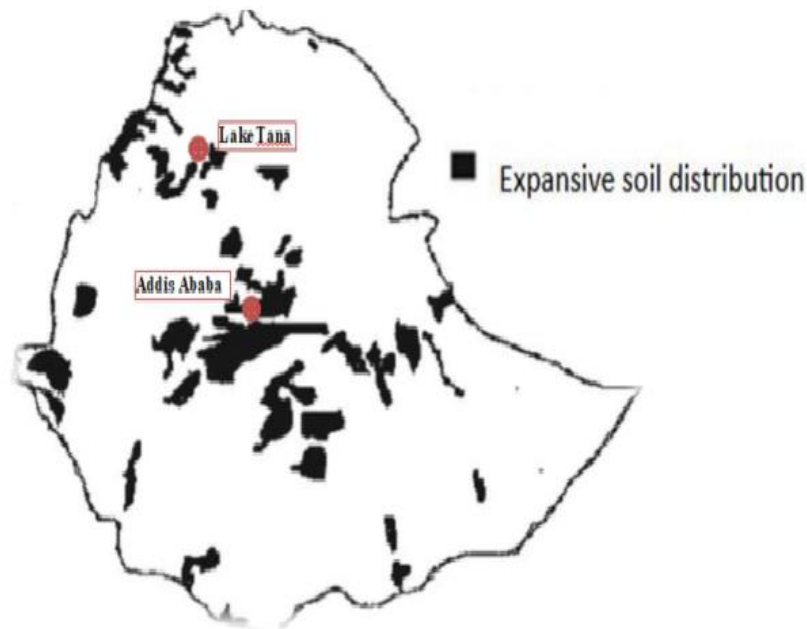


Figure 1.1: Distribution of Expansive Soils in Ethiopia (Sisay, 2004).

In Ethiopia expansive soils are widely spread and the distribution of this problematic soil hasn't been studied thoroughly. The major areas where expansive soil is covered in Ethiopia are southern, southeast, southwest of Addis Ababa, and areas where recent construction carried out and central part of Ethiopia like major trunk roads from Addis Ababa-Ambo, Addis Ababa-Waliso, Addis Ababa-Debrebrihan, Addis Ababa-Gohatsion, Addis Ababa-Modjo, and areas like Mekele, Gembella, and Bahirdar etc. are partly covered by expansive soils (Ayenew, 2004). Different techniques have been developed to address the challenges posed by the properties of expansive soils. Typically, the most effective solutions require either the removal of the inadequate soil and its replacement with an appropriate material, or the stabilization of the soil through chemical or mechanical interventions. Conventionally employed stabilizers such as cement and lime are frequently applied in practice (Atahu et al., 2019). Numerous researchers have explored various materials in combination with chemical stabilizers, including natural and synthetic fibers, and geosynthetic materials such as geogrids and geocells, to enhance the properties of expansive soils. Techniques for ground improvement or soil stabilization are categorized into four primary classifications:

mechanical modification, hydraulic modification, chemical and physical modification, and modification through inclusion and confinement (Haussmann, 1990).

Geogrid reinforcement constitutes a technique for the enhancement of soil properties, aimed at augmenting the load-bearing capacity and mitigating the settlement associated with shallow foundations situated upon expansive soils. Geogrids are constructed from polymeric materials and are strategically embedded within the soil matrix to confer supplementary strength and stability. Their operational mechanism involves the confinement of soil particles and the more equitable distribution of stresses, thereby diminishing the probability of foundation failure. To effectively enhance the bearing capacity and curtail the settlement of shallow foundations on expansive soils, the precise placement and configuration of geosynthetic materials, such as geogrids, as reinforcement is critical.

A comprehensive analysis of both unreinforced and geogrid-reinforced expansive soils was conducted utilizing the finite element-based software PLAXIS 3-D, wherein various parameters pertinent to geogrids, types of footings, and dimensional variations of shallow foundations were scrutinized. These parameters encompassed the number of reinforcement layers, the vertical spacing between successive reinforcement layers, the embedment depth of the initial reinforcement layer, the tensile stiffness of the reinforcement, the extension length of the geogrid relative to the width of the footing, the variation in footing types, and the result were compared with that of the unreinforced expansive clay soils

### **1.2. Statement of the Problem**

In numerous regions throughout our nation, expansive soils are prevalent, which can impose significant pressure on foundations, consequently resulting in structural damages, including the cracking of edifices, highways, railways, dams, and subterranean infrastructures established atop them, thereby incurring additional maintenance costs, catastrophic property damages, and potentially even fatalities. This phenomenon can be attributed to the presence of montmorillonite-type clay minerals within expansive soils, which exhibit a propensity for swelling and shrinkage in response to variations in moisture content. Nevertheless, a considerable number of lightweight residential and industrial structures have been erected upon these problematic soils, leading to their premature failure relative to their intended design lifespan. As a result, there is a pressing need for the enhancement of the strength of such soils through the incorporation of geosynthetics, such as geogrid materials. Consequently, improving the engineering properties of expansive soil is paramount to

ensuring the safety of structural foundations. One of the methodologies employed to ameliorate the engineering properties of such soils is ground improvement using geogrids as reinforcement to mitigate critical challenges faced within the construction industry.

### **1.3. Research Questions**

1. What is the effect of increasing the number of reinforcement layers and the embedment depths of the first reinforcement layer on the bearing capacity and settlement of expansive soil beneath square and rectangular footing?
2. What are the effects of vertical spacing and the length of reinforcement on the bearing capacity and settlement of expansive clay soils under square and rectangular footing?
3. How are the load-settlement characteristics of both reinforced and unreinforced expansive soil beneath a shallow foundation manifested, and how does the tensile modulus of reinforcement influence the bearing capacity and settlement of square and rectangular footing?
4. How does variation in footing type affect the bearing capacity and settlement of expansive soils under square and rectangular footing?

### **1.4. Objectives of the Study**

#### **1.4.1. General Objective**

The primary objective of this study is to investigate the bearing capacity and settlement of square and rectangular footing on geogrid-reinforced expansive soils using numerical analysis.

#### **1.4.2. Specific Objectives**

The specific objective is to:

- Investigate the influence of the number of geogrid layers and the embedment depth of the initial layer on bearing capacity and settlement of expansive soil.
- Analyze the influence of vertical spacing and extension lengths of geogrid layers on the performance of expansive soils.
- Assess the influence of reinforcement tensile modulus on the performance of expansive soil and analyze the load-settlement response in reinforced and unreinforced expansive soil.
- Evaluate the effects of footing type on the performance of expansive soils under shallow foundations.

### **1.5. Scope of the Study**

This research was compiled by reviewing different kinds of literature or journals related to the area and performing a series of numerical modeling on geogrid-reinforced expansive soil in more detail. It aimed to investigate the improvement in geotechnical properties of expansive soils with the addition of geosynthetic materials, especially geogrids. The numerical modeling performed on the performance of expansive soils reinforced with geogrids by varying the vertical spacing between successive geogrids, the embedment depth of top geogrid layers from the bottom of the footing, the extension length of geogrids relative to footing width, the tensile modulus of the geogrid, the number of layers of geogrids and compare the performance of square and rectangular with varying dimension on geogrid reinforced expansive soils. The numerical investigation on the performance of square and rectangular footing on both geogrid-reinforced and unreinforced expansive clay soils was investigated using the finite element-based computer program called PLAXIS 3-D and compared the analysis results and observed the effect of geogrids, footing type variations on bearing capacity improvement and settlement reduction and finally validates the numerical investigation work with experimental or laboratory work.

### **1.6. Significance of the Study**

Expansive soils are susceptible to volume changes due to variations in moisture content, leading to differential settlements that can adversely affect structures. Shallow foundations are commonly employed in such soils, and understanding their performance when reinforced with geogrids can offer insights into improving the stability and durability of structures. Numerical modeling allows for a detailed and comprehensive analysis of the complex interactions between the foundation, geogrid reinforcement, and the expansive soil. This can provide a more accurate prediction of the behavior of the foundation system under different conditions, helping engineers and researchers make informed decisions regarding design and construction. The study can contribute to the recommendations for the use of geogrid reinforcement in expansive soils, offering practical solutions to mitigate potential issues related to settlement, bearing capacity, heave, and overall foundation performance. Finally, the findings of this study can have practical implications for geotechnical engineering practices, potentially leading to improved design methodologies for foundations on expansive soils, thereby enhancing the overall safety and longevity of civil infrastructure.

### **1.7. Structure of the Thesis**

The thesis is divided into five chapters. The first chapter starts with the background, the statement of the problem, objectives, Scope, and significance of the study. The second chapter provides a brief literature review on expansive soil, geosynthetic, numerical, and laboratory investigation work on the performance of shallow foundations. The third chapter addresses the research materials, methods, and procedures used for the numerical investigation, as well as the numerical modeling protocols that were performed. The fourth chapter includes results and discussion as well as the validation of the findings or comparison of the numerical model results to other similar research outcomes. The fifth chapter focuses on the conclusions, and recommendations that can be drawn from this study.

## **CHAPTER TWO**

### **REVIEW OF RELATED LITERATURE**

#### **2.1. Expansive Soils**

Expansive soils refer to types of soils that undergo significant changes in volume due to variations in moisture content. These soils can swell when they absorb water and shrink when they dry out. The expansive nature of these soils is primarily attributed to the presence of certain clay minerals, such as Montmorillonite clays, which have a unique ability to absorb water and expand.

The swelling and shrinking behavior of expansive soils can pose challenges in construction and civil engineering projects. When these soils absorb water, they increase in volume, exerting pressure on structures and foundations. Conversely, during dry periods, the soil can shrink, potentially leading to settlement and instability. Expansive soils have characteristics whereby seasonal variations in moisture content produce swelling and shrinking of the soil volume, which results in structural damages this behavior can pose significant challenges for construction and engineering projects, leading to various problems foundation Damages, cracks in pavements and roads, disrupted drainage system, damages underground utilities (Canakci et.al., 2015). The key culprit behind expansive behavior is the presence of certain clay minerals, particularly montmorillonite. These minerals have a unique ability to absorb water between their layers, causing them to swell significantly in volume. The more water they absorb, the greater the expansion. Expansive soils are found throughout the world, but they are particularly common in arid and semi-arid regions where they experience pronounced wet and dry seasons. However, they can also be found in more humid areas, especially where clay-rich soils are present. The six natural hazards are earthquakes, landslides, expansive soils, hurricanes, tornadoes, and floods. Expansive tie with hurricane/storm surge second place among America's destructive natural hazards in terms of dollars losses to building. By the year 2000, losses due to expansive soil would exceed 4.5 billion dollars annually (Chen, 1988). Managing the effects of expansive soils is crucial in engineering design and construction to prevent damage to buildings and infrastructure. Engineers often employ specific foundation designs and soil stabilization techniques to mitigate the impact of expansive soils in construction projects.

## **2.2. Origin of Expansive Soils**

In general, there are many processes described for the formation of soils around the globe. The main process in the formation of soil from rock may be either through physical or chemical weathering. The physical process of soil formation is simply a changing of rock particle size which is most commonly undergoes due to the action of wind, water, or glacier erosion and also the cyclic action of freezing and thawing which creates cracks in rock mass. The resulting soil particles have the same mineralogical composition as that of the parent rock, but their particle size is too fine. However, chemical processes result in changes in the mineral form of the parent rock due to the action of water, especially if it contains traces or drops of acid or alkali, oxygen, and carbon dioxide. Chemical weathering results in the formation of groups of crystalline particles of colloidal size less than 0.002 mm, known as clay minerals. For example, the overall feldspar weathering process can be simplified as the alteration of sodium feldspar to common clay minerals, such as kaolinite (Yuan *et al.*, 2019). The parent materials associated with expansive soils are either basic igneous rocks or sedimentary rocks. Igneous rock is formed by the decomposition of feldspar and pyroxene and includes basalt, dolerite sills and dykes and gabros and norites, and sedimentary rocks, they are constituents of the rock itself and includes marls and limestone, and shales (Teferra and Mesfin, 1999). The parent materials of expansive soil are classified into two main classes, are basic Igneous rock which includes basalt, dolerite sills, and dykes and the second is sedimentary rocks that contain montmorillonite (Teferra, 2013).

## **2.3. Mineralogy of Expansive Clay Soils**

The type of clay minerals present plays a crucial role in determining the expansiveness of soil. Expansive soils have a very high clay content. There are three types of clay minerals and listed in increasing order of expansiveness

### **2.3.1. Kaolinite Groups**

Kaolinite clay minerals consist of a single silica tetrahedral sheet & alumina octahedral sheet and its structure is often referred to as the 1:1 lattice type with a typical basal spacing of about 7.2Å (Mitchell & Soga, 2005; Teferra and Mesfin, 1999). They are derived from the weathering of either sodium or potassium feldspar under acidic water action and contain no exchangeable cations (Yuan *et al.*, 2019). The bond between the tetrahedral and octahedral layers is a hydrogen bond which critically significant. This bonding holds the 1:1 layer tightly together leaving little or no interlayer space for absorption of water or cations, the

shrink & swell phenomenon is virtually non-existence and strong enough (Dixon, 1989). There is a high degree of regularity in the stacking of well-crystallized kaolinite units, with crystal diameters ranging from 0.5-4 $\mu$ m and a specific surface area of 10-20 m<sup>2</sup>/g (Chen, 1975). The theoretical formula of kaolinite is given as Al<sub>4</sub>Si<sub>4</sub>O<sub>10</sub>(OH)<sub>8</sub>. It is the least active clay mineral with the lowest plasticity and lowest capacity for adsorbing cations among the three clay mineral groups.

### **2.3.2. Illite Groups**

Illite is a basic Structural unit similar to that of montmorillonite. The structure of illite was formed of two silica tetrahedral sheets with a central sandwich of aluminum or magnesium octahedral sheets. The illite group was also arranged with a 2:1 lattice type, which is similar to the montmorillonite group in structural arrangements. They are derived from the weathering of silicates including mica and alkali feldspar under alkaline conditions (Mitchell & Soga, 2005; Teferra. A. and L. Mesfin, 1999). Illite has low plasticity and swelling potential compared to montmorillonite due to a larger particle diameter of 0.5-10 $\mu$ m and a lower specific surface area of 180m<sup>2</sup>/g (Chen, 1975). They have a common formula of [(K, H<sub>3</sub>O) (Al, Mg, Fe)<sub>2</sub> (Si, Al)<sub>4</sub>O<sub>10</sub>[(OH)<sub>2</sub>, (nH<sub>2</sub>O)]] and contain an inner layer potassium ion (K<sup>+</sup>) that is non-exchangeable. The shrink & swell potential of illite minerals is slightly higher than that of kaolinite, but much lower than that of smectite or montmorillonite group minerals.

### **2.3.3. Montmorillonite Groups**

Montmorillonite is the most common of the clay minerals and it is well known for its swelling properties. Its basic structure consists of an alumina sheet sandwiched between two silica sheets. The basic montmorillonite units are stacked one on top of the other, but the bond between the individual units is relatively weak so that water is easily able to penetrate between the sheets and cause their separation and hence swelling (Teferra. A. and L. Mesfin, 1999). Individual clay particles are plate-shaped with an average diameter of roughly 1 $\mu$ m and a thickness of 9.6Å detected under magnification of about 25,000 times using a scanning electron microscope with a typical basal spacing of 9.6-17.1Å or more (Mitchell & Soga, 2005). Montmorillonite minerals show extensive inner layer expansion on hydration.

The particle diameter ranges from 0.05-10  $\mu$ m with a large active specific surface area of about 50-840 m<sup>2</sup>/g exposed, allowing an enormous range of guest molecules like water to introduce because inter sheet bonding is mainly due to weak van der Waal's forces (Chen,

1975). Chemically, it was a hydrated sodium calcium aluminum magnesium silicate hydroxide, with a chemical formula  $(\text{Na}, \text{Ca})_3(\text{Al}, \text{Mg})_2(\text{Si}_4\text{O}_{10})(\text{OH})_2 \cdot n\text{H}_2\text{O}$ .

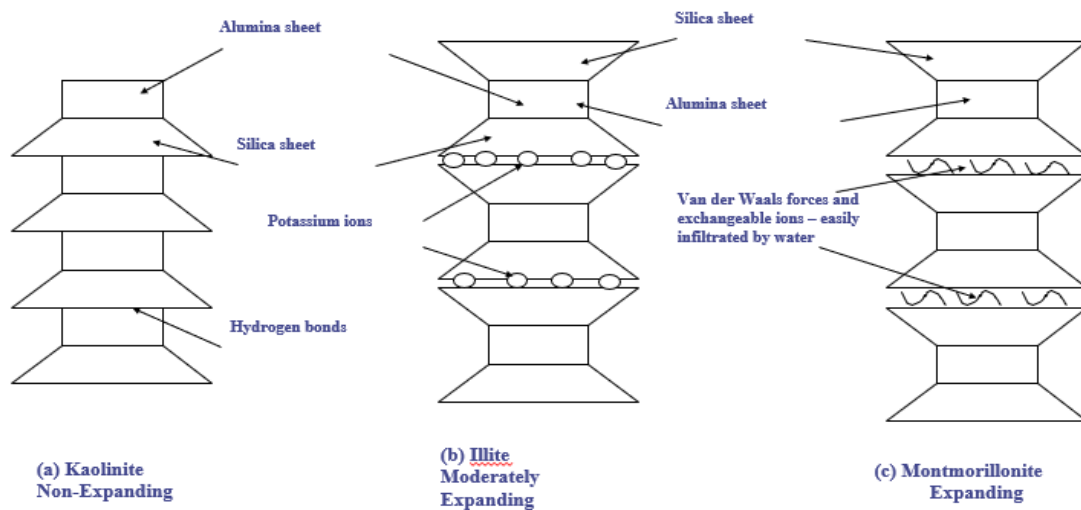


Figure 2.1: Structure of basic clay minerals (Teferra and Mesfin, 1999).

### 2.4. Methods of Identifying Expansive Soils

Generally, the Investigation of expansive soils on the earth's crust was done through two important methods. The method is through visual identification (Field identification) and recognizes the material as expansive soil and the second method is through sampling, characterizing, testing, and measuring of material properties to be used as the basis for design called laboratory identification.

#### 2.4.1. Field Identification

Expansive soils exhibit high swelling potential and can be identified in field observation, mainly during reconnaissance and preliminary investigation stages (Teferra, et. al., 2023, Nelson & Miller, 1975). Some of the important field identification methods that indicate the potential for the expansiveness of soil are the following (Abraham, 2015, Teferra, et. al., 2023).

- ✚ High dry strength and low wet strength.
- ✚ Sticking property and low traffic ability when it gets wet.
- ✚ Usually have a black or gray color.
- ✚ Wide or deep shrinkage cracks appear on the surface.
- ✚ Cut surfaces have a shiny appearance.
- ✚ Appearance of cracks on nearby structures.

These types of soil are most commonly found in arid and semi-arid areas of the globe because there is a large variation in temperature and rainfall.

### 2.4.2. Laboratory Identification

The laboratory identification techniques can be done through mineralogical identification and inferential techniques (Tefera, et. al., 2023).

A) Mineralogical Identification: The clay mineralogy is a basic governing factor that controls the behavior or the properties of expansive soils (Teferra, et. al., 2023, Nelson & Miller, 1975). The clay minerals are identified by different techniques among them are listed below.

-  X-ray diffraction (XRD)
-  Differential thermal analysis (DTA)
-  Dye adsorption
-  Chemical analysis
-  Electron microscope resolution (EMR)

According to (Chen, 1975), to achieve better and more reliable results, these strategies had to be combined. Unfortunately, these processes are limited to use in research laboratories since they require expensive, specialized equipment and expert analysis skills to produce the resultant data.

B) Inferential Testing Methods: Inferential testing methods for expansive soils aim to estimate their swell potential by linking readily obtainable index properties with the underlying clay mineralogy, which plays a crucial role in expansion behavior. This method can be classified into two main categories which are direct and indirect methods.

1) Indirect Methods: These methods assess the swell potential of soils by using some of the indices, such as the plasticity index, shrinkage index, and the like, along with soil index qualities like the liquid limit, shrinkage limit, and % clay size composition of soils (Asuri & Keshavamurthy, 2016).

a) Liquid Limit: The standard Casagrande method or the fall cone methods are used in the laboratory to estimate this upper bound of the plasticity limit. A soil's liquid limit is commonly understood to be its capacity to hold water, which is seen as a gauge of its potential for swell. Many classification schemes are available in the geotechnical engineering literature to recognize the

## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

degree of soil swell potential based on the liquid limit of fine-grained soils, as shown in the following table 2-1.

Table 2-1: Expansive soil classification based on Liquid Limit (LL) (Teferra, et. al., 2023)

| Swell Potential   | Liquid Limits (%) |                              |               |
|-------------------|-------------------|------------------------------|---------------|
|                   | Chen (1975)       | Snethan <i>et al.</i> (1977) | IS:1498(1970) |
| Low               | < 30              | < 50                         | 20 – 30       |
| Medium (Marginal) | 30 – 40           | 50 – 60                      | 35 – 50       |
| High              | 40 – 60           | > 60                         | 50 – 70       |
| Very High         | > 60              | -                            | 70 - 90       |

b) Plasticity Index: It is the difference between the liquid limit and the plastic limit of fine-grained soils. The higher the plasticity index, the more plastic the soil is and the higher would be the soil swell potential. Different schemes available to recognize the soil expansively based on the plasticity index of the soils are given in Table 2-2.

Table 2-2: Expansive soil classification based on Plasticity Index (PI) (Teferra, et. al., 2023)

| Swell Potential   | Plasticity Index (%)   |             |               |
|-------------------|------------------------|-------------|---------------|
|                   | Holtz and Gibbs (1956) | Chen (1975) | IS:1498(1970) |
| Low               | 0-15                   | 0-15        | <12           |
| Medium (Marginal) | 10-35                  | 10-35       | 12-23         |
| High              | 20-55                  | 20-55       | 23-32         |
| Very High         | >35                    | >35         | >32           |

c) Shrinkage limit: It represents the lower bound water content for any volume reduction of a soil mass and is regarded as a measure of the volume stability of the in-situ soils (Teferra, et. al., 2023). The table given below presents the schemes available to recognize the swelling potential of fine-grained soils based on shrinkage limit.

The table given below presents the schemes available to recognize the swelling potential of fine-grained soils based on shrinkage limit.

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Table 2-3: Expansive soil classification based on shrinkage limit SL (Tefera, et. al., 2023)

| Swelling Potential<br>Holta and Gibbs<br>(1956) | Shrinkage<br>Limit (%) | Volume Change<br>Altmeyer (1956) | Shrinkage Limit (%) |
|-------------------------------------------------|------------------------|----------------------------------|---------------------|
| Low                                             | >15                    | Non-Critical                     | >12                 |
| Medium                                          | 10-16                  | Marginal                         | 10-12               |
| High                                            | 7-12                   | Critical                         | <10                 |
| Very High                                       | <11                    |                                  |                     |

d) Shrinkage Index: It is defined by the Bureau of Indian Standards (IS: 2809, 1972) as the difference between the plastic limit and shrinkage limit. The classification of the swell potential of fine-grained soils based on their shrinkage index is given in the table below.

Table 2-4: Expansive soil classification based on Shrinkage Index SI (IS: 1498, 2007)

| Swelling Potential | Shrinkage Index |
|--------------------|-----------------|
| Low                | <15             |
| Medium             | 15-30           |
| High               | 30-60           |
| Very High          | >60             |

e) Free Swell Index: The free swell index is also one of the most commonly used simple test methods to estimate the swelling potential of expansive clay (Rao, 2006). In this method, two oven-dried samples weighing 10g each and passing through a 0.425 mm sieve were taken. One sample is put in a 100ml graduated glass cylinder containing kerosene which is nonpolar liquid and the other sample is put in a similar cylinder containing distilled water. Both the samples are gently stirred and left undisturbed for 24 hours, and then their volumes are noted. The free swell index is expressed as:

$$\text{Free Swell Index}(\%) = \left( \frac{V_w - V_k}{V_k} \right) * 100 \quad (1)$$

Where,  $V_w$  and  $V_k$  are final soil volumes soaked in water and Kerosene, respectively.

## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

Table 2-5: Relationship between FSI and degree of expansiveness (Rao, 2006)

| Degree of Expansiveness | Free Swell Index (%) |
|-------------------------|----------------------|
| Low                     | < 20                 |
| Moderate                | 20 - 35              |
| High                    | 35 - 50              |
| Very High               | > 50                 |

f) Free Swell Ratio: To determine swell property, the free swell ratio method of characterizing the soil swelling. The free swell ratio is defined as the ratio of sediments volume of 10 cm<sup>3</sup> oven-dried soil passing through a 0.425 mm sieve in distilled water to that of kerosene (Prakash & Sridharan, 2004).

$$\text{Free Swell Index}(\%) = \left( \frac{V_w}{V_k} \right) \quad (2)$$

Where:  $V_w$  and  $V_k$  are the final soil volume soaked in water and kerosene, respectively.

Table 2-6: Classification of soil based on (free swell ration) FSR (Prakash & Sridharan, 2004)

| FSR      | Soil expansiveness | Clay type                            | Dominant mineral type         |
|----------|--------------------|--------------------------------------|-------------------------------|
| <1.0     | Negligible         | Non-swelling                         | Kaolinite                     |
| 1.0 -1.5 | Low                | A mixture of swelling & non-swelling | Kaolinite and Montmorillonite |
| 1.5-2.0  | Moderate           | Swelling                             | Montmorillonite               |
| 2.0-4.0  | High               | Swelling                             | Montmorillonite               |
| > 4.0    | Very High          | Swelling                             | Montmorillonite               |

g) Cation Exchange Capacity (CEC): Cation Exchange Capacity, which is connected to clay mineralogy, is the number of exchangeable cations needed to balance the negative charge on the surface of the clay particles. It is represented in milli equivalents per 100 grams of dried clay. Clays with high CEC levels are more water-holding and have a high surface activity. Swell potential generally rises as the CEC does (Tefera E.T, et. al., 2023).

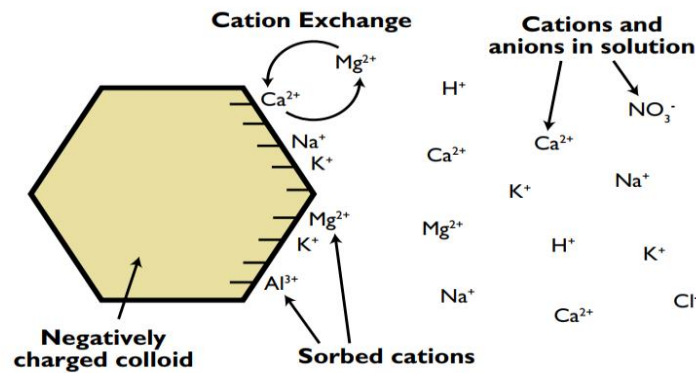


Figure 2.2: Simplified representation of cation exchange (Teferra, et. al., 2023).

Table 2-7: Typical CEC values of basic clay minerals (Teferra, et. al., 2023)

| Clay Minerals   | Cation Exchange Capacity (CEC)<br>(meq/100gm) |
|-----------------|-----------------------------------------------|
| Kaolinite       | 3 -15                                         |
| Illite          | 10 - 40                                       |
| Montmorillonite | 80 -150                                       |

h) Activity of Clay: The activity of a soil is normally calculated as the ratio of the plasticity index of the soil to its percentage clay size fraction. The soils can be classified based on their activity according to the guidelines given in Table (Asuri & Keshavamurthy, 2016).

$$Activity (A) = \frac{Plasticity\ Index}{\% \text{ Clay Fraction}} \quad (3)$$

Clays containing kaolinite will have relatively low activity and those containing montmorillonite will have high activity. Based on this classification:

- ✚ Montmorillonite clay (expansive clay) is defined as active.
- ✚ Illite clay as normal and,
- ✚ Kaolinite clay is inactive.

## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

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Table 2-8 Expansive soil classification based on the activity (Asuri & Keshavamurthy, 2016)

| Activity (Ac) | Nature of the Soil | Problem Degree of swell<br>Potential |
|---------------|--------------------|--------------------------------------|
| <0.75         | Inactive           | Low                                  |
| 0.75-1.25     | Normal             | Medium                               |
| >1.25         | Active             | High                                 |

2) Direct Measurement: The most satisfactory and convenient method of determining the swelling potential and swelling pressure of an expansive clay is by direct measurement. Direct measurement of expansive soils can be achieved by the use of conventional one-dimensional consolidation (Asuri & Keshavamurthy, 2016). These methods offer the most useful data by direct measurement, and tests are simple to perform and do not require complicated equipment.

### 2.5. Soil Classification System

Different soils have different origins, compositions, geological histories, locations, and a host of other features. Even though two soils were taken from nearby boring holes on the same construction site, their geotechnical characteristics can differ significantly. For engineers, however, it is more practical and comfortable when soils are grouped with similar engineering characteristics. Engineers can understand the approximate engineering qualities of such categorized soils without conducting laboratory or field testing. A process called soil categorization helps engineers with geotechnical engineering challenges in the early stages of design.

Many different systems for classifying soil are currently in use in numerous nations. These techniques primarily employ soil gradation data and consistency limits to classify soils. In the field of geotechnical engineering, two classification schemes are frequently employed.

- ✓ Unified soil classification system (USCS) and,
- ✓ American Association of State Highway and Transportation Officials (AASHTO) classification system.

### **2.5.1. Unified Soil Classification System (USCS)**

The Unified Soil Classification System (USCS), widely used in geotechnical engineering, has its roots in the vision and work of Arthur Casagrande. Though not the creator of the USCS itself, Casagrande played a pivotal role in its development. Before the 1930s, soil classification lacked standardization. Different engineers used various, often conflicting, systems, making it difficult to share information and compare results. Recognizing this need for a unified approach, Casagrande played a key role in organizing the First International Conference on Soil Mechanics and Foundation Engineering in 1936. This landmark event brought together engineers from around the world to discuss the challenges of soil mechanics and explore the possibility of a standardized classification system.

During World War II, Casagrande, commissioned by the Federal Aviation Administration (FAA), developed the Airfield Classification System (ACS). This system aimed to categorize soils based on their suitability for constructing stable airport runways. The ACS took into account factors like particle size distribution and plasticity, which are crucial for understanding soil behavior under load. Following the war, the USCS emerged as a refinement of the ACS. It incorporated further contributions from other engineers and adopted a two-letter symbol system to denote different soil types. The Casagrande plasticity chart, also developed by Casagrande, became an integral part of the USCS.

This chart, based on the concepts of liquid limit and plastic limit, continues to be used for classifying fine-grained soils based on their plasticity behavior. The Bureau of Reclamation in 1952 as the unified soil classification system which is currently incorporated on ASTM standard manual. According to this method, soils are divided into two sub-major categories.

- 1) Coarse-grained soil that is gravelly and sandy with less than 50% of the soil sample passing through the sieve size of 0.075 mm, i.e.  $F_{200} < 50\%$ . The naming of categorization starts with the prefix G for gravelly soils and S for sandy soils.
- 2) Fine-grained soils when 50% or more of the soil sample passes through the sieve size 0.075 mm, i.e.  $F_{200} > 50\%$ . The naming of the group symbol starts with M for inorganic silts, C for inorganic clays, O for organic silt and clays, and Pt for peats and muck for highly organic soils.

## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

Again, coarse-grained materials are subdivided into gravel and sand based on the amount of soil retained on a sieve having an opening size of 4.75 mm. When more than 50% of soil is retained on sieve No.4 the soil is gravel and when more than 50% of soil passes sieve No.4 material falls under sandy soil. Similarly, fine-grained soils are also subdivided into silt and clay based on their location on the plasticity chart shown in the figure below.

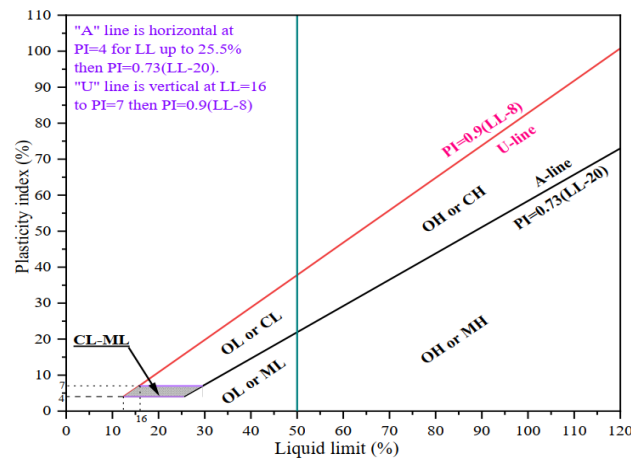


Figure 2.3: Plasticity chart for fine-grained soils classification by (ASTM D 2487, 2000)

Table 2-9: Soil classification based on particle size range by USCS

| Soil Type |        | Particle Size (mm) |
|-----------|--------|--------------------|
| Clay      |        | $\leq 0.002$       |
| Silt      |        | 0.002 - 0.075      |
| Sand      | Fine   | 0.075-0.425        |
|           | Medium | 0.425-2.0          |
|           | Coarse | 2.0-4.75           |
| Gravel    |        | 4.75-75            |

Additionally, some additional qualitative suffixes have been added to the group symbol of coarse-grained soils based on the amount of the liquid limit amount and plastic index, as summarized in Table 2-10, and the amount of the coefficient of uniformity ( $C_u$ ) and coefficient of curvature ( $C_c$ ) obtained from the gradation curve for fine-grained soils.

# Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

Table 2-10: Unified soil classification system chart (ASTM D 2487, 2000)

| Criteria for Assigning Group Symbols and Group Names Using Laboratory Tests <sup>A</sup> |                                                                     |                                              |                                            | Soil Classification                                |                                                                    |                            |
|------------------------------------------------------------------------------------------|---------------------------------------------------------------------|----------------------------------------------|--------------------------------------------|----------------------------------------------------|--------------------------------------------------------------------|----------------------------|
|                                                                                          |                                                                     |                                              |                                            | Group Symbol                                       | Group Name <sup>B</sup>                                            |                            |
| COARSE GRAINED SOILS<br>More than 50% retained on No. 200 sieve                          | Gravels<br>More than 50% of coarse fraction retained on No. 4 sieve | Clean Gravels                                | $C_U \geq 4$ and $1 \leq C_c \leq 3^C$     | GW                                                 | Well-graded gravel <sup>D</sup>                                    |                            |
|                                                                                          |                                                                     | Less than 5% fines <sup>E</sup>              | $C_U < 4$ and/or $1 > C_c > 3^C$           | GP                                                 | Poorly graded gravel <sup>D</sup>                                  |                            |
|                                                                                          |                                                                     | Gravel with Fines                            | Fines classify as ML or MH                 | GM                                                 | Silty gravel <sup>D,F,G</sup>                                      |                            |
|                                                                                          |                                                                     | More than 12% fines <sup>E</sup>             | Fines classify as CL or CH                 | Urule; 1>GC                                        | Clayey gravel <sup>D,F,G</sup>                                     |                            |
|                                                                                          | Sands<br>50% or more of coarse Fraction passes No. 4 sieve          | Clean sands                                  | $C_U > 6$ and $1 \leq CC \leq 3^C$         | SW                                                 | Well-graded sand <sup>H</sup>                                      |                            |
|                                                                                          |                                                                     | Less than 5% fines <sup>I</sup>              | $C_U < 6$ and/or $1 > C_c > 3^C$           | SP                                                 | Poorly graded sand <sup>H</sup>                                    |                            |
|                                                                                          |                                                                     | Sands with Fines                             | Fines classify as CL or CH                 | SM                                                 | Silty sand <sup>F,G,H</sup>                                        |                            |
|                                                                                          |                                                                     | More than 12% fines <sup>I</sup>             | Fines classify as CL or CH                 | SC                                                 | Clayey sand <sup>F,G,H</sup>                                       |                            |
|                                                                                          | FINE-GRAINE SOILS<br>50% or more passes the No. 200 sieve           | Silts and Clays<br>Liquid limit less than 50 | Inorganic                                  | PI > 7 and plots on or above “A” line <sup>J</sup> | CL                                                                 | Lean clay <sup>K,L,M</sup> |
|                                                                                          |                                                                     |                                              |                                            | PI < 4 or plots below “A” line <sup>J</sup>        | ML                                                                 | Silt <sup>K,L,M</sup>      |
| Organic                                                                                  |                                                                     |                                              | $\frac{LL(oven\ dried)}{LL(dried)} < 0.75$ | OL                                                 | Organic clay <sup>K,L,M,N</sup>                                    |                            |
|                                                                                          |                                                                     |                                              |                                            | OL                                                 | Organic silt <sup>K,L,M,O</sup>                                    |                            |
| Silt and Clays<br>Liquid limit 50 or more                                                |                                                                     | Inorganic                                    | PI plots on or above “A” line              | CH                                                 | Fat clay <sup>K,L,M</sup>                                          |                            |
|                                                                                          |                                                                     |                                              | PI plots below “A” line                    | MH                                                 | Elastic silt <sup>K,L,M</sup>                                      |                            |
|                                                                                          |                                                                     | Organic                                      | $\frac{LL(oven\ dried)}{LL(dried)} < 0.75$ | OH                                                 | Organic clay <sup>K,L,M,P</sup><br>Organic silt <sup>K,L,M,Q</sup> |                            |
|                                                                                          |                                                                     |                                              |                                            | HIGHLY ORGANIC SOILS                               |                                                                    |                            |
| Primarily organic matter , dark in color , and organic odor                              |                                                                     |                                              |                                            | PT                                                 | Peat                                                               |                            |

<sup>A</sup> Based on the material passing the 3-in. (75 mm) sieve. <sup>B</sup> If the field sample contained cobbles or boulders, or both, add "with cobbles or boulders, or both" to the group name. <sup>C</sup>  $C_U = D_{60}/D_{10}$  &  $CC = (D_{30})^2 / D_{10} \times D_{60}$ . <sup>D</sup> If soil contains > 15% sand, add "with sand" to the group name. <sup>E</sup> Gravels with 5 to 12% fines require dual symbols: GW-GM: well-graded gravel with silt, GW-GC: well-graded gravel with clay, GP-GM: poorly graded gravel with silt, GP-GC: poorly graded gravel with clay. <sup>F</sup> If fines classify as CL-ML, use the dual symbol GC-GM, or SC-SM. <sup>G</sup> If fines are organic, add "with organic fines" to the group name. <sup>H</sup> If soil contains > 15% gravel, add "with gravel" to the group name. <sup>I</sup> Sand with 5 to 12% fines require dual symbols: SW-SM: well-graded sand with silt, SW-SC: well-graded sand with clay, SP-SM: poorly graded sand with silt, SPSC: poorly graded sand with clay. <sup>J</sup> If Atterberg limits the plot in the hatched area, the soil is a CL-ML, silty clay. <sup>K</sup> If soil contains 15 to 29% plus No.200, add "with sand" or "with gravel," whichever is predominant. <sup>L</sup> If soil contains > 30% plus No.200, predominantly sand, add "sand" to the group name. <sup>M</sup> If soil contains > 30% plus No.200, predominantly gravel, and add "gravelly" to the group name. <sup>N</sup> PI > 4 and plots on or above the "A" line. <sup>O</sup> PI < 4 and plots below the "A" line. <sup>P</sup> PI plots on or above the "A" line. <sup>Q</sup> PI plots below the "A" line.

### **2.5.2. AASHTO Classification System**

The AASHTO (American Association of State Highway and Transportation Officials) Soil Classification System is a cornerstone of geotechnical engineering, specifically in the field of highway construction. Developed in 1928, this system categorizes soils based on their suitability for use in various highway components like subgrades, embankments, and bases. The AASHTO system groups soils into seven primary categories, denoted by the letters A-1 through A-7. Each group further encompasses subgroups based on specific characteristics, such as gradation (particle size distribution) and plasticity (the ability of soil to deform). According to this classification system, granular soils are soils in which 35% or less are finer than the No. 200 sieve. Silty clay soils are soils in which more than 35% are finer than the No. 200 sieve (Muni Budhu, 2010). The primary dividing line in the AASHTO system lies at the No. 200 sieve (75 microns). Soils with less than 35% passing this sieve fall into the A-1 to A-3 category, classified as granular materials. These soils are generally considered excellent for highway construction due to their good drainage, shear strength, and stability. Conversely, soils with more than 35% passing the No. 200 sieve are classified as A-4 to A-7 and are considered fine-grained. These soils have varying characteristics depending on their plasticity index (PI), a measure of their ability to deform plastically without crumbling. Soils with higher PI (A-6 and A-7) are generally less desirable for highway construction due to their potential for swelling and shrinkage with changes in moisture content. The procedure of classification uses an elimination process of columns, from the upper left corner toward downward and right. If the condition on the row is not satisfied, the entire column is eliminated, and it is never referred back. After the last row check for PI, one or possibly more than one column may survive this elimination process. If more than one column survived, the first column from the left is selected as a group or subgroup.

Classifying soil according to the AASHTO system involves a two-step process:

- 1) Gradation Analysis: The soil is sieved to determine the percentage of particles falling within different size ranges.
- 2) Atterberg Limits Test: Liquid limit (LL) and plastic limit (PL) are determined to calculate the PI.

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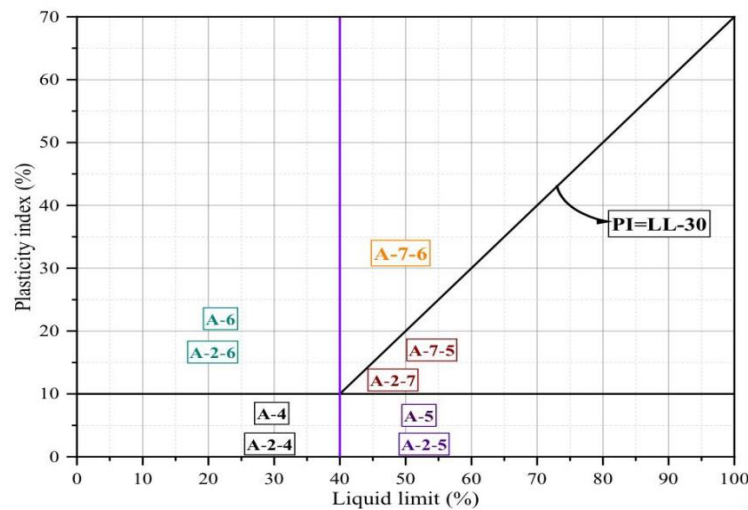


Figure 2.4: Liquid limit and plasticity index ranges for fine-grained materials (AASHTO:M 145-91, 2008)

Table 2-11: Classification of soils and soil-aggregate mixtures (AASHTO:M 145-91, 2008)

| General Classification                              | Granular Materials (35 Percent or Less Passing 75µm) |        |           |                                 |        |        |        | Silt-Clay Materials (More Than 35 Percent Passing 75µm) |        |              |                |
|-----------------------------------------------------|------------------------------------------------------|--------|-----------|---------------------------------|--------|--------|--------|---------------------------------------------------------|--------|--------------|----------------|
| Group Classification                                | A-1                                                  |        | A-3       | A-2                             |        |        |        | A-4                                                     | A-5    | A-6          | A-7            |
|                                                     | A-1-a                                                | A-1-b  |           | A-2-4                           | A-2-5  | A-2-6  | A-2-7  |                                                         |        |              | A-7-5<br>A-7-6 |
| Sieve analysis, percent passing 2.00mm(No.10)       | 50 max                                               | -      | -         | -                               | -      | -      | -      | -                                                       | -      | -            | -              |
| 0.425mm(No.40)                                      | 30 max                                               | 50 max | 51 min    | -                               | -      | -      | -      | -                                                       | -      | -            | -              |
| 75µm(No.200)                                        | 15 max                                               | 25 max | 10 max    | 35 max                          | 35 max | 35 max | 35 max | 36 min                                                  | 36 min | 36 min       | 36 min         |
| Characteristics of fraction passing 0.425mm (No.40) |                                                      |        |           |                                 |        |        |        |                                                         |        |              |                |
| Liquid limit                                        | -                                                    |        | -         | 40 max                          | 41 min | 40 max | 41 min | 40 max                                                  | 41 min | 40 max       | 41 min         |
| Plastic index                                       | 6 max                                                |        | NP        | 10 max                          | 10 max | 11 min | 11 min | 10 max                                                  | 10 max | 11 min       | 11 min         |
| Usual type of significant constituent materials     | Stone fragments, gravel and sand                     |        | Fine sand | Silty or clayey gravel and sand |        |        |        | Silty soils                                             |        | Clayey soils |                |
| General rating as subgrade                          | Excellent to Good                                    |        |           |                                 |        |        |        | Fair to Poor                                            |        |              |                |

<sup>a</sup> Plasticity index of the A-7-5 subgroup is equal to or less than LL minus 30 and, the Plasticity index of the A-7-6 subgroup is greater than LL minus 30. Placing A-3 before A-2 is necessary in the “left to right elimination process” and does not indicate the superiority of A-3 over A-2.

The group index (GI) value is appended additionally in parentheses to the main group to provide a measure of the quality of soil as highway subgrade material and calculated through the following formula.

$$GI = (F - 35) [0.2 + 0.005(LL - 40)] + 0.01(F - 15) (PI - 10) \quad (4)$$

Where: F is the percentage passing 75  $\mu\text{m}$  (No. 200) sieve, expressed as a whole number, LL is the liquid limit, and PI is the plasticity index.

When the calculated group index is negative, the group index shall be reported as zero and should be reported to the nearest whole number. Also, when the calculated GI is more than 20, it is assumed to be taken as 20. Soil having less GI has good strength and quality, but soil having a higher group index has less quality and is not appropriate to use as construction material.

## 2.6. Geosynthetic Materials

Geosynthetics have been increasingly used in geotechnical and environmental engineering for the last 4 decades. Over the years, these products have helped designers and contractors to solve several types of engineering problems where the use of conventional construction materials would be restricted or considerably more expensive (E. M. Palmeira, et. al., 2008). In civil engineering, geosynthetics are a frequently utilized and popular product, particularly in the construction of pavements. Geotextiles, geogrids, geocells, geonets, geomembranes, and geo-composites are examples of geosynthetics, which are categorized based on the material and the application. Numerous benefits come with geosynthetic goods associated with geotechnical materials, including long-term durability, environmental friendliness, and ease of installation. Since the early 1970s, geosynthetic products have been incorporated into the transportation network (Guangfan Zheng, 2020). Common types of geosynthetics used for soil reinforcement include geotextiles (particularly woven geotextiles), geogrids, and geocells (Bathurst, 2007).

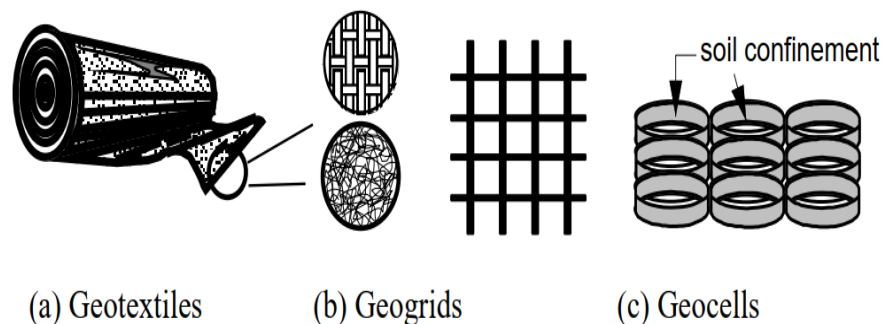


Figure 2.5: Geosynthetics commonly used for soil reinforcement (Bathurst, 2007).

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A wide variety of geosynthetic products can be used in environmental protection projects, including geomembranes, geosynthetic clay liners (GCL), geonets, geo-composites, and geopipes. Geomembranes are continuous flexible sheets manufactured from one or more synthetic materials. They are relatively impermeable and are used as liners for fluid or gas containment and as vapor barriers. Geosynthetic clay liners (GCLs) are geo-composites that are prefabricated with a bentonite clay layer typically incorporated between a top and bottom geotextile layer or bonded to a geomembrane or single layer of geotextile (Bathurst, R.J., 2007).

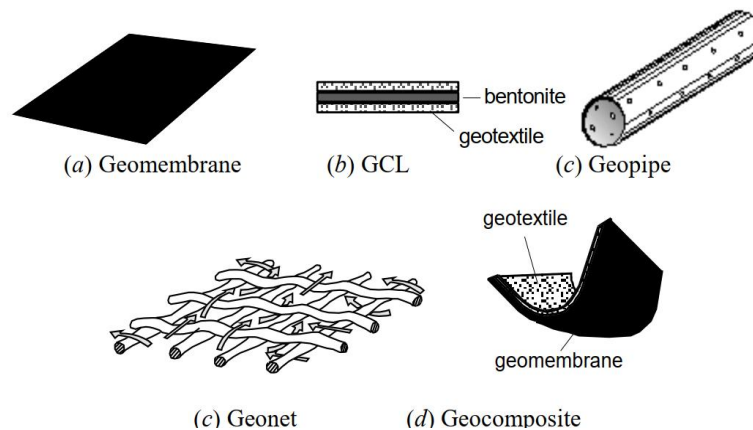


Figure 2.6: Schematic view of some typical geosynthetics used in environmental protection works (Bathurst, 2007).

Generally, there are five main functions of geosynthetics: Separation, filtration, drainage, containment, and reinforcement. Details for these main functions will be discussed below. They also have other functions such as stiffening, and limitation of crack development (Guangfan Zheng, 2020).

1. The first function of geosynthetics is separation: The permeable geosynthetic can maintain and keep the functionality and integrity of both materials intact when placed between two dissimilar materials, such as the interface between the base course layer and the subgrade layer. With the help of geosynthetics, the mixing between the different layers can be prevented, and each layer can keep its complete structure. The figure below shows the function of separation by comparing the pavements with and without the geosynthetics, where the distressed pavement has the mixed material from each layer and the intact pavement has separated asphalt layer, base course layer, and subgrade.

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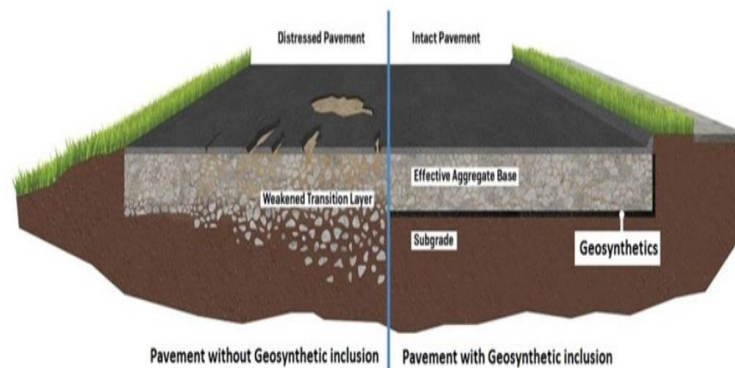


Figure 2.7: Comparison Between Pavement with and without the Geosynthetic (Guangfan Zheng, 2020).

2. The second function is filtration: The geosynthetics can stop soil particles from moving to the other layers by only allowing liquids to pass through their plane. As a result, during the pavement's service life, the small particles can stay in their layer and the pavement structure can be preserved.
3. The third function is drainage: This function is provided by the geosynthetics transmissivity, which allows gas and liquid to pass and go through within the plane of its structure. They can help to prevent the water from remaining inside the pavement system.
4. The fourth function is containment: where the geosynthetics can function as a gas- and liquid-tight barrier. This gas and hydraulic barrier can reduce and limit horizontal flow and movement.
5. The last main function of the geosynthetics is reinforcement: By developing tensile tensions, the geosynthetics enable the soil-geosynthetics composite to be stabilized. The geosynthetics inclusion can increase the service life for the pavement, especially over weak subgrade by transferring the overload to the geosynthetics materials. Two pavement factors the TBR (Traffic Benefit Ratio) and the BCR (Base Course Reduction) ratio can be improved with the use of geosynthetics. TBR is the ratio of the cycle of loads to reach a specific rutting depth between the reinforced and unreinforced pavement under the same conditions. When the pavement distress state is the same for both reinforced and unreinforced pavement with the same material qualities, the base course layer thickness reduction ratio, or BCR, is calculated. One of the most crucial features of geosynthetics is their ability to reinforce, which both increases the pavement's service life and lowers construction costs by lowering the thickness of the base course. These functions are illustrated in Figure below.

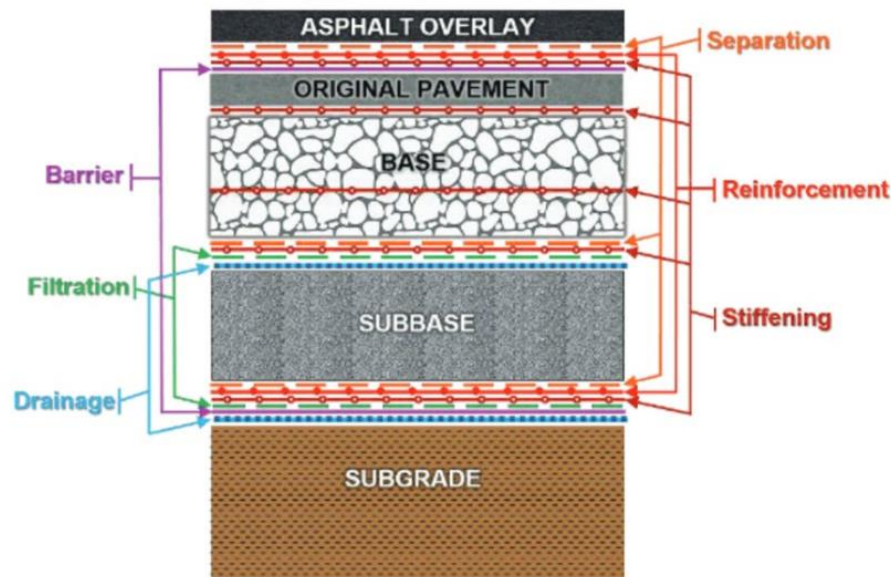


Figure 2.8: Main Functions of the Geosynthetic in Pavement (Guangfan Zheng, 2020).

### 2.6.1. Geogrids Reinforcement

One of the most widely recognized geosynthetic materials is geogrid, which is composed of polypropylene or polyethylene and is predominantly employed as a reinforcement mechanism in geotechnical engineering. The preponderance of geogrid products is accessible in two-dimensional configurations, which facilitate surface reinforcement applications. Among the three categories of geogrids, the most prevalent variants are the two-dimensional geogrids. Geogrids are categorized into uniaxial, biaxial, and triaxial types, all of which find utility in geotechnical construction. The uniaxial geogrid is commonly applied in slope and embankment reinforcement due to its linear configuration, which provides strength in a singular direction (Guangfan Zheng, 2020).

The primary use of biaxial and triaxial geogrids in the construction of pavement, retaining walls, slopes, foundations, etc. as reinforcement. They offer three and two directions of strength, respectively. The variations in their characteristics are caused by the differently shaped aperture. The aperture of a biaxial geogrid is rectangular. Because of its extended lifespan and strong tolerance to both short-term and moderate dynamic stresses, it is well-liked all around the world. Because the length of the geogrid ribs varies in the two directions, the strength does not equal zero in either direction. The triangular aperture of a triaxial geogrid is the most stable and often used in construction. In contrast to the Biaxial geogrid, these grids offer strength in three dimensions. Its

shape allows for the provision of more in-plane stress in many equilateral directions as well as better efficiency when transmitting stress from the aggregate to the stabilizing geogrid. Additionally, designers are using it more frequently since it is less expensive than biaxial geogrids (Guangfan Zheng, 2020).

In addition to serving as reinforcement, geogrid products can confine soil particles in the soil layer between them and the geogrid. By allowing the aggregates to lock with the geogrid, the opening aperture can provide interlocking pressures that strengthen the pavement's support layers. The aggregate particle-size distribution and the aperture size could be the elements influencing confinement.

## **2.7. Reinforced Soil Foundation**

### **2.7.1. Introduction**

Over the past thirty years, reinforced soil foundations (RSF) have been extensively implemented across a multitude of geotechnical engineering applications, including but not limited to bridge approach slabs, bridge abutments, building footings, and embankments. Empirical studies have indicated that the integration of reinforcement within soil foundations represents a fiscally advantageous approach to enhancing the ultimate bearing capacity and/or mitigating the settlement of shallow footings when juxtaposed with conventional methodologies, such as the substitution of natural soils or the augmentation of footing dimensions. The most common type of reinforcement used in soil foundation applications are geogrids, as shown in Figure 2.9.

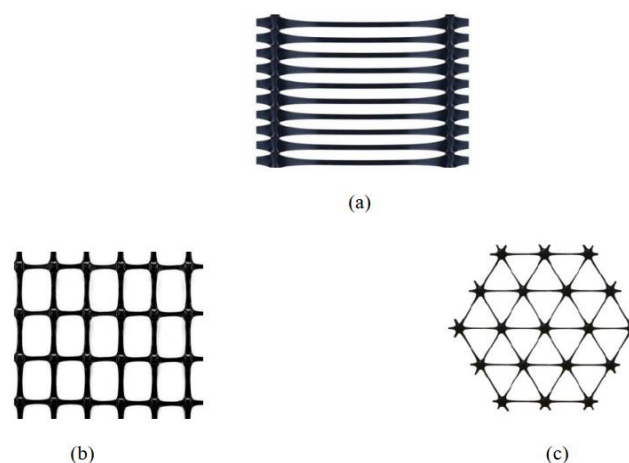


Figure 2.9: Three Types of Geogrids: (a) Uniaxial Geogrid; (b) Biaxial Geogrid; (c) Triaxial Geogrid (Guangfan Zheng, 2020).

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Atypical reinforced soil foundation along with the delineation of various geometric parameters is presented in Figure 2.10. The geometric parameters illustrated in the figure are designated as follows: (a) top layer spacing, or the depth to the initial reinforcement layer ( $u$ ), (b) quantity of reinforcement layers ( $N$ ), (c) cumulative depth of reinforcement ( $d$ ), (d) vertical separation between reinforcement layers ( $h$ ), (e) length of the reinforcement elements ( $L$ ), (f) embedment depth of the footing ( $D_f$ ).

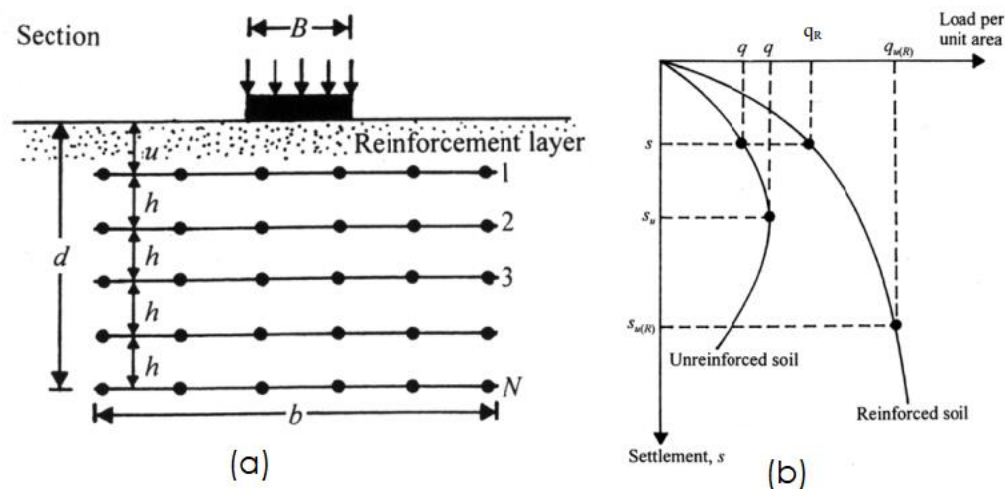


Figure 2.10: **(a)** Geometric parameters of foundation supported by reinforced soil; **(b)** typical load settlement curves for unreinforced and reinforced soil supporting a foundation (Mohamed G. Arab, 2017).

During the past thirty years, many experimental, numerical, and analytical studies have been performed to investigate the behavior of reinforced soil foundation (RSF) for different soil types (Biquet and Lee, 1975; Huang and Tatsuoka, 1990; Kurian et al., 1997; Chen, 2007).

Different scholars have proposed two theoretical concepts to assess the advantages of Reinforced Soil Foundations (RSF) (Chen 2007, AbuFarsakh et al. 2007): the first is the bearing capacity ratio (BCR), which is articulated as the proportion of the bearing capacity of the RSF relative to that of an unreinforced soil foundation. The second construct is the settlement reduction factor (SRF), which is defined in this context as the ratio of the immediate settlement experienced by a footing on an RSF compared to that on an unreinforced soil foundation under a designated surface pressure.

### **2.7.2. Reinforcement Mechanism of Reinforced Soil Foundation**

The improved performance of reinforced soil foundations can be attributed to three fundamental reinforcement mechanisms as described below (Chen, 2007).

- (1) Rigid boundary (Figure 2.11a): when the spacing of the upper layer ( $u$ ) exceeds a specific threshold, the reinforcement would function as a rigid boundary, leading to failure occurring above the reinforcement. (Binqet and Lee, 1975) were the initial researchers to document this observation. Subsequently, experimental investigations conducted by various scholars (Akinmusuru and Akinbolade, 1981; Mandal and Sah, 1992; Khing et al., 1993; Omar et al., 1993; Ghosh et al., 2005) have corroborated this observation.
- (2) Membrane effect (Figure 2.11b): Upon the application of load, both the footing and the underlying soil experience a downward displacement. Consequently, the reinforcement undergoes deformation and is subjected to tensile forces. Owing to its inherent tensile stiffness, the curved reinforcement generates an upward force to counterbalance the externally applied load. A specific degree of settlement is requisite to activate the tensioned membrane effect, and the reinforcement must possess sufficient length and rigidity to avert failure due to pullout and rupture. The pioneers in implementing this reinforcement mechanism to formulate a design methodology for a strip footing on reinforced sand, predicated on a simplified assumption regarding the shape of the reinforcement post-deformation (Binqet and Lee, 1975). This approach subsequently expanded to encompass a rectangular footing on reinforced sand (Kumar and Saran, 2003).
- (3) Confinement effect (lateral restraint effect) (Figure 2.11c): Due to relative displacement between soil and reinforcement, the friction force is induced at the soil-reinforcement interface. For grid reinforcement, the interlocking can be developed by the interaction of soil and reinforcement. Consequently, lateral deformation or potential tensile strain of the soil is restrained. As a result, the vertical deformation of soil is reduced. Since most soils are stress-dependent materials, improved lateral confinement can increase the compressive strength of soil and thus improve the bearing capacity. Substantiated this mechanism by successfully using short reinforcement having a length ( $L$ ) equal to the footing width ( $B$ ) to reinforce sand in their experimental study (Huang and Tatsuoka, 1990).

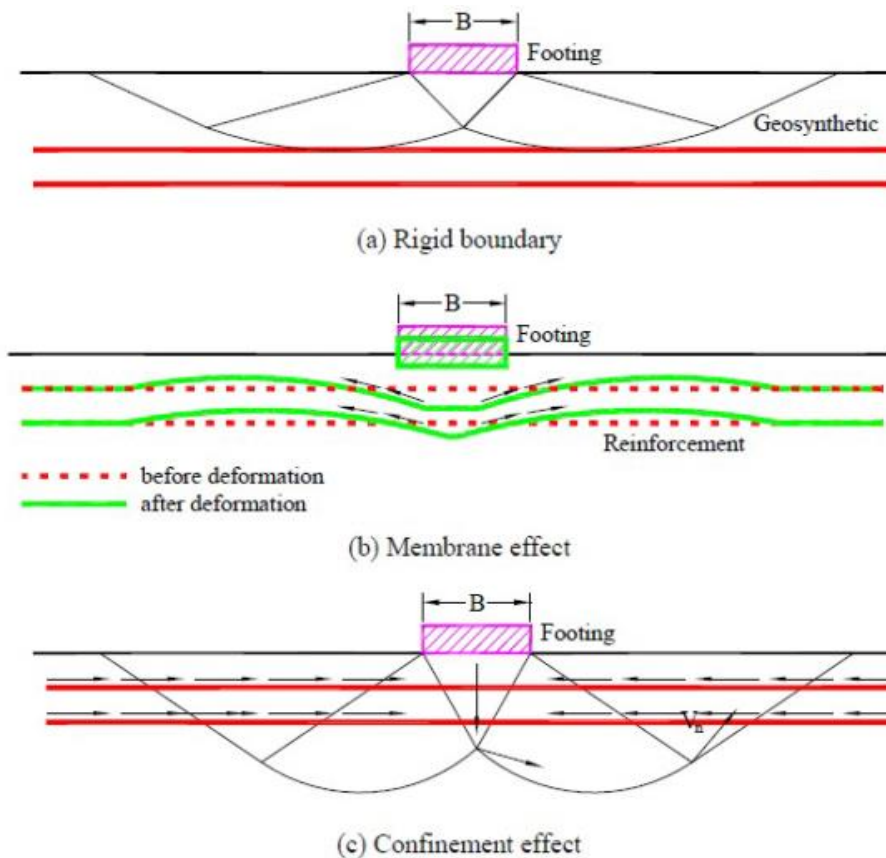


Figure 2.11: Reinforcement mechanisms (Chen, 2007)

### 2.7.3. Failure mechanisms in geogrid reinforced soil at ultimate load

The bearing capacity of shallow foundations resting on reinforced earth (Binqet and Lee, 1975). Based on this study, Binqet and Lee proposed failure mechanisms for geogrid-reinforced soils depending on the depth of the reinforcement and the number of reinforcement layers as shown in Figure 2.12a, 12b, and 12c.

The nature of failure in the soil mass shown in Figure 2.12a generally occurs when the first layer of reinforcement is located at a depth,  $u$ , greater than about  $0.67B$  ( $B$  = width of the foundation). The reinforcement may act in this arrangement as a rough rigid base located at a limited depth.

The type of failure shown in Figure 2.12b could occur if  $u/B$  is less than about 0.67 and the number of layers of reinforcement,  $N$ , is less than about 2–3. In this type of failure, reinforcement pull-out occurs. According to this study, the most beneficial effect of reinforced earth is obtained when  $u/B$

is less than about 0.67 and the number of reinforcement layers is greater than 4 but not more than 6–7 (Figure 2.12c).

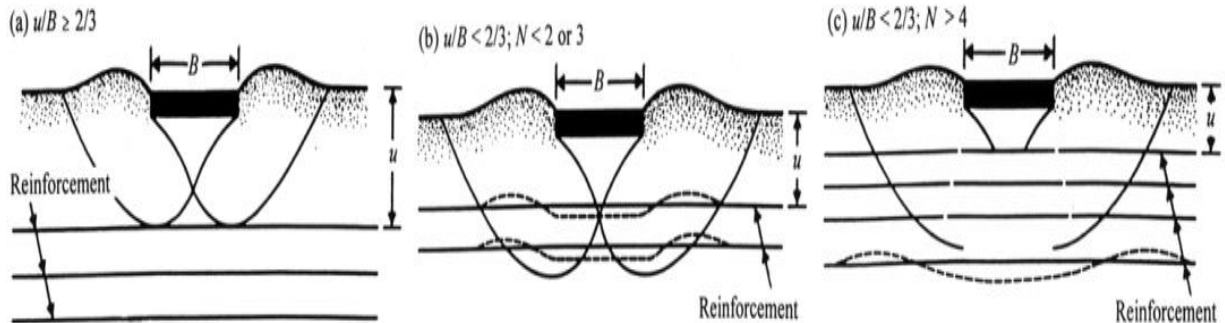


Figure 2.12: Three modes of bearing capacity failure of a strip foundation on reinforced earth (Binqet and Lee, 1975).

Based on the theory advanced by Binqet and Lee, 1975, Figure 2.13 shows an idealized condition for the development of the failure surface in soil for the condition shown in Figure 12. 2c. It consists of a central zone - Zone I - immediately below the foundation that settles along with the foundation with the application of load. On each side of Zone I, the soil is pushed outward and upward this is Zone II. The points A', A'', A'''... and B', B'', B'''.... define the limiting lines between Zones I and II can be obtained by considering the shear stress distribution,  $\zeta_{xz}$ , in the soil is caused by foundation load. The term  $\zeta_{xz}$  refers to the shear stress developed at a depth  $z$  below the foundation at a distance  $x$  measured from the center of the foundation. The nature of the variation of  $\zeta_{xz}$  at any given depth is shown by the broken lines in Figure 2. 13. Points A' and B' refer to the point at which the value of  $\zeta_{xz}$  is the maximum at  $z = z_1$ . Similarly, A'' and B'' refer to the points at which the value of  $\zeta_{xz}$  is maximum at  $z = z_2$ . The distance at which the maximum value of  $\zeta_{xz}$  occurs can be given as  $x = x_0$ .

It can be expected that failure in soil reinforced with geotextile or geogrid layers would be, in general, similar to that described by Binqet and Lee, 1975 for the case of metal strip reinforcement. However, the magnitude of the ultimate bearing capacity and the allowable bearing capacity for a given level of settlement (and thus BCRu and BCRs) would be a function of several factors, such as,

- a. The degree of compaction of soil;
- b. Relative stiffness of the geogrid or geotextile; and
- c.  $u/B$ ,  $b/B$ ,  $l/B$ ,  $h/B$ , and  $d/B$ .

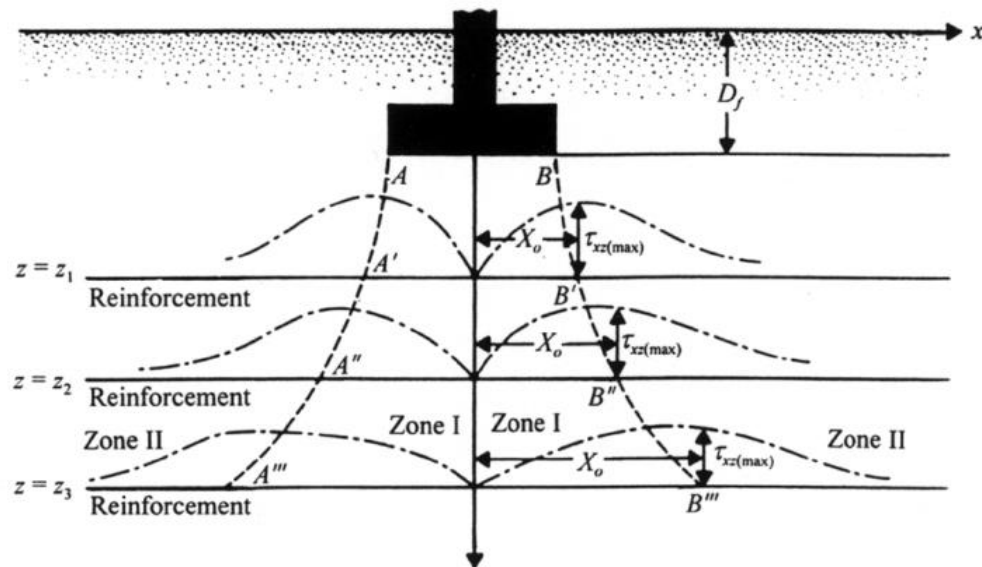


**Figure 2.13:** Failure mechanism under a strip foundation supported by reinforced earth-based (Binqet and Lee, 1975).

#### **2.7.4. Finite Element Studies on Reinforced Soil Foundations**

Reinforced soil consists of two constituents, namely, the soil and the reinforcement. Finite element modeling of reinforced soil foundation presented by researchers can be categorized into two groups: the first group treats reinforced soil as an equivalent homogeneous continuum media (Pruchnicki and Shahrour, 1994, Sawicki, 1999, and Chen et al., 2000). In this category of method, the reinforced soil was treated as a macroscopically homogeneous composite material, the properties of which depend on the respective properties of the constituents, their volume fractions, and their geometrical arrangement. The results obtained based on this kind of method can determine the failure mode and bearing capacity of RSF.

The second group models the reinforcement and soil as two separate components (Yetimoglu et al., 1994; Kurian et al., 1997; Maharaj, 2002). The reinforcement is generally treated as a linear elastic material in these studies.

The soil-reinforcement interface is generally modeled using two approaches: constraint approach and contact elements. The constraint approach generally assumes that separation is not allowed between the soil and reinforcement in a normal direction, while in a tangential direction, slip can occur. In the use of the contact element, the normal stiffness is often given a very high value to prevent the interpenetration of nodes.

Finite element analysis was performed on rectangular footing sitting on top of geogrid-reinforced sands for the small-scale model footing tests they conducted. In this study, the analyses were conducted under axis-symmetric conditions. The rectangular footing was treated as an equivalent circular plate of the same footing area. The geogrid reinforcement and the footing were represented by a series of discrete axis-symmetric shell elements and the sand was represented by an assembly of axis-symmetric quadrilateral and triangular elements. Vertical loads were applied sequentially in an equal increment and each load increment was divided into five steps to achieve better computational accuracy (Yetimoglu et al., 1994). The stress-strain behavior of the sand was simulated by the modified Duncan hyperbolic model (Duncan et al. 1980) and was represented by an assembly of axis-symmetric quadrilateral and triangular elements. The strains developed in the geogrid reinforcement at failure were thought to be very small and hence a constant secant modulus determined at an axial strain of 1% was used for the geogrid in the analyses. The nominal thickness of the geogrid was 0.95 mm.

Their studies indicated that the optimum value of depth ratio at which the BCR was the highest is around 0.3 for single-layer reinforced sand and around 0.25 for multilayer reinforced sands. Their studies also indicated that the optimum vertical spacing of reinforcement layers on geogrid-reinforced sands varied between 0.2B and 0.4 B. The BCR increased with an increasing number of reinforcement layers; however, the rate of increase in BCR was less significant beyond a depth of 1.5B. And the BCR generally increased slightly with increasing reinforcement size. The increase was more pronounced for reinforcement size ratio ( $L/B$ ) up to approximately 4.5, beyond which the BCR remained more or less constant. The BCR increases with the increase of reinforcement stiffness and an axial stiffness beyond 1,000 kN/m would not result in significant increases in the BCR.

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The settlement of footing on reinforced sand by using 3D finite element analysis. The results of the analysis were then compared with those from laboratory model tests.

An 8-node brick element was used to discretize the soil, while a 3D truss element was used to discretize the reinforcement. A 3D soil-reinforcement interface friction element developed based on the Goodman element was used in the analysis. Both the reinforcement and the interface elements were geometrically 3D line elements. The stress-strain behavior of sand was modeled by the Duncan-Chang model, while the footing and the reinforcements were assumed to be linearly elastic. The sand used in their study had an effective particle size ( $D_{10}$ ) of 0.23mm, a uniformity coefficient ( $C_u$ ) of 1.34, and a Poisson's ratio of 0.3. The friction angle determined by the triaxial test was about  $38^\circ$ .

The reduction of settlement in the reinforced sand at higher loads was seen as compared to unreinforced sand (Kurian et al., 1997). The numerical results also indicated that a small increase in settlement occurred in reinforced sand at the initial stage of the loading process. A possible explanation of this phenomenon given by Kurian et al. (1997) was that the normal load was too small to mobilize enough friction between soil and reinforcement, i.e. a weak plane was initially presented with the inclusion of reinforcement. The relative movement between soil and reinforcement increased with the increase of load and decreased with the increase of reinforcement depth. The maximum shear stress at the soil-reinforcement interface occurred at a relative distance ( $x/B$ ) of about 0.5 from the center of the footing. The tension developed in the reinforcement was maximum at the center and gradually decreased towards the end of the reinforcement. As compared to unreinforced sand, the vertical stress contours shifted downwards in reinforced sand, i.e. spreading the stress deeper.

The bearing capacity behavior of strip footing on the geogrid reinforced sand slope was investigated through the finite element method. In his study, a footing pressure producing a footing settlement of 10% of the footing width ( $0.1B$ ) at the footing center was taken as the ultimate bearing capacity (Yoo, 2001). In the finite element modeling the initial stress condition was established first by applying the gravity force due to soil in steps with geogrid reinforcements in place. In Yoo's (2001) finite element analysis of strip footing on a geogrid-reinforced sand slope, the non-linear behavior of the fill was modeled using the modified version of the hyperbolic stress-

strain and bulk modulus model proposed by Duncan et al. while the foundation and the geogrid were treated as a linear elastic material. The results showed the failure zone of the reinforced slope loaded with a footing was wider and deeper than that of the unreinforced slope. More geogrid reinforcement benefit was observed when placed at a depth equivalent to the footing width below the footing base than at shallower depths. Critical geogrid layout parameters for which maximum benefit was achieved were independent of the footing location concerning the slope face, except the effective length of the geogrid and the geogrid tensile modulus.

The influences of top layer spacing, vertical spacing of reinforcement layers, size of the reinforcement, and the number of layers on the settlement of strip footing on reinforced clay using two-dimensional nonlinear finite element analysis were conducted by (Maharaj, 2002). The footing and soil were discretized into four-node isoparametric finite elements while the reinforcement was discretized into four nodes one-dimensional isoparametric elements. Drucker-Prager yield criteria were used to model clay. The footing and reinforcement were assumed to be a linear elastic material. The clay used in the model had a Poisson's ratio of 0.45 and an elasticity modulus of 13,000 kN/m<sup>2</sup>. The cohesion intercept and friction angle of clay were 10.84 kN/m<sup>2</sup> and 0°. The stiffness of reinforcement used in the model ranged from 500 kN/m to 20,000 kN/m. From finite element analysis of strip footing on reinforced clay, Maharaj concluded that in the case of a single layer of reinforcement, the optimum top layer spacing ratio ( $u/B$ ) was found to be around 0.125 in reinforced clay. He also found that the effective length ratio ( $l/B$ ) of reinforcement was around 2.0, the influence depth depended on the stiffness of reinforcement and the increase in geosynthetics' stiffness resulted in reducing the settlement of the footing.

The numerical analyses with PLAXIS (Version 7.12) investigate the bearing capacity of circular and ring footings on reinforced sand (Boushehrian and Hataf, 2003). The Mohr-Coulomb model was used for soil; the axis-symmetric condition and 15-node triangular elements were used for the analysis. To model the slip between the soil and the reinforcement elements are combined with interfaces. Reinforcements are slender objects with a normal stiffness but with no bending stiffness and can only sustain tensile forces and no compression. They are simulated by the use of special tension elements. The only material property of reinforcement is an elastic normal (axial) stiffness.

The effects of the depth of the first layer of reinforcement, vertical spacing, and number of reinforcement layers on the bearing capacity of the footings were investigated. Their results indicated that, when a single layer of reinforcement is used there is an optimum reinforcement embedment depth for which the bearing capacity is greatest. There also appeared to be an optimum vertical spacing of reinforcing layers for multi-layer reinforced sand.

The bearing capacity was also found to increase with the increasing number of reinforcement layers if the reinforcements were placed within a range of effective depths. In addition, the analysis indicated that increasing reinforcement stiffness beyond a threshold value does not result in a further increase in the bearing capacity.

Finite element analysis was performed by using PLAXIS to perform two-dimensional plane strain models of RSF (El Sawwaf, 2007). In his analysis, the initial stress condition was established first by applying the gravity force due to soil in steps with the geogrid reinforcements in place. A prescribed footing load was then applied in increments (load control method) accompanied by iterative analysis up to failure. The modeled boundary conditions were assumed such that the vertical boundaries are free vertically and constrained horizontally while the bottom horizontal boundary is fully fixed. The non-linear behavior of sand was modeled with a hardening soil model, which is an elastoplastic hyperbolic stress-strain model, formulated in the framework of friction-hardening plasticity. The interaction between the geogrid and soil is modeled at both sides utilizing interface elements, which allow for the specification of reduced wall friction compared to the friction of the soil. The effect of the number of geogrid layers, the effect of geogrid layer length, the effect of depth to top layer, and the vertical spacing of the geogrid were studied and he concluded that for optimum response, the recommended depth of reinforcing geogrid and geogrid spacing are 0.6 and 0.5 of the footing width. The geogrid length should be greater than or equal to five times the footing width and the recommended number of geogrid layers is 3.

The finite element analysis to investigate the performance of embankment construction over weak subgrade soil (Ahmet et al., 2008). A two-dimensional plain strain condition was adopted and only half of the physical model is considered due to an axisymmetric at the center of the footing. The displacement is restricted to zero in the x-direction along the centerline of the model due to symmetry and the right side of the model for the subgrade layer only. Also, the displacement is

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zero in x- and y- directions along the exposed bottom of the model and the displacement for the exposed ground surface of the sample is free to move in x- and y- directions. All the dead load was defined and separately solved as a linear elastic model. They adopted a modified cam-clay model for clay and a non-linear elastic-plastic (i.e. hyperbolic) model for sand.

The linear elastic model was used to represent geosynthetic materials and the slip surface model was used to model the interaction characteristics between soil and reinforcement.

They reported that geogrid performed much better than geotextile. The best performance was achieved when geosynthetic reinforcement was located nearest to the footing. The strain within geosynthetics became almost negligible after a distance equal to six times the footing width. Better stress distribution and deformation patterns within the embankment were obtained when the geosynthetics were introduced.

The behavior of a geotextile-reinforced sand bed subjected to strip loading was analyzed using the finite element method (Basudhar et al., 2008). The problem domain is divided into a finite number of four noded rectangular elements for soil and two noded linear elements for geotextile. The geotextile element is modeled as an axial element with a linear approximation for the displacement in the x-direction. No interface element is used but the interface is modeled as a contact problem. Mohr-Coulomb criterion is adopted for the slip between the soil and geotextile. Their results showed that for a single layer of geotextile reinforcement, the optimal placement depth is  $0.6B$  and the shear force in the geotextile increases till the reinforcement length from the central line is equal to  $0.5$  of footing width and then decreases.

The numerical simulations were performed on square footings resting on sand (Latha and Somwanshi, 2009). The elastic-perfectly Mohr-Coulomb model was used to model the behavior of sand. The effect of the type and tensile stiffness of geosynthetic material, the depth of the reinforced zone, the spacing of reinforcement layers, and the width of reinforcement were studied and they concluded that the layout and configuration of reinforcement play a vital role in bearing capacity improvement rather than the tensile strength of the geosynthetic material. They also reported that the effective depth of the zone of reinforcement below a square footing is twice the width of the footing.

Within the effective reinforcement zone, the optimum spacing of reinforcing layers is about 0.4 times the width of the footing. The optimum width of reinforcement is about 4 times the width of the square footing.

A series of finite element analyses (FEA) were performed on footings with different sizes using the commercial ABAQUS program to numerically study the scale effect of reinforced soil foundations (Chen and Abu-Farsakh, 2011). The soil is simulated as an isotropic elastic-perfectly plastic continuum. The yield criterion is described by the extended Drucker-Prager model with a linear form. The reinforcement is simulated as a membrane, which transmits in-plane force only and has no bending stiffness. The stress-strain behavior of reinforcement is modeled by a linear elastic model. The surface-based contact interaction is used in their study to model the soil reinforcement interface. The results showed that the load-settlement curves of unreinforced soil are the same if the settlement is expressed in a nondimensional settlement ratio of  $s/B$ . The bearing capacity of reinforced soil decreases with increasing footing size if the total depth ratio of reinforcement ( $d/B$ ), the vertical spacing ratio ( $h/B$ ) of reinforcement layers, and hence the number of reinforcement layers ( $N$ ) are kept constant. However, the difference in the bearing capacity is negligible if the total depth ratio ( $d/B$ ) of reinforcement and the reinforced ratio ( $R_r$ ) remains constant for all sizes of footing.

Expansive soils are poor in strength and they will lead to poor pavement support and ultimately affect the pavement performance and its life period. Geogrids significantly improve the CBR of subgrade expansive soils and decrease pavement thickness (M. Kaur and S.K. Aggarwal, 2020). Clay is fine-grained soil, which is plastic due to its cohesive nature at relative moisture content. Clay soils exhibit alternate swell and shrink in variation with moisture content and possess low CBR value. Engineering properties such as Shear Strength and CBR are evaluated and the engineering properties increase when geogrids are provided (Jayashree Jayakumar, et. al., 2020).

The seasonal changes of expansive soils (periodic wetting and drying) cause detrimental effects on the overlying road pavements. Such detrimental behavior of expansive soils was simulated in a controlled laboratory environment by allowing cyclic wetting and drying of an expansive soil underlying a pavement section.

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The shrink/swell effects of the expansive soil subgrade were examined by monitoring its change in moisture and measuring the deformation of the overlying pavement section. A geogrid layer in a reinforced pavement section can reduce surface differential shrinking and swelling deformation (Richard Shumbusho, et. al., 2021). Bearing capacity refers to the maximum average contact pressure a soil can support before shear failure occurs. Square, rectangular, and strip footing is evaluated on clayey, sandy, and sandy underlay by silty clay soil. The bearing capacity decreases as the depth of the first geogrid layers from the footing increases and with increasing geogrids layers increase both bearing capacity and bearing capacity ratio. For the shape of footing, the square footing showed a maximum value of bearing capacity of foundation on silty clay and sandy soil compared to other types of foundations (Ressol R. Shakir and Zahraa Hameed jawad, 2022).

The main cause of problematic soil failure under a certain load is low bearing capacity and excessive settlement. With a growing interest in employing shallow foundations to support heavy structures, it is important to study soil improvement techniques. The analysis of reinforced and unreinforced soil foundations was conducted numerically and analytically. A series of conditions were tested by varying the number (N) and the width (b) of the geogrid layers. The geogrid could improve the footing's bearing capacity and reduce settlement (Hasan, I.N, et. al., 2020).

The design of foundation governs the two different requirements: one is the ultimate bearing capacity of soil below the foundation and the second is the acceptable settlement that a footing can undergo without any adverse effect on the superstructure. In geotechnical engineering, bearing capacity is the power of the foundation soil to hold the forces from the superstructure without undergoing shear failure or excessive settlement (foundation soil is that portion of ground that is subjected to additional stresses when the foundation and superstructure are constructed on the ground). Low bearing capacity and high settlement behavior of expansive soils are the challenge for engineers to work on it (Love Sharma, et. al., 2015). The bearing capacity of a shallow foundation significantly improved by providing the geogrids in the soil under a shallow foundation (Love Sharma, et. al., 2015).

Table 2-12: Summary of optimum parameters for reinforced soil foundations

|                    | <b>Ramaswamy &amp; Purushothaman (1992)</b> | <b>Mandal and Sah (1992)</b> | <b>Shin et al (1993)</b> | <b>Yetimoglu et al (1994)</b> | <b>Das et. al (1996)</b> | <b>Maharj (2003)</b> | <b>Basudhr et al. (2008)</b> | <b>Alamshahi and Hataf (2009)</b> |
|--------------------|---------------------------------------------|------------------------------|--------------------------|-------------------------------|--------------------------|----------------------|------------------------------|-----------------------------------|
| Study Type         | Experimental                                | Experimental                 | Experimental             | Experimental                  | Experimental             | Numerical            | Numerical                    | Numerical                         |
| Footing Type       | Circular                                    | Square                       | Strip                    | rectangular                   | Strip                    | Strip                | Strip                        | Strip                             |
| Soil Type          | Clayey soil                                 | Clayey soil                  | Clayey soil              | Sand                          | Clayey soil              | Clayey Soil          | Sand                         | Sand                              |
| Reinforcement Type | Geogrid                                     |                              |                          | Geogrid                       |                          | Geogrid              | Geotextile                   | Geogrid                           |
| $u/B$              | 0.5                                         | 0.175                        | 0.4                      | 0.25~0.3                      | 0.4                      | 0.125                | 0.6                          | 0.75                              |
| $h/B$              | -                                           | -                            | -                        | 0.2~0.4                       | -                        | -                    | -                            | 0.75                              |
| $L/B$              | 4                                           | -                            | 4.5~5                    | 1.5~4.5                       | 5                        | -                    | -                            | -                                 |
| $d/B$              | -                                           | -                            | 1.8                      | -                             | 1.75                     | -                    | -                            | -                                 |

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Table 2-13: Summary of Finite Element Material Models of Reinforced Soil Foundations

| Author                       | Footing Type      | Analysis Type | Reinforcement Model/Element      | Soil Type   | Soil Model                    | Interaction Model/Interface Element |
|------------------------------|-------------------|---------------|----------------------------------|-------------|-------------------------------|-------------------------------------|
| Yetimoglu et al. (1994)      | Rectangular       | Axi-symmetric | Linear elastic Shell element     | Sand        | Modified Duncan (1980)        | Friction                            |
| Nataraj and McManis (1996)   | Strip             | Plane-Strain  | Linear elastic Truss element     | Sand        | Duncan                        | Interface element                   |
| Nainan et al. (1997)         | Rectangular       | 3D            | Linear elastic Truss element     | Sand        | Duncan Zhang (1970)           | Nonlinear                           |
| Yoo (2001)                   | Strip             | Plane Strain  | Linear elastic Truss element     | Sand        | Duncan (1980)                 | -                                   |
| Boushehrian and Hataf (2003) | Circular and Ring | Axi-symmetric | Linear elastic/ tension elements | Sand        | Mohr-Coulomb                  | -                                   |
| Maharaj (2003)               | Strip             | Plane-Strain  | -                                | Clay        | Drucker Prager                | -                                   |
| Sugimoto (2003)              | Strip             | Plane-Strain  | Nonlinear Truss Elements         | Sand        | Drucker Prager                | Line interface element              |
| EI Sawwaf (2007)             | Strip             | Plane-Strain  | Beam element                     | Sand        | friction hardening plasticity | Friction                            |
| Ahmed et al. (2008)          | Strip             | Plane-Strain  | Linear Elastic                   | Clay & Sand | Modified Cam and hyperbolic   | Slip-surface model                  |
| Alamshahi and Hataf (2009)   | Strip             | Plane-Strain  | Linear elastic Tensile element   | Sand        | non-linear Mohr – Coulomb     | Friction                            |

## **CHAPTER THREE**

### **METHODOLOGY OF THE STUDY**

#### **3.1. Numerical Modeling of Reinforced Soil Foundations**

The finite element modeling of reinforced soil foundations (RSF) encompasses geometric modeling, load modeling, prescribed displacement modeling, and material modeling. The commercial finite element analysis (FEM) software PLAXIS (PLAXIS 3D Connect Edition v20 Update 4) was employed in this investigation. PLAXIS 3-D represents a sophisticated finite element analysis tool. It has been extensively utilized within the domain of geotechnical engineering on a global scale. The PLAXIS 3-D software is competent in executing both static and/or dynamic analyses and simulations of intricate geotechnical engineering challenges. It is capable of addressing bodies subject to different loads, settlements, and varying environmental conditions. In the current research, PLAXIS 3-D was utilized to evaluate the performance of both 2m x 2m square, as well as 2m x 3m, 2m x 4m, and 3m x 4m rectangular shallow foundations situated on reinforced expansive soils.

##### **3.1.1. Geometry Model**

The study delineates various configurations of square and rectangular footing that sustain the edifice/structures, characterized by widths extending from 20 meters to 30 meters and lengths also spanning from 20 meters to 30 meters, with a consistent depth of 30 meters. This design is predicated on the analysis of vertical stress distribution and the pressure isobars resulting from the application of both point loads and line loads across the diverse variants of shallow foundations, as previously articulated (Professor J. Boussinesq, 1885). For this study, a dimension of 20 meters by 20 meters accompanied by a depth of 20 meters has been used.

A three-dimensional model was employed to simulate the performance of square and rectangular footings situated on geogrid-reinforced expansive soil. The boundary dimensions for the finite element model were established through a series of analyses utilizing various mesh sizes to identify the dimensions that ensure the footing's bearing capacity and settlement remain unaffected by the boundary conditions. A sensitivity analysis was further conducted to ascertain the optimal mesh size that would mitigate mesh-dependent effects. Initially, a variety of finite element meshes with differing levels of refinement were tested to determine the suitable mesh for analyzing square and rectangular footings on geogrid-reinforced expansive soils.

The very fine mesh was selected for this study to reduce the influence of mesh dependency on the finite element modeling of scenarios involving variations in the quantity, length, and location of geogrid layers, as well as variations in footing type and tensile modulus of the geogrid. The soil, footings, and geogrids were discretized employing ten-noded tetrahedral elements, and the interaction between the soil and geogrid was modeled with surface elements following the Mohr-Coulomb friction law.

### 3.1.2. Load Modeling and Boundary Conditions

The foundation is characterized as rigid; thus, the imposition of specified displacement on the foundation corresponds to the application of designated vertical downward displacement and compressive axial loads from the superstructure obtained from the structural analysis and applied at the central nodes located directly on the foundation (Yetimoglu et al., 1994). Horizontal displacements at the interface between the foundation and the underlying soil in both x and y directions were restrained or constrained to zero, predicated on the assumption of perfect roughness at both the interface and the foundation surfaces. The vertical displacement was introduced in increments of 1000 to facilitate a continuous pressure-displacement response curve. Within the analytical framework, a foundation pressure that results in an allowable settlement of 75mm for clay soil (EBCS-7, 1995) and total load from the superstructure at the center of the foundation was identified as the ultimate bearing stress and total settlement of the studied foundation type (Chungsik, 2001).

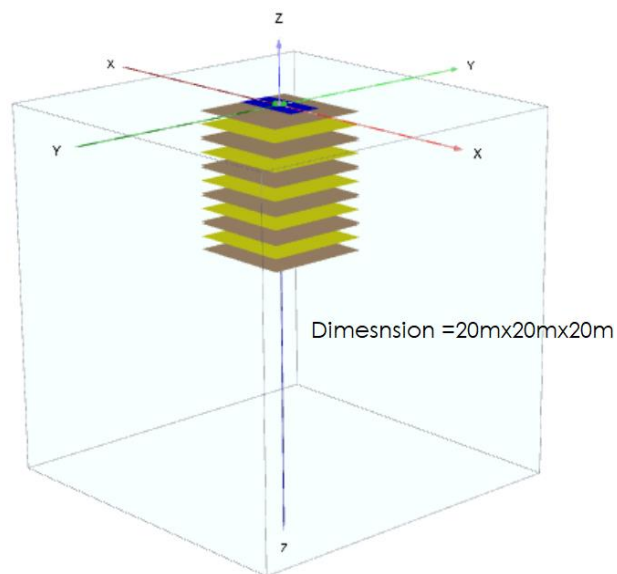


Figure 3-1: Typical sample model of footing, prescribed point displacement, reinforcement, and interface for finite element analysis of 2mx4m rectangular footing

### **3.1.3. Material Model**

The material representations of geogrid-reinforced soil encompass the soil model, the geogrid model, the concrete footing model, the interaction model between soil and concrete footing, as well as the interaction model between soil and geogrid, which are elucidated in the subsequent sub-sections.

#### **3.1.3.1. Soil Modeling**

The soil was discretized using ten noded tetrahedral elements and was modeled as an isotropic elasto-plastic continuum described by the Mohr-Coulomb model. The Mohr-Coulomb plasticity model is an isotropic elasto-plastic model that was used in many studies in the literature to represent the behavior of soft clay soil under a shallow foundation.

##### **3.1.3.1.1. Development of Soil Parameters Used for Finite Element Modeling**

The foundation soil under footings investigation is one of the basic tasks in this study it was about assessing its general suitability to be used as foundation material. The laboratory test data of the soil are collected from JEROCCIA Geotechnical Service and Engineering PLC. as secondary data and tabulated as follows which is conducted in Addis Ababa Bole Sub-city Client Ethiopian Airlines and Project name Component maintenance shop (PK-2).

## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

Table 3.1: Foundation Soil Laboratory Test Data collected from (JEROCCIA Geotechnical Service and Engineering PLC.)

| Bore Hole ID | Depth (m) | Atterberg limit (AASHTO T89 & 90) |    | Soil Classification (AASHTO M- 145) | Proctor Density (AASHTO T-180) |         | 3-Point CBR AASHTO T-193 |                    |         |        |           | MC (%) | Gs   | Average CBR |            |
|--------------|-----------|-----------------------------------|----|-------------------------------------|--------------------------------|---------|--------------------------|--------------------|---------|--------|-----------|--------|------|-------------|------------|
|              |           | LL                                | PI |                                     | MDD (g/cc)                     | OMC (%) | No of Blows              | Dry Density (g/cc) | CBR (%) |        | Swell (%) |        |      | CBR @ 2.54  | CBR @ 5.08 |
|              |           |                                   |    |                                     |                                |         |                          |                    | 2.54mm  | 5.08mm |           |        |      |             |            |
| 1            | 3.00-3.50 | 110                               | 60 | A-7-6                               | 1.42                           | 22.50   | 10.00                    | 1.35               | 3.10    | 3.00   | 12.51     | 17.40  | 2.45 | 4.30        | 4.03       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.38               | 4.30    | 4.10   | 10.94     | 19.00  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.40               | 5.50    | 5.00   | 9.30      | 21.00  |      |             |            |
| 1            | 5.20-5.70 | 105                               | 57 | A-7-6                               | 1.36                           | 24.20   | 10.00                    | 1.41               | 3.20    | 3.00   | 13.00     | 23.30  | 2.42 | 4.37        | 4.13       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.38               | 4.60    | 4.30   | 10.80     | 25.60  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.39               | 5.30    | 5.10   | 8.70      | 26.20  |      |             |            |
| 1            | 7.20-8.00 | 105                               | 53 | A-7-6                               | 1.40                           | 23.10   | 10.00                    | 1.42               | 3.30    | 3.10   | 13.10     | 24.50  | 2.47 | 4.30        | 4.07       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.41               | 4.50    | 4.20   | 10.30     | 27.70  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.40               | 5.10    | 4.90   | 8.90      | 24.60  |      |             |            |
| 2            | 3.20-3.80 | 96                                | 43 | A-7-6                               | 1.24                           | 22.70   | 10.00                    | 1.21               | 2.40    | 2.40   | 14.46     | 19.40  | 2.45 | 3.77        | 3.60       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.22               | 4.00    | 3.70   | 12.68     | 21.40  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.24               | 4.90    | 4.70   | 10.98     | 23.70  |      |             |            |
| 2            | 8.50-8.95 | 95                                | 47 | A-7-6                               | 1.26                           | 25.90   | 10.00                    | 1.25               | 2.70    | 2.50   | 11.50     | 27.90  | 2.51 | 3.27        | 3.07       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.20               | 3.20    | 3.10   | 10.10     | 29.00  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.23               | 3.90    | 3.60   | 8.50      | 24.20  |      |             |            |
| 3            | 4.00-4-50 | 110                               | 58 | A-7-6                               | 1.35                           | 23.20   | 10.00                    | 1.29               | 2.40    | 2.20   | 13.30     | 18.50  | 2.45 | 3.10        | 2.88       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.32               | 3.10    | 2.95   | 10.80     | 20.60  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.41               | 3.80    | 3.50   | 8.54      | 22.70  |      |             |            |
| 3            | 6.00-6.50 | 85                                | 36 | A-7-6                               | 1.34                           | 24.10   | 10.00                    | 1.32               | 4.60    | 4.10   | 10.20     | 25.30  | 2.35 | 5.00        | 4.67       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.35               | 4.90    | 4.50   | 8.40      | 23.60  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.31               | 5.50    | 5.40   | 7.60      | 24.90  |      |             |            |
| 4            | 3.00-3.50 | 90                                | 43 | A-7-6                               | 1.39                           | 23.90   | 10.00                    | 1.32               | 4.00    | 3.90   | 10.38     | 20.60  | 2.5  | 4.50        | 4.27       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.36               | 4.30    | 3.90   | 9.43      | 21.80  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.39               | 5.20    | 5.00   | 8.56      | 23.30  |      |             |            |
| 4            | 6.00-6.50 | 90                                | 46 | A-7-6                               | 1.80                           | 24.10   | 10.00                    | 1.39               | 3.90    | 3.40   | 12.80     | 24.70  | 2.4  | 4.27        | 3.95       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.34               | 3.90    | 3.65   | 10.60     | 25.80  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.38               | 5.00    | 4.80   | 8.30      | 25.40  |      |             |            |
| 5            | 2.50-2.90 | 100                               | 46 | A-7-6                               | 1.45                           | 23.20   | 10.00                    | 1.35               | 4.10    | 3.95   | 12.10     | 24.60  | 2.48 | 4.67        | 4.38       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.37               | 4.50    | 4.25   | 10.20     | 23.20  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.45               | 5.40    | 4.95   | 8.30      | 24.70  |      |             |            |
| 5            | 5.00-5.50 | 101                               | 51 | A-7-6                               | 1.38                           | 25.50   | 10.00                    | 1.41               | 2.50    | 2.30   | 13.40     | 25.50  | 2.51 | 3.07        | 2.75       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.37               | 3.10    | 2.70   | 10.90     | 24.80  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.35               | 3.60    | 3.25   | 8.50      | 26.20  |      |             |            |

The soil data collected from the laboratory test results from JEROCCIA Geotechnical Service and Engineering PLC. as secondary data in (Table-3.1) reveals that the liquid limits are mainly clustered between 85 and 110. The PI values range from 36 to 60, and the property of the soil is highly plastic soil. The classification test showed that these soils fall into A-7-6, as per the AASHTO soil classification system, indicating a poor material requiring improvement using geosynthetic material like geogrid. In addition to the AASHTO soil classification tests, the CBR value is used to determine the soil shear strengths. Wherever soil with a CBR value of less than 5.5% in both 2.54mm and 5.08mm penetration depth is occurring within the design depth, it should be replaced with better material or improved with reinforcement having a good bearing strength.

### 3.1.3.1.2. Basic Geotechnical Properties

The general properties required for simulating the soil material as per the Mohr-Coulomb model mainly include: bulk unit weight ( $\gamma$ , kN/m<sup>3</sup>), saturated unit weight ( $\gamma_{sat}$ , kN/m<sup>3</sup>), the at-rest coefficient of horizontal soil stress ( $K_o$ )...etc.

The bulk unit weight ( $\gamma_{unsat}$ , kN/m<sup>3</sup>) of the cohesive soil has been calculated (Eq. 3.1) by using the index property correlation recommended by (Carter, M. and Bentley S. P, 2016). Table A-2 in the appendix

$$\gamma_{unsat} = \gamma_d(1 + w) \quad [3.1]$$

$$K_o = 1 - \sin \phi' \quad [3.2]$$

For a saturated state the degree of saturation  $S = 100\%$

$$eS = wG_s \quad [3.3]$$

$$\gamma_{sat} = \left( \frac{G_s + e}{1 + e} \right) * \gamma_w \quad [3.4]$$

#### **3.1.3.1.3. Shear Strength Characteristics Parameters**

The strength characteristics required for simulating the soil material as per the Mohr-Coulomb model mainly include effective cohesion ( $c''$ , kN/m<sup>2</sup>), effective angle of internal friction ( $\phi''$ , °), and initial angle of dilatancy ( $\psi$ , °). The relationship between the effective shear strength parameter ( $\phi''$ ) and plasticity index (PI) for remolded clays has been established by (Carter, M. and Bentley S. P., 2016).

$$\phi'' = 0.085PI^{1.4} - 0.75PI + 31.9 \quad [3.5]$$

The other shear strength parameter effective cohesion value ( $c''$ ) had empirically correlated to effective friction angle ( $\phi''$ ), as recommended by (Burt G. Look, 2007) Table A-3 in the appendix.

#### **3.1.3.1.4. Elastic Properties of Materials or Stiffness Characteristics**

The elastic deformation parameters of the soil material required as per Mohr Coulomb model include: Young's modulus (E) and Poisson's ratio ( $\nu$ ). The stiffness parameter (Young's modulus, E) has been correlated with the California bearing ratio (CBR) value based on the poisson's ratio (Elsa Eka Putri, et. al, 2012).

$$E = 863.83 \text{ CBR(kPa)}, \nu = 0.0 \quad [3.6]$$

$$E = 840.53 \text{ CBR(kPa)}, \nu = 0.3 \quad [3.7]$$

$$E = 751.00 \text{ CBR(kPa)}, \nu = 0.4 \quad [3.8]$$

## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

Typical values for Young's modulus and Poisson's ratio of soft clay materials (Elsa Eka Putri, et. al, 2012) were correlated and presented in the appendix Table A-2.

Table 3.2: Foundation Soil Data for Finite Element Analysis

| Soil Parameter                                  | Sub-Soil          | SI- Unit             |
|-------------------------------------------------|-------------------|----------------------|
| Material model                                  | Mohr-Coulomb (MC) | —                    |
| Depth                                           | 0.00 - 20.00      | (m)                  |
| Type of material behavior                       | undrained         | —                    |
| Bulk unit weight ( $\gamma_{\text{unsat}}$ )    | 17.00             | (kN/m <sup>3</sup> ) |
| Saturated unit weight ( $\gamma_{\text{sat}}$ ) | 19.00             | (kN/m <sup>3</sup> ) |
| Over-consolidation ratio                        | 1.00              | —                    |
| Poisson's Ratio ( $\nu$ )                       | 0.35              | —                    |
| Young's modulus (E)                             | 3.23              | (Mpa)                |
| Cohesion ( $C_{\text{ref}}$ )                   | 7.50              | (kN/m <sup>2</sup> ) |
| Friction angle ( $\Phi_{\text{eff}}$ )          | 15.00             | (Degree)             |
| Dilatancy angle ( $\Psi$ )                      | 0.00              | (Degree)             |
| Lateral earth coefficient $K_0$                 | 0.74              | —                    |

### 3.1.3.2. Geogrid Modeling

The typical strain distribution of geogrid in reinforced soil foundations is less than 2%, so geogrid can be assumed to be linear elastic (Abu-Farsakh et al., 2009). Four types of geogrids with different equivalent tensile moduli were used in the finite element analysis to investigate the effect of geogrid tensile strength on the performance of shallow foundations resting on expansive soils (Jie Gu, 2011).

Table 3.3: Geogrid material properties for finite element analysis (Jie Gu, 2011).

| Geogrid Type     | Reference Name | Elastic Modulus (kPa) | Poisson's Ratio ( $\nu$ ) | Area (m <sup>2</sup> ) | EA (kN)   |
|------------------|----------------|-----------------------|---------------------------|------------------------|-----------|
| Geogrid Type I   | GGI            | 585,100.00            | 0.3                       | 0.06                   | 35,106.00 |
| Geogrid Type II  | GGII           | 660,000.00            | 0.3                       | 0.06                   | 39,600.00 |
| Geogrid Type III | GGIII          | 860,000.00            | 0.3                       | 0.06                   | 51,600.00 |
| Geogrid Type V   | GGV            | 950,000.00            | 0.3                       | 0.06                   | 57,000.00 |

### 3.1.3.3. Shallow Foundation Modeling

Square and rectangular footing were modeled using finite element-based soft wares PLAXIS 3-D. The reinforced concrete square and rectangular footings were modeled as a reinforced concrete element with proper interface properties and necessary parameters used for finite element modeling collected from (EBCS EN, 1992-1-1:2013).

Table 3.4: Reinforced Concrete Properties for Finite Element Analysis (EBCS EN, 1992-1-1:2015).

| Materials           | Concrete Grades | E-modulus of Elasticity | Unit weigh        | Poisson's Ratio | Depth of Footing |
|---------------------|-----------------|-------------------------|-------------------|-----------------|------------------|
| Reinforced Concrete | C-30            | $3.1 \times 10^7$       | 24                | 0.15            | 0.50             |
| SI Units            | Unitless        | kN/m <sup>2</sup>       | kN/m <sup>3</sup> | Unit Less       | m                |

**Note:** Depth of footing 0.5m was taken based on previous site experience for shallow foundations.

### 3.1.3.4. Modeling of Geogrid- Soil and RC footing- Soil Interface

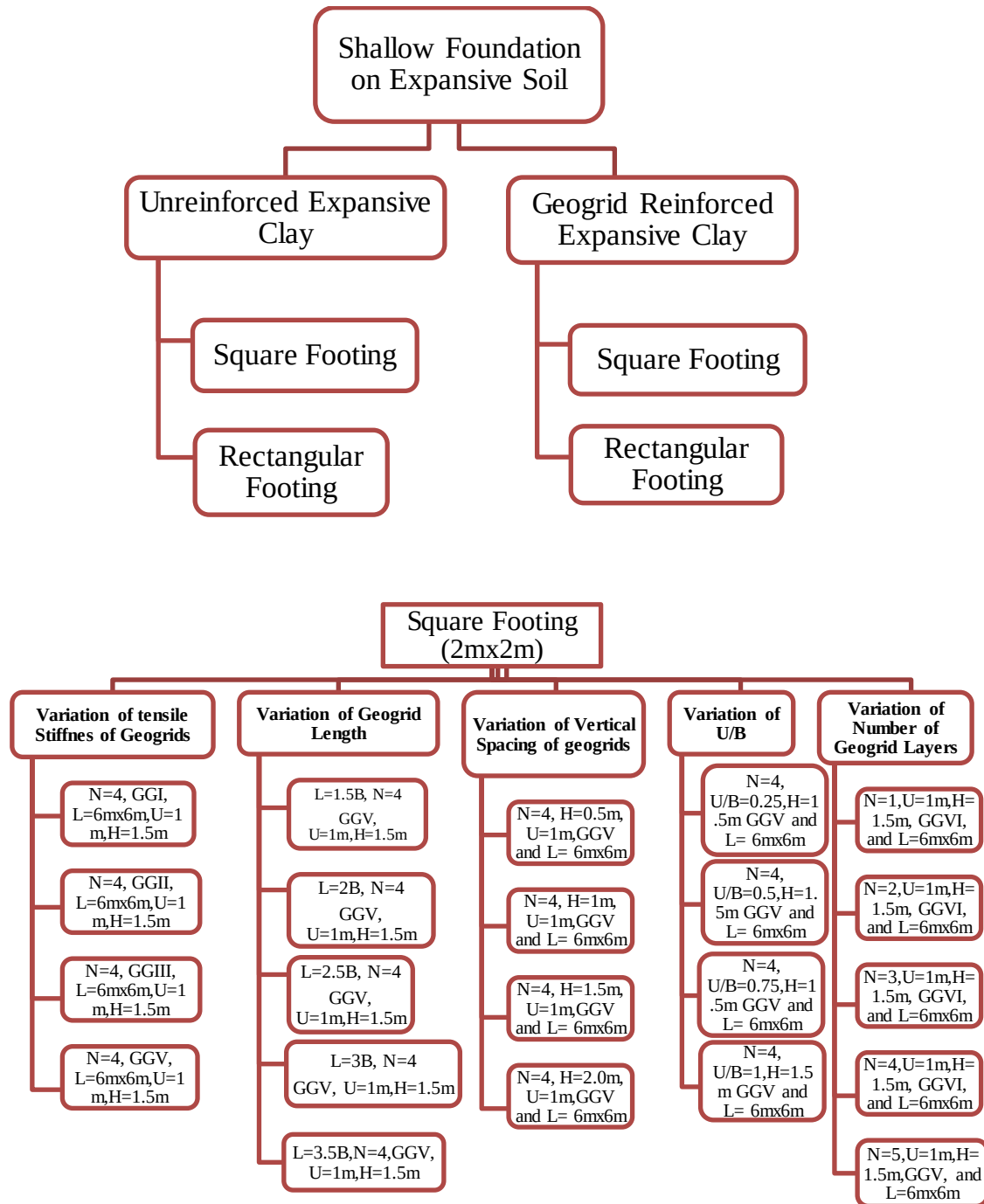
Interface elements are available in PLAXIS 3-D Foundation to model the interaction between smooth and rough surfaces i.e. between geogrid and soil, and soil and footing. Interface elements can simulate gap and slip displacements, which are normal and parallel to the interface, respectively. The loss of strength at the interface is modeled with a reduction factor ( $R_{inter}$ ), which relates the interface strength to the soil shear strength through friction angle ( $\phi$ ) and cohesion ( $c$ ):

$$C_i = R_{inter} * C_{soil} \quad [3.9]$$

$$\tan \phi_i = R_{inter} * \tan \phi_{soil} \leq \tan \phi_{soil} \quad [3.10]$$

For modeling soil geogrid interaction, an interface element has been used at the contact point of soil and geogrid.  $R_{inter}$  parameter has been used for the definition of shear strength between soil and reinforcement. The numerical value for  $R_{inter}$  between geogrids and soils is considered as 0.9 ( $R_{inter} = 0.9$ ) (Bergado and Teerawattanasuk, 2008). The reinforced concrete footing is rigid enough so that the interaction between the reinforced concrete footing and soil  $R_{inter}$  is unity ( $R_{inter} = 1$ ).

### 3.1.4. Finite Element Matrix



# Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

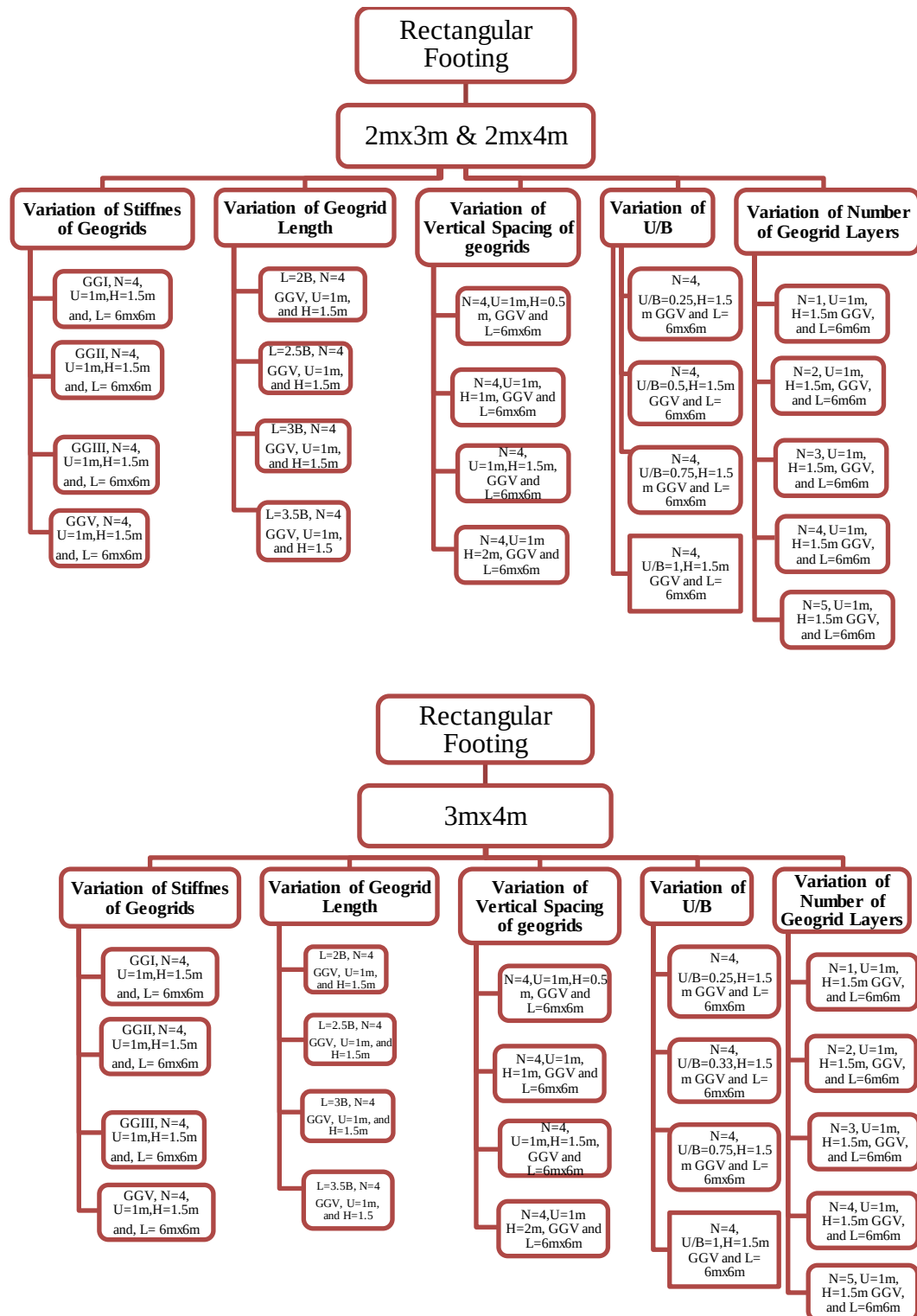


Figure 3-2: Schematic Illustration for FEM mat

## **CHAPTER FOUR**

### **RESULT AND DISCUSSIONS**

#### **4.1. Introduction**

Finite element-based software analyses were conducted on both unreinforced and reinforced expansive soil to evaluate the influence of various factors affecting the performance of square, and rectangular footing on geogrid reinforced studied soils. A total of 89 FEA models were conducted using PLAXIS-3D-Connect edition V20 Update 4 to obtain the bearing capacity and settlement of square and rectangular footing resting on expansive soils. The basic factors included in this study are the tensile modulus of reinforcement layers, Length of reinforcement layers relative to the footing width, Vertical spacing of consecutive reinforcement layers, Embedment depth of first reinforcement layers from the booting of the footing, and number of reinforcement layers.

For each case, the load-deformation curve, derived from the finite element simulations, was utilized to ascertain the bearing capacity and settlement of both square and rectangular footings subjected to an allowable settlement of 75mm (EBCS-7,1995) and structural loads determined through the structural analysis of buildings using ETABS 2019 and positioned at the center of the footing ( $P=2500\text{KN}$ ). The results of these variables were elaborated upon in the subsequent section, and the advantages of reinforced soil foundation (RSF) were evaluated in terms of settlement, rate of change in settlement, bearing capacity, bearing capacity ratio (BCR), and variation in the rate of bearing capacity.

#### **4.2.Parametric Study of Geogrid-Reinforced Expansive Soils Under Shallow Foundations**

Expansive soils pose a significant challenge for shallow foundations due to their tendency to shrink and swell with seasonal moisture variations. Geogrids, a type of geosynthetic material, offer a promising technique to improve the performance of such foundations. This can be achieved through a parametric study that analyzes how different geogrid properties, placement configurations, and location of groundwater level influence the foundation's behavior. The effect of each study parameters investigated under this study were discussed in detail in the following section.

### 4.2.1. Effects of groundwater on the performance of square and rectangular footing

Groundwater enhances pore water pressure, subsequently diminishing the effective stress within the soil matrix. This decrement causes an elevation in compressibility, rendering the soil increasingly susceptible to settlement when subjected to external loads. Upon saturation of the soil underlying the foundation, there occurs a transformation in the soil structure. Saturated soils, notably those that are fine-grained such as clay, demonstrate greater settlements in comparison to their unsaturated counterparts. Water infiltrates the interstitial spaces among soil particles, thereby decreasing friction and resulting in more pronounced deformation under applied loads. The existence of groundwater adversely affects the shear strength of the soil. When the water table is situated near or at the foundation's base, the soil's capacity to sustain loads is compromised as pore water pressure counteracts the soil's intrinsic resistance to shear forces. The bearing capacity of the soil is inherently linked to the effective stress. Elevated groundwater levels correspond with diminished effective stress due to augmented pore water pressure, thereby reducing the bearing capacity of the soil. This phenomenon is particularly significant in clay and granular soils, which possess a heightened sensitivity to fluctuations in water content.

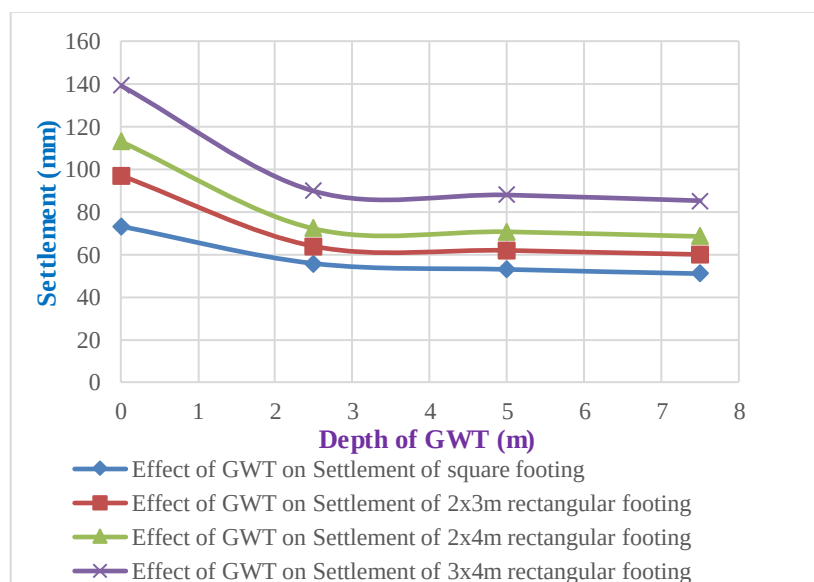


**Figure 4.1:** Effects of groundwater on settlement of square and rectangular footing using finite element analysis PLAXIS 3-D.

## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

The finite element analysis conducted by PLAXIS 3-D, as illustrated in Figure 4-1, reveals that maximum settlement and minimum bearing capacity occur when the groundwater aligns with the foundation's base; these extreme scenarios have been considered for subsequent performance assessments of both square and rectangular footings on soft clay under this study.

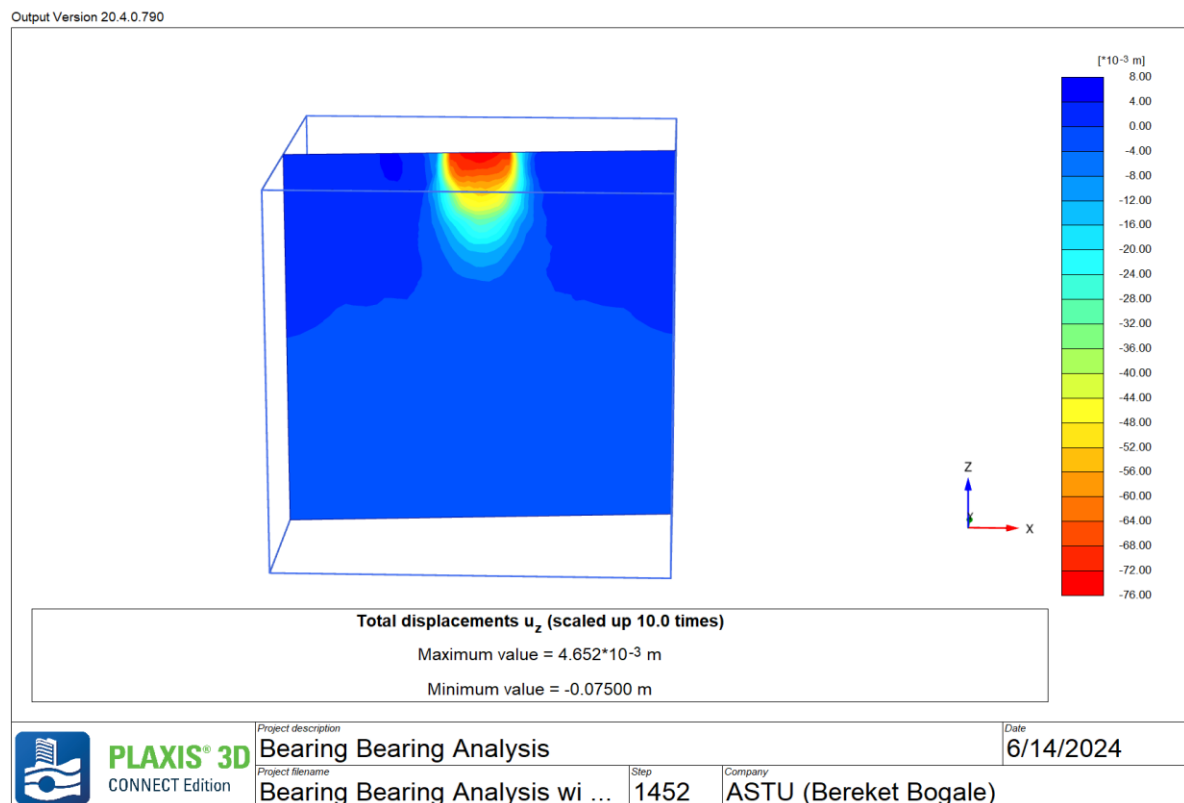


Figure 4.2: PLAXIS 3-D output view (Sample) of total vertical displacement [m] of 2mx4m rectangular footing.

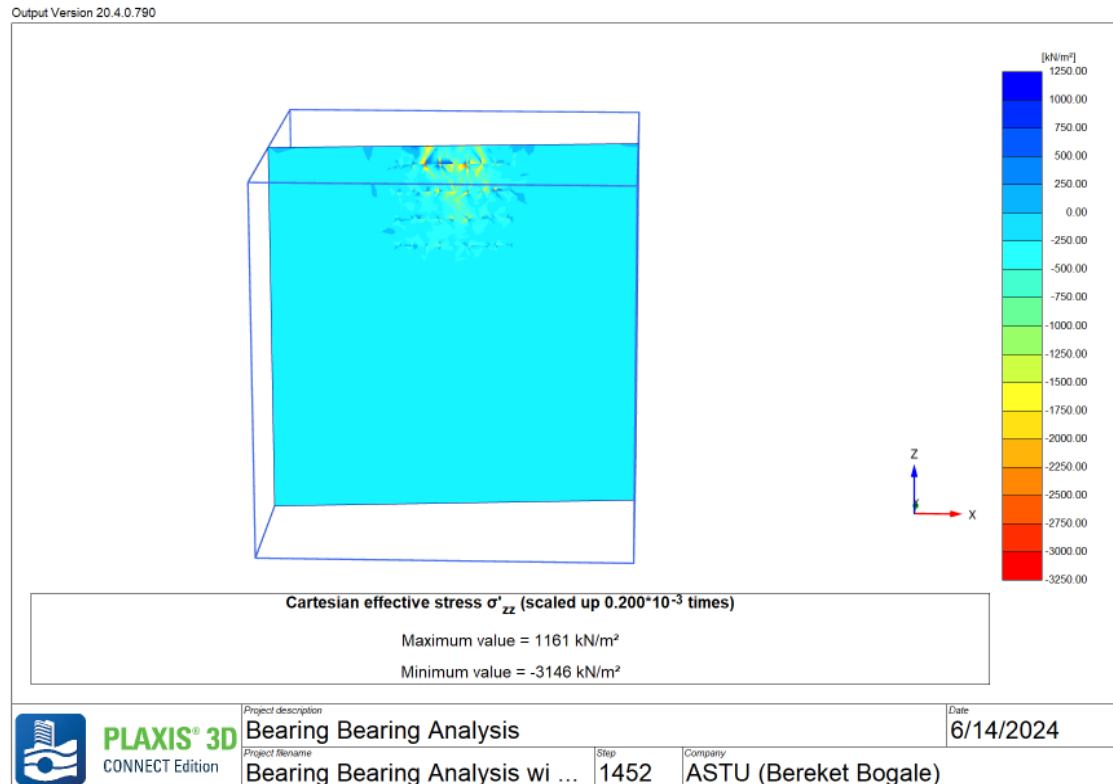


Figure 4.3: PLAXIS 3-D output view (Sample) of cartesian effective stress (kN/m<sup>2</sup>) of 2mx4m rectangular footing

## 4.2.2. Effect of Tensile Modulus of Reinforcement

The performance of square and rectangular footings on reinforced soils is greatly affected by the tensile modulus, one of the most crucial characteristics of geogrids. The present investigation aimed to investigate the impact of four distinct types of biaxial geogrids, each with a different tensile modulus, on the bearing capacity and settlement of square and rectangular footings. A series of finite element analyses were conducted for each tensile modulus using four layers of reinforcement placed within the effective depth of 1<sup>st</sup> layers of reinforcement at 0.5B, Length of reinforcement  $L=3B$ , for 2mx2m, 2mx3m, and 2mx4m rectangular, and 0.33B, length of reinforcement  $L=2.5B$  for 3mx4m rectangular footing respectively at a uniform spacing  $h = 1.5m$ . The term “bearing capacity ratio” (BCR) is commonly used to express and compare the bearing capacity of the reinforced and unreinforced soils. The following well-established definition (Binqet and Lee, 1975) is used for BCR analysis:

$$BCR = \frac{q_R}{q_0} \dots \dots \dots (4.1)$$

## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

Where  $q_R$  and  $q_o$  are the bearing capacity for the reinforced and unreinforced soils, respectively. The calculated bearing capacity with normalized settlement ( $s/B$ ), the bearing capacity ratio, the rate of bearing capacity, the settlement, and the rate of settlement as a function of the geogrid tensile modulus is described in Figures 4.4, 4.5, 4.6, 4.7, and 4.8 for both square and rectangular footings, respectively. Regardless of the number of reinforcement layers, the vertical spacing between geogrid layers, the placement depth of the first reinforcement layer, and the reinforcement length relative to the footing width, footings reinforced with geogrids of higher tensile modulus exhibit significantly greater load-bearing capacity, bearing capacity ratio, rate of change in bearing capacity, while concurrently exhibiting a significant reduction in settlement and settlement rate when compared to those reinforced with geogrids characterized by a lower tensile modulus. The load-bearing capacity increased by (47.09%, 49.14%, 53.44%, 54.94%) for square, (43.38%, 45.38%, 49.47%, 50.91%) for 2x3m, (43.21%, 45.04%, 48.85%, 50.20%) for 2x4m, and (42.17%, 44.15%, 48.26%, 49.20%) for 3x4m, and the settlement decrease by (31.71%, 34.63%, 36.32%, 39.44%), for square (27.01%, 30.15%, 32.57%, 35.02%) for 2x3m, (29.31%, 30.89%, 33.40%, 37.00%) for 2x4m, and (20.99%, 30.58%, 33.14%, 35.25%) for 3x4m rectangular footings respectively. Among all footing types studied, square footings experienced the most significant bearing capacity increment and reduced the settlement with the use of higher tensile modulus reinforcement.

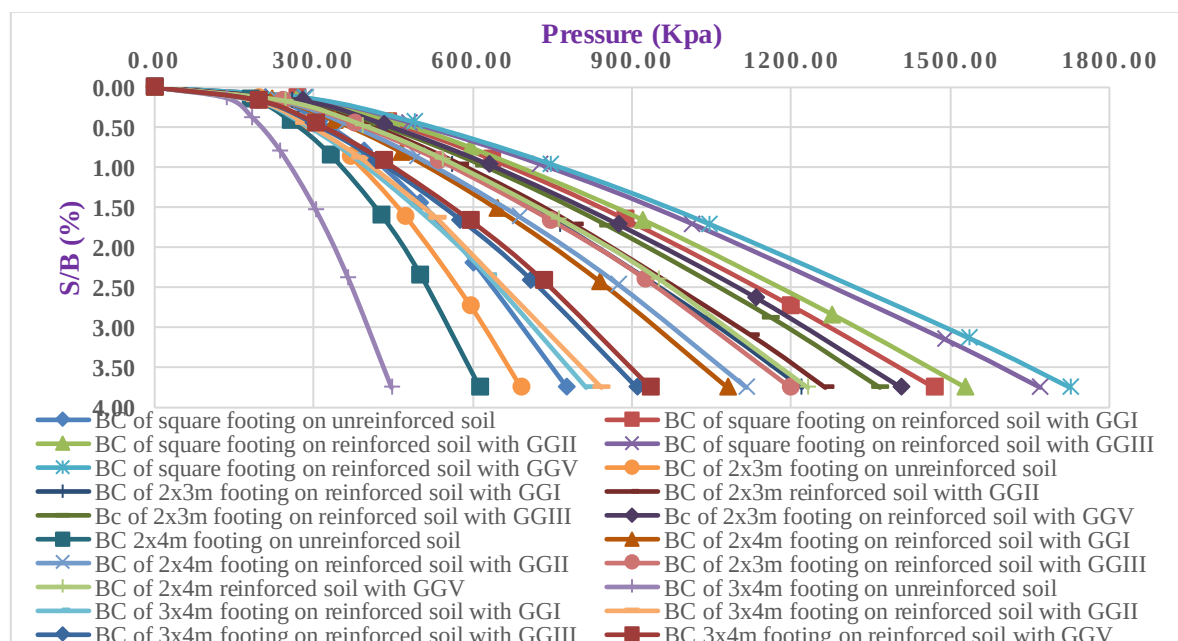


Figure 4.4: Effect of tensile modulus of reinforcement on the bearing capacity of square and rectangular footings

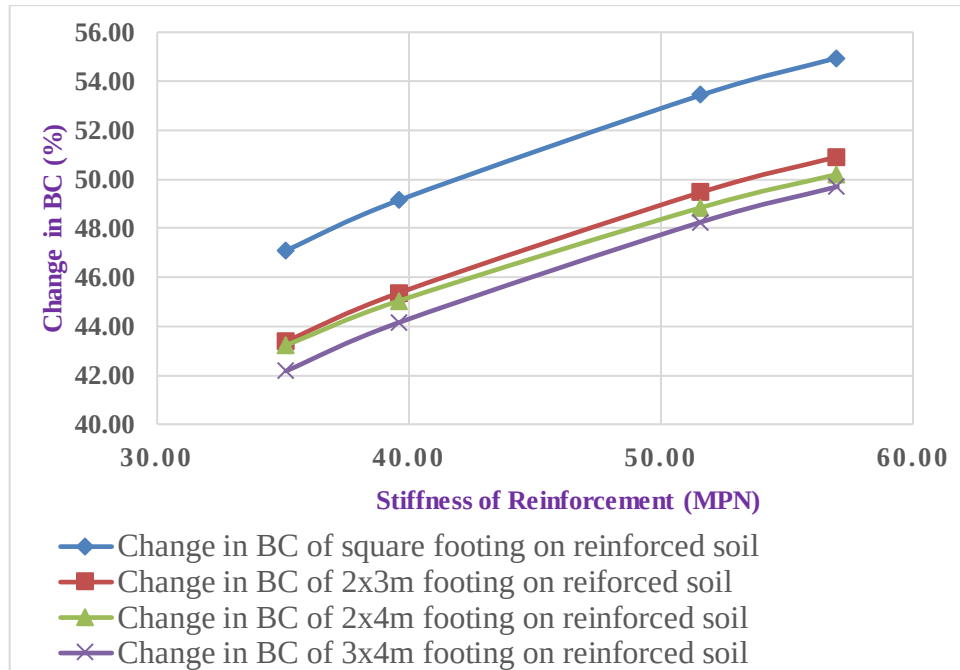


Figure 4.5: Effect of tensile modulus of reinforcement on change in BC of square and rectangular footings

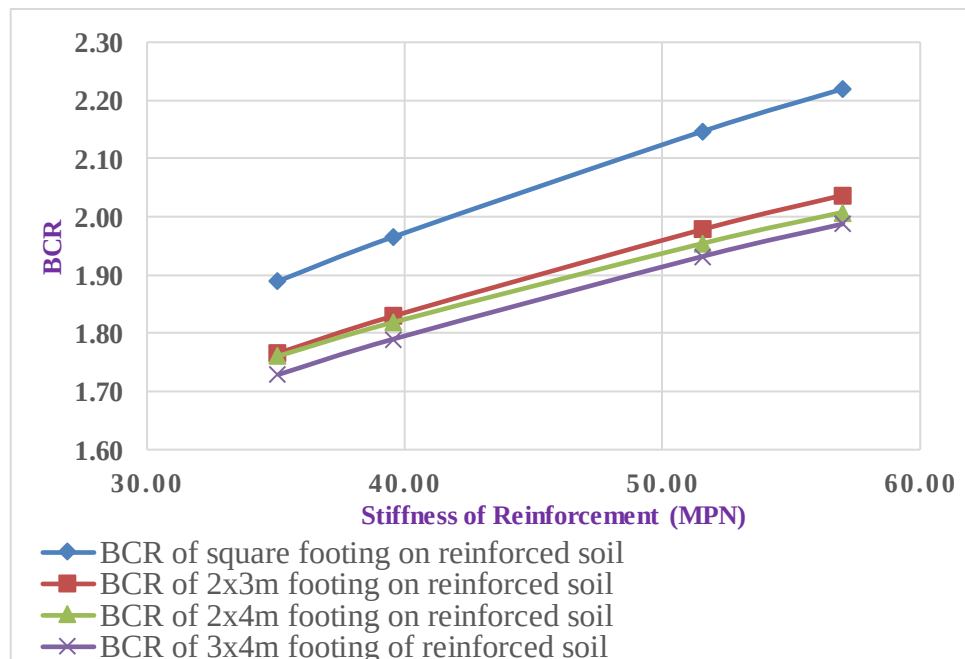


Figure 4.6: Effect of tensile modulus of reinforcement on BCR of square and rectangular footings

## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

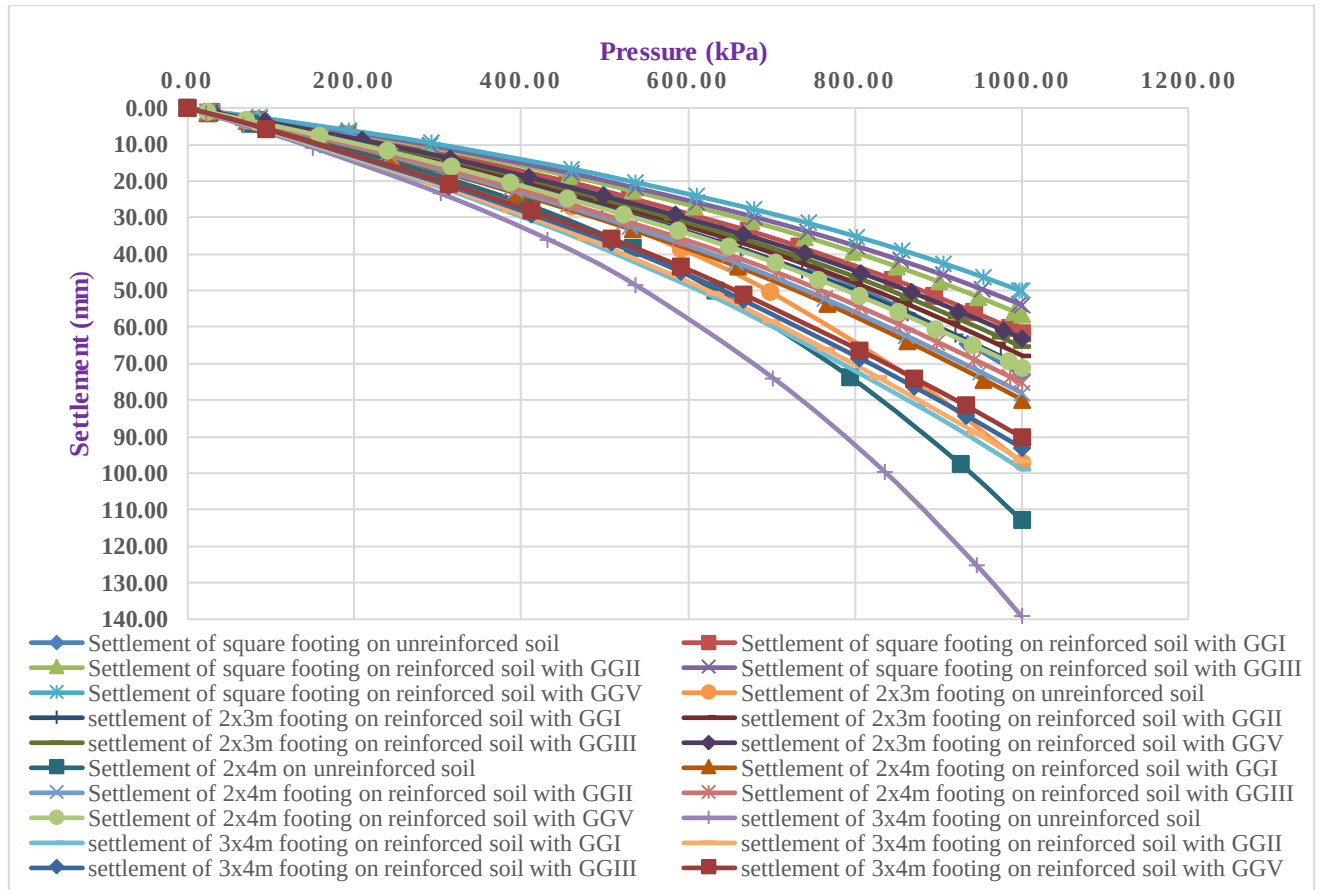


Figure 4.7: Effects of tensile modulus of reinforcement on the settlement of square and rectangular footing



Figure 4.8: Effect of tensile modulus of reinforcement on the Settlement of square and rectangular footings

#### **4.2.3. Effect of Consecutive Reinforcement Vertical Spacing**

The influence of sequential reinforcement vertical spacing ( $h$  or  $h/B$ ) on the bearing capacity, the BCR, the change in rate of bearing capacity, settlement, and change in the rate of settlement were systematically analyzed by changing the vertical spacing of reinforcement layers within the initial reinforcement layer depth at  $U=0.5B$ , length  $L=3B$ , for  $2 \times 2\text{m}$ ,  $2\text{m} \times 3\text{m}$ , and  $2\text{m} \times 4\text{m}$  footings, and at  $U=0.33B$ , length  $L=2.5B$ , for  $3\text{m} \times 4\text{m}$  rectangular footing, respectively. Finite element analyses were performed on the footing-reinforced soil model utilizing four layers and one type of geogrid (GGV), which possesses a high tensile modulus and was positioned at four distinct spacings. The subsequent configurations of vertical spacing for the reinforcement layers were scrutinized: four layers at ( $h=0.5\text{m}$ ,  $h=1\text{m}$ ,  $h=1.5\text{m}$ , and  $h=2\text{m}$ ) spacing were implemented in succession. Figures 4.9, 4.10, 4.11, 4.12, and 4.13 delineate the correlation among the pressure-settlement curves, vertical spacing versus bearing capacity ratios, the rate of change in bearing capacity, load-settlement, and rate of change in settlement of square and rectangular footing respectively. The load-bearing capacity, the rate of variation in load-bearing capacity, and the load-bearing capacity ratio of shallow foundations demonstrated an enhancement as the inter-reinforcement spacing increased to  $1.5\text{m}$  (optimum), which was subsequently followed by a decline. In contrast, the settlement and the rate of change in settlement exhibited a decrease of up to  $1.5\text{m}$  (optimum), after which an increase was observed. The rate of increase in bearing capacity of the footing, which is attributable to the vertical spacing between reinforcement layers, can be quantitatively expressed as (49.79%, 51.62%, 54.61%, & 43.54%) for the square footing, (43.33%, 46.42%, 51.30%, & 40.86%) for the  $2\text{m} \times 3\text{m}$  configuration, (60.40%, 61.84%, 64.20%, & 55.47%) for the  $2\text{m} \times 4\text{m}$  configuration, and (75.38%, 76.28%, 77.75%, & 72.32%) for the  $3\text{m} \times 4\text{m}$  rectangular footings. Furthermore, the rate of reduction in settlement of a footing can be observed as (32.65%, 35.21%, 37.71%, 29.40%) for square footings, (29.87%, 30.43%, 32.87%, 26.62%) for the  $2\text{m} \times 3\text{m}$  configuration, (23.08%, 27.78%, 30.76%, 22.22%) for the  $2\text{m} \times 4\text{m}$  configuration, and (31.11%, 33.71%, 35.90%, 28.16%) for the  $3\text{m} \times 4\text{m}$  rectangular footing, as the spacing ( $H$ ) increases to  $0.5\text{m}$ ,  $1\text{m}$ ,  $1.5\text{m}$ , &  $2\text{m}$ , respectively. The vertical spacing between reinforcement layers significantly augmented the rate of change in the bearing capacity of the  $3\text{m} \times 4\text{m}$  rectangular footing.

## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

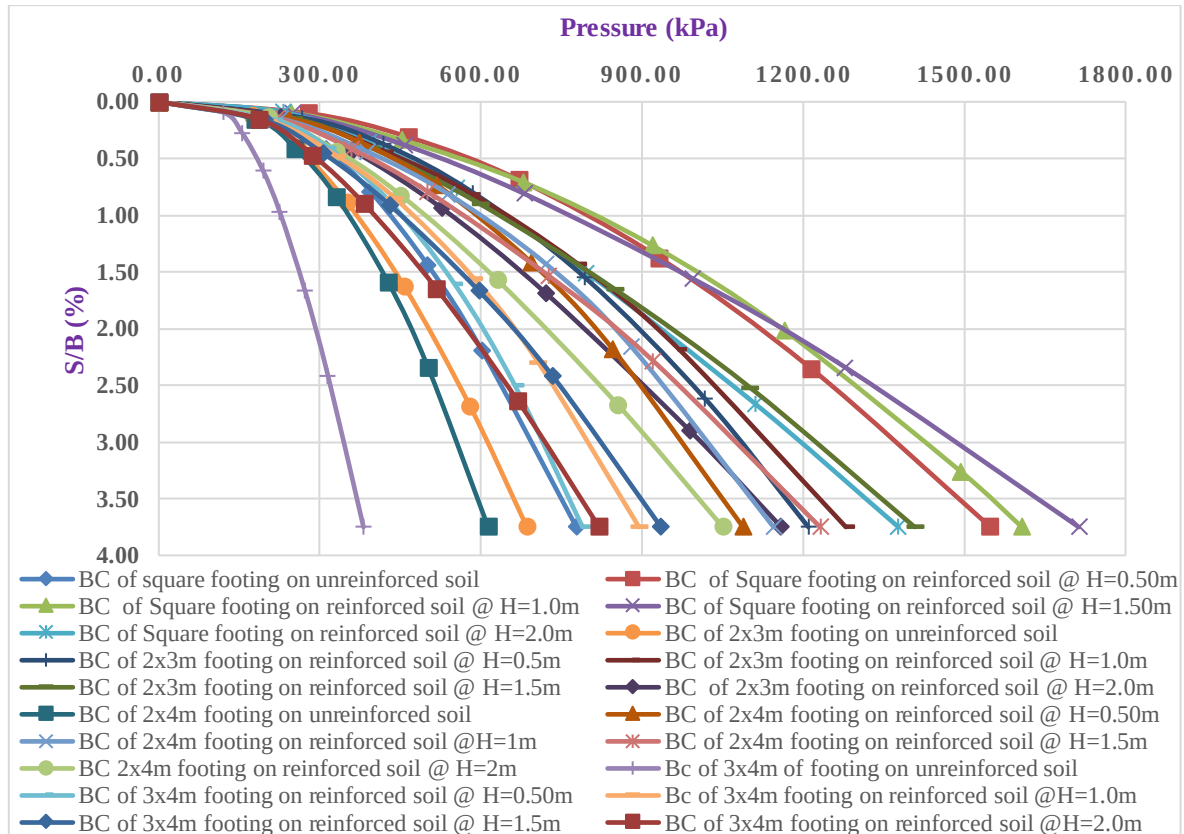


Figure 4.9: Effect of vertical spacing between consecutive layers of reinforcement on the bearing capacity of square and rectangular footings

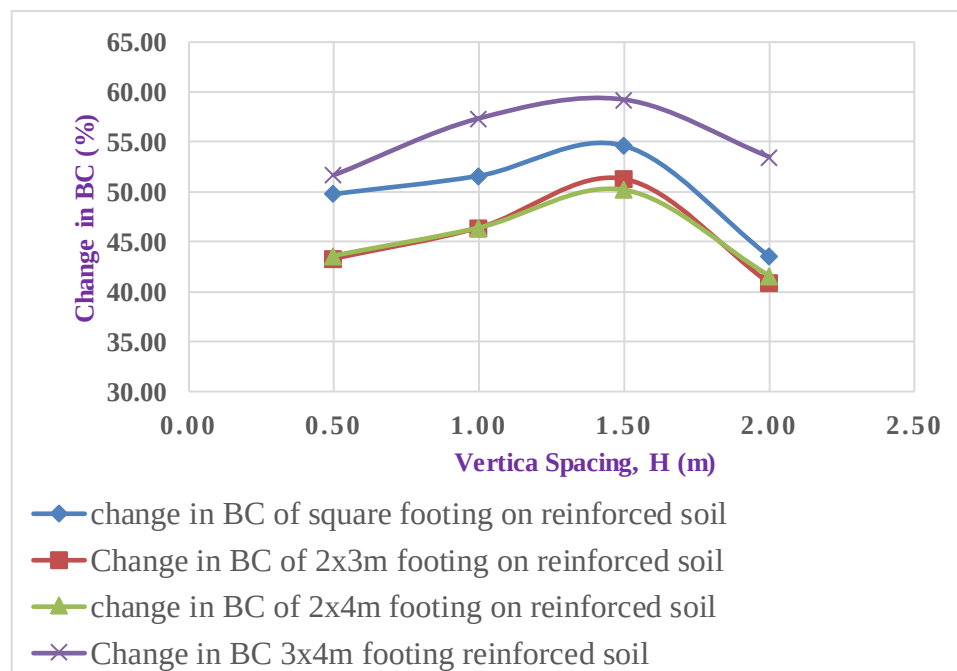


Figure 4.10: Effect of vertical spacing between consecutive layers of reinforcement on the Change in rate of BC of square and rectangular footing

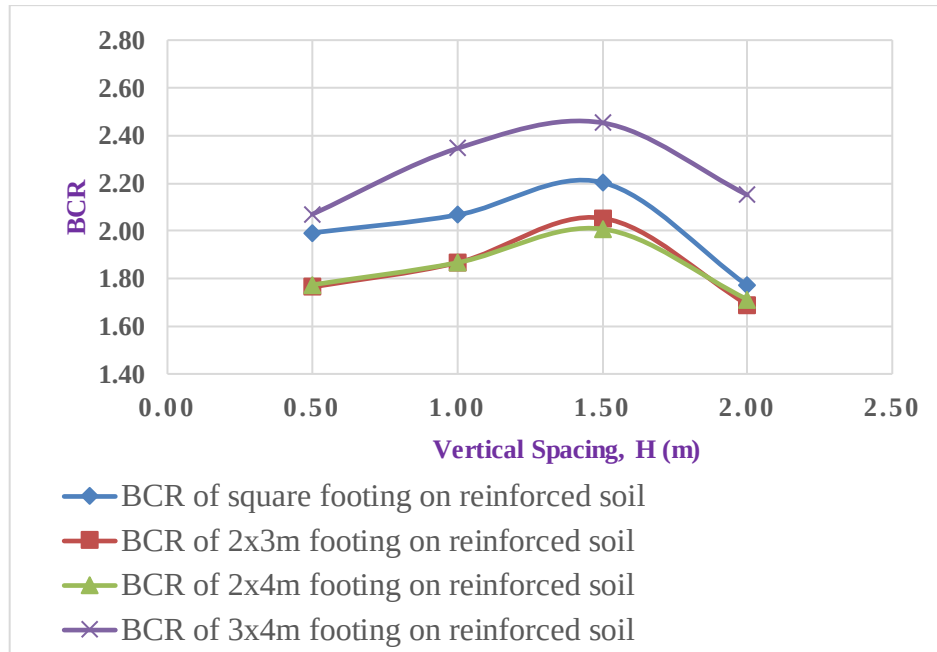


Figure 4.11: Effect of vertical spacing between consecutive layers of reinforcement on the BCR of square and rectangular footing

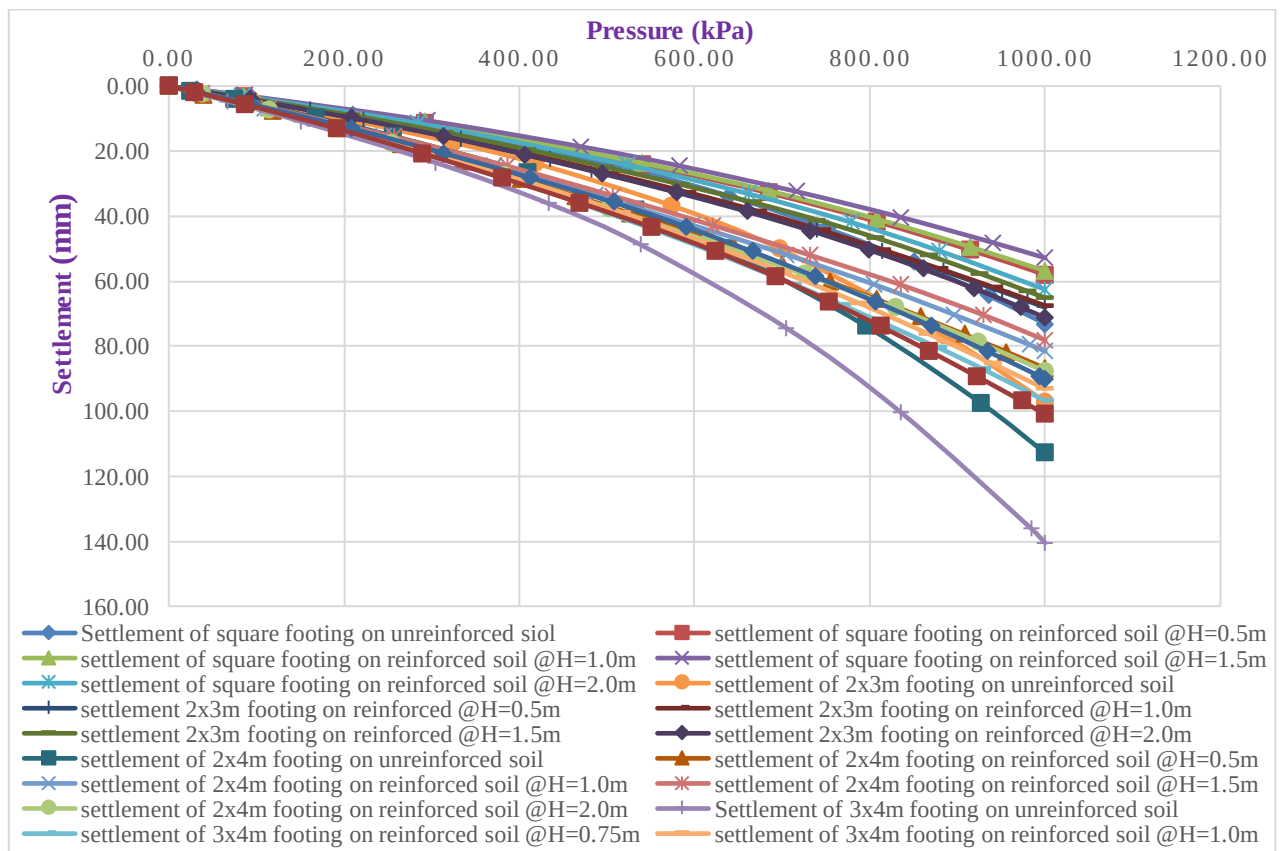


Figure 4.12: Effect of vertical spacing between consecutive layers of reinforcement on the Settlement of square and rectangular footings

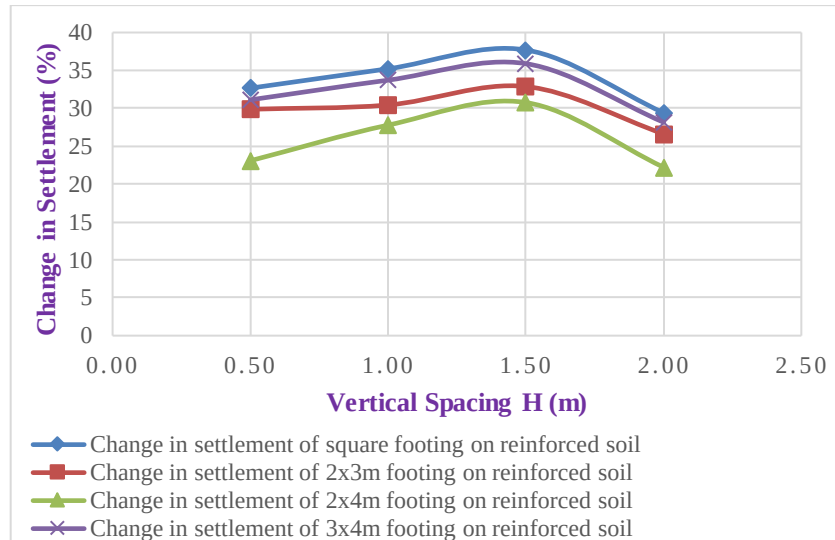


Figure 4.13: Effect of vertical spacing between consecutive layers of geogrids on the change in settlement of square and rectangular footing

#### 4.2.4. Effect of Depth of First Layer Reinforcement from the Bottom of Footing

The formulation of reinforced soil foundations necessitates the assessment of the effective (or influence) depth of the initial layer of reinforcement situated beneath the base of the footing, below which the incorporation of reinforcement yields a significant enhancement in footing efficiency. To ascertain the effective depth of the primary reinforcement layer from the base of the footings, comprehensive finite element analyses were executed on both footing configurations employing GGV types of geogrids, with an inter-geogrid spacing of ( $h=1.5\text{m}$ ), a total of four geogrids ( $N=4$ ), and an extension length of geogrid ( $L=3B$  for square footings, specifically ( $2\text{m}\times 3\text{m}$  and  $2\text{m}\times 4\text{m}$ ), and  $L=2.5B$  for the ( $3\text{m}\times 4\text{m}$ ) rectangular footing, wherein  $B$  denotes the footing width. The embedment depths for the initial layers of reinforcement at ( $U=0.25B$ ,  $U=0.5B$ ,  $U=0.75B$ , and  $U=1B$ ) were taken into account for square and  $2\text{m}\times 3\text{m}$  and  $2\text{m}\times 4\text{m}$  rectangular footings, whereas ( $U=0.25B$ ,  $U=0.33B$ ,  $U=0.75B$ , and  $U=1B$ ) were considered for the  $3\text{m}\times 4\text{m}$  rectangular footing within the scope of this study. According to the findings derived from the finite element analysis, it was observed that the bearing capacity of the footings demonstrated an enhancement, while the rate of settlement exhibited a reduction up to  $U=0.5B$  for square,  $2\text{m}\times 3\text{m}$ , and  $2\text{m}\times 4\text{m}$  footings, and  $U=0.33B$  for  $3\text{m}\times 4\text{m}$  rectangular footings, subsequently followed by a decreased the bearing capacity and increased the settlement of all types of footing. This indicates that the values of  $0.5B$  and  $0.33B$  correspond to the optimal depths at which the bearing capacity is maximized and settlement is minimized for  $2\text{m}\times 2\text{m}$ ,  $2\text{m}\times 3\text{m}$ , and  $2\text{m}\times 4\text{m}$  footings, as well as for

the 3x4m footing, respectively. The pressure-settlement curve, the relation between the initial layers of reinforcement and the rate of change in bearing capacity, as well as BCR, the load-settlement relationship, and the rate of change in settlement for all categories of footing analyzed in this investigation, as illustrated in Figures 4.14, 4.15, 4.16, 4.17, and 4.18 for square and rectangular footings, respectively. The enhancement in the rate of bearing capacity result from the change in the depth of the primary geogrid layer can be quantified as (54.61%, 59.05%, 50.81%, 45.48%) for square, (52.88%, 56.52%, 48.49%, 39.99%, 48.49%, 39.99%) for the 2m x 3m, (51.91%, 55.95%, 46.05%, 35.42%) for the 2m x 4m, and (42.64%, 54.72%, 42.71%, 34.95%) for the 3m x 4m rectangular footing, while the reduction rate of settlement can be observed as (18.27%, 24.76%, 17.71%, 11.11%) for square, (24.55%, 27.71%, 24.29%, 18.88%) for the 2m x 3m, (32.60%, 34.75%, 31.43%, 25.77%) for the 2m x 4m, and (30.98%, 32.50%, 26.71%, 24.45%) for the 3m x 4m rectangular footing, respectively. The findings indicate a markedly superior increase in the bearing capacity and a reduction in settlement for the square footings when compared with the rectangular footing types encompassed in this study.

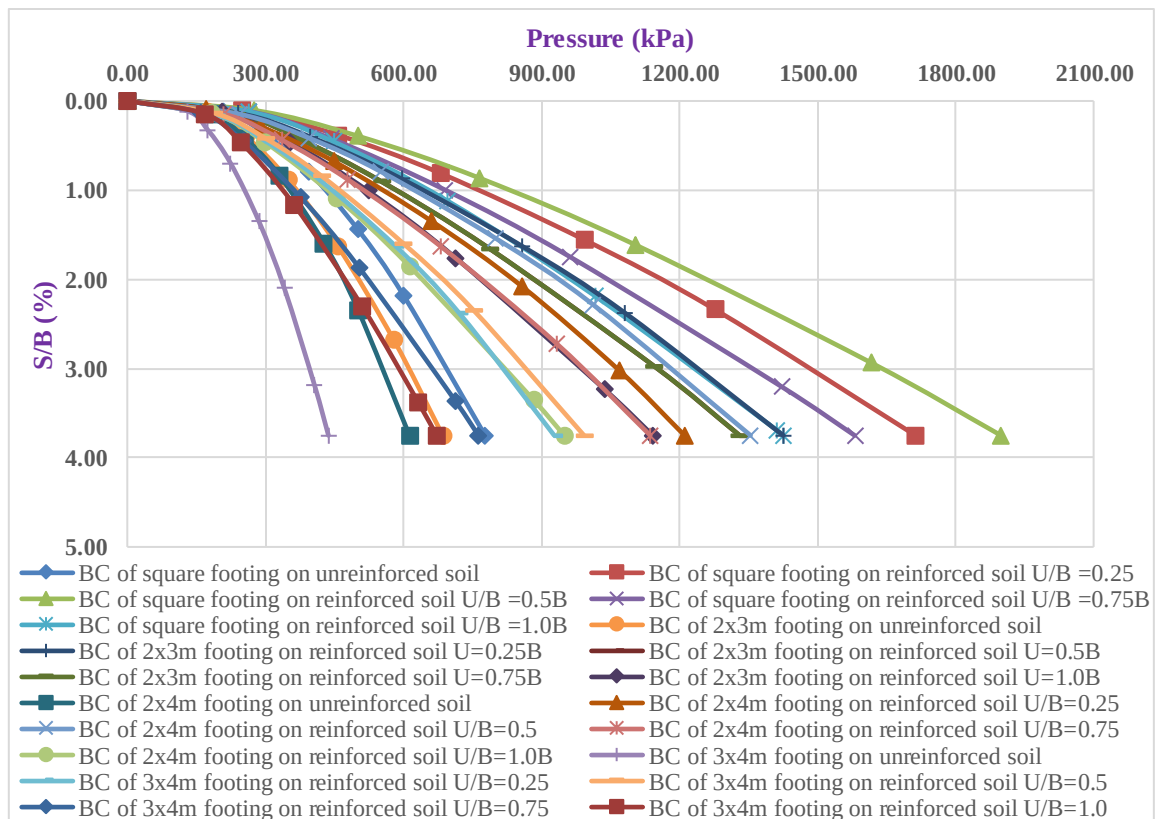


Figure 4.14: Effect of depth of first layer of reinforcement on the bearing capacity of square and rectangular footings

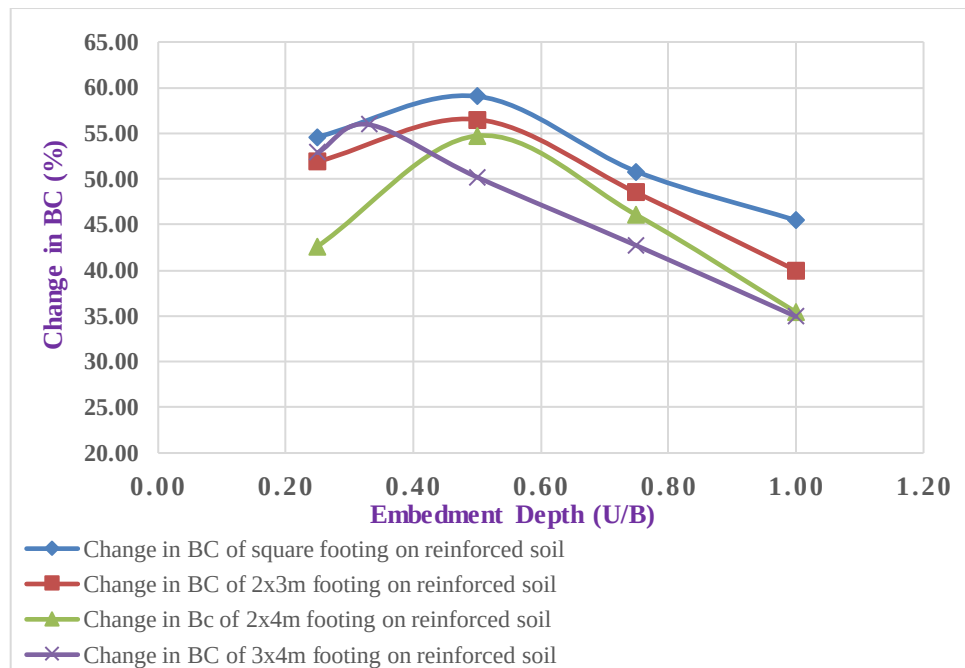


Figure 4.15: Effect of depth of the first layer of reinforcement on the change in bearing capacity of square and rectangular footings

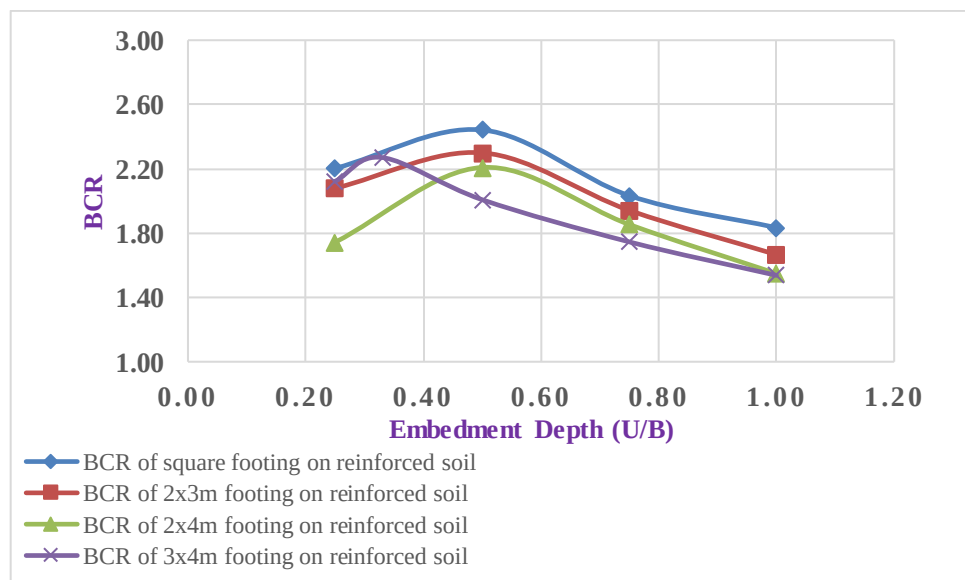


Figure 4.16: Effect of depth of the first layer of reinforcement on BCR of square and rectangular footings

## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

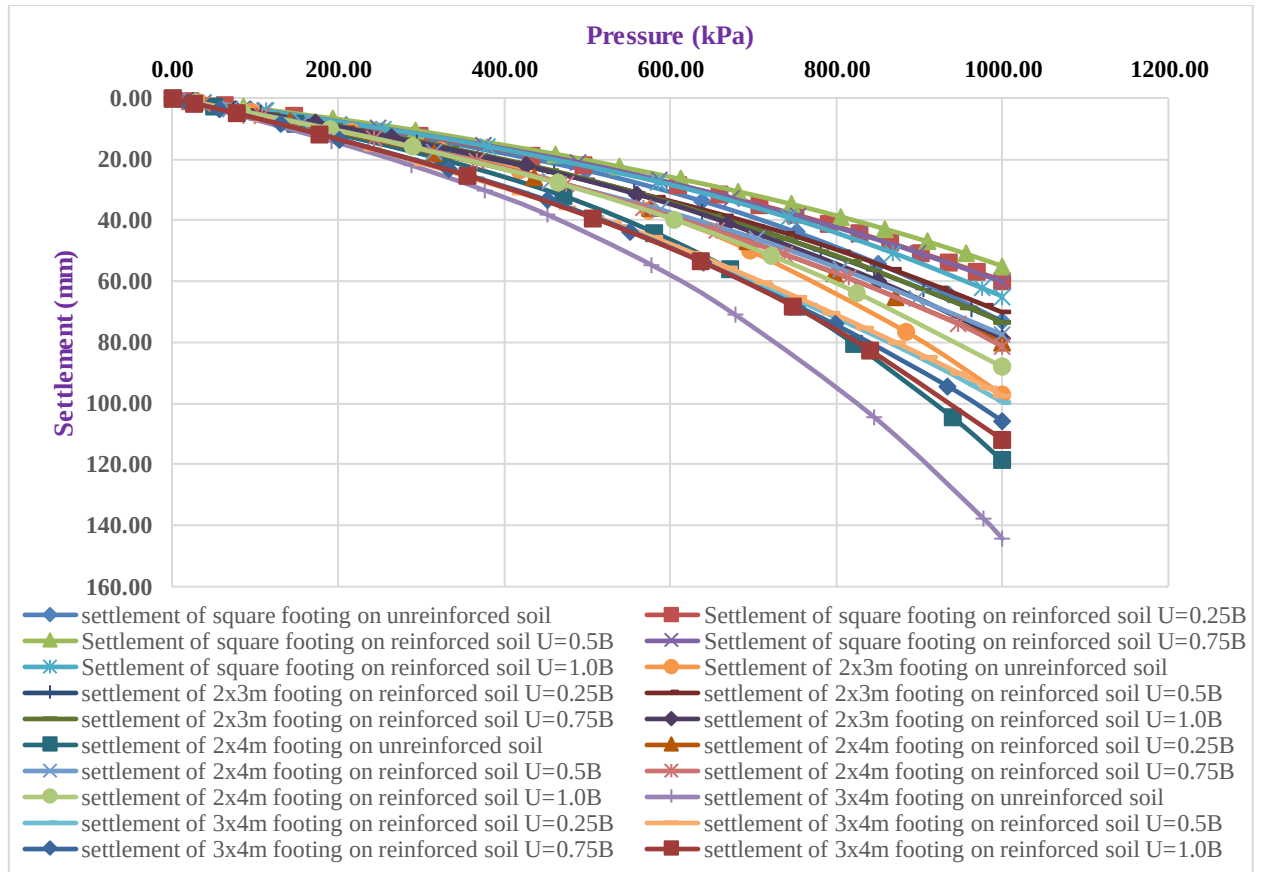


Figure 4.17: Effect of depth of first layers of reinforcement on the Settlement of square and rectangular footings

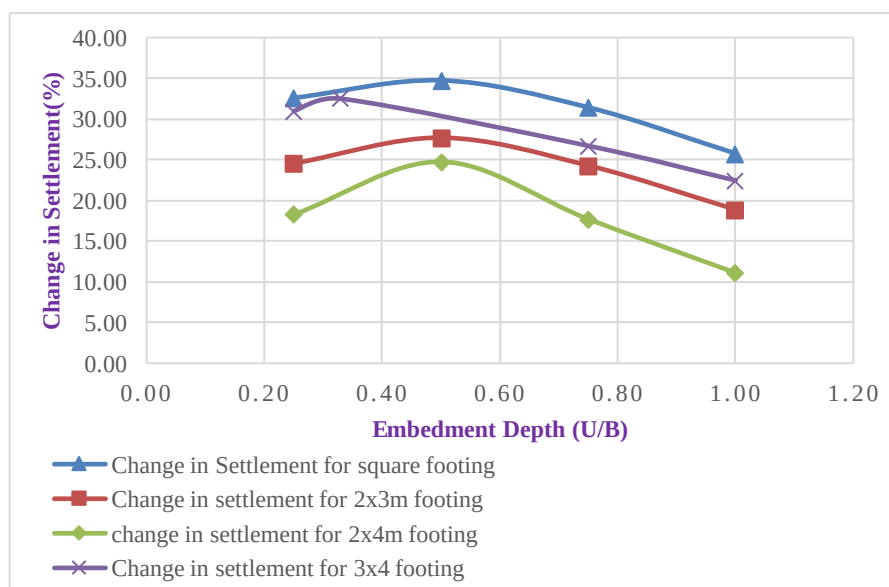


Figure 4.18: Effect of depth of the first layer of reinforcement on the change in the rate of settlement of square and rectangular footing.

#### **4.2.5. Effect of Length of Reinforcement**

Geogrid reinforcement constitutes a specific category of geosynthetic materials employed to enhance soil stability and augment its engineering characteristics. A principal advantage associated with the utilization of geogrids resides in their capacity to elevate the bearing capacity and reduce the settlement of expansive soils. Typically, an increase in the length of the geogrid correlates with a corresponding enhancement in bearing capacity and reduces the settlement of square and rectangular footings. The geogrid functions analogously to a tensile mesh, facilitating the distribution of loads over a more extensive soil area while simultaneously confining the soil mass. This mechanism mitigates stress concentration on the underlying soil, thereby permitting greater loads to be sustained before failure. It is important to recognize that there exists a threshold beyond which prolonging the geogrid length yields negligible additional advantages. The geogrid must engage effectively with the soil to fulfill its reinforcing role. Extending the geogrid beyond the influence zone pertinent to soil mechanics is unlikely to yield significant improvements in bearing capacity and settlement reduction. A series of finite element analyses were conducted on square footings by varying the geogrid extension lengths ( $L=1.5B$ ,  $L=2B$ ,  $L=2.5B$ ,  $L=3B$ , and  $L=3.5B$ ), as well as for rectangular footings ( $L=2B$ ,  $L=2.5B$ ,  $L=3B$ , &  $L=3.5B$ ) at a constant spacing  $H=1.5m$ , geogrid type GGV, and four layers of geogrids. The comprehensive analysis demonstrated that the bearing capacity, the bearing capacity ratio, and the rate of enhancement in bearing capacity increase until a reinforcement extension length of  $L=3B$  for square,  $2m \times 3m$ , and  $2m \times 4m$  rectangular footings, and  $L=2.5B$  for the  $3m \times 4m$  rectangular footing, after which a decline is observed; conversely, the settlement of both square and rectangular footings decreases up to the optimal length, subsequently exhibiting an increment. The result of the analysis is shown in the subsequent Figures 4.19, 4.20, 4.21, 4.22, and 4.23 for square and rectangular footings, respectively. The change in rate of BC and rate of settlement of footing can be (56.14%, 60.10%, 62.32%, 58.86%) for square, (47.94%, 49.92%, 51.30%, 48.35%) for  $2m \times 3m$ , (44.21%, 48.01%, 50.20%, 48.22%) for  $2m \times 4m$ , and (49.70%, 52.60%, 52.74%, 51.91%) for  $3m \times 4m$  rectangular, and (28.00%, 30.84%, 32.87%, 34.14%, 30.88%) for square, (19.20%, 22.11%, 25.26%, 27.59%, 24.35%) for  $2 \times 3m$ , (25.78%, 27.35%, 27.78%, 30.00%, 27.95%) for  $2 \times 4m$ , (28.64%, 32.14%, 31.07%, 27.95%) for  $3 \times 4m$  rectangular footings respectively. The increase in bearing capacity and the rate of settlement reduction for square footings is high when compared with the other types of rectangular footings analyzed in this study.

## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

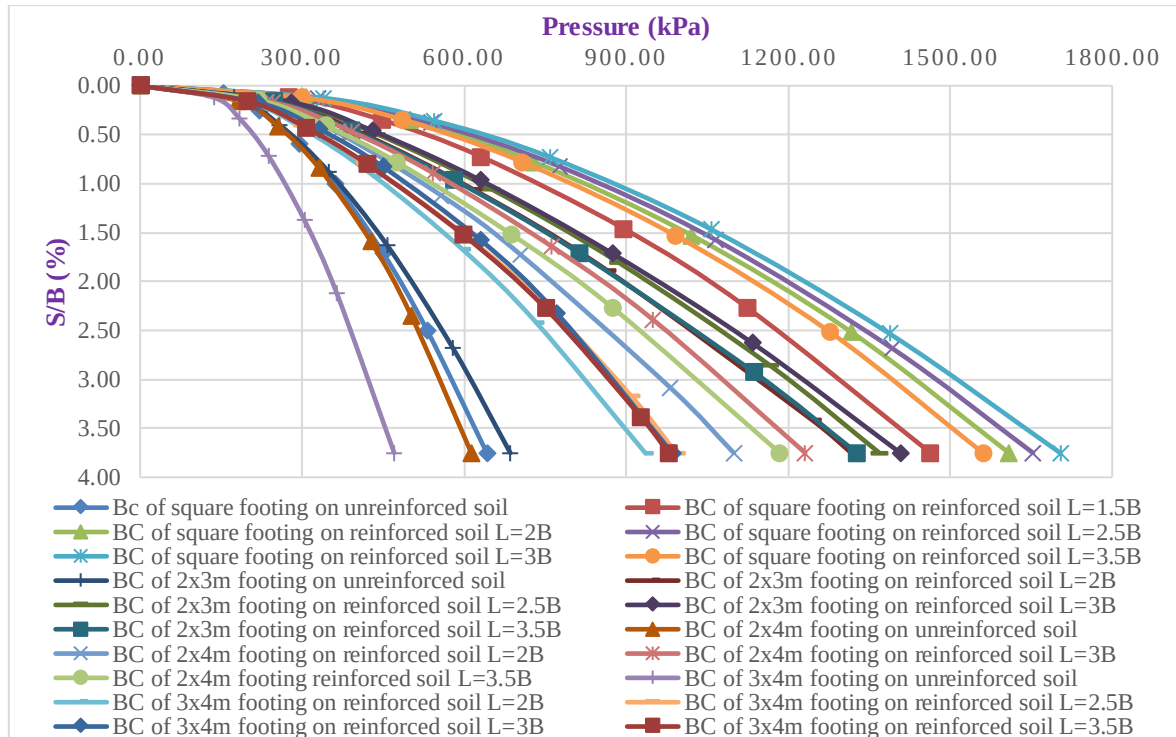


Figure 4.19: Effect of Length of Reinforcement on the Bearing Capacity of square and rectangular footings

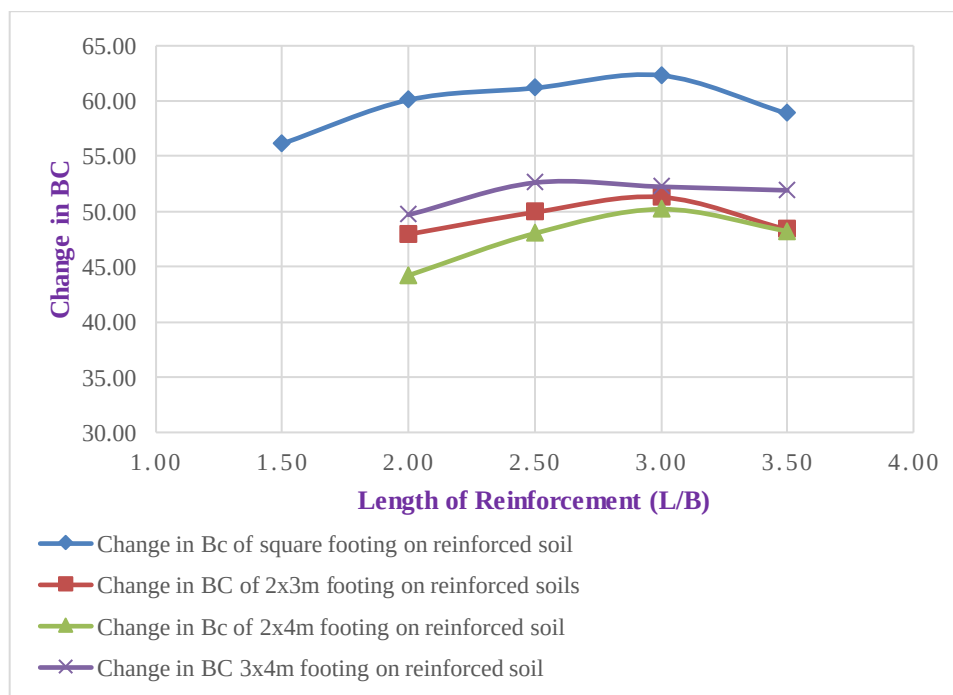


Figure 4.20: Effect of length of reinforcement on change in rate of BC of square and rectangular footings

## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

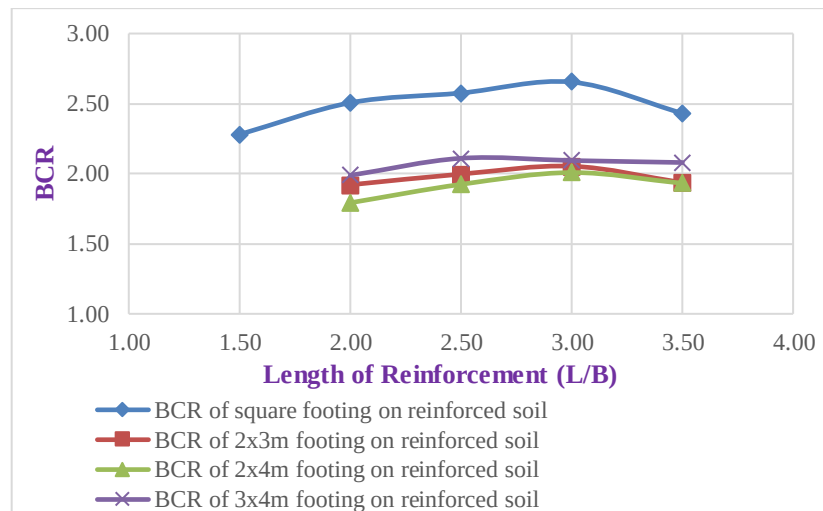


Figure 4.21: Effect of length of reinforcement on the BCR of square and rectangular footings

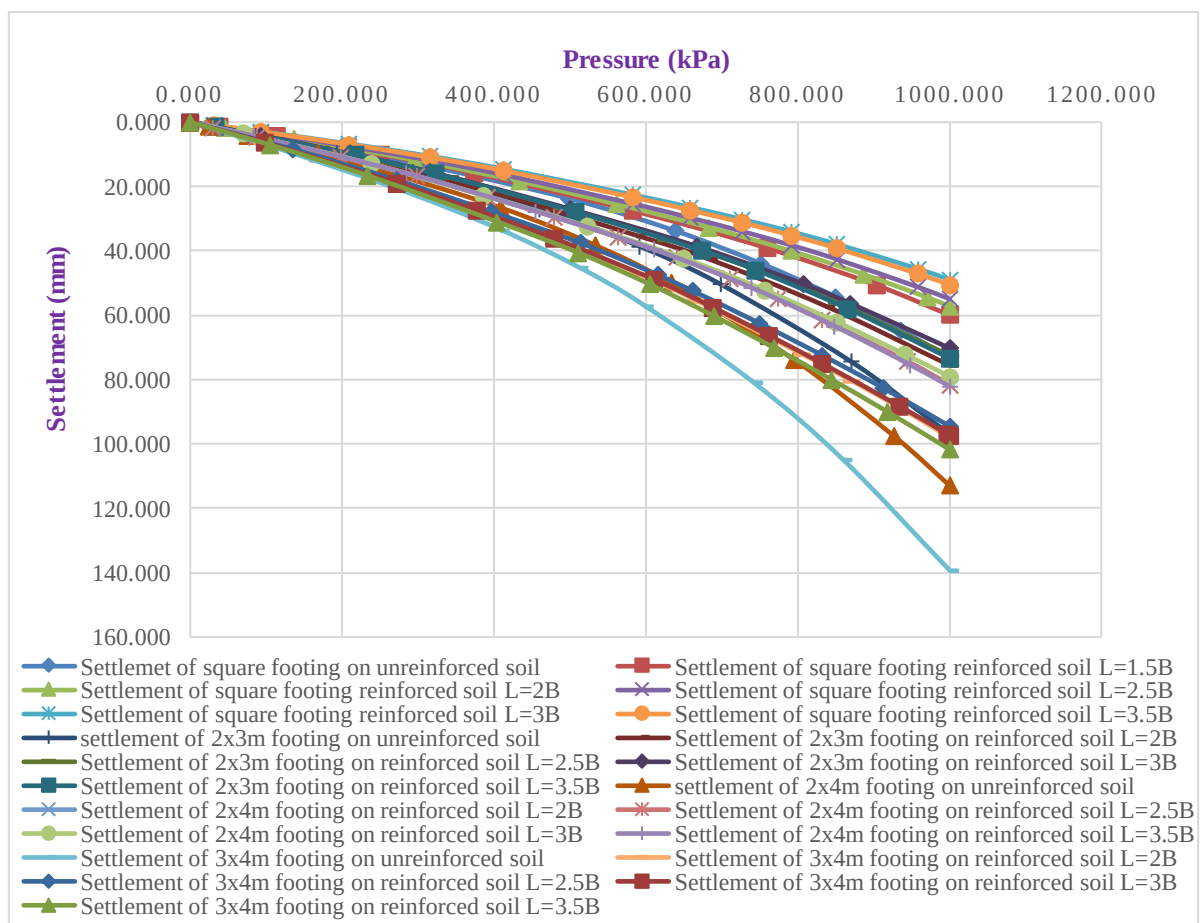


Figure 4.22: Effect of extension length of geogrid on the settlement of square and rectangular footing

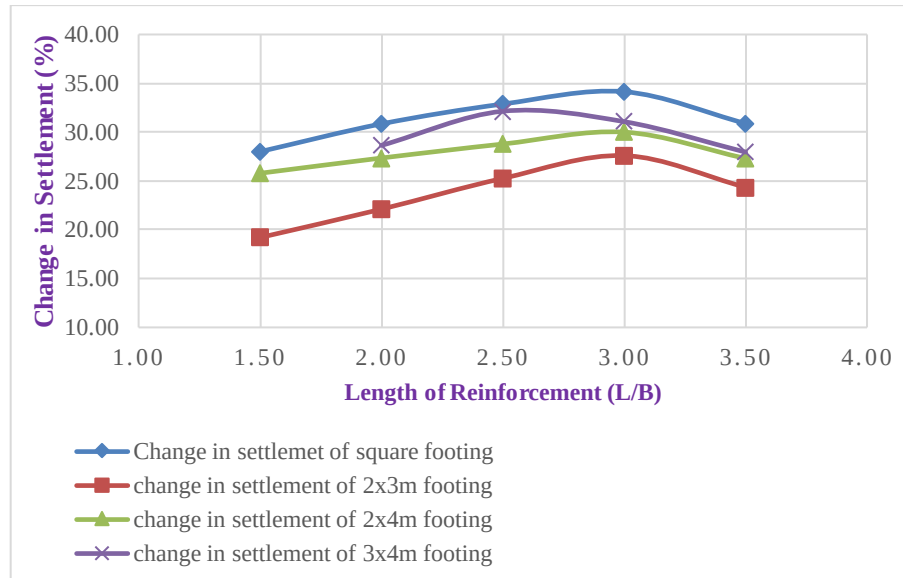


Figure 4.23: Effect of length of reinforcement on the change in settlement of square and rectangular footing.

#### 4.2.6. Effect of Number of Layers of Reinforcement

The incorporation of additional layers of geogrids within a shallow foundation situated on expansive soils has demonstrated a multi-layered impact on its operational efficiency. A singular layer: provides a constrained interaction with the soil, which may conclude in a moderate bearing capacity. Such a capacity could suffice for structures of reduced mass or minimal design loads. Multiple layers: facilitate the mobilization of an increased soil volume due to enhanced confinement, thereby yielding an elevated bearing capacity. This enhancement permits the accommodation of more substantial structures or increased design loads while minimizing the foundation's spatial footprint. A series of finite element analyses were conducted on both square and rectangular footings by varying the number of geogrid layers positioned beneath the foundation footprint. The vertical interval between geogrids employed for this investigation is established at ( $h = 1.50\text{m}$ ), with the depth of the initial geogrid layer from the foundation base specified as ( $U=0.50B$ ) were used for square, 2x3m, and 2x4m and ( $U=0.33B$ ) for 3mx4m rectangular footings, respectively. The increment of the number of reinforcement layers typically results in an increment of the bearing capacity and a significant decrement of settlement of both square and rectangular footing. The bearing capacity, bearing capacity ratio, rate of change in settlement, and load settlement for both footing configurations, as illustrated in Figures 4.24, 4.25, 4.26, 4.27, and 4.28. The alteration in the rate of bearing capacity and rate of change in settlement attributable to the

## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

number of reinforcement layers can be quantified as (27.41%, 44.66%, 52.07%, 53.33%, 54.57%) for square footings, (25.31%, 38.62%, 46.92%, 48.94%, 50.91%) for the 2mx3m rectangular footing, (23.28%, 38.16%, 46.27%, 48.83%, 50.20%) for the 2mx4m rectangular footing, (20.08%, 36.36%, 45.00%, 47.05%, 49.70%) for the 3mx4m, and (21.37%, 28.17%, 31.63%, 38.48%) for square, (17.56%, 23.24%, 26.92%, 28.95%) for 2x3m, (21.37%, 27.49%, 29.41%, 37.00%) for 2x4m, (19.49%, 25.03%, 28.56%, 35.30%) for 3x4m rectangular footing. A significant enhancement in the bearing capacity and settlement reduction of square footings is high when compared with the other rectangular footing types assessed in the study.

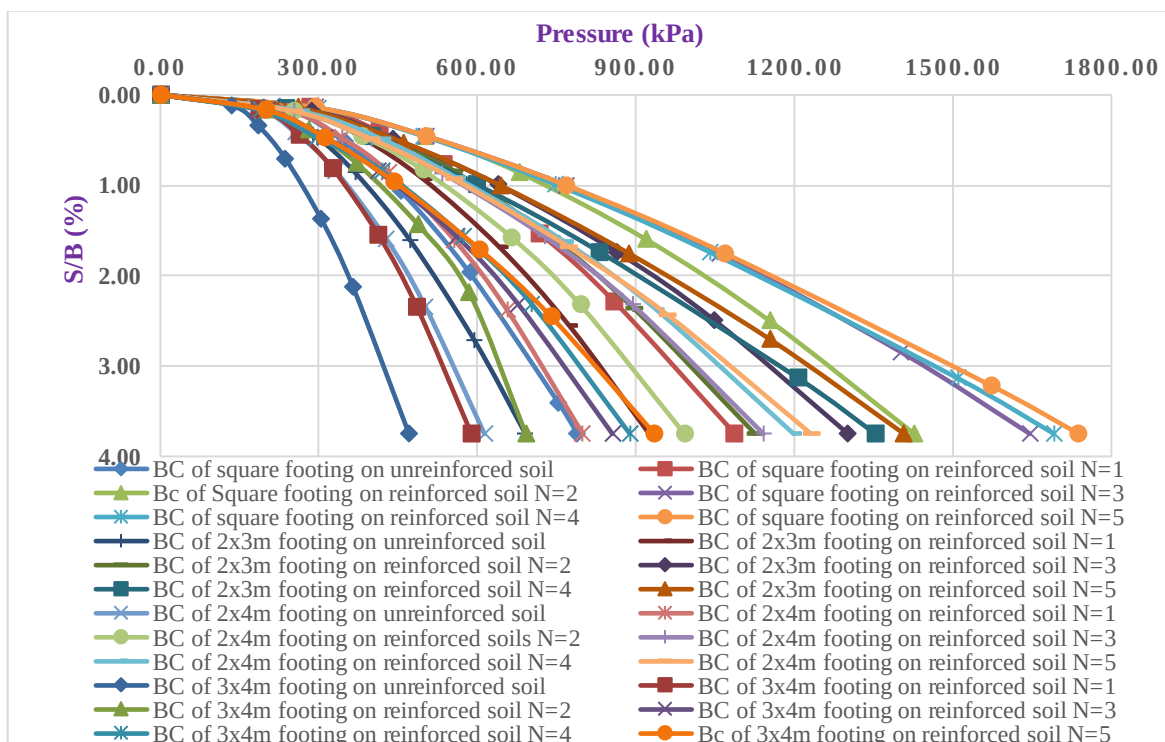


Figure 4.24: Effect of the number of reinforcement layers on the bearing capacity of square and rectangular footing

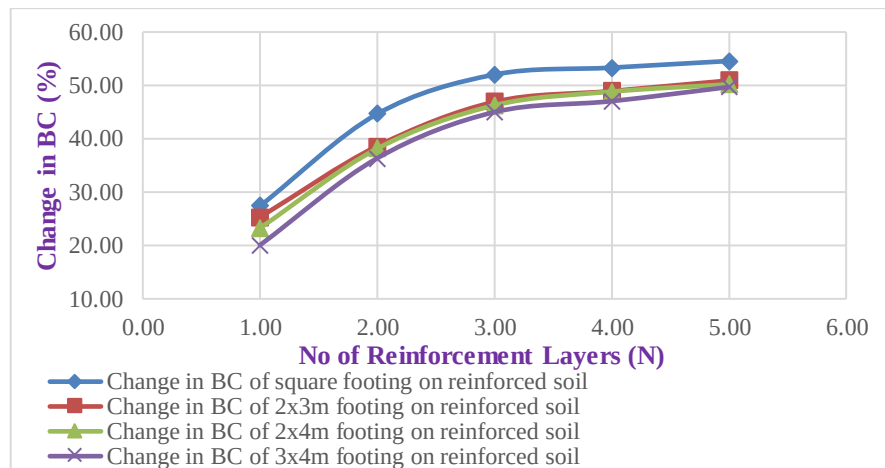


Figure 4.25: Effect of the number of reinforcement layers on change in the rate of BC of square rectangular footings

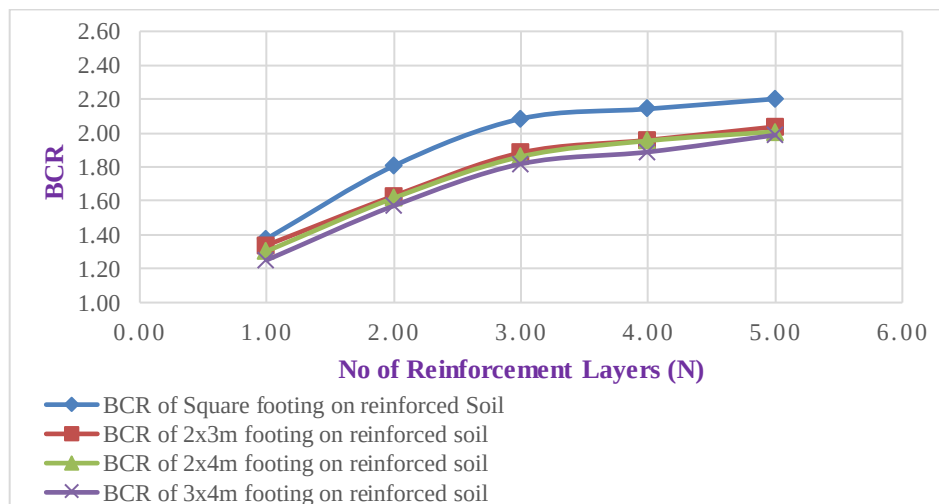


Figure 4.26: Effect of Number of reinforcement layers on BCR of square and rectangular footings

## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

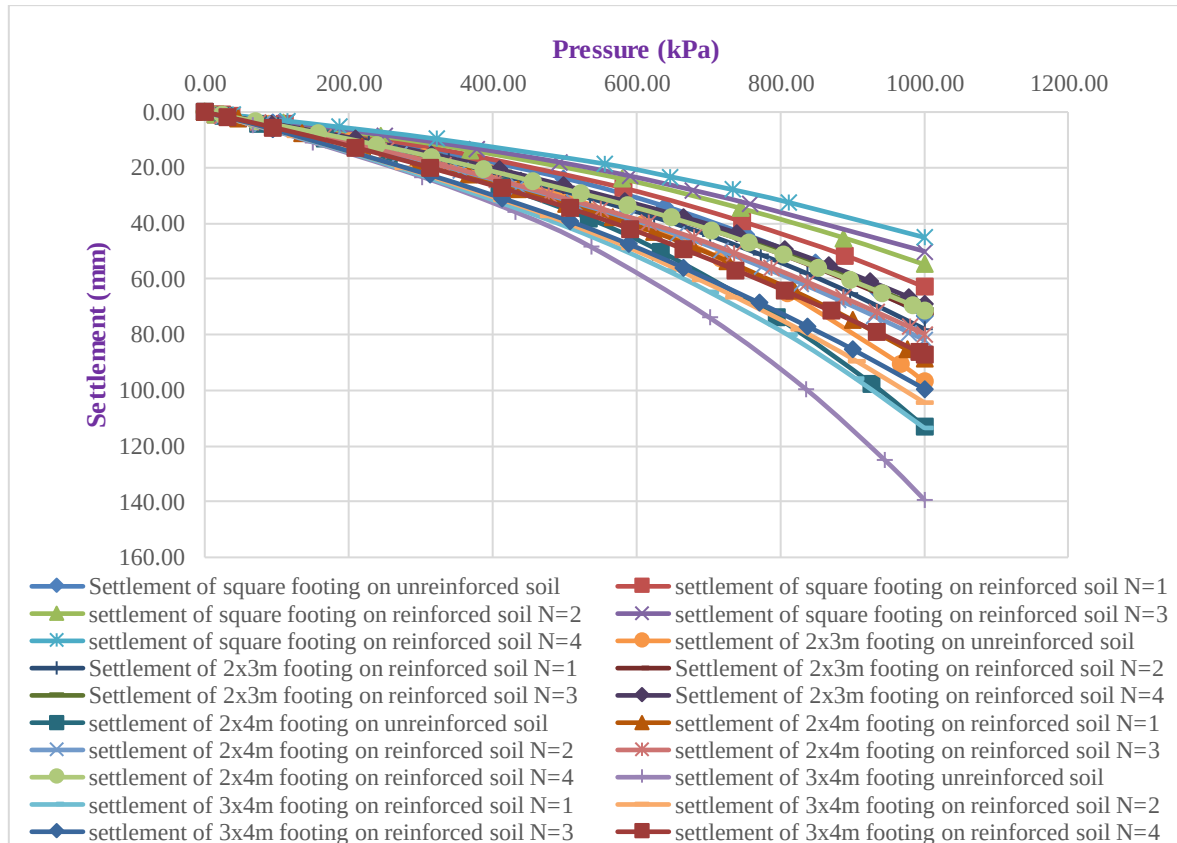


Figure 4.27: Effect of the number of reinforcement layers on settlement of square and rectangular footings

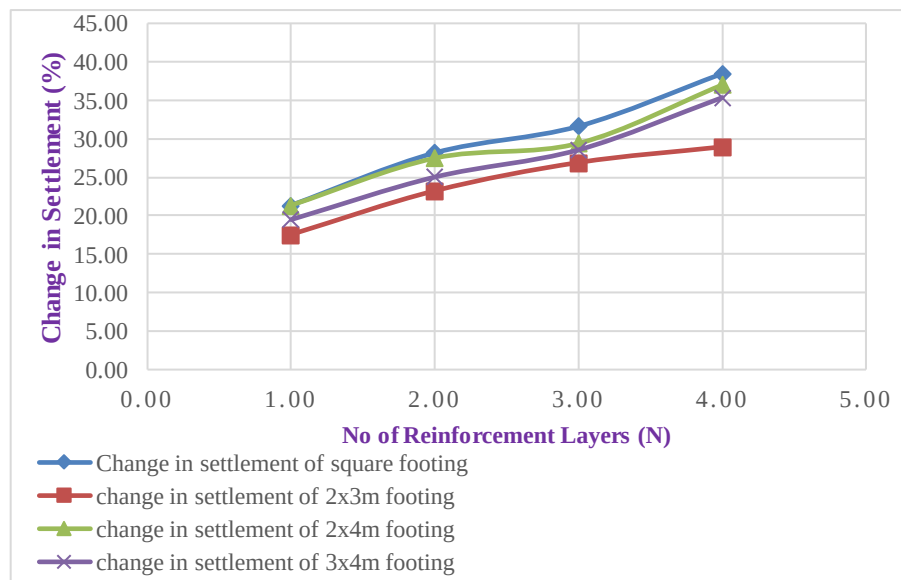


Figure 4.28: Effect of the number of reinforcement layers on change in the rate of settlement of square and rectangular footing

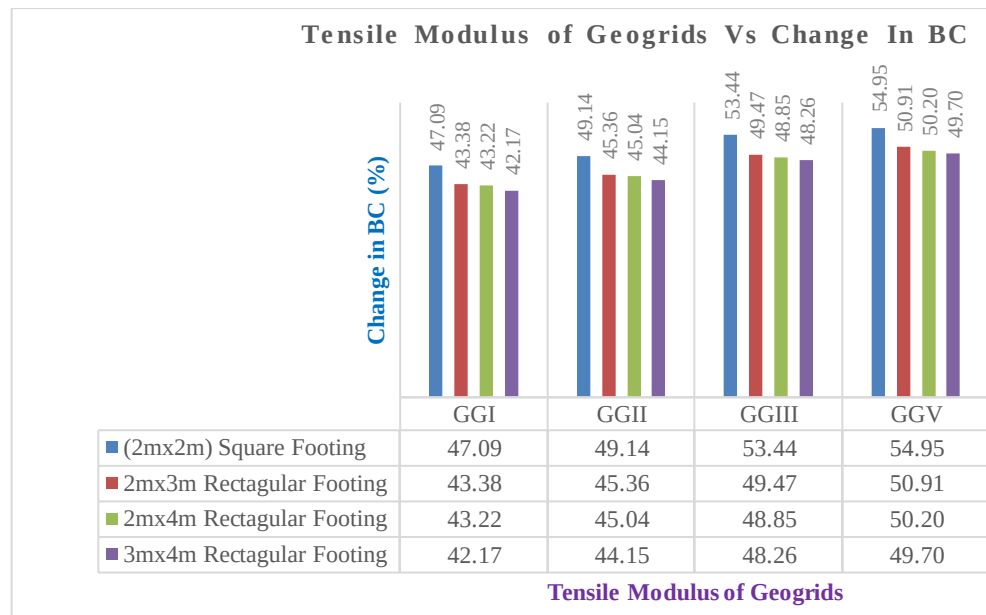


Figure 4.29: Effect of tensile modulus of reinforcement on change in bearing capacity of square and rectangular footing

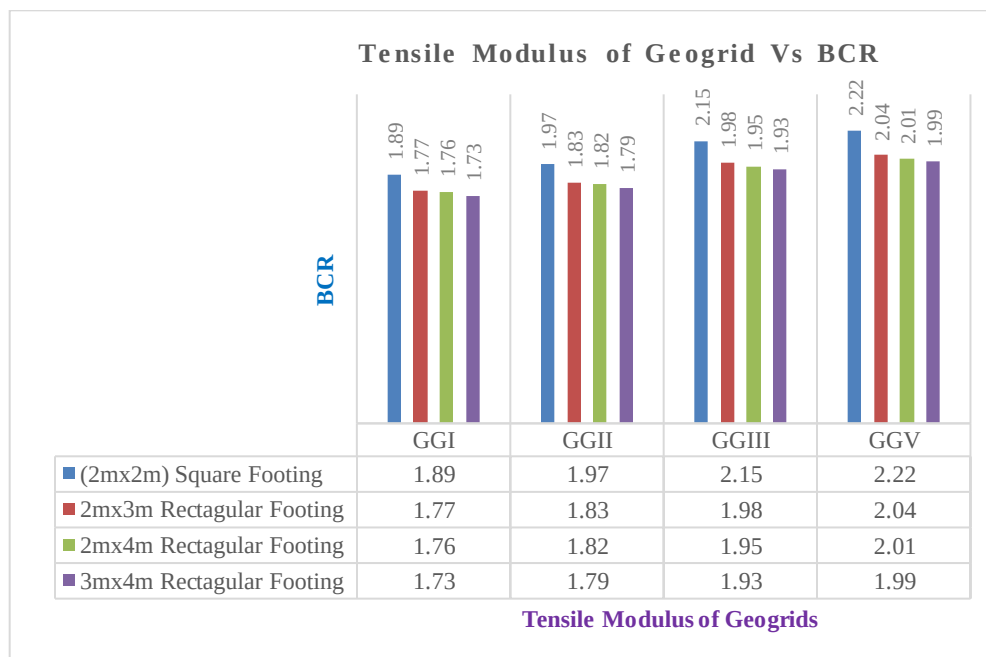


Figure 4.30: Effect of tensile modulus of reinforcement on BCR of square and rectangular footing

## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

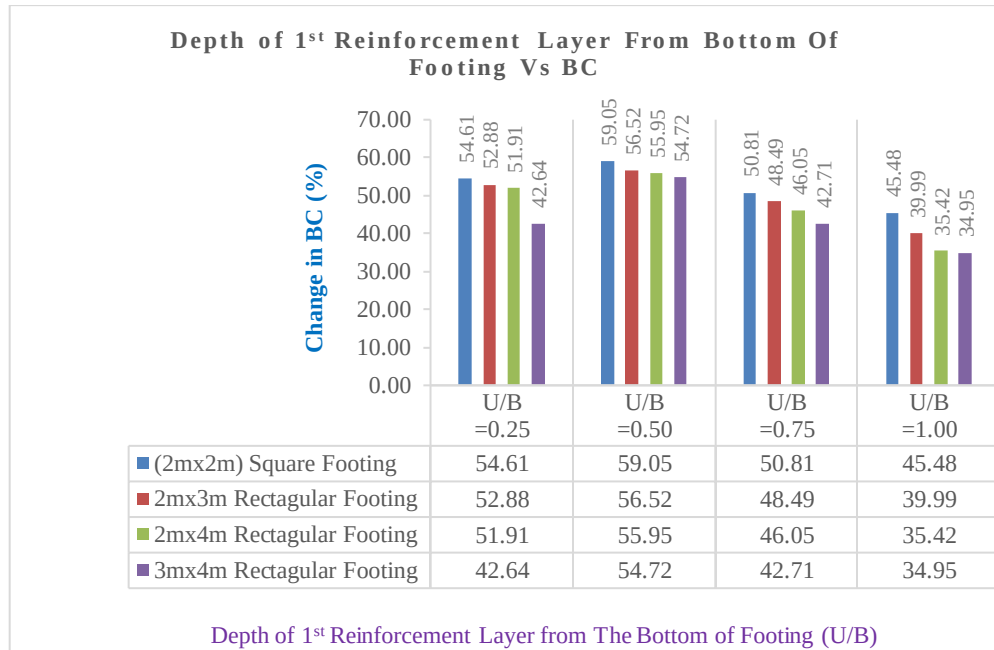


Figure 4.31: Effect of depth of first geogrid layers on change in bearing capacity of square and rectangular footing.

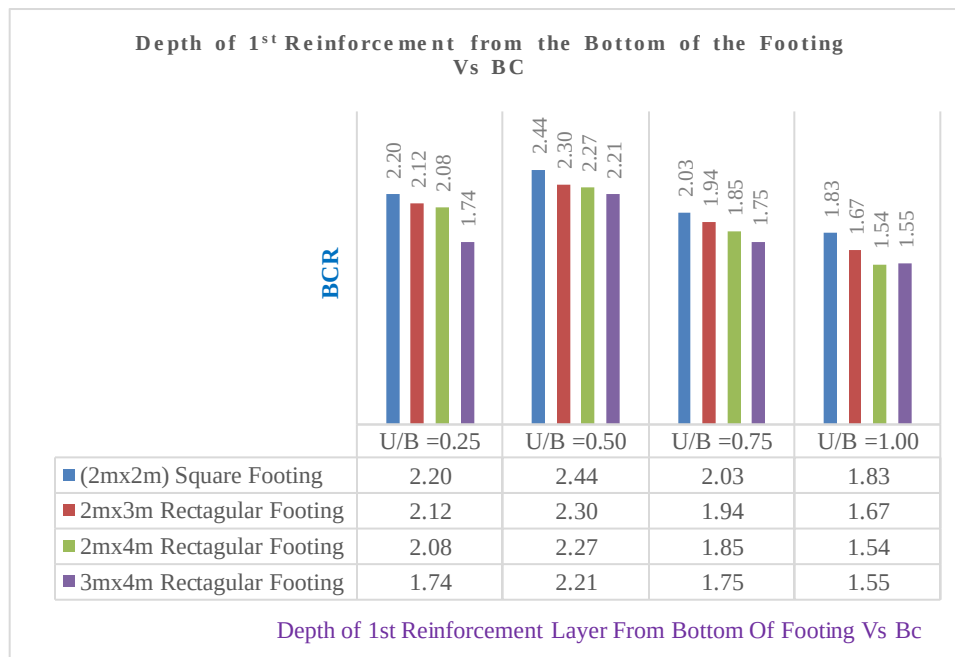


Figure 4.32: Effect of depth of first reinforcement layers on BCR of square and rectangular foundation

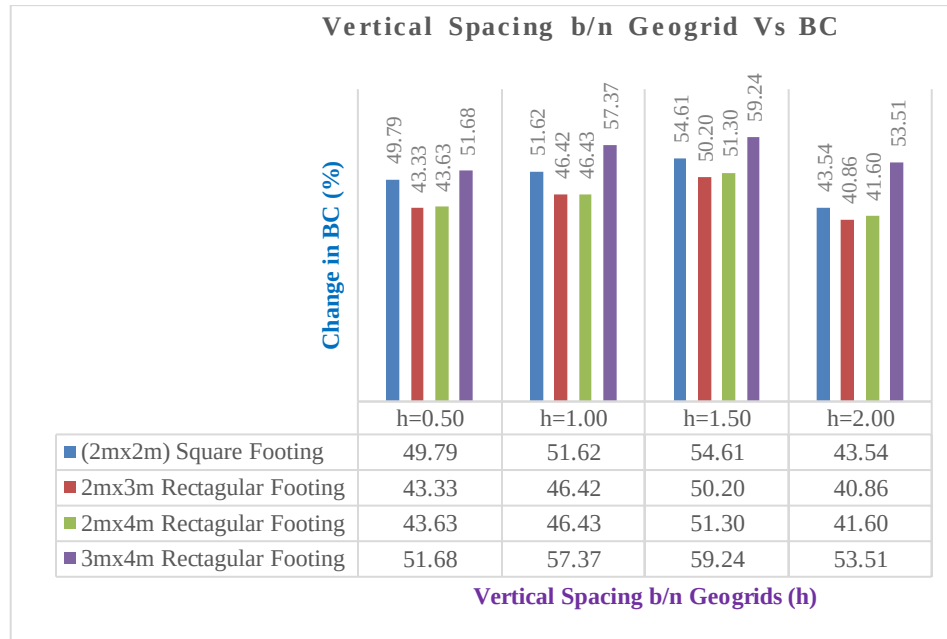


Figure 4.33: Effect of vertical spacing between geogrid layers on change in bearing capacity of square and rectangular footing.

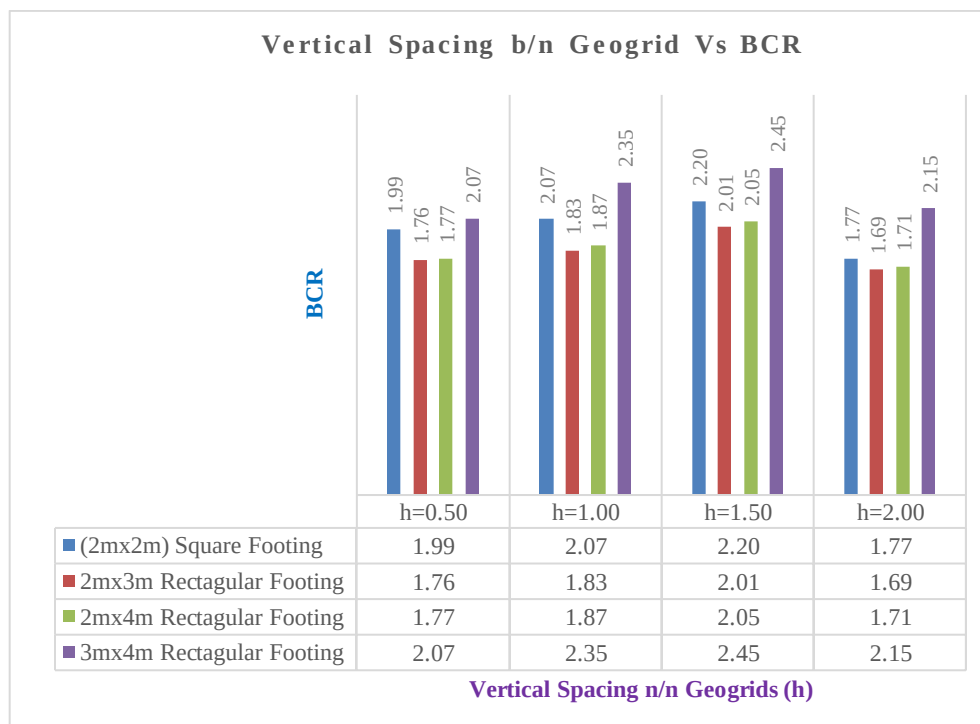


Figure 4.34: Effect of vertical spacing between reinforcement layers on BCR of square and rectangular footing

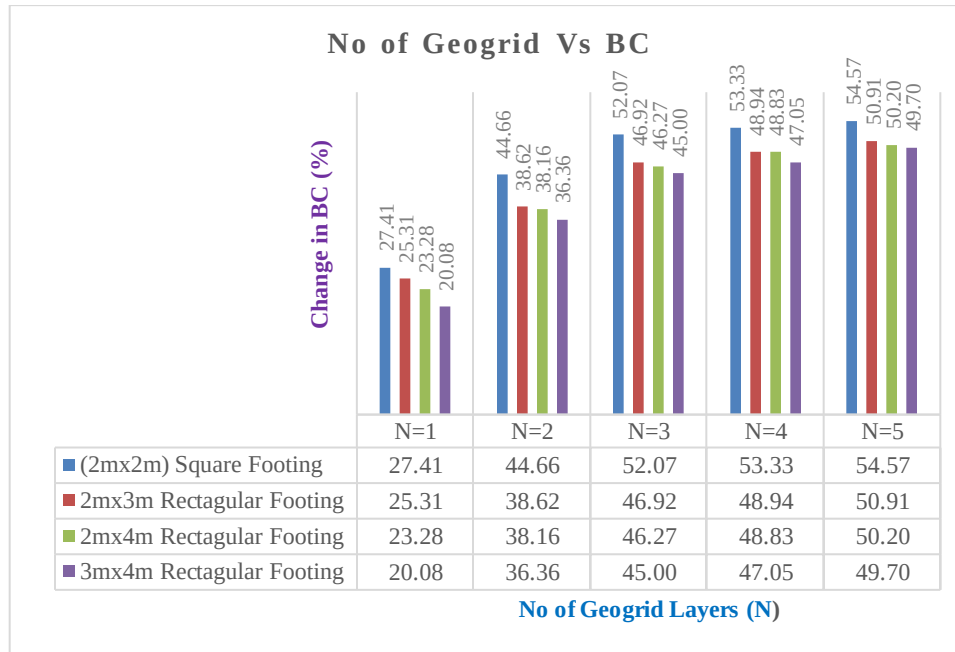


Figure 4.35: Effect of the number of reinforcement layers on change in BC of square and rectangular footings

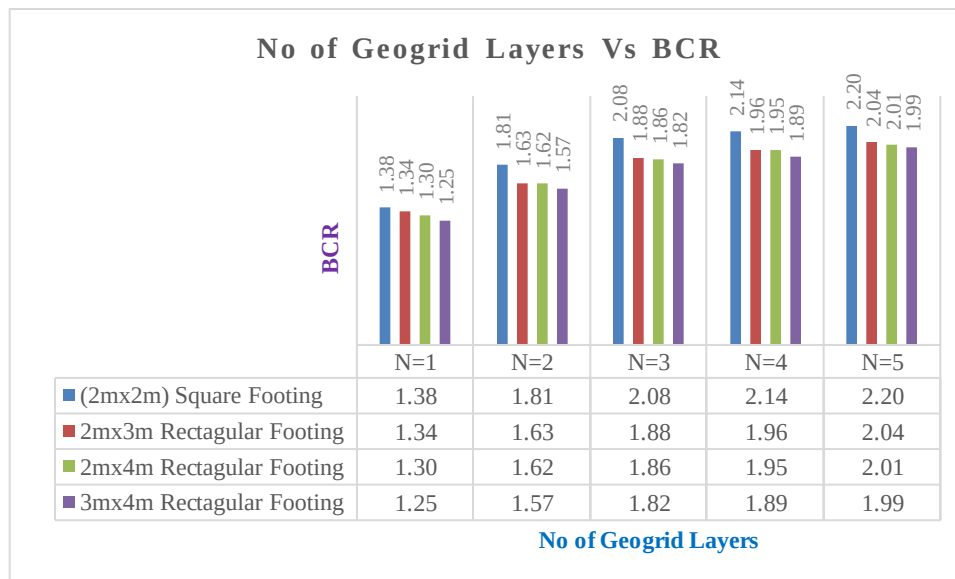


Figure 4.36: Effect of number of reinforcement layers on BCR of square and rectangular footings

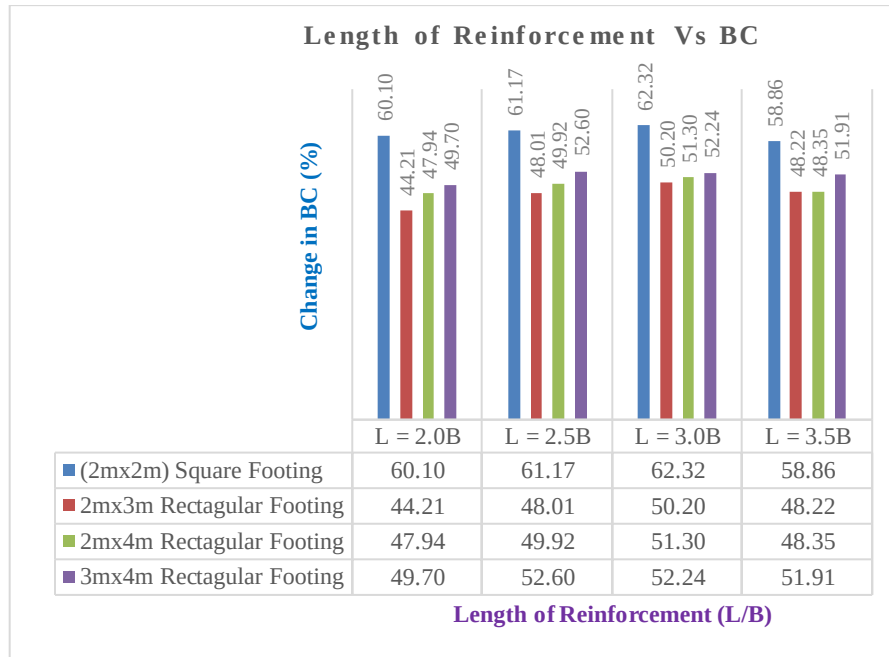


Figure 4.37: Effect of length of reinforcement on change in BC of square and rectangular footings

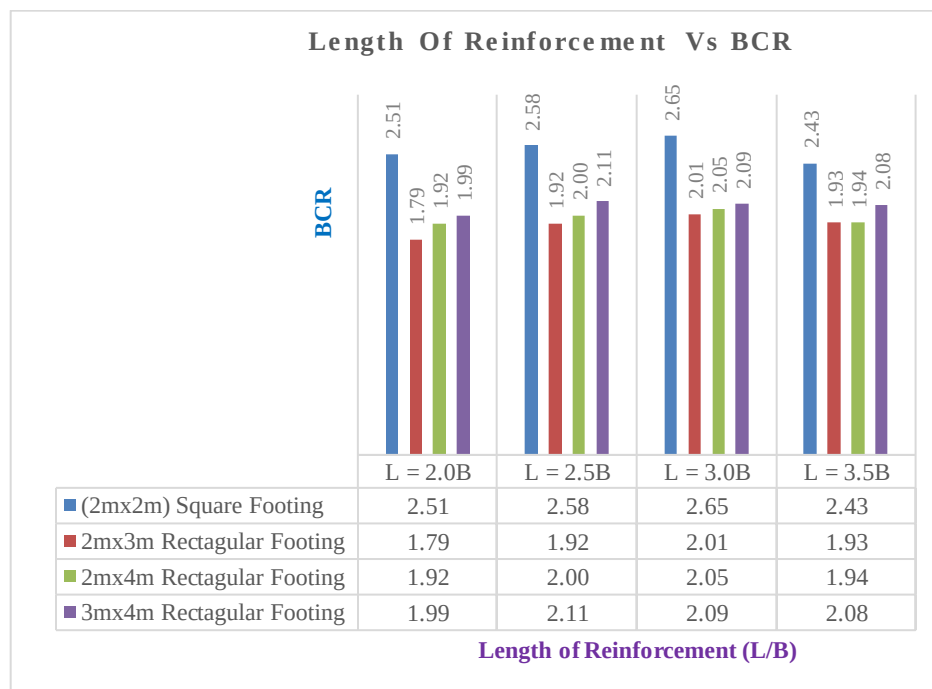


Figure 4.38: Effect of length of reinforcement on BCR of square and rectangular footings

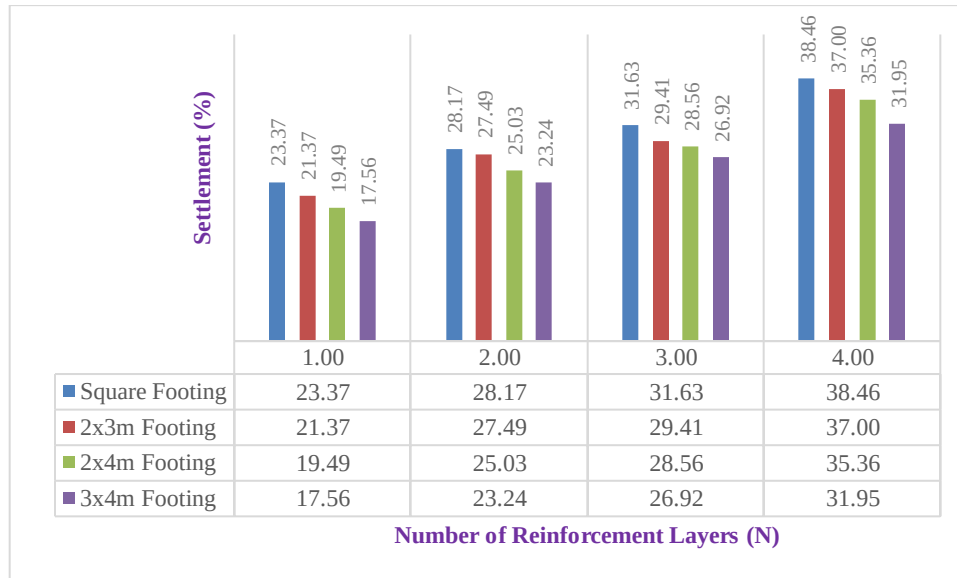


Figure 4.39: Effects of the number of reinforcement layers on settlement of square and rectangular footing

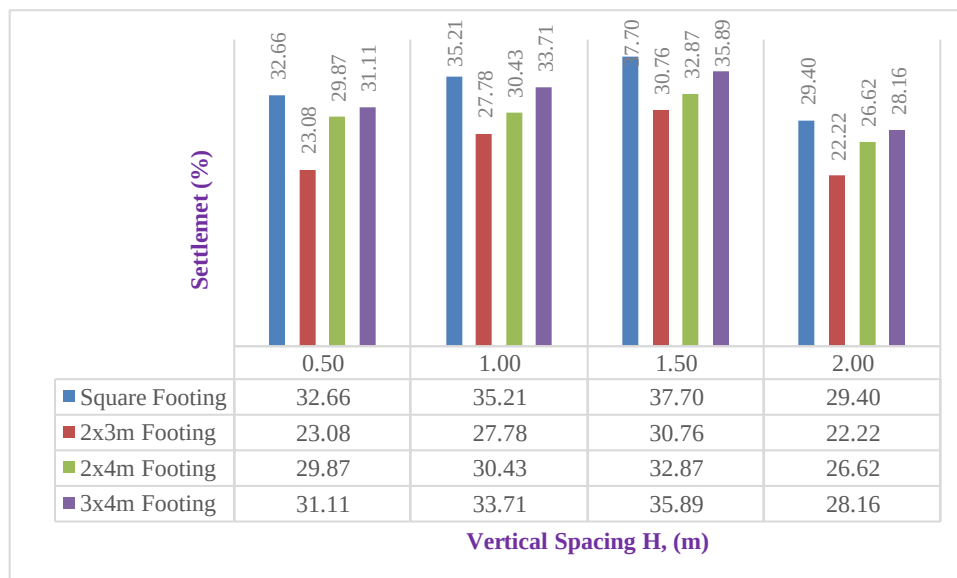


Figure 4.40: Effects of vertical spacing between reinforcement layers on settlement of square and rectangular footing

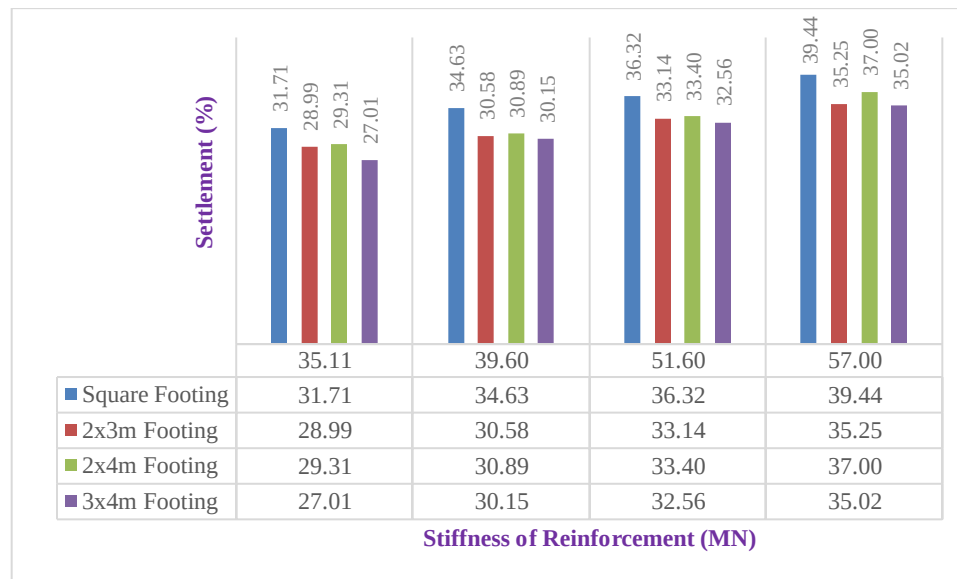


Figure 4.41: Effects of stiffness of reinforcement layers on settlement of square and rectangular footing

#### 4.3. Validation of Finite Element Analysis: Building Trust in the Simulation

Finite Element Analysis (FEA) represents a sophisticated engineering methodology employed to simulate the behavior of soil constituents under different loading and boundary conditions. Nonetheless, the precision of the FEA outcomes is liable upon a pivotal procedure. Validation determines that the FEA model accurately expresses real-world conditions, rendering the results reliable for informed design decisions. To verify the bearing capacity of the selected material models relating to the soil, footings, geogrids, geogrid-soil interaction, and footings-soil interaction, finite element analyses were initially compared with empirical data derived from laboratory model tests for geogrid-reinforced granular soil beds utilized in shallow foundation applications, as documented by (Beshoy M. Hakeem, 2022). The experimental model employed in the laboratory comprised steel plates with a circular footing featuring a diameter of 100 mm and a thickness of 10 mm, while the model test was conducted within a steel tank measuring 0.6m in length, 0.6m in width, and 0.6m in depth. The geogrid utilized possessed an equivalent mesh thickness of 5.2 mm and an elastic modulus of 320,000 kPa. Figures 4.39 and 4.40 illustrate comparing the finite element analyses and the laboratory model tests concerning unreinforced and two-layer geogrid-reinforced shallow foundations on granular soil beds.

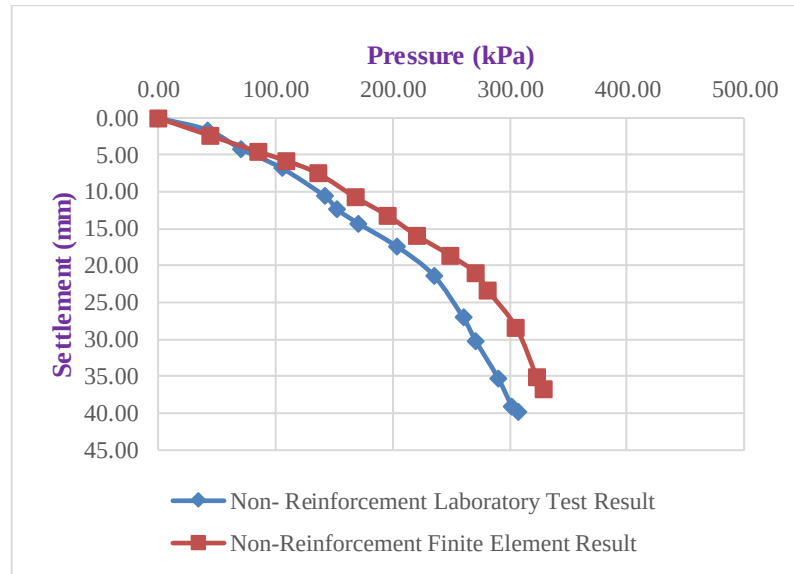


Figure 4.42: the comparison between the finite element analyses and the laboratory model tests for unreinforced soil

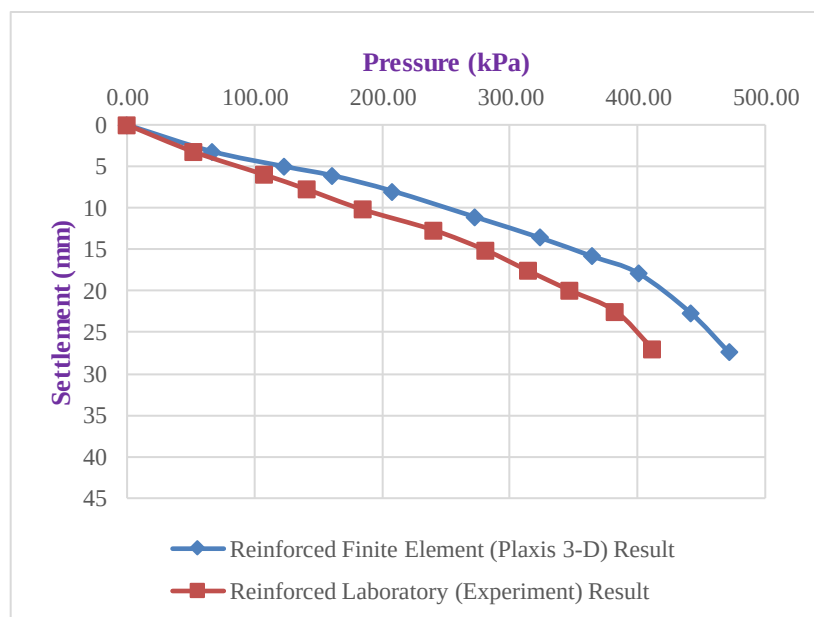


Figure 4.43: the comparison between the finite element analyses and the laboratory model tests for reinforced soil

The results of the analysis indicate that the finite element analysis conducted with (PLAXIS 3-D) demonstrates a satisfactory correlation with the results of model tests, although certain discrepancies between the two are less pronounced in proximity to the bearing pressure and settlement of soil. Consequently, the established finite element model may be employed with confidence in the parametric investigation aimed at assessing the influence of various

factors, including the tensile modulus of reinforcement, the length of the reinforcement, the vertical spacing of successive reinforcement layers, the embedment depth of the first reinforcement layers from the base of the footing, and the number of reinforcement layers on the bearing capacity and settlement of square and rectangular footing situated on expansive soils.

#### **4.4. Discussion and Comparing Results with Literature**

Three-dimensional finite element analysis was performed using PLAXIS 3-D connect edition v20 update 4 to investigate the influence of the study parameters on the bearing capacity and settlement of both square and rectangular footing resting on expansive soils. Square and rectangular footing on expansive soils were simulated using PLAXIS 3-D with different tensile modulus of reinforcement, vertical spacing between consecutive layers of reinforcement, embedment depth of 1<sup>st</sup> reinforcement layers from the bottom of the footing, extension length of reinforcement relative to the footing width, and number of reinforcement layers to determine the bearing capacity, settlement, bearing capacity ratio, rate of change in bearing capacity, and rate of settlement of square and rectangular footing resting on expansive soils were analyzed. The study mainly focused on the bearing capacity and settlement of both rectangular and square footing on weak soils is usually governed by bearing capacity and settlement scenarios

As clearly illustrated before the performance of geogrid-reinforced expansive soil concerning bearing capacity, change in the rate of bearing capacity, and bearing capacity ratio, shows a significant increment but the settlement and rate of change in settlement shows a significant decrement. It was demonstrated that there is also a significant increment in bearing capacity and decrement in settlement of the ground is reinforced with the convenient combination of geogrid reinforcement. The bearing capacity of reinforced expansive soil was increased by more than 40% and the settlement decreased by more than 25% for all types of square and rectangular footing included in this study than unreinforced soil.

Reinforcement in expansive soil can be used to increase the bearing capacity, bearing capacity ratio, and rate of change in bearing capacity but decrease the settlement and rate of settlement of both square and rectangular footings. The increment in bearing capacity and decrement of settlement were obtained as a function of the shear strength and depth of the soft clay layer. The geogrid reinforcement significantly increases the bearing capacity of the foundation or increases the nondimensional parameters called bearing capacity ratio and

reduces the overall settlement of the foundations (Braja M. Das, 2017). Geogrid reinforcement increases the bearing capacity and reduces the settlement of both foundation soil and soil under flexible pavement (Jie Gu, 2011). The bearing capacity of granular soil bed increases, but reduces the settlement due to geogrid reinforcement under square footing (Beshoy M. Hakeem, 2022). The bearing capacity and settlement of footing on soft clay were improved by geogrid reinforcement embedded in granular fill material under footing (Mustafa Laman et.al, 2022).

The ultimate bearing capacity of the reinforced soil footing increased as the number of reinforcement layers within the zone of influence and geogrids stiffness increased and for a single-layer reinforced soil the optimum depth ratio ( $u/B$ ) at which the BCR was the highest was approximately 0.5 to 0.6, although, for the multilayer reinforced soil, this ratio was approximately 0.3~0.4 (M. Y. Abu-Farsakh, et.al, 2004). The laboratory investigations were conducted on the performance of square footing resting on geogrid-reinforced clayey soils. The effects of top layer spacing of geogrid from the bottom of the footing, number of reinforcement layers, the vertical spacing of reinforcement, stiffness of geogrids, and types of reinforcement on the bearing capacity and settlement of square footing on clayey soils. The inclusion of reinforcement significantly improves the bearing capacity of the soils and decreases the settlement of the footing. With three or more reinforcement layers the settlement could be reduced by 50% and geogrids that have high stiffness have a large contribution to decreasing the footing settlement and vertical stiffness and increasing the bearing capacity of soil under footing (Chen, et. all, 2007).

locally produced geogrid material improves the strength of expansive subgrade soil and the use of geogrid reinforcement can significantly improve the bearing capacity and reduce the settlement of weak subgrade soil (Aga, 2021). Geogrid reinforcement increases the bearing capacity and reduces the settlement of subgrade soil, increases both soaked and unsoaked CBR of subgrade soil, and decreases the depth of pavement layers (V. Gayathri Devi, 2019). The bearing capacity of dunes improved under a strip shallow foundation by the inclusion of geogrid reinforcement and also decreased the rate of settlement (Sameh Abu El-Soud1 & Adel M. Belal, 2019).

The improvement of the bearing capacity and settlement of silty clay soil within the sand layer on the top was by placing geogrid reinforcement layers at different depths (P. K. Kolay,

et. al, 2013). The bearing capacity of sand soil was increased by providing one, two, and three layers of geogrids reinforcement by increasing the confinement and tensile properties of sand soil under shallow foundations (Mohammad Mahdi, et, al, 2021). The bearing capacity of foundations is one of the interesting subjects in geotechnical engineering. In many cases, constructing foundations on natural or artificial soil slopes to develop the infrastructures is controversial. The performance of shallow strip foundations constructed on the geosynthetic reinforced sand slope was increased by the inclusion of geogrid reinforcement (Javdanian. H, 2017).

Finite Element software (ABAQUS) was used to investigate the performance of strip foundations resting on geogrid-reinforced low to medium-plastic clay soils. By varying reinforcement depth, vertical spacing of consecutive geogrid layers, stiffness of geogrids, soil-geogrids interaction coefficient, top depth of first geogrid layers, embedment depth of footing and footing width and investigate the effects on bearing capacity and settlement of strip foundation. From the study vertical spacing, number of geogrid layers, normal stiffness, and coefficient of soil geogrid interaction increased bearing capacity ratio also increased but the settlement significantly decreased. But footing embedment depth and footing width increased both bearing capacity ratio and settlement decreased slightly (M.Y. Abu-Farsakh et. all, 2004). Numerical modeling includes various methods among them finite element (FEM), discrete element (DEM), and boundary element (BEM). Numerical modeling of the performance of shallow foundations on geogrid-reinforced expansive soils was investigated using PLAXIS 2D. The result shows that the bearing capacity of the footing improved and the settlement of the footing was reduced by the inclusion of geogrids reinforcement (Morteza Alemyparvin, 2020).

Mechanical stabilization of expansive subgrade soils with polypropylene fibers and geogrids is sustainable strength of expansive soils improved using polypropylene fibers and geogrids. The tensile strength capacity of expansive soils extensively increased very quickly using geogrids. The combined effect of geogrids and polypropylene fibers was evaluated on the strength of expansive soils with the conduction of different laboratory tests UCS, a large direct shear test was conducted and the combined effect of geogrids and polypropylene fibers increased the subgrade shear strength ranging from 3.8%-139.9% and easily treated the performance of expansive soils (N. Tiwari & N. Satyam, 2022).

## **CHAPTER FIVE**

### **CONCLUSIONS AND RECOMMENDATIONS**

#### **5.1. Conclusions**

Based on results obtained from the numerical investigation about the performance of square and rectangular footing placed on geogrid-reinforced expansive soils, the following conclusions are organized:

1. Groundwater increases pore water pressure, reducing effective stress and enhancing soil compressibility, which leads to greater settlement and lowers the bearing pressure of both square and rectangular footing under loads.
2. The performance of the reinforced soil exhibited an enhancement associated with the increase of the geogrid tensile modulus (or stiffness). The enhancement in load-bearing capacity was observed to be (47.09%, 49.14%, 53.44%, 54.95%) for square, (43.38%, 45.36%, 49.47%, 50.91%) for 2mx3m, (43.22%, 45.04%, 48.85%, 50.20%) for 2mx4m, (42.17%, 44.15%, 48.26%, 49.70%) for 3mx4m and the reduction of settlement to be (31.71%, 34.63%, 36.32%, 39.44%) for square (27.01%, 30.15%, 32.57%, 35.02%) for 2x3m, (29.31%, 30.89%, 33.40%, 37.00%) for 2x4m, and (20.99%, 30.58%, 33.14%, 35.25%) for 3x4m rectangular footings respectively.
3. The bearing capacity increment and reduction of settlement on geogrid-reinforced expansive soils exhibited the augmentation of reinforcement spacing up to 1.5m, followed by a subsequent decline and rise respectively. The enhancement in load-bearing capacity and settlement was observed to be (49.79%, 51.62%, 54.61%, & 43.54%) for square footings, (43.33%, 46.42%, 51.30%, & 40.86%) for 2mx3m rectangular footings, (60.40%, 61.84%, 64.20%, & 55.47%) for 2mx4m, (75.38%, 76.28%, 77.75%, & 72.32%) for 3mx4m, and (32.65%, 35.21%, 37.71%, 29.40%) for square, (29.87%, 30.43%, 32.87%, 26.62%) for 2m x 3m, (23.08%, 27.78%, 30.76%, 22.22%) for 2m x 4m, and (31.11%, 33.71%, 35.90%, 28.16%) for the 3m x 4m rectangular footing respectively.

4. The bearing capacity and settlement were enhanced to a maximum of  $U=0.5B$ , for square,  $2m \times 3m$ , and  $2m \times 4m$  and  $U=0.33B$  for  $3m \times 4m$  rectangular footings after which it exhibited a decline. The augmentation of bearing capacity and settlement was recorded at (54.61%, 59.05%, 50.81%, and 45.48%) for square, (52.88%, 56.52%, 48.49%, 39.99%, 48.49%, 39.99%) for  $2m \times 3m$ , (51.91%, 55.95%, 46.05%, 35.42%) for  $2m \times 4m$ , and (42.64%, 54.72%, 42.71%, 34.95%) for  $3m \times 4m$  and (18.27%, 24.76%, 17.71%, 11.11%) for square, (24.55%, 27.71%, 24.29%, 18.88%) for the  $2m \times 3m$ , (32.60%, 34.75%, 31.43%, 25.77%) for the  $2m \times 4m$ , and (30.98%, 32.50%, 26.71%, 24.45%) for the  $3m \times 4m$  rectangular footing, respectively.
5. The performance of square,  $2m \times 3m$  and  $2m \times 4m$  exhibits an enhancement up to a length  $L = 3B$ , whereas the rectangular footing of  $3m \times 4m$  achieves a peak at  $L = 2.5B$ , after which a decline is observed; consequently, the improved bearing capacities and settlement can be quantified as (56.14%, 60.10%, 62.32%, 58.86%) for square, (47.94%, 49.92%, 51.30%, 48.35%) for  $2m \times 3m$ , (44.21%, 48.01%, 50.20%, 48.22%) for  $2m \times 4m$ , (49.70%, 52.60%, 52.74%, 51.91%) for the  $3m \times 4m$  and (28.00%, 30.84%, 32.87%, 34.14%, 30.88%) for square, (19.20%, 22.11%, 25.26%, 27.59%, 24.35%) for  $2m \times 3m$ , (25.78%, 27.35%, 27.78%, 30.00%, 27.95%) for  $2m \times 4m$ , (28.64%, 32.14%, 31.07%, 27.95%) for  $3m \times 4m$  rectangular footings respectively, in comparison to the unreinforced soil.
6. The performance of reinforced soil exhibits an enhancement as the quantity of reinforcement layers is augmented, reaching a maximum of four layers of reinforcement, followed by a marginal improvement across all categories of footings. The enhanced load-bearing capacity and settlement quantified as (27.41%, 44.66%, 52.07%, 53.33%, 54.57%) for square, (25.31%, 38.62%, 46.92%, 48.94%, 50.91%) for  $2m \times 3m$ , (23.28%, 38.16%, 46.27%, 48.83%, 50.20%) for  $2m \times 4m$ , (20.08%, 36.36%, 45.00%, 47.05%, 49.70%) for  $3m \times 4m$ , (21.37%, 28.17%, 31.63%, 38.48%) for square, (17.56%, 23.24%, 26.92%, 28.95%) for  $2m \times 3m$ , (21.37%, 27.49%, 29.41%, 37.00%) for  $2m \times 4m$ , (19.49%, 25.03%, 28.56%, 35.30%) for  $3m \times 4m$  rectangular footing in comparison to unreinforced soil.
7. Square footing has a higher bearing capacity for the reinforced expansive soil compared to rectangular footing.

## **5.2. Recommendations**

Based on the findings of this study, it is evident that further research in this field can yield practical and valuable results. Hence, future studies should focus on:

1. Using the finite element model for the reinforced expansive soil foundation to simulate a full-scale geogrid reinforced approach of shallow foundation and compare the finite element results with field measurements from monitoring instrumental of expansive soils.
2. Static point load and prescribed displacement were considered in this study to determine the bearing capacity and settlement of both square and rectangular footing. But different types of loads like dynamic loads (Seismic loads) have critical effects on the performance of shallow foundations.

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## APPENDICES

### Appendix A: Data Collection and Correlation

Table A-1: Laboratory test data collected for Foundation soil

| Bore Hole ID | Depth (m) | Atterberg limit (AASHTO T89 & 90) |    | Soil Classification (AASHTO M- 145) | Proctor Density (AASHTO T-180) |         | 3-Point CBR AASHTO T-193 |                    |         |        |           | MC (%) | Gs   | Average CBR |            |
|--------------|-----------|-----------------------------------|----|-------------------------------------|--------------------------------|---------|--------------------------|--------------------|---------|--------|-----------|--------|------|-------------|------------|
|              |           | LL                                | PI |                                     | MDD (g/cc)                     | OMC (%) | No of Blows              | Dry Density (g/cc) | CBR (%) |        | Swell (%) |        |      | CBR @ 2.54  | CBR @ 2.54 |
|              |           |                                   |    |                                     |                                |         |                          |                    | 2.54mm  | 5.08mm |           |        |      |             |            |
| 1            | 3.00-3.50 | 110                               | 60 | A-7-6                               | 1.42                           | 22.50   | 10.00                    | 1.35               | 3.10    | 3.00   | 12.51     | 17.40  | 2.45 | 4.30        | 4.03       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.38               | 4.30    | 4.10   | 10.94     | 19.00  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.40               | 5.50    | 5.00   | 9.30      | 21.00  |      |             |            |
| 1            | 5.20-5.70 | 105                               | 57 | A-7-6                               | 1.36                           | 24.20   | 10.00                    | 1.41               | 3.20    | 3.00   | 13.00     | 23.30  | 2.42 | 4.37        | 4.13       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.38               | 4.60    | 4.30   | 10.80     | 25.60  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.39               | 5.30    | 5.10   | 8.70      | 26.20  |      |             |            |
| 1            | 7.20-8.00 | 105                               | 53 | A-7-6                               | 1.40                           | 23.10   | 10.00                    | 1.42               | 3.30    | 3.10   | 13.10     | 24.50  | 2.47 | 4.30        | 4.07       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.41               | 4.50    | 4.20   | 10.30     | 27.70  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.40               | 5.10    | 4.90   | 8.90      | 24.60  |      |             |            |
| 2            | 3.20-3.80 | 96                                | 43 | A-7-6                               | 1.24                           | 22.70   | 10.00                    | 1.21               | 2.40    | 2.40   | 14.46     | 19.40  | 2.45 | 3.77        | 3.60       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.22               | 4.00    | 3.70   | 12.68     | 21.40  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.24               | 4.90    | 4.70   | 10.98     | 23.70  |      |             |            |
| 2            | 8.50-8.95 | 95                                | 47 | A-7-6                               | 1.26                           | 25.90   | 10.00                    | 1.25               | 2.70    | 2.50   | 11.50     | 27.90  | 2.51 | 3.27        | 3.07       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.20               | 3.20    | 3.10   | 10.10     | 29.00  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.23               | 3.90    | 3.60   | 8.50      | 24.20  |      |             |            |
| 3            | 4.00-4.50 | 110                               | 58 | A-7-6                               | 1.35                           | 23.20   | 10.00                    | 1.29               | 2.40    | 2.20   | 13.30     | 18.50  | 2.45 | 3.10        | 2.88       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.32               | 3.10    | 2.95   | 10.80     | 20.60  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.41               | 3.80    | 3.50   | 8.54      | 22.70  |      |             |            |
| 3            | 6.00-6.50 | 85                                | 36 | A-7-6                               | 1.34                           | 24.10   | 10.00                    | 1.32               | 4.60    | 4.10   | 10.20     | 25.30  | 2.35 | 5.00        | 4.67       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.35               | 4.90    | 4.50   | 8.40      | 23.60  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.31               | 5.50    | 5.40   | 7.60      | 24.90  |      |             |            |
| 4            | 3.00-3.50 | 90                                | 43 | A-7-6                               | 1.39                           | 23.90   | 10.00                    | 1.32               | 4.00    | 3.90   | 10.38     | 20.60  | 2.5  | 4.50        | 4.27       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.36               | 4.30    | 3.90   | 9.43      | 21.80  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.39               | 5.20    | 5.00   | 8.56      | 23.30  |      |             |            |
| 4            | 6.00-6.50 | 90                                | 46 | A-7-6                               | 1.80                           | 24.10   | 10.00                    | 1.39               | 3.90    | 3.40   | 12.80     | 24.70  | 2.4  | 4.27        | 3.95       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.34               | 3.90    | 3.65   | 10.60     | 25.80  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.38               | 5.00    | 4.80   | 8.30      | 25.40  |      |             |            |
| 5            | 2.50-2.90 | 100                               | 46 | A-7-6                               | 1.45                           | 23.20   | 10.00                    | 1.35               | 4.10    | 3.95   | 12.10     | 24.60  | 2.48 | 4.67        | 4.38       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.37               | 4.50    | 4.25   | 10.20     | 23.20  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.45               | 5.40    | 4.95   | 8.30      | 24.70  |      |             |            |
| 5            | 5.00-5.50 | 101                               | 51 | A-7-6                               | 1.38                           | 25.50   | 10.00                    | 1.41               | 2.50    | 2.30   | 13.40     | 25.50  | 2.51 | 3.07        | 2.75       |
|              |           |                                   |    |                                     |                                |         | 30.00                    | 1.37               | 3.10    | 2.70   | 10.90     | 24.80  |      |             |            |
|              |           |                                   |    |                                     |                                |         | 65.00                    | 1.35               | 3.60    | 3.25   | 8.50      | 26.20  |      |             |            |

# Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

## A-2. Data Correlated

Table A - 2: Correlation of basic Geotechnical properties for Foundation soil

| Bore Hole ID | Depth (m) | Soil Type | Natural Moisture Content w (%) | MC (%) | ρd (kg/m3) | γd (kN/m3) | Gs   | Void Ratio (e) | γunsat (kN/m3) | γsat (kN/m3) |
|--------------|-----------|-----------|--------------------------------|--------|------------|------------|------|----------------|----------------|--------------|
| 1            | 3.00-3.50 | Soft Clay | 35.12                          | 17.40  | 1350.00    | 13.24      | 2.45 | 0.86           | 15.55          | 17.79        |
|              |           |           |                                | 19.00  | 1380.00    | 13.54      |      |                | 16.11          |              |
|              |           |           |                                | 21.00  | 1400.00    | 13.73      |      |                | 16.62          |              |
| 1            | 5.20-5.70 | Soft Clay | 32.77                          | 23.30  | 1410.00    | 13.83      | 2.42 | 0.79           | 17.05          | 17.92        |
|              |           |           |                                | 25.60  | 1380.00    | 13.54      |      |                | 17.00          |              |
|              |           |           |                                | 26.20  | 1390.00    | 13.64      |      |                | 17.21          |              |
| 1            | 7.20-8.00 | Soft Clay | 23.27                          | 24.50  | 1420.00    | 13.93      | 2.47 | 0.57           | 17.34          | 19.33        |
|              |           |           |                                | 27.70  | 1410.00    | 13.83      |      |                | 17.66          |              |
|              |           |           |                                | 24.60  | 1400.00    | 13.73      |      |                | 17.11          |              |
| 2            | 3.20-3.80 | Soft Clay | 28.23                          | 19.40  | 1210.00    | 11.87      | 2.45 | 0.69           | 14.17          | 18.57        |
|              |           |           |                                | 21.40  | 1220.00    | 11.97      |      |                | 14.53          |              |
|              |           |           |                                | 23.70  | 1240.00    | 12.16      |      |                | 15.05          |              |
| 2            | 8.50-8.95 | Soft Clay | 33.10                          | 27.90  | 1250.00    | 12.26      | 2.51 | 0.83           | 15.68          | 18.25        |
|              |           |           |                                | 29.00  | 1200.00    | 11.77      |      |                | 15.19          |              |
|              |           |           |                                | 24.20  | 1230.00    | 12.07      |      |                | 14.99          |              |
| 3            | 4.00-4-50 | Soft Clay | 31.50                          | 18.50  | 1170.00    | 11.48      | 2.45 | 0.77           | 13.60          | 18.18        |
|              |           |           |                                | 20.60  | 1310.00    | 12.85      |      |                | 15.50          |              |
|              |           |           |                                | 22.70  | 1410.00    | 13.83      |      |                | 16.97          |              |
| 3            | 6.00-6.50 | Soft Clay | 28.53                          | 25.30  | 1320.00    | 12.95      | 2.35 | 0.67           | 16.23          | 18.08        |
|              |           |           |                                | 23.60  | 1350.00    | 13.24      |      |                | 16.37          |              |
|              |           |           |                                | 24.90  | 1310.00    | 12.85      |      |                | 16.05          |              |
| 4            | 3.00-3.50 | Soft Clay | 29.90                          | 20.60  | 1320.00    | 12.95      | 2.5  | 0.75           | 15.62          | 18.58        |
|              |           |           |                                | 21.80  | 1360.00    | 13.34      |      |                | 16.25          |              |
|              |           |           |                                | 23.30  | 1390.00    | 13.64      |      |                | 16.81          |              |
| 4            | 6.00-6.50 | Soft Clay | 33.94                          | 24.70  | 1390.00    | 13.64      | 2.4  | 0.81           | 17.00          | 17.72        |
|              |           |           |                                | 25.80  | 1340.00    | 13.15      |      |                | 16.54          |              |
|              |           |           |                                | 25.40  | 1380.00    | 13.54      |      |                | 16.98          |              |
| 5            | 2.50-2.90 | Soft Clay | 29.29                          | 24.60  | 1350.00    | 13.24      | 2.48 | 0.73           | 16.50          | 18.57        |
|              |           |           |                                | 23.20  | 1370.00    | 13.44      |      |                | 16.56          |              |
|              |           |           |                                | 24.70  | 1450.00    | 14.22      |      |                | 17.74          |              |
| 5            | 5.00-5.50 | Soft Clay | 33.72                          | 25.50  | 1410.00    | 13.83      | 2.51 | 0.85           | 17.36          | 18.18        |
|              |           |           |                                | 24.80  | 1370.00    | 13.44      |      |                | 16.77          |              |
|              |           |           |                                | 26.20  | 1350.00    | 13.24      |      |                | 16.71          |              |
|              |           |           |                                |        |            | Average    |      |                | 17.00          | 19.00        |

# Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

Table A - 3: Correlation of Shear Strength Characteristics for Foundation Soil

| Bore Hole ID | Depth (m) | Soil Type      | Atterberg limit (AASHTO T89 & 90) |       | Effective Angle of Internal Friction ( $\phi'$ ) | Effective Cohesion (C') |
|--------------|-----------|----------------|-----------------------------------|-------|--------------------------------------------------|-------------------------|
|              |           |                | LL                                | PI    |                                                  |                         |
| 1            | 3.00-3.50 | Soft Clay Soil | 110.00                            | 60.00 | 13.13                                            | 6.58                    |
| 1            | 5.20-5.70 | Soft Clay Soil | 105.00                            | 57.00 | 13.56                                            | 6.77                    |
| 1            | 7.20-8.00 | Soft Clay Soil | 105.00                            | 53.00 | 14.20                                            | 7.09                    |
| 2            | 3.20-3.80 | Soft Clay Soil | 96.00                             | 43.00 | 16.10                                            | 8.05                    |
| 2            | 8.50-8.95 | Soft Clay Soil | 95.00                             | 47.00 | 15.29                                            | 7.65                    |
| 3            | 4.00-4.50 | Soft Clay Soil | 110.00                            | 58.00 | 13.42                                            | 6.71                    |
| 3            | 6.00-6.50 | Soft Clay Soil | 85.00                             | 36.00 | 17.73                                            | 8.86                    |
| 4            | 3.00-3.50 | Soft Clay Soil | 90.00                             | 43.00 | 16.10                                            | 8.05                    |
| 4            | 6.00-6.50 | Soft Clay Soil | 90.00                             | 46.00 | 15.48                                            | 7.74                    |
| 5            | 2.50-2.90 | Soft Clay Soil | 100.00                            | 46.00 | 15.48                                            | 7.74                    |
| 5            | 5.00-5.50 | Soft Clay Soil | 101.00                            | 51.00 | 14.54                                            | 7.28                    |
| Average      |           |                |                                   |       | 15.00                                            | 7.50                    |

Table A - 4: Geogrid material properties (Jie Gu, 2011)

| Geogrid Type     | Reference Name | Elastic Modulus (kPa) | Poisson's Ratio ( $\nu$ ) | Area (m <sup>2</sup> ) | EA (kN)   | Shear Modulus G (kN/m <sup>2</sup> ) |
|------------------|----------------|-----------------------|---------------------------|------------------------|-----------|--------------------------------------|
| Geogrid Type I   | GGI            | 585,100.00            | 0.3                       | 0.06                   | 35,106.00 | 225,038.46                           |
| Geogrid Type II  | GGII           | 660,000.00            | 0.3                       | 0.06                   | 39,600.00 | 253,846.15                           |
| Geogrid Type III | GGIII          | 860,000.00            | 0.3                       | 0.06                   | 51,600.00 | 330,769.23                           |
| Geogrid Type V   | GGVI           | 950,000.00            | 0.3                       | 0.06                   | 57,000.00 | 365,384.62                           |

## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

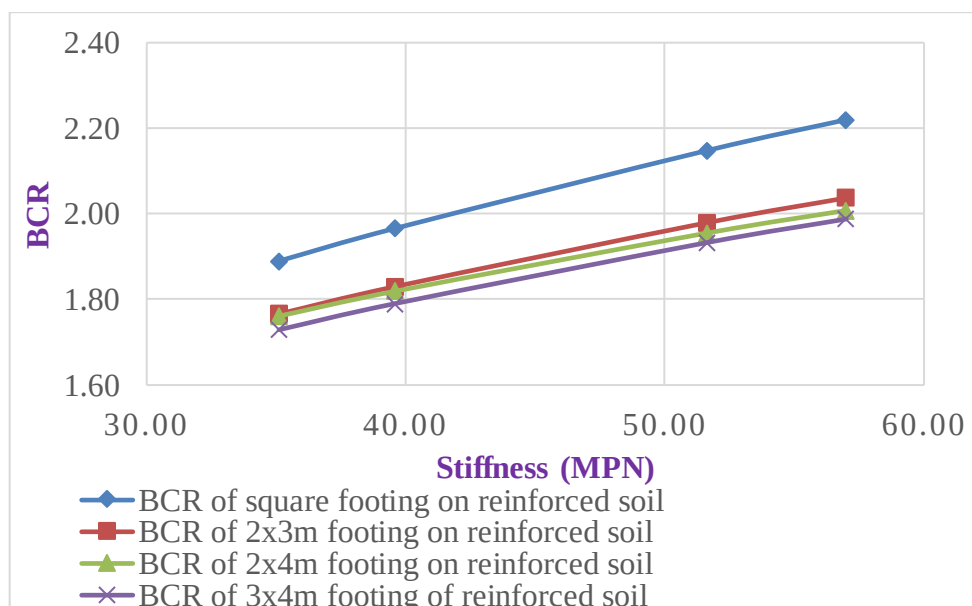
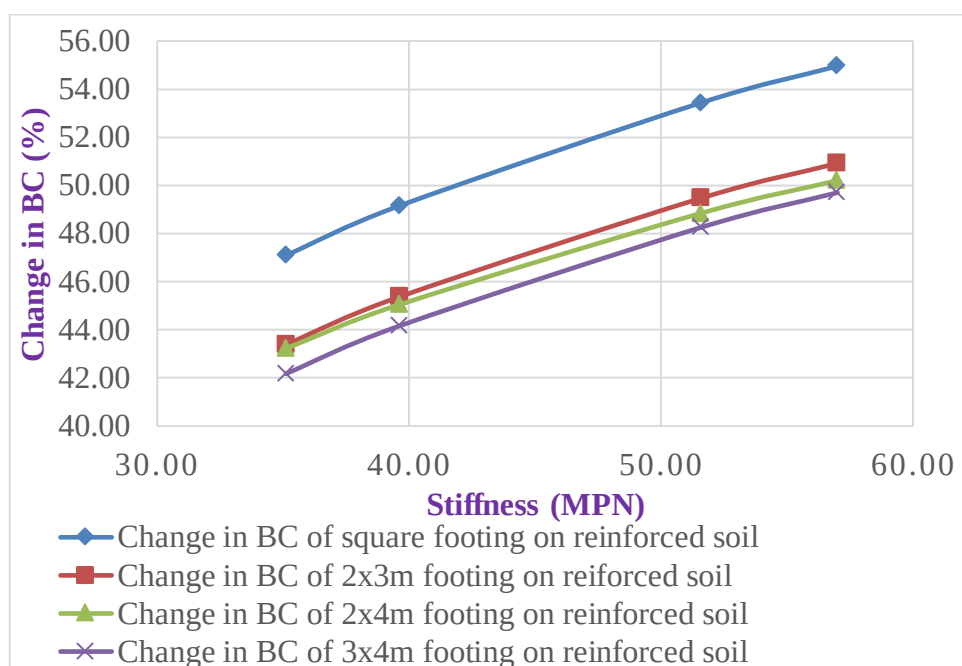
Table A - 5: Correlation of Elastic Properties or Strength Characteristics of Foundation Soil

| Bore Hole ID | Depth (m) | Soil Type | C'min (kPa) | C'max (kPa) | C' (kPa) | Emin (Mpa) | Emax (Mpa) | Average CBR @ 2.54 | Average CBR @ 5.08 | E' (Mpa) @ 2.54, v = 0 | E' (Mpa) @ 2.54, v = 0.3 | E' (Mpa) @ 2.54, v = 0.4 | E' (Mpa) @ 5.08, v = 0 | E' (Mpa) @ 5.08, v = 0.3 | E' (Mpa) @ 5.08, v = 0.4 | E' (Mpa) @ 2.54, v = 0.35 | E' (Mpa) @ 5.08, v = 0.35 | E (MPa) |
|--------------|-----------|-----------|-------------|-------------|----------|------------|------------|--------------------|--------------------|------------------------|--------------------------|--------------------------|------------------------|--------------------------|--------------------------|---------------------------|---------------------------|---------|
| 1.00         | 3.00-3.50 | Soft Clay | 5.00        | 10.00       | 6.58     | 1.00       | 15.00      | 4.30               | 4.03               | 3.71                   | 3.61                     | 3.23                     | 3.48                   | 3.39                     | 3.03                     | 3.42                      | 3.21                      | 3.42    |
| 1.00         | 5.20-5.70 | Soft Clay | 5.00        | 10.00       | 6.77     | 1.00       | 15.00      | 4.37               | 4.13               | 3.77                   | 3.67                     | 3.28                     | 3.57                   | 3.47                     | 3.10                     | 3.48                      | 3.29                      | 3.48    |
| 1.00         | 7.20-8.00 | Soft Clay | 5.00        | 10.00       | 7.09     | 1.00       | 15.00      | 4.30               | 4.07               | 3.71                   | 3.61                     | 3.23                     | 3.52                   | 3.42                     | 3.06                     | 3.42                      | 3.24                      | 3.42    |
| 2.00         | 3.20-3.80 | Soft Clay | 5.00        | 10.00       | 8.05     | 1.00       | 15.00      | 3.77               | 3.60               | 3.26                   | 3.17                     | 2.83                     | 3.11                   | 3.03                     | 2.70                     | 3.00                      | 2.86                      | 3.00    |
| 2.00         | 8.50-8.95 | Soft Clay | 5.00        | 10.00       | 7.65     | 1.00       | 15.00      | 3.27               | 3.07               | 2.82                   | 2.75                     | 2.46                     | 2.65                   | 2.58                     | 2.31                     | 2.60                      | 2.44                      | 2.60    |
| 3.00         | 4.00-4.50 | Soft Clay | 5.00        | 10.00       | 6.71     | 1.00       | 15.00      | 3.10               | 2.88               | 2.68                   | 2.61                     | 2.33                     | 2.49                   | 2.42                     | 2.16                     | 2.47                      | 2.29                      | 2.47    |
| 3.00         | 6.00-6.50 | Soft Clay | 5.00        | 10.00       | 8.86     | 1.00       | 15.00      | 5.00               | 4.67               | 4.32                   | 4.20                     | 3.76                     | 4.03                   | 3.93                     | 3.51                     | 3.98                      | 3.72                      | 3.98    |
| 4.00         | 3.00-3.50 | Soft Clay | 5.00        | 10.00       | 8.05     | 1.00       | 15.00      | 4.50               | 4.27               | 3.89                   | 3.78                     | 3.38                     | 3.69                   | 3.59                     | 3.21                     | 3.58                      | 3.40                      | 3.58    |
| 4.00         | 6.00-6.50 | Soft Clay | 5.00        | 10.00       | 7.74     | 1.00       | 15.00      | 4.27               | 3.95               | 3.69                   | 3.59                     | 3.21                     | 3.41                   | 3.32                     | 2.97                     | 3.40                      | 3.14                      | 3.40    |
| 5.00         | 2.50-2.90 | Soft Clay | 5.00        | 10.00       | 7.74     | 1.00       | 15.00      | 4.67               | 4.38               | 4.03                   | 3.93                     | 3.51                     | 3.78                   | 3.68                     | 3.29                     | 3.72                      | 3.49                      | 3.72    |
| 5.00         | 5.00-5.50 | Soft Clay | 5.00        | 10.00       | 7.28     | 1.00       | 15.00      | 3.07               | 2.75               | 2.65                   | 2.58                     | 2.31                     | 2.38                   | 2.31                     | 2.07                     | 2.44                      | 2.19                      | 2.44    |
| Average      |           |           |             |             |          |            |            |                    |                    |                        |                          |                          |                        |                          |                          | 3.23                      | 3.02                      | 3.23    |

## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

Table A-6: FEA on the effect of tensile modulus of reinforcement on BC, BCR and Change BC of square and rectangular footing.

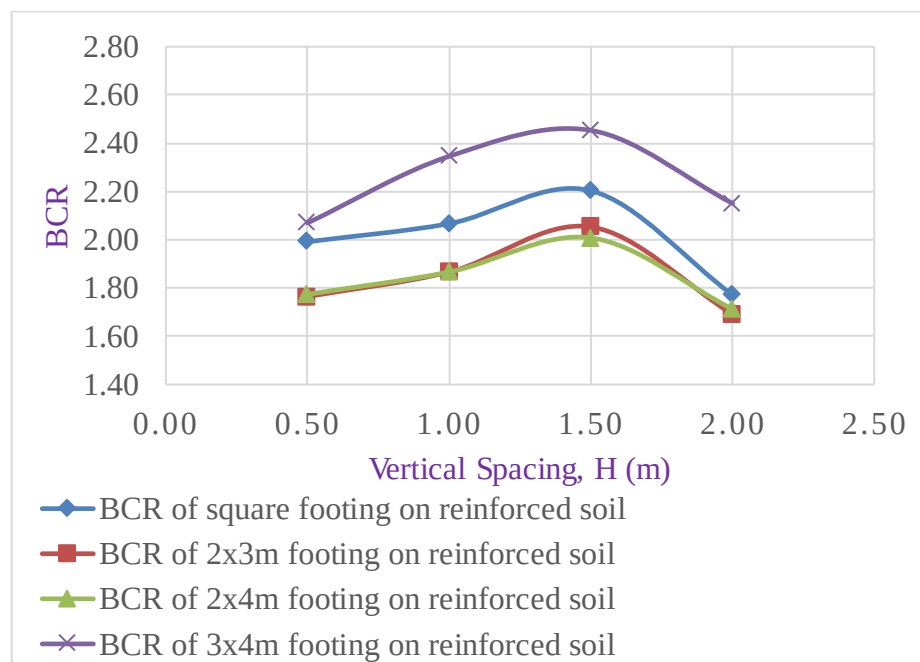
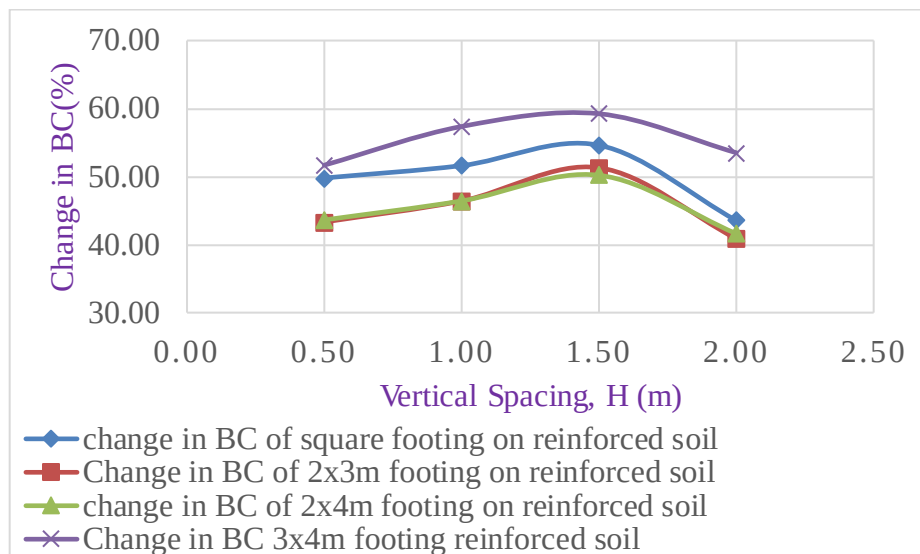
| stiffness<br>Value (kN) | square Footing  |      | 2x3m Footing    |      | 2x4m Footing    |      | 3x4m Footing    |      |
|-------------------------|-----------------|------|-----------------|------|-----------------|------|-----------------|------|
|                         | change<br>in BC | BCR  | change<br>in BC | BCR  | change<br>in BC | BCR  | change<br>in BC | BCR  |
| 35.11                   | 47.09           | 1.89 | 43.38           | 1.77 | 43.22           | 1.76 | 42.17           | 1.73 |
| 39.60                   | 49.14           | 1.97 | 45.36           | 1.83 | 45.04           | 1.82 | 44.15           | 1.79 |
| 51.60                   | 53.44           | 2.15 | 49.47           | 1.98 | 48.85           | 1.95 | 48.26           | 1.93 |
| 57.00                   | 54.95           | 2.22 | 50.91           | 2.04 | 50.20           | 2.01 | 49.70           | 1.99 |



## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

Table A-7: FEA on the effect of variation of vertical spacing on BC, BCR, and Change in BC of 2mx3m rectangular footing

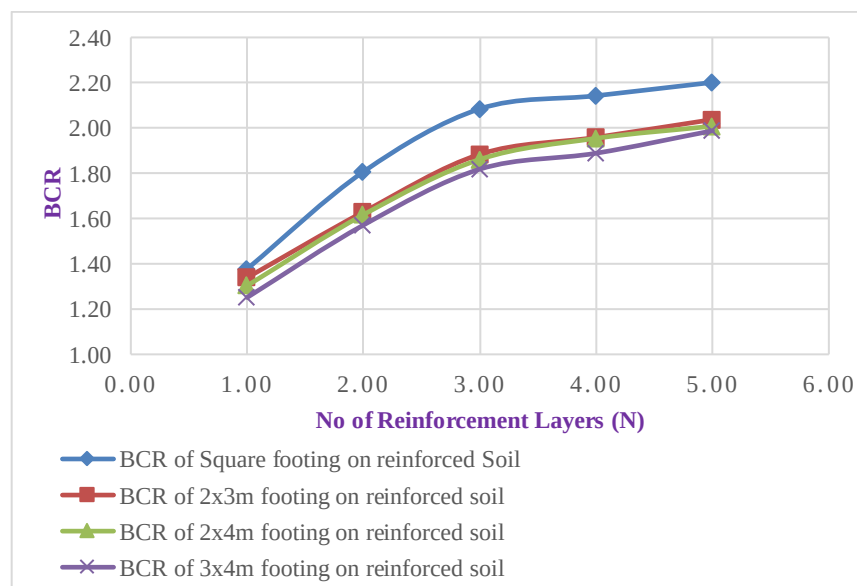
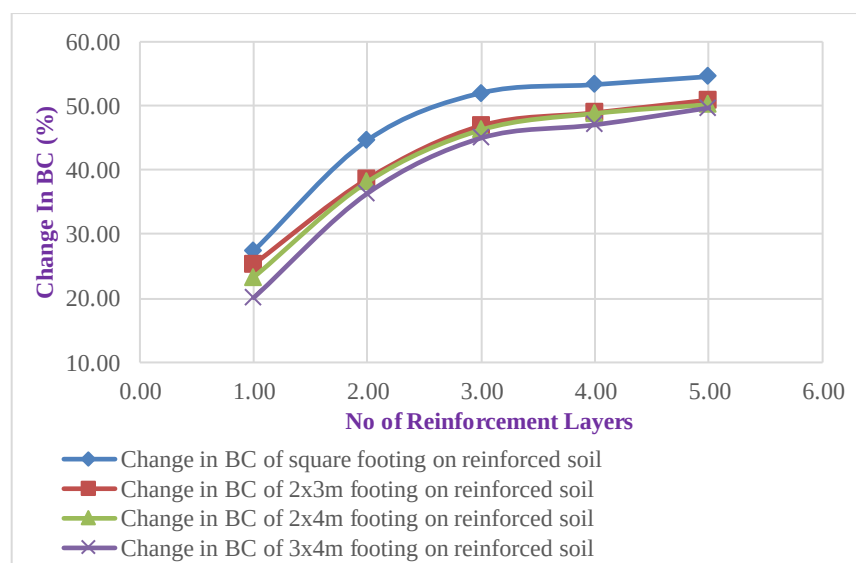
| Spacing | Square footing |      | 2x3m footing |      | 2x4m footing |      | 3x4m footing |      |
|---------|----------------|------|--------------|------|--------------|------|--------------|------|
| H       | BC (%)         | BCR  | BC (%)       | BCR  | BC (%)       | BCR  | BC (%)       | BCR  |
| 0.50    | 49.79          | 1.99 | 43.33        | 1.76 | 43.63        | 1.77 | 51.68        | 2.07 |
| 1.00    | 51.62          | 2.07 | 46.42        | 1.87 | 46.43        | 1.87 | 57.37        | 2.35 |
| 1.50    | 54.61          | 2.20 | 51.30        | 2.05 | 50.20        | 2.01 | 59.24        | 2.45 |
| 2.00    | 43.54          | 1.77 | 40.86        | 1.69 | 41.60        | 1.71 | 53.51        | 2.15 |



## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

Table A-8: FEA on the effect of number of reinforcement layers on BC, BCR, and change BC for 2mx4m rectangular footing.

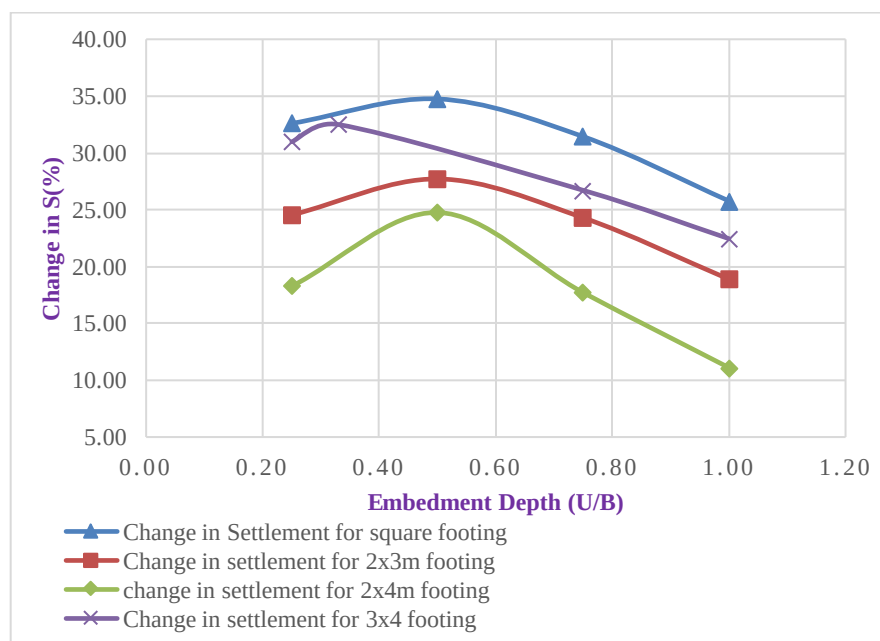
| No of Layers | Square Footing |        | 2x3m footing |        | 2x4m footing |        | 3x4m footing |        |
|--------------|----------------|--------|--------------|--------|--------------|--------|--------------|--------|
| N            | BCR            | BC (%) | BCR          | BC (%) | BCR          | BC (%) | BCR          | BC (%) |
| 1.00         | 1.38           | 27.41  | 1.34         | 25.31  | 1.30         | 23.28  | 1.25         | 20.08  |
| 2.00         | 1.81           | 44.66  | 1.63         | 38.62  | 1.62         | 38.16  | 1.57         | 36.36  |
| 3.00         | 2.08           | 52.03  | 1.88         | 46.92  | 1.86         | 46.27  | 1.82         | 45.00  |
| 4.00         | 2.14           | 53.33  | 1.96         | 48.94  | 1.95         | 48.83  | 1.89         | 47.05  |
| 5.00         | 2.20           | 54.57  | 2.04         | 50.91  | 2.01         | 50.20  | 1.99         | 49.70  |



## Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

Table A-9: FEA on the effect of top reinforcement depth on Settlement of both square and rectangular footing

| Depth | Square Footing | 2x3m Footing   | 2x4m Footing   | 3x4m Footing   | Spacing for 3x4m footing only |
|-------|----------------|----------------|----------------|----------------|-------------------------------|
| U/B   | Settlement (%) | Settlement (%) | Settlement (%) | Settlement (%) |                               |
| 0.25  | 32.60          | 24.55          | 18.27          | 30.98          | 0.25                          |
| 0.50  | 34.75          | 27.71          | 24.76          | 32.50          | 0.33                          |
| 0.75  | 31.43          | 24.29          | 17.71          | 26.71          | 0.75                          |
| 1.00  | 25.77          | 18.88          | 11.11          | 22.45          | 1.00                          |



| No of reinforcement | Square Footing | 2x3m Footing   | 2x4m Footing   | 3x4m Footing   |
|---------------------|----------------|----------------|----------------|----------------|
| N                   | Settlement (%) | Settlement (%) | Settlement (%) | Settlement (%) |
| 1.00                | 23.37          | 21.37          | 19.49          | 17.56          |
| 2.00                | 28.17          | 27.49          | 25.03          | 23.24          |
| 3.00                | 31.63          | 29.41          | 28.56          | 26.92          |
| 4.00                | 38.46          | 37.00          | 35.36          | 31.95          |

# Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

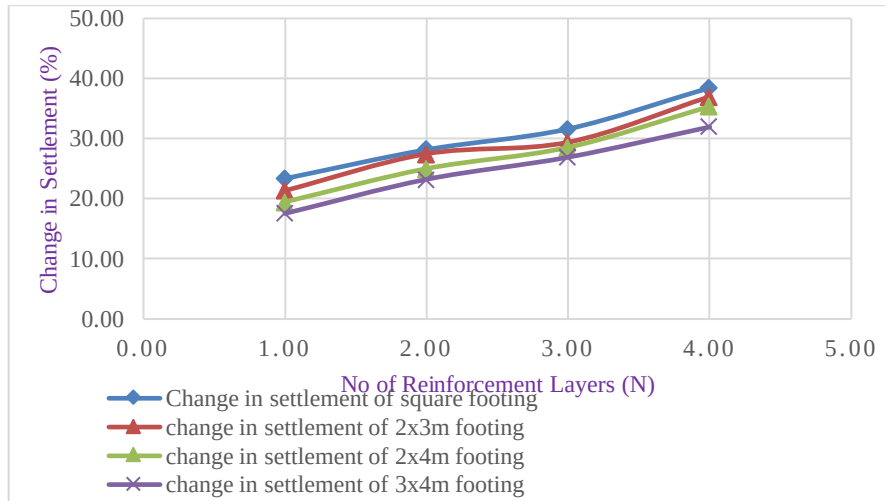


Table A-10: FEA on the effect of length of reinforcement Settlement of both square and rectangular footing

## Square Footing

| Soil                        |                 | Reinforced with L=1.5B      |                 | Reinforced with L=2B        |                 | Reinforced with L=2.5B      |                 | Reinforced with L=3B        |                 | Reinforced with L=3.5B      |                 |
|-----------------------------|-----------------|-----------------------------|-----------------|-----------------------------|-----------------|-----------------------------|-----------------|-----------------------------|-----------------|-----------------------------|-----------------|
| Stress (kN/m <sup>2</sup> ) | Settlement (mm) | Stress (kN/m <sup>2</sup> ) | Settlement (mm) | Stress (kN/m <sup>2</sup> ) | Settlement (mm) | Stress (kN/m <sup>2</sup> ) | Settlement (mm) | Stress (kN/m <sup>2</sup> ) | Settlement (mm) | Stress (kN/m <sup>2</sup> ) | Settlement (mm) |
| 0.00                        | 0.00            | 0.00                        | 0.00            | 0.00                        | 0.00            | 0.00                        | 0.00            | 0.00                        | 0.00            | 0.00                        | 0.00            |
| 31.27                       | 1.25            | 38.36                       | 1.45            | 45.59                       | 1.70            | 31.02                       | 1.07            | 31.02                       | 0.96            | 31.02                       | 0.99            |
| 93.70                       | 3.75            | 114.27                      | 4.33            | 136.09                      | 5.09            | 92.99                       | 3.22            | 92.99                       | 2.87            | 92.99                       | 2.97            |
| 209.07                      | 8.71            | 251.10                      | 10.03           | 294.60                      | 11.70           | 207.95                      | 7.49            | 207.95                      | 6.66            | 207.95                      | 6.89            |
| 315.47                      | 13.71           | 374.15                      | 15.85           | 434.20                      | 18.43           | 315.71                      | 11.88           | 315.71                      | 10.57           | 315.71                      | 10.93           |
| 498.93                      | 23.72           | 583.16                      | 27.55           | 561.93                      | 25.50           | 412.68                      | 16.35           | 412.68                      | 14.55           | 412.68                      | 15.04           |
| 638.88                      | 33.78           | 760.21                      | 39.16           | 683.47                      | 32.74           | 583.25                      | 25.37           | 583.25                      | 22.58           | 583.25                      | 23.34           |
| 752.14                      | 43.96           | 903.65                      | 50.67           | 791.08                      | 39.99           | 657.44                      | 29.67           | 657.44                      | 26.41           | 657.44                      | 27.30           |
| 849.58                      | 54.17           | 1000.00                     | 59.92           | 885.66                      | 47.21           | 727.47                      | 33.95           | 727.47                      | 30.21           | 727.47                      | 31.23           |
| 935.13                      | 64.49           |                             |                 | 970.84                      | 54.46           | 791.51                      | 38.23           | 791.51                      | 34.03           | 791.51                      | 35.17           |
| 1000.00                     | 73.13           |                             |                 | 1000.00                     | 57.15           | 850.70                      | 42.53           | 850.70                      | 37.85           | 850.70                      | 39.12           |
|                             |                 |                             |                 |                             |                 | 957.72                      | 51.15           | 957.72                      | 45.53           | 957.72                      | 47.06           |
|                             |                 |                             |                 |                             |                 | 1000.00                     | 54.94           | 1000.00                     | 48.89           | 1000.00                     | 50.54           |

## 2x3m Footing

| Soil                        |                 | Reinforced with L=2B        |                 | Reinforced with L=2.5B      |                 | Reinforced with L=3B        |                 | Reinforced with L=3.5B      |                 |
|-----------------------------|-----------------|-----------------------------|-----------------|-----------------------------|-----------------|-----------------------------|-----------------|-----------------------------|-----------------|
| Stress (kN/m <sup>2</sup> ) | Settlement (mm) | Stress (kN/m <sup>2</sup> ) | Settlement (mm) | Stress (kN/m <sup>2</sup> ) | Settlement (mm) | Stress (kN/m <sup>2</sup> ) | Settlement (mm) | Stress (kN/m <sup>2</sup> ) | Settlement (mm) |
| 0.00                        | 0.00            | 0                           | 0               | 0                           | 0               | 0.00                        | 0.00            | 0.00                        | 0.00            |
| 28.62                       | 1.39            | 113.04                      | 5.45            | 25.42                       | 1.15            | 92.93                       | 4.17            | 32.68                       | 1.47            |
| 85.67                       | 4.18            | 372.43                      | 20.19           | 76.02                       | 3.44            | 209.58                      | 9.76            | 216.81                      | 10.18           |
| 193.52                      | 9.78            | 587.42                      | 35.15           | 171.84                      | 8.01            | 315.40                      | 15.38           | 322.31                      | 15.94           |
| 292.39                      | 15.43           | 682.49                      | 42.49           | 341.46                      | 17.14           | 499.52                      | 26.92           | 507.44                      | 27.85           |
| 460.60                      | 26.84           | 837.15                      | 57.18           | 488.95                      | 26.59           | 667.58                      | 38.60           | 673.30                      | 39.86           |
| 590.79                      | 38.48           | 1000.00                     | 75.52           | 627.42                      | 36.31           | 808.34                      | 50.39           | 744.03                      | 45.84           |
| 698.16                      | 50.31           |                             |                 | 748.28                      | 46.11           | 869.36                      | 56.30           | 865.60                      | 57.89           |
| 870.59                      | 74.42           |                             |                 | 850.62                      | 55.97           | 1000.00                     | 70.20           | 1000.00                     | 73.34           |
| 1000.00                     | 96.95           |                             |                 | 1000.00                     | 72.46           |                             |                 |                             |                 |

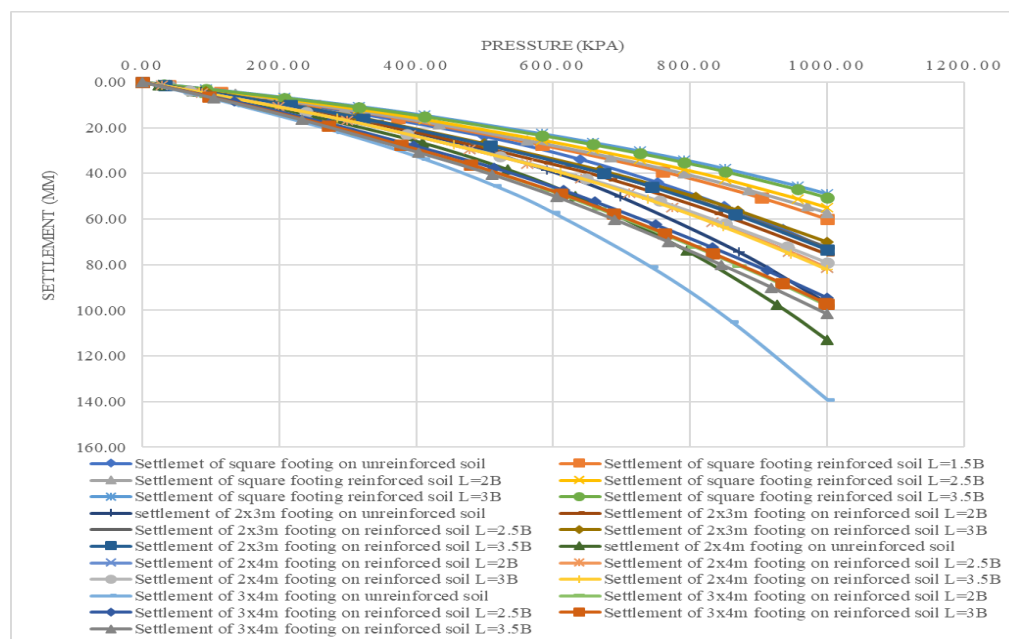
# Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

## 2x4m Footing

| Soil                        |                 | Reinforced with L=1.5B      |                 | Reinforced with L=2B        |                 | Reinforced with L=2.5B      |                 | Reinforced with L=3B        |                 | Reinforced with L=3.5B      |                 |
|-----------------------------|-----------------|-----------------------------|-----------------|-----------------------------|-----------------|-----------------------------|-----------------|-----------------------------|-----------------|-----------------------------|-----------------|
| Stress (kN/m <sup>2</sup> ) | Settlement (mm) | Stress (kN/m <sup>2</sup> ) | Settlement (mm) | Stress (kN/m <sup>2</sup> ) | Settlement (mm) | Stress (kN/m <sup>2</sup> ) | Settlement (mm) | Stress (kN/m <sup>2</sup> ) | Settlement (mm) | Stress (kN/m <sup>2</sup> ) | Settlement (mm) |
| 0.00                        | 0.00            | 0.00                        | 0.00            | 0.0                         | 0.0             | 0.00                        | 0.00            | 0.00                        | 0.00            | 0.00                        | 0.00            |
| 24.91                       | 1.38            | 30.14                       | 1.58            | 29.4                        | 1.5             | 29.39                       | 1.52            | 69.42                       | 3.56            | 83.30                       | 4.28            |
| 74.34                       | 4.14            | 90.07                       | 4.75            | 87.9                        | 4.6             | 87.92                       | 4.56            | 239.30                      | 13.07           | 284.70                      | 15.85           |
| 167.47                      | 9.67            | 203.15                      | 11.12           | 198.3                       | 10.7            | 198.34                      | 10.66           | 386.50                      | 22.71           | 455.28                      | 27.65           |
| 254.75                      | 15.28           | 305.51                      | 17.52           | 299.0                       | 16.8            | 299.05                      | 16.82           | 522.89                      | 32.40           | 610.28                      | 39.47           |
| 409.61                      | 26.63           | 400.03                      | 24.03           | 390.9                       | 23.1            | 390.90                      | 23.05           | 648.81                      | 42.18           | 738.83                      | 51.36           |
| 533.10                      | 38.21           | 575.21                      | 37.13           | 478.5                       | 29.4            | 478.54                      | 29.37           | 755.87                      | 52.09           | 848.13                      | 63.31           |
| 632.92                      | 49.98           | 719.68                      | 50.31           | 562.7                       | 35.7            | 562.74                      | 35.71           | 851.74                      | 62.10           | 947.33                      | 75.28           |
| 794.97                      | 73.75           | 840.92                      | 63.56           | 641.3                       | 42.1            | 641.32                      | 42.07           | 941.52                      | 72.15           | 1000.00                     | 82.06           |
| 926.95                      | 97.57           | 948.91                      | 76.83           | 710.8                       | 48.5            | 710.76                      | 48.48           | 1000.00                     | 79.02           |                             |                 |
| 1000.00                     | 112.88          | 1000.00                     | 83.77           | 773.7                       | 54.9            | 773.71                      | 54.92           |                             |                 |                             |                 |
|                             |                 |                             |                 | 832.7                       | 61.4            | 832.74                      | 61.40           |                             |                 |                             |                 |
|                             |                 |                             |                 | 944.9                       | 74.4            | 944.90                      | 74.39           |                             |                 |                             |                 |
|                             | 25.78412        |                             |                 | 1000.0                      | 81.6            | 1000.00                     | 81.57           |                             |                 |                             |                 |

## 3x4m Footing

| Soil                        |                 | Reinforced with L=2B        |                 | Reinforced with L=2.5B      |                 | Reinforced with L=3B        |                 | Reinforced with L=3.5B      |                 |
|-----------------------------|-----------------|-----------------------------|-----------------|-----------------------------|-----------------|-----------------------------|-----------------|-----------------------------|-----------------|
| Stress (kN/m <sup>2</sup> ) | Settlement (mm) | Stress (kN/m <sup>2</sup> ) | Settlement (mm) | Stress (kN/m <sup>2</sup> ) | Settlement (mm) | Stress (kN/m <sup>2</sup> ) | Settlement (mm) | Stress (kN/m <sup>2</sup> ) | Settlement (mm) |
| 0.00                        | 0.00            | 0.00                        | 0.00            | 0.00                        | 0.00            | 0.00                        | 0.00            | 0.00                        | 0.00            |
| 20.85                       | 1.44            | 93.73                       | 6.07            | 134.13                      | 8.35            | 97.63                       | 6.29            | 105.16                      | 7.05            |
| 61.99                       | 4.32            | 313.22                      | 22.44           | 271.60                      | 18.00           | 272.58                      | 18.99           | 233.04                      | 16.54           |
| 140.52                      | 10.10           | 412.68                      | 30.67           | 395.68                      | 27.74           | 377.30                      | 27.49           | 404.09                      | 30.93           |
| 285.26                      | 21.75           | 507.56                      | 38.88           | 513.69                      | 37.52           | 479.00                      | 36.08           | 511.16                      | 40.58           |
| 409.59                      | 33.48           | 590.77                      | 47.10           | 615.37                      | 47.42           | 611.16                      | 48.92           | 605.05                      | 50.33           |
| 513.19                      | 45.24           | 666.04                      | 55.37           | 661.48                      | 52.41           | 688.70                      | 57.58           | 689.27                      | 60.19           |
| 599.06                      | 57.07           | 805.48                      | 72.02           | 749.30                      | 62.42           | 762.31                      | 66.31           | 768.92                      | 70.11           |
| 742.12                      | 80.90           | 870.82                      | 80.34           | 832.59                      | 72.46           | 832.84                      | 75.04           | 845.21                      | 80.06           |
| 859.92                      | 104.86          | 933.80                      | 88.63           | 912.16                      | 82.53           | 933.55                      | 88.14           | 918.61                      | 90.03           |
| 1000.00                     | 139.20          | 1000.00                     | 97.95           | 1000.00                     | 94.46           | 996.69                      | 96.86           | 1000.00                     | 101.69          |
|                             |                 |                             |                 |                             |                 | 1000.00                     | 97.34           |                             |                 |



# Numerical Investigation on the Performance of Square and Rectangular Footing on Geogrid Reinforced Expansive Soils.

Table A-11: FEA on the effect of vertical spacing of reinforcement BC of both square and rectangular footing

|        | Unreinforced Soil                     |        | Reinforced Soil<br>H=0.5m             |        | Reinforced Soil<br>H=1m               |        | Reinforced Soil<br>H=1.5m             |        | Reinforced Soil<br>H=2m               |        |        |
|--------|---------------------------------------|--------|---------------------------------------|--------|---------------------------------------|--------|---------------------------------------|--------|---------------------------------------|--------|--------|
| Point  | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | Square |
| 0.00   | 0.00                                  | 0.00   | 0.00                                  | 0.00   | 0.00                                  | 0.00   | 0.00                                  | 0.00   | 0.00                                  | 0.00   |        |
| 50.00  | 208.98                                | 0.12   | 279.94                                | 0.10   | 247.84                                | 0.10   | 249.38                                | 0.10   | 231.71                                | 0.09   |        |
| 100.00 | 310.68                                | 0.42   | 465.88                                | 0.31   | 452.33                                | 0.34   | 458.24                                | 0.38   | 390.47                                | 0.36   |        |
| 150.00 | 394.46                                | 0.79   | 670.35                                | 0.69   | 679.84                                | 0.71   | 680.36                                | 0.81   | 555.48                                | 0.76   |        |
| 200.00 | 500.70                                | 1.44   | 932.31                                | 1.38   | 918.82                                | 1.27   | 994.58                                | 1.56   | 795.92                                | 1.51   |        |
| 250.00 | 601.30                                | 2.19   | 1214.73                               | 2.35   | 1164.61                               | 2.02   | 1277.68                               | 2.34   | 1109.89                               | 2.66   |        |
| 300.00 | 777.53                                | 3.75   | 1548.61                               | 3.75   | 1493.37                               | 3.26   | 1712.94                               | 3.75   | 1377.18                               | 3.75   |        |
| 350.00 |                                       |        |                                       |        | 1606.98                               | 3.75   |                                       |        |                                       |        |        |
| Point  | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | 2x3m   |
| 0.00   | 0.00                                  | 0.00   | 0.00                                  | 0.00   | 0.00                                  | 0.00   | 0.00                                  | 0.00   | 0.00                                  | 0.00   |        |
| 50.00  | 174.33                                | 0.12   | 267.62                                | 0.14   | 247.69                                | 0.14   | 251.16                                | 0.14   | 227.40                                | 0.13   |        |
| 100.00 | 258.87                                | 0.40   | 418.49                                | 0.37   | 420.23                                | 0.44   | 396.25                                | 0.41   | 360.86                                | 0.43   |        |
| 150.00 | 349.87                                | 0.88   | 585.24                                | 0.80   | 582.76                                | 0.81   | 598.69                                | 0.90   | 527.26                                | 0.94   |        |
| 200.00 | 457.93                                | 1.63   | 793.93                                | 1.55   | 779.45                                | 1.43   | 848.99                                | 1.65   | 721.13                                | 1.69   |        |
| 250.00 | 579.54                                | 2.68   | 1016.79                               | 2.62   | 967.61                                | 2.18   | 1101.51                               | 2.52   | 989.78                                | 2.90   |        |
| 300.00 | 685.45                                | 3.75   | 1209.46                               | 3.75   | 1279.36                               | 3.75   | 1407.42                               | 3.75   | 1159.11                               | 3.75   |        |
| Point  | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | 2x4m   |
| 0.00   | 0.00                                  | 0.00   | 0.00                                  | 0.00   | 0.00                                  | 0.00   | 0.00                                  | 0.00   | 0.00                                  | 0.00   |        |
| 50.00  | 180.00                                | 0.15   | 240.81                                | 0.14   | 226.91                                | 0.15   | 220.43                                | 0.15   | 205.60                                | 0.14   |        |
| 100.00 | 255.47                                | 0.42   | 373.97                                | 0.35   | 387.15                                | 0.44   | 359.34                                | 0.42   | 332.03                                | 0.44   |        |
| 150.00 | 331.80                                | 0.84   | 516.60                                | 0.73   | 538.47                                | 0.81   | 500.61                                | 0.79   | 451.24                                | 0.83   |        |
| 200.00 | 427.46                                | 1.59   | 692.50                                | 1.41   | 720.26                                | 1.43   | 725.96                                | 1.53   | 631.22                                | 1.58   |        |
| 250.00 | 501.50                                | 2.34   | 844.65                                | 2.18   | 880.38                                | 2.16   | 920.35                                | 2.28   | 854.43                                | 2.67   |        |
| 300.00 | 613.23                                | 3.75   | 1087.85                               | 3.75   | 1144.66                               | 3.75   | 1231.31                               | 3.75   | 1050.11                               | 3.75   |        |
| Point  | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | $\bar{\sigma}_z$ (kN/m <sup>2</sup> ) | Uz(mm) | 3x4m   |
| 0.00   | 0.00                                  | 0.00   | 0.00                                  | 0.00   | 0.00                                  | 0.00   | 0.00                                  | 0.00   | 0.00                                  | 0.00   |        |
| 50.00  | 118.99                                | 0.06   | 214.47                                | 0.11   | 204.65                                | 0.11   | 196.45                                | 0.11   | 187.33                                | 0.10   |        |
| 100.00 | 154.67                                | 0.18   | 314.95                                | 0.27   | 330.08                                | 0.32   | 305.21                                | 0.30   | 287.51                                | 0.32   |        |
| 150.00 | 193.53                                | 0.40   | 424.74                                | 0.57   | 439.10                                | 0.57   | 431.19                                | 0.61   | 382.86                                | 0.60   |        |
| 200.00 | 225.62                                | 0.65   | 550.35                                | 1.07   | 586.05                                | 1.04   | 595.64                                | 1.11   | 517.82                                | 1.10   |        |
| 250.00 | 272.30                                | 1.11   | 663.30                                | 1.67   | 707.29                                | 1.54   | 732.82                                | 1.61   | 669.30                                | 1.76   |        |
| 300.00 | 315.08                                | 1.61   | 788.95                                | 2.50   | 894.22                                | 2.50   | 935.20                                | 2.50   | 819.86                                | 2.50   |        |
| 350.00 | 381.19                                | 2.50   |                                       |        |                                       |        |                                       |        |                                       |        |        |

