BEARING CAPACITY OF CLAYEY SOIL REINFORCED WITH GEOGRID

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IN

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CANDIDATE DECLARATION

I, PRACHI LINGWAL, 2k16/GTE/12, student of MTech, (Geotechnical Engineering), hereby declare that the project Dissertation titled "Bearing Capacity of Clayey Soil Reinforced with Geogrid" which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associate ship, Fellowship or other similar title or recognition.

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CERTIFICATE

This is to certify that the work, which is being presented in this dissertation on the title "Bearing Capacity of Clayey Soil reinforced with Geogrid", submitted by PRACHI LINGWAL (2K16/GTE/12), in partial fulfillment for the award of degree of Master of Technology in Geotechnical Engineering, is a record of project work carried out by her under my supervision. To the best of my knowledge this work has not been submitted in part or full for any degree or diploma to this university or elsewhere.

Place: Delhi **Prof. A.K GUPTA**

Date: **SUPERVISOR**

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ABSTRACT

In many cases, shallow foundations built up on top of cohesive soil deposits or soil embankment having high plasticity, results in low load bearing capacity and excessive differential settlement of the footing more than the permissible limit, or low shearing resistance of soil. This may lead to the structural damage, reduction in the durability of the structure, or decrease in the performance of the structure. To counteract these problems suitable engineering measures are required for ensuring satisfactory performance from structure. Conventionally the weak cohesive soil was excavated and replaced with a sufficiently thick layer of stronger granular fill, or by increasing the dimensions of the footing, or by combination of the two methods. These methods of improving bearing capacity of soil were not economical solutions and were time consuming. Also, stability of soft cohesive soil was difficult because of low permeability of soil which will take lot of time to consolidate. Therefore, the use of geosynthetic material has emerged. Now days the use of geosynthetic material has been widely increased in geotechnical structures like slopes, retaining wall, embankment etc. It can also be used to reinforce cohesive soils and give an alternative method and more economical solution.

Geosynthetic is synthetic products used to stabilize terrain. They are polymeric products and are widely been used to solve many civil engineering problems. There are total eight main categories of geosynthetic product available: geotextile, geonets, geogrids, geomembrane, geosynthetic clay liner, geofoam, geocells, and geocomposite. Their polymeric nature makes them suitable for use in soil where high durability is required. For e.g. - for construction of road, for stable embankment, for stabilizing retaining wall, for stabilizing earthen slope.

Foundation failure mechanism as explained by Terzaghi has 3 zones of failure, so reinforcement is provided to attain stability. The ideal pattern of providing the reinforcement is in direction of principal tensile strain. Therefore in order to satisfy the requirement , reinforcement is provided horizonatlly below the footing and then progessively become vertical after some distance.

An attempt is made to study the behavior of foundations on geosynthetic reinforced clayey soil of intermediate plasticity and aims to examine the potential profit of using reinforcement in soil to advance bearing capacity of the clay and lower the settlement. For fulfilling this objective, 28 numbers of tests were performed in which 23 tests were successful HEICO engineering laboratory investigate the behavior of reinforced soil. A model footing prepared in laboratory is a square steel plate with dimensions of 75 mm×75mm and tests were performed on a steel tank with acrylic sheet in front having 750mm×450mm×375mm and the parameters on which degree of improvement depends are investigated in the study includes the top layer spacing, the number of reinforcement layers, the vertical spacing between layers, and the stiffness and type of reinforcement and its effect on the ultimate bearing capacity and settlement of the foundation.

The results of test performed showed with the incorporation of the reinforcement in the clay can increase the bearing capacity of clay and reduces the settlement of the footing as compared to unreinforced soil. The results also showed that the bearing capacity of the clay increases with increase in number of reinforcement layers up to influence depth, also increases with decreasing the vertical spacing between reinforcement layers and is also dependent on the stiffness of the geogrid.

DEDICATION

I dedicate this thesis

to my family, my teachers and my friends
for supporting me all the way & doing all
the wonderful things for me.

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LIST OF SYMBOLS, ABBREVIATIONS

BCR	Bearing Capacity Ratio
B or D	Width of footing
u	Depth of first layer of reinforcement from base of footing
h	Vertical spacing between reinforcement layer
N	Number of reinforcement layers
$q_{\mathrm{reinforced}}$	Bearing pressure of soil when reinforced
$q_{\mathrm{unreinforced}}$	Bearing pressure of soil when unreinforced
$s_{\mathrm{reinforced}}$	Settlement of footing on reinforced soil
$s_{\mathrm{unreinforced}}$	Settlement of footing on unreinforced soil
MD*	Machine Direction
CD*	Cross Machine Direction

CHAPTER 1

INTRODUCTION

1.1 GENERAL

From thousands of years in past insertion of different materials with soil has been done. Incorporation of materials that were naturally available were used to support the soil to lift the load coming on the soil. Natural materials were used in road construction to uphold roadway and their edges in Roman time and were also used in steep slope as with pyramids in Egypt. Ziggurats of Mesopotamia, 3000-year-old, made up of clay bricks reinforced with woven mat of reed laid horizontally on sand and gravel layer. Great wall of China, 7th century BC to about 17th century AD, eastern section is made with bricks ad chiseled stone while in western part is made from less durable material like clay, pounded earth reinforced with tree branches. Coconut leaf mattresses were also used in road construction on weak soil. Abode bricks, earth bricks made by Arabs in 7000BC, had embedded straw in it which improved tensile strength of the brick and resisted tearing and squeezing. In rural India, wall made of mud were embedded with bamboo mats as a reinforcing material. The early material that were used in reinforcing the soil and giving strength were generally made of fibers, vegetation that were naturally available and were mixed with soil to enhance the quality of soil, especially when the construction was to be done on soft, unstable soil.

Major problem with natural materials to be used as reinforcing material to improve property of soil was their biodegradable nature. Microorganisms present in soil degrade the material with time and thus the potential of material get reduced. Hence the durability and strength of the structure get affected. With the introduction of polymers in the 20th century a stable, durable material became available that can be used in place of less stable and degradable natural fabric material for stabilization. These polymeric materials are known as geosynthetic materials.

In the 20th century early application of polymeric material as reinforcement started. Corduroy mats were used in south California in 1920 for the construction of roads accessing to forest. Fabric filters were also used by Terzaghi. Japan used polyvinyl bags for sea wall instead of straw bags. In Netherland, geotextile tubes were used for dykes.

Soft soil having low shear strength, and is highly compressible with low permeability is termed as a soft soil. It is generally having shear strength less than 40 kPa and can be easily molded by finger by applying light pressure. Construction on soft soil is a great challenge for geotechnical engineers. General problems that comes while working or after construction in this type of soil are inadequate bearing capacity, excessive settlement after construction of structure, instability of soil while excavation. Due to settlement load carrying system of soil gets changed and if ground water table at the location of construction is high, water will also apply buoyancy force thus influencing the total surcharge on soil.

We already know that when footings are laid above soil which are weak in strength at lower depth or are built up on top of cohesive soil deposit or soil of medium to high plasticity, it leads to many engineering problems to the superstructure constructed. It has low load bearing capacity or can face excessive settlement of the foundation more than the permissible limit. This further leads to structural damage or reduction in the performance of the structure or affects the durability of the structure. Thus, making structure fail before serving its intended purpose. Earlier method was adopted in which top existing cohesive soil is removed and was later filled with adequately thick layer of granular fill to increase the load bearing capacity or for reduction in settlement of the foundation. Another method which was adopted was to increase the footing size so that load can be distributed to a larger area and lesser pressure is induced in the soil. Sometimes both the methods were adopted to safeguard the structure. But these methods were not economical and didn't provide sufficient strength as actually required. Now with the increase in use of geosynthetic material in many engineering works as a reinforcement and has wide applications like, mechanically stabilizing the earth walls, slopes, pavements, earth structure, reinforcing foundation of soil, or for long lasting road constructions, stable embankment over soft soil. It can also be used to reinforce the foundation but has not got very attention till now and research are still going whether it will be fruitful to use it as a reinforcement or not and how will it affect the load bearing capacity of the foundation soil and what will its effect on the settlement of the foundation.

The perks of incorporation of reinforcement within the soil to improve the bearing capacity and curtail the settlement have been widely known. Many theories have been given regarding the failure mechanism of the reinforced soil mass. however, the working of reinforcement in improvement of reinforcement is still not fully understood. Therefore, it is necessary to find out the mechanism of soil which is reinforced.

Das and Omar [1] studied the effect of footing width on model tests on sand and reached the conclusion that the bearing capacity ratio (BCR) was practically constant when the width of a footing was equal to or greater than 130 mm to 140 mm. The BCR here is defined as the ratio of the bearing capacity of reinforced soil to that of unreinforced soil.

Every structure built is having two major parts i.e. superstructure and its foundation. Foundation is a buried but very essential part for any structure build up on soil of any type whether it is an offshore or onshore structure. It receives heavy load from the superstructure build upon it and give away evenly to the soil beneath it so that structure is safe and stable. The performance of structure depends upon the performance of its foundation. So, it is very important that foundations are designed properly.

With the increase in population and rapid development taking place all over the world availability of suitable lands have become insufficient. So, it has become necessary to make the unsuitable land suitable for use. The purpose is basically to increase the load carrying capacity of soil or making it stable so that it does not fail under the load to which it will be subjected in future. For that various techniques, have been developed in past but most of them were time consuming and were not economical. The introduction of geosynthetic materials in 20th century has been a relief for civil engineering structures that were to be built on weak, fragile or soft soils, plus they are easy to work on and are highly economical in comparison to conventional methods.

Geosynthetics are fabricated materials that are being widely used to stabilize terrains. Their polymeric nature makes them applicable in places where high durability and strength is required. They are developed per specific function for which they will be used and have wide applications in geotechnical engineering like in construction of roads, railroad, earth structures, dams, canals. to stabilize slopes, embankment over soft soil, pavements etc. They are now the modern civil engineering construction materials because of it application in it. They modify the behavior of soil and make them better for further use.

Geosynthetic is a well-known technique in soil reinforcement. The use of it can significantly improve the soil performance and reduce costs in comparison with conventional designs. There are two major groups of geosynthetics, one is geotextile and another is geomembrane. The fabric of geotextile is permeable while geomembrane is impermeable. Both geosynthetic can be used per their properties.

Geotextiles are continuous sheets of woven, nonwoven, knitted, or stitch-bonded fibers or yarns. The sheets are flexible and permeable and generally have the appearance of a fabric.

Every group of geosynthetics can be used for different applications. Groups of geosynthetics and their applications are listed below

Geospacers: impermeable spacer used within the drains
Geowebs: an American term for cellular geotextile
Geogrid: large rectangular apertures or non-rectangular apertures
Geosynthetics: geotextile, geomembrane but not included natural fibers
Geofabrics: geotextile related product excluding geomats.
Geospacers: geosynthetics related product included natural fibers
Geocomposites: made by two or more products

1.2 Fibers for geosynthetics

Different fibers obtained both from natural as well as synthetic category can be used as geotextiles for various applications.

1.2.1 Natural fiber

Paper strips, jute nets, wood shavings or wool mulch are the used to make a geotextile. Generally Natural fibers are utilized for prevention of soil erosion until vegetation can become properly established on the ground surface. Major group of Natural fiber are Ramie and Jute.

1.2.2 Synthetic fiber

Polyester, polyamide, polyethylene and polypropylene are the four-major group of synthetics fiber. Another group of polymers with a long production history is the polyamide family

1.3 Geogrid

Out of all the geosynthetic materials at present, Geogrid is the one which is used as reinforcement in the soil. Geogrid, figure 1.1, is a planar, polymeric structure having regular opening for proving tensile strength, bonding has a uniformly distributed array of apertures between their longitudinal and transverse elements. The polymeric materials from which geogrid are generally made are high-density polyethylene, polyester, and polypropylene. These materials are the important component in the design of geogrid. It has stiffness and tensile strength which make it widely usable as a reinforcing material. Geogrid has large apertures which enables soil to act as a single material and allow proper bonding between the soil. When the geogrid is incorporated with the soil, it takes up the tensile load coming in the soil and helps in distributing it uniformly in the soil beneath. Due to this reason, geogrid is high in demand in the construction world these days.

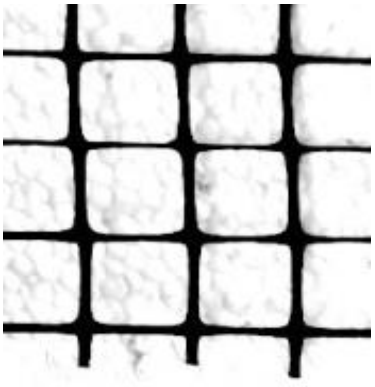


Figure 1.1 Geogrid

1.3.1 Manufacturing of Geogrid

The grids of the geogrid are formed by the ribs which are properly intersected by the manufacturer along two directions. The first direction is the machine direction (MD), which is the direction in the manufacturing process. The second direction is called the cross-machine direction (CMD), which is perpendicular to the machine direction**.** The ribs of the geogrid form a matrix structured material. The open area between the perpendicular ribs is known as aperture. The size of aperture varies from 2.5cm to base on the arrangement of the ribs in longitudinal and transverse direction.

Among different types of geosynthetics material available, Geogrid are stiffer. The strength at the joint of the ribs is considered as important as load is transferred to the soil through these joints coming from the adjacent ribs. The three most used methods for the manufacturing of Geogrid are as follows.

1.3.1.1 By Extruding

In this method of manufacturing of geogrid, flat plastic sheets are extruded into required configuration. The material used in the manufacturing can be a high-density polyethylene or high-density polypropylene. Then the punching pattern is placed above these sheets to give the sheet desired shape and form proper grids.

The punching in the sheet will form pattern of holes known as apertures. Now the material is stretched in longitudinal as well as transverse direction to develop tensile strength in the geogrid.

Figure1.2 Geogrid sample manufactured by Extruding
(Courtesy: The Constructors: Civil Engineering Home for Civil Engineers)

1.3.1.2 By Knitting or Weaving

In this method of manufacturing, polyester or polypropylene material yarn undergoes the process of either weaving or knitting to form flexible junction. These materials have high tenacity so that geogrid manufactured is having tensile strength and other basic properties. Then these geogrids are coated with bitumen or latex or polyvinyl.

.

Figure 1.3 Geogrid sample manufactured by knitting

(Courtesy: The Constructors: Civil Engineering Home for Civil Engineers)

1.3.1.3 By Welding and Extrusion

This is the latest developed method of manufacturing of geogrid. in this method polyester or polypropylene sheets are extruded by passing them through roller. This is done in a machine which adjusts automatically and runs at different speed, which stretches the ribs of geogrid and this increases its tenacity.

1.3.2 Functions of Geogrid

- **Stabilize Soil Mass**

The geogrid serves the objective of holding the particles together whether it is a soil or an aggregate. This interlocking helps in mechanically stabilizing the earthwork. The aperture helps in proper interlocking between the soil and aggregate.

- **Improvement of Bearing Capacity**

Installation of geogrid helps in the reduction of lateral movement of aggregates. This would further result in the elimination of stresses. Geogrid possess frictional resistance which resist the lateral movement of the subgrade. Thus, improving the bearing capacity of soil due to the formation of inward stresses.

- **Lateral Restraining Capability**

Due to the wheel load on the pavement, results in lateral movement of aggregate, which disturbs the stability of the aggregates. The geogrid here acts as a restraining agent, which restrains the aggregate movement.

1.3.3 Types of Geogrid

Based on manufacturing:

- Extruded Geogrid
- Woven Geogrid
- Bonded Geogrid

Based on direction of stretching during manufacturing:

1.3.3.1 Uniaxial Geogrid

These types of geogrid are formed because of stretching of ribs of geogrid in longitudinal direction. So, this type of geogrid possesses high tensile strength in longitudinal direction than that on transverse direction.

1.3.3.2 Biaxial Geogrid

In this type, stretching in the geogrid is done in both the directions, longitudinal as well as transverse. Hence tensile strength is equally distributed in both the direction.

1.3.4 Application of Geogrid

- **In construction of Retaining Wall**

It holds the soil backfill which results in the stable backfill. It also increases the soil structural integrity and thus help in distribution of load. The geogrid makes the whole structure to behave as a single unit. Thus, by increasing the length of geogrid, whole mass of structure will increase thus help in making taller wall.

- **In Foundation Soil**

When the geogrid is placed in the foundation of structure, it acts as a reinforcing material. Geogrid has high tensile strength and stiffness thus making it a good reinforcing material. It improves the bearing capacity of the foundation soil enabling it to carry more load.

- **In pavement construction**

Placement of geogrid in the subgrade, make it solid and strong which is the most important load bearing layer. it also helps in stiffening the base course of pavement thus reducing the thickness of the base course. It also increases life of pavement.

1.3.5 Advantages of Geogrid in Construction

- It is easy to handle and use in field. And can be laid in any weather condition.
- It helps in bringing unsuitable land in use. Thus, proper utilization of land.
- Helps in soil stabilization.
- Helps in obtaining soil mass of higher strength.
- Helps in reduction of soil erosion.
- Easily available.
- Highly durable and require less maintenance cost.

The main objective for the research presented in this dissertation is to contribute towards the design of safe, durable, and economical structure which is constructed on reinforced soil. To full fill this condition, soil is reinforced with Geogrid in our research study.

1.4 Objective of the study

After reviewing literature survey, it is revealed that limited information is available and few researches have been done in past on reinforced clayey soil with geosynthetic material provided as reinforcement. In this study laboratory model, has been prepared of steel tank of dimension 750mm×450mm×375mm with acrylic sheet in front. Steel footing of dimension 75mm×75mm will be used. Load will be applied through Compressive Testing Machine (CTM). Parameters that will be considered in the test will be top layer spacing between footing base and reinforcing layer (u), number of reinforcement to be provided (N), vertical spacing between the reinforcing layers (h), stiffness of the reinforcement and the type of reinforcement to be provided.

Main objectives of the proposed study are-

- To investigate the benefits of using reinforced soil foundation to improve Ultimate Bearing Capacity of cohesive soil.
- To check the optimum numbers of reinforcing layers to be provided below the footing.
- To study the effect of different parameters on the behavior reinforced soil.

CHAPTER 2

LITERATURE REVIEW

2.1 General

Foundation laid at a shallow depth creates problem in structure when built up above a cohesive soil. Settlement in cohesive soil is not immediate and take place over a long period even after the construction is over unlike in sandy soil which shows immediate settlement after load application. Therefore, footing on cohesive soil need more attention and care should be taken to avoid excessive settlement. Conventionally technique of removing top cohesive soil up to depth of footing was adopted and backfilled with adequately thick granular fill material of sufficient strength to safely take up the load and distribute it evenly in the ground below. Another technique that was adopted was to increase the dimensions of the footing as it will increase the base area of the footing and the pressure that will be acting at the base of the footing will get minimized. Sometimes both the methods were adopted but these methods were time consuming and were not economical. Hence researches are being conducted to investigate methods that will be efficient in reducing the settlement of the footing to a considerable level and along with it increase the bearing capacity of the footing. For this purpose, installation of geosynthetic material as reinforcement is tested.

From the past work done by various researchers it has been recorded that inclusion of reinforcement in the soil improves the bearing capacity of the soil mass. One of the noticeable input in this area was done by Binquet & K.L [2] who gave a new method for finding the BCR, bearing capacity ratio. Thereafter researchers evaluated the potential of providing reinforcement in form of bearing capacity ratio. They focused on finding parameters which would directly influence the BCR.

From the presented literature study's results show that improvement in the bearing capacity is observed when the reinforcement is placed within certain limit beyond which there will be no noticeable improvement. Researchers have also given the range for layer spacing between footing and reinforcement, number of layers of reinforcement to be provided, optimum vertical spacing between each layer. The enhancement in the bearing capacity of the reinforced soil mass is dependent on bearing capacity of unreinforced soil mass and reinforcement properties like stiffness, rupture strength, also dependent on reinforcement shape, its rib thickness and aperture shape, also dependent on layout of reinforcement such as depth, spacing.

Sakti & Das [3] presented laboratory investigation on model strip footing placed over soft clay bed. The clay is reinforced with geotextile which is heat-bonded nonwoven polypropylene. From the results, it was concluded that with the incorporation of geotextile in saturated clay, improves its bearing capacity. The optimum distance between footing base and first reinforcement is between 0.35B to 0.40B. The reinforcement placed below a distance equal to width of footing has no influence on bearing capacity. The ultimate bearing capacity occurred at a settlement of 0.16*B* to 0.18*B* and the optimum length of reinforcement is 4B.

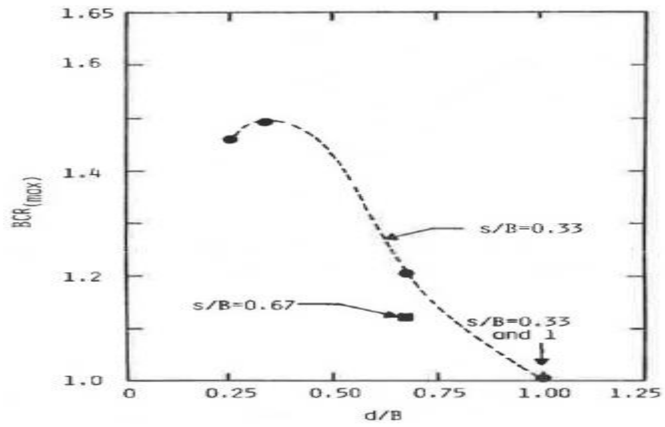


Figure 2.1 Variation of BCR with d/B

Mandal & Sah [4] studied the improvement in bearing capacity of the clay subgrade when reinforced with geogrid placed horizontally. Square footing was laid on the clay. The results of the experimental investigation showed that with the inclusion of reinforcement, bearing capacity of the clay subgrade increases. It was observed that the optimum distance between the base of footing and the reinforcement first layer is 0.175*B* and at this location Bearing capacity ratio 1.36. Maximum reduction in the settlement is about 45% and occurred at 0.25*B* from footing base.

Das & Omar [1] presented model test results on sand bed reinforced with geogrid. Model footing was taken as a strip footing. Only one type of geogrid was used for experiments and uniform fine sand was used. The relative density of sand and the width of the foundation were varied in the test to determine their effects on the bearing capacity ratio (BCR). It was observed that BCR decreased with increase in the foundation width up to certain limit. However, beyond 130mm-140mm foundation width, the BCR was practically constant.

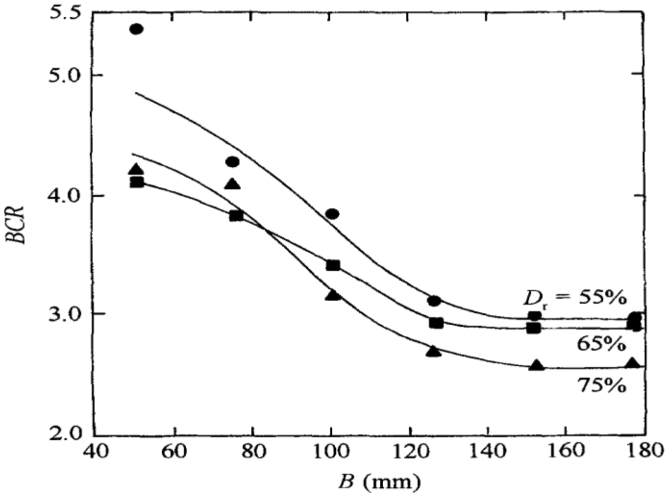


Figure 2.2 Variation of bearing capacity ratio BCR with foundation width B

Yetimoglu, et al. [5] investigated the bearing capacity of rectangular footing on sand reinforced with geogrid both by experimental and finite element analysis. The parameters that were investigated were vertical spacing from footing base to geogrid first layer, width of reinforcement, number of reinforcing layers. From both experimental and finite element analysis, it was observed that optimum embedment depth is at which bearing capacity was highest was when single layer of reinforcement was used. The bearing capacity also increased with increase in number of reinforcing layers and width of reinforcement when placed in effective zone. It was also concluded that beyond a certain value increase in stiffness of reinforcement would not increase the bearing capacity.

Das, et al. [6] did a comparative study on bearing capacity of surface strip foundation on geogrid reinforced sand and clay. Only one type of geogrid was used for the comparative study. Parameters studied in the tests were top layer spacing, number of reinforcement. He concluded that the settlement in clay for both reinforced and unreinforced are same but in sand the increases in ultimate load with reinforcement increases the settlement. The first layer of geogrid was placed at 0.3*B* to 0.4*B* to obtain maximum benefit. For maximum bearing capacity ratio, the optimum width of reinforcement in sand is 8*B* and in case of clay it is 5*B*.

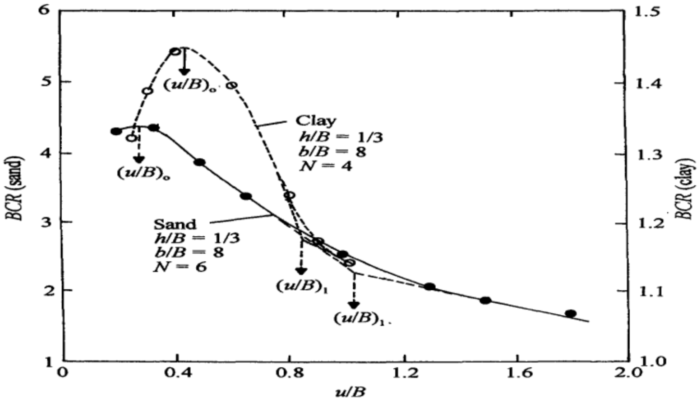


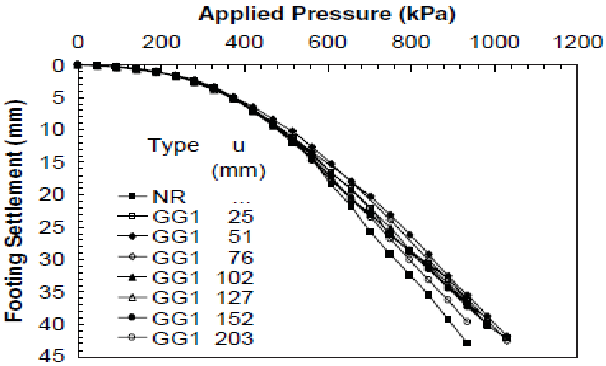
Figure 2.3 Variation of BCR with u/B

Mandal & Gupta [7] carried experimental investigation on soft clayey soil using geocell as a reinforcement to find reinforcement effect on the soft soil. Laboratory model tests were conducted on marine clay overlaid by a sand layer to obtain the bearing capacity in reinforced and unreinforced condition. Strip footing was used as footing. It was concluded that up to a settlement ratio of 5-10% geocell layer exhibit beam action and after 20% it exhibits membrane action. The stiffness of the sand layer increased due to geocell layer. bearing capacity increases with increase in thickness and opening of geocell. For maximum profit at low settlement, geocell of smaller opening should be used and at higher settlement, geocell of large opening should be used.

Adams & Collin [8] studied the benefits of soil reinforced with geosynthetic material. Tests were performed on large scale model footing. 34 tests were performed to observe the effect of single and multiple layers of geosynthetic reinforcement. Tests were performed on shallow spread footing. Two types of geosynthetic material were used: a stiff biaxial geogrid and a geocell. The parameters which were considered during tests were thickness between reinforcement layers, depth of first reinforcement layer from footing base, plan area of reinforcement, spacing between layers and soil density. Test results showed increase in ultimate bearing capacity of footing by a factor of 2.5.

Kumar & Saran [9] performed a total of 74 tests on closely spaced strip and square footing on sand reinforced with Geogrid to study the effect of spacing between footings, reinforcement size and continuous and discontinuous reinforcement layers on bearing capacity and tilt of footing. It was concluded that there was insignificant effect of interference on bearing capacity and settlement of closely spaced square footing in comparison to isolated footing on reinforced sand. Improvement in tilt of adjacent square footing was also observed. Also, improvement in bearing capacity, tilt and settlement was also observed in closely spaced strip footing.

Chen, et al. [10] studied the behavior of foundations on geosynthetic-reinforced clayey soil of low to medium plasticity. They used laboratory model footing made of a steel plate with dimensions of 152mm × 152 mm. They studied the effect of the top layer spacing, the number of reinforcement layers, the vertical spacing between layers, and the stiffness and type of reinforcement on the settlement. The effect on the vertical stress and the strain distribution was also investigated. The result showed increased bearing capacity and reduction in settlement. Settlement could be reduced to more than 50% after providing three or more reinforcing layers. Performance of high stiffness geogrid was better than lower stiffness geogrid. Result also showed insignificant strain beyond effect length of 6.0B (B is length of footing).



Figure, 2.4 Pressure–settlement curves for model footing tests with single layer of GG1 placed at different top layer spacing

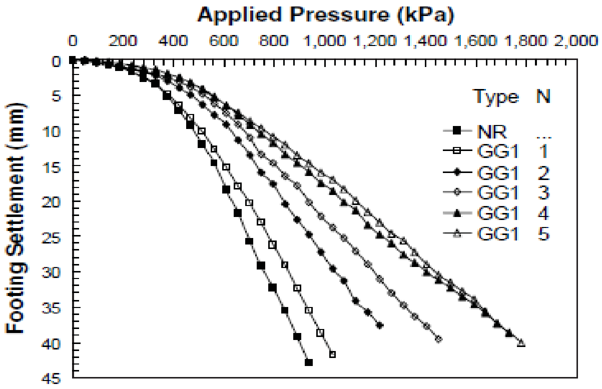


Figure. 2.5 Pressure–settlement curves for model footing tests with different number of reinforcing layers of GG1

Sawwaf [11] studied the benefit of providing reinforcement on a replaced sand layer near slope crest. Laboratory investigations were carried out using a square footing of dimension 75mm×75mm. geogrid were used as a reinforcing material. Parameters considered in the study were replaced sand depth, footing location with respect to slope crest. Finite element analysis was carried on prototype slope with two-dimensional plane strain condition using Plaxis software. The results obtained showed that with the incorporation of geogrid in replaced sand improves performance of footing and reduce allowable settlement. The efficiency of system increased with increasing number of layers and length of geogrid

Boushehrian & Hataf [12] studied the effect of reinforcement on soil when as a shallow foundation is laid. In this, load is transferred in the clayey soil through ring and circular footing and geogrid is used as a reinforcement. The researchers presented both laboratory and numerical investigations. The parameters studied in the tests were distance of first reinforcement from footing base, distance between the reinforcement layers, optimum reinforcement depth, stiffness of reinforcing material. From the results, it was observed that, using a higher stiffness geogrid does not always results in increase in bearing capacity ratio. Bearing capacity ratio increases by increasing number of reinforcement up to influence depth. The effect of reinforcement in improving bearing capacity was more on circular footing than that of ring footing. Bearing capacity of sandy soil was more than that of a fine-grained soil.

Sharma, et al. [13] formed analytical solutions for calculating the ultimate bearing capacity of geogrid reinforced sandy soil and silty clay soil. Proposed analytical solution was verified by large scale model test and the data reported in the literature. The predicted bearing capacity values from analytical solutions are in good agreement with the test results

Latha & Somwanshi [14] presented laboratory model test result and numerical stimulation on square footing resting on sand to evaluate bearing capacity and effect of reinforcement. Parameter studied were type and tensile strength of geosynthetic material, amount of reinforcement, layout and configuration of geosynthetic layers below the footing. Steel tank of size 900×900×600mm was used and four different type of geogrid were used as reinforcement. Test result of unreinforced and reinforced footing were compared. Result showed that effective depth of reinforcement is twice the width of footing and optimum spacing of geosynthetic layers is half the width of the footing. It was also observed that layout configuration of footing also plays an important role in bearing capacity improvement.

Tafreshi & Dawson [15] studied strip footing on geocell and planar reinforced sand beds. Parameters studied were width o reinforcement, number of layers of geotextile, height of geocell below the base of footing. They investigated performance at low settlement level. Result showed decrease in efficiency of reinforcement by increasing number of planar reinforcement performance, height of geocell reinforcement and width of reinforcement. For the same mass of geotextile material used at the settlement level of 4%, the maximum improvement in bearing capacity (IF) and percentage reduction in footing settlement (PRS) were obtained as 2.73 and 63% with the provision of geocell, respectively, while these values compare with 1.88 and 47% for the equivalent planar reinforcement. Conclusion obtained from the test was that geocell reinforcement behaves much stiffer and have more load carrying capacity and settles less as compared to equivalent planar reinforcement.

Farsakh, et al. [16] did finite element analysis to evaluate the benefits of providing reinforcement of crushed limestone below strip footing to find out the effect on bearing capacity and reduction in settlement of footing. The crushed limestone was modeled using the Drucker- Prager constitutive model, and the crushed limestone reinforcement interaction was modeled using the Coulomb friction model. Result showed that there exists an optimum depth of first reinforcement where highest bearing capacity is obtained. Regression analysis was also performed on the results of FEA to develop a model that evaluates the increase in the bearing capacity of reinforced crushed limestone.

Tafreshi & Dawson [17] presented laboratory test results of strip footing supported in unreinforced and geotextile reinforced sand bed which was subjected to static and repeated loads. The influence of repeated load and number of geotextile layer on the footing were investigated. It was observed that rate of settlement decreased as number of loading cycle increased and with increases in amplitude of repeated load footing settlement increases irrespective of reinforcement layer.

Lavasan & Ghazavi [18] presented experimental investigation performed on two closely spaced footing one having square shape and other having circular shape. The experiments were done to investigate the effect of geogrid on the bearing capacity, settlement and tilt of the footings. The results obtained showed increase in the ultimate bearing capacity of the interfering footing of about 25-40% but it also showed increase in settlement of order 60-100% and tilt by 45% with one geogrid layer and 75% with two geogrid layers.

Javdanian, et al. [19] studied the effect on bearing capacity due to the interference phenomenon of footings. The behavior of footing gets strongly affected by the distance between the two footings. Tests were conducted on interfering strip shallow footings over sand reinforced with geogrid. Tests were conducted on a cubical metal box of size 1.10m×0.75m×0.60m anchored with braces to arrest lateral deflection due to loading. Correlation parameters were also derived for quantifying the results. For interference factor, artificial neutral network (ANN) model was used. The study showed significant improvement in behavior of interfering footing.

Farsakha, et al. [20] studied behavior of foundation on geosynthetic reinforced sandy soil. And, studies the factors which effect the performance using laboratory test model. Parameters investigated were top layer spacing, number of reinforcement, vertical spacing, tensile modulus, type of geosynthetic reinforcement, its embedment depth, shape of footing. Test result showed that layout of configuration of reinforcement has significant effect on behavior of reinforced sand footing. With two or more reinforcement layer settlement, can be reduces to about 20%. Result also showed that sand reinforced with composite of geogrid and geotextile performed better than sand reinforced with geogrid or geotextile alone. Reinforcement also distribute load more uniformly hence reducing stress concentration.

Altalhea, et al. [21] presented behavior of a strip footing supported on a single layer of geotextile and by row of soil nails in sandy soil. Comparison between the two was also presented in the paper. Parameters that were studied in the study was varying depth of reinforcement layer, edge distance of footing, location of row of soil nail, location of footing relative to slope crest. Comparison between bearing capacity of un-stabilized and stabilized slope was also done. Result indicated that bearing capacity has been increased after the use of geotextile layer and soil nail. The improvement in the result increases by decreasing the spacing between the soil nails and with N=3 optimum bearing capacity is obtained.

Martho, et al. [22] presented a review study showing the effect of geogrid reinforcement on bearing capacity of soil under static loading. It was concluded that use of geogrid makes bearing capacity and settlement relation almost linear until reaching at failure. With increase in number of reinforcement and reinforcement width, the bearing capacity increased. Top layer thickness from footing to geogrid is important and geogrid has no effect when the ration of top layer spacing and width of footing is equal to 0.5. Bearing capacity increased as the thickness between the number of reinforcement decreased. Efficiency in reducing settlement decreases as the width of geogrid increased.

Kolay, et al. [23] presented study of improved bearing capacity of silty clay soil with thin sand layer at top and geogrid placed at different depth. Test showed that bearing capacity increases with increasing number of reinforcement layer. Bearing capacity increased with average value of 16.67% with one geogrid layer soils with u/Bequal to 0.667, the bearing capacity increases with an average of 33.33% while using one geogrid in middle of sand layer with u/Bequal to 0.33.

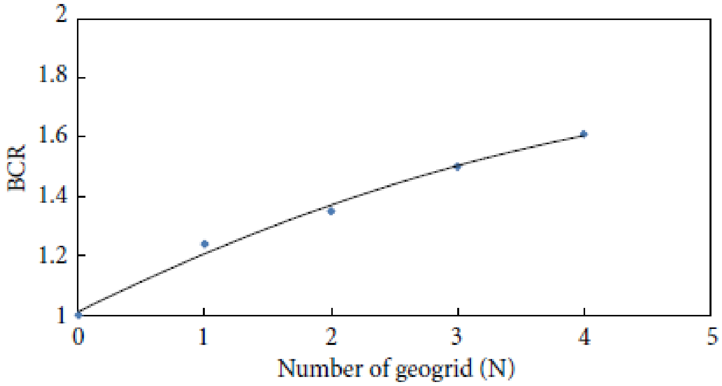


Figure. 2.6 Bearing capacity ratio BCR with number of geogrid (N) in two-layer soil system

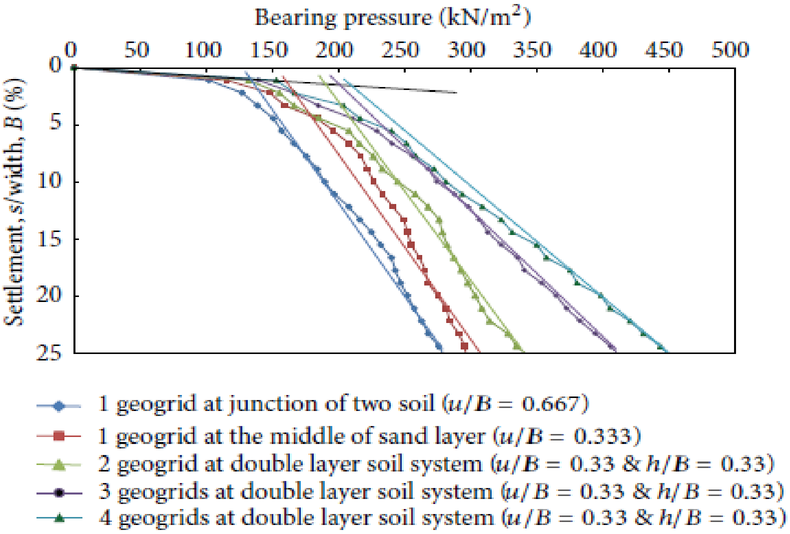


Figure 2.7 Estimation for ultimate bearing capacity (qu) from bearing pressure versus s/B (%).

Dixit & Patil [24] studied the behavior of river sand reinforced with glass fiber geogrid to improve the bearing capacity of the sand locally available. A square footing was used for the experiments and the model tests were conducted on a steel tank of dimension 900mm×1200mm×1000mm. Tests were conducted at 83% relative density and the parameters which were considered for the tests were the depth of the top layer of geogrid reinforcement below footing and gradation of sand. Sand was designated as sand 1, sand 2, sand 3. It was concluded that the bearing capacity and settlement has improved in compared to unreinforced sand.

Ciceka, et al. [25] presented laboratory result of model strip footing on unreinforced and reinforced sand bed to investigate effect of reinforcement length. Different size of footing was tested, and number of reinforcement were also varied to know the influence on optimum reinforcement length. Load, settlement and bearing ratio were obtained from test. From result, the length of footing required to achieve optimum improvement was determined for different numbers of reinforcement layers and different reinforcement types.

Infante, et al. [26] presented paper on circular footing on unreinforced and geogrid reinforced granular soil. He used two geogrid layers i.e. uniaxial and biaxial at the interface of sub-base and granular base and test were conducted to determine improvement in performance by providing the geogrid reinforcement over unreinforced soil. Also, studied improvement by anchoring geogrid at edge. Result showed improvement in bearing capacity and reduction in settlement and better results were observed when geogrid was anchored.

Prasad, et al. [27] conducted experimental investigation ton model square footing to obtain load-settlement response on unreinforced and reinforced granular beds. The experimental work was conducted for two cases: (a) geogrid-reinforced sand layer and (b) geogrid-reinforced layered system having aggregate layer over a sand layer. Parameters considered were aggregate layer thickness, depth of reinforcement from base of footing in sand layer and aggregate layer, reinforcement width and relative density of bed. Relative density of 50% and 70% was achieved from plate vibrator. A model tank of dimension 1m×1m×1m was used on which all tests were conducted. A square footing was used, and load was applied using a 100kN actuator in displacement control mode. It was concluded that bearing capacity has increased with aggregate thickness over sand bed. Optimum depth of reinforcement in sand was found to be 0.45 times the width of footing and in aggregate over sand it was found to be 0.3 times width of footing. Bearing capacity at optimum depth for sand only increased about 66% and for aggregate over sand it increased about 27%.

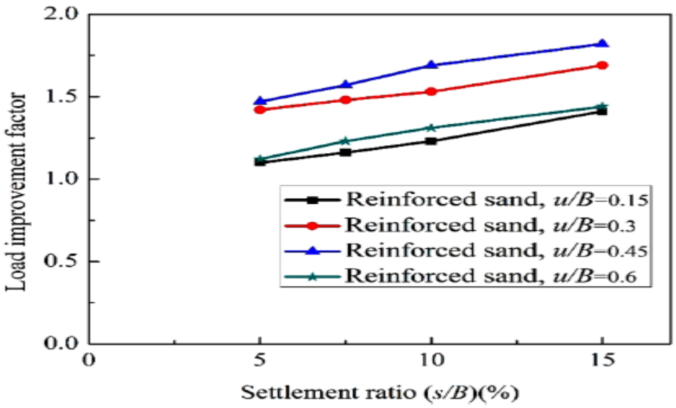


Figure 2.8 Variation of load improvement factor with settlement ratio (s/B) for reinforced sand

Makarchian & Badakhshan [28] presented paper which studied circular and square footing resting on reinforced sand bed. The steel model footing with 12 cm diameter and square footing with 10.6 cm width in sand. Result show bearing capacity improvement is more in square footing than in circular and when reinforcements used with embedment depth (*u/D*=0.42 or *u/B*=0.47), the bearing capacity ratio (BCR) was increased greatly in circular footing in comparison with square footing. Result also showed that BCR increases with increase in number of reinforcement layer for both square and circular footing.

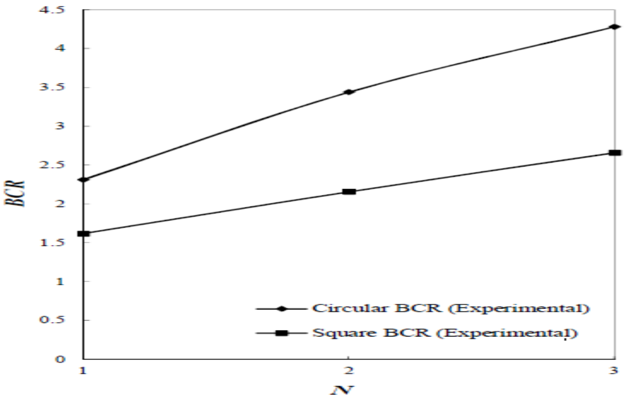


Figure. 2.9 BCR versus N (number of geogrid layers) for circular and square footings.

Munawir [29] presented an experimental study on a strip footing resting on a geogrid reinforces sand. Series of load tests were first conducted on unreinforced sand and then on reinforces sand to compare the results. In the experiment, only the top layer thickness from footing to first geogrid layer and the number of geogrid used were varied. The u/B is varied as 0.25*B*, 0.5*B* and 0.75*B* and number of reinforcement is taken as 3. The test results showed optimum value of top layer spacing from the base of the footing to the first reinforcement layer u=0.5B.

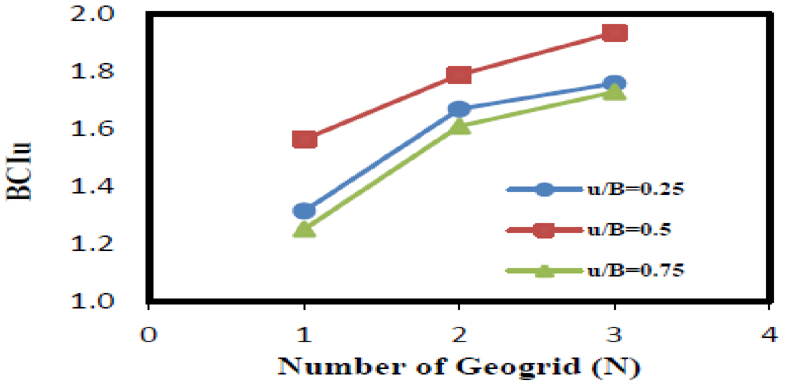


Figure 2.10 BCIu vs.

Shadmand, et al. [30] presented load carrying characteristic of large scale square footing of steel with 500mm×500mm×30mm dimensions and the tests were performed on sand reinforced with two different reinforcing methods i.e geocell with an opening reinforcement (GOR) and full geocell reinforcement (FGR). Parameters investigated are depth of geocell from surface, width of opening in geocell in the GOR type, relative density of sand and number of layers of geocell. Results showed that the use of both type of reinforcement improved the load carrying capacity, reduced footing settlement and decreased surface heave. With increase in geocell number from 1 to 2 for both reinforcement, bearing pressure has increased, settlement have reduced, surface heave has also decreased.

Connecting some results from the literature study show that, i) the optimum vertical spacing between the footing base and the first reinforcement layer is at a depth *u*, of 0.25*B* to 0.4*B*. Laying the first layer of reinforcement below this limit will result in no improvement in the bearing capacity. ii) The maximum depth *d*, for the placement of reinforcement is 1.3*B* to 2.0*B.* iii) the horizontal length of reinforcement, *b,* 3*B to* 8*B.* iv) the maximum number of reinforcement which will improve the bearing capacity four to five number of layers.

Table 2. 1 Comparative Literature study

Paper no.	Model footing	Reinforcement type	$\frac{u}{B}$	$\frac{b}{B}$	$\frac{h}{B}$
chen et.al	Square (152mm×152mm)	Geogrid Geotextile	0.33	3	0.167
Sharma et.al	Square (152mm×152mm)	Geogrid	0.33	-	0.44
Latha et.al	Square (150mm×150mm)	Weak biaxial geogrid(WG), Strong biaxial geogrid (SG), Uniaxial geogrid(UG), geonet	0.5	5-6	0.5
Tafreshi et.al	Strip footing	Geocell, Planar form of geotextile reinforcement	0.35	4.2, 5.5	1.5-2.0
Farsakha et.al	Strip footing	Grid reinforcement	0.35	4	-
Farsakha et.al	Square (152mm×152mm) Rectangular(152mm×254mm)	Geogrid, Geotextile, geocomposite	0.33	6	0.2
Altalhea et.al	Strip	Geotextile (single layer), Row of soil nail	0.5	-	-
Kolay et.al	Rectangular (284.48mm×114.3mm)	Geogrid	0.33	6	0.33
Ciceka et.al	Strip	Woven geotextile, geogrid	0.35	5	0.4
Makarchian et.al	Circular(d=12mm) Square(a=104.7mm)	Geogrid	0.25	-	0.5
Shakti et al.	Strip	geotextile	0.35-0.40	4	-
Mandal et al.	square	geogrid	0.175	-	-

CHAPTER 3

EXPERIMENTAL INVESTIGATION

3.1 Equipment's and Materials

Experimental investigation in this study is done on a clay soil of high plasticity. The basic objective of this experimental study is to determine the bearing capacity of clay soil when reinforced and to find potential gain in bearing capacity of clay soil and reduction in settlement of footing due to reinforcement. Compression testing machine (CTM) is used to apply concentrated point load on mild steel square footing which passes the load to clay soil beneath it. Here clay of intermediate plasticity is used and two different types of geogrid are used as reinforcing material. Test tank of dimension 0.750m×0.450m×0.375m is used on which all the experiments are carried out.

3.2 Material Used

3.2.1 Clay

3.2.1.1 Sample collection

The clay used in experimental investigation is collected from Tekanpur Town, near Gwalior City, Madhya Pradesh. Clay was intermediate plastic clay having plasticity index 22. Clay then went through cleaning process to free it from grass roots, debris, leaves and other organic matter etc. After cleaning process, it was dried in oven for 24 hrs. to remove all moisture from it. The dried clay was passed through 75 mm IS sieve and passed soil was used for our study purpose.

3.2.1.2 Characterization of soil

The experiments were done on clay of intermediate plasticity. Average unit weight of clay is Coefficient of internal friction of clay is 4° and cohesion is 0.85. Characteristic of clay and the grain size distribution used in the study are listed in the table 3.1 and figure 3.1 below.

Table 3.1 Properties of Clayey soil

Properties	Value
Specific Gravity	2.70
Percentage passing IS Sieve 75 micron (%)	83.0
Liquid Limit (%)	43.0
Plastic limit (%)	21
Plasticity index (%)	2
Maximum dry density (kN/m^3)	16.1

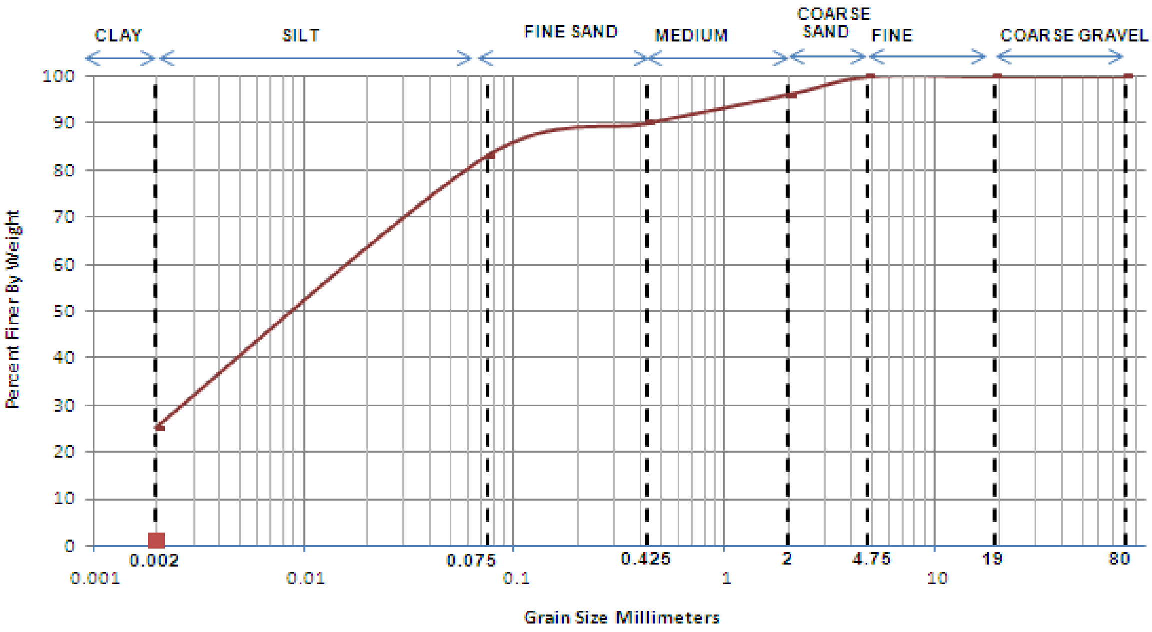


Figure 3.1 Grain Size Analysis

3.2.2 Geogrid

Geogrid are planer polymeric material made up of polymers like polyester, alcohol, polypropylene, polyvinyl or polyethylene and are formed by joining the ribs at the intersection. They are principally designed for reinforcement purpose. They have high tensile strength and large opening evenly distributed in between longitudinal and transverse rib. The direction of ribs is called as Machine Direction (MD) and perpendicular to Machine Direction is known as Cross Machine Direction (CMD or CD)). The opening is known as aperture and allows clay to be in direct contact and thus improves the interaction between clay and geogrid thus improving tensile strength. They are made from high modulus and high-density polymer. The properties of geogrid vary per polymer type and cross-sectional proportion. Based on the direction of strength in geogrid they are classified as Uniaxial having strength in one direction only and biaxial is having strength in both longitudinal and transverse direction. And on basis of rigidity they are classified as Flexible and Rigid geogrid. Due to applied load when soil strains, tensile force are generated in geogrid. This is because of the internal friction developed between the geogrid and the soil. The tensile force developed in the reinforced soil keep the soil in equilibrium. They are used for reinforcement of steep slopes, in roadway base, in foundations, retaining walls etc. Generally, for base reinforcement biaxial geogrid is used. In this study, two types of geogrid are used as shown in figure 3.2 and figure 3.3. One is named as Geogrid 1 (GG1) and other is Geogrid 2 (GG2). GG1 is geogrid of high stiffness and GG2 is of relatively low stiffness and the polymeric material of both the geogrid is polypropylene. Below is the table 3.2 showing property of geogrid used.

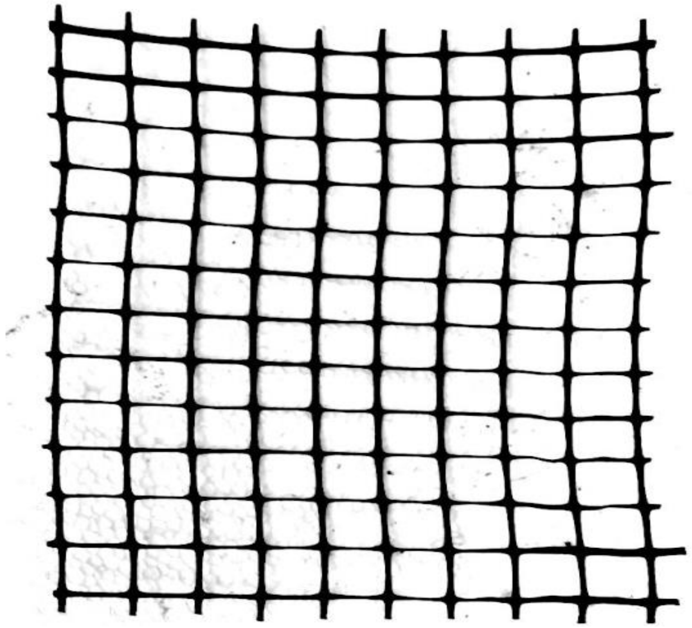


Figure 3.2 Geogrid 1 (GG1)

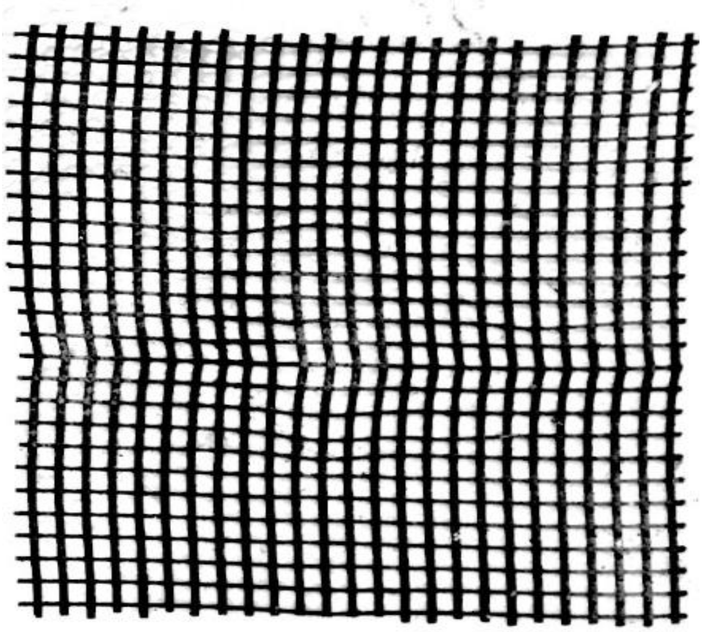


Figure 3.3 Geogrid 2 (GG2)

Table 3.2 Properties of Geogrid

Abbreviation	Type	Tensile strength (kN/m)		Tensile modulus (kN/m)		Aperture size (mm)
		MD*	CD*	MD*	CD*	
GG1	Polypropylene	5.5	7.4	274	372	30×30
GG2	Polypropylene	3.6	5.1	182	255	10×10

3.2.3 Test Tank

The tank used for carrying all the experimental study is of dimension 750mm×475mm×350mm. The dimension of the tank is decided from IS code and referring various literatures. As per IS 1888-1962, minimum size of testing tank should be at least 5 times the width of test plate to develop the full failure zone without any interference of side of the tank. Figure 3.4 shows geometric model of tank. Keeping in mind the above criteria the dimension of the tank is appropriate for square footing of dimension 75mm×75mm×25mm. The front length side of the tank is made up of with acrylic sheet of 8mm to observe the settlement of the footing and rest of the tank is made up of mild steel of thickness 8 mm. Horizontal bracing of 10mm thickness is provided on the front side of the tank to avoid bulging of clay due to load acting on soil.

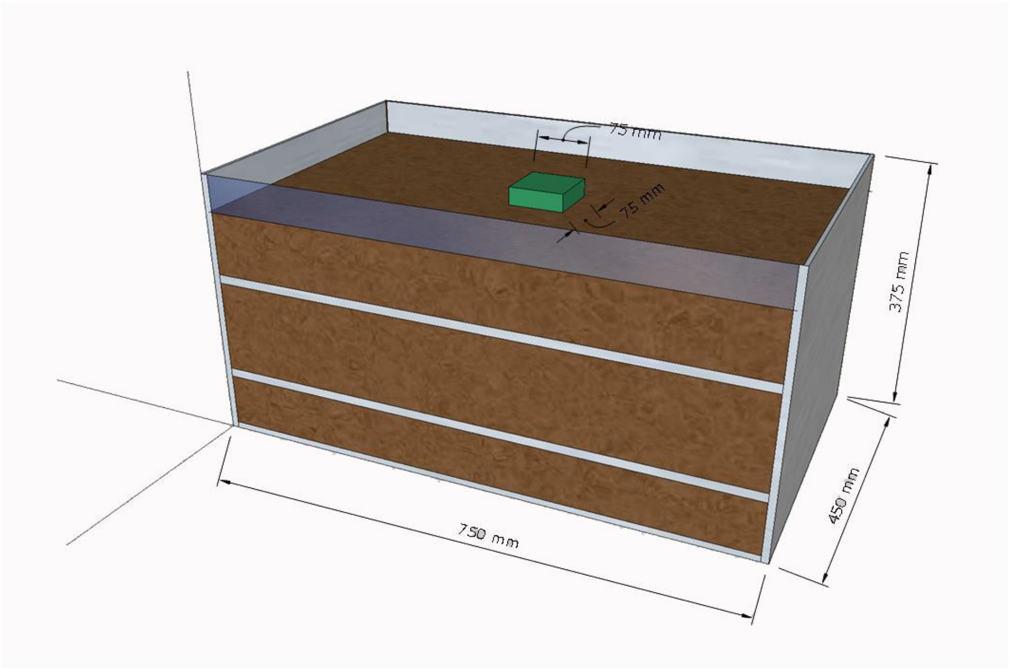


Figure 3.4 Geometric model for central vertical loading case

3.2.4 Equipment's Used

3.2.4.1 Static Loading Unit

A compression testing machine (CTM) is used to apply static concentrated load on the footing resting on clay bed. The machine is hydraulically operated and the loading frame consists of two vertical columns (for reaction purpose), a load cell, and a base platen. The Compression Testing Machine has inbuilt mechanism to measure load acting on the footing which is displayed over the data logger.

3.2.4.2 Dial gauge

A dial gauge is used to measure the settlement of the footing up to 20mm, which is having least count of 0.01mm. It is placed at one of the end of the footing to measure the settlement due to load increment. The dial gauge is supported over magnetic stand which is attached to one of the side of testing tank.

3.2.4.3 Model footing

A 25mm thick mild steel footing is used in the experimental work. Footing is square in shape, having dimension 75mm×75mm. It is placed at the surface of clay bed at center of the loading tank to eliminate eccentric load. The other face of the footing is made rough to develop proper bonding between the soil and footing base.

3.3 Model Test and Methodology

3.3.1 General

The study of observing the bearing capacity of square footing placed over clay bed reinforced with multilayer geogrid of two different types has been done in laboratory on testing tank. Testing is done on square footing resting on surface of clay with depth of embedment of footing as zero.

3.3.2 Sample Preparation

3.3.2.1 Placement of clay

The dimension of testing tank is measured from inside and accordingly the weight of the clay to fill the tank at specified desired height is calculated. Then the clay is mixed with hand at optimum moisture content calculate from standard proctor test. The clay is then placed in testing tank and compacted in 3 layers with help of rammer falling freely from a height varying between 25mm to 102mm depending upon reinforcement spacing. The reinforcement is provided at suitable depth from the base of the footing.

3.3.2.2 Placement of Geogrid

Geogrid of required size was cut and placed in the soil at the appropriate location as calculated. After placement of geogrid, soil was again filled in the tank up to top location.

3.3.3 Equipment Setup

After placing the clay soil in tank for unreinforced or reinforced condition, square footing is placed at the center of the tank to overcome the effect of the eccentric load. The footing is placed in such a way that the side of footing is parallel to the wall of the tank. Figure 3.5 shows loading arrangement of geogrid reinforced soil foundation. The cylindrical shaft of the loading unit is brought in contact with the footing to apply load. A dial gauge is also placed at one corner of the footing. Figure 3.6 shows equipment setup.

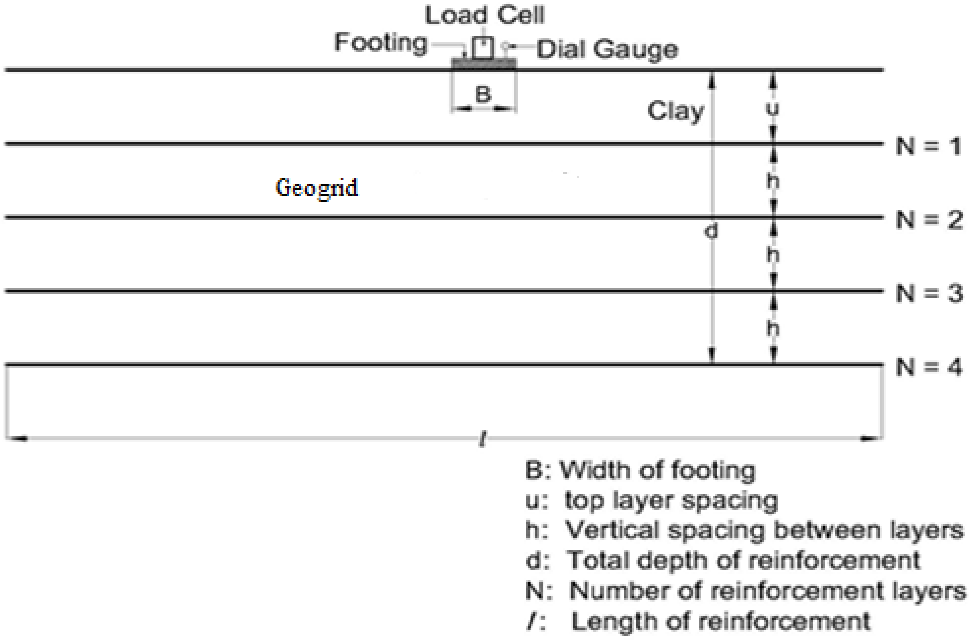


Figure 3.5 Geogrid reinforced soil foundation

Figure 3.6 Equipment Setup

3.3.4 Model Test Procedure

- First the model setup is prepared for unreinforced condition. So, the test tank is filled with clay soil without any reinforcement. Footing is placed at the surface of tank at center.
- After the arrangement of model setup and placing footing at center of clay bed, attach dial gauge at required position, initial reading of dial gauge is noted and as the load increases reading is jot down.
- The load on the footing is applied progressively on the footing and it can settle under the load.
- The load is applied continuously in increasing manner until ultimate bearing state is reached. Ultimate bearing state is defined as the state at which maximum load has reached or the state when footing settles continuously without any further increase in the load. The ultimate state is also said to have reached when there is abrupt change in the load settlement curve which can be observed the load settlement data.
- For the next test, the tank is emptied and the clay is again filled in the tank at same moisture content. Now reinforcement is provided at required depth. First, the tests are performed for Geogrid 1 (GG1) reinforcement.
- At first, the tests are done for the “Top Layer Spacing (*u*)” from the bottom of footing. A layer of geogrid is placed at a depth of 15 mm from footing base, loading is increased and settlement corresponding to load increment is noted.
- Again, the testing procedure is repeated for different “Top Layer Spacing *(u*)” at a depth of 26mm, 38mm, and 50mm. The “Top Layer Spacing *(u*)” at which maximum ultimate bearing state is reached is adopted for further testing.
- After obtaining “Top Layer Spacing *(u*)”, tests are done for “Number of reinforcement layers *(N)*” and “Spacing between reinforcement layer *(h)*”.
- After Geogrid 1 (GG1), same test procedure is repeated for Geogrid 2 (GG2).

- From the data collected, pressure-settlement curve is plotted and from double tangent method experimental bearing capacity is extracted.

Figure 3.7 Settlement of footing

3.3.5 MODEL TEST SERIES

Table 3.3 Summary of Model Test

Test no	Reinforcement configuration	u, mm	u/B	h, mm	h/B	q, kPa	BCR
1	unreinforced	-	-	-	-	520	-
2	GG1, N=1	15	0.20	-	-	560	1.08
3	GG1, N=1	26	0.35	-	-	580	1.12
4	GG1, N=1	38	0.51	-	-	575	1.11
5	GG1, N=1	50	0.67	-	-	545	1.05
6	GG1, N=2	26	0.35	26	0.35	680	1.31
7	GG1, N=3	26	0.35	26	0.35	730	1.40
8	GG1, N=4	26	0.35	26	0.35	780	1.50
9	GG1, N=3	26	0.35	15	0.20	800	1.54
10	GG1, N=3	26	0.35	26	0.35	730	1.40
11	GG1, N=3	26	0.35	38	0.51	700	1.35
12	GG1, N=3	26	0.35	50	0.67	675	1.30
13	GG2, N=1	15	0.20	-	-	620	1.19
14	GG2, N=1	26	0.35	-	-	660	1.27
15	GG2, N=1	38	0.51	-	-	650	1.25
16	GG2, N=1	50	0.67	-	-	580	1.12
17	GG2, N=2	26	0.35	26	0.35	740	1.42
18	GG2, N=3	26	0.35	26	0.35	830	1.60
19	GG2, N=4	26	0.35	26	0.35	840	1.62
20	GG2, N=3	26	0.35	15	0.20	860	1.65
21	GG2, N=3	26	0.35	26	0.35	800	1.54
22	GG2, N=3	26	0.35	38	0.51	780	1.50
23	GG2, N=3	26	0.35	50	0.67	690	1.33

CHAPTER 4

EXPERIMENTAL RESULTS

4.1 General

Tests are performed on square footing of dimension 75mm×75mm×25mm that is resting over unreinforced and reinforced clay bed placed in a rectangular steel box of dimension 750mm×450mm×375mm having acrylic sheet of 8mm thickness along one of the length of the box. Load on the square footing is applied through Compression Testing Machine. First the test is performed for unreinforced soil and then for reinforced soil. For reinforced clay case, two different types of geogrid are used. Geogrid 1 (GG1) and Geogrid 2 (GG2). Geogrid, GG1 and GG2 have same material property, manufactured from same material, polypropylene but they differ in their tensile strength (T) and tensile modulus (E) both along machine direction (MD) and cross machine direction (CMD). In reinforces case, test is first performed with single layer of geogrid reinforcement below square footing.

The vertical spacing between the footing base and the first reinforcement layer, *u*, is varied for finding out the optimum spacing between the two. Load in increased gradually, pressure corresponding to the settlement is jotted down. Optimum result is obtained by plotting graph between pressure and settlement relation up to 20mm settlement of the footing. Ultimate bearing capacity of the soil is attained in the graph plotted by double tangent method. The ultimate bearing pressure point in the graph is obtained by double tangent method. In this method, a tangent is drawn from the starting straight part of the curve and the second tangent is drawn from the end straight part. The point where the two tangents intersect with each other gives the point of ultimate bearing capacity.

Multiple number of reinforcement layer (*N*= 1, 2, 3, 4) have been used in the test for obtained optimum reinforcement value. For this case, spacing between each reinforcement layer is kept constant and is equal to the value of optimum vertical spacing between footing base and the first reinforcement layer, *u*. Ultimate bearing capacity of each case is noted down. Further tests are done for obtaining optimum vertical spacing between each reinforcing layer. For this, the vertical spacing is varied between the layers and the spacing at which maximum ultimate bearing capacity is obtained is chosen as the optimum value.

4.2 Unreinforced clay

The result of the unreinforced case is presented below in form of a graph plotted between pressure and settlement shown in Figure 4.1. From the graph plotted, observations are recorded for the behavior of square footing on unreinforced clayey soil.

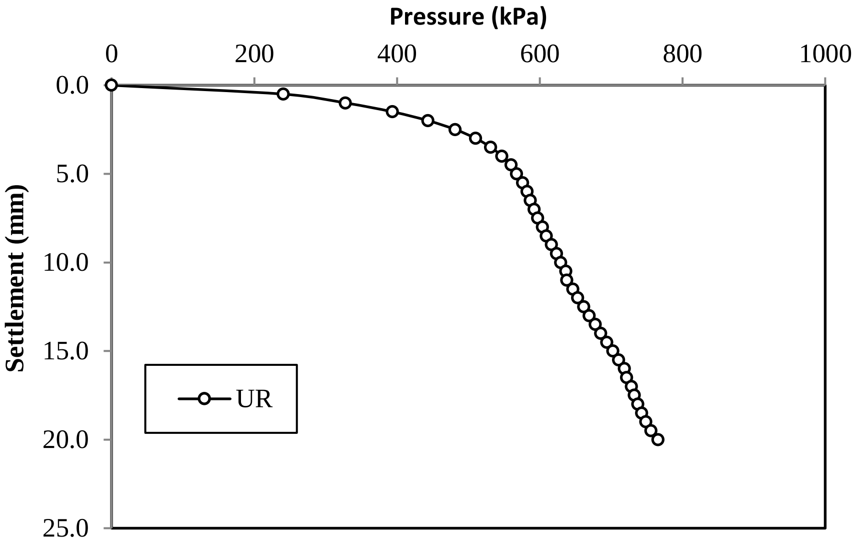


Figure 4.1 Pressure vs. settlement curve for unreinforced clay soil

Ultimate Bearing Capacity = 520kPa

4.3 Reinforced clay

4.3.1 Optimum value of first reinforcement layer from the footing base

Laboratory model tests were performed for finding Optimum vertical spacing between footing base and first reinforcement layer, *u*. The tests were first performed for geogrid 1 (GG1) and then same tests were repeated for geogrid 2 (GG2). The spacing between footing base and first reinforcement layer is varied as 15mm, 26mm, 38mm, and 50mm. After the test bed was prepared, square footing was placed on the surface at the center of the tank and load was applied gradually on the footing with help of Compression Testing Machine. Pressure corresponding to settlement was noted.

4.3.1.1 Soil + GG1

The following figures are the result of pressure-settlement of clay reinforced with GG1 for different values of u. Figure 4.2 to figure 4.5 shows the relation between pressure and settlement for u values equal to 15mm, 26mm, 38mm, and 50mm.

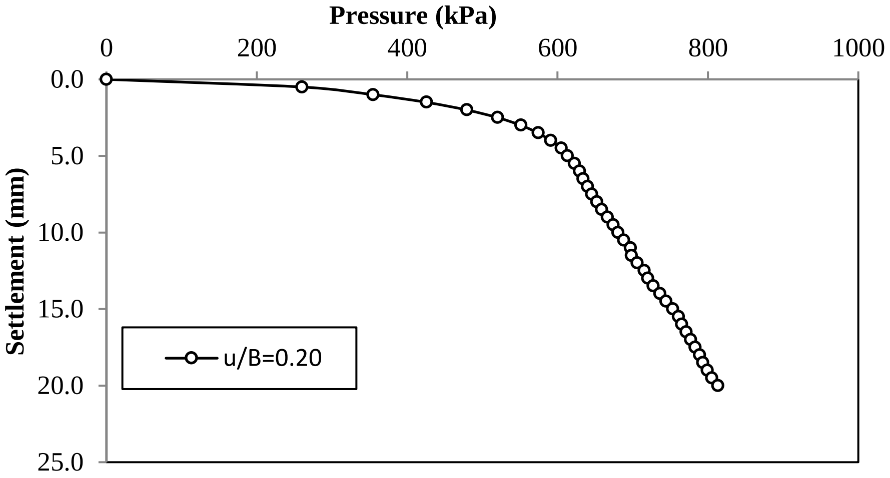


Figure 4.2 Pressure vs. settlement curve for GG1, u=15mm

Ultimate Bearing Capacity = 560kPa

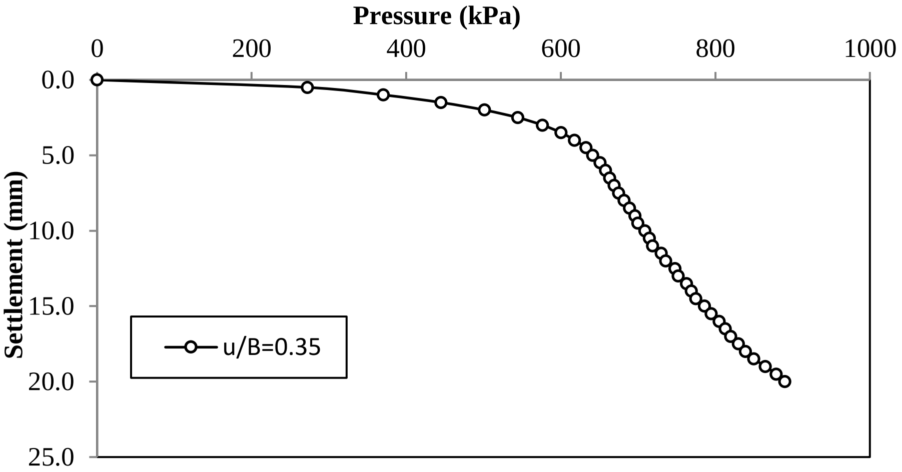


Figure 4.3 Pressure vs. settlement curve for GG1, u=26 mm

Ultimate Bearing Capacity = 580kPa

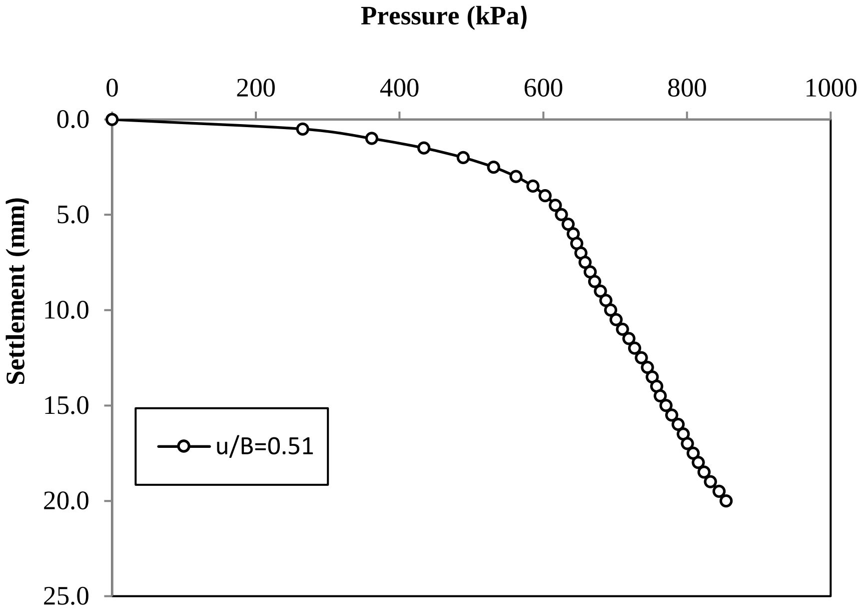


Figure 4.4 Pressure vs settlement curve for GG1, u=38mm

Ultimate Bearing Capacity = 575kPa

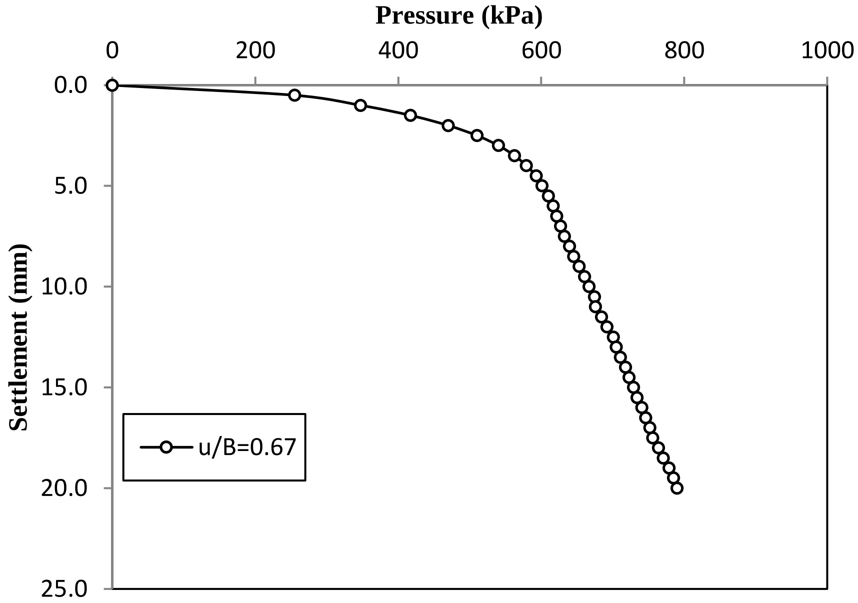


Figure 4.5 Pressure vs. settlement curve for GG1, u=50mm

Ultimate Bearing Capacity = 545kPa

4.3.1.2 Soil + GG2

The following figures are the result of pressure-settlement of clay reinforced with GG2 for different values of *u*. Figure 4.6 to figure 4.9 shows the relation between pressure and settlement for *u* values equal to 15mm, 26mm, 38mm, and 50mm.

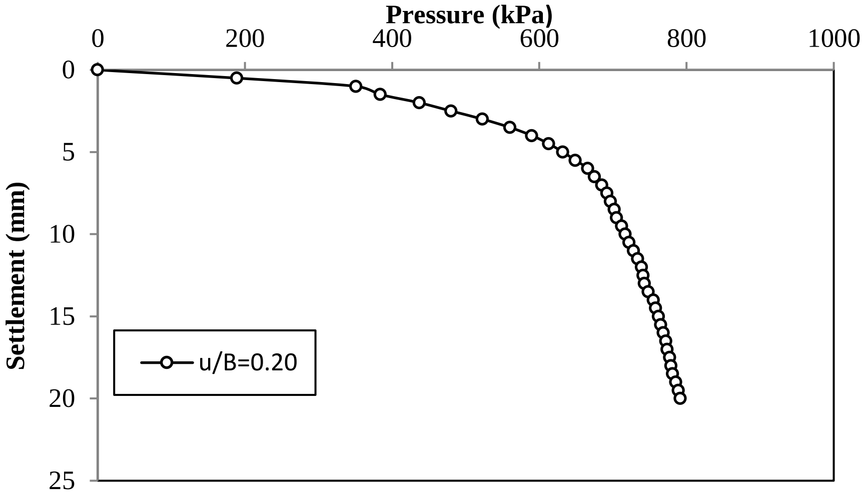


Figure 4.6 Pressure vs. settlement curve for GG2, u=15mm

Ultimate Bearing Capacity = 620kPa

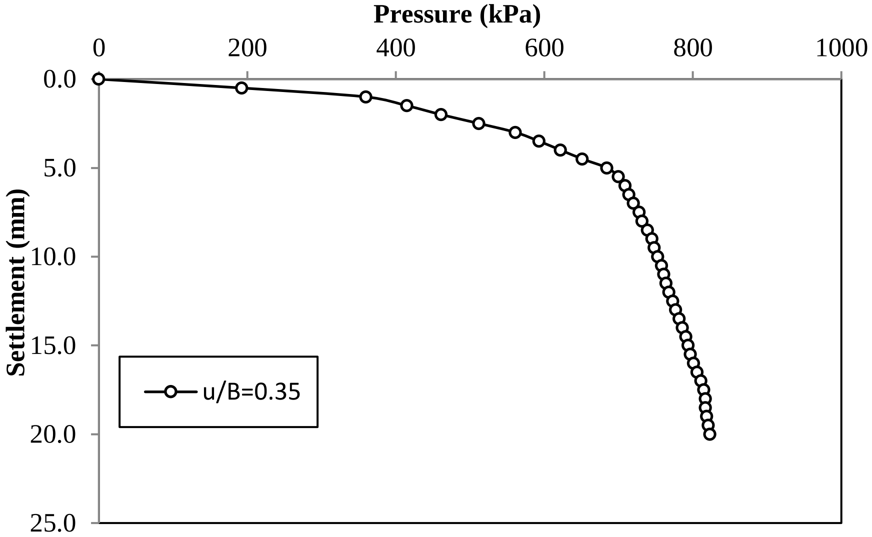


Figure 4.7 Pressure vs. settlement curve for GG2, u=26mm

Ultimate Bearing Capacity = 660kPa

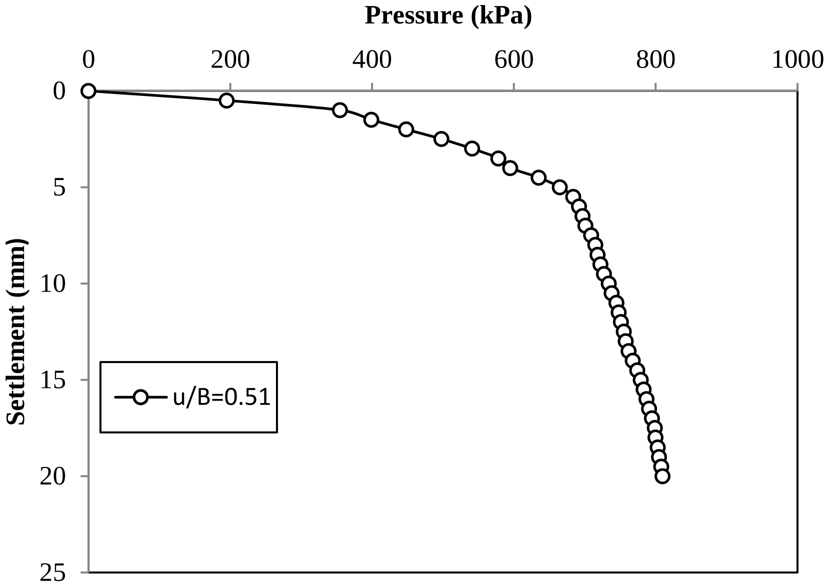


Figure 4.8 Pressure vs. settlement curve for GG2, u=38mm

Ultimate Bearing Capacity = 650kPa

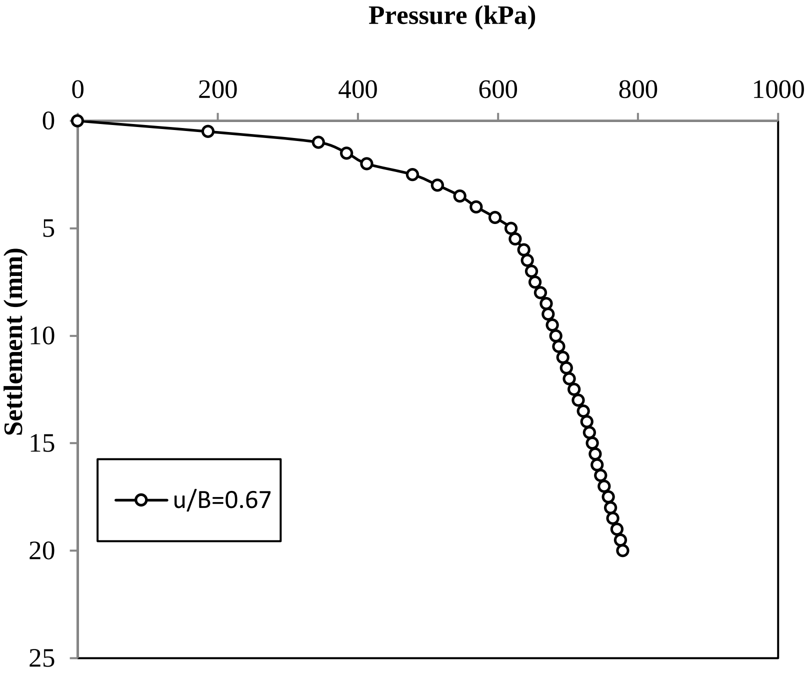


Figure 4.9 Pressure vs. settlement curve for GG2, u=50mm

Ultimate Bearing Capacity = 580kPa

4.3.2 Optimum number of reinforcement layers

After carrying out tests for determining Optimum vertical spacing between footing base and first reinforcement layer, *u*, tests were performed for finding out Optimum number of reinforcement layers, *N*, to be provided below the footing to get maximum Ultimate bearing capacity. It was done to find number of reinforcing layers beyond which there will be no significant increase in the ultimate bearing capacity of the soil. Again, the tests were first performed for Geogrid 1 (GG1) and then for Geogrid 2 (GG2). Number of layers provided was varied in the sequence of *N=1, 2, 3, 4* and the spacing between each layer is kept as the optimum value obtained from graph plotted between Pressure vs. Settlement for different *u*. The ultimate load bearing capacity is obtained in each case by double tangent method.

4.3.2.1 Soil + GG1

Figure 4.10 to figure 4.1 are the results of pressure and settlement when different layers of geogrid GG1 were placed below the footing in varying number as 1, 2, 3, and 4 with vertical spacing between each reinforcement layer equal to 26mm.

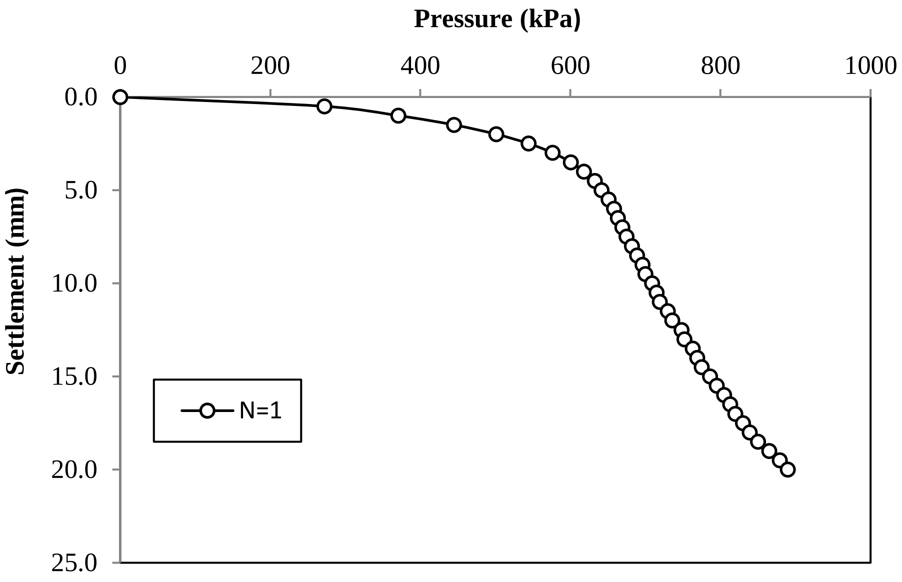


Figure 4.10 Pressure vs. settlement curve forGG1, N=1

Ultimate Bearing Capacity = 584kPa

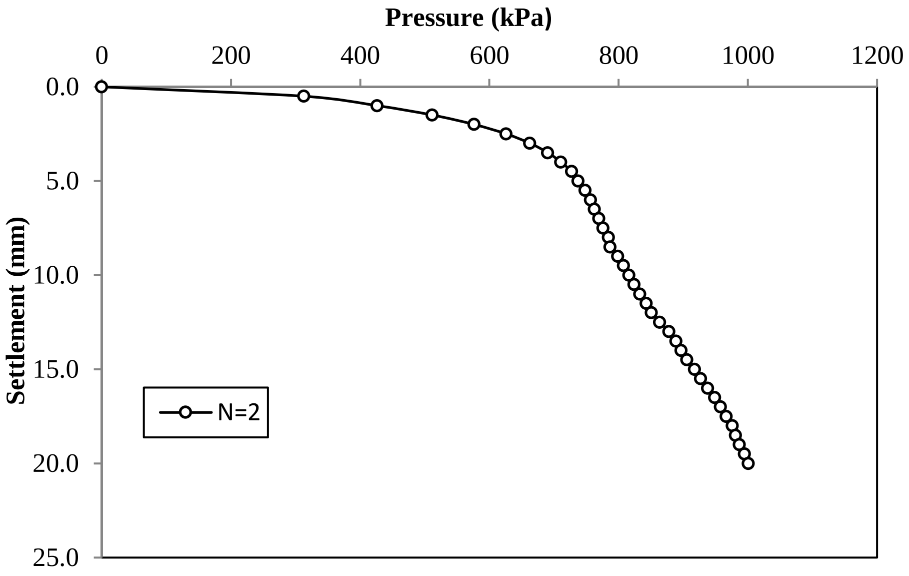


Figure 4.11 Pressure vs. settlement curve for GG1, N=2

Ultimate Bearing Capacity = 680kPa

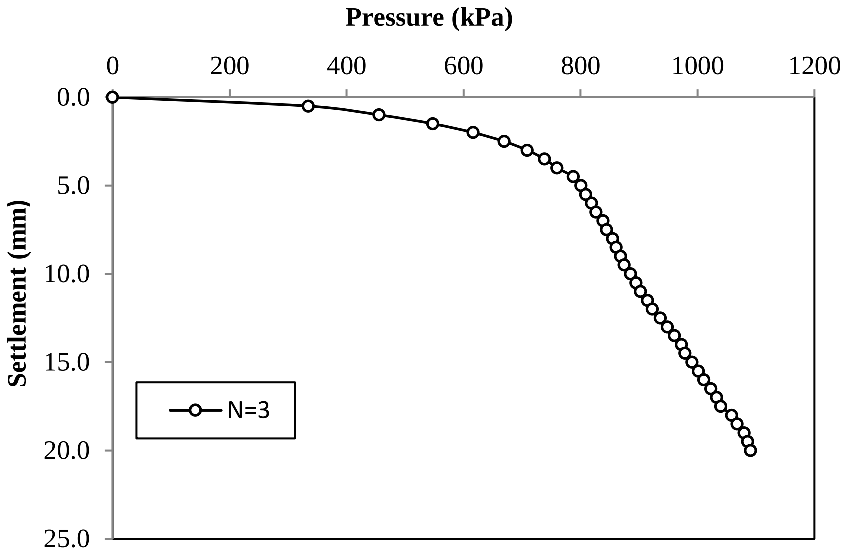


Figure 4.12 Pressure vs. settlement curve for GG1, N=3

Ultimate Bearing Capacity = 730kPa

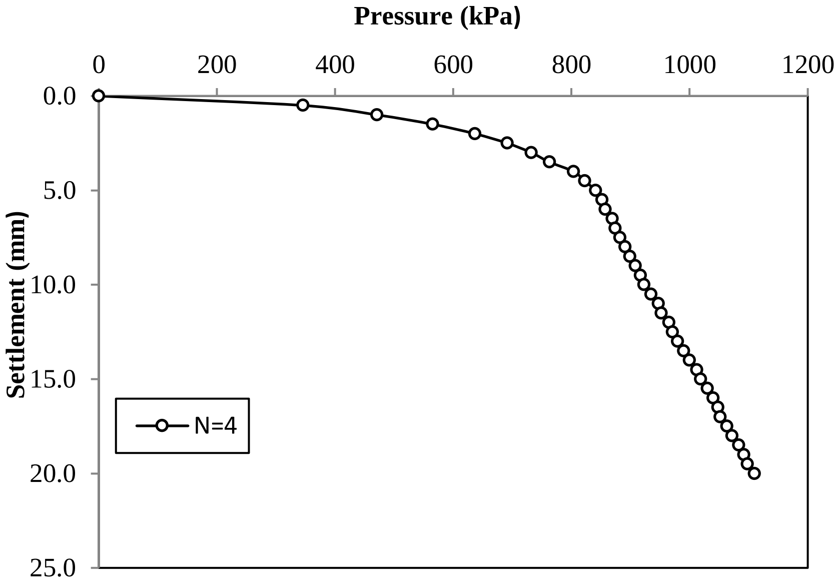


Figure 4.13 Pressure vs. settlement curve for GG1, N=4

Ultimate Bearing Capacity = 780kPa

4.3.2.2 Soil + GG2

Figure 4.14 to figure 4.17 are the results of pressure and settlement when different layers of geogrid GG2 were placed below the footing in varying number as 1, 2, 3, and 4 with vertical spacing between reinforcement layer equal to 26mm.

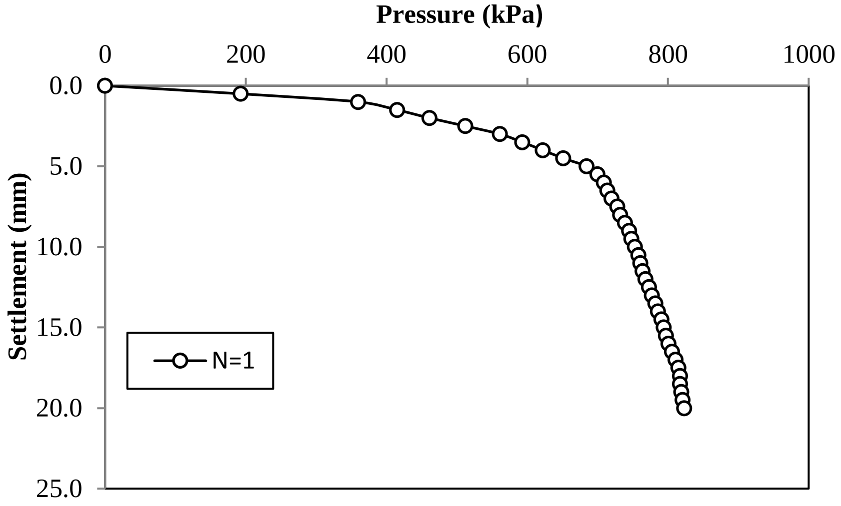


Figure 4.14 Pressure vs. settlement curve for GG2, N=1

Ultimate Bearing Capacity = 660kPa

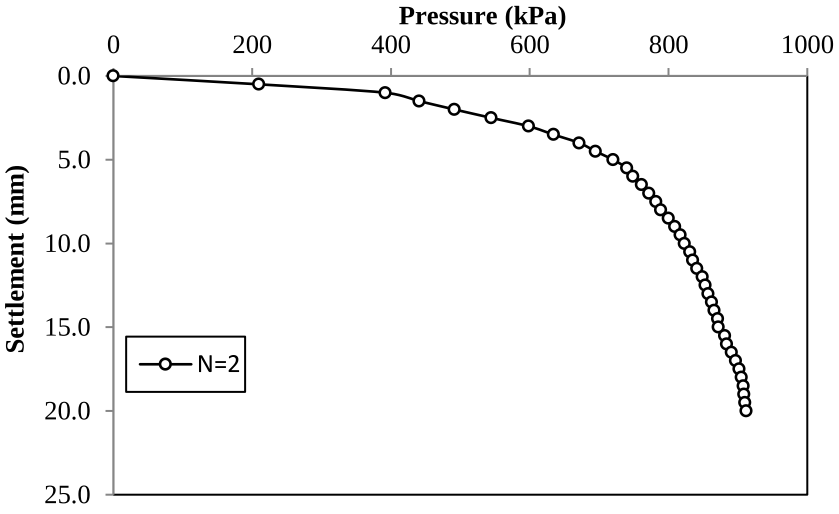


Figure 4.15 Pressure vs. settlement curve for GG2, N=2

Ultimate Bearing Capacity = 740kPa

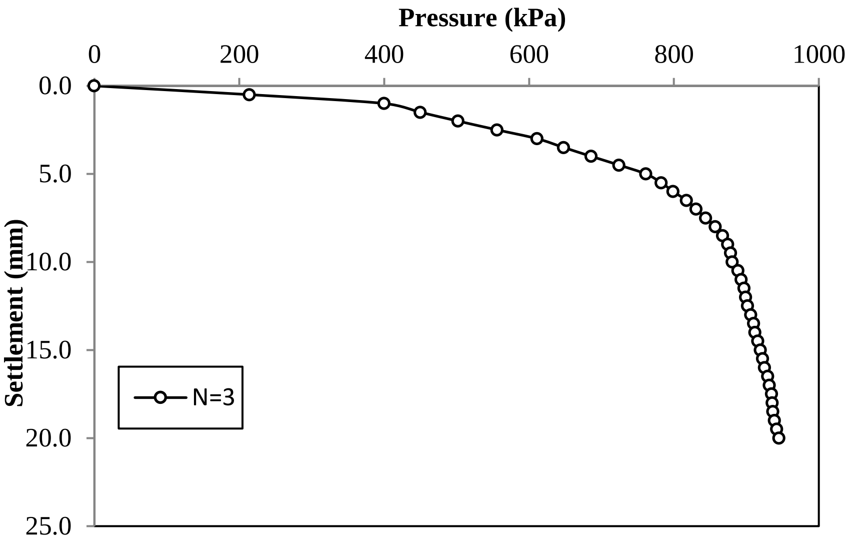


Figure 4.16 Pressure vs. settlement curve for GG2, N=3

Ultimate Bearing Capacity = 830kPa

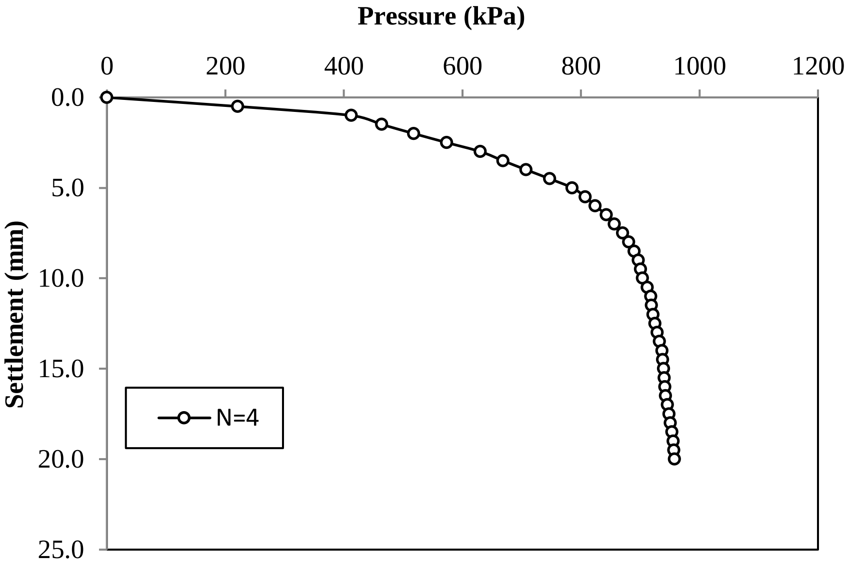


Figure 4.17 Pressure vs. settlement curve for GG2, N=4

Ultimate Bearing Capacity = 840kPa

4.3.3 Optimum vertical spacing between reinforcing layers

In these tests, Optimum vertical spacing between reinforcing layers, *h*, are found. For this total three layers (*N*=3) of geogrid reinforcement are used. The spacing between the reinforcing layers were varied as *h*= 15mm, 26mm, 38mm, 50mm. Pressure-settlement curves are plotted for each case and the ultimate bearing capacity is obtained by double tangent method. Again, the tests were first performed for geogrid 1 (GG1) and then for geogrid 2 (GG2).

4.3.3.1 Soil + GG1

Figure 4.18 to figure 4.21 shows variation of Pressure and settlement when three layers of geogrid 1 (GG1) were placed at a vertical spacing varying as 15mm, 26mm, 38mm and 50mm with first layer of reinforcement placed at 26mm from footing base.

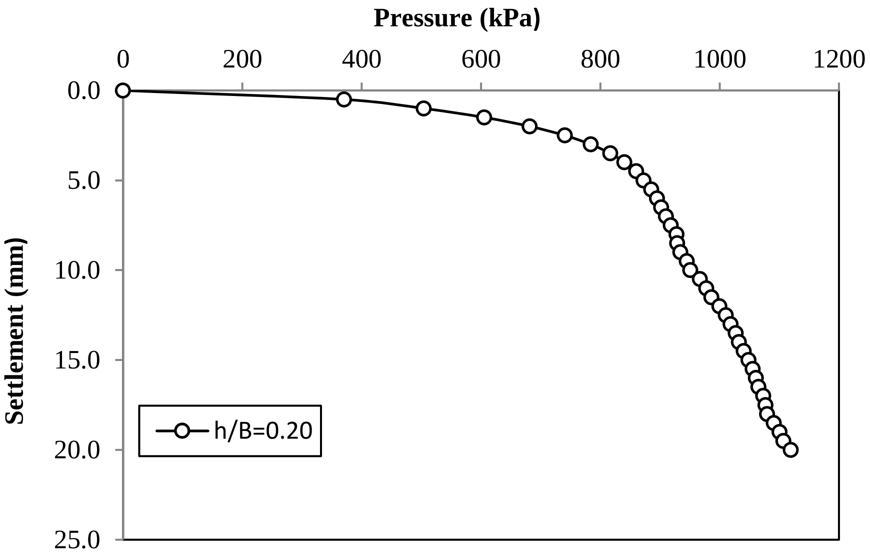


Figure 4.18 Pressure vs. settlement curve for GG1, h=15mm

Ultimate Bearing Capacity = 800kPa

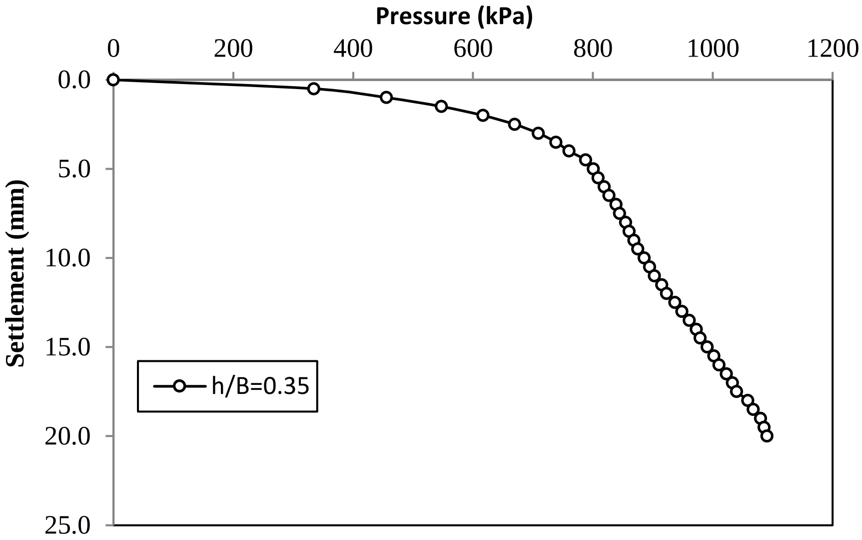


Figure 4.19 Pressure vs. settlement curve for GG1, h=26mm

Ultimate Bearing Capacity = 730kPa

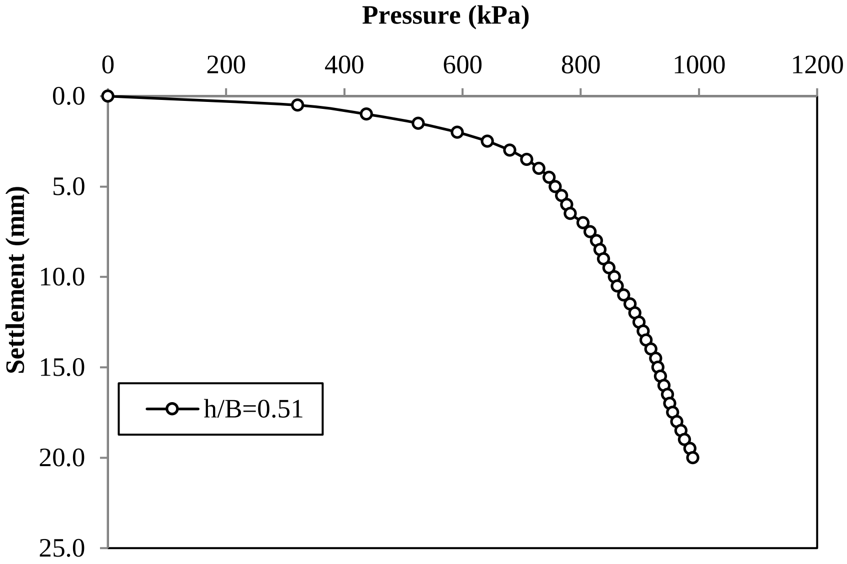


Figure 4.20 Pressure vs. settlement curve for GG1, h=38mm

Ultimate Bearing Capacity = 700kPa

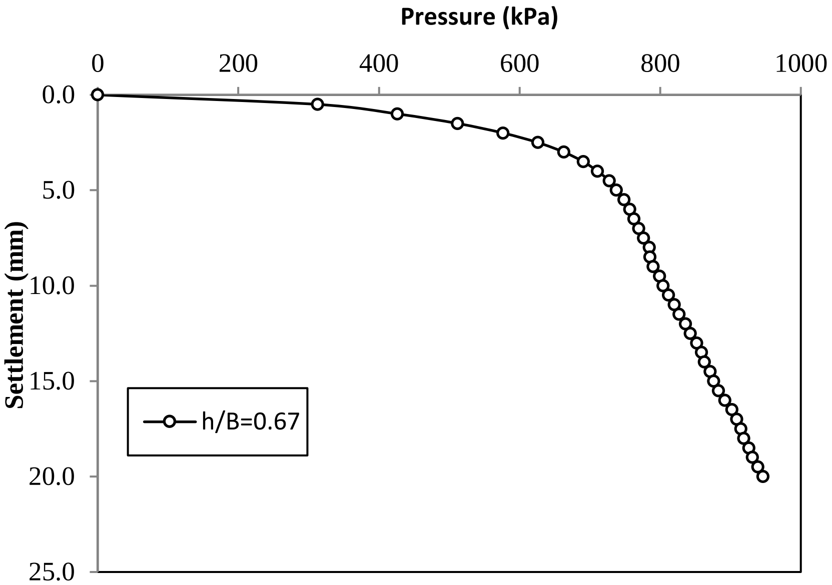


Figure 4.21 Pressure vs. settlement curve for GG1, h=50mm

Ultimate Bearing Capacity = 675kPa

4.3.3.2 Soil + GG2

Figure 4.22 to figure 4.25 shows variation of Pressure and settlement when three layers of geogrid2 (GG2) were placed at a vertical spacing varying as 15mm, 26mm, 38mm and 50mm with first layer of reinforcement placed at 26mm from footing base.

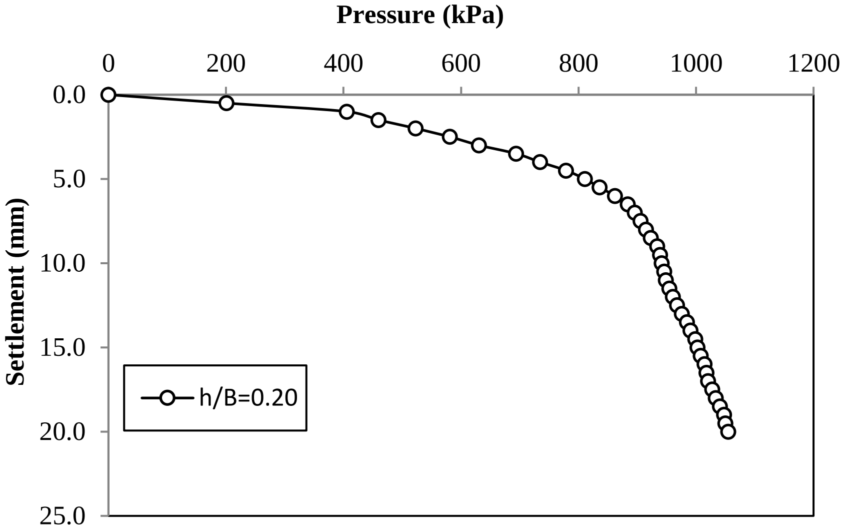


Figure 4.22 Pressure vs. settlement curve for GG2, h=15mm

Ultimate Bearing Capacity = 860kPa

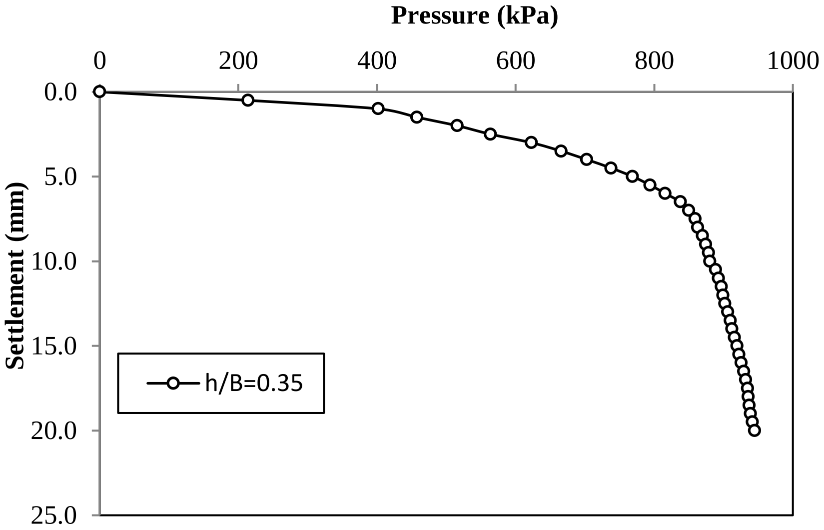


Figure 4.23 Pressure vs. settlement curve for GG2, h=26mm

Ultimate Bearing Capacity = 800kPa

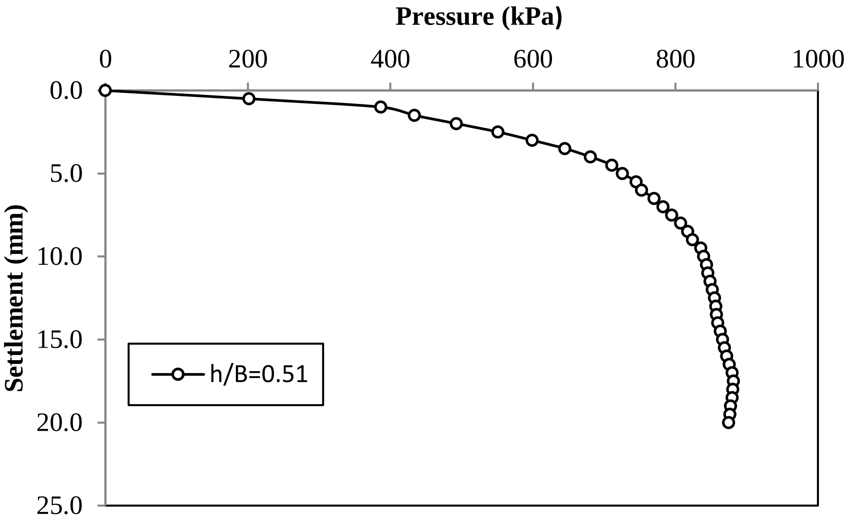


Figure 4.24Pressure vs. settlement curve for GG2, h=38mm

Ultimate Bearing Capacity = 780kPa

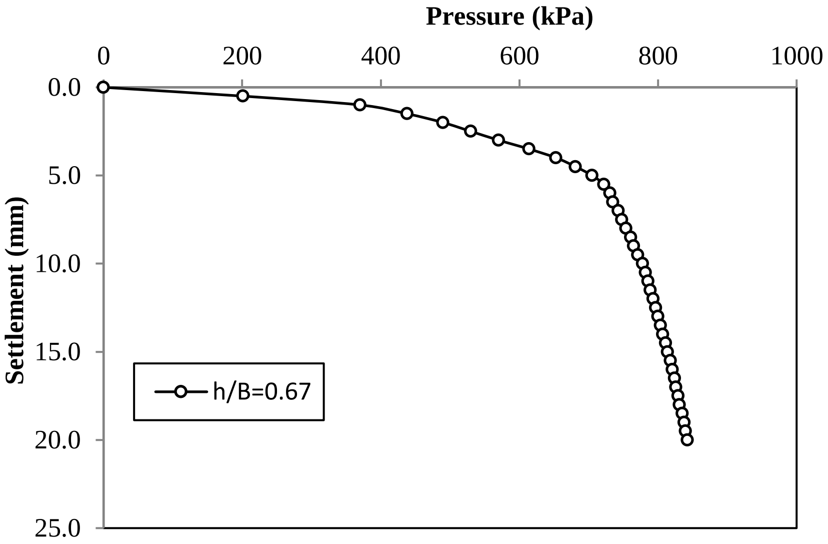


Figure 4.25 Pressure vs. settlement curve for GG2, h=50mm

Ultimate Bearing Capacity = 690kPa

CHAPTER 5

COMPARISON AND RESULT ANALYSIS

5.1 Optimum value of first reinforcement layer from the footing base

Optimum vertical spacing between footing base and first reinforcement layer, *u*, single layer of reinforcement of both type of geogrid, GG1 and GG2 were placed below the base of footing. Optimum value of reinforcement spacing was found out by varying the distance from the base to the first layer in sequence of 15mm, 26mm, 38mm, 50 mm. Figure 5.1 and figure 5.2 shows comparative variation of pressure with settlement for Geogrid 1(GG1) and Geogrid 2 (GG2). From the figures, it is observed that as the distance of vertical spacing increases bearing capacity increases up to maximum value at 26mm, *u/B* = 0.35, after which there is a decrease in the bearing capacity.

u/B is “top layer spacing ratio” and is defined as the distance of the first reinforcement from the base *(u)* to the width of the footing *(B).* And it is found to be 0.35 in both the cases i.e. the vertical distance from the base of footing to reinforcement first layer is 26mm.

Similar observation was noted by Sakti & Das, [3], Chen, et al., [10], Shin, et al., [31]. Sakti & Das [3] observed that the maximum bearing pressure was at a depth of 0.34B for single and multilayer geotextile layers when load was applied on strip footing. Chen, et al., [10] reported that maximum bearing pressure is found at 0.33B depth when the clay is reinforced with geogrid. Shin, et al. [31], reported that for a strip footing in a clay, optimum value of top layer spacing is 0.4B with 4 layers of geogrid. Mandal & Sah [4] noted that for a 100mm square footing on clay reinforced with single layer of geogrid, the value of top layer spacing is 0.175B. Ramaswamy & Puroshothama [32] for a 40mm circular footing on clay with one layer of reinforcement obtained maximum bearing capacity at u/B=0.5. This variation in the optimum value of top layer vertical distance below base to first reinforcement layer can be because of the different properties of reinforcing material used in testing. The variation can further be because of the difference in the soil properties of different locations.

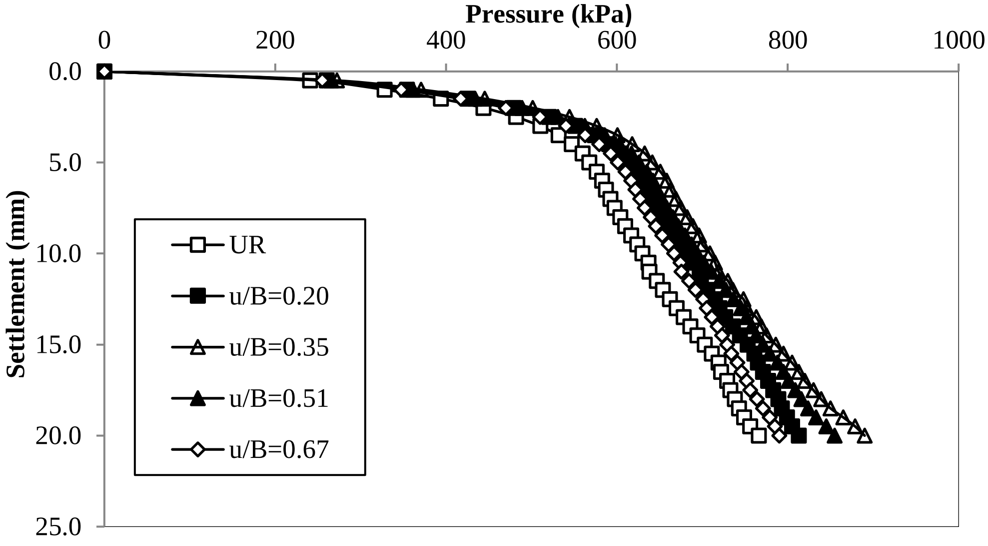


Figure 5.1 Pressure–settlement curves for model footing test with single layer of GG1 placed at different top layer spacing

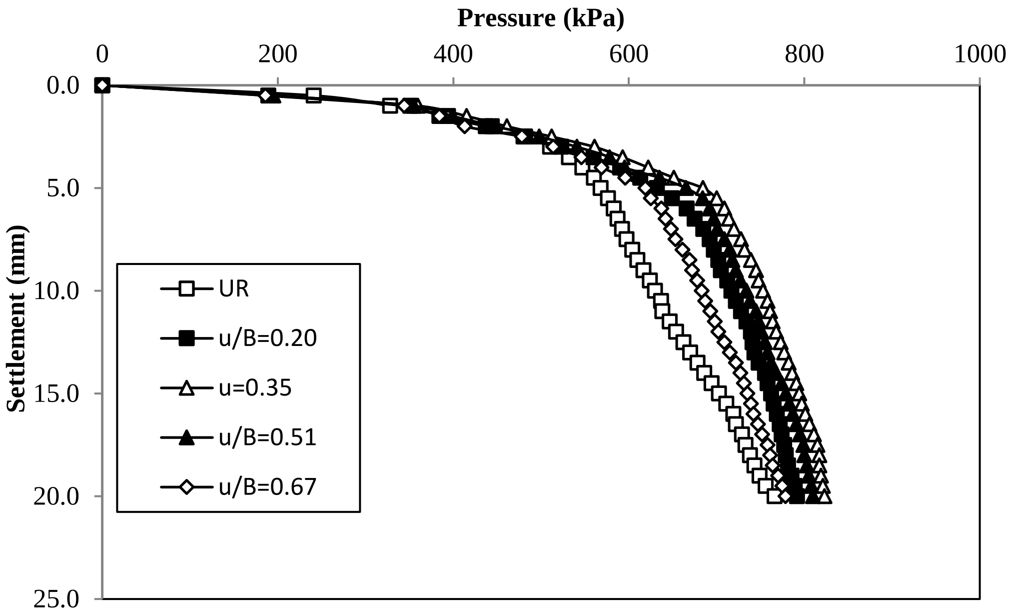


Figure 5.2 Pressure–settlement curves for model footing tests with single layer of GG2 placed at different top layer spacing.

5.2 Optimum number of reinforcement layers

Laboratory tests were conducted on model footing resting over clay bed with various layers of reinforcement of two different types geogrid placed at a constant distance of 26mm in between each layer. Figure 5.3 and figure 5.4 shows variation of pressure with increase in reinforcing layers for both type of geogrid, GG1 and GG2. From the figure, it is observed that the pressure increases with increases in number of reinforcement, N varying from 1 to 4. However, the rate of increase in bearing capacity became slight when the influence depth has reached. The increases in bearing capacity were slight after N=3 form both the geogrid. The influence depth is defined as a depth below which further increase in the number of reinforcing layers will not result much increase in the bearing capacity ratio. From the test results, the influence depth is observed to be at a depth of 1.38B. Chen, et al. [10] reported influence depth as 1.4*B* for a square footing for geogrid reinforcement in clay and 1.24B for geotextile reinforcement in clay. Shin, et al. [31] noted that influence depth for strip footing over geogrid reinforced clay as 1.8B. Sakti & Das [3] suggested that the geotextile reinforced clayey soil could not improve bearing capacity below 1.0*B*.

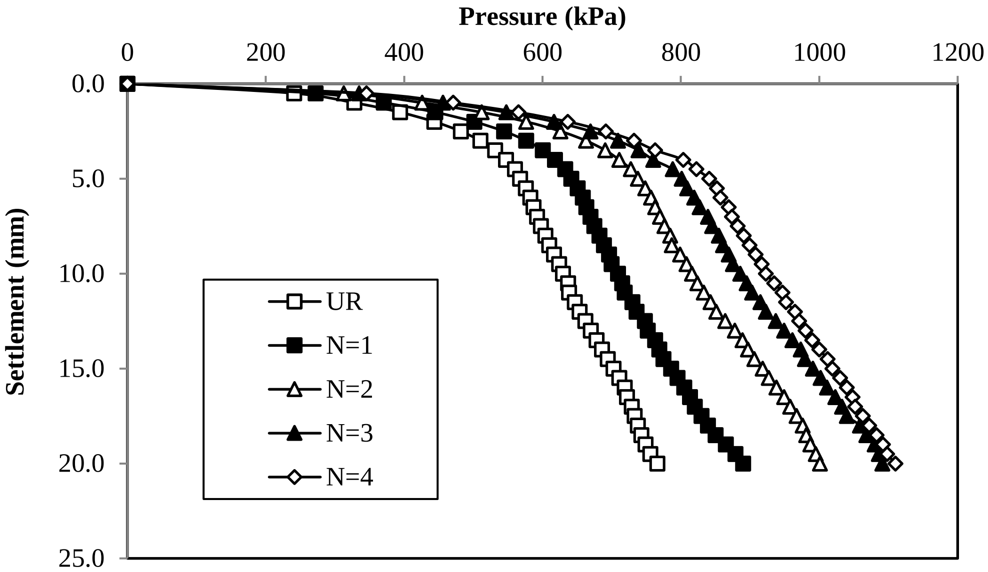


Figure 5.3 Pressure–settlement curves for model footing tests with different number of reinforcing layers: GG1 geogrid

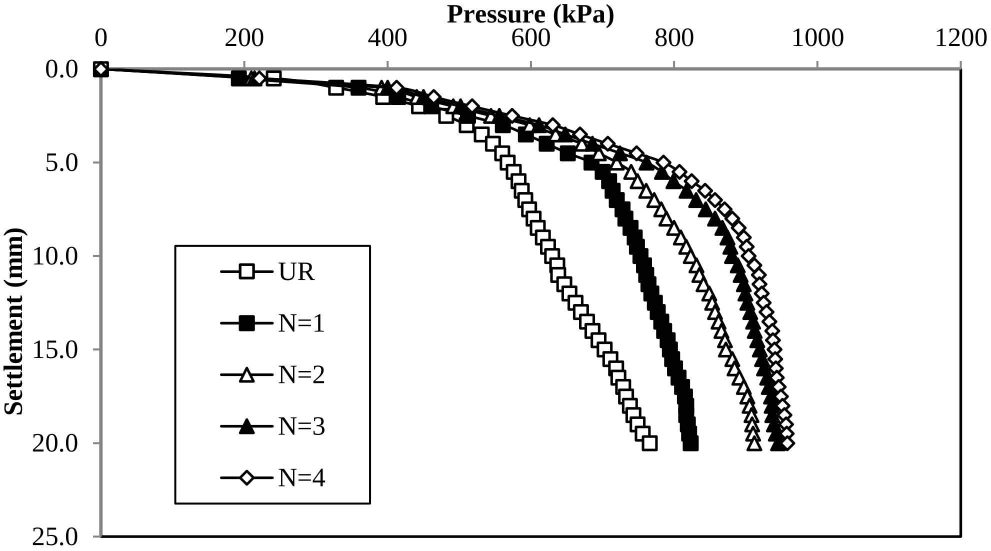


Figure 5.4 Pressure–settlement curves for model footing tests with different number of reinforcing layers: GG2 geogrid

5.3 Effect of Vertical Spacing of Reinforcement Layers

Vertical spacing between the reinforcement effect was incorporated by using 4 layers of reinforcement of both type of geogrid. The top layer spacing from the base of the footing to first layer of geogrid was taken equal to optimum value i.e. 0.34B. The variation in the geogrid layers was from 0.2*B* to 0.67*B*. Figure 5.5 and 5.6 shows the variation of pressure with settlement with varying vertical spacing between the layers of reinforcement. *h/B* is defined as the ratio of vertical distance between the reinforcing layers *(h)* to the width of the footing *(B)*. It was observed that the ultimate bearing capacity decreases with the increase in the vertical spacing between the reinforcing layer with maximum value of ultimate bearing capacity at 0.2*B*. The smaller the spacing between the reinforcing layer more is the bearing capacity. As suggested by many researchers, effect of vertical spacing between reinforcement layer on ultimate bearing capacity was driven by other factors also, like spacing between footing and first reinforcement layer *(u)*, number of reinforcing layers *(N)*, modulus of elasticity of geogrid. The graph also indicates that there is no optimum value of vertical spacing between reinforcing layers. Similar observations were reported by Ingold & Miller [33], on clay reinforced with geogrid. In contrast to this, Yetimoglu, et al. [5], conducted study on geogrid reinforced sand below rectangular footing reported that optimum vertical spacing between reinforcement having 4 layers of reinforcement is 0.2*B* with top layer spacing as 0.3*B*.

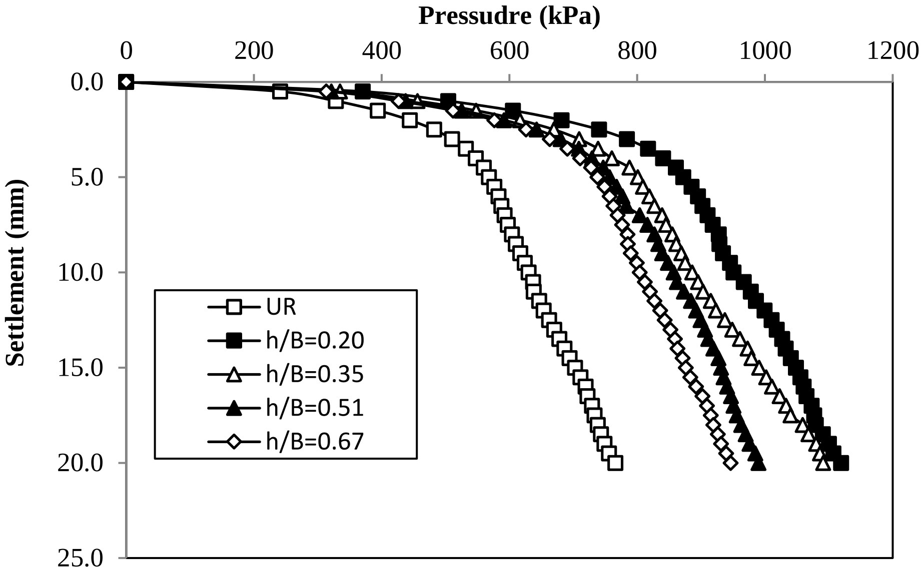


Figure 5.5 **Pressure–settlement curves for model footing tests with three layers of GG3 placed at different vertical spacing.**

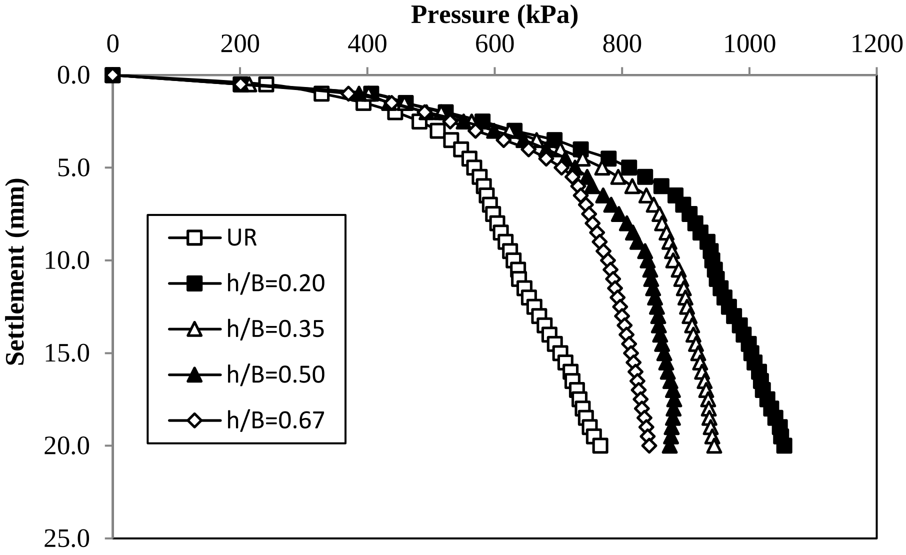


Figure 5.6 Pressure–settlement curves for model footing tests with three layers of GG3 placed at different vertical spacing.

5.4 Effect of type of reinforcement and Stiffness

Graph is plotted between Bearing Capacity Ratio (BCR) and Reinforcement Type. Bearing Capacity Ratio (BCR) is defined as the ratio of ultimate bearing capacity of reinforced soil to that of unreinforced soil.

Two different type of geogrid are used in the experimental work having different stiffness. The general properties of the two-geogrid reinforcement are presented in table 3.2. The two geogrid GG1 and GG2 are made from same material that is polypropylene with same size of the aperture. As seen from the figure 5.7, geogrid having higher stiffness performs better than that with lower stiffness that is GG1 performed better than GG2. Figure 5.7 shows that as the stiffness of the geogrid increases there is an improvement in the bearing capacity ratio. It was also observed that it is also dependent on the settlement of the footing. Similar results were presented by Chen et al [10] on a square footing resting on a clay bed with four different type of reinforcement. Similar observation was observed by Huang & Tatsuoka [34] on strip footing on reinforced sand. It was observed that the behavior of reinforcement with different stiffness was similar until settlement reached a certain value. Lee & Manjunath [35] conducted a study on geogrid reinforced sand. It was observed that geogrid which was having highest stiffness and smallest aperture performed better.

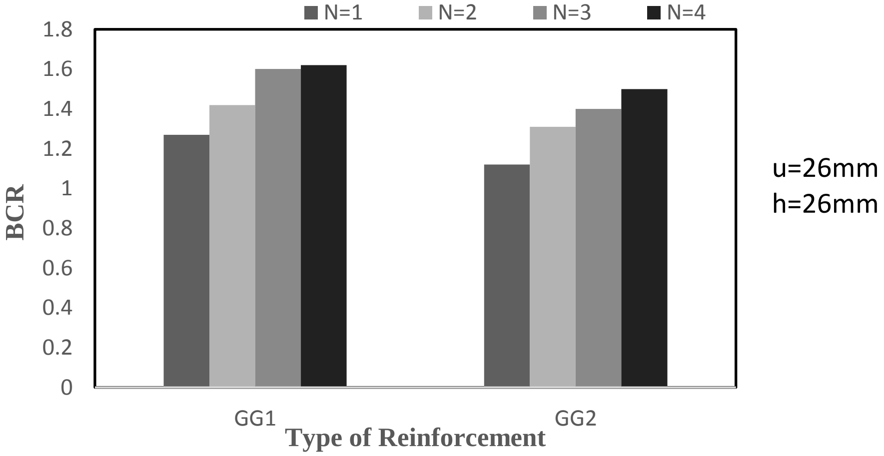


Figure 5.7 BCR versus type of reinforcement

CONCLUSIONS

Based on the experimental test results, following conclusions are drawn:

- The optimum spacing of the top reinforcement from the base of the footing was found to be 0.35*B* for square footing on geogrid reinforced clayey soil.
- The bearing capacity of the soil increases with increase in number of reinforcement layers. The importance of adding new reinforcement layer decreases with increase in number of layers.
- Bearing capacity of the soil decreases with increase in the vertical spacing between the reinforcement layers.
- Soil reinforced with high stiffness geogrid has high bearing capacity in comparison to the soil reinforced with low stiffness geogrid.

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