ENHANCEMENT OF BEARING CAPACITY OF SOFT SOIL USING GEOSYNTHETICS

A Thesis

by

MD LOKMAN HOSSAIN

MASTER OF SCIENCE IN CIVIL ENGINEERING

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

ISLAMIC UNIVERSITY OF TECHNOLOGY

GAZIPUR, BANGLADESH

JULY, 2022

ENHANCEMENT OF BEARING CAPACITY OF SOFT SOIL USING GEOSYNTHETICS

A Thesis

by

Md Lokman Hossain

Submitted to the Department of Civil and Environmental Engineering, Islamic University of Technology (IUT), Gazipur in partial fulfilment of the requirements for the degree

of

MASTER OF SCIENCE IN CIVIL ENGINEERING

ISLAMIC UNIVERSITY OF TECHNOLOGY

BOARD BAZAR, GAZIPUR,

BANGLADESH

July, 2022

The thesis titled "**Enhancement of Bearing Capacity of Soft Soil Using Geosynthetics**"**,** submitted by Md Lokman Hossain, Roll No. 145620, Session 2014-2015 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Civil Engineering on 29 July, 2022.

BOARD OF EXAMINERS

______________________________ Prof. Dr. Hossain Md. Shahin (Supervisor) Department of Civil and Environmental Engineering Islamic University of Technology, Board Bazar, Gazipur, Bangladesh	Chairman and Ex-officio
______________________________ Prof. Dr. Md. Rezaul Karim Department of Civil and Environmental Engineering Islamic University of Technology, Board Bazar, Gazipur, Bangladesh	Member
______________________________ Prof. Dr. Md. Tarek Uddin Department of Civil and Environmental Engineering Islamic University of Technology, Board Bazar, Gazipur, Bangladesh	Member
______________________________ Prof. Dr. Shakil Mohammad Rifaat Department of Civil and Environmental Engineering Islamic University of Technology, Board Bazar, Gazipur, Bangladesh	Member
______________________________ Prof. Dr. Mohammad Shariful Islam Department of Civil Engineering, Bangladesh University of Engineering and Technology Dhaka, Bangladesh	Member (External)

DECLARATION

It is hereby declared that this thesis and the studies embodied in it are the result of the investigation carried out by the author under the supervision of Dr. Hossain Md. Shahin, Professor, Department of Civil and Environmental Engineering, Islamic University of Technology, Gazipur, Bangladesh. Wherever contributions of others were involved, every effort has been made to indicate this clearly with due reference to the literature and acknowledgement of collaborative research and discussions. Neither thesis nor any part of it has been submitted to or is being submitted to for any other purposes (except for publication).

Name of Supervisor:
Dr. Hossain Md. Shahin
Professor
Department of Civil and Environmental Engineering
Islamic University of Technology,
Board Bazar, Gazipur, Bangladesh
Date:

Name of Candidate:
Md Lokman Hossain
Student No: 145620
Academic Year: 2014-2015
Date:

DEDICATION

This thesis has been dedicated to my family.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENT

All praises are due to Almighty Allah, the most merciful and the most beneficent.

I would then like to express my gratitude and profound indebtedness to my supervisor Dr. Hossain Md. Shahin, Professor, Department of Civil and Environmental Engineering, Islamic University of Technology, Gazipur, Bangladesh, for his constant supervision, continuous guidance, helpful criticism, valuable suggestions, generous help, and unfailing enthusiasm at all stages of this work. It is his kindness to provide the author with the necessary references and knowledge to carry out the work smoothly. His relentless expert guidance, keen interest in this topic, valuable advice, encouragement, interest, contribution to new ideas, and supervision were the sources of inspiration to the author.

The author is grateful to Dr. Mohammad Shariful Islam, Professor, Department of Civil Engineering, Bangladesh University of Engineering and Technology, for his support and guidance.

Last but not the least, the author is grateful to the family members for their patience, efforts, and moral support during the course of this study.

ABSTRACT

The vast areas of Bangladesh are composed of very soft to soft fine-grained soil with high compressibility. Thus, the ground undergoes excessive settlement due to the construction of any structure over the ground. As such conventional foundation systems could not be chosen in this kind of soil due to its low bearing capacity. In such a case, ground improvement or reinforcing the ground is necessary. Thus, research has been carried out to find out an appropriate ground improvement technique with the application of ground reinforcement and study its effectiveness against the reduction of ground deformation and improvement of bearing capacity. Here, numerical analysis has been carried out with the finite element method, using the elastoplastic subloading t_{ij} model.

Bearing capacities for different over consolidation ratios (OCRs) have been analyzed. Then the effect of reinforcement was compared by changing its depth below the foundation for different OCRs. Bearing capacity is also checked by replacing the soft clay with granular soil between the foundation and reinforcement. Bearing capacity has been analyzed with and without reinforcing the ground below the foundation. It is found that higher values of OCRs have a positive effect on the bearing capacity. Again, reinforcement increases the bearing capacity of the soft clay, and the increment of the bearing capacity depends on the depth of the reinforcement, OCR, and improved area of the ground underneath the foundation.

For a higher value of OCR, the bearing capacity of soft soil is increased. Once ground below the foundation is reinforced, its effect on bearing capacity varies with its location. The effect has been analyzed by placing reinforcement at D/B=0.05, D/B=0.10 and D/B=0.20, where D is the depth of reinforcement and B is the width of the foundation. There is an increasing trend of bearing capacity once the location of reinforcement has been changed from D/B=0.05 to D/B=0.10. On the contrary, the bearing capacity decreases for the placement of reinforcement at D/B=0.20. Bearing capacity is further increased by introducing a granular layer between the foundation and reinforcement.

NOTATIONS

λ	Virgin Compression Index or Slope of Virgin Loading Curve in e-log p Curve at the Loosest State (where e is void ratio and p is consolidation pressure)
κ	Unloading Compresssion Index or Slope of Unloading-reloading Curve in e-log p Curve at the Loosest State $R_{CS=}(\sigma_1/\sigma_3)_{cs(comp.)}$) Critical State Stress Ratio
N	Reference Void Ratio on Normally Consolidation line (at mean principal stresses, p=98 kPa and at q= 0 kPa)
υ	Poison's Ratio
β	Model Parameter for Shape of Yield Surface
α	Parameter for Influence of Density and Confining Pressure Cohesion
ϕ	Angle of Internal Friction
γ	Unit Weight
q_u	Unconfined Compression Strength
n	Coefficient of Progressive Failure (ranging from 0.5~1.0; average value 0.75)
G_s	Specific Gravity
ε_a	Axial Strain
ε_f	Failure Strain
e_0	Initial Void Ratio
e_N	Critical Void Ratio

CHAPTER 1:INTRODUCTION

1.1 Background

South-West region of Bangladesh is composed of very soft to soft fine-grained soil materials of recent origin. Subsoils of coastal districts in this region consist of fine-grained soil deposits predominantly with peat and muck. As such it is soft and compressible. As a result, the soilis subjected to massive total & differential settlement and exhibits low bearing capacity. To deal with this kind of soil, engineers are facing difficulties in addressing the issue of geotechnical engineering-related problems such as bearing capacity failure and slope stability. The general foundation system is unsuitable for this soft soil due to environmental constraints and its expensive and time-consuming nature. For the construction in very soft soil, excavation and replacement were standard methods in the past. But this is expensive and not always practical. This research focuses on reinforcing the soft ground using geosynthetics to increase bearing capacity and reduce ground settlement. In the contemporary periods, many researchers used the base reinforcement technique as a solution to increase the bearing capacity of soft ground using the tensile strength of the reinforcement (Khing et al., 1993; Omar et al., 1993;Yetimoglu et al., 1994; Patra et al., 2004; Cicek et al., 2015; Shahin et al., 2014 and Shahin et al., 2017). The reinforcement used in the ground is for withstanding predominantly tensile forces coming from the load of the superstructures.

The effectiveness of geosynthetics has been confirmed for ground improvement in field-scale experiments considering square footings (Adams et al., 1997). A significant increase in bearing capacity wasgained by using geosynthetics in the foundation systems at the academic and residential buildings constructed at Khulna Medical College which is located in the South-West region of Bangladesh (Alamgir et al., 2004). In the same region, at Khulna University, the foundation for the four-story academic building-I was constructed over mat by replacing top soft ground and peat layer, whereas academic building-II was constructed on a floating foundation resulting in settlement of 700 mm and 19 mm, respectively (Hossain et al., 1999). It was found that fixed edges of the reinforcing members with the ground are more effective than that of the free edges of the reinforcement (Shahin et al., 2017) which was also proven during the Great East Japan Earthquake on March 11, 2011.

In this study, numerical analyses were performed with the finite element program FEMtij-2D using the elastoplastic subloading t_{ij}model (Nakai et al., 2004) and (Nakai, 2012). The validity of the model has already been verified in previous research (Shahin et al., 2014 and (Shahin et al., 2017). This model can describe the typical stress deformation and strength characteristics of soils, such as the influence of the intermediate principal stress, stress path dependency of plastic flow and the density and/or confining pressure.

Terzaghi (1948), Meyerhof (1963) and Hansen (1970) gave the general formula for bearing capacity of soil considering cohesion and internal friction parameters, respectively, for clay and sand. Their analysis was based on elastic theory and/or rigid plastic theory. Thus they ignored the effect of soil-water interaction, anisotropy and stress history of the soil. To be more realistic, there are FinteElementbased constitutive models but all of them do not address above mentioned effects. The extended Subloading t_{ij} model can address the real field scenario like the effect of intermediate principal stress, direction of plastic flow on stress paths, influence of density, confining pressure, and bonding on the deformation and strength of soils.

Due to deltaic land South-West coastal region of Bangladesh contains fine grain soil with the presence of organic soil deposits. Khulna being situated in this region is no exception of it. Soil of this region is soft, and compressible with a substantial amount of organic matter, thus lacking in bearing capacity. So, the civil infrastructure suffers for a very large amount of total and differential settlement. The sub-soil contains soft clay layers, loose sand, an organic layer, and clayey silt at the surface where the firm layer exists at a depth generally unreachable. The organic layer is very much compressed and eventually contributes to a large settlement for secondary consolidation. Excessive settlement occurs even in mat foundation (Alamgir et al.,. 2004). Negative skin friction may occur in the case of pile foundation. So it is necessary to increase the pile length which results in high cost. Due to this inherent limitation, the foundation design for the construction of civil infrastructure, it needs special caution and consideration, which leads to high cost for the preparation of underground structure in this region. It is necessary to determine a technique for the enhancement of bearing capacity of soft soil in the Khulna region of Bangladesh so that shallow foundation can easily be built considering Over Consolidation Ratio (OCR), bonding and strength anisotrophy.

1.2 Objectives of the Study

The main objectives of this research work are as follows:

(1) To investigate the influence of geotextiles along with replacement of soft soil underneath the foundation with improved ground on the bearing capacity of the foundation.

(2) To analyze load settlement characteristics of a shallow foundation with and without reinforcement.

1.3 Scope of the Study

The scope of the study is to find out appropriate ground reinforcement technique so that bearing capacity of soft soil deposits found at the subsoil of South-West region of Bangladesh can be improved by adopting numerical analyses which were performed with the finite element program FEM tij-2D using the elastoplastic subloading t_{ij} model (Nakai et al., 2004) and (Nakai, 2012).

1.4 Outline of Thesis

There are total five chapters which are chronologically developed on the basis of the research work towards its main objective. Brief descriptions of the five chapters are given below:

Chapter One deals with the background and objectives of the research. It also gives a brief overview of the other chapters.

ChapterTwo is devoted to reviewing past research related to the theme of this research.

Chapter Three describes the methodology of the research works.

Chapter Four illustrates results and discussions with specific findings.

Chapter Five describes conclusions and recommendations for further studies.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The idea of earth reinforcement was introduced by Casagrande.Subsequently it took its modern form by Vidal in 1960s. He formed a composite material from flat reinforcing strips laid horizontally in a frictional soil and achieved the interaction between the soil and the reinforcing members by friction caused by gravity (Jones et al., 1996).

Many soil improvement techniques have been adopted by the practitjioner engineers all over the world to overcome the difficulties associated with settlement, bearingcapacity and shear strength of soil. Among them, a few common techniques are -soil improvement without admixtures (soil replacement, preloading, sand drains, vertical drains etc.), soil improvement with admixtures or inclusions (stone columns, sand piles,etc.), soil improvement using stabilization with additives and grouting methods (chemical stabilization, deep mixing jet grouting,etc.), soil improvement using thermal methods such as heating, freezing (Gaafer et al., 2015).

Large areas of South-East region of Bangladesh consist of fine-grained soil deposits predominantly with peat and muck. As the soil is composed of organic substances, it is soft and compressible. Thus soil exhibits very large total and differential settlement causing bearing capacity and slope stability failure to geotechnical structures. The general foundation system is not suitable in this kind of soft soil. Limitations of conventional foundation systems caused the practiced geotechnical engineers to adopt alternative means of techniques such as soil reinforcement and soil improvement methods (Alamgir et al., 2004).

2.2 Ground Improvement Methods, Suitability and their Applications

When there exists a problematic ground at the work site, we might have to opt for either one: (1) Replace the ground with a more suitable material (2) Problematic work site may be avoided by choosing the new location or poor ground is negotiated by the use of deep foundation (3) Design of the structure may be adjusted to conform with the ground limitations. By adopting the ground improvement technique, the designer has the fourth option to set the problematic ground and prepare it to meet the demand (Jha et al., 2012).

Common geotechnical problems include bearing failure, large total and differential settlements, hydrocompression, ground heave, instability, liquefaction, erosion, and water seepage. To address these problems geotechnical engineers' adopt ground improvement techniques. These techniques can impart five major functions in soil: (1) to increase the bearing capacity, (2) to control deformations and accelerate consolidation, (3) to provide lateral stability, (4) to form seepage cut-off and environmental control, and (5) to increase resistance to liquefaction. Ground improvement methods practiced currently can be divided into eight categories i.e. (1) densification, (2) consolidation, (3) weight reduction, (4) reinforcement, (5) chemical treatment, (6) thermal stabilization, (7) electro-treatment, and (8) biotechnical stabilization (Jha et al., 2012).

Ground improvement by soil densification enhances bearing capacity, reduce settlement, and increase resistance to liquefaction. Densification at depth is attained by adopting the methods i.e., (1) vibro-compaction, (2) dynamic compaction, (3) blasting, and (4) compaction grouting. In dynamic compaction, large weights are dropped repeatedly on the ground surface at a predetermined grid pattern. Drop heights are usually 12 to 24 m, and the drop points are several meters apart. In case of densification by blasting, explosive is detonated in the loose soils and buried at depth. Shock waves caused by the blast breaks the soil structure and create a liquefaction condition that enables the soil particles to rearrange themselves into a denser packing. In compaction grouting, mortar grout is injected into the soil by pressure. Generally, grout does not enter into the soil pores, but remains as a homogeneous lump and compress the surroundings (Jha et al., 2012).

Effectiveness of soil densification is affected by : (1) the presence of fines in the soil, (2) the ability of soil to dissipate excess pore water pressure, (3) the energy felt by the soil , (4) the presence of boulders, utilities and adjacent structures, and (5) the ageing phenomenon. Fines present in soil act as lubricants reducing the frictional resistance between soil particles of the densified mass. It also affects the drainage properties of soil. Again the presence of excessive fines or cohesive soils will slow down the densification process. To eliminate this, use of vertical drain or fissuring can be adopted.

Soft soil can be reinforced to improve its engineering properties by inserting reinforcing elements into the soil. Reinforcing materials help to improve shear strength of the soil, arrest settlement once load is applied and reduce liquefaction effect. To get the reinforcing effect, any methods such as: (1) mechanical stabilization, (2) soil nailing, (3) soil anchoring, (4) micro piles, (5) stone columns, and (6) fibre reinforcement can be adopted.

For mechanical stabilization, reinforcing materials are normally laid between layers of compacted soil. Reinforcing materials are connected to facings that contain the compacted soil at the face and save the reinforcing materials from erosion. Soil nailing is used primarily for the support of excavation and reinforcement of slopes to increase the shear strength of soil and to restrain its displacement during and after the excavation.

Now, which ground improvement method to be adopted, is a concern of design engineer. Key factors that govern the selection of ground improvement methods are: (1) the ground, (2) the pore water, (3) construction considerations, (4) environmental issues, (5) sustainability, conservation and operational requirements, (6) contracting, politics, and tradition, and (7) cost (Jha et al., 2012).

Soil characteristics have a major role in selecting the ground improvement technique. The densification and reinforcement techniques are suitable for frictional soils such as sands and gravels. Stone column is suitable for ground having fine cohesive soils. Consolidation methods such as preloading and vacuum are also applicable for fine cohesive soils. When ground is reinforced with extensible elements such as geotextiles, soils of relatively low residual strengths are less compatible for such systems. When ground is inaccessible to the movement of heavy equipment, ground improvement using geotextile as reinforcement is preferred. In regards to chemical stabilization, permeation grouting is not suitable for fine-grained cohesive soils; lime stabilization is suitable only in clayey soils that have enough silica and alumina constituents to induce pozzolanic reaction. Although Jet grouting is suitable for all types of soil, but its effectiveness is affected by the presence of some soil elements such as boulders and organic materials.

2.3 Geosynthetic as Geomaterial Reinforcement

To reinforce the soil structure organic materials such as timber, straw or reed were used first in the early 19th century. Pasley first used the canvas as a reinforcing membrane. But canvas had its limitations in respect to its longevity. Thus canvas as geotextile reinforced structures was not durable. Scenario got changed with the development of synthetic polymer. Synthetic fabrics were developed prior to 1940 but it was not until 1970s that they earned their popularity. It was due to the longevity of advanced synthetic fabrics and geotextile produced materials (Jones et al., 1996).

The application of the concept of reinforcing soils by introducing tension-resisting elements such as strips, bars, sheets, meshes, and fibers has become a common practice in geotechnical engineering projects. The flexible nature of reinforced soil mass enables it to withstand a large differential settlement without any major distress. In certain difficult situations, the concept of reinforced soil is the only valid technical solution. Although the soil reinforcing mechanism differs for different types of reinforcements, the soil-reinforcement friction/adhesion is fundamental to the concept of all types of reinforced soil described here. The inclusion of reinforcement in a soil mass inhibits the tensile strains and develops the strength of the soil. If geosynthetics are used as reinforcement in a soil mass, they improve the strength and settlement characteristic of the soil mass by showing the following effects: shear stress reduction effect, confinement effect, membrane effect, and interlocking effect. The case studies presented in this chapter as well as those presented by Shukla (2002, 2012) and Shukla and Yin (2006) develop confidence in applications of geosynthetic reinforcements for technically effective and/or economic solutions to many geotechnical problems.

Polymer materials need to possess four characteristics to be applied as soil reinforcement. These are: strength, stiffness, durability and bondage with soil. Once used as reinforcement, polymer materials must be strong enough to withstand against the force generated by the structures.

The requirement of geotextile is that is has to be stiff so that the required force caused by the deformation of the soil can be mobilised as a tensile strain which is compatible to its strength. The concept of strain compatibility between the reinforced soil and the soil itself is implicit in any reinforced soil structure. The allowable tensile strain depends on the application.

The durability of the polymeric reinforcement depends on time and environment. Designer has to consider this factor for any permanent structure. The bond between the reinforcement and the soil is a function of the form of the polymer reinforcement. Geogrids and conventional geotextiles provide good bond with the soil. For geotextiles, it is due to the large surface area offered by them but for the geogrids, it is due to the soil/reinforcement interlock.

To address the corrosion and economies of production, initial development of polymeric reinforcment took place. In some parts of the world pulverised fuel ash is used as a fill in conjunction with geosynthetic reinforcement. It can save costs as well as offer technical benefits arising from the cohesive nature of many of these fills which produce a lighter and inherently stronger structure. For these obvious reasons indigenous (cohesive) fill is commonly used against steepened slopes.

The acute lack of suitable frictional fill in some countries such as parts of Japan has lead to the use of cohesive fill. Notable uses of cohesive fill were used in widening of railway network. It is established in Japan that geosynthetic reinforced soil structure formed using cohesive or cohesive-frictional fills are potentially more stable than structures formed from purely frictional fills. It is notable that this form of construction survived the Kobe earthquake. This technology also gained popularity in France. A great advantage of using geosynthetic reinforcements is that on-site material can be used for construction irrespective of its nature.

In the past when dealing with very soft soil, excavation and replacement was used as the construction method. This is expensive and not always practical; as a result, treatment of such type of soil earned popularity. The most common method to stabilize soft soil is by preloading, and frequently used in conjunction with vertical drains. When the soil is extremely soft, commonly referred to as a super soft soil, where the moisture content is higher than the liquid limit, preloading is not possible as the foundation has no effective bearing capacity. In that case, a primary construction stage may be created to perform as working platform on which remedial treatment can be based. The working platform (primary construction) frequently consists of geosynthetic reinforcement laid on the surface of the super soft soil supporting a thin uniform layer of cohesionless fill.

A number of methods have been used to form a fill layer over super soft soil using a geosynthetic membrane or reinforcement. Fig. 2.1 illustrates the schematic diagram of reinforced soil using geosynthetic. Although this construction technique is demonstrably successful but there is no general consensus in regards to the reinforcing mechanism or how the reinforcement improves the bearing capacity.

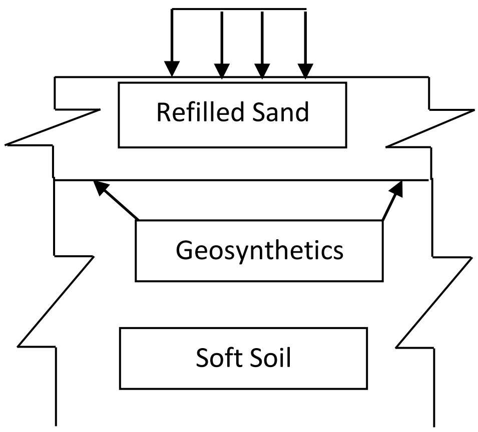


Fig. 2.1: Schematic diagram of reinforced soil using geosynthetic

Once geotextile is subjected to pullout load or direct shear; a normal scenario for geotextile reinforced structure, its stress-strain behavior is a major concern. When geotextile is used as a reinforcing element to attain slope stability then its success depends on the stress that the geotextile can sustain and the displacement it undergoes. Again, mechanical interaction between the geotextile and soil is characterized by the shear strength developed between soil and geotextile. When geotextile is used to reinforce the soil, high contact shear strength is required. But when geotextile is allowed to move against each other, a low contact shear strength is required. The shear strength is governed by the angle of internal friction developed between soil and geotextile. Thus shear strength of the soil-geotextile interface is the outcome of the stress-strain behavior of the geotextile when subjected to pull-out force (Sabitet al., 1996).

Surface roughness has a significant effect on the bond angle obtained in pull out test. If the surface roughness increases the coefficient of friction also increases. The interlocking of sand particles depends primarily on the ratio of the apparent opening size of the geosynthetic to the diameter of soil particles. Regarding the effect of soil particle size and the deformability of geotextiles on direct shear and pullout test, it is found that the friction angle between the geosynthetic and the cover material increases with an increase in geotextile opening size (Sabitet al., 1996).

Fabric structure and surface roughness has an effect on the peak or ultimate pullout load. When two fabrics have same apparent opening sizes, the geotextile with the slit film filling yarn, demonstrate higher pullout resistance. Pullout resistance is higher when soil grain size is smaller than the apparent opening size of the geotextiles To reinforce the soil structure organic materials such as timber, straw or reed were used first in the early 19th century. Pasley first used the canvas as a reinforcing membrane.But canvas had its limitations in respect to its longevity. Thus canvas as geotextile reinforced structures was not durable. Scenario got changed with the development of synthetic polymer. Synthetic fabrics were developed prior to 1940 but it was not until 1970s that they earned their popularity. It was due to the longevity of advanced synthetic fabrics and geotextile produced materials (Sabit et al., 1996).

There has been a rapid growth of geosynthetics industry in the recent decades. Prime cause behind this fact is the advancement in the functions of geosynthetics to meet the contemporary demand of mankind i.e., corrosion resistance, durability, flexibility, ease of storage & installation, environment friendly, resistance to biological & chemical degradation. Their types also vary to conform to the applications, such as - (1) geotextiles, (2) geogrids, (3) geonets, (4) geomembranes, (5) geosynthetic clay liners, (6) geopipe, (7) geofoam, and (8) geocomposites.But they are selected according to their functions. Table2.1 summarizes the different types of geosynthetics and their functions. It is to be noted that geotextiles and geocompositespossess most of the functional characteristics, so they are used in many applications (Han, 2015).

Table-2.1 Function of Geosynthetics (Han, 2015)

Type of Geosynthetics (GS)	Function						
	Separation	Reinforcement	Filtration	Drainage	Containment	protection	Erosion control
Geotextile (GT)	✓	✓	✓	✓		✓	
Geogrid (GG)		✓					
Geonet (GN)				✓			
Geomembrance (GM)					✓		
Geosynthetic Clay Liner (GCL)					✓		
Geopipe (GP)				✓		✓	✓
Geofoam (GF)	✓						
Geocomposite (GC)	✓	✓	✓	✓	✓		

To analyse the effectiveness of reinforcement in cohesionless soil many investigations were carried out. Effectiveness of reinforcement mainly depends on its position and skin friction. It is found that in sandy soil reinforcing effect is almost zero when reinforcement is placed beyond a certain depth (D/B=0.5). Once reinforcement length is slightly greater than the width of the foundation, it gives better result. Due to the reinforcement a wider and deeper region of shear strain is developed (Nakai et al., 2009). Maximum tensile force is produced at the central part of reinforcement.

In sandy soil, the maximum reinforcing effect is found when it is set up between D/B=0.05 to D/B=0.20 irrespective of loading conditions (concentric and eccentric load). But when reinforcement is set up at D/B=0.40 or beyond, its effect is poor and thus not desired. Again fixed edges of the reinforcing members with the ground are more effective than that of the free edges of the reinforcement (Nakai et al., 2012) which was also proven during a tremor of the Great East Japan Earthquake on March 11, 2011. Again once geosynthetics under the foundation is placed at an appropriate depth, differential settlement can also be controlled in eccentric loading (Nakai et al., 2012).

The effectiveness of geosynthetics as soil reinforcment has been established since long. Ghosh et al. (2005) and Patra et al. (2005, 2006) confirmed the effectiveness of geosynthetics for improving the bearing capacity andreducing settlement once footing is placed under a thin aggregate layer over soft subgrade. For the last couple of decades, professional engineers had been looking for a viable and robust solution in dealing with shallow foundation over soft soil.

In reclaimed areas of Dhaka city, low lying lands are filled by dredged soil. This dredged fill material composed of silty sand with high fines (Moin,2017). In reclaimed areas there exist a soft organic clay layer below the dredged fill. Shallow foundation in reclaimed areas of Dhaka city once reinforced with geosynthetics caused significant improvement in bearing capacity and optimum result obtained once reinforcement was placed at D/B=0.10 (Moin, 2017).

2.4 Bearing Capacity of Foundation Soil

Tarzaghi in 1943, outlined the concept of strip foundation. Subsequently in 1948 Tarzaghi and Peck gave load spreading theory to determine the strip footing on sand overlying clay. Later on, semi-empirical solutions of Meyerhof (1974) and Hanna & Meyerhof (1980) were widely practiced. They introduced the punching shear models and assumed that sand layer would subject to passive failure along vertical planes beneath the footing edges. Terzaghi and Peck (1948); Houlsbyetal.(1989) introduced another approach i.e., load spread model in which the sand layer is assumed to merely spread the load to the underlying clay. In this technique shear strength of sand is ignored and surcharge load is taken care by clay layer. To calculate the bearing capacity of multilayered soils, Chen and Davidson (1973), Florkiewicz (1989), and Michalowski and Shi (1995 introduced the upper bound theorem of limit analysis. Then Davis, 1968; Chen, 1975; Sloan, 1988, 1989 introduced lower bound theorem of limit analysis so that the accurate result can be bracketed from above and below.

Various elasto-plastic parameters are responsible for the stability of structures facing natural phenomena. Thus issues related to behavior of subsoil under surcharge such as soil-water interaction, over consolidation ratio (OCR), bonding effect or structured soil, anisotropy of soil etc. need to be addressed to predict the bearing capacity of soils. Finite element (FE) analysis is an effective approach to address the above mentioned issues and already gained wide attention due to its versatility in application.However, to conduct FE analyses accurately, constitutive models of soils have a significant role.

Available constitutive models such as Cam Clay model (Roscoe and Burland, 1968), Drucker-Prager Model, Mohr-Coloumb Model cannot properly consider or explain soil behavior of different densities, influence of intermediate principal stress etc. However, in this paper extended Subloading t_{ij}model (Nakai and Hinokio, 2004; Nakai et al., 2011) is used which can consider the influence of intermediate principal stress on the deformation and strength of soils, dependence of the direction of plastic flow on the stress paths, influence of density and/or confining pressure and bonding effect on the deformation and strength of soils (Shahin et al., 2004; Nakai et al., 2011).

2.5 Effect of Soil Reinforcement on the Shallow Foundation

In the shallow foundation, bearing capacity improvement and settlement reduction can be done by the incorporation of reinforcement beneath the footing. Variation in laying depth of reinforcement has a significant effect as investigated by Shahin etal. (2013). They found out that the effectiveness of reinforcement mainly depends on its laying depth below the footing and the significant effect noticed once it is placed up in between D/B= 0.05 to 0.20.Once reinforcement is placed at a deeper zone i.e., D/B≥0.40, its effect is insignificant.

To design shallow foundation settlement has to be considered. It has overriding effect over bearing capacity of soil. Thus it needs to set a settlement criterion i.e. a margin of settlement tolerance and then adopt the bearing capacity improvement technique for foundation soil.Again bearing capacity of soil varies depending on type of reinforcing materials, number of its layers & location, details of reinforcing materials, foundation details (footing width and depth of footing), type of soil and unit weight or density of soil. Ferdous (2007) conducted the research on geotechnical characteristics of the problematic soil of Khulna City Corporation (KCC) area. He suggested shallow foundation on top of rammed aggregate pier (RAP) for low to medium rise building at KCC area and piled raft foundation system for tall building where basement is required.

It is now a established fact that incorporation of geosynthetic materials as a reinforcing element below the footing of shallow foundation can improve the bearing capacity of soil.Yoon et al. (2004), Ghosh et al. (2005), Patra et al. (2005, 2006) used model tests to study the influence of different types of reinforcement on the bearing capacity and settlement of the footing. They confirmed the beneficial effect of geotextile on the enhancement of bearing capacity and found to have a relevant reinforcing effect only when used under a thin aggregated layer on a soft subgrade.In this regard construction work at Khulna Medical College campus is mentioned worthy where geotextile and other reinforcing materials were used beneath the footing to reinforce the shallow foundation. Long term settlement was monitored after six years of construction and performance of the adopted system was quite satisfactory (Alamgir et al., 2004).

2.6 Case Studies

It was neither feasible nor meaningful to reinforce the soil by adopting stage making technique which was a common practice in the past in order to construct the reinforced soil layer. Chao, Sao-Jeng (2008) followed the process of experimental work, site performance evaluation, and FEM numerical simulation by employing geosynthetic reinforced technique to overcome these difficulties at Ilan, Taiwan thus strengthened the properties of weak soil; a cost effective solution for civil engineering. He found out that the worse condition of subsurface clay soil provides the better efficient ratio for reinforcement.

Sub-soil of Khulna region of Bangladesh consists of fine-grained alluvial soil deposits. Soil profile of Khulna University Campus is illustrated through Fig.2.2 (Hossain et al., 1999). Approximately the top 6 feet from existing ground level consists of soft grey clay. Below this, a very soft layer of dark grey and black organic clay (decomposed wood and vegetation) extends from reduce level 0 to 12 feet (sec Fig. 2.2) exists. This layer is underlain followed by a thick layer (R.L 12 feet to 70 feet) of soft grey clay with silt and trace of organic matter. After this layer, clay with silt and fine sand exists up to the end of the bore holes. Soil properties of these regions are enlisted in Table 2.2 It is enriched with organic substances and thus subjected to high volumetric change once under pressure. Thus sub-soil of Khulna region undergoes large total and differential settlement (Alamgir et al 2004). Some ground improvement techniques can be mentioned here which were practiced in this region.

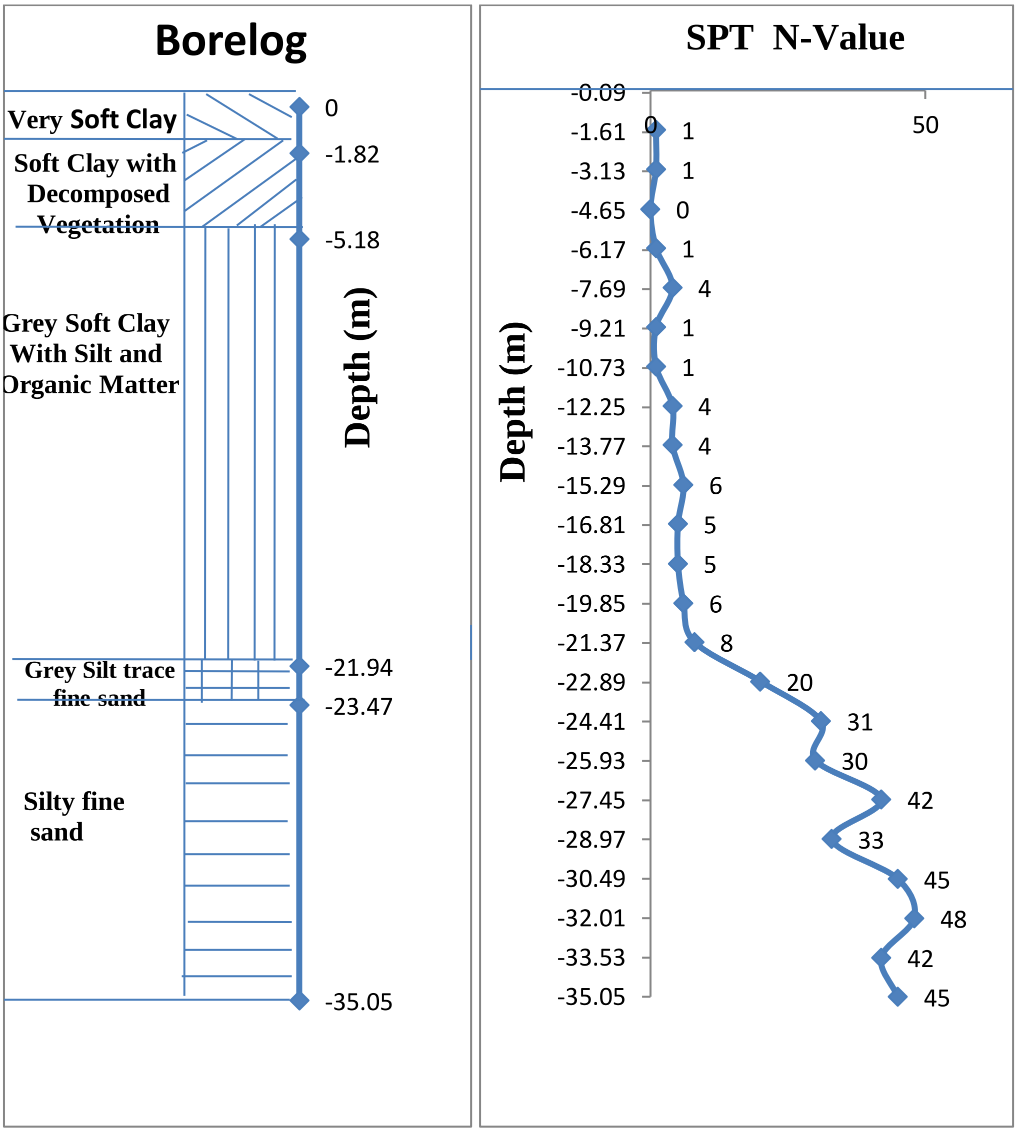


Fig.2.2 Soil Profile at Khulna University Site (Ferdous, 2007)

Table 2.2: Geotechnical Engineering Properties of sub-soil of typical site of Khulna Region (Alamgir et al., 2004)

		Physical PProperties		Compressibility Properties			Strength properties	
Depth (m)	Soil strata	Water content, Liquid Limit, Plastic limit ($w\%, w_l\%, w_p\%$)	Unit weight γ(kN/m^3), Specific gravity, G_s	Initial void ratio, e_0	Compression index, C_c	Coefficient of Consolidation C_v (m^2/sec)	Undrained shear strength, S_u (kPa)	N Value
0-1.5	Fine sand	33, --, --	-------, 2.75	---	---	---	----	6
1.5-3.0		39, --, -	-------, 2.73	---	---	---	----	2
3-4.5	Clay	45, 59, 31	25.56, 2.73	1.706	0.257	3.83×10^{-7}	12.0	2
4.5-6.0	Organic clay	58, 77, 39	17.50, 2.57	2.170	0.391	5.00×10^{-7}	26.0	4
6-7.5		223, 112, 55	7.46, 2.50	7.962	1.308	3.66×10^{-7}	30.0	4
7.5-9.0	Clay	36, 51, 39	14.93, 2.50	1.207	0.249	7.20×10^{-7}	43.0	7
9-10.5		36, 47, 31	18.58, 2.71	1.404	2.176	12.2×10^{-7}	44.0	7
10.5-12.0		46, 42, 32	13.96, 2.67	1.501	0.137	8.83×10^{-7}	25.0	4
12.0-13.5		47, 49, 33	14.25, 2.88	1.464	0.154	9.96×10^{-7}	40.0	7
13.5-15.0		24, 37, 36	13.45, 2.64	1.568	0.169	7.81×10^{-7}	37.0	6
15.0-16.5	Silty Clay	47, 50, 35	14.47, 2.62	1.474	0.156	14.8×10^{-7}	46.0	8
16.5-18.0	Clay	39, 48, 34	13.80, 2.65	1.502	0.166	6.60×10^{-7}	55.0	11
18.0-20.0	Silty Clay	45, 50, 36	14.50, 2.62	1.480	0.154	13.6×10^{-7}	48.0	8

At Khulna Medical College, shallow foundation system based on compacted brick aggregates reinforced with geosynthetics was used.Soil profile of Khulna Medical College site is illustrated in Fig. 2.3 (Ferdous, 2007). A foundation system replacing the soft compressible soil layer of 6m depth by compacted sand and then building was placed on mat foundation for the construction of Academic Building-I of Khulna University (Alamgir et al., 2004).

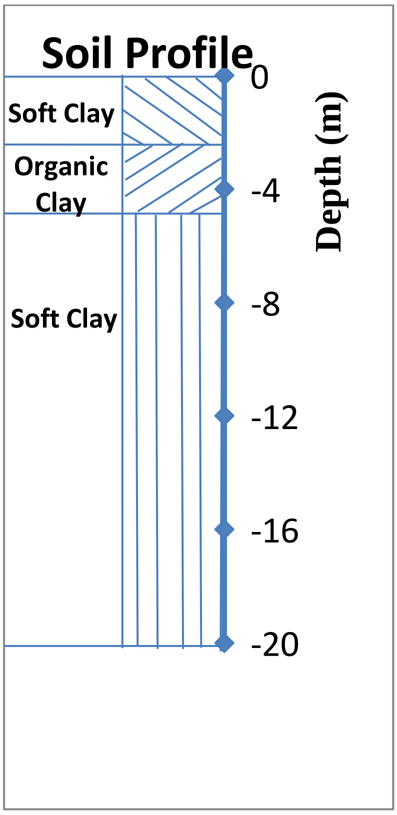


Fig.2.3 Soil Profile at Khulna Medical College Site (Ferdous, 2007)

At Khulna Medical College project, shallow foundation system was based on two layers of compacted sand having different FM followed by a densified brick aggregate and sand mixed layer beneath which geotextile reinforcement was placed over natural soil. But at Academic Building-1 of Khulna University foundation system was based on replaced compacted sand for a considerable depth where geotextile was not used. To measure the settlement over the years, settlement plate was installed in both the projects. Values were recorded for more than three years in Khulna Medical College site whereas it was recorded for six years at Khulna University site. At Khulna Medical College, it served well for the Academic building, Hostels and some residential buildings despite large uniform settlement. But excessive total and differential settlements were observed particularly at two residential buildings of Khulna Medical College resulting tilting of the structures. At Khulna University site 765mm settlement was observed at the Academic building-I. It was very large and uniform but caused adverse effect on its serviceability.

Khulna medical college was facilitated with 250 bed hospital complex. It was extended to accommodate the infrastructural facilities required for the medical college campus. The project site lies on thick and highly compressible clay and organic deposits. Water table varies during with seasons but lies close to 1.5 m below the ground surface during dry. At the Top a layer of 1.5 m in thick with brownish gray of very soft clayey silt exist. It was followed by 1.5 m to 6m thick layer of dark decomposed organic and soft clayey silt. Then a layer of very soft to soft clayey silt layer from 6m to 13m in depth. It was followed by a dark gray organic clayey silts layer from 13m to 18m in depth.

At the base of foundation system of academic building, boys & girls hostels and residential building geotextile was used. Typical cross sections of foundation system for the academic and residential buildings are given in Fig.2.4 and Fig.2.5 below. Settlement of the foundation system was monitored for more than three years. Actual value of settlement did not match with the predicted/designed value. Heavily loaded academic building underwent very low settlement (60mm) while it was abnormally high (600mm) for lightly loaded residential buildings. Foundation system served satisfactorily for academic building, hostels and some of the residential buildings despite of their large uniform settlement. Excessive total and differential settlement occurred at two residential buildings. Thus severely affect their serviceability (Hossain et al.,1999).

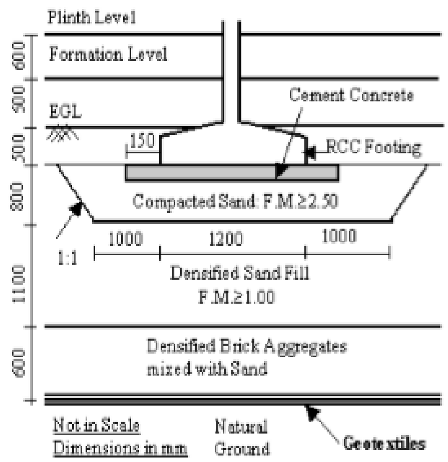


Fig. 2.4: Academic Building of Khulna Medical College and its Foundation System (Hossain et al.,1999)

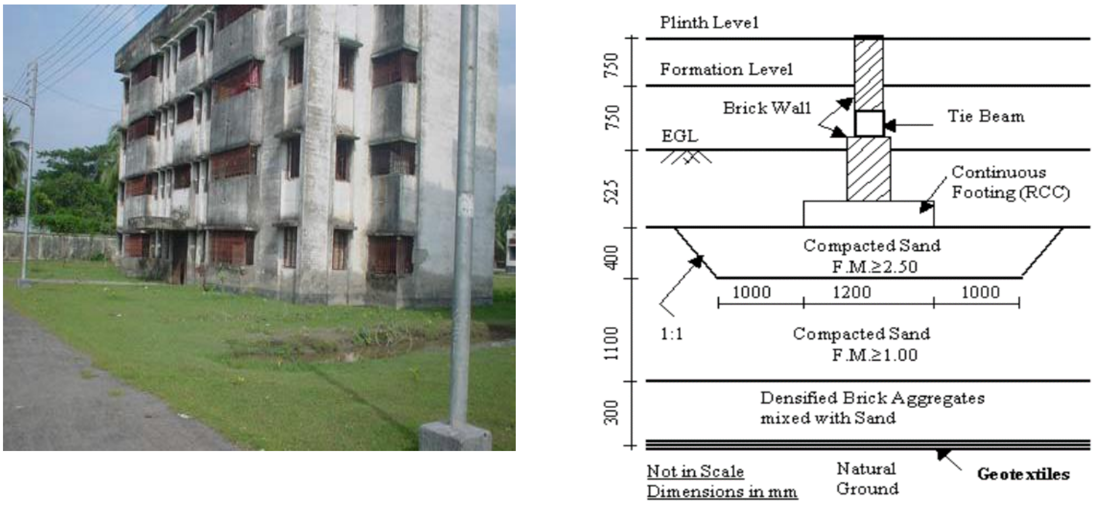


Fig. 2.5: Residential Building of Khulna Medical College and its Foundation system (Hossain et al.,1999)

2.7 Research Gap

In cohesionless soil, reinforcing mechanism of geosynthetics and soil has been analysed with laboratory model tests and the relevant numerical analyses. It has been revealed that reinforcement length greater than foundation width is desirable. Shear strain developed to a wider and deeper region once reinforcement is placed in certain depth beneath the foundation (between D/B=1/8 to D/B=1/2) (Shahin et. al., 2009).It was also revealed that in sandy soil, bearing capacity of the underlain ground can be improved by soil-reinforcement. Its effectiveness depends mainly on the position of reinforcement and better result found once it is placed between D/B=0.05 to D/B=0.20 irrespective of loading condition (Shahin et al., 2012).

In laying shallow foundation within reclaimed areas of Dhaka city where dredged fill (poorly graded sandy soil) is laid over organic clay and silty clay, bearing capacity can be improved significantly by the soil-reinforcement at D/B=0.10 (Moin, 2017). Again, shallow foundation was laid over soft clay deposits of South-West region of Bangladesh (Khulna Medical College) and it was reinforced by geotextiles to improve its bearing capacity. Here, foundation was laid over improved ground below which geotextile was placed over natural clay deposits (Alamgir et al., 2004). For designing such kind of foundation system over soft clay soil no analyses were done. Therefore, in this study numerical analyses have been carried out to see the effectiveness of the soil-reinforced system in enhancement of bearing Capacity of the ground consisting soft clay layer.

CHAPTER 3: METHODOLOGY

3.1 Introduction

In this study, bearing capacities of the ground with and without reinforcement including improved ground have been simulated with Finite Element Method. The numerical simulations have been carried out with the two-dimensional finite element program named FEMtij-2D. For modeling the soil elastoplastic subloading t_{ij} model (Nakai et al., 2004) and (Nakai, 2012) was used. The model was validated in various fields of geotechnical engineering, such as bearing capacity (Shahin et al. 2010, Islam et al. 2014), soil-reinforcement (Nakai et al., 2009;Islam and Shahin, 2013; Shahin et al., 2012, 2014, 2017; and Moin, 2017). Frictional behavior has been considered for getting the soil-reinforcement interaction effect. In the finite element analyses, the frictional behavior between reinforcement and soil was modelled with elastoplastic interface element (Nakai, 1985).

3.2 Finite Element Model

Fig.3.1 represents a typical mesh used in the numerical analyses. The left and right boundaries of the finite element model are kept fixed in the horizontal direction and free in the vertical direction. The bottom boundary of the model is kept fixed in both horizontal and vertical directions. Isoperimetric four-nodded elements are used for soil elements, and elastic beam elements are used to simulate reinforcements. Axial stiffness of the reinforcement of 1314 kN/m was used in the analyses.

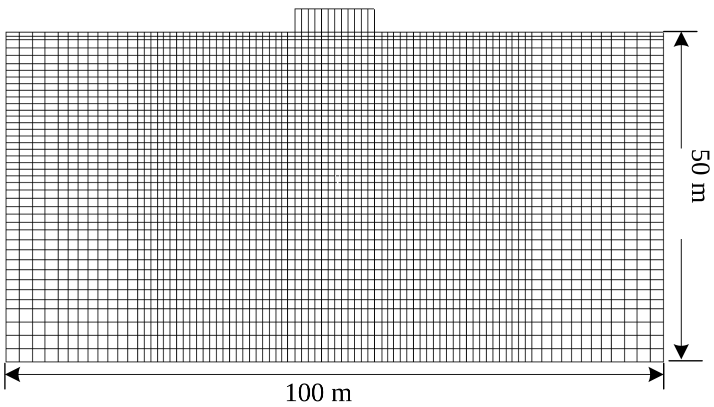


Fig.3.1 A typical mesh for finite element analysis

The frictional behavior between the reinforcement and soil, and the foundation/ground is modeled employing the elastoplastic joint element (Nakai, 1985). The friction angle between foundation and soil is δ=15^0. Fig.3.2 refers to the reinforcement set up. Here, D depicts the depth of the reinforcement and L represents the length of the reinforcement. In this study, the length of the reinforcement is kept constant which is 14.4 m, and the width of the foundation (B) is 12.0 m.The edges of the reinforcement are kept fixed with the ground considering the same movement of the nodes of the reinforcement and soil. Three depths of the reinforcement are considered to find the effective depth for getting maximum benefit, D/B= 0.05, 0.10, and 0.20.

Bearing capacity is checked replacing the soft clay with granular soil in between the foundation and reinforcement for all D/B. The material parameters of granular soil are listed in Table 2. Four different over consolidation ratios, OCR = 1.0, 2.0, 4.0, and 8.0 are considered to check the interaction of ground stiffness and reinforcement. In addition, in some cases the soft soil below the foundation has been replaced till the reinforcement with improved granular soil which is usually followed in real field construction.

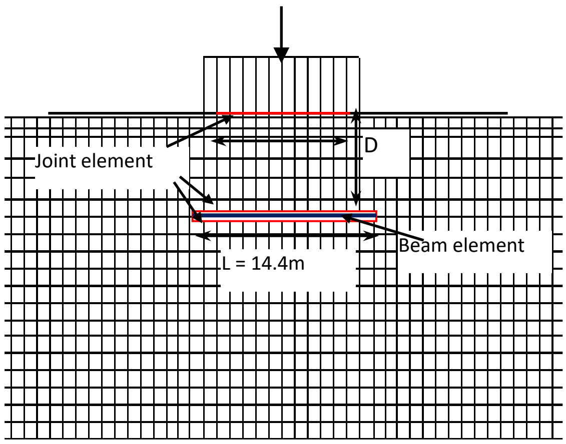


Fig. 3.2 Reinforcement Setup

3.3 Subloading t_{ij} Model

Subloading t_{ij} model (Nakai et al., 2004 and Nakai, 2012) is a non-linear elastoplastic constitutive model for soils. This model can describe typical stress deformation and strength characteristics of soils such as the influence of intermediate principal stress, the influence of stress path dependency of plastic flow and the influence of density and/or confining pressure. The parameters of the subloading tij model are given below:

(1) Compressive Index, λ

(2) Swelling Index, κ

(3) Void ratio at atmospheric pressure (98 kPa), N

(4) Critical state stress ratio, R_{cs}

(5) Poisson's ratio, ν_e

(6) Shape of the yield surface, β

(7) Influence of density, a

The parameters of the model are fundamentally the same as those of the Cam clay model, except for the parameter a, which is responsible for the influence of the density and the confining pressure. The parameter β represents the shape of the yield surface. The parameters can easily be obtained from traditional laboratory tests such as oedometer test and triaxial test.

Material Properties of Soft Clay and Granular Soil are listed in Table3.1 and Table 3.2, respectively. Here, parameters of Dhaka Clay are also added to validate the model parameters of the soft soilused for this research works.

Table 3.1Material parameters of clay soil (Islam et al. 2014)

Parameter	Notation	Value		Remarks
		Dhaka Clay	Fujinomori Clay	
Compression index	λ	0.080	0.10390	Same parameters as Cam-clay model
Swelling index	κ	0.078	0.00990	
Reference void ratio on normally consolidation line at p= 98 kPa&q= 0 kPa	N	0.80	0.9220	
Critical state stress ratio R_{cs}= $(\sigma_1/\sigma_3)_{cs(comp.)}$	$R_{CS}=(\sigma_1/\sigma_3)_{CS(comp.)}$	3.82	3.20	
Poisson's ratio	ν_e	0.20	0.20	
Shape of yield surface (same as original Cam clay at β= 1)	β	1.50	1.50	
Influence of density and confining pressure	a	600	500	

Table 3.2 Material parameters of granular soil (Improved soil)

Parameters	Notations	Value
Compressive Index	λ	0.040
Swelling Index	κ	0.0045
Void ratio at atmospheric pressure (98 kPa)	N	1.10
Critical state stress ratio	R_{cs}	2.0
Poisson's ratio	ν_e	0.2
The shape of the yield surface	β	1.5
Influence of density	a	200

3.4 Procedures of Numerical Simulations

Steps of the numerical simulations are as follows:

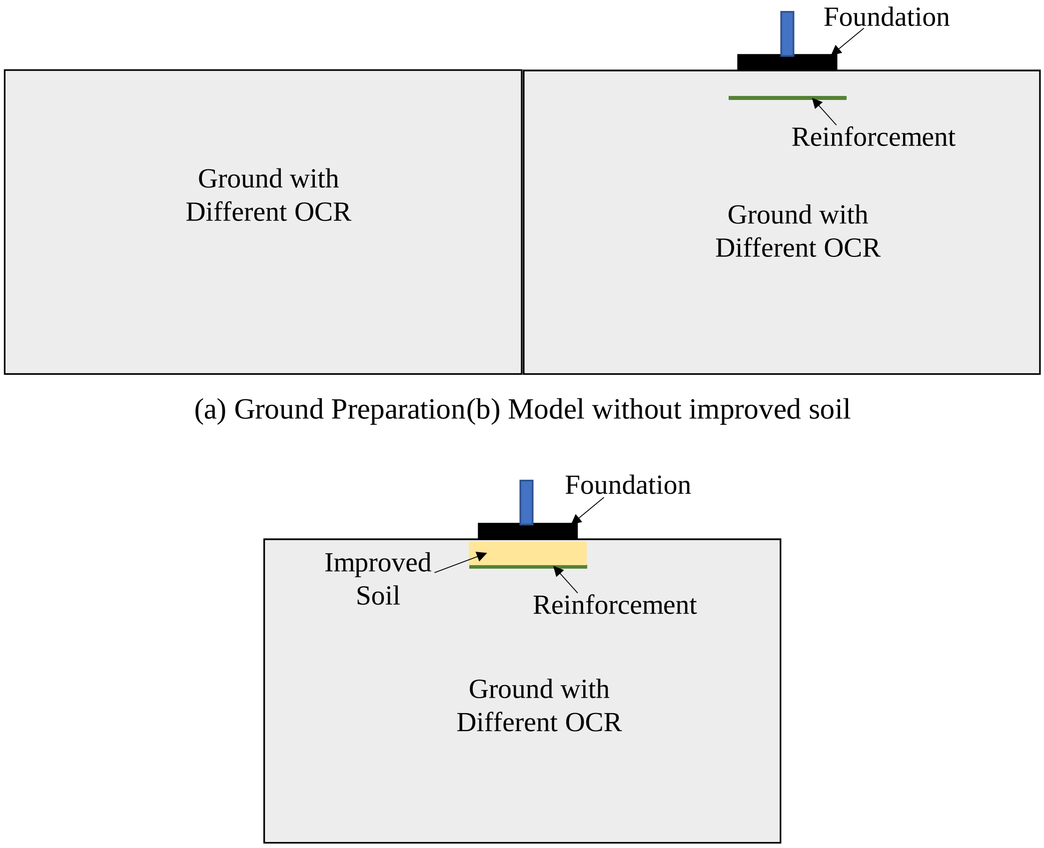
(1) Initial ground is made with specific over consolidation ratio such as OCR = 1.0, 2.0, 4.0, and 8.0.

(2) In case of the replacement of the soil, the soft soil is replaced with improved granular soil. Fig. 3.3 illustrates the model with and without reinforcement.

(3) Beam element (geotextile) and interface element are activated.

(4) Applying settlement at the foundation until failure.

The output of the numerical simulations is then processed to draw load – settlement curves, and distribution of shearing strain of the ground.



(a) Ground Preparation(b) Model without improved soil

(c) Model with improved soil

Fig. 3.3 Model with and without improved soil

Chapter 4: Results and Discussions

4.1 General

For determining the bearing capacity of subsoils of South-West coastal districts of Bangladesh, material parameters listed in Table 3.1 and Table3.2 were used. In this chapter, the results of the effect of depth of the reinforcement, and the effect of reinforced ground with improved soil have been discussed.

4.2 Effect of Depth of Reinforcement

Figure 4.1 illustrates the load -displacement curves for the ground at OCR=1. Graph with Diamond marks shows the bearing capacity of ground where no reinforcement was used. Graph with square mark describes bearing capacity of ground for reinforcement at D/B=0.05. Graph with triangle marks represents the bearing capacity of ground for reinforcement at D/B=0.10. Dashed line depicts bearing capacity of ground where reinforcement was used at D/B= 0.20. For OCR=1.0 at lower value of load-displacement, bearing capacity is found greater for reinforcement at D/B=0.05 but at higher value it is found greater for reinforcement at D/B=0.20.

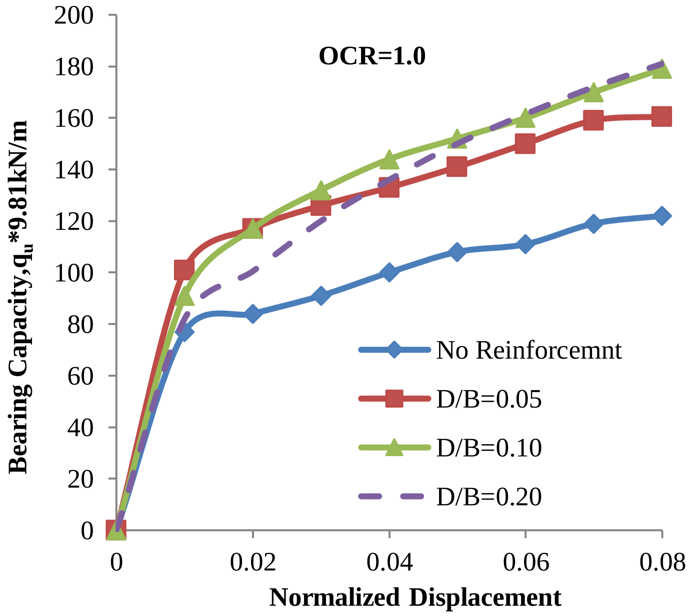


Fig. 4.1 Relation of bearing capacity with normalized displacement at OCR=1.0

Fig. 4.2 describes the load -displacement curves for the ground at OCR=2.0. Graph with Diamond marks depicts the bearing capacity of ground where no reinforcement was used. Graph with square mark illustrates bearing capacity of ground for reinforcement at D/B=0.05. Graph with triangle marks represents the bearing capacity of ground for reinforcement at D/B=0.10. Dashed line describes bearing capacity of ground where reinforcement was used at D/B= 0.20. For OCR=2.0, at lower value bearing capacity is found greater for reinforcement at D/B=0.05 but at higher value it is found greater for reinforcement at D/B=0.10.

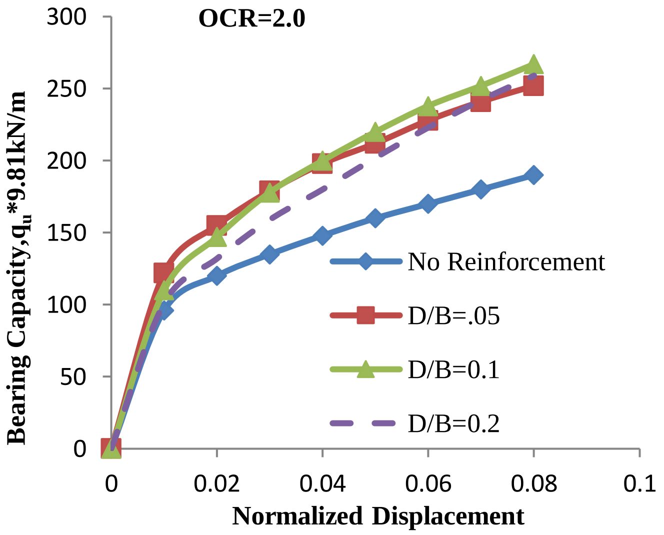


Fig.4.2 Relation of bearing capacity with normalized displacement at OCR=2.0

Fig.4.3 depicts the load -displacement curves for the ground at OCR=4.0. Graph with Diamond marks represents the bearing capacity of ground where no reinforcement was used. Graph with square mark illustrates bearing capacity of ground for reinforcement at D/B=0.05. Graph with triangle marks describes the bearing capacity of ground for reinforcement at D/B=0.10. Dashed line represent bearing capacity of ground where reinforcement was used at D/B= 0.20. For OCR=4.0, at lower value of load-displacement, bearing capacity is found greater for reinforcement at D/B=0.05 but at higher value of OCR it is found greater for reinforcement at D/B=0.10.

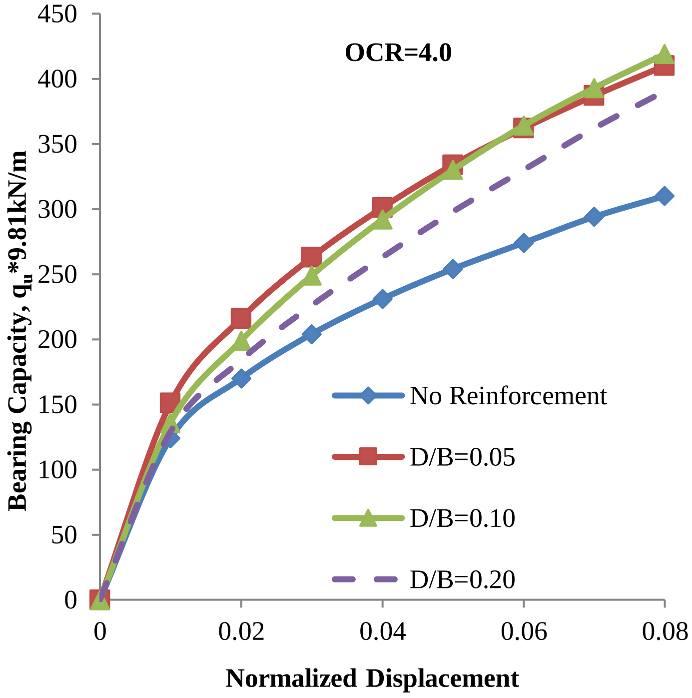


Fig.4.3 Relation of bearing capacity with normalized displacement at OCR=4.0

Fig.4.4 represents the load -displacement curves for the ground at OCR=8.0. Graph with Diamond marks depicts the bearing capacity of ground with no reinforcement. Graph with square mark illustrates bearing capacity of ground for reinforcement at D/B=0.05. Graph with triangle marks describes the bearing capacity of ground for reinforcement at D/B=0.10. Dashed line represents bearing capacity of ground where reinforcement was used at D/B= 0.20. For OCR=8.0, at lower value of load-displacement, bearing capacity is found greater for reinforcement at D/B=0.05 but at higher value it is found greater for reinforcement at D/B=0.10.

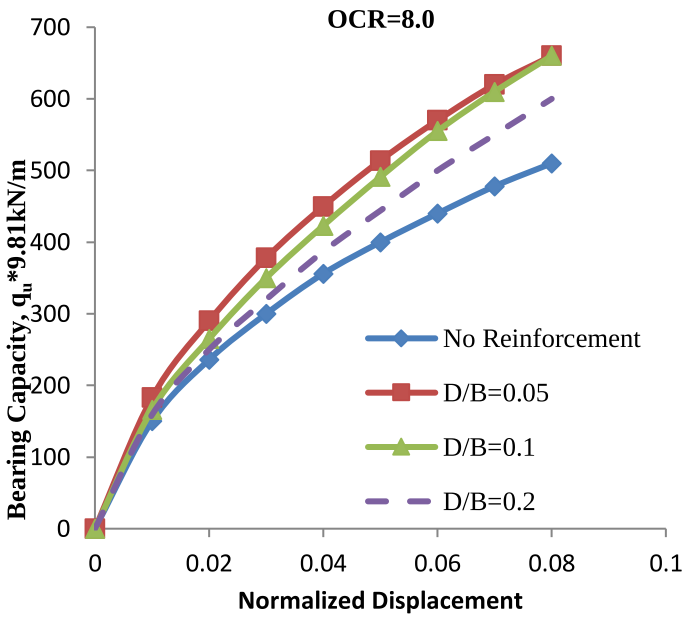


Fig. 4.4 Relation of bearing capacity with normalized displacement at OCR=8.0

Fig.4.5 shows percentage increment in bearing capacity with respect to ground without reinforcement against load-displacement for OCR=1.0. Vertical axis represents percentage increment in bearing capacity whereas abscissa illustrates load displacement. Here graph with diamond mark describes percentage increment in bearing capacity when ground is reinforced at D/B=0.05. Graph with rectangle mark describes increment in bearing capacity when ground is reinforced at D/B=0.1. Graph with triangle mark explains percentage increment in bearing capacity when ground is reinforced at D/B=0.2. For load displacement of ground reinforced at D/B= 0.05, there is a declining trend in percentage increment in bearing capacity. But for the increment in bearing capacity of ground reinforced at D/B=0.1 & D/B=0.20, there exist a positive trend.

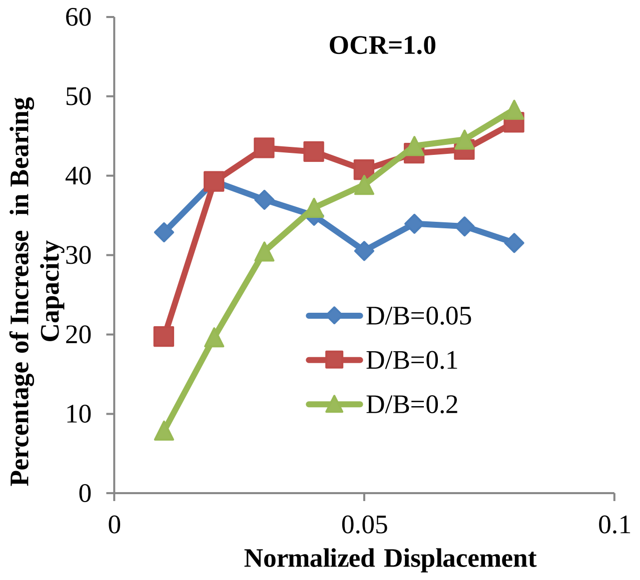


Fig. 4.5 Relation of % of the increase in bearing capacity with respect to no-reinforcement against normalized displacement at OCR=1.0

Fig.4.6 illustrates percentage increment in bearing capacity with respect to ground without reinforcement against load-displacement for the ground OCR=2.0. Vertical axis represents percentage increment in bearing capacity in respect to bearing capacity of ground without reinforcement whereas abscissa relates with load displacement. Here graph with diamond mark depicts percentage increment in bearing capacity when ground is reinforced at D/B=0.05. Graph with rectangle mark shows percentage increment in bearing capacity when ground is reinforced at D/B=0.2. Graph with triangle mark represent percentage increment in bearing capacity when ground is reinforced at D/B=0.2. Although initially percentage incrment in bearing capacityfor ground reinforced at D/B= 0.1 and D/B=0.2 maintain distinct differane but beyond 5% of normalized displacement, they are almost same and parallel.

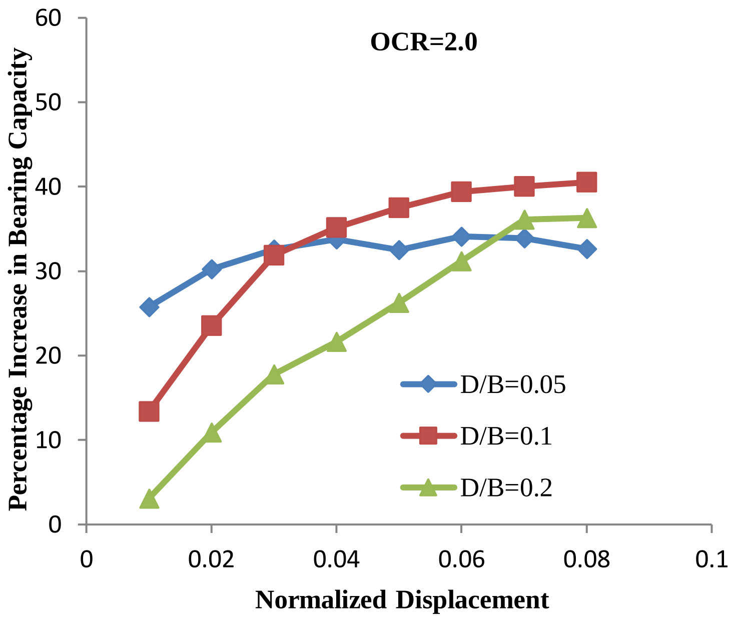


Fig. 4.6 Relation of % of the increase in bearing capacity with respect to no-reinforcement against normalized displacement at OCR=2.0

Fig.4.7 represents percentage increment in bearing capacity with respect to ground without reinforcement against load-displacement for the ground OCR=4. Vertical axis illustrates percentage increment in bearing capacity in respect to bearing capacity of ground without reinforcement whereas abscissa depicts load displacement. Here graph with diamond mark shows percentage increment in bearing capacity when ground is reinforced at D/B=0.05. Graph with rectangle mark represents percentage increment in bearing capacity when ground is reinforced at D/B=0.1. Graph with triangle mark relates percentage increment in bearing capacity when ground is reinforced at D/B=0.2. Initially rate of increment in bearing capacity for ground reinforced at D/B=0.05 is at top but at higher value of load displacement, it is crossed by the graph depicts the same for reinforcement at D/B=0.10. Finally increment rate reaches to the peak for ground reinforced at D/B= 0.1at higher value of normalized displacement.

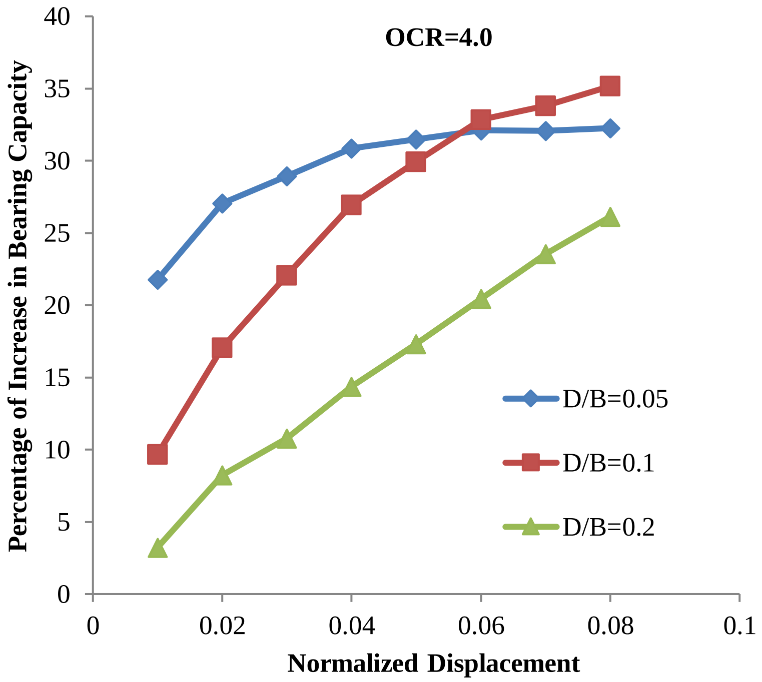


Fig. 4.7 Relation of % of the increase in bearing capacity with respect to no-reinforcement against normalized displacement at OCR=4.0

Fig.4.8 illustrates percentage increment in bearing capacity with respect to ground without reinforcement against load-displacement for the ground OCR=8. Vertical axis shows increment in bearing capacity in respect to bearing capacity of ground without reinforcement whereas abscissa relates load displacement. Here graph with diamond mark depicts increment in bearing capacity when ground is reinforced at D/B=0.05. Graph with rectangle mark describes percentage increment in bearing capacity when ground is reinforced at D/B=0.1. Graph with triangle mark shows percentage increment in bearing capacity when ground is reinforced at D/B=0.2. Rate of increment in bearing capacity for ground reinforced at D/B=0.05 is positive and flatter than others but lies at the top at lowervalue of load displacement. Once reinforcement is placed at D/B= 0.1, at higher value of load displacement, rate of increment in bearing capacity exceeds from the same once reinforcement is replaced at D/B=0.05. But increment rate for ground reinforced at D/B= 0.2 maintains a positive & moderate state and overall it lies below (Figure 10) others.

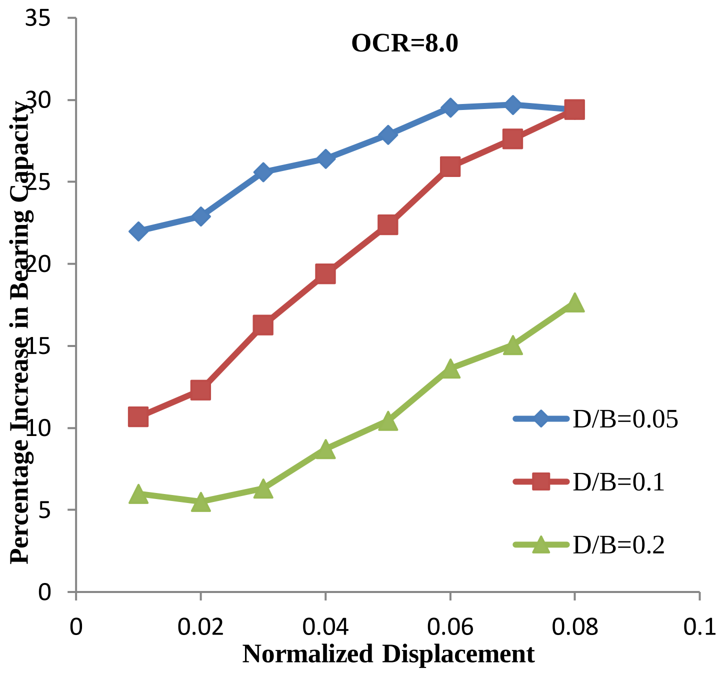


Fig. 4.8 Relation of % of the increase in bearing capacity with respect to no-reinforcement against normalized displacement at OCR=8.0

4.3 Effect of Ground Conditions

Fig.4.9 depicts bearing capacity against load-displacement for different OCRs' value when reinforcement is placed at D/B=0.05. Vertical axis represents bearing capacity whereas abscissa shows load displacement. Here graph with diamond mark describes bearing capacity at OCR=1. Graph with rectangle mark represents bearing capacity at OCR=2. Graph with rectangle mark illustrates bearing capacity at OCR=4. Graph with dashed line explains bearing capacity at OCR=8. For corresponding normalized displacement, bearing capacity is the lowest at OCR=1 whereas it is the maximum in case of OCR=8. Increasing rate of bearing capacity is flatter for OCR=1 whereas it is very steep for OCR=8.

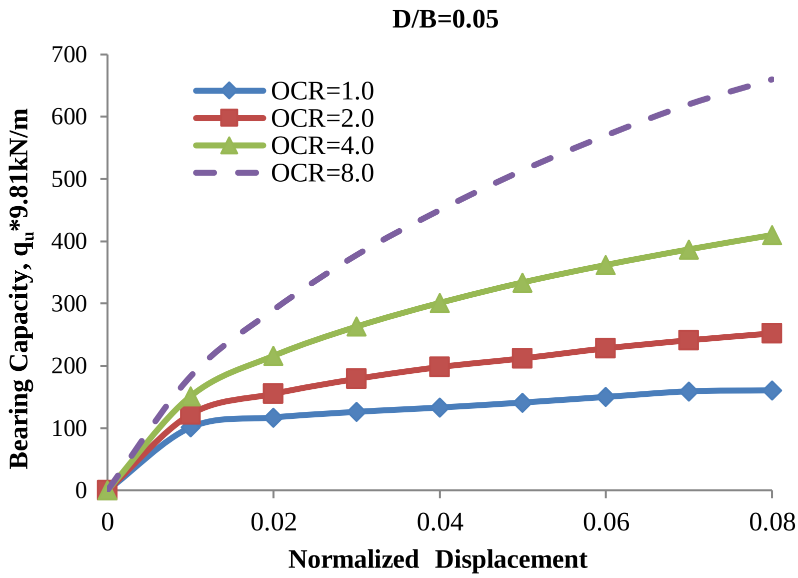


Fig. 4.9 Relation of bearing capacity with respect to normalized displacement at different OCRs for D/B=0.05

Fig.4.10 represents bearing capacity against load-displacement for different OCRs' value when reinforcement is placed at D/B=0.1. Vertical axis depicts bearing capacity whereas abscissa shows load displacement. Here graph with diamond mark illustrates bearing capacity at OCR=1. Graph with rectangle mark shows bearing capacity at OCR=2. Graph with rectangle mark describes bearing capacity at OCR=4. . Graph with dashed line explains bearing capacity at OCR=8. Though increasing rate of bearing capacity trends to be similar but there is a slight increase in bearing capacity in corresponding load-displacement from the previous graph corresponding to D/B=0.05i.e. graphs corresponding to D/B=0.1 is steeper than that of graphs corresponding to D/B=.05.

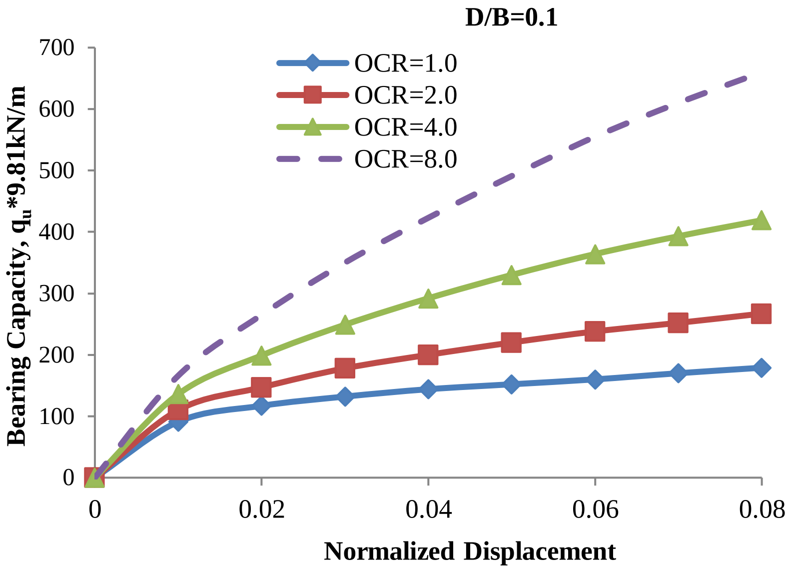


Fig.4.10 Relation of bearing capacity with respect to normalized displacement at different OCRs for D/B=0.1

Fig.4.11 illustrates bearing capacity against load-displacement for different OCRs' value when reinforcement is placed at D/B=0.2. Vertical axis shows bearing capacity whereas abscissa represents load displacement. Here graph with diamond mark describes bearing capacity at OCR=1. Graph with rectangle mark shows bearing capacity at OCR=2. Graph with rectangle mark describes bearing capacity at OCR=4. Graph with dashed line explains bearing capacity at OCR=8. Bearing capacity is the lowest for OCR=1 whereas it is the maximum in case of OCR=8. In respect to bearing capacity for any particular normalized displacement, it is lower than its corresponding value once reinforcement is placed at D/B=0.1 i.e. in comparison to bearing capacity graph displayed in Figure 12 & 13, bearing capacity situation has improved once reinforcement is placed at D/B=0.1.

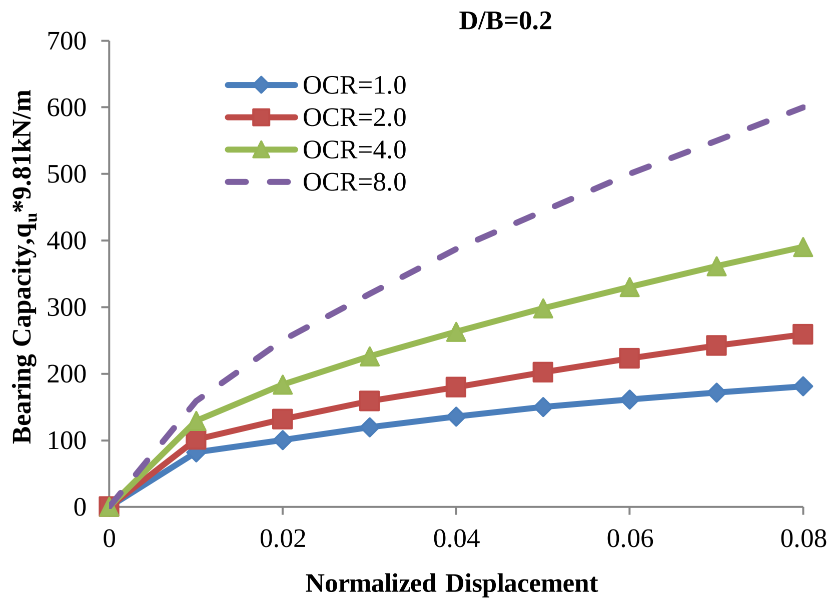


Fig. 4.11 Relation of bearing capacity with respect to normalized displacement at different OCRs for D/B=0.2

It is evident from Figs. 9, 10 & 11 that for a particular OCR and for a specific normalized displacement bearing capacity gradually improves once reinforcement is placed at D/B=0.05 and attain greater strength once reinforcement is placed at D/B=0.1.If reinforcement is placed beyond D/B=0.1, it is then reduced.

4.4 Effect of Ground Improvement

Fig.4.12 depicts bearing capacity against load displacement for OCR=1 with different situations for ground reinforcement (D/B=0.05) & improvement. Vertical axis represents bearing capacity of ground whereas abscissa shows load displacement. Here graph with square mark shows bearing capacity with ground improved and reinforced at D/B=0.05. Graph with triangle mark describes bearing capacity of ground when reinforced at D/B=0.05 but without ground improvement. Graph with green dashed line illustrates bearing capacity of ground after improvement but without reinforcement. Graph with black solid line explains bearing capacity without ground improvement & without reinforcement. There was gradual increase in bearing capacity from ground without improvement to subsequent improvement & reinforcement.

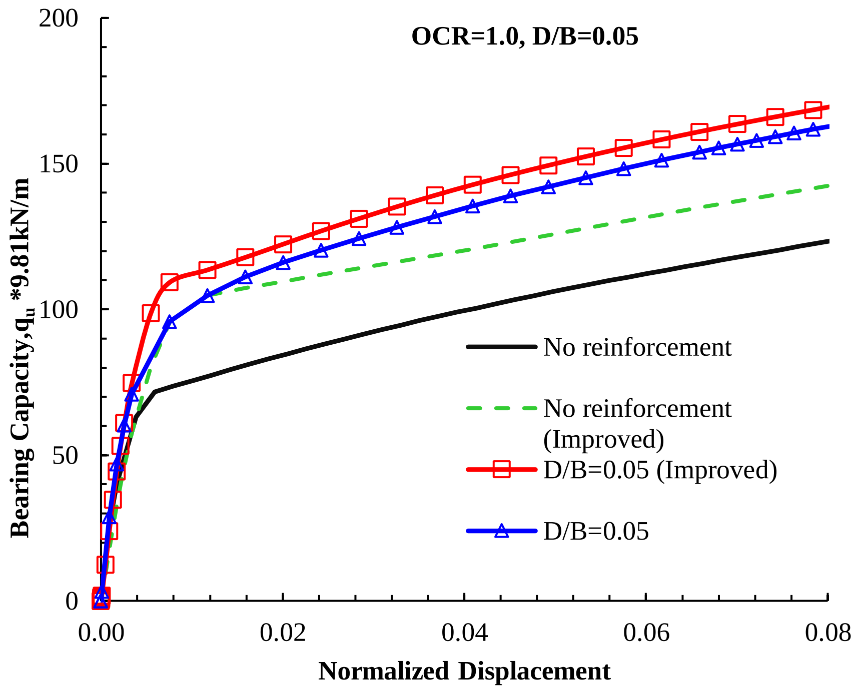


Fig. 4.12 Effect of Ground Improvement with & without Reinforcement for OCR=1.0 and D/B=0.05

Fig.4.13 illustrates bearing capacity against load displacement for OCR=1 with different situations for ground reinforcement (D/B=0.1) & improvement. Vertical axis shows bearing capacity of ground whereas abscissa represents load displacement. Here graph with square mark shows bearing capacity with ground improved and reinforced at D/B=0.1. Graph with triangle mark depicts bearing capacity of ground when reinforced at D/B=0.1 but without ground improvement. Graph with green dashed line explains bearing capacity of ground after improvement but without reinforcement. Graph with black solid line describes bearing capacity without ground improvement & without reinforcement. There was gradual increase in bearing capacity from ground without improvement to subsequent improvement & reinforcement. Again for the same OCR value, bearing capacity against each value of normalized displacement found greater when reinforcement is placed at D/B=0.1 than that of D/B=0.05. If other conditions remain same then bearing capacity increases with the increased value of OCR.

.

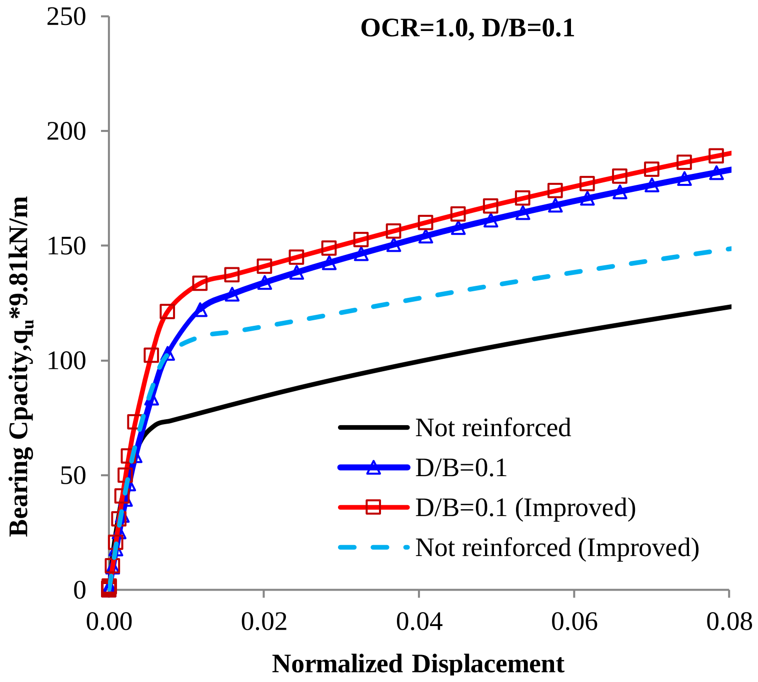


Fig. 4.13 Effect of Ground Improvement with & without Reinforcement for OCR=1.0 and D/B=0.01

Fig.4.14 depicts bearing capacity against load displacement for OCR=2 with different situations for ground reinforcement (D/B=0.05) & improvement. Vertical axis illustrates bearing capacity of ground whereas abscissa describes load displacement. Here graph with square mark explains bearing capacity with ground improved and reinforced at D/B=0.05. Graph with triangle mark describes bearing capacity of ground when reinforced at D/B=0.05 but without ground improvement. Graph with green dashed line illustrates bearing capacity of ground after improvement but without reinforcement. Graph with black solid line explains bearing capacity without ground improvement & without reinforcement. There was gradual increase in bearing capacity from ground without improvement to subsequent improvement & reinforcement. Bearing capacity has increased substantially once reinforcement has been placed at D/B=0.05. Again bearing capacity has increased as the OCR value has changed from OCR=1.0 to OCR=2.0.

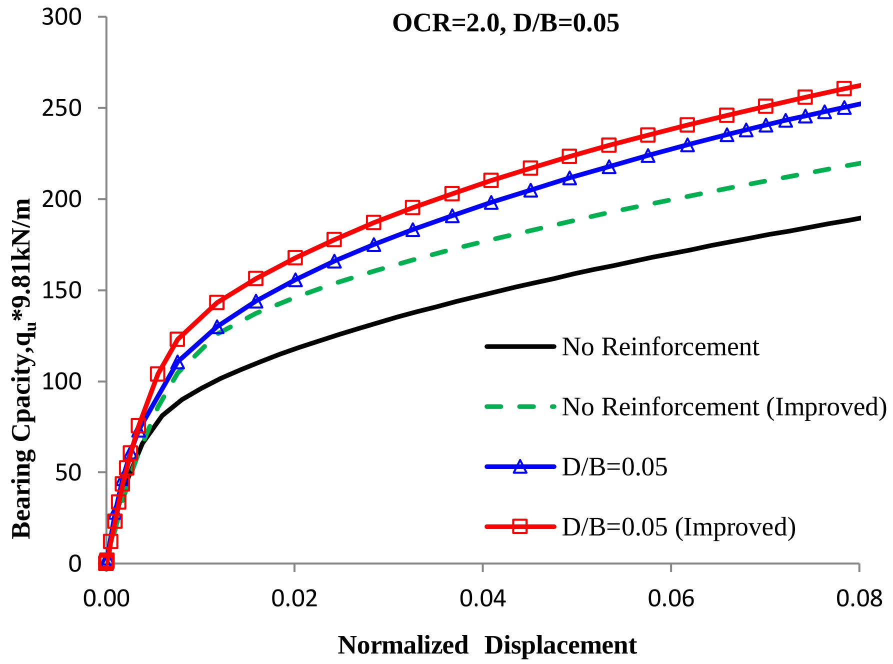


Fig. 4.14 Effect of Ground Improvement with & without Reinforcement for OCR=2.0 and D/B=0.05

Fig.4.15 depicts bearing capacity against load displacement for OCR=2 with different situations for ground reinforcement (D/B=0.1) & improvement. Vertical axis illustrates bearing capacity of ground whereas abscissa describes load displacement. Here graph with square mark explains bearing capacity with ground improved and reinforced at D/B=0.1. Graph with triangle mark describes bearing capacity of ground when reinforced at D/B=0.1 but without ground improvement. Graph with green dashed line illustrates bearing capacity of ground after improvement but without reinforcement. Graph with black solid line explains bearing capacity without ground improvement & without reinforcement. There was gradual increase in bearing capacity from ground without improvement to subsequent improvement & reinforcement**.** Again for the same OCR value, there was remarkable improvement in bearing capacity against each normalized displacement due to changing the location of reinforcement from D/B=0.05 to D/B= 0.1 (comparing Figure 4.14 and 4.15).

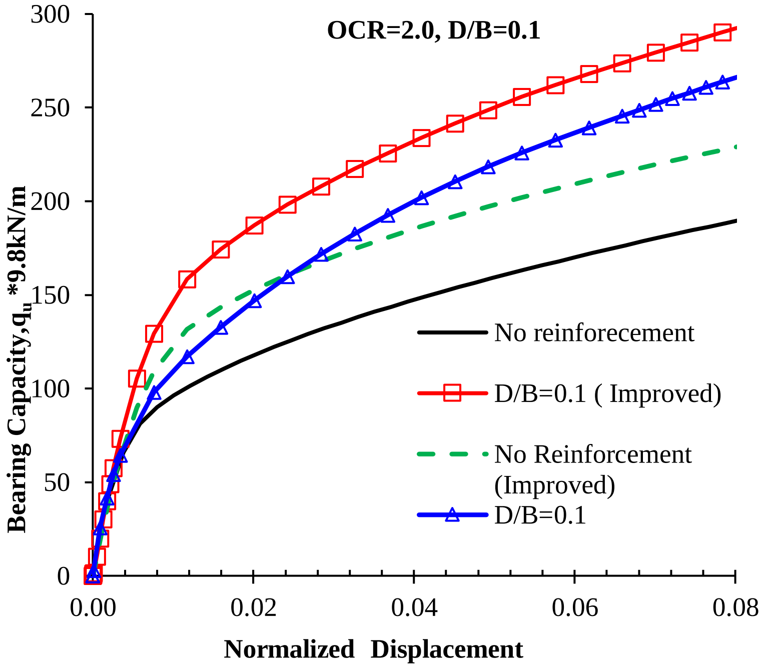


Fig. 4.15 Effect of Ground Improvement with & without Reinforcement for OCR=2.0 and D/B=0.1

Fig.4.16 depicts bearing capacity against load displacement for OCR=4 with different situations for ground reinforcement (D/B=0.05) & improvement. Vertical axis illustrates bearing capacity of ground whereas abscissa describes load displacement. Here graph with square mark explains bearing capacity with ground improved and reinforced at D/B=0.05. Graph with triangle mark describes bearing capacity of ground when reinforced at D/B=0.05 but without ground improvement. Graph with green dashed line illustrates bearing capacity of ground after improvement but without reinforcement. Graph with black solid line explains bearing capacity without ground improvement & without reinforcement. There was gradual increase in bearing capacity from ground without improvement to subsequent improvement & reinforcement against each value of normalized displacement. For higher value of OCR, there was improvement in bearing capacity against each value of normalized displacement.

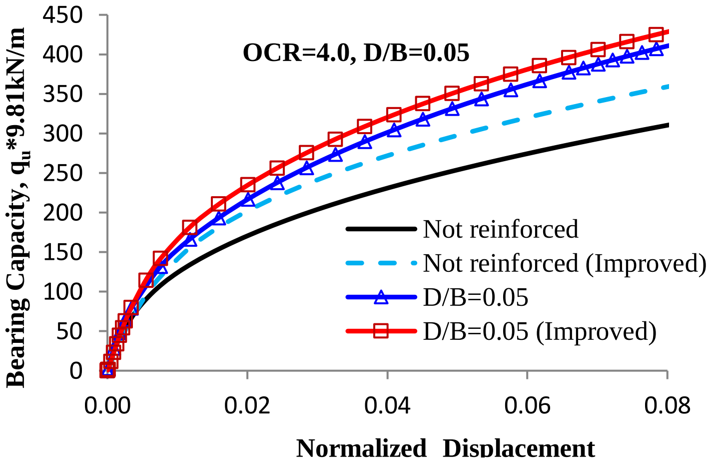


Fig. 4.16 Effect of Ground Improvement with & without Reinforcement for OCR=4.0 and D/B=0.05

Fig.4.17 depicts bearing capacity against load displacement for OCR=4 with different situations for ground reinforcement (D/B=0.1) & improvement. Vertical axis illustrates bearing capacity of ground whereas abscissa describes load displacement. Here graph with square mark explains bearing capacity with ground improved and reinforced at D/B=0.1. Graph with triangle mark describes bearing capacity of ground when reinforced at D/B=0.1 but without ground improvement. Graph with green dashed line illustrates bearing capacity of ground after improvement but without reinforcement. Graph with black solid line explains bearing capacity without ground improvement & without reinforcement. There was gradual increase in bearing capacity from ground without improvement to subsequent improvement &reinforcementagainst each value of normalized displacement. Again for the same OCR value, there was remarkable improvement in bearing capacity against each normalized displacement due to changing the location of reinforcement from D/B=0.05 to D/B= 0.1 (comparing Figure 4.16 and 4.17).

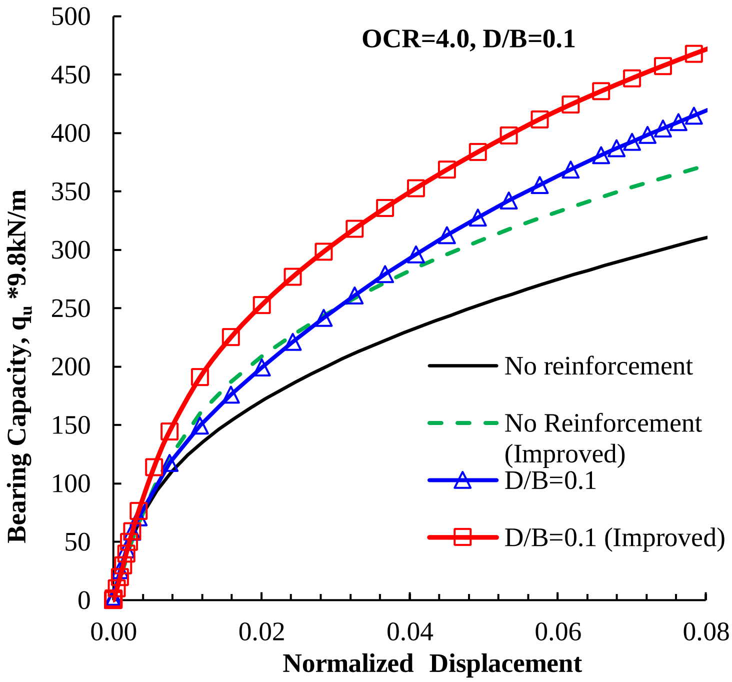


Fig. 4.17 Effect of Ground Improvement with & without Reinforcement for OCR=4.0 and D/B=0.1

Fig.4.18 depicts bearing capacity against load displacement for OCR=8 with different situations for ground reinforcement (D/B=0.05) & improvement. Vertical axis illustrates bearing capacity of ground whereas abscissa describes load displacement. Here graph with square mark explains bearing capacity with ground improved and reinforced at D/B=0.05. Graph with triangle mark describes bearing capacity of ground when reinforced at D/B=0.05 but without ground improvement. Graph with green dashed line illustrates bearing capacity of ground after improvement but without reinforcement. Graph with black solid line explains bearing capacity without ground improvement & without reinforcement. There was gradual increase in bearing capacity from ground without improvement to subsequent improvement & reinforcement against each value of normalized displacement. For higher value of OCR, there was improvement in bearing capacity against each value of normalized displacement.

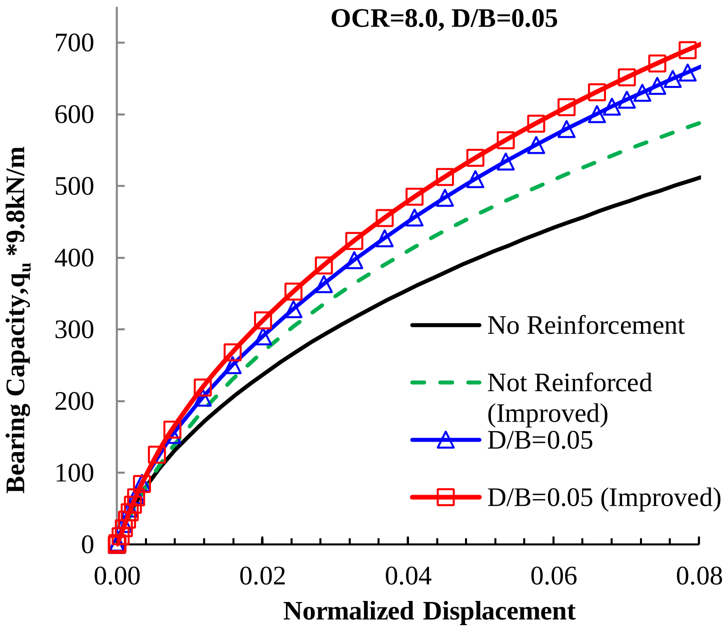


Fig. 4.18 Effect of Ground Improvement with & without Reinforcement for OCR=8.0 and D/B=0.05

Fig.4.19 depicts bearing capacity against load displacement for OCR=8 with different situations for ground reinforcement (D/B=0.1) & improvement. Vertical axis illustrates bearing capacity of ground whereas abscissa describes load displacement. Here graph with square mark explains bearing capacity with ground improved and reinforced at D/B=0.05. Graph with triangle mark describes bearing capacity of ground when reinforced at D/B=0.05 but without ground improvement. Graph with green dashed line illustrates bearing capacity of ground after improvement but without reinforcement. Graph with black solid line explains bearing capacity without ground improvement & without reinforcement. There was gradual increase in bearing capacity from ground without improvement to subsequent improvement & reinforcement against each value of normalized displacement. For higher value of OCR, there was improvement in bearing capacity against each value of normalized displacement**.** Again for the same OCR value, there was remarkable improvement in bearing capacity against each normalized displacement due to changing the location of reinforcement from D/B=0.05 to D/B= 0.1 (comparing Figure 4.18 and Figure 4.19).

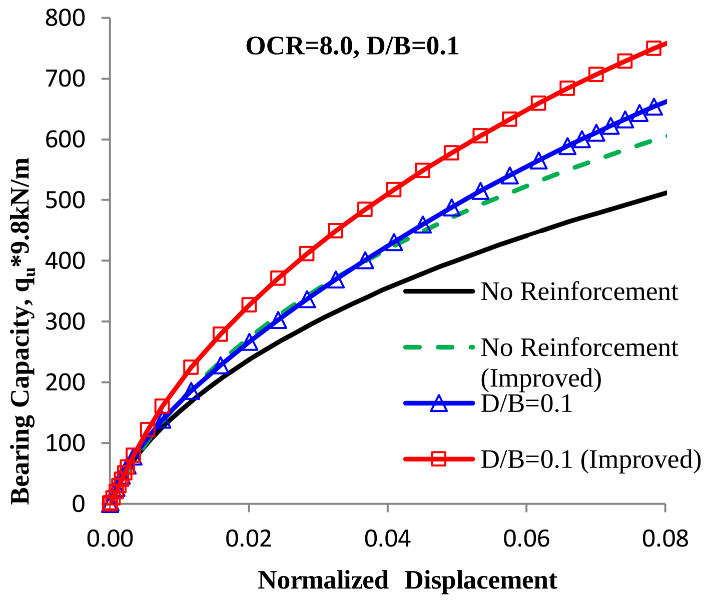


Fig. 4.19 Effect of Ground Improvement with & without Reinforcement for OCR=8.0 and D/B=0.1

Fig. 4.20 depicts the bearing capacity against normalized displacement at OCR=1.0 for ground improvement & reinforcement at D/B=0.05 and D/B=0.1. The vertical axis represents bearing capacity of ground whereas abscissa describes normalized displacement. Here graph with square mark explains bearing capacity with ground improved and reinforced at D/B=0.05. Graph with triangle mark describes bearing capacity with ground improved and reinforced at D/B=0.1. Graph with dashed line illustrates bearing capacity of ground without improvement but reinforced at D/B=0.05. Graph with black solid line illustrates bearing capacity of ground without improvement but reinforced at D/B=0.1. With the application of reinforcement at D/B=0.05, there was increase in bearing capacity from the natural ground itself. Conditions further improved with the application of reinforcement at D/B=0.05 and ground improvement beneath the footing. But bearing capacity further increased with the application of ground reinforcement at D/B=0.1 alone. Again bearing capacity improved further with the simultaneous application of reinforcement at D/B=0.1 and ground improvement beneath the footing. Thus for specific normalized displacement peak value of bearing capacity attained at simultaneous application of ground reinforcement at D/B=0.1and ground improvement.

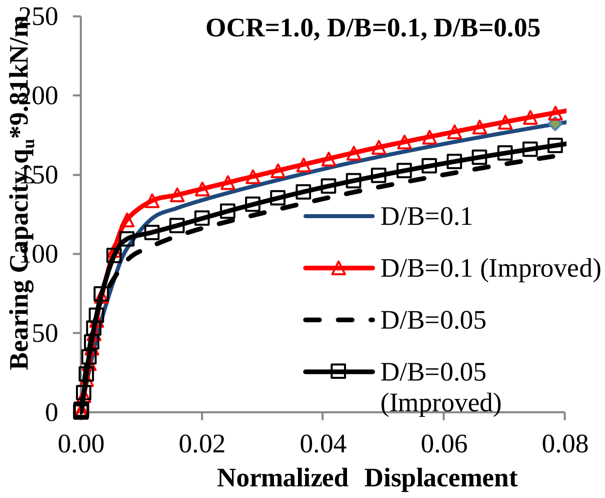


Fig. 4.20 Effect of Different Locations of Ground Improvement &Reinforcement at OCR=1.0

Fig. 4.21 depicts the bearing capacity against normalized displacement at OCR=2.0 for ground improvement & reinforcement at D/B=0.05 and D/B=0.1. The vertical axis represents bearing capacity of ground whereas abscissa describes normalized displacement. Here graph with square mark explains bearing capacity with ground improved and reinforced at D/B=0.05. Graph with triangle mark describes bearing capacity with ground improved and reinforced at D/B=0.1. Graph with dashed line illustrates bearing capacity of ground without improvement but reinforced at D/B=0.1. Graph with solid line illustrates bearing capacity of ground without improvement but reinforced at D/B=0.05.Overall situation in respect to bearing capacity has improved from the ground having OCR=1 to the ground having OCR=2. Like the previous ground having OCR=1, bearing capacity for ground reinforced at D/B=0.05 is the lowest for any value of normalized displacement. Situation further improved with the simultaneous application of reinforcement and ground improvement beneath the footing. And for a specific normalized displacement, it reaches its peak value with the simultaneous application of ground reinforcement at D/B=0.1 and ground improvement. At lower value of normalized displacement (<6%), bearing capacity is greater for simultaneous application of reinforcement at D/B=0.05 and ground improvement than that is attained by ground reinforcement at D/B=0.1 alone. But at higher value of normalized displacement (>6%), this situation is reverse i.e. bearing capacity for ground reinforced at D/B=0.1 is greater than that is being attained for ground reinforced at D/B=0.05 and improved.

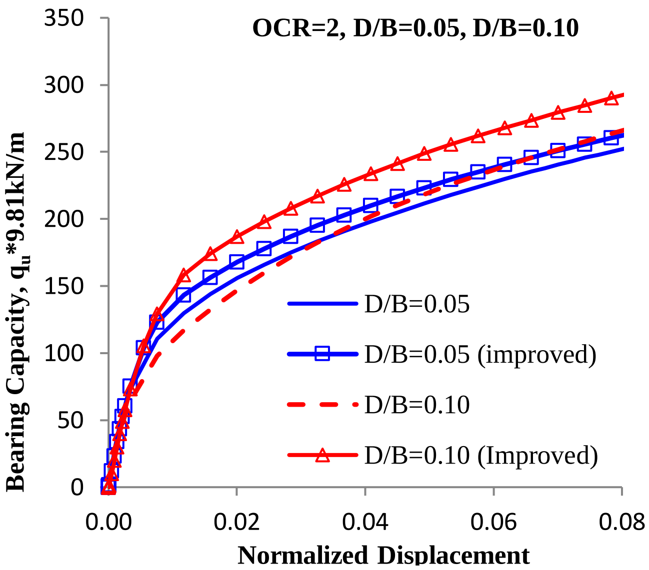


Fig. 4.21 Effect of Different Locations of Ground Improvement &Reinforcement at OCR=2.0

Fig. 4.22depicts the bearing capacity against normalized displacement at OCR=4.0 for ground improvement & reinforcement at D/B=0.05 and D/B=0.1. The vertical axis represents bearing capacity of ground whereas abscissa describes normalized displacement. Here graph with square mark explains bearing capacity with ground improved and reinforced at D/B=0.05. Graph with triangle mark describes bearing capacity with ground improved and reinforced at D/B=0.1. Graph with dashed line illustrates bearing capacity of ground without improvement but reinforced at D/B=0.05. Graph with solid line illustrates bearing capacity of ground without improvement but reinforced at D/B=0.1. There was substantial improvement in bearing capacity with the application of reinforcement from ground without improvement to subsequent application of both improvement & reinforcement. There is distinct increased in bearing capacity once reinforcement has been placed from D/B=0.05 to D/B=0.1.In addition to that changed OCR value from OCR=2 to OCR=4 caused further improvement of bearing capacity.

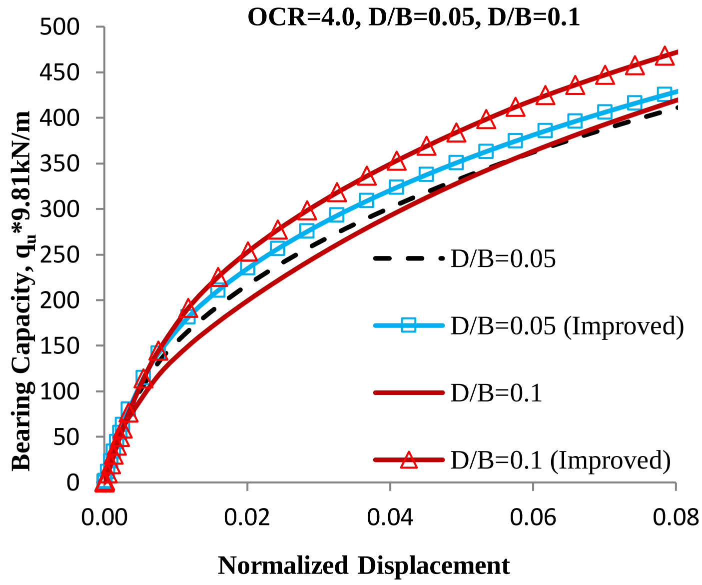


Fig. 4.22 Effect of Different Locations of Ground Improvement &Reinforcement at OCR=4.

Fig. 4.23depicts the bearing capacity against normalized displacement at OCR=4.0 for ground improvement & reinforcement at D/B=0.05 and D/B=0.1. The vertical axis represents bearing capacity of ground whereas abscissa describes normalized displacement. . Here graph with square mark explains bearing capacity with ground improved and reinforced at D/B=0.05. Graph with triangle mark describes bearing capacity with ground improved and reinforced at D/B=0.1. Graph with dashed line illustrates bearing capacity of ground without improvement but reinforced at D/B=0.05. Graph with solid line illustrates bearing capacity of ground without improvement but reinforced at D/B=0.1. There was gradual improvement in bearing capacity with the application of reinforcement from ground without improvement to subsequent application of both improvement & reinforcement. . There is remarkable increased in bearing capacity once reinforcement has been placed from D/B=0.05 to D/B=0.1.In addition to that changed OCR value from OCR=4 to OCR=8 caused overall improvement of bearing capacity.

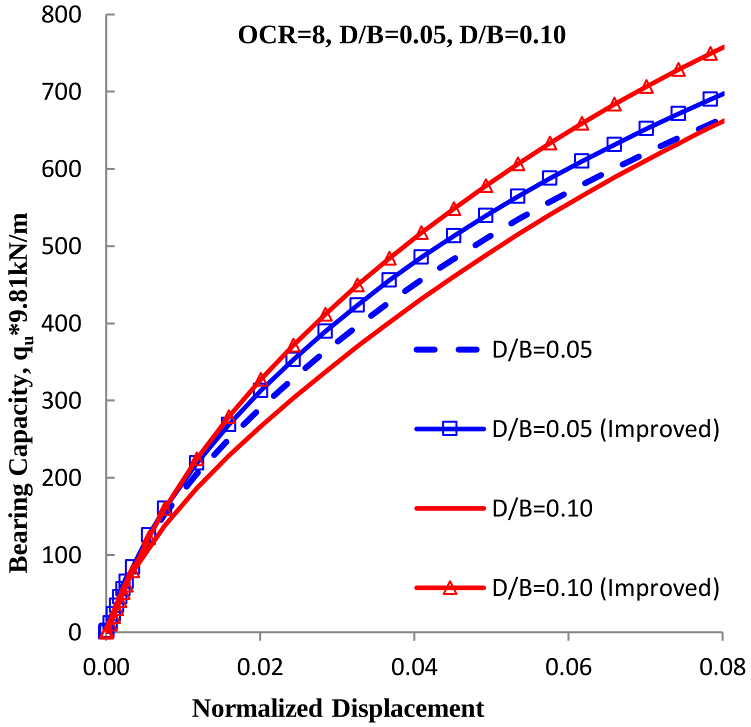
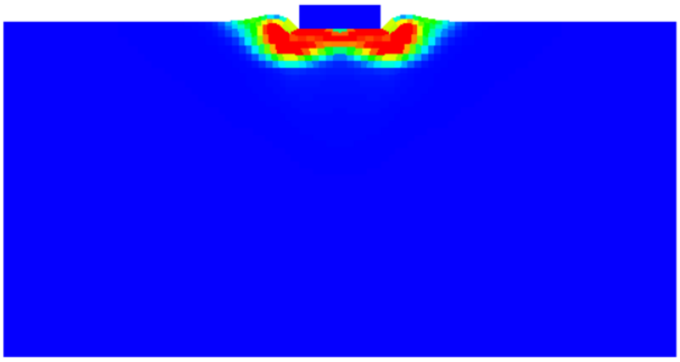


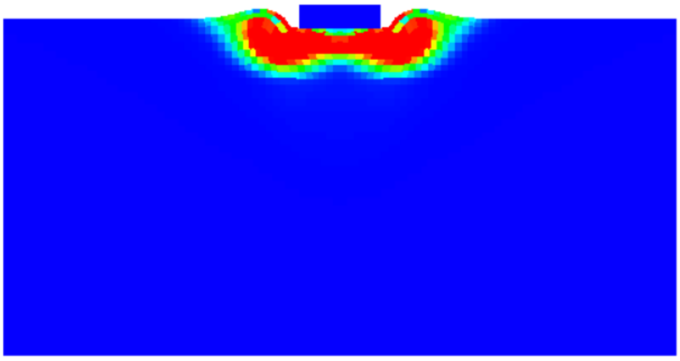
Fig. 4.23 Effect of Different Locations of Ground Improvement &Reinforcement at OCR=8.0

4.5 Distribution of Deviatoric Strain

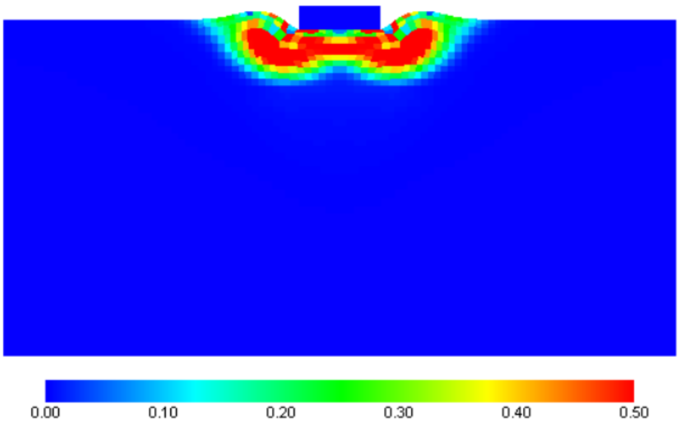
Fig. 4.24 show the distributions of deviatoric strain for OCR 1 and OCR 2. It is seen that the area of strain concentration is narrower in the case where geotextile was not used compare to the case where geotextile was used. The geotextile takes the tensile force as a result the load is been spreaded in a wider area underneath the foundation, therefore, the load bearing capacity is more in this case. Comparing the results of the locations of the geotextile, a higher strain concentration is seen in the shallower depth of the geotextile those of the deeper geotextiles.



(a) no reinforcement

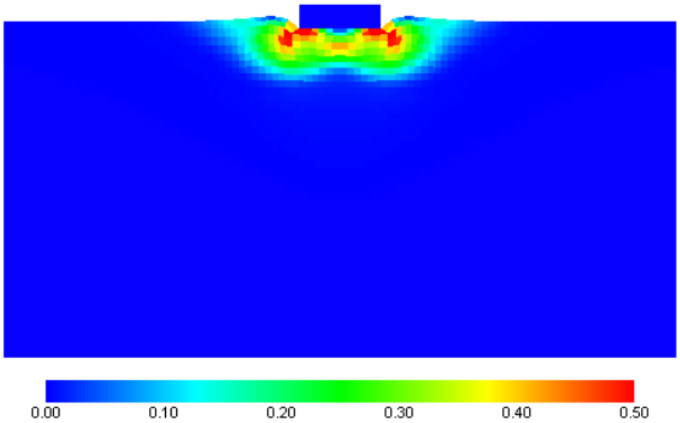


(b) D/B = 0.05

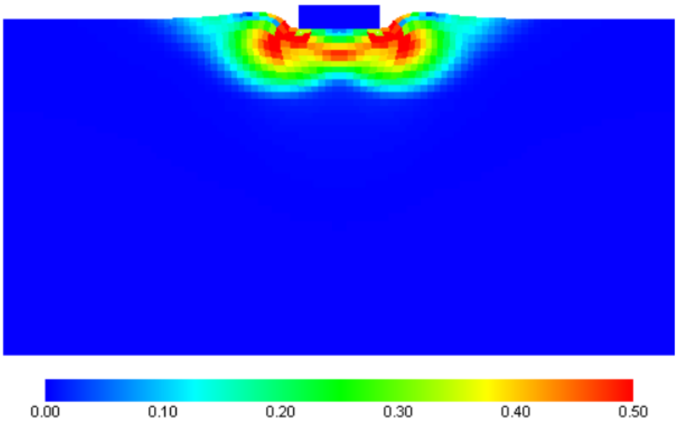


(c) D/B = 0.10

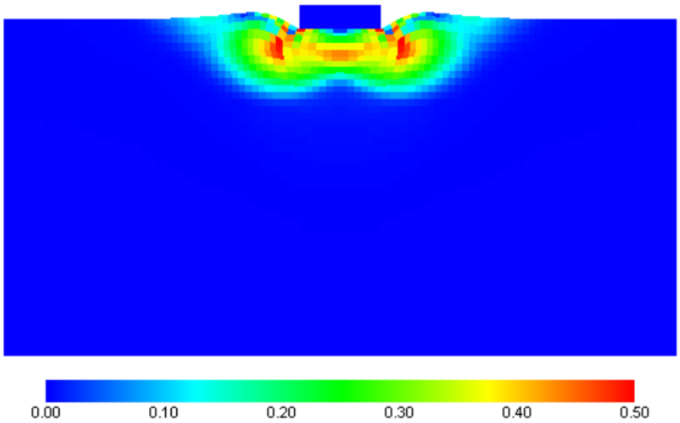
Fig. 4.24 Deviatoric strain distribution: OCR 1.0



(a) no reinforcement



(b) D/B = 0.05



(c) D/B = 0.10

Fig. 4.25 Deviatoric strain distribution: OCR 2.0

4.6 Bearing Capacity Corresponding to Allowable Settlement

According to Bangladesh National Building Code (BNBC 2020) allowable settlement for isolated footing and mat foundation in clay type soil is 75 mm and 100 mm respectively. Accordingly, allowable bearing capacities of the foundation with and without reinforcement have been illustrated in this section in graphical and tabular forms.

Fig.4.26 shows bearing capacity corresponding to 75mm settlement for OCR=1.0 with reinforcement but without ground improvement.Fig. 4.27 illustrates bearing capacity corresponding to 100mm settlement for OCR=1.0 with reinforcement but without ground improvement. Fig. 4.28 representsbearing capacity corresponding to 75mm settlement for OCR=2.0 with reinforcement but without ground improvement. Fig.4.29 explains bearing capacity corresponding to 100mm settlement for OCR=2.0 with reinforcement but without ground improvement. In respect to ground with OCR=1.0, bearing capacityis the highest for the reinforcement installed at D/B=0.05 which is 23.7% and 33.33% higher than that of the ground without reinforcement corresponding tosettlement of 75mm and100mm, respectively. For the ground with OCR=2.0, bearing capacity is the highest for the reinforcement installed at D/B=0.05 the same as the OCR=1.0, which is 20.6% and 26.67% higher than that of the ground without reinforcement corresponding to settlement of 75mm and 100mm, respectively.

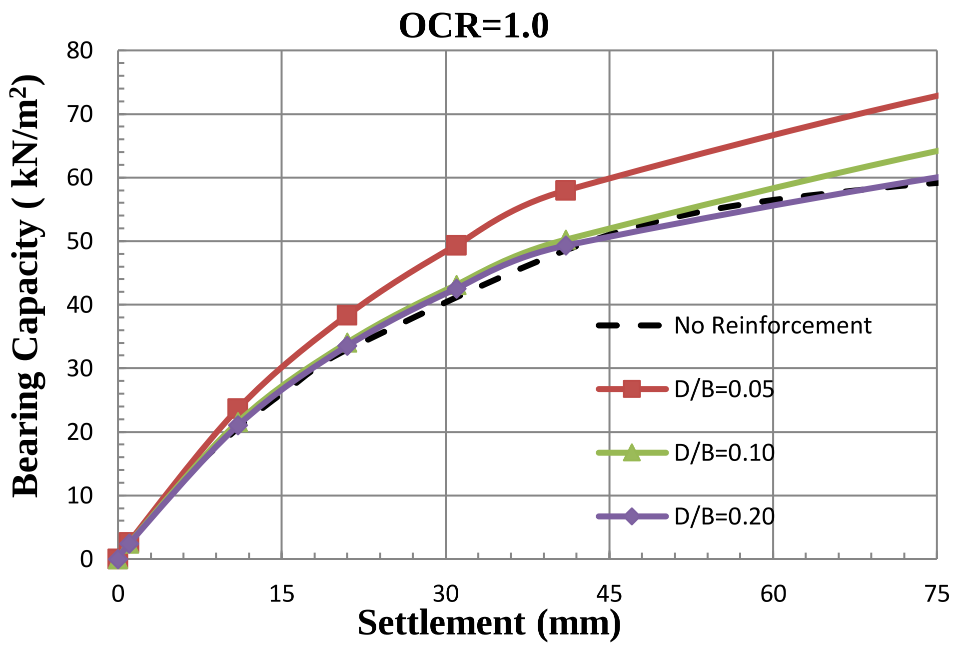


Fig.4.26 Bearing capacity corresponding to 75mm settlement for OCR=1.0 with reinforcement but without ground improvement

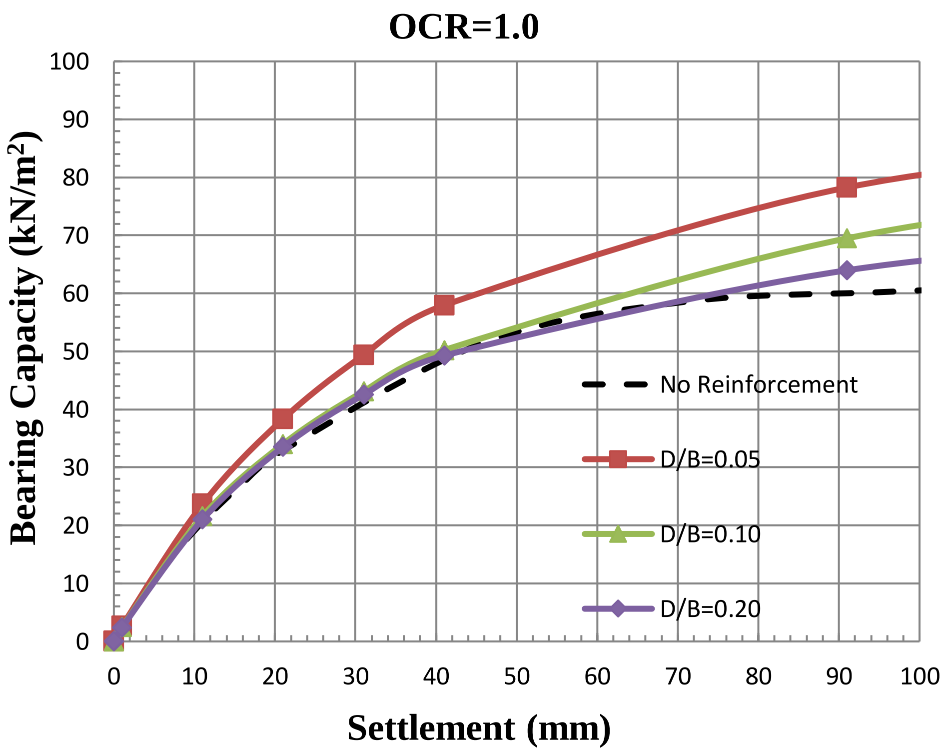


Fig. 4.27 Bearing capacity corresponding to 100mm settlement for OCR=1.0 with reinforcement but without ground improvement

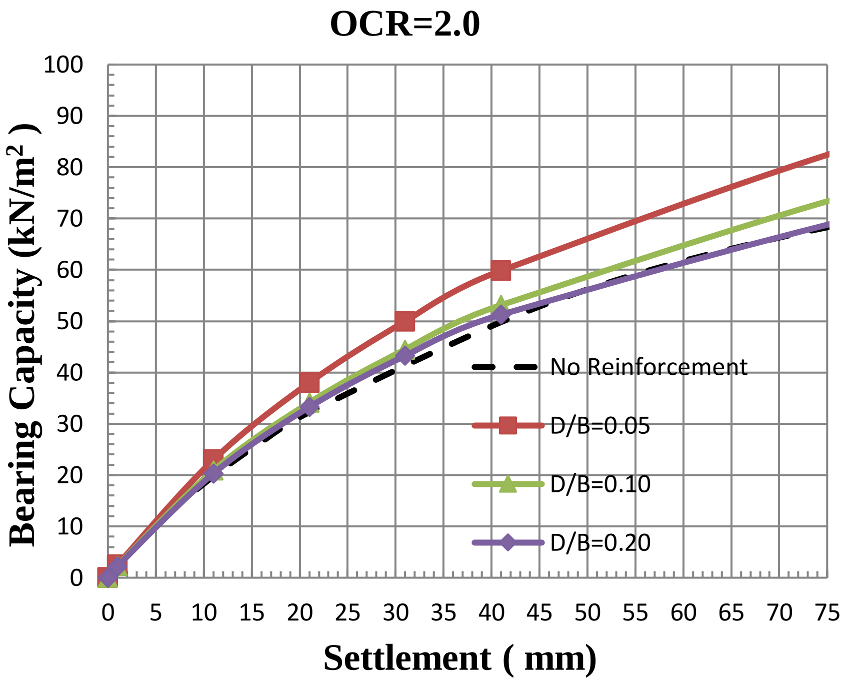


Fig. 4.28 Bearing capacity corresponding to 75mm settlement for OCR=2.0 with reinforcement but without ground improvement

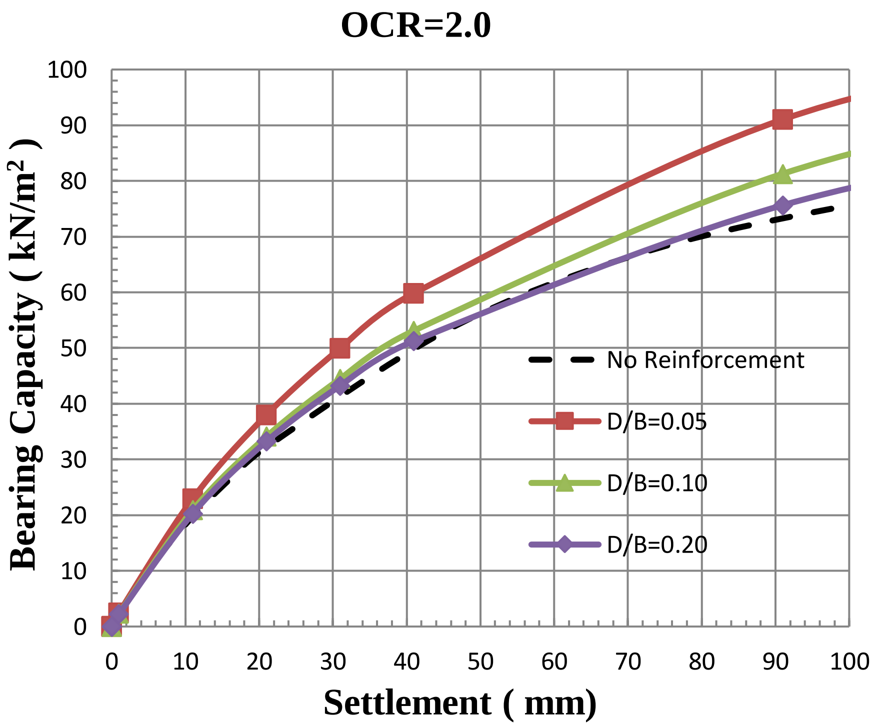


Fig.4.29 Bearing capacity corresponding to 100mm settlement for OCR=2.0 with reinforcement but without ground improvement

Table 4.1 Bearing Capacity at Different OCRs with ground reinforcement but without ground improvement for Settlement at 75mm and 100mm

Ground Reinforcing Conditions	Bearing Capacity (kN/m^2) for Ground with OCR=1.0		Bearing Capacity (kN/m^2) for Ground with OCR=2.0	
	At 75 mm Settlement	At 100 mm Settlement	At 75 mm Settlement	At 100 mm Settlement
Ground without Reinforcement	59	60	68	75
Reinforcement at D/B=0.05	73	80	82	95
Reinforcement at D/B=0.10	64	72	73	84
Reinforcement at D/B=0.20	60	65	68	78

Fig.4.30 shows bearing capacity corresponding to 75mm settlement for OCR=1.0 with and without ground reinforcement in the improved ground.Fig.4.31illustrates bearing capacity corresponding to 100mm settlement for OCR=1.0 with and withoutgroundreinforcement in the improved ground. Fig.4.32 representsbearing capacity corresponding to 75mm settlement for OCR=2.0 with and without ground reinforcement in the improved ground. Fig.4.33explains bearing capacity corresponding to 100mm settlement for OCR=2with and withoutgroundreinforcement in the improved ground. In respect to ground with OCR=1.0, bearing capacity is the highest for the ground with reinforcement installed at D/B=0.1,which is 54.23% and 70% higher than that of the ground without reinforcementcorresponding tosettlement of 75mm and 100mm, respectively. For the ground with OCR=2.0, bearing capacity is the highest for the ground wherein reinforcement is installed at D/B=0.1,which is 38.32% and 48% higher than that of the ground without reinforcement and

improvement (natural ground)corresponding to settlement of75mm and 100mm, respectively.

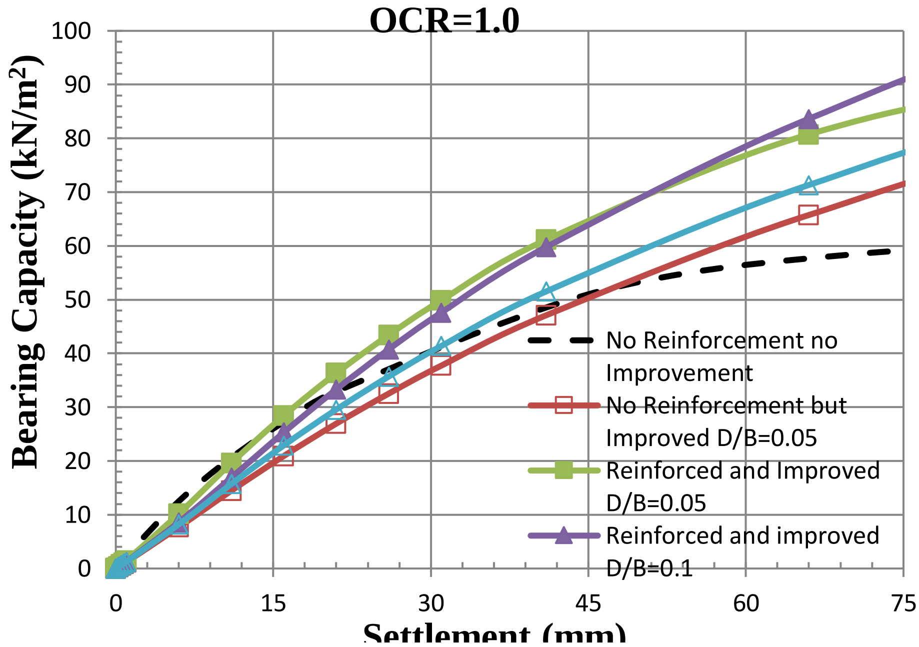


Fig.4.30 Bearing capacity corresponding to 75mm settlement for OCR=2 with & without ground reinforcement and improvement

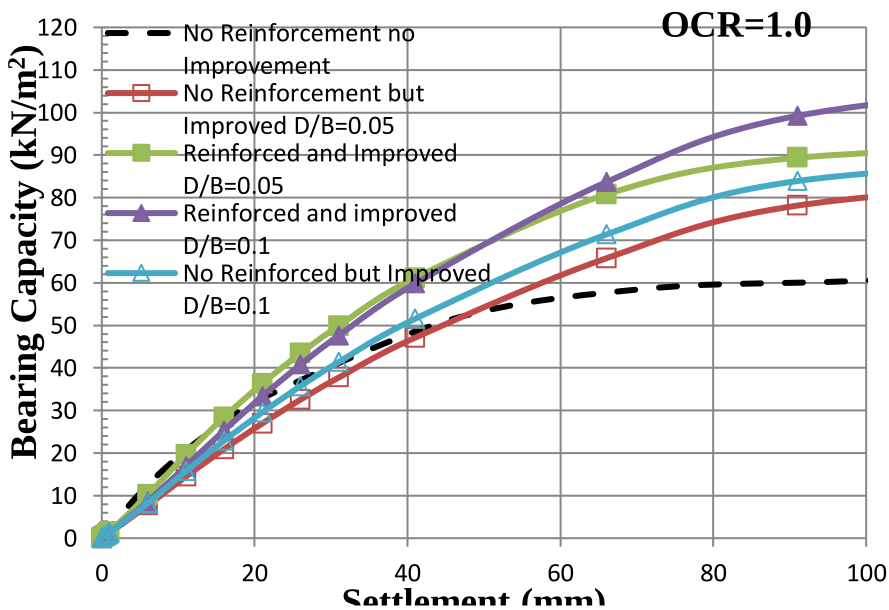


Fig.4.31 Bearing capacity corresponding to 100mm settlement for OCR=1 with & without reinforcement and ground improvement

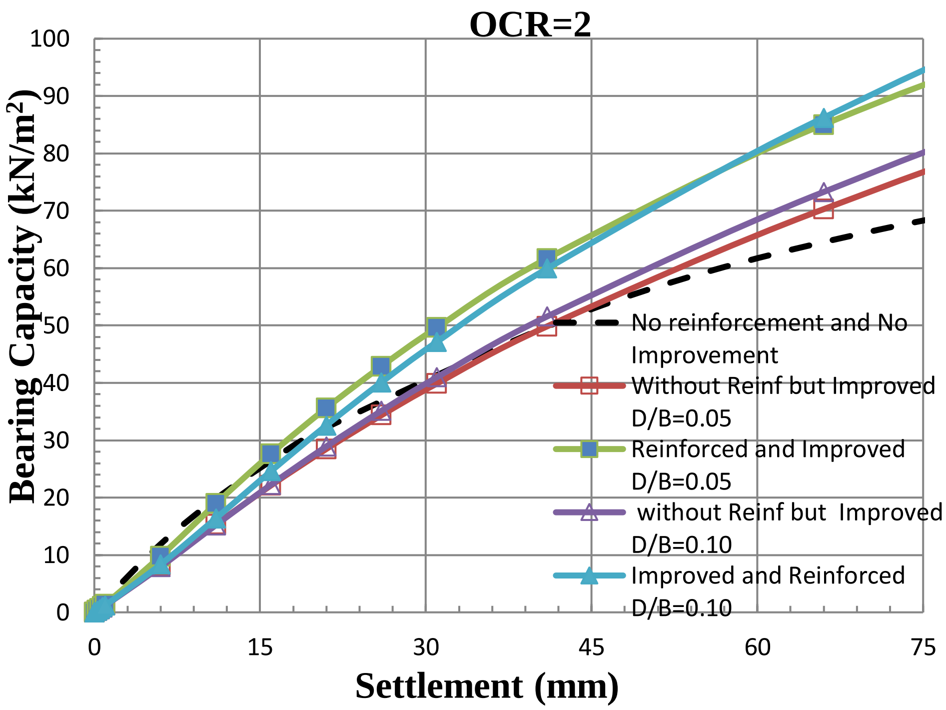


Fig.4.32 Bearing capacity corresponding to 75mm settlement for OCR=2.0 with reinforcement and ground improvement

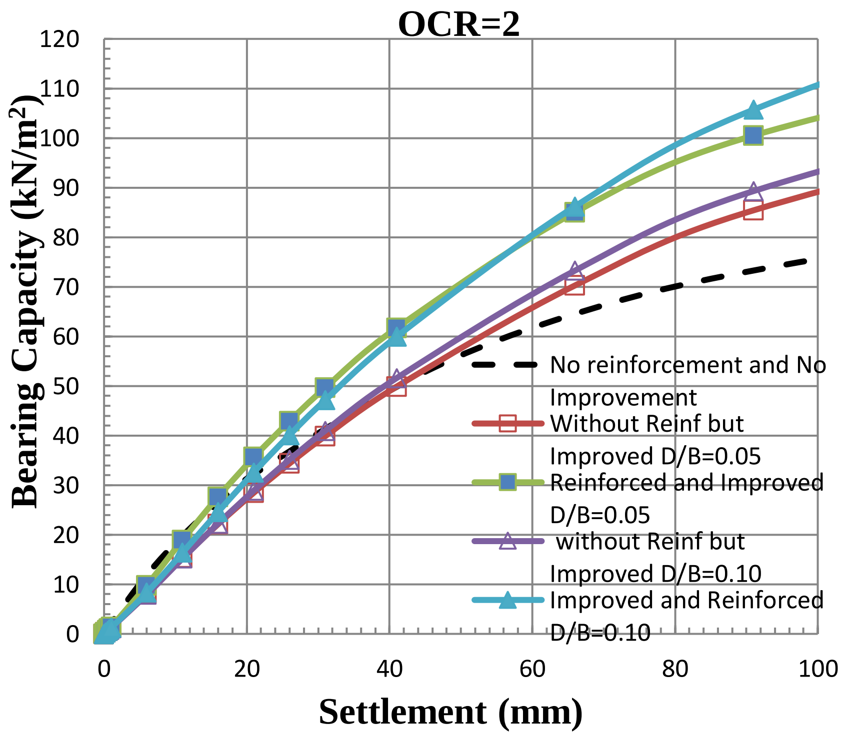


Fig.4.33 Bearing capacity corresponding to 100mm settlement for OCR=2.0 with reinforcement and ground improvement

Table 4.2 Bearing Capacity at Different OCRs with ground improvement and reinforcement for settlement at 75mm and 100mm

Ground Reinforcing Conditions	Bearing Capacity (kN/m^2) for Ground with OCR=1.0		Bearing Capacity (kN/m^2) for Ground with OCR=2.0	
	At 75 mm Settlement	At 100 mm Settlement	At 75 mm Settlement	At 100 mm Settlement
Ground without reinforcement and improvement (Natural Condition)	59	60	68	75
Not reinforced but improved at D/B=0.05	71.5	80	77	89
Reinforced and improved at D/B=0.05	85	90	92	104
Not reinforced but improved at D/B=0.10	77	85	80	93
Reinforced and improved at D/B=0.10	91	102	94	111

CHAPTER 5: CONCLUSION

5.1 General

The main focus of this study was to investigate the influence of geotextiles along with replacement of soft soil underneath the foundation with improved ground on the bearing capacity of the foundation and then analyseload settlement characteristics of a shallow foundation with and without reinforcement. Material properties for clay and granular soil were specified. Reinforcement was then placed at different depths below the footing in relation to the breadth of footing.

5.2 Conclusions

From the analyses presented in this paper, the following conclusions can be drawn according to the objectives of this research.

(1) Corresponding to the first objective (to investigate the influence of geotextiles along with replacement of soft soil underneath the foundation with improved ground on the bearing capacity of the foundation), the conclusions are -

i) Bearing capacity of reinforced ground is higher than that of the non-reinforced ground.

ii) Maximum bearing capacity is found for the installation depth of the reinforcementin between D/B= 0.05 to 0.10, where D is the depth of the reinforcement and B is the width of the foundation.

iii) Bearing capacity of soft soilsignificantly increases for both installingreinforcement and replacing the existing ground with improved soil above the reinforcement.

iv) The position of the reinforcement relative to the foundation is an important factor in increasing the bearing capacity.

(2) Corresponding to the second objective (to analyze load settlement characteristics of a shallow foundation with and without reinforcement), the conclusions are–

i) Slope of the load – settlement curve is stiffer forthe reinforced ground, i.e., the reinforced ground can carry higher load than that of the non-reinforced ground for a specific settlement.

ii) The contribution of the reinforcement in increasing load carrying capacity of shallow foundation is significant in larger settlement.

In the South-West region of Bangladesh, the technique can be used to build low-rise building at a cheaper cost. The technique can also be used in the region where a thick soft soil layer exists to build low-rise buildings.

5.3 Recommendations for Future Study

From the analyses presented in this paper, it can be recommended that,

(1) Model tests can be done at laboratory preparing the ground in layers with soft soil considering field conditions.

(2) Bearing capacity of multi-layer geotextiles and improvedlayercan be investigated.

REFERENCES

Adams, M. T., Collin, J. G. (1997). The large model spread footing load tests on geosynthetic reinforced soil foundations. J. of Geotech. Geoenviron. Eng., 123(1), 66–72.

Alamgir, M. and Chowdhury, K. H. (2004). Ground improvement methods recently practiced to solve the geotechnical engineering problems in Bangladesh. Proceedings of 5th International Conference on Case Histories in Geotechnical Engineering, Scholars' Mine, USA.

Cicek, E., Guler, E., Yetimoglu, T. (2015). Effect of reinforcement length for different geosynthetic reinforcements on strip footing on sand soil, Soils and Foundations, 55(4), 661-677.

Das, B. M. (1985). Advanced Soil Mechanic", International Student Edition, McGraw-Hill Book Co. (Singapore), ISBN 0-07-015416-3.

Das, B. M. (2005). Principles of Foundation Engineering, 5th Edition, Eastern Press Pvt. Ltd., Bangalore.

Ferdous,S. M. (2007). Geotechnical characterization of the subsoil in Khulna City Corporation (KCC) area, M.Sc. Engg. thesis, Department of Civil Engineering, Bangladesh University of Engineering & Technology, Dhaka, Bangladesh.

Han, J. (2015).Principles and practices of ground improvement, Wiley, ISBN 978-1-118-25991-7.

Hansen, J.B. (1961). A General Formula for Bearing Capacity, Danish Geotech, Inst. Bull, Vol. 11, pp. 38-46.

Hossain, M. M. and Razzaque, M. A.(1999), Structural advantages of floating foundation over traditionalmat foundation for soft clay- A case study, Pre-Conference Symposium on Ground Improvement and Geosynthetics, 5th November, in Conjunction with Asian Institute of Technology, Thailand.

Hossain,M. L., Shahin, H. M. and Nakai, T. (2019): Enhancement of bearing capacity of soft soil using geosynthetics, International Journal of GEOMATE. Vol.17, Issue 64, pp. 238- 244.

Islam, M. S. (1999). Strength and Deformation Anisotropy of Clays.M. Sc. Engineering Thesis, Department of Civil Engineering, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh.

Islam, M. S.and Shahin, H. M. (2013). Reinforcing effect of vetiver (Vetiveriazizanioides) root in geotechnical structures - experiments and analyses, Journal of Geomechanics and Engineering, Vol. 5 (4), pp.313-329, DOI: http://dx.doi.org/10.12989/gae.2013.5.3.313.

Islam, M. S., Shahin, H. M., Banik,S.and Azam, F. (2014): Elasto-plastic Constitutive Model Parameters and Their Application to Bearing Capacity Estimation for Dhaka Sub-soil, Journal of Civil Engineering (IEB), Vol.42(2), pp. 171-188.

Jha, J. N. and Singh, H. (2012). Ground improvement Techniques: Issues, methods and their selection. Proceeding of the All India Council for Technical Education (AICTE), January 2012.

Jones, C.J.F.P., Fakher, A., Hamir R. & Nettleton I. M. (1996). Geosynthetic materials with improved reinforcement capabilities, Proc. of the International Symposium on Earth reinforcement, Fukuoka, Japan, Earth Reinforcement Volume 2, pp. 865-870.

Khing, K. H., Das, B. M., Puri, V. K., Cook, E. E., Yen, S. C. (1993). Bearing capacity of strip foundation on geogrid-reinforced sand. Geotextile and Geomembranes, 12(4), 351–361.

Meyerhof, G.G. (1974). Ultimate bearing capacity of footings on sand layer overlying clay", Can. Geotech. J., Vol. 11, No. 2, pp. 223-229.

Nakai, T., Hinokio, M., (2004). A simple elastoplastic model for normally and overconsolidated soils with unified material parameters. Soils and Foundations. 44(2), 53-70.

Nakai, T. (2012): Constitutive Modeling of Geomaterials: Principles and Applications, 1st ed. Boca Raton, London, New York, USA.

Nakai, T., 1985. Finite element computations for active and passive earth pressure problems of retaining wall. Soils and Foundations, 25(3), 98-112

Nakai, T., Shahin, H. M., Watanabe, A. & Yonaha, S. (2009). Reinforcing mechanism of Geosynthetics on bearing capac-ity problems – model tests and numerical simulations. Proc. of the 17th International Conference on Soil Mechanics and Geotechnical Engineering, Alexandria, Egypt, October, pp. 917-920

Nakai T, Shahin H M, Kikumoto M, Kyokawa H, Zhang F, Farias M M (2011) A simple and unified one-dimensional model to describe various characteristics of soils, Soils and Foundations, 51(6): 1129-1148.

Nakai, T., Shahin, H., Kikumoto ,M., Kyokawa, H., Zhang F., & Farias, M. (2011). Asimple and unified one-dimensional model to describe various characteristics of soils, Soils and Foundation, 51(6),1129-1148.

Omar, M. T., Das, B. M., Puri, V. K., Yen, S. C. (1993). Ultimate bearing capacity of shallow foundations on sand with geogrid reinforcement. Can. Geotech. J., 30, 545–549.

Patra, C.R., Das, B.M., Atalar, C. (2005). Bearing capacity of embedded strip foundation on geogrid reinforced sand. Geotextiles and Geomembranes, 23(5), 454 – 462.

Razzaque, M.A. and Alamgir, M. (1999). Long -term Settlement Observation of a Building in Peat Deposits of Bangladesh, Civil and Environmental Engineering Conference, New Frontiers and Challenges, Bangkok, Thailand.

Sabit, A, Sumita,M.andHonglian, Z. (1996). Analysis of geotextile-soil interaction in pull-out tests.Proc. of the International Symposium on Earth reinforcement Fukuoka, Japan, Volume 1, pp. 3.

Shahin, H. M., Nakai, T., Yoshida, Y. & Mio, S. (2012). Effec-tive reinforcing method for increasing bearing capacity. Proc. of the 5th Sino-Japan Geotechnical Symposium, Chi-na, pp. 457-463.

Shahin, H. M., Masuda, S., Nakai, T., Morikawa, Y. and Mio, S. (2013). Reinforcing effect of geosynthetics on bearing capacity, 3rd International Conference on

Geotechnique. Construction Materials and Environment, Nagoya, Japan, November, pp. 199-204.

Shahin, H. M., Morikawa, Y., Masuda, S., Nakai, T.,and Mio, S. (2014). Bearing capacity of reinforced sandy ground, Computer Methods and Recent Advances in Geomechanics, Kyoto, September, pp. 935-940.

Shahin, H. M., Nakai, T., Morikawa, Y., Masuda, S.,and Mio, S.(2017). Effective use of geosynthetics to increase the bearing capacity of shallow foundations, Canadian Geotechnical Journal, Vol. 54, pp. 1647–1658, doi.org/10.1139/cgj-2016-0505.

Terzaghi, K. (1943). Theoretical Soil Mechanics, Wiley, New York.

Tomlinson M. J. (1986) Foundation design and construction. Pitman, London.

Uddin,M. M. (2017). A method for improving bearing capacity of foundation in reclaimed areas of Dhaka City, M.Sc. Engg. thesis, Department of Civil Engineering, Bangladesh University of Engineering & Technology, Dhaka, Bangladesh.

Yetimoglu, T., Wu, J., Saglamer, A. (1994). Bearing Capacity of Rectangular Footings on Geogrid-Reinforced Sand. J. of Geotechnical Engineering, 120(12), 2083–2099.