REPUBLIC OF TURKEY
MUĞLA SITKI KOÇMAN UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DEPARTMENT OF CIVIL ENGINEERING

A NUMERICAL STUDY ON THE DEFORMATION BEHAVIOUR OF GEOTEXTILE ENCASED STONE COLUMN

MASTER OF SCIENCE THESIS

TUNCAY DOĞAN

T. DOĞAN DEPT. OF CIVIL ENGINEERING MASTER OF SCIENCE THESIS MUĞLA 2019

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APPROVAL OF THE THESIS

The thesis submitted by **TUNCAY DOĞAN** with the title of **"A NUMERICAL STUDY ON THE DEFORMATION BEHAVIOUR OF GEOTEXTILE ENCASED STONE COLUMN"** has been unanimously accepted by the jury members on the 20th of December 2019 to fulfil the requirements for the degree of Master of Science in the Department of Civil Engineering by the jury listed below.

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I hereby declare that all information and conclusions obtained and presented in the scope of this study are obtained by myself in accordance with academic and scientific ethical rules. Also, I declare that all information and conclusions which have not been obtained during this thesis study and belong others are cited and referenced as requirement of academic and scientific ethical rules.

Tuncay DOĞAN
22/04/2020

ABSTRACT

A NUMERICAL STUDY ON THE DEFORMATION BEHAVIOUR OF GEOTEXTILE ENCASED STONE COLUMN

Tuncay DOĞAN

Master of Science (M.Sc.) Thesis
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Construction of embankments over soft soils is considered to be risky due to its inadequate load carrying capacity and high factor of compressibility. Majority being close to a sea or between rivers, large part of world is covered with soft clayey grounds, yet excessive need for new areas for urbanisation enforces the improvement of these weak grounds. Providing the rapid construction, consolidation acceleration, total and differential settlement reduction and adjacent facility protection advantages; stone column supported embankments become one step forward among variety of available techniques. Stone column is a cost-effective method for improving especially the weak ground under highways, railways and urban infrastructure.

The stone column ensures its bearing capacity by means of the passive earth pressure resistance against the lateral deformation provided by the surrounding soil thus its performance depends on the shear strength of the soft clay soil. The encasement of stone column with a proper type of geosynthetic material is a widely used method to provide the required lateral confinement and to avoid dispersion of granular material into the soft clay. Along with improving the bearing capacity and reducing the settlement and bulging, geosynthetic encasement preserves stone columns easy drainage ability.

Despite being widely investigated by many precious researchers with numerous valuable laboratory and in-situ experiments and numerical studies, there are still additional efforts needed to determine the performance, to fully understand the deformation behaviour and to predict long term serviceability of geosynthetic encased stone column.

This study presents the results of finite element analyses of a hypothetical geotextile encased column supported embankment on a soft soil deposit which is improved by a geogrid reinforced sand mat on top. Numerical results of 2D analyses were validated by using field and experimental data of former studies at first, afterward parametric studies were carried out on two-dimensions finite elements model considering the effect of the soft soil thickness, the geosynthetic encasement length and stiffness, basal reinforcement (sand mat) thickness and geosynthetic reinforcement stiffness. Also, a group of floating stone columns in soft ground were modelled in two-dimensions and differential settlement behaviour was determined. By the parametric studies performed in the study; the optimum sand mat layer thickness, the geosynthetic stiffness, the optimum encasement length and the geosynthetic stiffness will be advised to be used for the preliminary design.

This will contribute to the development of economic design methods for end-bearing and floating types of vertically encased stone columns and geosynthetic reinforced sand mat layers. Thus, the usage of stone columns on soft clay soils which is an easy and economical ground improvement method because of providing the design flexibility through the soil material in the field, can become widespread.

Keywords: Soft Soil, Clay, Stone Column, Granular Column, Sand Mat, Basal Reinforcement, Vertical Encasement, Geosynthetics, Geogrid, Geotextile, Numerical Analysis, Finite Elements Method, Vertical Displacement, Settlement Behaviour, Lateral Deformation, Bulging Behaviour

ÖZET

GEOTEKSTİL SARGILI TAŞ KOLONUN DEFORMASYON DAVRANIŞI ÜZERİNE BİR NÜMERİK ÇALIŞMA

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Nisan 2020, XVI + 75 sayfa

Yumuşak zeminlerde yapılaşma, zeminin yetersiz taşıma gücü ve yüksek sıkışabilirlik oranı nedeniyle riskli olarak değerlendirilmektedir. Çoğunluğu denize yakın veya akarsular arasında olmak üzere dünyanın oldukça büyük bir kısmı yumuşak kil zeminlerden oluşmakla birlikte artan şehirleşme bu zayıf zeminlerin iyileştirilerek yeni inşa alanları oluşturulmasını zorunlu kılmaktadır. Taş kolonla iyileştirme yöntemi, hızlı imalat imkânı tanıması, konsolidasyon hızını artırması, bağıl ve toplam oturmaları azaltması ve bitişik yapıları olumsuz etkilememesi gibi avantajları nedeniyle diğer birçok yöntem arasından bir adım öne çıkmaktadır. Taş kolon özellikle üzerinde otoyollar, demiryolları ve kentsel altyapı tesisleri bulunan zayıf zeminlerin iyileştirilmesi için etkin ve uygun maliyetli bir yöntemdir.

Taş kolon taşıma gücünü kendini çevreleyen zeminin kolondaki yanal deformasyona karşı geliştirdiği pasif dirençten almaktadır, bu nedenle verimliliği yumuşak kil zeminin kayma direncine bağlıdır. Taş kolonların uygun bir geosentetik malzeme ile sargılanması; ihtiyaç duyulan yanal sargı etkisinin sağlanması ve taneli malzemenin yumuşak kil içerisine yayılmasının engellenmesi amaçlarıyla sıkça başvurulan bir yöntemdir. Geosentetik sargılama zemin taşıma gücünü iyileştirme, oturma ve şişmeleri azaltmanın yanında kolonun kolay drenaj kabiliyetini de olumsuz etkilememektedir.

Değerli birçok araştırmacı tarafından yapılan kapsamlı çok sayıda laboratuvar ve saha deneyleri ile sayısal çalışmalara rağmen, geosentetik sargılı taş kolonun performansının belirlenmesi, şekil değiştirme davranışının tümüyle anlaşılması ve uzun vadeli servis kabiliyetinin tahminlenebilmesi için halen ilave çabalar gerekmektedir.

Bu çalışma, içerisinde geosentetik sargılı taş kolonlar ve üzerinde geosentetik donatılı kum yatağı ile iyileştirilmiş varsayımsal bir zayıf zemin üstüne inşa edilen toprak set üzerinde yapılan sayısal analiz sonuçlarını içermektedir. Öncelikle sonlu elemanlar yöntemiyle yapılan iki boyutlu analizlerden elde edilen sayısal veriler evvelki saha çalışmaları ve deneysel çalışmalardan elde edilen değerlerle karşılaştırılarak doğrulanmış; sonrasında yumuşak zemin tabaka kalınlığı, geosentetik sargı uzunluğu ve sağlamlığı, taban güçlendirme tabakası (kum yatağı) kalınlığı ve geosentetik donatı sağlamlığı gibi değişkenleri içeren iki boyutlu değiştirgesel sayısal çözümlemeler yapılmıştır. İlaveten aynı yumuşak zemin içerisinde yüzer taş kolon grubu iki boyutlu olarak modellenerek bağıl oturma davranışı incelenmiştir. Çalışma kapsamında gerçekleştirilen parametrik analizlerle, ön tasarımda faydalanmak üzere optimum kum yatağı tabakası kalınlığı ve geosentetik donatı sağlamlığı, optimum dikey sargı boyu ve geosentetik sargı sağlamlığı belirlenmeye çalışılmıştır.

Bu çalışma ile soketli ve yüzer tip boyuna sargılı taş kolonların ve geosentetik donatılı kum yataklarının ekonomik olarak tasarlanabilmesine katkı sağlamak amaçlanmıştır. Bu şekilde zayıf kil zeminler için sahadaki mevcut malzemelerin kullanımına imkân tanıması yönünden kolay ve ekonomik bir zemin iyileştirme yöntemi olan taş kolonların kullanımının artabileceği değerlendirilmektedir.

Anahtar Kelimeler: Yumuşak Zemin, Kil, Taş Kolon, Taneli Kolon, Kum Yatağı, Taban Güçlendirme, Boyuna Sargı, Geosentetik, Geogrid, Geotekstil, Sayısal Yöntemler, Sonlu Elemanlar Metodu, Düşey Yer Değiştirme, Oturma Davranışı, Yanal Şekil Değiştirme, Şişme Davranışı

To family…

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

ANFIS	Adaptive Neuro-Fuzzy Inference System
c'	Effective Cohesion
CA	Centric Arching
CAD	Computer Aided Design
CSE	Column Supported Embankment
D	Column Diameter
DC	Drained Condition
E	Elastic Modulus
e	Void Ratio at Unit Pressure
ERBF	Exponential Radial Basis Kernel Function
ESC	Encased Stone Column
ϕ'	Effective Friction Angle
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Method
γ'	Effective Unit Weight
GEC	Geosynthetic Encased Column
GESC	Geosynthetic Encased Stone Column
GR	Geosynthetic Reinforcement
GRCSE	Geosynthetic Encased Column Supported Embankment
GRPS	Geogrid Reinforced Pile Supported
GRSB	Geosynthetic Reinforced Sand Bed
GRSM	Geosynthetic Reinforced Sand Mat
h	Vertical Encasement Height
H	Soft Clay Layer Height
HRSC	Horizontally Reinforced Stone Column
HS	Hardening Soil Model
HS-Small	Hardening Soil Small Model
φ'	Dilation Angle
JR	Jointed Rock Model
k	Permeability
K	Slope of Swelling Line
λ	Slope of the Virgin Consolidation Line
L	Column Length
M	Slope of the Critical State Line

m	Sand Mat Thickness
MC	Mohr-Coulomb Model
MCC	Modified Cam-Clay Model
OSC	Ordinary Stone Column
POLY	Polynomial Kernel Function
PSE	Pile-Supported Embankment
RBF	Radial Basis Kernel Function
s	Stone Column Spacing
SCR	Stress Concentration Ratio
SS	Soft Soil Model
SSC	Soft Soil Creep Model
SVR	Support Vector Regression
υ	Poisson’s Ratio
UC	Undrained Condition
USB	Unreinforced Sand Bed
USM	Unreinforced Sand Mat
VESC	Vertically Encased Stone Column
w	Weight of Loading Plate

1. INTRODUCTION

1.1. General

Embankment construction over inadequate grounds to reclaim new areas for highways, railways, airport runway and urban infrastructure has several inconveniences with regard to the inadequate load carrying capacity, high factor of compressibility and vulnerability to the lateral flows. Among variety of available techniques (preloading, surcharging, excavation and replacement, vertical drainage, vacuum consolidation, column supported embankments), the use of column supported embankments (CSEs) provides rapid construction, consolidation acceleration, total and differential settlement reduction and adjacent facility protection (Hughes et al., 1975; Barksdale & Bachus, 1983; Han et al., 2004; Borges & Marques, 2011). However, it appears to be impossible to improve very soft clayey soils with CSEs, due to inadequacy of the lateral confinement effect and excessive lateral bulging of column material (Madhav, 2006).

In soils types such that, insufficient confinement requirement can be persuaded by encasing the column with a proper geosynthetic material (Van Impe & Silence, 1986; Kempfert et al., 1997; Raithel & Kempfert, 2000; Raithel et al., 2002; Paul & Ponomarjow, 2004; Raithel et al., 2005; Alexiew et al., 2005; Brokemper et al., 2006; Di Prisco et al., 2006; Kempfert & Gebreselassie, 2006; Murugesan & Rajagopal, 2007; De Mello et al., 2008). Van Impe & Silence (1986) first introduced the idea of encasing columns with geotextile and proposed analytical design criteria for the necessary tensile strength of geotextile reinforcement material. In proportion to the growth in the construction sector and the progress in geosynthetic production technology, new design procedures were developed. In 1995, the first project with a seamless geotextile encased column was successfully implemented in Germany. Later, Kempfert et al. (1997), Raithel & Kempfert (2000) and Raithel et al. (2002) conducted both numerical and analytical model tests to determine the performance of geosynthetic-encased stone columns (GESCs). The technique using the data of recent projects has been expertly adopted in Europe (Raithel et al., 2005) and (Alexiew et al., 2005) than lately in South America (De Mello et al., 2008).

The efficiency of geosynthetic reinforcement, on the load carrying capacity and vertical deformation behaviour of the soft ground has been studied via both laboratory tests and field experiments (Sharma et al., 2004; Ayadat & Hanna, 2005; Liu et al., 2007; Murugesan & Rajagopal, 2007; Malarvizhi & Ilamparuthi, 2007; Wu & Hong, 2009; Murugesan & Rajagopal, 2010; Ali et al., 2012; Yoo, 2010; Almeida et al., 2015). Ayadat & Hanna (2005) conducted an experimental program on encased stone columns to determine the profits of encasement.

Liu et al. (2007) published the in-situ results of a case study of a pile-supported highway embankment which is improved by basal geogrid reinforcement. Vertical and lateral deformations, pore-water pressures, pressures acting on the surface of soil and the pile were gathered and compared to those obtained from FEA results. The study reveals that because of the soil arching, a load transfer was occurred from the soft soil to the piles thus pore-water pressure in the soft soil was turned down significantly. The pressure on the piles was measured to be fourteen times bigger than on the soil between the pile system. The decrease at the lateral deformation of the subgrade beneath the tip of the embankment due to the basal reinforcement verified by the field data.

Murugesan & Rajagopal (2007) asserted that the most effective parameter in the strength of the instrumented GECs in the small-footing tests was encasement stiffness. They also indicated that the greatest radial geosynthetic strain occurred at the top of the column and columns should be encased in the length of 4-fold diameter. Malarvizhi & Ilamparuthi (2007) conducted scaled laboratory tests and carried out numerical analysis in order to thoroughly understand the settlement behaviour of fully encased stone columns. Additionally, they revealed that the increment at geosynthetic stiffness significantly reduces the settlement.

Murugesan & Rajagopal (2010) examined the influence of the properties of materials and the geometry of the model for both encased and non-encased stone columns in a large-scale laboratory test setup. They suggested design codes for specific load and settlement conditions. Ali et al. (2012) performed scaled laboratory tests on both short, end-bearing and floating individual columns reinforced by various types of geosynthetics. It was found that the geogrid is the most suitable type of geosynthetic encasement for fixed stone columns; whereas it is geotextile for floating columns.

Yoo & Lee (2012) carried out field load tests to analyse the influence of encasement length and column strain on the ultimate load capacity improvement and settlement reduction of GECs. Almeida et al. (2015) performed a research for the soft soil treatment. A trial embankment supported with geotextile-encased columns was constructed on soft soil and instrumented to research the vertical stresses acting on column, settlement behaviour of the improved ground, lateral deformation of columns, excess porewater pressure of soft soil and the hoop strain in the geotextile encasement.

Also, there are countless accomplished samples of numerical studies on encased granular columns in the literature such as (Shin et al., 2002; Murugesan & Rajagopal, 2006; Yoo & Kim, 2009; Gniel & Bouazza, 2009; Lo et al., 2010; Yoo, 2010; Pulko et al., 2011; Khabbazian et al., 2011; Riccio et al., 2012; Elsawy, 2013; Almeida et al., 2013; Hosseinpour et al., 2014; Yoo et al., 2015).

Murugesan & Rajagopal (2006) carried out numerical analyses on single ESCs and implied that the GESCs were more stiff than ordinary stone columns. They justified that the optimum encasement length should be equal to 2-fold of column diameter. Yoo & Kim (2009) evaluated the usability of continuum elements instead of membrane elements on a full three-dimensional model of GESCs. Using continuum elements provided the consideration of axial encasement stiffness. They suggested that optimum encasement length differs for different loading conditions.

Gniel & Bouazza (2009) carried out scaled laboratory tests using unit cell boundary conditions focusing on the effect of encasement length on the vertical strain reduction. The test results showed that the constrained unit cell loading enabled the encased column displace laterally without failing. Lo et al. (2010) presented the findings of a fully coupled set of experiments to verify the settlement reduction of ESC supported embankment.

Yoo (2010) performed a numerical study on several parameters such as the consistency degree of soil, the area replacement ratio and the strength of the encasement. The results indicated that the effect of geosynthetic encasement was far more distinct for wider spacing states and for inadequate grounds. Also, it was implied that a full encasement may be necessary to benefit properly from the settlement reduction under different loading conditions, unlike the single column behaviour.

Pulko et al. (2011) developed an analytical solution considering the initial stresses in the conventional stone columns and the geotextile encased stone columns. They prepared charts regarding column spacing and the stiffness of encasement material for preliminary design to ensure the desired settlement. Khabbazian et al. (2011) utilized three different forms of hyperbolic model in 3D finite element (FE) analyses and compared the stress-settlement behaviour with the results of the analyses performed using the procedures described in Duncan & Chang (1970), Kulhawy & Duncan (1972) and Duncan (1980). Although being implemented to the specific case of GEC, they asserted that it applies equally to simulate soil mass is at or near failure. They successfully modelled the soil near failure behaviour which was essential for accurately simulating the deformation behaviour of GECs. Elsawy (2013) applied consolidation analyses to determine the long-term behaviour of the soft soil and carried out FE analyses in order to investigate the deformation behaviour of geogrid-encased stone columns under embankment loads. According to the results of the study, stone column accelerated the excess pore-water dissipation and the increased stress concentration obviously accelerates the consolidation.

Hosseinpour et al. (2014) presented a full-scale test results of geotextile-encased granular column supported embankment. The vertical stresses and surface settlements read atop of the stone column and soil between, and porewater pressures were compared to those obtained from the numerical results of a simulated axisymmetric unit cell. Yoo et al. (2015) conducted a 3D numerical study considering the effect of variables such as strength and layer thickness of soft soil, the encasement length and geosynthetic material stiffness, the height of the embankment fill and the area replacement ratio. They also presented charts for preliminary design on estimation of the ultimate vertical deformation and the stress concentration ratio (SCR).

In cases where the column tip cannot reach the rigid ground, constructing floating columns are more feasible (Tabesh & Poulos, 2007). The frictional force along the column surface effects the geosynthetic encased stone columns (GESCs) behaviour, therefore the relative settlement between the pile and the surrounding soft soil should be kept in mind (Lu et al., 2009; Jenck et al., 2009; Bhasi & Rajagopal, 2013; Zhang et al., 2015; Bhasi & Rajagopal, 2014). Although previous researches have contributed valuable information and research for concerning the performance of GESCs, previous studies are mostly focusing on individual fixed reinforced columns and offer a very limited data on the group of encased floating columns. Further examination is still required for the design of embankments over floating encased column installed soft grounds (Satibi, 2009; EBGEO, 2010; Eekelen et al., 2011).

In recent years, the horizontal (basal) geogrid reinforcement has been used in combination with CSEs over soft clay soils in circumstances of high embankment loads to create a geosynthetic reinforced column supported embankment (GRCSE) (Lawson, 1992; Russell & Pierpoint, 1997; Kempton et al., 1998; Rowe & Taechakumthorn, 2011; Briançon & Simon, 2012). The usage of the geogrid reinforcement over the composite ground improves the transfer of loads from the embankment into the stone columns, provides controllable deformation, global stability and eliminates the need of inclined columns by resisting horizontal thrust on the edges of the embankment (Han & Gabr, 2002; Chai & Miura, 2002; Rowe & Li, 2005; Shen et al., 2005; Stewart & Filz, 2005; Abdullah & Edil, 2007; Liu et al., 2007; Smith & Filz, 2007; Chen et al., 2008; Zheng et al., 2009; Lai et al., 2014; Liu et al., 2007).

The complicated load transfer mechanism of GRCSEs includes soil arching, geosynthetic reinforcement materials tension force and the transfer of stresses from soft ground into the pile due to the stiffness differentiation between them (Han & Wayne, 2000). The deformation behaviour of GRCSE have been investigated both experimentally or numerically by many researchers over the past few years such as (Rowe et al., 2015; Eekelen et al., 2012; Ariyarathne et al., 2013; Eekelen et al., 2003; Girout et al., 2014; Lai et al., 2014; Yapage & Liyanapathirana, 2014; Rowe & Liu, 2015; Zhuang & Wang, 2015; Bhasi & Rajagopal, 2015; Khabbazian et al., 2015).

Zhang et al. (2015) presented the performance results of a case study on a basal reinforced coastal embankment with a geotextile layer at the bottom of the embankment. The contribution of the geotextile reinforcement on the deformation behaviour of soil under the embankment loading was analysed with numerical study and compared with field monitored results. Bhasi & Rajagopal (2015) searched the time dependent soil arching formation and surface friction distribution along the pile of embankments which supported by both geosynthetic-reinforced fixed piles as well as floating piles in means of using full three-dimensional models. Numerical values were compared to those recommended in British Standard, BS 8006-1 (2010).

Khabbazian et al. (2015) stated that a hypothetical geosynthetic reinforced embankment supported with GECs can be modelled numerically using either 2D axisymmetric or 3D model unit cell idealization as deep foundation elements.

1.2. Scope and Objective

This study presents the findings of FEA of a hypothetical geotextile encased column supported embankment (GECSE) on a soft soil deposit which is improved by a geogrid reinforced sand mat (GRSM) on top.

The published literature focusing on long-term vertical and lateral deformation behaviour of geosynthetic encased stone column (GESC) is limited. Model studies in the literature on this subject are usually on stone columns socketed on solid ground. Many recent studies have dealt with the load carrying capacities and settlements of unreinforced embankments supported with GESCs, nevertheless the effect of reinforcement at the base of embankment has not considered yet. Also, the mechanics of load transfer and the lateral deformation (bulging) behaviour of the GESCs are not thoroughly determined.

Numerical results of 2D and 3D FE analysis were validated by using field and experimental data of former studies at first, afterward parametric studies were carried out on two-dimensions finite elements model considering the influence of the soft soil thickness, the length of column, geotextile encasement length and stiffness, basal reinforcement stiffness and the embankment fill height.

Also, a group of floating stone columns in soft ground were modelled in two-dimensions and both horizontal and vertical deformation behaviours were determined. By the parametric studies performed in the study; the optimum sand mat thickness, the geogrid stiffness, the optimum encasement length and the geotextile stiffness will be advised to be used for the preliminary design. This will contribute to the development of economic design methods for both floating and end-bearing vertically encased stone columns (VESC) and geogrid reinforced sand mat (GRSM) layers. Thus, the usage of stone columns on soft clay soils which is an easy and economical ground improvement method because of providing the design flexibility through the soil material in the field, can become widespread.

Therefore; in order to enhance the performance of GESCs and to fill the gaps for the above-mentioned issues, the main objectives of present study can be listed briefly as follows;

- to investigate the performance of vertical geotextile encasement on stone columns and geogrid reinforcement at sand mat layer,
- to determine the optimum sand mat layer thickness and the optimum geogrid reinforcement stiffness,
- to determine the optimum vertical geotextile encasement stiffness (tensile strength) and the adequate length of the column encasement,
- to consider the effect of geotextile encasement on the settlement (vertical displacement) and lateral deformation (bulging) behaviour of stone columns,
- to compare the performance of fixed and floating stone columns in terms of vertical displacement and lateral deformation behaviour.

2. LITERATURE REVIEW

2.1. Site Experiments and Case Studies

Liu et al. (2007) explored a pile-supported and geogrid-reinforced weak highway embankment (GRPS) (Figure 2.1). Pore-water pressures, acting pressures, vertical displacements and lateral deformations of the piles and soil surfaces gathered from field data was back analysed with finite element analysis and result were compared and discussed. The study revealed the so-called effect of soil arching, which is basically the load transfer from the soil into the piles thus excessive pore-water pressure in the soft ground was greatly reduced. The measured lateral-vertical deformation (bulging/settlement) ratio was significantly reduced according to the predictions of two common existing design methods suggesting lateral expansions can be reduced and embankment stability can be enhanced significantly with the usage of geogrid-reinforced and pile-supported (GRPS) system.

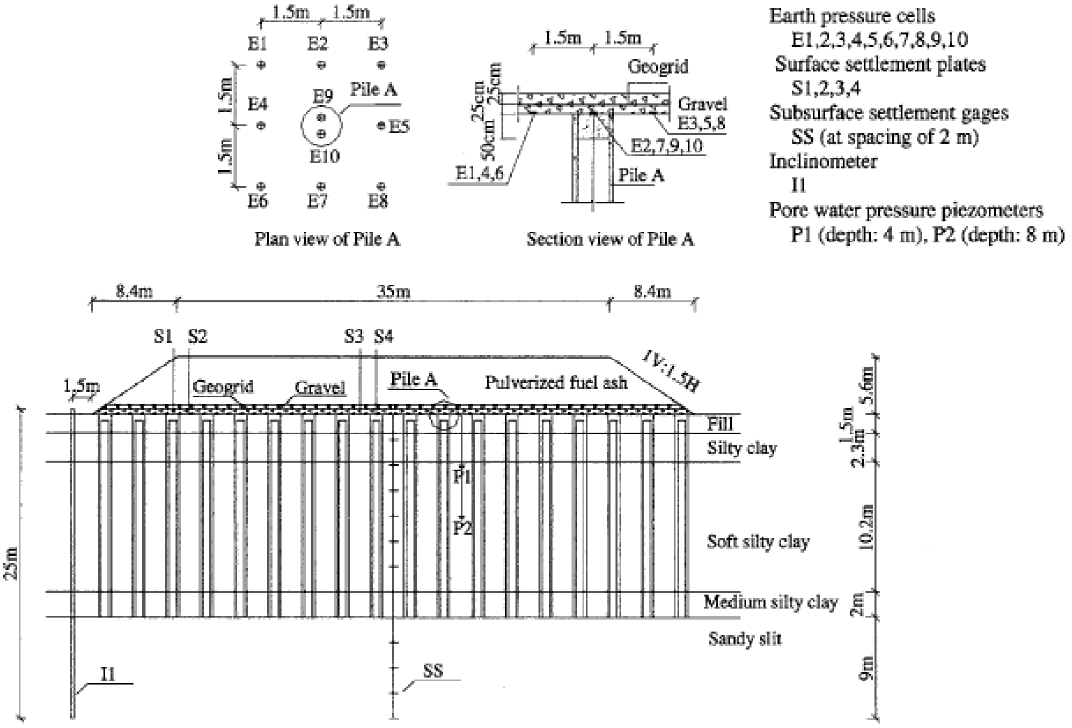


Figure 2.1. Profile view of instrumented test embankment (Liu et al., 2007)

Yoo & Lee (2012) implemented two different full-scale load tests at a site with multi-layered soft ground and a railway construction site in Korea. The study focuses on load-carrying capacity improvement, settlement reduction of a geogrid encased stone column (GESC) and investigates the effect of encasement length on column strain using field-scale load tests (Figure 2.2). OSC, individual GESC and rammed-aggregate pier behaviours were compared to each other. The study brought out that additional confinement provided by -even with partial- the geogrid encasement reduced the vertical displacement of the soft ground and increased the maximum load capacity of the stone column significantly.

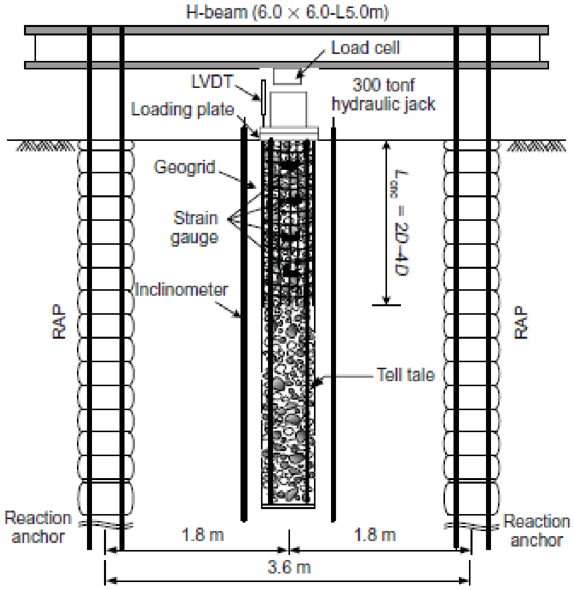


Figure 2.2. Full-scale load test setup (Yoo and Lee, 2012)

Van Eekelen et al. (2014) validated a series of former analytical models by van Eekelen et al. (2012a; 2012b; 2013) with the results of seven sets of full-scale experiments and four series of scaled-laboratory tests on the GR (geosynthetic reinforcement) in a pile-supported embankment. The study describes arching with a new model called “Centric Arching (CA) Model” which interprets better overlap than Hewlett and Randolph’s (1988) “Single Arch Model” and Zaeske’s (2001) “Multi-Scale Model” according to the comparisons between the measured and calculated data. The study revealed that, if the sub-soil support is sufficient the load distribution is approximately uniform and the geosynthetic reinforcement (GR) strain is low, otherwise the load distribution giving the least GR strain matching up with the measurements should be determined.

Almeida et al. (2015) instrumented a region of a bi-directional geogrid reinforced pile-supported embankment which has been built on a nearly 2.50 m thick pre-existing fill over a 10.0 m high soft clay layer (Figure 2.3). Both 2D and 3D layouts have been used and acquired settlement values and reinforcement strains were compared with other studies in the literature and they seem to match up.

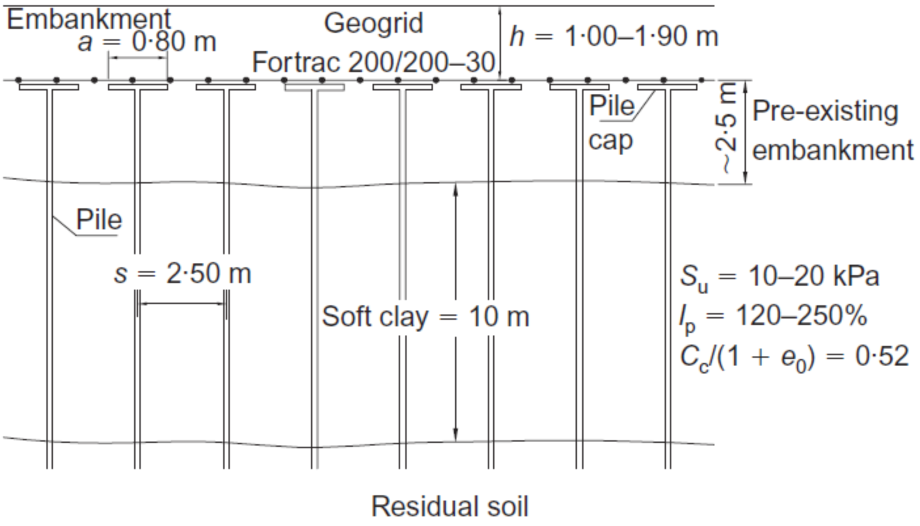


Figure 2.3. Typical site cross-section and geometry (Almeida et al., 2015)

Almeida et al. (2015) instrumented both the geotextile-encased stone columns and the soft foundation under a test embankment. Vertical stresses and surface displacements, radial deformation of the geotextile encasement material and excess pore pressure were gathered within the study. The relative settlement and stress concentration difference between the GESC and the soft ground were studied. Result indicated that the encased column has supported two times greater vertical stress than the soft soil due to arching. Also, as consolidation progressed the increase in vertical stress on the encased column kept up unlike to the soft soil.

Chen et al. (2015) assessed tensile strength of the geogrid reinforcement placed in the sand mat under a full-scale high-speed railway embankment (Figure 2.4). The stiffness of the geogrid was measured to be about 12% of that calculated according to the BS8006. Thus, study reveals that the calculation method prescribed in the code is reliable for geogrid reinforcement tensile strength determination.

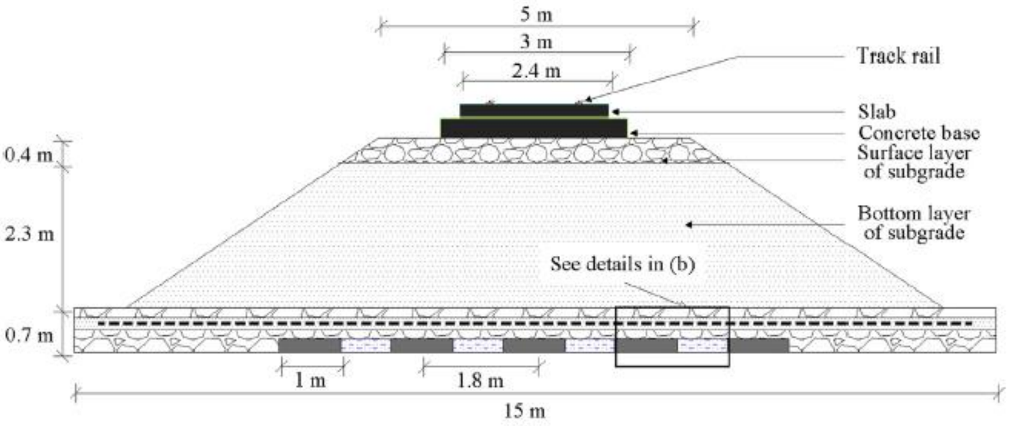


Figure 2.4. Cross-section of the test model (Chen et al., 2015)

Hosseinpour et al. (2015) conducted a full-scale test on geotextile-encased granular columns constructed in a soft ground under an embankment load. The improved foundation was instrumented to determine the surface vertical stresses and settlements of the encased column and surrounding soft soil, excess pore pressures and the radial deformation of the encasement material. The results of field measurements were compared with those gathered through 3D finite elements analysis (Figure 2.5). The study asserted that the settlement values on the top differs from the encased column to the surrounding soil and there is a correlation between embankment's maximum vertical displacement and expansion of the geotextile material.

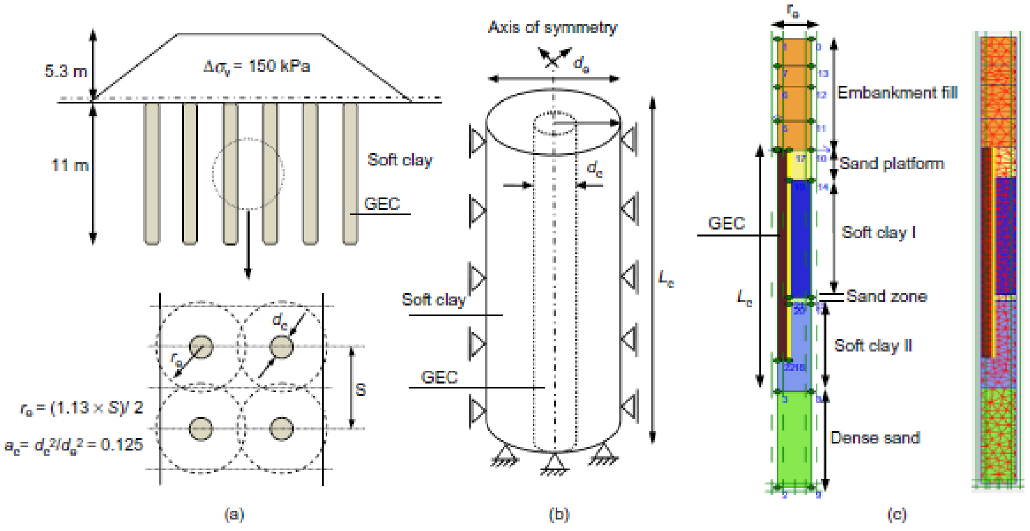


Figure 2.5. Geometry of the encased column reinforced embankment and the FE model used in numerical analysis (Hosseinpour, Almeida and Riccio, 2015)

Zhang et al. (2015) presented a case history of a coastal embankment on a soft ground which has been improved by a geotextile reinforced layer at the bottom of the embankment (Figure 2.6). The porewater pressure change of the soil and the vertical displacement of the embankment were recorded along and after the construction process. FE analysis were conducted in order to understand the reinforced soil behaviour under embankment load and to determine the performance of the encasement material. The influence of the geotextile reinforcement on reducing the vertical displacements was verified with both in-situ and simulation results. The results shown that geotextile reinforcement can help preventing sudden failure of subsoil during the construction process of the embankment, however it has no contribution the overall factor of safety.

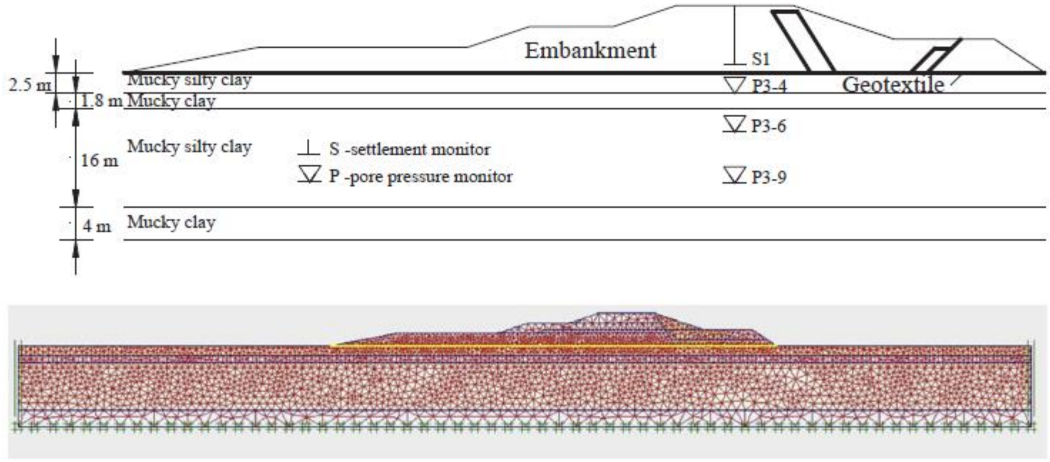


Figure 2.6. Cross-section of embankment and FE mesh used in analysis (Zhang et al., 2015)

Shenkman & Ponomaryov (2016) presented results of numerical analyses of a GESC reinforced inadequate clayey soil ground in the permafrost region of Russia. The study includes both materials of in-situ results of a current project and numerical analyses carried out on PLAXIS 3D. Experimental study consist of stamp and triaxial tests of large-scale GESC models. Also, paper focuses on the deformation estimation of reinforced ground and cost-effective application areas of the improvement technique. They suggest to use this type of ground improvement in uninhabited areas where it is hard to reach plant-mixed concrete, foundations of temporary structures and subbase improvement of highway or railways for resource extraction.

2.2. Scaled Laboratory Experiments

Indraratna et al. (2006) performed an extensive laboratory experiment in order to examine the usage fields of geosynthetics for improving the deformation behaviour and the effects of different types (geotextiles, geogrids, geocomposites) of geosynthetic reinforcement materials to enhance the performance of railway ballast and formation soil. A prismoidal triaxial rig with a large-scale was used and finite element analyses on PLAXIS were performed to most efficient type and instalment location of geosynthetics in railway track sub-structure (Figure 2.7). The study points out that inclusion of a geosynthetic layer in a fresh and recycled ballast prevents the degradation of the tracks thus decreases vertical deformations. Also, it decreases the breakage index almost equal to that of fresh ballast that settlement reduction becomes even better than that of the ordinary (unreinforced) new ballast.

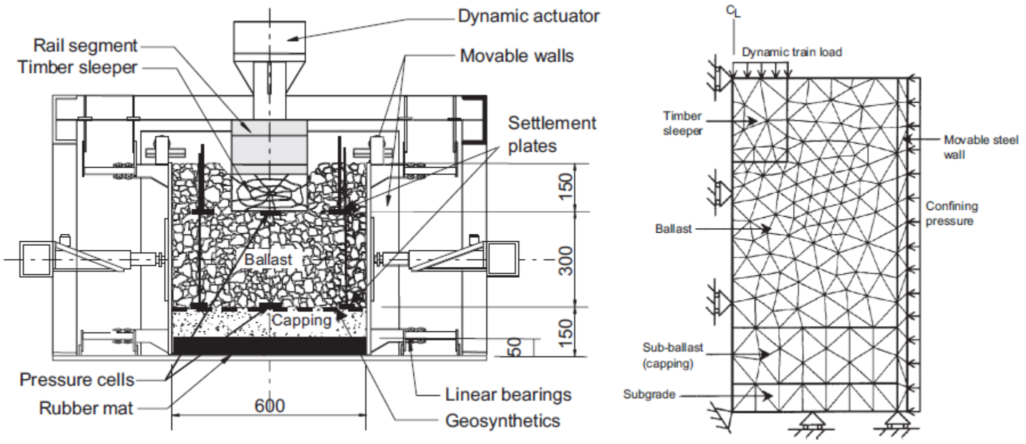


Figure 2.7. Schema of prismoidal triaxial test apparatus and FE mesh used at PLAXIS (Indraratna, Shahin and Salim, 2006)

Malarvizhi & Ilamparuthi (2007) carried out scaled model laboratory experiments and analysed these models using PLAXIS FE software in order to fully comprehend the characteristics of ESC constructed in soft ground and to find out the effective parameters on load share mechanism and vertical deformation reduction in the reinforced soil (Figure 2.8). A parametric study was conducted to investigate the L/D ratio of the stone column, tensile strength of the geogrid reinforcement and granular materials angle of internal friction.

The study revealed that geogrid encasement improves the load capacity of the stone column and the parametric study shown that increase in the encasement strength up to 2000 kN/m²/m reduces the settlement, beyond that contribution becomes insignificant. The increase at the L/D ratio of the stone column up to 10 times reduces settlement beyond that contribution becomes negligible. Numerical studies point out that the lateral deformation of stone column is effective up to 4D which complies former studies of Greenwood (1970) and Hughes & Withers (1974).

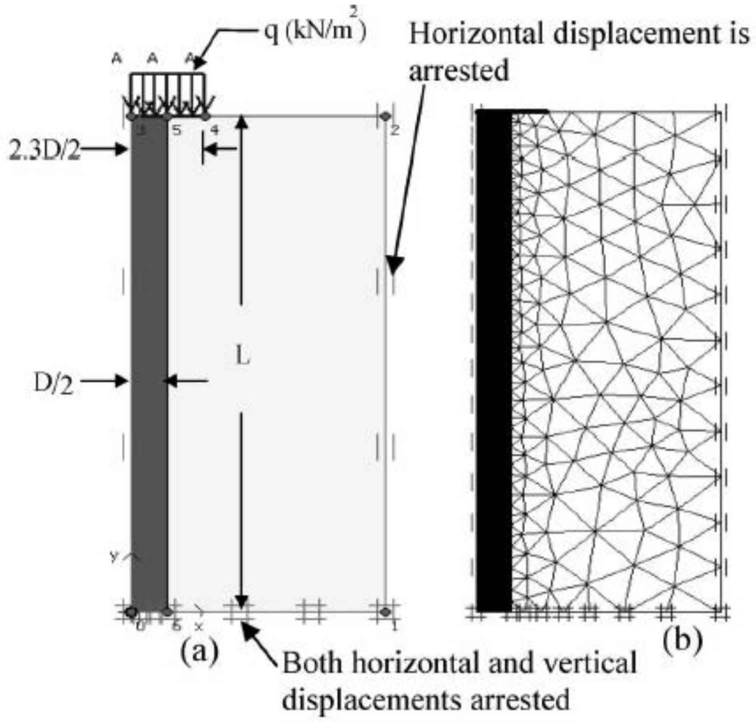


Figure 2.8. FE model used at PLAXIS (Malarvizhi and Ilamparuthi, 2007)

Gniel & Bouazza (2010) carried out a series of medium-scale tests to compare the performance of geogrid reinforcement created by superimposing the encasement by a specific length to those which created by rolling into a sleeve and welding using specialized equipment (Figure 2.9). The study indicates that this overlapping method provides an economical and convenient method for in situ encasement production. Biaxial geogrids are the most suitable reinforcement to this technique and the column bearing capacity increases in line with an increase at encasement stiffness according to the study.

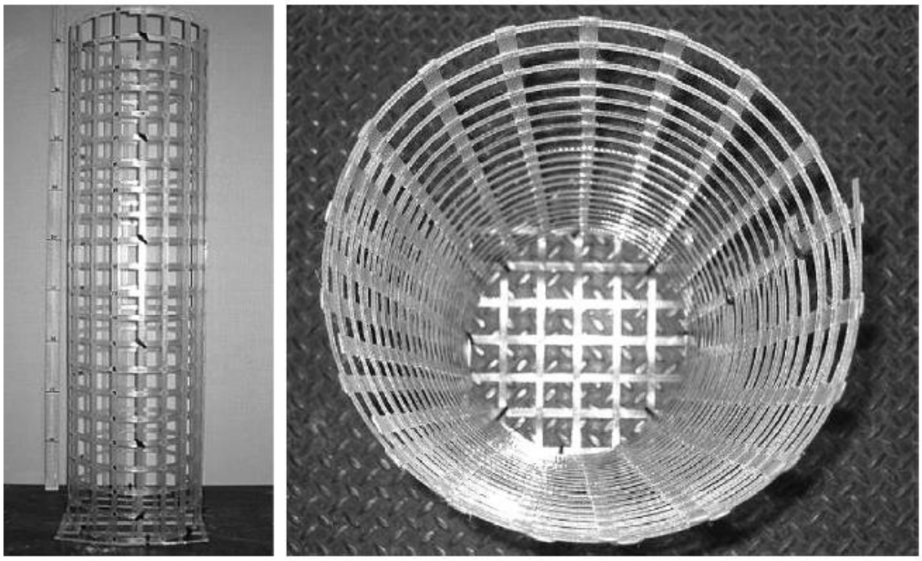


Figure 2.9. Typical encasement created using the overlap technique used at medium-scale tests conducted by (Gniel and Bouazza, 2010)

Ali et al. (2012) conducted model tests on fixed and floating types of ordinary and encased single columns constructed in soft ground to measure the relative improvement (Figure 2.10). The study reveals that irrespectively to the type of material, reinforcing the fixed stone column is more effective than the floating stone column. Additionally, geogrid is the most effective material for horizontal stripping and geotextile performs better as encasement material for floating stone columns while geogrid appears to be the most suitable material to be used as both vertical encasement material and horizontal strip reinforcement for fixed stone columns.

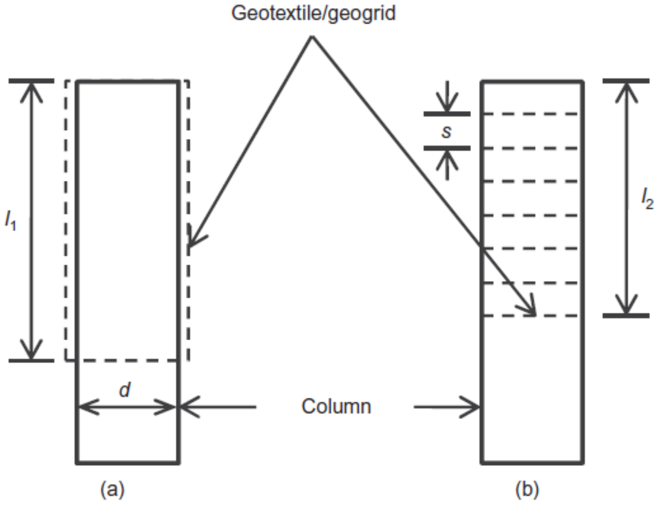


Figure 2.10. Types of reinforcement methods on stone columns: a. vertical encasement and b. horizontal strips (Ali, Shahu and Sharma, 2012)

Van Eekelen et al. (2012a; 2012b) conducted a series of 3D scaled laboratory experiments on piled embankments in a two-part study (Figure 2.11). The bearing loads, settlements and geogrid reinforcement strains were measured and analysed. Results were discussed on the basis of various effective parameters such as the sub-soil and filler material properties, the specifications of reinforcement material in the first part. The measurements and analytical calculations based on EBGEO (2010) were compared in the second part of the study. The results were discussed in consideration of influencing factors and possible improvements on the analytical model were suggested. The study indicates that consolidation of the sub-soil tends to an incremental load transfer through the geogrid reinforcement and also a boost of arching depending on the fill's friction angle. Results shown that the difference in the usage of a geogrid reinforcement or a geotextile encasement is negligible.

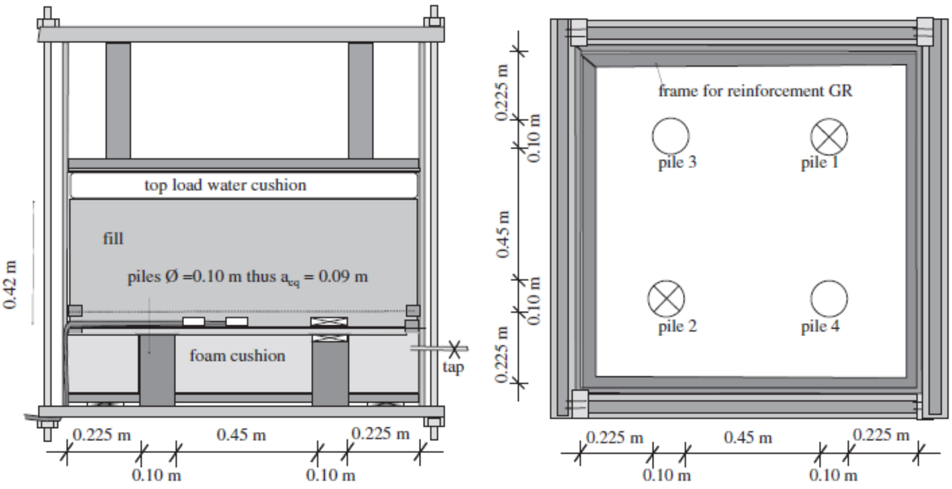


Figure 2.11. Side and top views of test set-up (Van Eekelen et al., 2012a, b)

Kongkitkul et al. (2012) performed a series of scaled-model laboratory experiments on a GRPS embankment to examine the effect of the geosynthetic reinforcement on the load transfer mechanism. Various embankment configurations with several height of embankments and two geogrid types -which one's stiffness is twice the other- were adopted to compare the relative settlements between the top of reinforced piles and soft soil. The study shown that, on a basal reinforced and pile supported embankment, the additional vertical stress acting on the piles can be seen explicitly if only adequate relative settlement was allowed. Also, the usage of stronger geogrid increases the reinforcement effect.

Tandel et al. (2012) conducted scaled-model laboratory tests with different geosynthetic modules and carried out several FE analyses to investigate the settlement behaviour of conventional stone column and encased stone column under different loading conditions (Figure 2.12). The results indicate an obvious enhancement in load carrying capacity of the ESC. The data gathered from the experiments and the result of FE analysis conform to each other.

Figure 2.12. Schematic view and test set up by (Tandel et al., 2012)

Ali et al. (2013) conducted scaled model experiments on floating and fixed stone columns by singles and groups, with and without reinforcement to determine the failure stress of reinforced ground for vaious types of reinforcement (Figure 2.13). For floating column case study reveals that, both types of reinforcements were equally effective in cases of encasement and horizontal stripping; for fixed columns geogrid appears to be the most effective geosynthetic reinforcement.

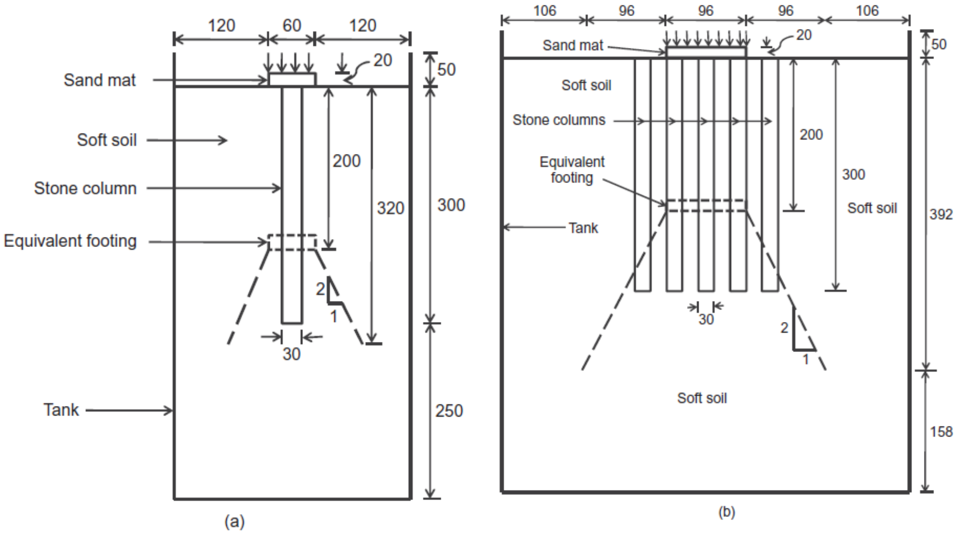


Figure 2.13. Schematic view of; a. single stone column, b. stone column group (Ali et al. 2013)

Dash & Bora (2013) carried out an experimental program consisting a series of scaled-model loading experiments on a stone column supported composite ground and an unreinforced -without stone column- soft ground (Figure 2.14). The study indicates that partially encased floating columns perform better than fully encased ones. On the contrary, at the case of fixed stone columns, full-length encased stone columns perform better than the partially encased ones. The confinement effect of the encasement increases the maximum load capacity of fixed stone columns and deeper bulge occurrence makes the enhancement possible for floating columns.

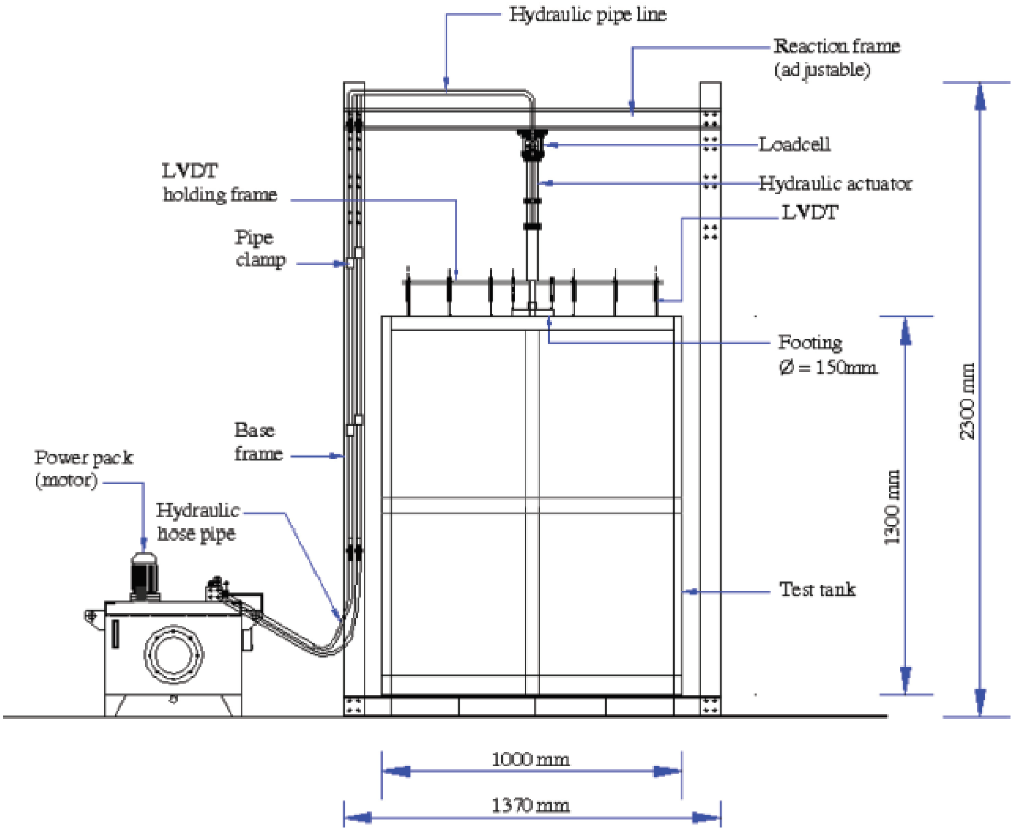


Figure 2.14. Schematic diagram of test set-up (Dash and Bora, 2013)

Afshar & Ghazavi (2014) carried out laboratory test on vertically encased stone columns (VESC) and horizontally reinforced stone columns (HRSC) to investigate the influence of encasement type on the bearing capacity (Figure 2.15). The study reveals that both vertical and horizontal reinforcement makes positive contribution to the ultimate load capacity of stone columns moreover influence strengthen with an increase at reinforcement stiffness. Results shown that by using geosynthetics and increasing the strength of the reinforcement material, the SCR increases while the lateral deformation of the column decreases.

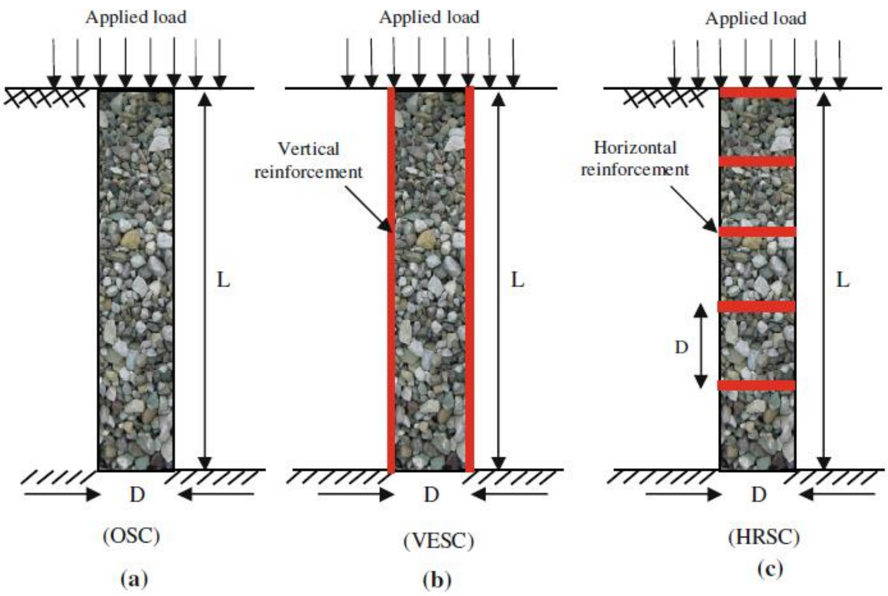


Figure 2. 15. Schema of a. ordinary granular column, b. vertically encased granular column and c. horizontally reinforced granular column (Afshar and Ghazavi 2014)

Ali (2014) performed laboratory test on both fixed and floating single stone columns on ordinary and reinforced conditions. The stone column was reinforced with varying encasement length. The study points that fully reinforcement perform better than partial reinforcement both on floating and fixed stone columns. Additionally, fixed stone columns are superior to the floating columns according to the tests.

Vogt et al. (2014) presented the results of a large-scale laboratory experiment to investigate the effect of bending stiffness on the buckling load of an individual GEC installed in ultra-soft ground. The density of the infill material seems to be the dominant property at bending and buckling tests on the stiffness of geosynthetic material. Thus, bending stiffness appears to be a decisive parameter on GECs.

Han et al. (2015) conducted four series of large-scale laboratory experiments in a testing tank to research the effect of different lengths of geosynthetic encasement for the lateral and vertical deformation behaviour on conventional and encased stone columns established in a soft clay ground (Figure 2.16). The results indicate that geogrid encasement enhances the maximum load carrying capacity of the soft soil significantly and the effective encasement length appears to be 3 or 4 times the column diameter (3D or 4D) by the means of performance and economy.

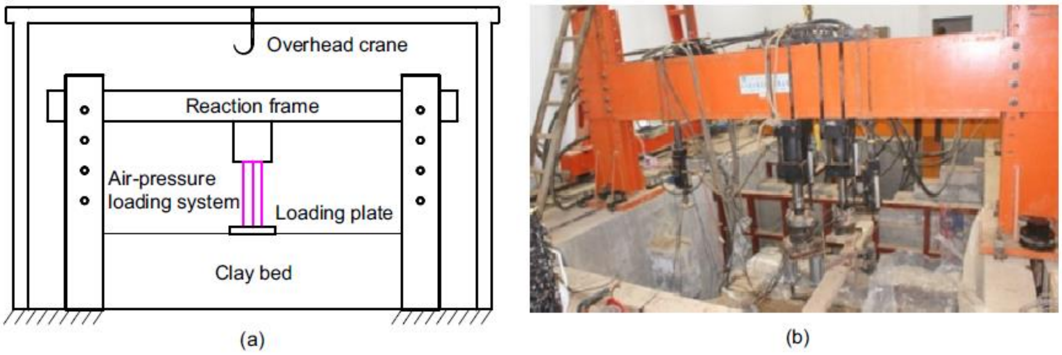


Figure 2.16. a. Schematic diagram of the plate load, b. Photo of loading system (Han et al., 2015)

Mohapatra & Rajagopal (2016) carried out an experimental study to analyse geosynthetic encased stone column's (GESC) capacity of shear load and compared experimental results with a 3D numerical model created with FLAC^{3D} program. The study approves that the additional confinement acting on the aggregates provided by geosynthetic encasement helps to improve the performance of GESC.

Miranda & Da Costa (2016) conducted triaxial compression test on both conventional and encased types of granular columns to investigate the contribution of the additional confinement influence on the granular column material's angle of friction. The results referred an obvious enhancement with encasement of columns and the improvement is more obvious for lower values of confining pressures.

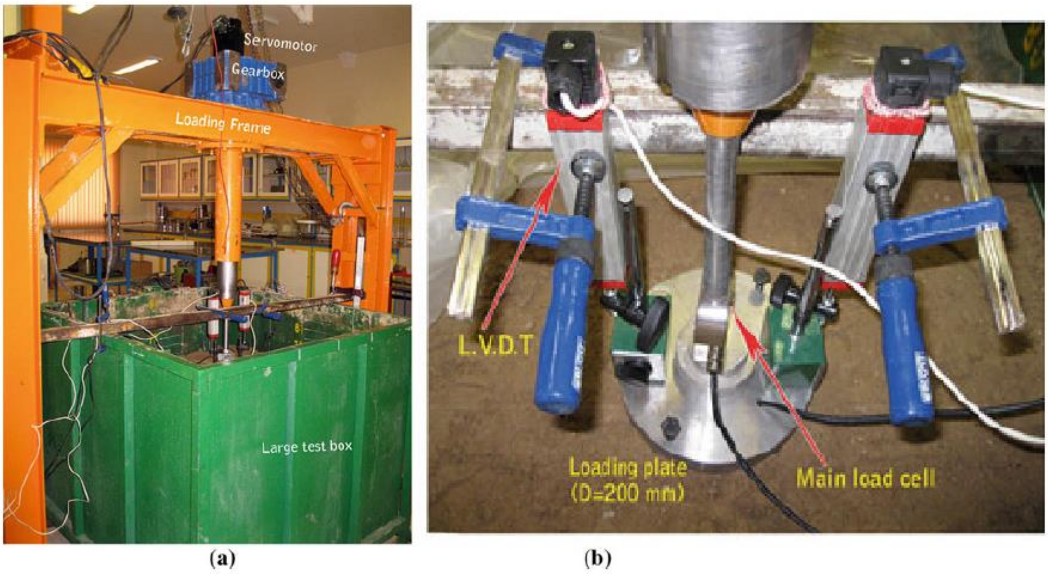


Figure 2.17. a. Test box and loading frame, b. loading plate and data collecting instruments (Afshar and Ghazavi, 2017)

Afshar & Ghazavi (2017) conducted laboratory test on both unreinforced stone columns, vertically encased stone columns (VESC) and horizontally reinforced stone columns (HRSC) with various diameters and a L/D ratio of 5 (Figure 2.17). The study focused on the efficiency of the type of encasement under same conditions. The results shown that using both vertical encasement and horizontal reinforcement contribute to the columns load carrying capacity. Moreover, encasing the columns and increasing the strength of geosynthetic material increases the stress concentration ratio and decreases lateral expansion and bulging failure.

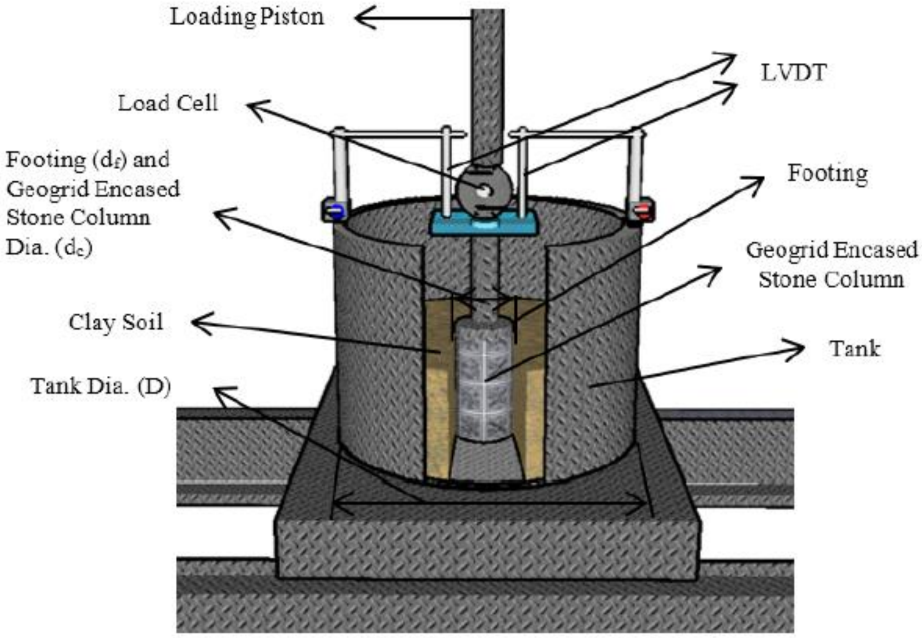
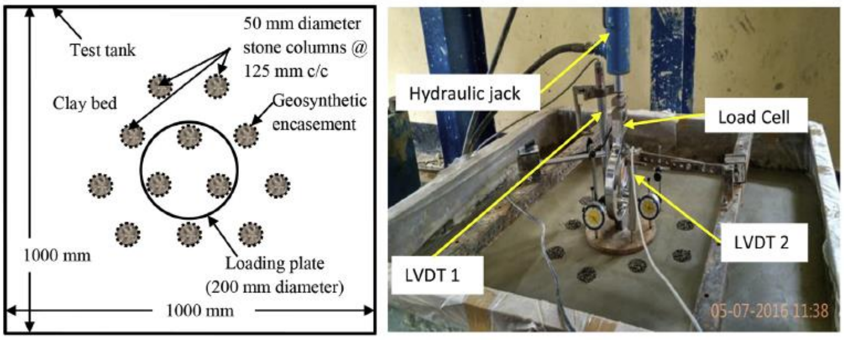


Figure 2.18. Layout of apparatus used at the model tests (Demir and Sarıcı, 2017)

Demir & Sarıcı (2017) performed a series of experiments in order to investigate the deformation behaviour of stone columns in a soft clay deposit and carried out numerical analyses with PLAXIS program to validate the experimental results (Figure 2.18). Parametric analyses were conducted on bearing capacity of ordinary and encased stone columns, length and strength of encasement, internal friction angle of granular material and diameter and bulging behaviour of stone columns within the study. The results shown that stone columns can be utilized as a soft ground improvement technique and an obvious gain in the bearing capacity was monitored by the means of additional confinement effect of geosynthetic reinforcement. Additionally, geogrid rigidity and depth of encasement minimizes the lateral bulging according to the tests.

Debnath & Dey (2017) carried out a series of scaled laboratory tests on a floating vertically encased stone column (VESC) supported soft ground which has been improved by an unreinforced sand bed (USB) and a geogrid-reinforced sand bed (GRSB) in turns (Figure 2.19). The experimental findings were compared to ABAQUS 3D numerical analyses results. The study approves that an obvious increase in ultimate load capacity and a respectable reduction at lateral deformation was observed by the courtesy of the GRSB placed over VESC.



(a) (b)

Figure 2.19. a. Schematic plan and b. pictorial view of test setup (Debnath and Dey, 2017)

Hong et al. (2017) performed an experimental study on a soft clay deposit reinforced by encased stone column and carried out FE analyses using FLAC program to verify the performance of the GESC. Bearing stress - settlement response and the pressure - column length distribution was investigated. The results shown that the stiffness of the encasing material obviously effects the maximum lateral deformation occurring depth of an encased granular column. Also, study reveals that a column diameter increment causes an obvious confining pressure reduction thus leading to the bearing capacity improvement reduction.

Naeini & Gholampoor (2018) performed scaled laboratory experiments on the shear deformation behaviour of soft clay grounds reinforced with stone column and shear forces acting on the column because of the soil movements (Figure 2.20). Parametric analyses concerning encasement length and encasing material stiffness, angle of friction and gradation of granular material and number, diameter and allocation of stone columns carried out and various normal pressures were evaluated by direct shear tests.

Results shown that geosynthetic encasement significantly improves the shear strength behaviour of stone column installed in wet clay ground and the improvement degree increases depending on physical properties of the infill and the encasement material.

Figure 2.20. Photography of direct shear test setup (Naeini and Gholampoor, 2018)

2.3. Numerical Studies

Fattah & Khudhair (1999) conducted a set of FE of both conventional and ESC supported composite grounds under various conditions using CRISP2D. The effect of encasement on load carrying capacity improvement and settlement reduction of the stone column was investigated through a parametric study. The study indicates that the improvement on bearing capacity and settlement reduction scales up with an increase in encasement length and the improvement effect increases depending upon an increment at shear strength of the fixation soil. The results shown that the stone column takes full benefit of end bearing soil support when it is fully encased.

Latha & Rajagopal (2007) simulated a geocell reinforced soft ground to investigate the improvement in the stiffness of composite ground (Figure 2.21). Various dimensions and stiffness values of the geosynthetic material, different infill soil material and increasing depths of the foundation layer adopted for the parametric FE analysis on the geocell-supported embankment via GEOFEM. The study indicates that foundation depth effects the performance of geocell reinforced embankment adversely possibly because of the incremental plastic failure with the deepening of foundation layer.

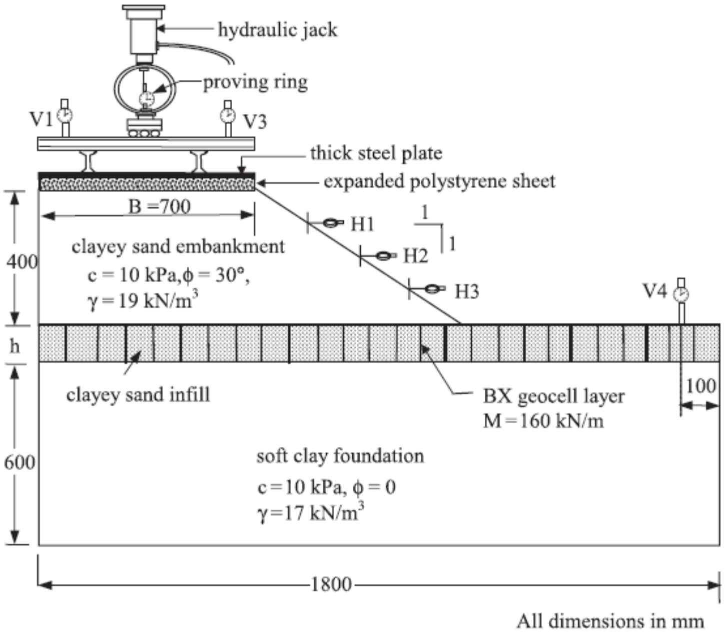


Figure 2.21. Experimental embankment adopted by (Latha and Rajagopal, 2007)

Wang et al. (2009) proposed a method in order to solve sinkhole problems encountered in highway projects. The method relies on a geosynthetic layer placed over the drilled shaft walls to support the highway embankment. A case sample that represents the model geometry that possesses the typical material properties was adopted and investigated numerically with analyses including settlement, geosynthetic layer tension and the total axial force in the shafts using FLAC^{2D}. Also, surface and base settlements of the embankment were calculated. The study indicates that the spacing of the shaft walls has an obvious impact on the embankment performance. The geosynthetic stiffness has a more dominant role on the settlement behaviour at the embankment base in comparison with the surface.

Yoo & Kim (2009) carried out a study on an axisymmetric unit cell model, a three-dimensional model and a full 3D model. Three different FEM approaches were compared for modelling reinforced soft grounds with geosynthetic-encased stone columns (GESC) (Figure 2.22) within the study. The geosynthetic encasement's contribution on the stone column performance constructed in a soft ground under an embankment load was investigated in light of the result gathered from the analysis. The study revealed that for modelling GESC in rapid embankment construction, the 3D column modelling and the axisymmetric unit cell approaches are convenient. The maximum lateral deformation of the stone column appeared to be occurring underside the stone column. Thus, fully encasing is necessary to achieve the ultimate benefit.

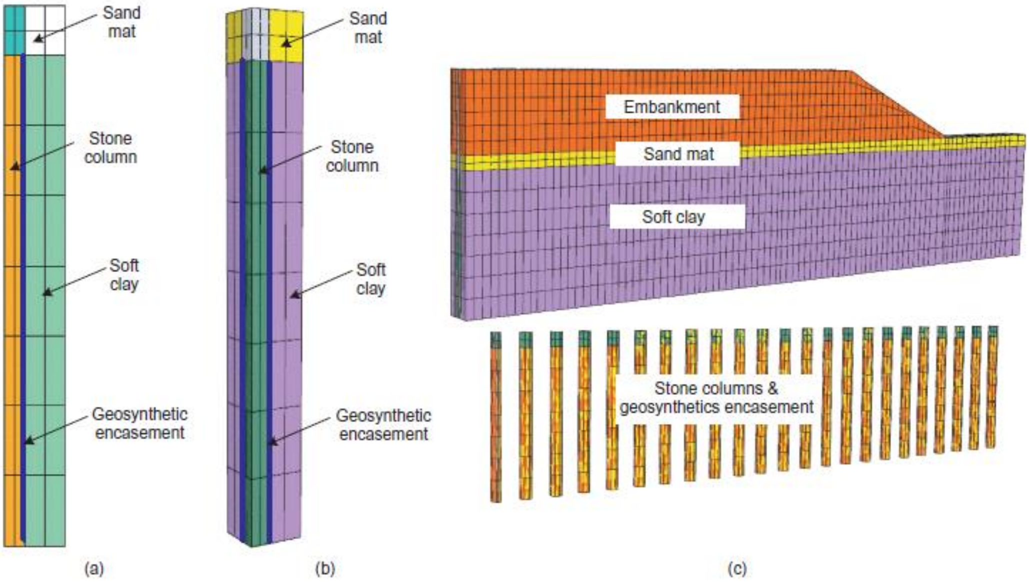


Figure 2.22. FEM considering: a. axisymmetric unit cell, b. 3D column and c. equivalent full 3D (Yoo and Kim, 2009)

Khabbazian et al. (2010) performed 3D FE analysis on a simulated model to investigate the deformation behaviour of a singular granular column (ordinary and encased) in a soft deposit to investigate the influence of geosynthetic material's strength, the angle of friction and the angle of dilation of the granular material and the effective length of encasement by using ABAQUS software. The results indicate that the ultimate load carrying capacity and the stress-settlement behaviour of stone columns can be signally enhanced by encasing them and the tensile strength of the encasing material has a major effect. According to the study, the optimum encasement length appears to be a function of the affecting stress on partially encased columns.

Yoo (2010) presented the findings of a numerical study conducted on a 3D FE model in which a soft ground under an embankment load was reinforced by geosynthetic encased stone columns (GESCs). The FE model was created using ABAQUS (Figure 2.23). Parametric analyses were carried out on the stability of the composite ground concerning the length of encasement, encasing material stiffness, the replacement ratio and the fill material. The results indicate that the strength of the stone column increased by geosynthetic encasement and the overall settlement reduced with the decrease of load transferred to the soft ground. The study also reveals that geosynthetic encasement has a more appreciable influence on cases with wider stone columns and weaker soils.

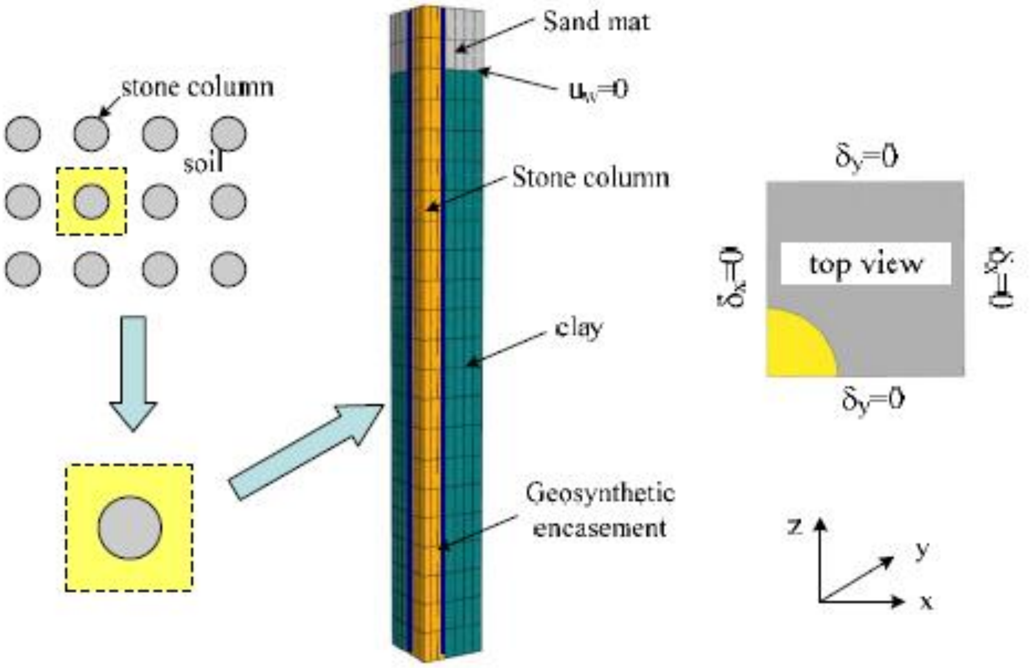


Figure 2.23. 3D column model adopted by (Yoo, 2010)

Lo et al. (2010) conducted a series of numerical experiments on the performance of GESC built in soft ground. The study implies that the usage of geosynthetic encasement can obviously improve the stone column performance in soft clay thus validates former studies.

Choobbasti & Pichka (2012) carried out numerical analyses on a GESC reinforced soft clay bed. FE analyses were conducted using PLAXIS software to evaluate the reinforced ground stiffness for settlement estimation. The results shown that the stiffness improvement of the ESC is not only due to the confinement effect after loading, it also contributes during stone column installation process.

Kaliakin et al. (2012) conducted a series of 3D FE analyses in order to understand the individual geosynthetic encased stone column’s behaviour in soft clay (Figure 2.24). The behaviour of both dense and loose granular column materials within the encasement were compared by performing parametric analyses. Different constitutive models (overall, hyperbolic, elastoplastic and elastic models) were used at the analysis conducted using ABAQUS software within the study to provide useful insight for future researches.

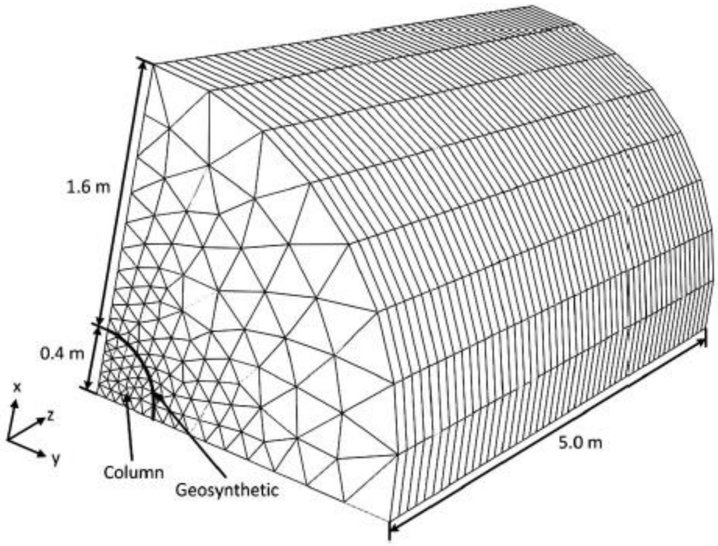


Figure 2.24. FE mesh used at (Kaliakin et al., 2012)

Zhang et al. (2012) proposed a theoretical solution for the GESC reinforced soft foundation’s consolidation calculation. The strains of the column and the soft ground were adopted from former studies and both the vertical and horizontal flows have been taken in consideration. The contribution of geosynthetic encasement on the consolidation of composite ground was analysed and the results shown that the additional confinement of the encasement has an obvious effect on consolidation acceleration in the elastic phase.

Almeida et al. (2013) conducted a two-dimensional FEA with PLAXIS software to investigate the performance of a soft deposit under an embankment load which has been reinforced by geosynthetic-encased stone columns. Parametric studies were conducted with various tensile stiffness of encasement and for different soft soil layer thicknesses for a set of column and soft ground parameters. The study shown that the settlement reduction of geosynthetic encasement is more apparent in shallow soft grounds.

Elsawy (2013) carried out a consolidation analysis to investigate the long-term behaviour of ordinary and geogrid encased stone column reinforced Bremerhaven clay under an embankment load. The study confirmed that stone column improves the ultimate load carrying capacity of soft ground and accelerate the pore water dissipation. According to the study, the stress concentration caused by the geotextile encasement increases this effect. Moreover, it also contributes obviously to the soil consolidation acceleration.

Nagy (2013) used ABAQUS program to perform FE analysis to investigate the performance of GESC supported soft grounds under different conditions and various parameters including the column size, the stiffness of encasing material and shear strength of the soft ground. The results ratify the confinement effect provided by the encasement causes stiffer columns thus leading stone column to bear higher vertical loads.

Wu & Hong (2014) proposed a method of estimation for the bearing capacity of geosynthetic encased granular columns. According to this simplified approach, an empirical correlation was employed between the expansion rate and deviatoric stress of infill material in order to calculate the lateral expansion of deformed encased columns. A simple relationship between the excessive confinement pressure and encasement stiffness/column diameter ratio can be obtained through the constant volume assumption hence stiffness of encasing material and diameter of the column are the only needed information. Results acquired from the proposed estimation approach were validated with those gathered from former experiments and found compatible.

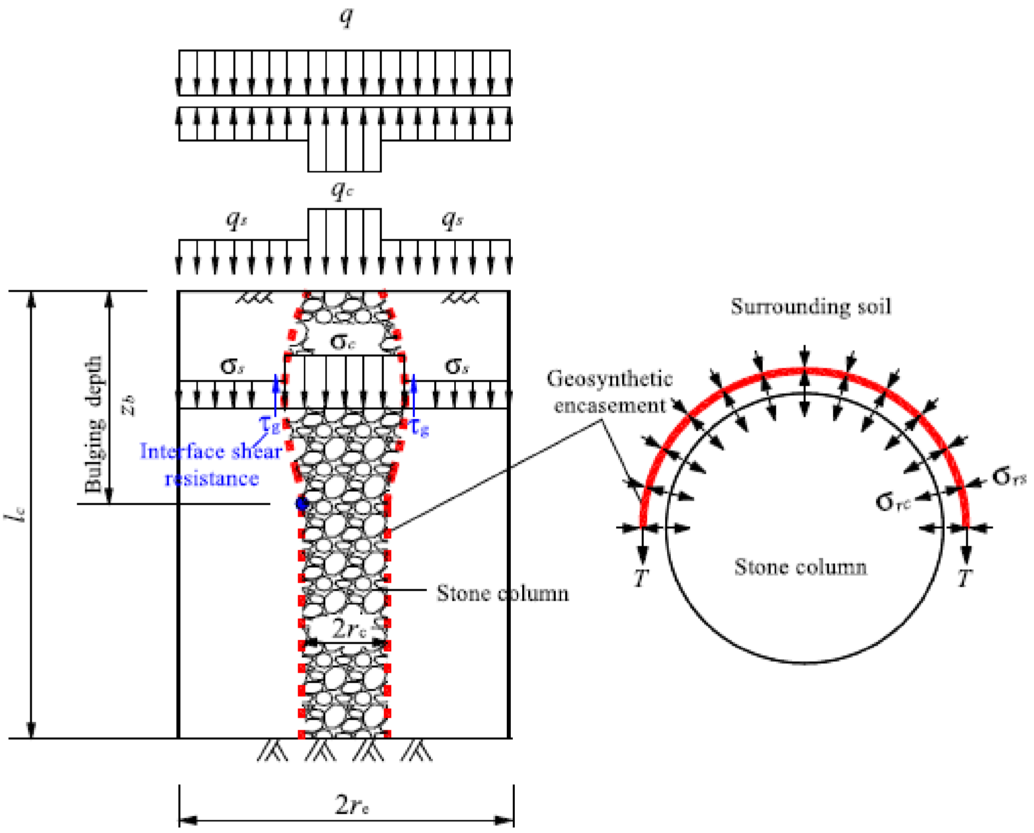


Figure 2.25. Considered model of GESC (Zhang and Zhao, 2014)

Zhang & Zhao (2014) proposed an analytical method to foresee the deformation behaviour of an individual GESC at any depth. The confining stress was stated with the passive earth pressure in the ground and the shear stress between the GESC and the surrounding soil was also considered (Figure 2.25). In order to observe the influences on deformation behaviour, parametric analyses were carried out on geosynthetic encasement stiffness, column diameter and column spacing. The results shown that with an increase in stiffness values, the contribution of the encasement on settlement and bulging reduction rises. Moreover, it was indicated that column diameter and spacing should be taken into the account while selecting the stiffness of geosynthetic material considering they have obvious effect on settlement reduction.

Khabbazian et al. (2015) carried out an axisymmetric unit cell, a three-dimensional unit-cell and a full 3D analyses of a hypothetical embankment supported by geogrid reinforced columns in order to investigate how valid the unit-cell concept is. Study reveals that a three-dimensional idealization is essential to determine the tension forces more precisely. Still, results show that design parameters such as the maximum settlement of the foundation ground, the average vertical stresses and the lateral expansion of the geosynthetic encased column can be estimated via unit-cell analyses.

Tang et al. (2015) conducted 3D FE analyses to examine the settlement behaviour of a slightly sloped saturated sand strata using GESC. Design parameters effecting lateral ground deformation such as the permeability and the tensile strength of geosynthetic material, the encased stone column’s diameter and the loading characteristics were investigated. The study confirms that geosynthetic encasement reduces lateral deformation and composite grounds stiffness enhances significantly as the stiffness of geosynthetic increase by a gradually decreasing efficiency. The results shown that the larger embankment load produce remarkably less displacements and nearly no plastic deformation.

Tandel et al. (2015) performed numerical analyses on a simulated group of reinforced granular columns considering the reinforcement length, stiffness and the area replacement ratio. The contribution of the geotextile reinforcement was evaluated in terms of bearing ratio, settlement ratio, stress concentration factor and lateral deformations. The study implies that area replacement ratio and geosynthetic stiffness are the dominant parameters for maximizing the performance of the reinforced stone column.

Yoo (2015) focused on a fully coupled 3D FE model which can reflect the soil-geosynthetic-pore pressure interaction realistically and carried out a parametric study with ABAQUS on primary parameters such as the layer thickness and stability of soft soil, the length and strength of the encasement, the area replacement ratio and the height of embankment fill (Figure 2.26). The study implies that, fully encasing the stone column is essential in order to minimize the settlements. Additionally, design charts for estimating the maximum settlement and SCR during preliminary design were given based on the results.

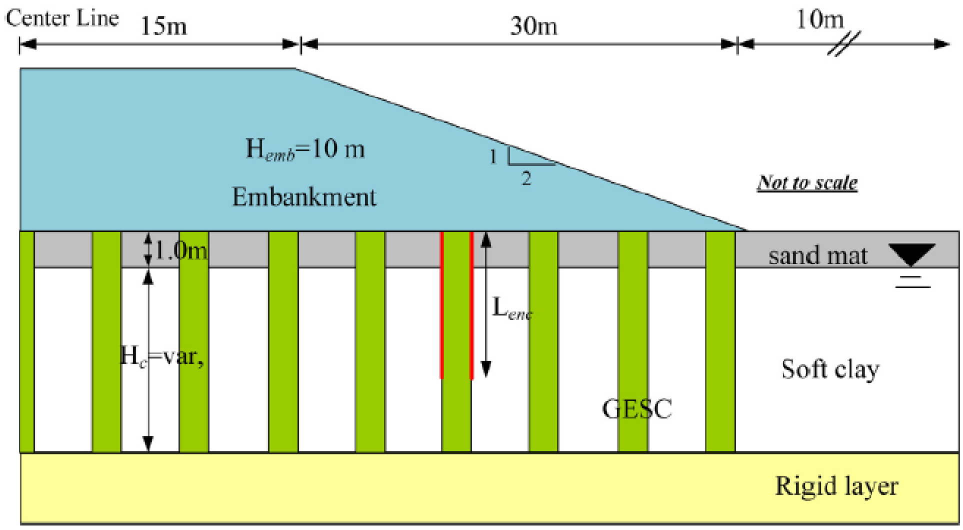


Figure 2.26. Cross-sectional view of GESC installed in a soft clay ground (Yoo, 2015)

Kahyaoğlu (2017) presented a two-dimensional FE analyses on a GRSM and a GESC in order to investigate the results of additional confinement effect of the geosynthetic reinforcement and encasement on the vertical deformation of stone columns and soft ground. Also, parallel analyses were conducted on unreinforced embankment to compare with the performance of the basal reinforced embankment. Moreover, parametric analyses were carried out to determine the influence of stiffer geosynthetic material on the settlement behaviour of the composite ground. The study approves former studies that encasement has an obvious improvement effect on the stress-settlement behaviour of stone column. Additionally, results imply that with basal reinforcement the settlement on the surface of the soft soil reduces significantly but the reinforcement material's tensile strength does no significant contribution to the settlement behaviour of GESC.

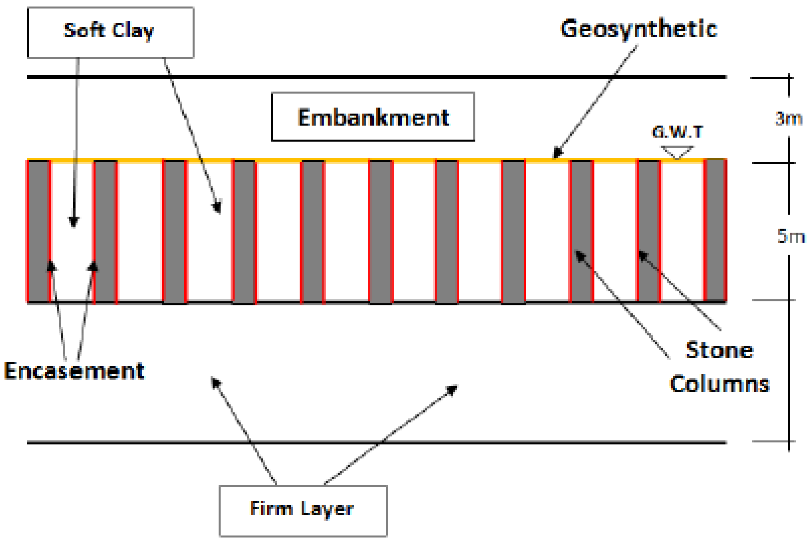


Figure 2.27. Cross-sectional view of GEC reinforced embankment (Kahyaoğlu, 2017)

Rajesh (2017) conducted numerical analyses with PLAXIS to investigate the influence of encasement length and the column length on the deformation behaviour of GESC and to compare the performances of geosynthetic encasements with different stiffness values (Figure 2.27). The study focuses on time-dependent behaviour of end bearing and floating GESC. Results show that encasing stone columns with a geosynthetic material tends to a remarkable settlement and lateral deformation reduction and speeds up the of excess pore water pressure reduction.

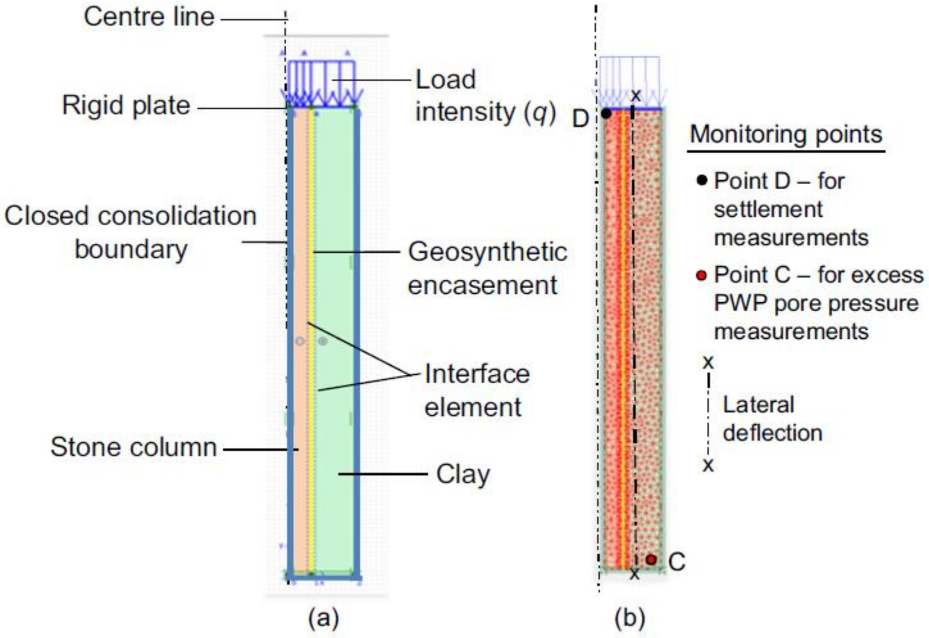
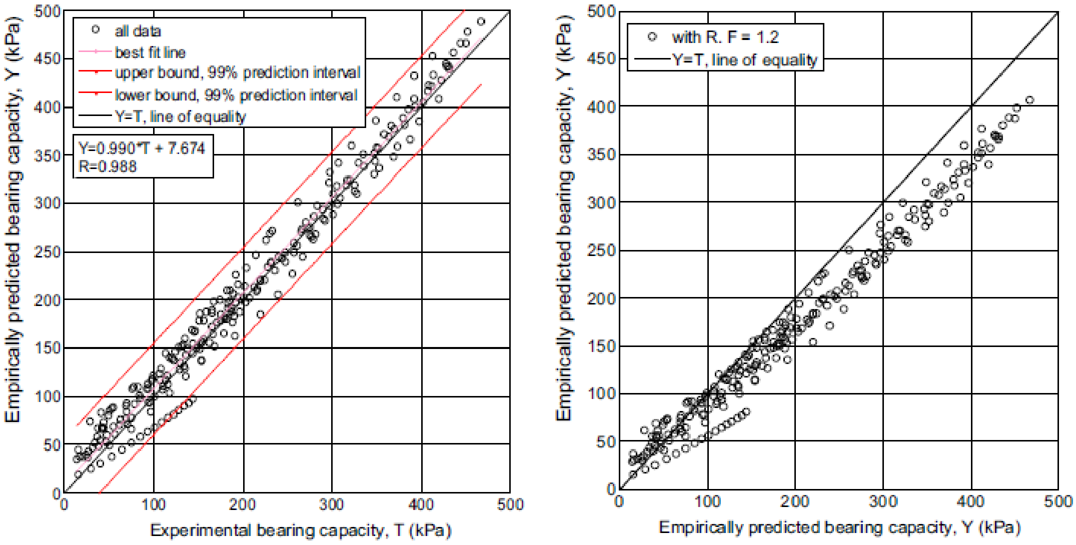


Figure 2.28. a. Axisymmetric unit cell in PLAXIS, b. FE mesh model (Rajesh, 2017)

Kadhim et al. (2018) carried out 3D finite element analyses in FLAC^{3D} in means of evaluating the effectiveness of geotextile-encased stone column in terms of various parameters including geosynthetic encased stone column (GESC) length and diameter, ground thickness, encasement length and stiffness, angle of friction and angle of dilation of the infill material. The results shown that the geotextile encasement had an obvious contribution on the performance of the GESC and higher geotextile stiffness increases the contribution. Additionally, GESC with larger diameter experienced more vertical and lateral deformation by comparison to smaller ones. Also, the optimum encasement length depends upon the load effecting on the column.



(a) Without R.F

(b) With R.F =1.2

Figure 2.29. a. Experimental bearing capacity, b. empirically predicted bearing capacity by (Debnath and Dey, 2019)

Debnath & Dey (2019) presents an empirical design chart for ultimate load capacity of ordinary and geogrid-reinforced sand bed over a soft clay deposit improved with a group of floating VESCs (Figure 2.28). The bearing capacity values were predicted using four different models based on 245 different experimental databases. Among these namely exponential radial basis kernel function (ERBF), radial basis kernel function (RBF), polynomial kernel function (POLY) three support vector regression (SVR) and an adaptive neuro-fuzzy inference system (ANFIS); SVR-ERBF model outperformed others in learning and predicting the bearing capacity. The study suggests an empirical equation and presents a design chart to predict bearing capacity for practical application purposes.

Kahyaoğlu & Vaníček (2019) presented the results of a three-dimensional FE analyses on a hypothetical base-reinforced embankment supported by encased floating columns installed in soft ground (Figure 2.29). The effect of the tensile strength of vertical encasement and basal reinforcement materials, the embankment fill height and effective length of the encasement were investigated by parametric studies and results were evaluated with comparative graphics. Results shown that the basal geogrid reinforcement stiffness increment promotes settlement reduction but after a certain point contribution becomes insignificant. Similarly, encasement stiffness increment results a decrease in bulging but after a certain point influence becomes insignificant. Additionally, the study reveals that embankment height is effective factor on both the columns and the soft ground.

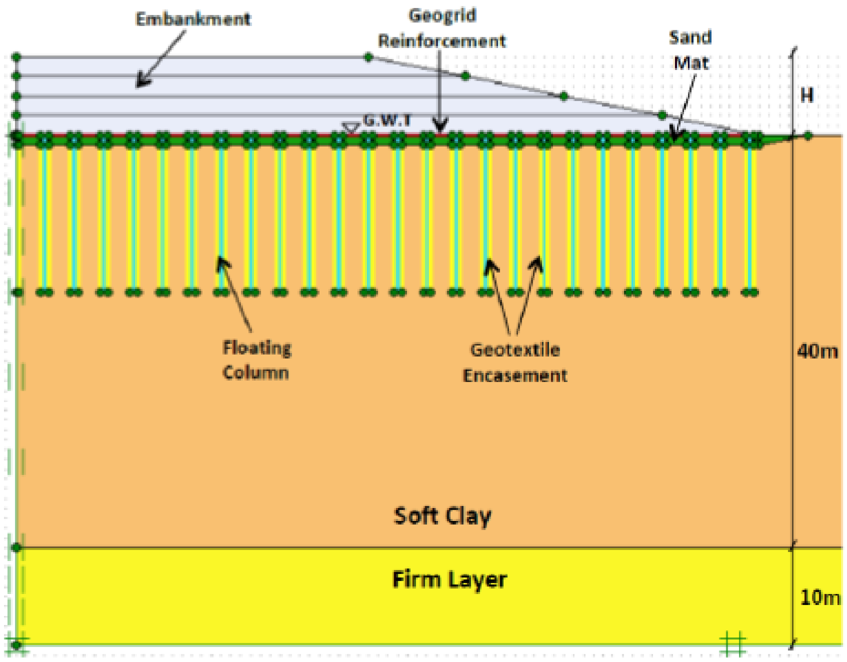


Figure 2.30. Cross-section of the geometry model at (Kahyaoğlu and Vaníček, 2019)

Xue et al. (2019) performed a set of scaled triaxial loading tests on OSC and GESC. Different stone columns encased with varying types of geotextiles and with various diameters were subjected to increasing values of different confining pressures. The influence of the encasement on the strength of the stone column was explained by the increase of cohesion or incremental confining pressure. Also, the study suggests a modified hyperbolic model to define the stress-strain relationship of GESC.

3. METHODS OF THE STUDY

3.1. Numerical Analyses

By the beginning of the 2000's, numerical analyses using either finite element or finite difference methods have been frequently employed to understand the behaviour of the GEC system. They can simulate the interaction mechanisms between soil and geosynthetic material by adopting the stress-strain coupled formulation with reasonable accuracy (Figure 3.1). Numerical analyses, especially adopting the finite element method, provide a more fundamental understanding of GEC behaviour through parametric analyses to evaluate the effect of the input parameters, which were mostly verified with experimental investigations.

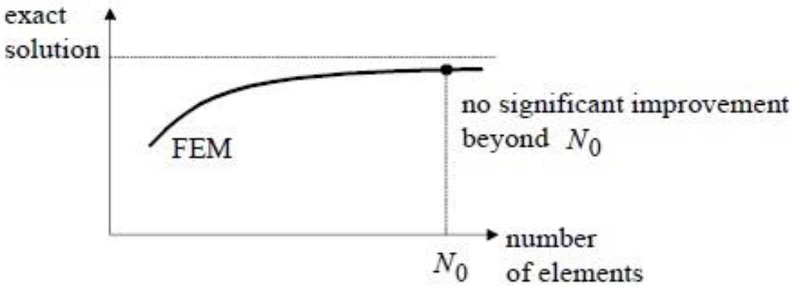


Figure 3.1. Convergence in results

3.1.1. History of FEM

Because of the soil has a complex structure and there are many parameters that effect the soil behaviour; various acceptances are being made to make the interpret of the behaviour possible. Several methods are used to determine the behaviour of soils under load and unloaded (Figure 3.2). The theoretical solutions and empirical formulas developed in this context are far from obtaining the desired realistic results due to the complexity of the soil nature. However, all parameters affecting the behaviour of the soil should be included in the solution thus makes the problem very difficult to solve and the solution process takes time. Numerical methods have been developed to solve these problems and with the usage of the computer programs, solution is easy and quick as never before.

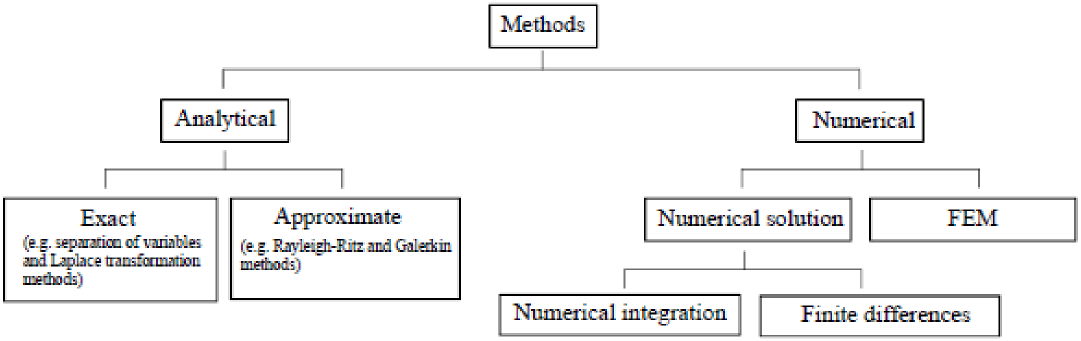


Figure 3.2. Classification of the most common methods for solving the general in-situ problems (Barkanov, 2001)

In recent years numerical modelling studies have found wide application areas especially in engineering studies. Numerical methods can be examined in two main groups as differential methods and integral methods. In addition, hybrid method and distinct element methods are also being used. One of these methods is the finite elements method which is one of the differential methods. Realistic stress and deformation values in different load and material properties can be obtained by using finite elements methods (Selçuk, 2009).

Being primarily developed for continuum mechanics and structural engineering applications in 1950's, the finite element method (FEM) is being applied to problems encountered by geotechnical engineers since 1960's. It is difficult to quote a date of the invention of FEM but the origins can be seen in the work of Euler in the 16th century. While it can be traced back to mathematical papers of Schelback (1851) and Courant (1943), it was reclaimed by engineers to solve aerospace and civil engineering problems on structural mechanics. The technique which now widely being used by geotechnical engineers appeared with the name finite element method at plane stress analysis in a paper by Turner et al. (1956). Followed by Argyris (1957) and Babuska & Aziz (1972).

After great number of researches have been made and lots of research papers have been published, the FEM is now well accepted as an engineering tool with a wide applicability. FEM is used in various assertive applications such as thermo-mechanical problems, biomechanics and biomedical engineering, fluid-structure interaction, electromagnetics and geotechnical engineering. The most important advantage of this method is the applicability on both materials that show non-linear and linear stress-strain behaviour.

3.1.2. Finite Elements Method

The FEM is the most widely used numerical technique for solving the engineering problems. Problems which can be described by a partial differential equation creates the subject of FEM. A large system of interest is subdivided into smaller parts called finite elements. The discretized formulation of the continuous physical problem ends up in a set of algebraic equations. FEM approximates the desired function over discretized domain. The simplified equations are then reunified into one large equation that defines the entire problem (Nikishkov, 2010).

Two advantages of the finite element method are worth to be mentioned;

- Partial approximation of FEM works precisely even on simple function approximations thus any required precision can be ensured by increasing the number of elements.
- The localness in approximating function of FEM causes fewer equations for a discretized system. This leads us solving equations with lots of nodal unknowns.

Main steps of the finite element solution procedure can be summarized in general terms and listed as below (Nikishkov, 2010).

- Dividing the continuous problem: The first step is to discretize the domain of interest into finite elements. The finite element mesh -which can be defined by elemental connections and coordinates of nodes- is created by a pre-processor program (Figure 3.3).

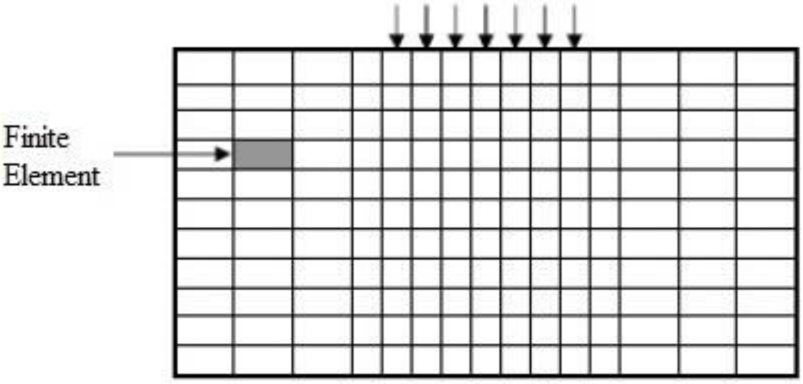


Figure 3.3. Discretization of a continuous system to finite elements

- Selecting the functions of interpolation: Usually polynomials are preferred for interpolating the variables over the elemental connection and the number of assigned nodes determines the degree of the polynomial (Figure 3.4).

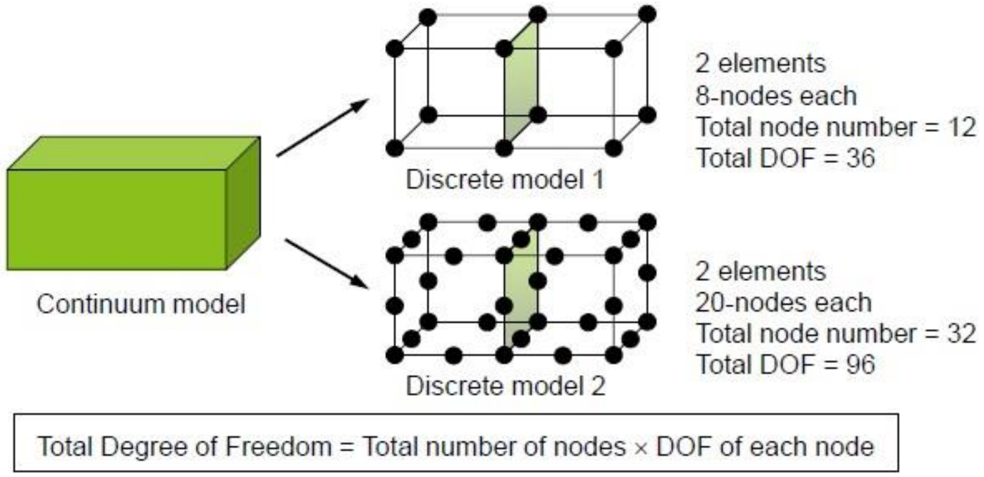


Figure 3.4. The degree of the polynomial

- Finding the properties of the elements: Different approaches -preferably variational approach and the Galerkin method- can be used to build a matrix equation to tie up the nodal values to other parameters.
- Assembling the discrete equations: After implementing the boundary conditions -which were not considered in elemental equations- all discrete elemental equations should be assembled in order to find the global equation. Elemental connectivities for the whole solution region are used for the combination process.
- Solving the global equation system: Since the FE equation system possess symmetric, positive definite and sparse characteristic, the solution requires less storage and computing time. Direct solution methods can be used for moderate sized problems and iterative methods are preferable for larger problems due to less computing time requirement. Desired functions nodal values at the domain of interest are obtained as the result of the solution.
- Computing for additional results: After solving the global equation system, additional parameters can be calculated. For example, beside the displacements, stress and strains can be needed in mechanical problems.

Generally, while solving the problems of geotechnical engineering with finite element method, operations are performed based on displacement (stiffness) method (Demir, 2011).

3.2. PLAXIS 2D FE Analysis Program

Computers are now being used to solve the systems created using finite element method. Some engineers write computer programs using software languages to make specific solutions to their problems and there are companies which have created ready-made computer programs for the wider usage purpose. Programs like ANSYS, ABAQUS, PLAXIS and MIDAS etc. are commonly used examples. In geotechnical engineering; stresses, lateral and vertical deformations, pore water pressures and groundwater flow, consolidation ratio etc. can be determined using FEA computer programs (Figure 3.5).

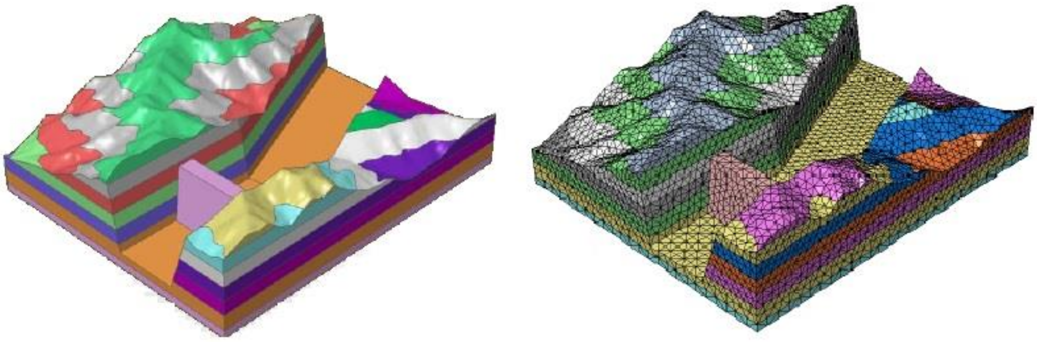


Figure 3.5. Modelling with computer programs using FEM

This study discusses the deformation behaviour of geotextile encased stone columns. Numerical analysis on ordinary and encased stone column systems were carried out using PLAXIS 8.6 computer program. PLAXIS is a finite element analysis program which was originated to assist users to solve the geotechnical engineering problems.

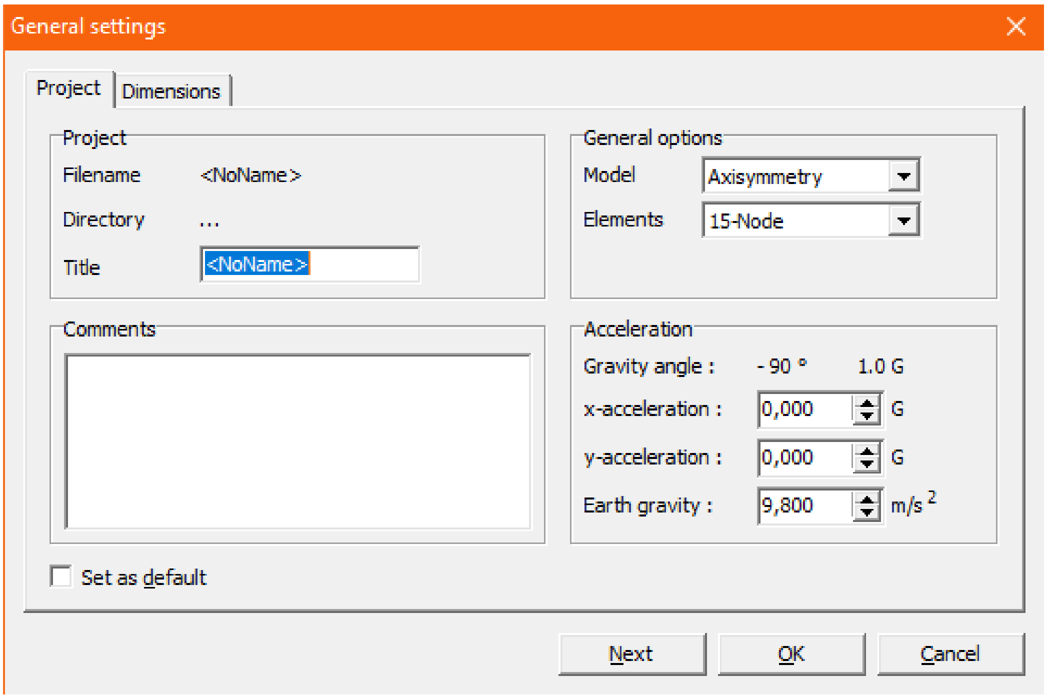
PLAXIS was created by Delft Technical University in 1987 for the use of Dutch Department of Public Works and Water Management. The main objective was to create a user friendly 2D FE program to be used at river embankments built on soft soil in Holland’s low lands. Within years, usage of PLAXIS became widespread almost all possible areas of geotechnical engineering.

Since soil is a multi-phase material, more sophisticated models are necessary to overcome the pore pressure impact and to simulate the time-dependent and non-linear behaviour of soils. PLAXIS is a 2D FE software most especially designed to accomplish stability and deformation analysis for geotechnical projects. An accurate simulation of real situation can be achieved with a detailed definition of soil layers, materials and loading conditions and an appropriate drawing (CAD) of model. Either axisymmetric model or plane strain model can be used to simulate the real situation and a finite element mesh will be automatically generated from created geometry model.

PLAXIS user interface consists of four sub-programs namely as Input, Calculation, Output and Curves, respective to the process order. A brief introduction of the sub-programs will be given in the following section.

3.2.1. Input Sub-Program

The input sub-program includes all tools to create or modify the geometry of the model, to generate the convenient type of FE mesh and to effectuate the initial conditions.



Project
Filename <NoName>
Directory ...
Title <NoName>

Comments

General options
Model Axisymmetry
Elements 15-Node

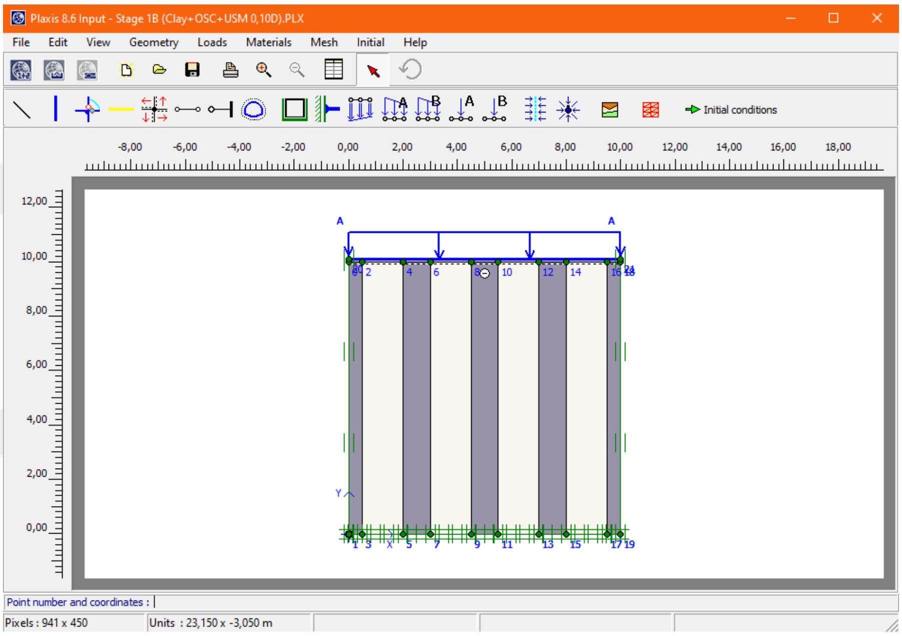
Acceleration
Gravity angle : - 90 ° 1.0 G
x-acceleration : 0,000 G
y-acceleration : 0,000 G
Earth gravity : 9,800 m/s^2

☐ Set as default

Figure 3.6. A view of the general settings menu of PLAXIS

Project title and comments, model geometry type and gravitational acceleration data are defined through the project tab and units, workspace geometry and grids are defined through the dimensions tab in general settings window (Figure 3.6). Either plain strain or axisymmetric FE models can be carried out by PLAXIS. Program uses triangular elements to create soil and other cluster materials, either 6-noded or 15-noded triangular elements can be chosen.

Model can be created by using the premade materials such as plate, geogrid, anchor, tunnel, drain, well and interface element or by the geometry line section through the "Geometry" tab (Figure 3.7).



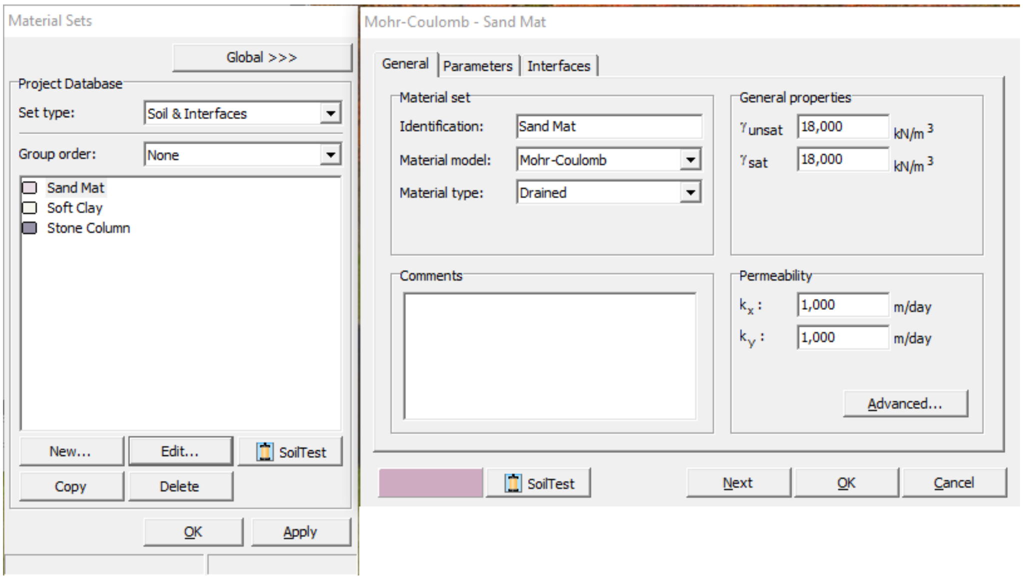
Point number and coordinates :

Pixels : 941 x 450

Units : 23,150 x -3,050 m

Figure 3.7. A general view of the input sub-program of PLAXIS

Soil and interface elements, plates, geogrids and anchor elements are defined through the materials tab (Figure 3.8). Various material models such as Mohr-Coulomb (MC) model, jointed rock (JR) model, hardening soil (HS) model, hardening soil small (HS-Small) model, soft soil (SS) model, soft soil creep (SSC) model and modified cam-clay (MCC) model are supported by PLAXIS. Various soil elements with different properties and strength parameters can be defined at "Soil" section. "Plate" section can be used to simulate loading plates, pile, wall and shell elements. Geosynthetic reinforcement elements with different strength parameters can be defined at the "Geogrid" section. After the model is created and materials are defined, data sets can be assigned by dragging and dropping or double clicking the desired clusters or objects.



Set type: Soil & Interfaces

Group order: None

☐ Sand Mat
☐ Soft Clay
▨ Stone Column

Identification: Sand Mat

Material model: Mohr-Coulomb

Material type: Drained

γ_{unsat} 18,000 kN/m^3

γ_{sat} 18,000 kN/m^3

k_x : 1,000 m/day

k_y : 1,000 m/day

Figure 3.8. A view of the material sets window of PLAXIS

Point and distributed loads or prescribed displacements can be defined through the “Loads” tab and can be assigned by clicking or keyboard input. Also, vertical, horizontal or standard fixities (zero prescribed displacements) and boundary conditions can be applied to geometry lines and points through the same tab.

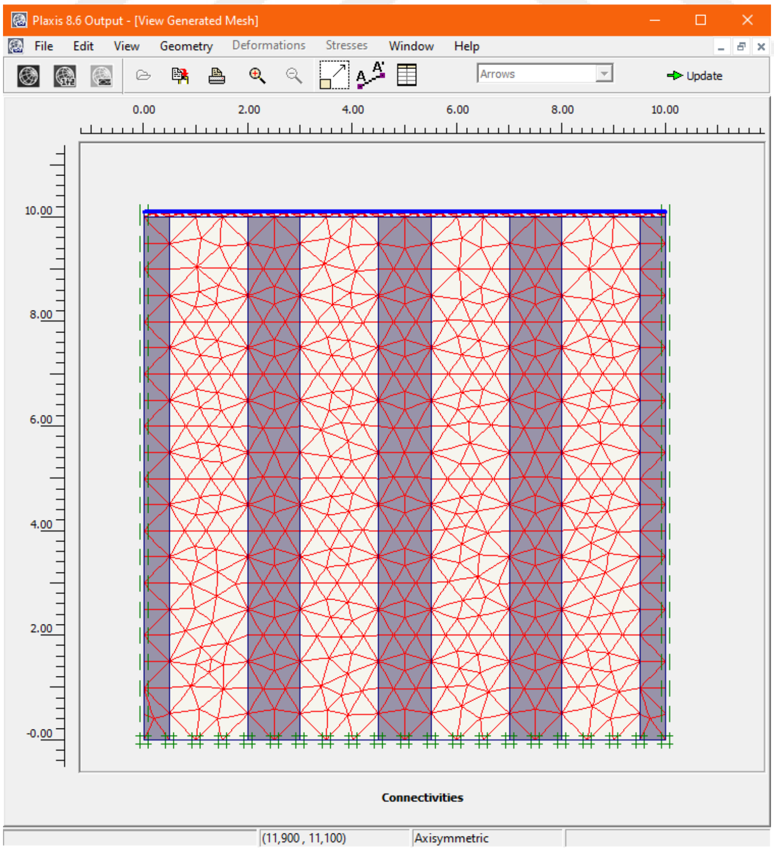
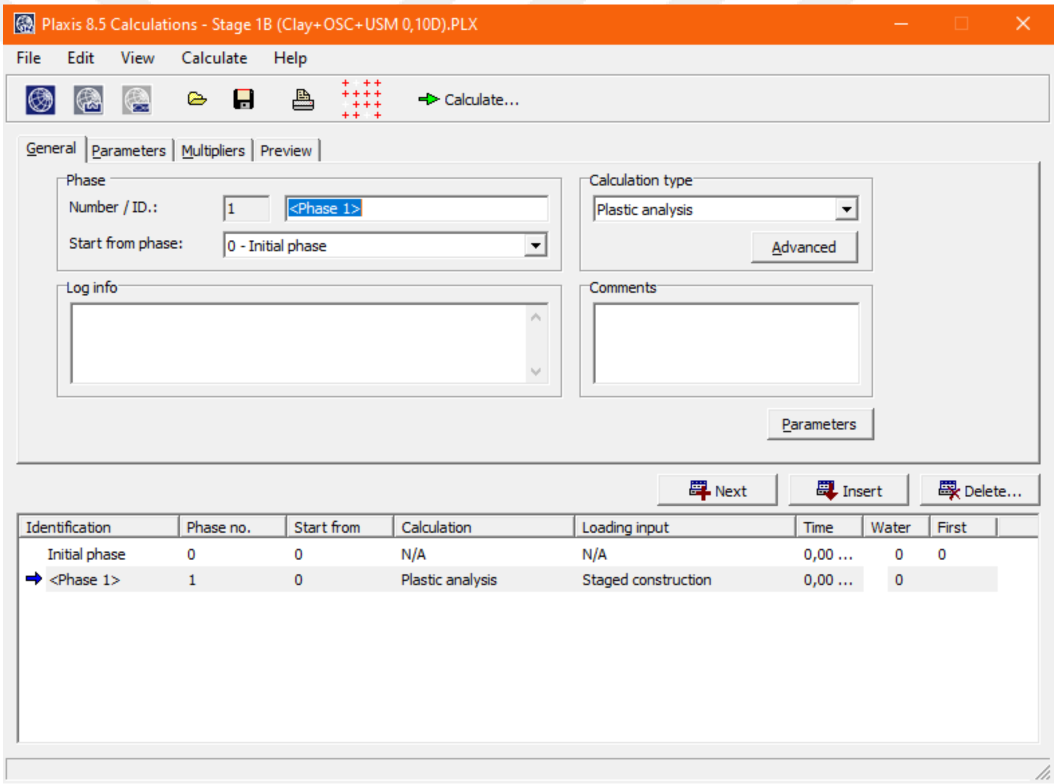


Figure 3.9. A view of FE mesh generation of PLAXIS

When the geometric model is fully created and material properties were assigned, a mesh is generated to perform finite elements calculations through the “Mesh” tab (Figure 3.9). Then initial conditions (stresses and pore water pressures) are initiated through the “Initial” tab.

3.2.2. Calculations Sub-Program

Three types of calculations (plastic calculation, consolidation analysis and phi-c reduction) are available in PLAXIS. Additionally, dynamic calculation can be carried out with the optional dynamic module of PLAXIS. The calculation types can be selected from “General” tab of calculations sub-program (Figure 3.10).



Number / ID.: 1 <Phase 1>

Start from phase: 0 - Initial phase

Calculation type: Plastic analysis

Identification	Phase no.	Start from	Calculation	Loading input	Time	Water	First
Initial phase	0	0	N/A	N/A	0,00 ...	0	0
<Phase 1>	1	0	Plastic analysis	Staged construction	0,00 ...	0	

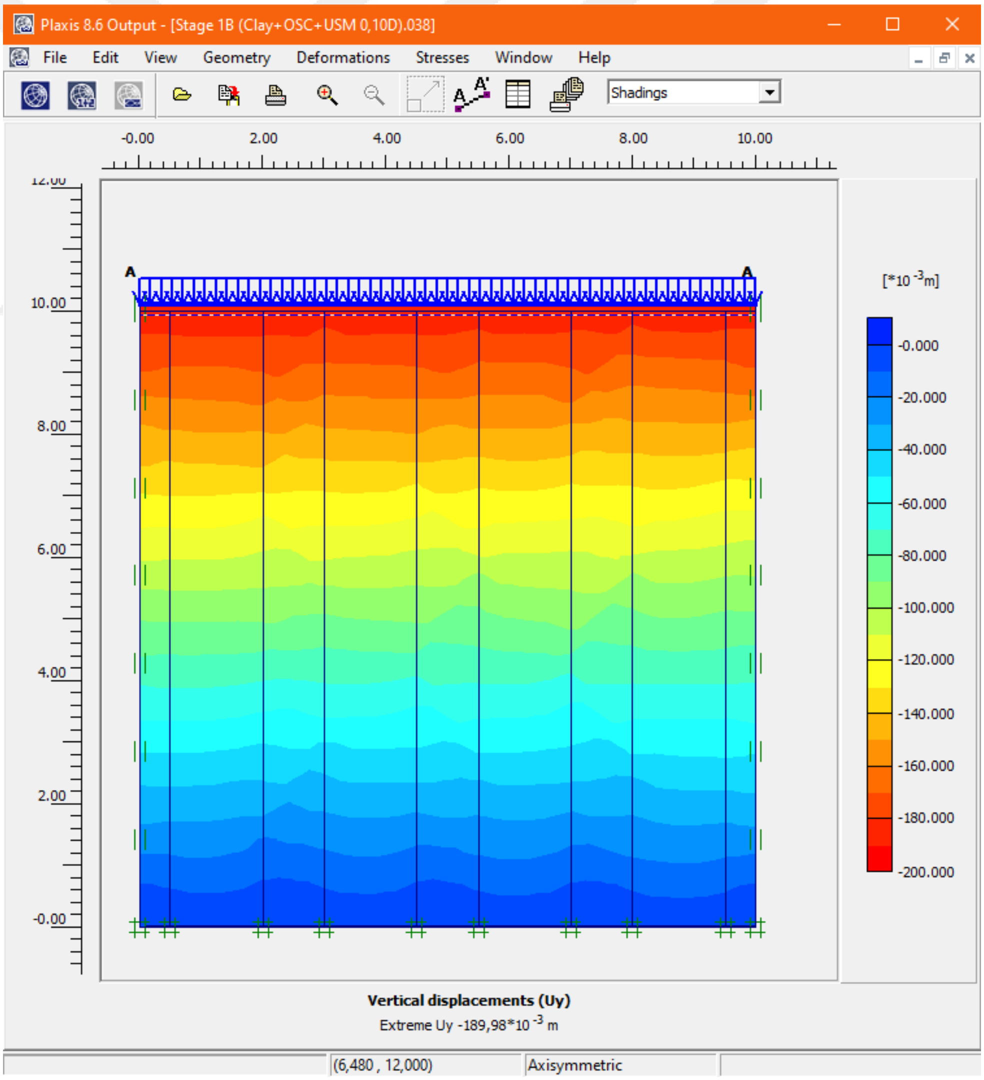
Figure 3.10. A view of the calculation sub-program of PLAXIS

Three different loading types; staged construction, total multipliers and incremental multipliers can be used at the analyses. The loading types and iterative procedures can be selected from “Parameters” tab of calculations sub-program.

After defining the calculation phases and before starting the calculation process, up to ten user desired points can be selected for generating the curves or stress paths.

3.2.3. Output Sub-Program

The deformations and the strains can be visualised from the “Deformations” section, the deformed mesh can be reached from the “Deformed Mesh” section, the vertical, horizontal and total displacements, incremental displacements, phase displacements, total strains and cartesian strains, incremental strains and cartesian strain increments can be plotted from the “Total, Vertical and Horizontal Displacements” section and effective stresses, cartesian effective stresses, total stresses, cartesian total stresses, over-consolidation ratio, plastic points, active pore pressures, excess pore pressures, groundwater head, flow field and degree of saturation can be obtained from the “Stresses” section and the output data such as deformations and stresses for plates and geogrids can be reached through the “Structures and Interfaces” section (Figure 3.11).



Vertical displacements (Uy)

Extreme Uy -189,98*10 $^{-3}$ m

(6,480 , 12,000) Axisymmetric

Figure 3.11. A general view of output sub-program of PLAXIS

3.2.4. Curves Sub-Program

The sub-program of Curves can be used to generate load/time-displacement curves and stress-strain diagrams/paths for the pre-selected points at the calculation sub-program. After the definition of calculation phase and before the calculation phase desired points may be selected to create the required curves. The points can be created from the "Select Points for Curves" option of the View menu and selected points are referred by letters according to alphabetical order (Figure 3.12). Required curves can be created by "New" option in the "File" menu of Curves sub-program.

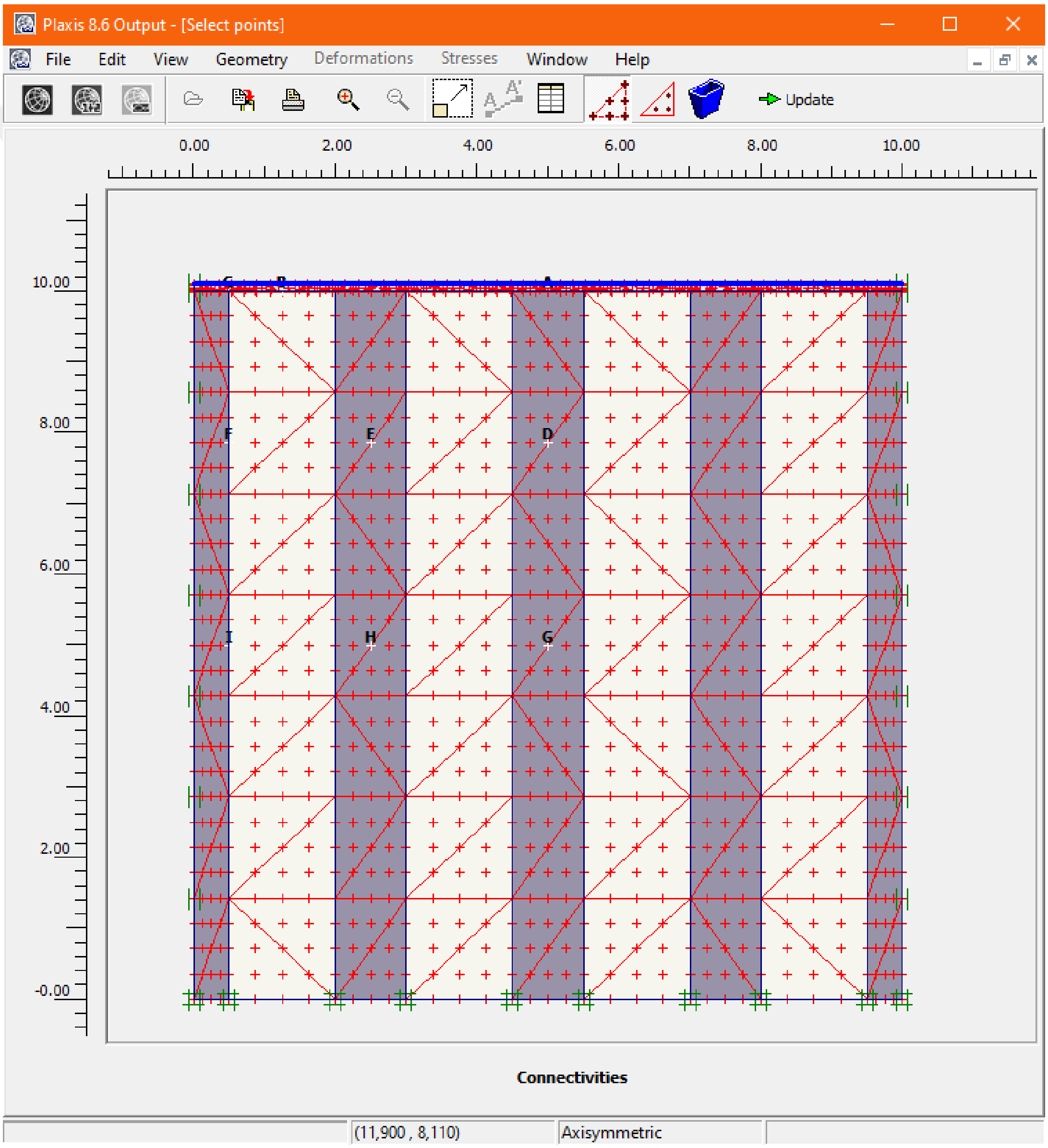


Figure 3.12. Selection of points for curve sub-program of PLAXIS

4. NUMERICAL ANALYSES

4.1. Numerical Model

Within the context of this thesis, numerical analyses were carried out to comprehend the deformation behaviour of a soft clay deposit improved with geogrid reinforced sand mat layer and geotextile encased stone columns via PLAXIS 8.6 two-dimensional finite elements analysis package program.

A hypothetical composite ground system was idealized by unit cell concept and the model was verified with 2D finite element analyses using PLAXIS, with the soft ground at former study of Raju (1997). Then, parametric studies were carried out for a various parameter including the sand mat layer thickness, geogrid reinforcements tensile strength, geotextile encasements stiffness, bearing capacity, vertical settlement and bulging behaviour of encased stone column, effective encasement length and deformation behaviour of fixed and floating encased stone column. Align with the radial symmetry of the chosen hypothetical composite ground system, axisymmetric model was used in analyses. The cross-sectional view and finite element mesh are shown in Figure 4.1.

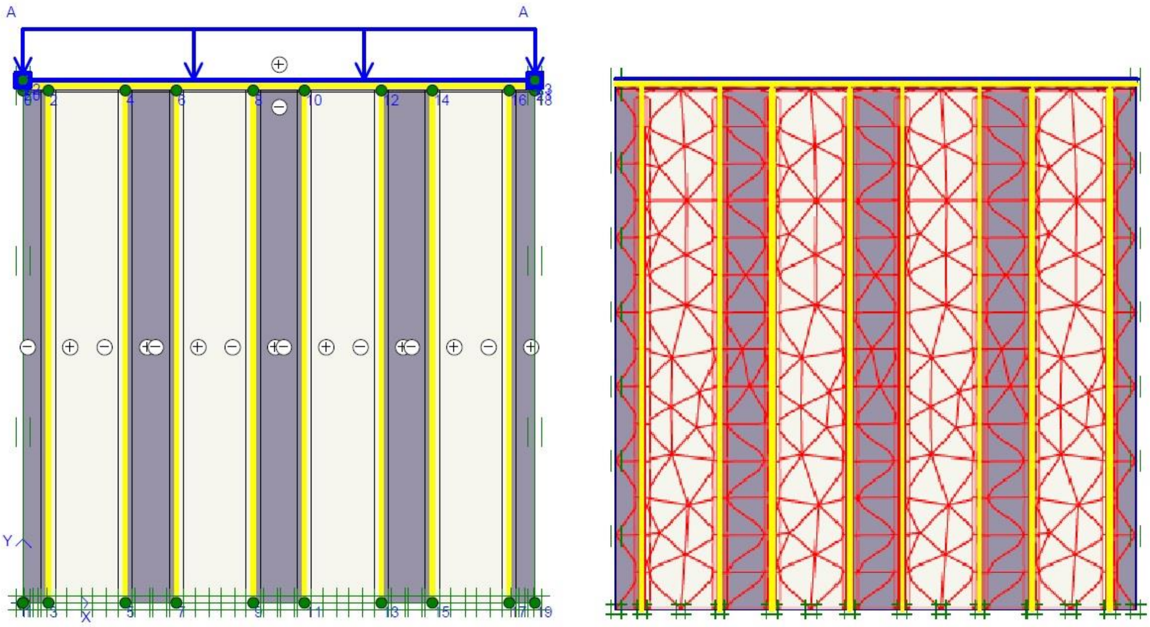


Figure 4.1. Cross-section and FE mesh of PLAXIS model

4.2. Material Properties

4.2.1. Soil Elements

In this study three types of soil materials have been used to simulate the soft soil, sand mat layer and granular column element. Known to be accurately capturing the behaviour of the soft soil between columns, Modified Cam-Clay (MCC) Model was used to simulate the soft soil in undrained condition, in line with the advice of Khabbazian et al. (2012, 2015). Stone columns and the sand may layer were modelled as granular soil according to the suggestions of Ambily & Gandhi (2007) and idealized by Mohr-Coulomb (MC) Model as a homogenous drained soil material.

Fifteen node triangular elements were used to identify the soil materials at FEM since it gives the most accurate stress results in compressible soils.

Detailed information about the soft soil, sand mat layer and granular column element are given below (Table 4.1).

Table 4.1. Material properties used in the numerical analyses

Parameter	**Column Material** ***Stone Soil*** (Ambily & Gandhi, 2007)	**Sand Mat Material** ***Sacramento River Sand*** (Kaliakin, 2012)	**Soft Clay Material** ***Bangkok Clay*** **(**Yoo, 2007)
Model Type	Mohr-Coulomb	Mohr-Coulomb	Modified Cam Clay
Eff. Unit Weight, γ' (kN/m^3)	19	18	15
Eff. Friction Angle, ϕ'(°)	43	32	-
Elastic Modulus, E (kPa)	55000	15000	-
Poisson's Ratio, υ	0.3	0.3	0.3
Eff. Cohesion, c′(kPa)	1	1	-
Permeability, k (m/s)	1x10^{-2}	1x10^{-3}	1x10^{-6}
Dilation Angle, φ'(°)	10	3	-
Slope of the Critical State Line, M	-	-	1.0
Slope of the Virgin Consolidation Line, λ	-	-	0.4
Slope of Swelling Line, K	-	-	0.02
Void Ratio at Unit Pressure, e	-	-	1.0

4.2.2. Plate Element

In order to transfer the distributed load to the soil elements uniformly, a rigid plate element acting as a load plate has been placed between the distributed load and the soil element; clay, stone column or sand mat layer according to the type of the analysis. An interface element was modelled between the soil element and the loading plate.

Table 4.2. Properties of the plate element

Parameter	
Material Type	Elastic
EA (kN/m)	1.00×10^9
EI (kNm²/m)	1.00×10^8
w (kN/m/m)	25.00
υ	0

4.2.3. Geosynthetic Elements

The geogrid reinforcement and geotextile encasement materials were modelled not to have bending stiffness; only having axial stiffness they can sustain just the tensile force. Geogrid elements of PLAXIS were used to simulate the geogrid reinforcement material in sand mat layer and the geotextile encasement material for stone columns. Since fifteen node soil materials were used in the FE model, the geosynthetic elements were defined by five nodes accordingly.

The interaction between the soft clay soil, the sand mat and geosynthetic materials were modelled using PLAXIS interface elements within the range of 0.45 to 0.80 as proposed by the program user’s manual.

Seven different geotextile encasement materials with axial stiffness (EA) values of 500, 1,000, 1,500, 2,000, 2,500, 3,000 and 3,500 kN/m and seven different geogrid reinforcement materials with axial stiffness (EA) values of 1,000, 2,000, 3,000, 4,000, 5,000, 6,000 and 7,000 kN/m are used to define geosynthetic elements.

4.2.4. Dimensions, Fixities and Boundary Conditions

In the analyses, the FE model limits were 12 m in horizontal direction and 10 m to 20 m in vertical dimension. The side boundary conditions of the axisymmetric model were shear free, with no horizontal movement and the bottom boundary was also prevented moving both horizontally and vertically.

The height of the soft clay layer adopted was 10 meters and extended up to 20 meters with 1-meter intervals in order to simulate the floating column behaviour.

Ordinary (conventional) stone columns (OSC) and vertically encased stone columns (VESC) with varying diameters of 0.60, 1.00 and 1.40 were selected and composed with varying spacing ratios of 2, 3 and 4 within the analyses.

4.2.5. Mesh Generation and Water Condition

After the geometry model creation and assignation of pre-defined material properties to all clusters and structural objects, PLAXIS’s medium mesh was chosen to disintegrate the model into finite elements which will be used to perform calculations. In zones in which stresses and strains are expected to be high -like upper part of the stone column and the surrounding soil- the FE mesh was refined.

After the FE mesh has been generated, the water table has been levelled to the soft soil surface this way external water pressures and pore pressures and were taken to be zero.

4.2.6. Model Verification

A case study by Raju (1997) in which a stone-column-supported embankment constructed in Kebun, Malaysia was adopted and simulated with PLAXIS numerically. Marine clay soil material with a CPT resistance of 0.1 to 0.3 MPa for the top 11 meters can be seen at the soil profile of the project (Table 4.1). Total settlement was read as 0.4 m on the top of the stone columns by the settlement gauges. Under same circumstances, the settlement occurred as 1 m for untreated ground.

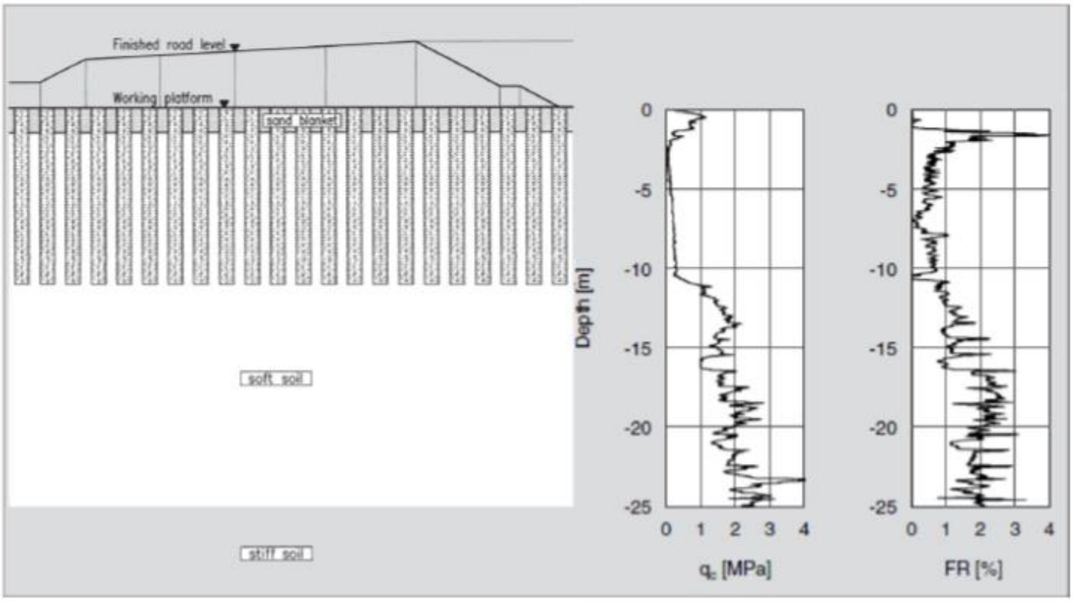


Figure 4.2. a. Schematic view, b. Tip resistance with depth and c. Friction ratio with depth (Raju, 1997)

The settlement results and the vertical stress transferred to both the stone column and the soft soil obtained from the numeric study were compared with those measured at the Kebun project (Figure 4.2). The results appear to be overlapping and the coherence between two results makes the simulated model convenient to use at the parametric studies.

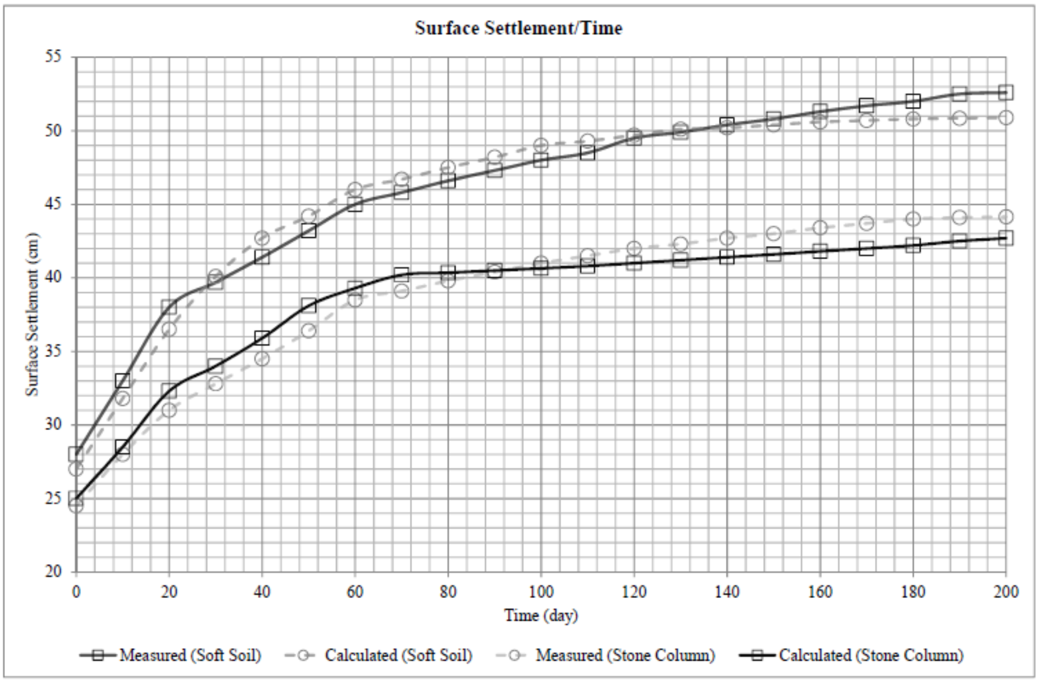


Figure 4.3. Comparison of measured vs. calculated settlements of soft soil and stone column

4.3. Numerical Analysis and Parametric Study

4.3.1. Numerical Analysis

Firstly, in order to choose the most suitable column profile to be used in analyses, column diameter (D) was pre-selected as 0.60 meters and relative settlement diagram was drawn for increasing load for both drained and undrained conditions. Bearing capacity corresponding to relative settlement of 20% column diameter value was determined as 165 kPa (Figure 4.4). Relative settlement can be described as the ratio of the settlements between the top of stone column and soft clay layer. Obtained load of 165 kPa was decided to be used at further analyses.

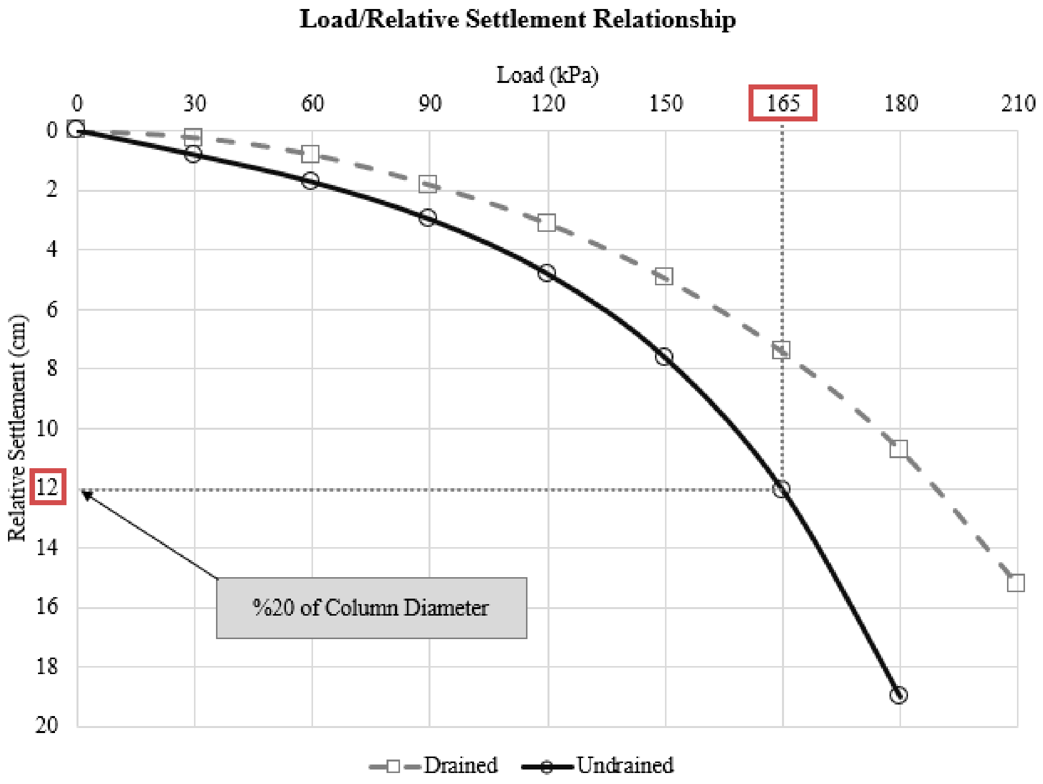


Figure 4.4. Load - relative settlement relationship

Then stone column variations of 0.60 m, 1.00 m and 1.40 m diameters (D) and 2, 3 and 4 spacing ratios (s/D) have been subjected to 165 kPa for both drained and undrained conditions, lateral deformation-depth diagrams were drawn and maximum bulging values were noted (Figures 4.5, 4.6 and 4.7).

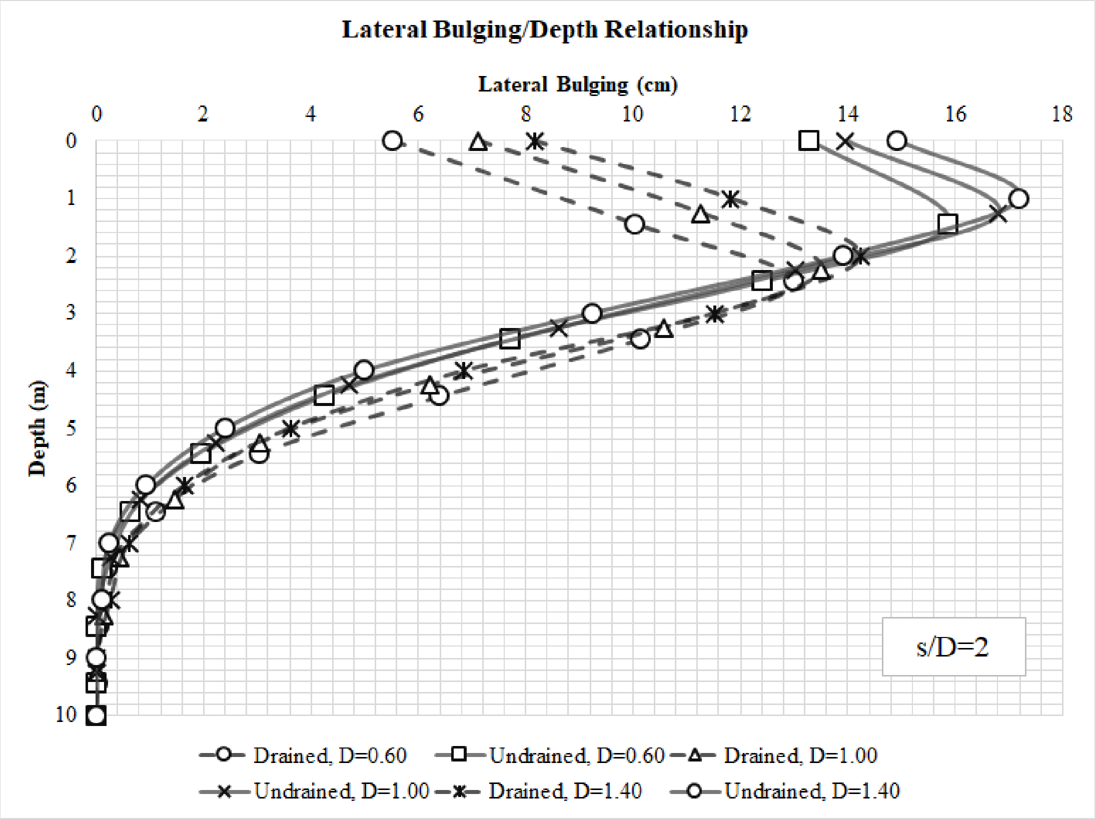


Figure 4.5. Bulging - depth relationship for s/D=2

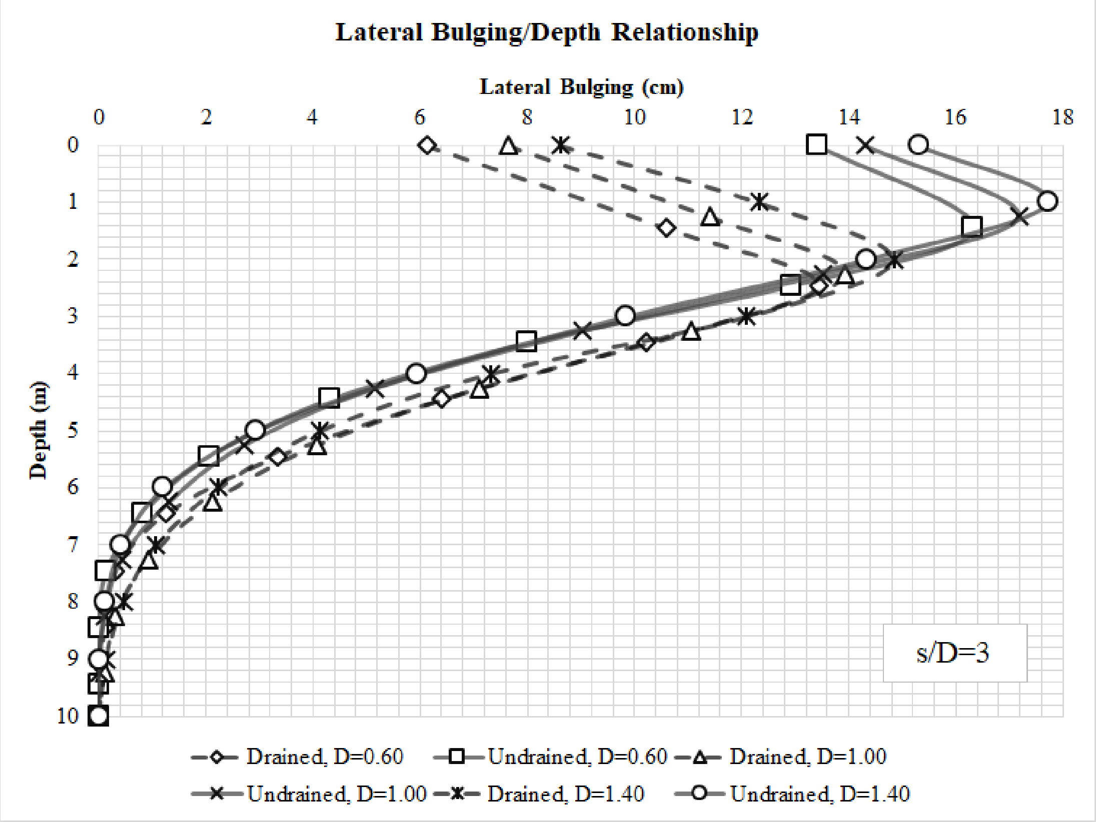


Figure 4.6. Bulging - depth relationship for s/D=3

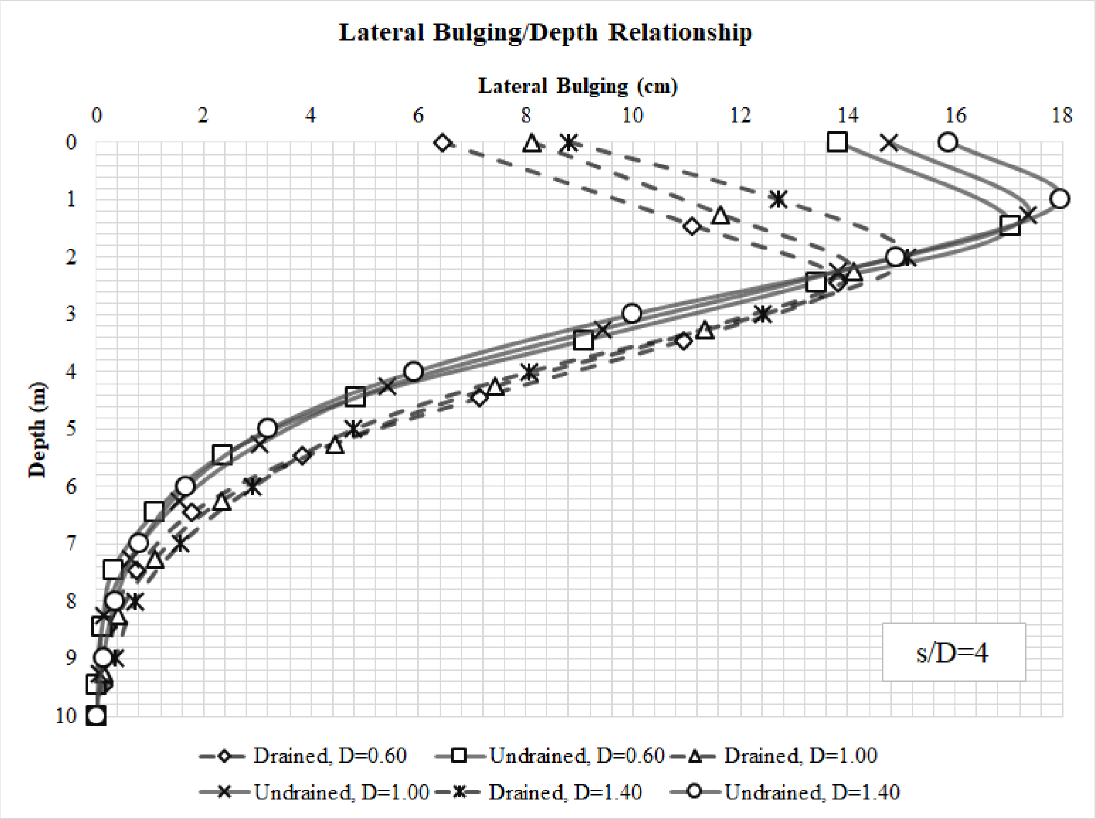


Figure 4.7.Bulging - depth relationship for s/D=4

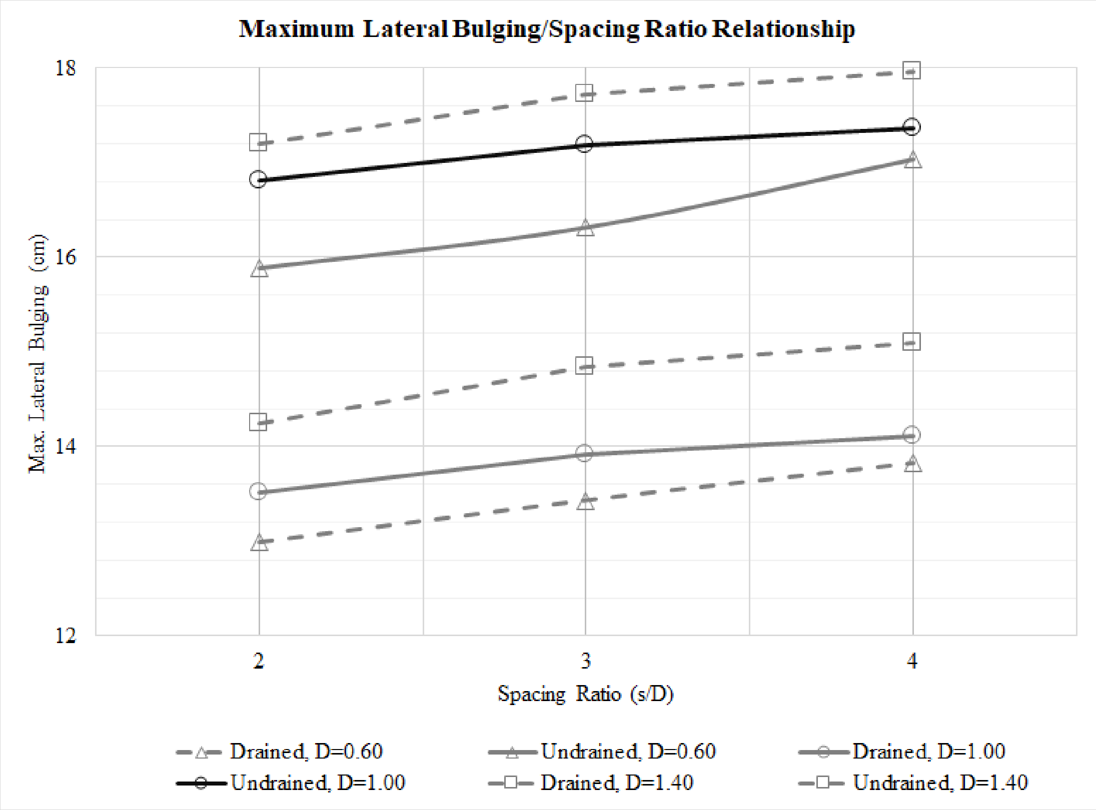


Figure 4.8. Maximum lateral deformation - spacing ratio (s/D) relationship

Noted numerical data were reflected on the maximum lateral deformation – spacing ratio diagram (Figure 4.8) and the stone column profile with the least diversion (the most linear) was determined to be D=1.00 m and s/D=3 at undrained condition (UC). This stone column profile was decided be used at further analyses within the study.

4.3.2. Parametric Study

The simulated soft ground model and chosen stone column profile (D=1.00 m, s/D=3 at UC) were used at all further analyses and parametric study was performed in below summarized five steps respectively,

1. Improvement effect of sand mat layer on an OSC installed soft ground and determination of the optimum sand mat thickness,
2. Investigating the improvement effect of reinforcing the sand mat layer with geogrid and determining the optimum geogrid stiffness,
3. Investigating the additional confinement effect of vertical encasement, its contribution to vertical and horizontal deformation reduction and determination of the optimum geotextile stiffness,
4. Determining the optimum encasement length and investigating its effect on vertical and horizontal deformation reduction,
5. Floating behaviour of the vertically encased stone columns (VESC) under geogrid reinforced sand mat (GRSM).

The varying material properties and reinforcement scenarios evaluated in parametric study were summarized at Table 4.3.

Table 4.3. Parameters evaluated in the parametric analyses

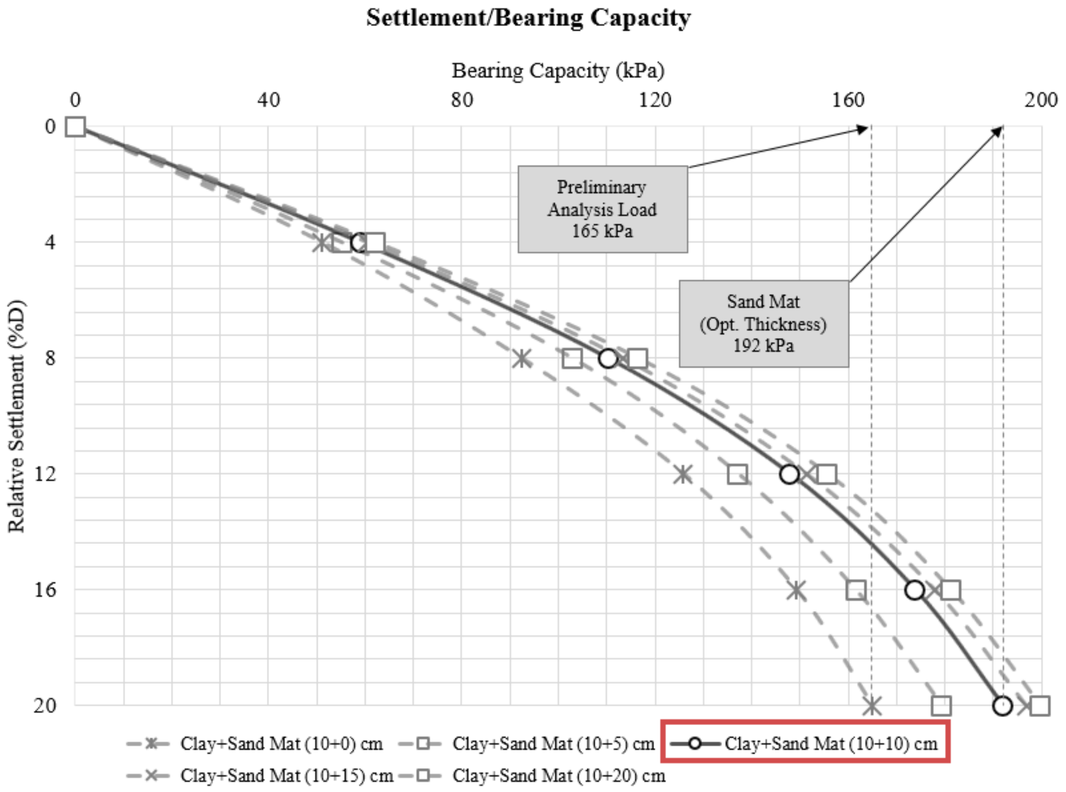
Parameter	
Soft Soil Layer Height (H) (m)	10, 11, 12, 13, 14, 15, 16, 18, 20
Column Diameter (m)	0.60, 1.00, 1.40
Spacing Ratio (s/D)	2, 3, 4
Sand Mat Thickness (m)	0.00, 0.05, 0.10, 0.15, 0.20
Geogrid Stiffness (J) (kN/m)	1000, 2000, 3000, 4000, 5000, 6000, 7000
Geotextile Stiffness (E) (kN/m)	500, 1000, 1500, 2000, 2500, 3000, 3500
Encasement Length (h/L)	0.10, 0.20, 0.30, 0.40, 0.50, 0.80, 1.00

5. RESULTS AND DISCUSSIONS

The results of numeric analyses and parametric study are shared in this section, the findings were compared and discussed by the light of former studies in the literature. The contribution ratio of applied improvement at that step was calculated, compared with the initial state and previous improvement step.

5.1. Effect of Sand Mat Thickness

An unreinforced sand mat layer (USM) that have a thickness varying of 0.0 to 0.2 meters with 0.05 meters intervals was deployed on an ordinary stone column (OSC) reinforced soft clay ground in turns. A series of numerical analyses were carried out and bearing capacity – relative settlement diagrams were drawn using the data obtained (Figure 5.1).



Preliminary Analysis Load 165 kPa

Sand Mat (Opt. Thickness) 192 kPa

Figure 5.1. Bearing capacity - relative settlement diagram for sand mat thickness

Sand mat thickness appears to be improving the bearing capacity obviously until 0.2 meters and beyond that the effect is not obvious. A sand mat layer of 0.2 meters thick was selected as optimum sand mat and decided to be used at the continuing steps of numerical study. In an early study by Debnath & Dey (2017), optimum thickness of USB giving maximum performance improvement was indicated about 0.2 times the diameter of the footing (i.e., 0.2D) in composite foundation systems. The calculated sand mat thickness conforms to the referent study. The selected optimum sand mat was calculated to be causing an increase up to 1.16-fold on the bearing capacity of OSC installed in soft ground.

5.2. Effect of Geogrid Reinforcement Stiffness

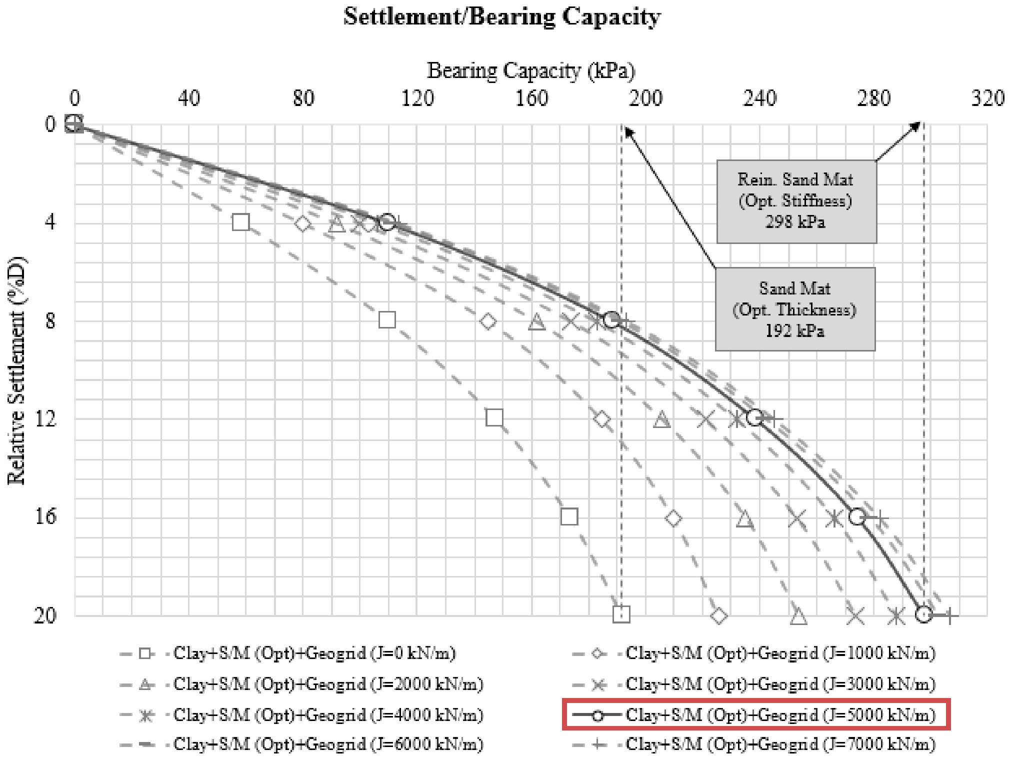


Figure 5.2. Bearing capacity - relative settlement diagram for geogrid stiffness

The optimum sand mat of 0.2 meters thick was reinforced with varying axial stiffness of geogrid reinforcement material; 1000, 2000, 3000, 4000, 5000, 6000 and 7000 kN/m representing a scale of low to very high strength geosynthetic material. Bearing capacity – relative settlement diagrams were drawn using the data obtained from the series of numerical analyses conducted (Figure 5.2).

According to the Figure 5.2, bearing capacity increases with the increasing stiffness values of geogrid reinforcement until J=5000 kN/m but beyond that the improvement becomes insignificant. Similar results have been reported at former studies. Zhang et al. (2015) implies a maximum settlement reduction of 10% provided by the basal geosynthetic under the embankment. Kahyaoğlu and Martin (2019) points out a decrease of the long-term maximum settlement ratio of 0.30 between the reinforced and unreinforced sand mat cases. Geogrid reinforcement with 5000 kN/m stiffness was selected as optimum and decided to be used in ongoing numerical study. The selected optimum GRSM was calculated to be increasing the bearing capacity of the soft ground up to 1.55-fold and 1.81-fold compared to OSC+USM and OSC, respectively.

5.3. Effect of Geotextile Encasement Stiffness

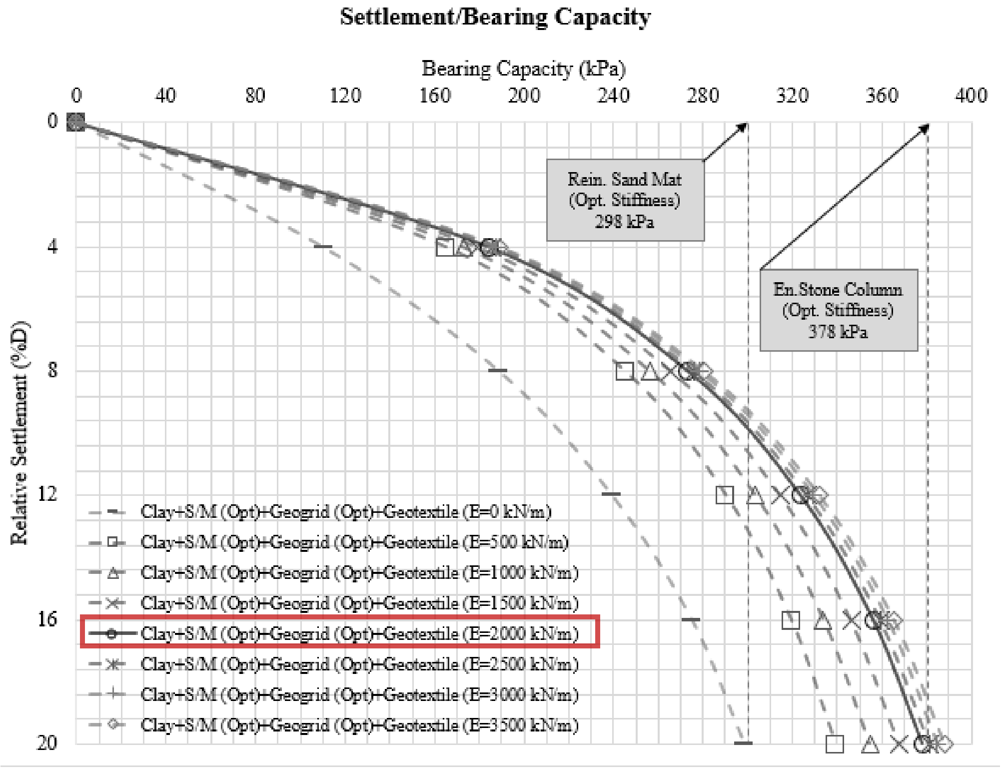


Figure 5.3. Bearing capacity - relative settlement diagram for geotextile stiffness

The ordinary stone columns (OSC) installed in the soft ground under optimum geogrid reinforced sand mat (GRSM) (m=0.2 m and J=5000 kN/m) were encased with varying axial stiffness of geotextile material; 500, 1000, 1500, 2000, 2500, 3000 and 3500 kN/m representing a scale of low to very high strength geosynthetic material.

Bearing capacity – relative settlement (Figure 5.3) and lateral deformation – depth diagrams (Figure 5.4) were drawn by using the data obtained from the series of numerical analyses performed.

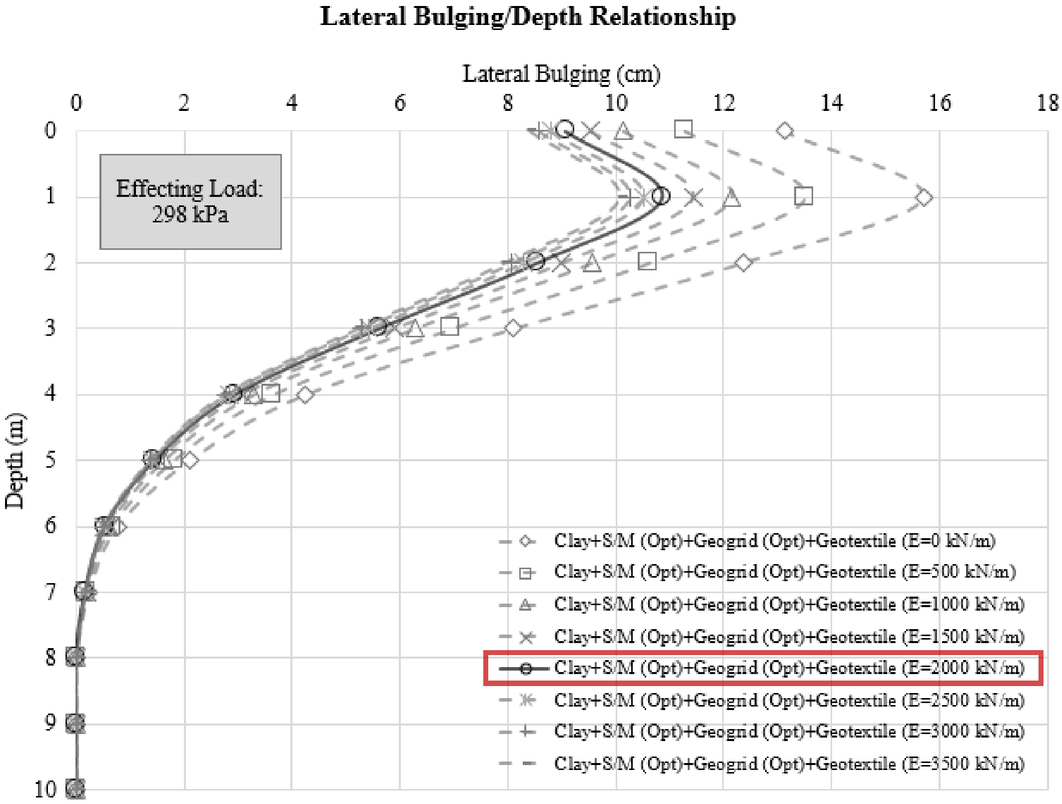


Figure 5.4. Lateral deformation - depth diagram for geotextile stiffness

According to the Figures 5.3 and 5.4, additional confinement due to the increasing stiffness of the geosynthetic encasement material appears to be significantly contributing to both the bearing capacity and the bulging reduction until the stiffness value of E=2000 kN/m and beyond that enhancement is not obvious. Thus, stiffness value of 2000 kN/m for vertical encasement was chosen as optimum and decided to be used at continuing steps of numerical study. The selected optimum GRSM+VESC calculated to be increasing the bearing capacity of the soft ground up to 1.27-fold, 1.97-fold and 2.29-fold compared to GRSM+OSC, USM+OSC and OSC and reducing the lateral deformation up to 31% compared to GRSM+OSC, respectively. Debnath & Dey (2017) refers an increase on bearing capacity of soft soil by 1.72-fold with provision of OSC and 2,68-fold with VESC. The bearing capacity of soft soil can be increased by 3.63-fold and 8,45-fold when VESC coupled together with USB or GRSB respectively.

Ali (2014) points out an increase of bearing capacity 1.28-fold with GESC compared to OSC. Tandel & Solanski (2012) implies a bearing capacity increase of 1.5-fold and a bulging reduction up to 75% compared to OSC. A settlement reduction of 40% (Nagy, 2013) and 50% (Malarvizhi & Ilamparuthi, 2007) was referred by encasing the columns with proper geosynthetics. Former studies conform the load carrying capacity improvement and settlement reduction of SCs with the provision of geosynthetic encasement.

5.4. Effect of Vertical Encasement Length

The analyses on optimized GRSM reinforced (m=0.2 m and J=5000 kN/m) and VESC (E=2000 kN/m) improved soil model were repeated for different encasement lengths which the ratio of vertical encasement length to column length (h/L) varying 0.0 to 1.0 with 0.1 intervals. Bearing capacity – relative settlement (Figure 5.5) and lateral deformation – depth graphics (Figure 5.6) were drawn using the data obtained from analyses.

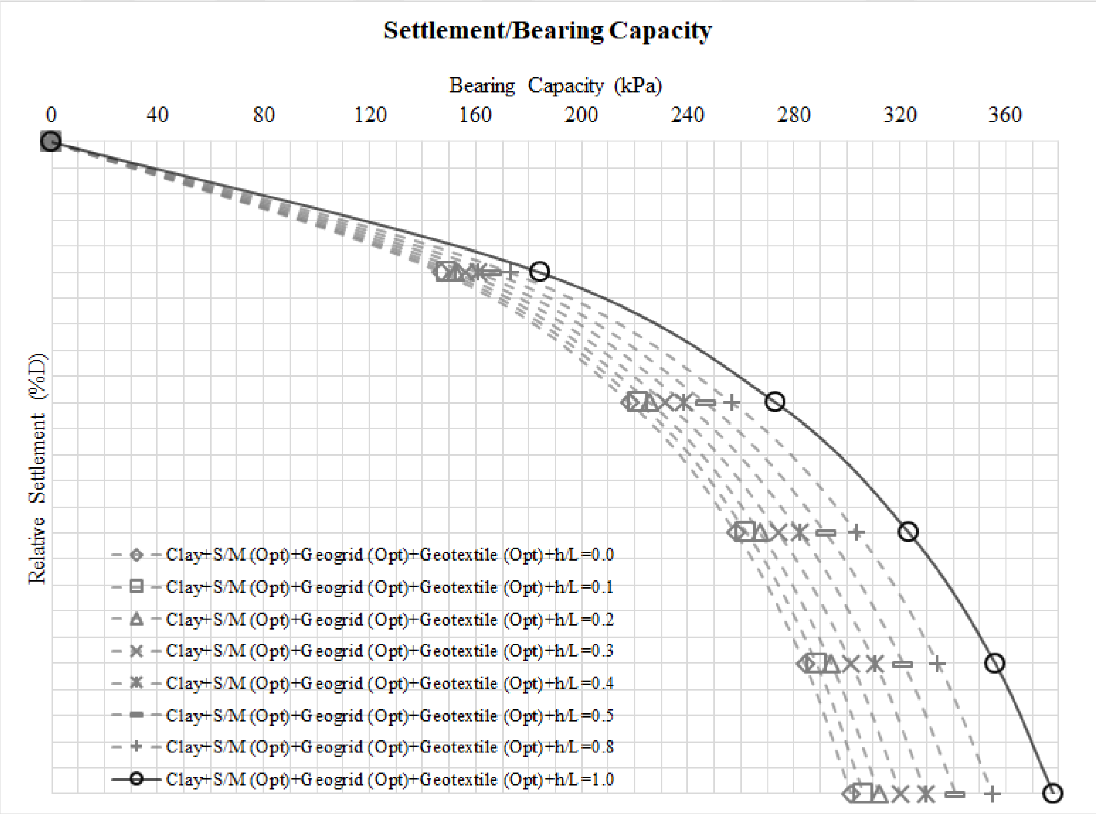


Figure 5.5. Bearing capacity - relative settlement diagram for varying encasement lengths

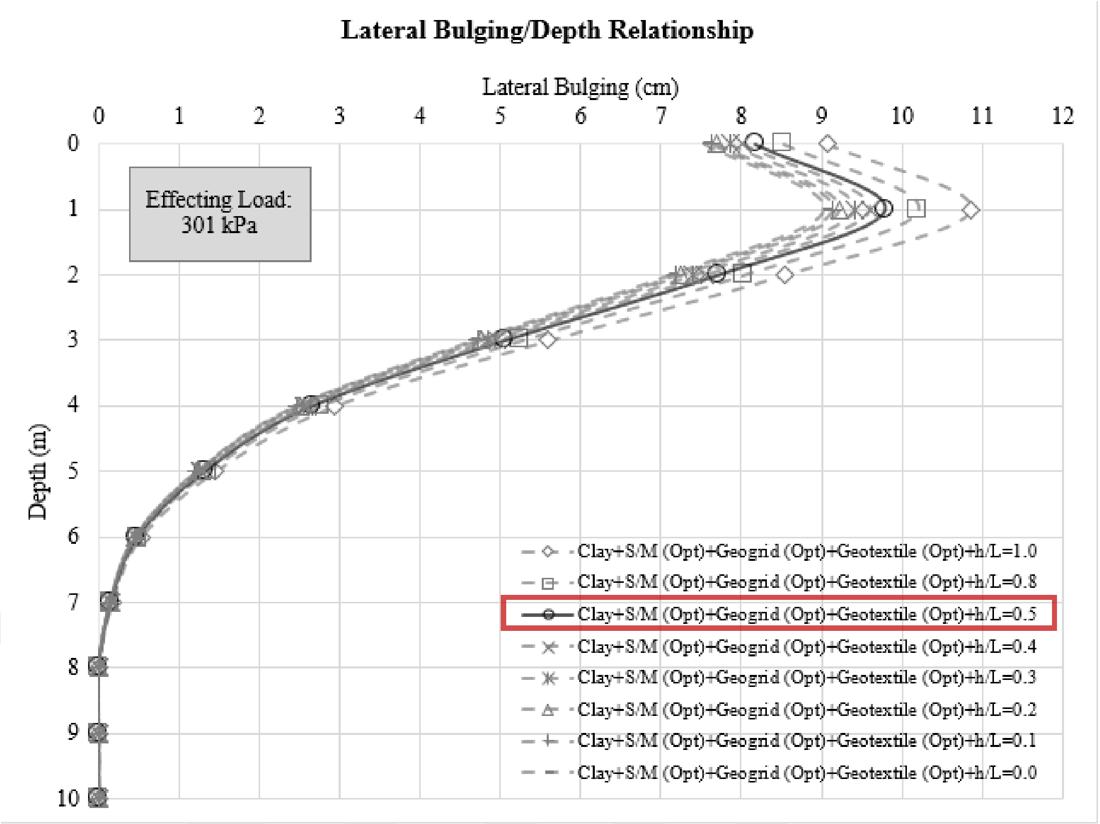


Figure 5.6. Lateral deformation - depth diagram for varying encasement lengths

According to the Figures 5.5 and 5.6, a vertical encasement from the top to the middle of column (h/L=0.5) appears to be obviously contributing to both the bearing capacity and the bulging reduction of SC under GRSM. For lengths beyond the middle of the column, the encasement's contribution is insignificant. Similar results have been reported at former studies. Malarvizhi & Ilamparuthi (2007) indicate that the maximum bulging occurs at 4D from top of the column. Ali & Shahu (2012) refers that the higher failure stress occurs at upper half of the column.

Despite the fact of 50% encasement length reduction as a result of encasing the upper half of stone column, the decrease of bearing ratio of composite ground is determined as 10%. This suggests that the stone column can be encased partially on condition of reinforcing up to where lateral deformation is maximum. Tandel & Solanski (2012) implies a 14% decrease in maximum load capacity despite the 50% decrease at encasement length. The calculated load carrying performance of partially encased stone column conforms to the referent study.

5.5. Floating Column Behaviour

The height of the soft clay layer adopted was extended from 10 m up to 20 m with 1 m intervals in order to simulate the floating column behaviour and analyses were repeated. Relative settlement – layer extension ratio (H/L) diagram (Figure 5.7) was drawn within the data gathered from the series of numerical analyses.

According to the Figure 5.7, an obvious decrease on relative settlement was monitored with the increase at the layer height. Similarly, Dash & Bora (2013) confirms the significant enhancement on the bearing capacity of geosynthetic encased floating stone columns and implies that long stone columns (i.e., L≥3D) could effectively reduce differential settlements in the foundation beds.

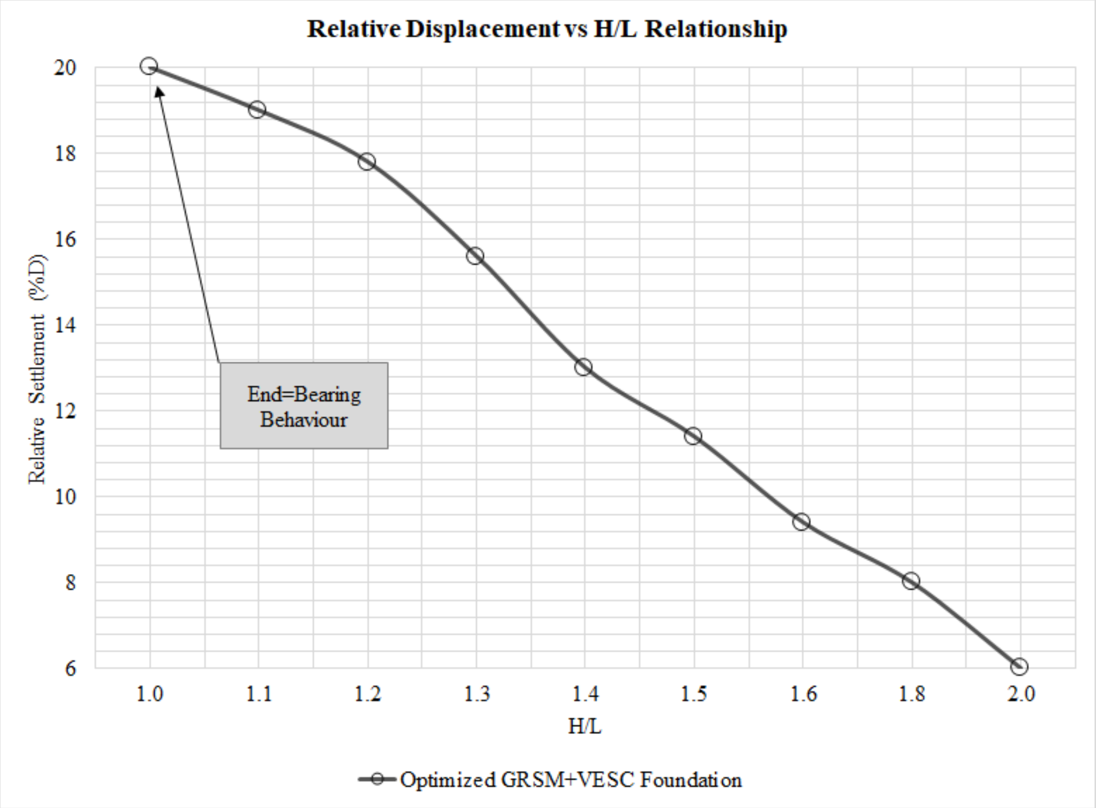


Figure 5.7. Relative settlement - layer extension ratio diagram for floating behaviour

6. CONCLUSIONS

The conclusions of study are summarised respective to the analyses order,

- **Basal Reinforcement:** Composition of a sand mat at the base of the embankment reduces the relative settlement between the soft soil and the stone column. Sand mat thickness appears to be improving the bearing capacity obviously until 0.2D and beyond that the effect is not obvious.

  Utilizing a layer of geogrid reinforcement in the sand mat increases the effect up to the axial stiffness of J=5000 kN/m, behind that contribution is insignificant. The optimum GRSM (0.2D thick and reinforced by a J=5000 kN/m geogrid layer) was calculated to be causing an increase up to 1.16-fold on the bearing capacity of OSC installed in soft ground,

- **Vertical Encasement:** The stress/settlement response of the stone columns can be significantly altered by the geosynthetic encasement. Also, encasing the stone columns with a geotextile reduces the lateral deformations. Geotextile encasement up to the stiffness of E=2000 kN/m appears to be the optimum, behind that contribution is insignificant. The optimum GRSM+VESC (vertically encased by a geotextile of E=2000 kN/m stiffness) calculated to be increasing the bearing capacity of the soft ground up to 1.27-fold, 1.97-fold and 2.29-fold compared to GRSM+OSC, USM+OSC and OSC and reducing the lateral deformation up to 31% compared to GRSM+OSC, respectively.
- **Encasement Length:** For end-bearing (fixed) stone columns, an encasement length of 0.5L appears to be contributing significantly to both the bearing capacity and the bulging reduction of SC under GRSM. For lengths beyond the middle of the column, the encasement's contribution is not obvious.
- **Fixed vs. Floating Column Behaviour:** Floating column behaviour significantly reduces the relative settlements between the column and the soft soil ground. Thus, installing floating stone columns in soft ground could effectively contribute the stability of foundation beds and embankments over them.

7. SUGGESTIONS ON FUTURE STUDIES

The results of the numerical study and parametric analysis within this thesis were presented and discussed in the light of former studies at 5th section and the conclusions were summarized at section 6. The need for further analyses were indicated according to the findings of this thesis and potential topics for future studies are summarized below.

- There is a certain need for full-scale field tests and experimental studies on reinforced sand mat layers and individual/group of encased stone columns for creating new design approaches or validating the existing ones aiming on column bearing capacity prediction and encasement or reinforcement material performance.
- Scaled laboratory experiments should be performed to understand partially or fully drained behaviour of soft clay layer and conjoint numerical analyses should be carried out in order to evaluate composite ground performance under variable load and drainage conditions.
- Additional studies needed to determine the long-term stability and performance under dynamic loads of encased stone column.

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