Enhancing Problematic Soils Using Waste Materials as Stone Columns

Mahdi Z. M. Alnunu

Submitted to the
Institute of Graduate Studies and Research
in partial fulfilment of the requirement for the degree of

Master of Science
in
Civil Engineering

Eastern Mediterranean University
August 2017
Gazimağusa, North Cyprus

Approval of the Institute of Graduate Studies and Research

Assoc. Prof. Dr. Ali Hakan Ulusoy
Acting Director

I certify that this thesis satisfies the requirements as a thesis for the degree of Master of Science in Civil Engineering.

Assoc. Prof. Dr. Serhan Sensoy
Chair, Department of Civil Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Civil Engineering.

Prof. Dr. Zalihe Sezai
Supervisor

Examining Committee

1. Prof. Dr. Zalihe Sezai
2. Assoc. Prof. Dr. Huriye Bilsel
3. Asst. Prof. Dr. Eriş Uygar

ABSTRACT

Nowadays, the rapid population growth and economic development have made the finding of construction lands in good conditions more and more difficult. Usually encountered soil problems are excessive settlement in soft clays, low bearing capacity and liquefaction in fully saturated loose sands. To mitigate such problems, ground improvement alternatives become the best option, technically and economically. In recent years, ground improvement methods have undergone significant developments and their use in construction projects has increased over the years. Among the various ground improvement methods, stone column application is considered to be one of the most practical and economical ground improvement techniques. Stone columns are used to enhance the bearing capacity of poor ground and reduce the compressibility of soft clays. The aim of this study is to evaluate the effectiveness of stone column on the compressibility of soft clay; settlement and densification of loose sand for higher bearing capacity value. The study also provides guidelines for the selection of the most effective and economical material for stone column construction. In the study, waste materials from different construction sites were selected: crushed bricks and crushed waste concrete and the stone columns were constructed with these recycled materials. Crushed stone were also used as a third stone column material. Load-settlement response of the single and group of stone column reinforced and unreinforced soils were determined under the same loading condition. It was found out that the use of selected waste materials in the construction of stone column is promising. They resulted in very good improvement in the compressibility and the load bearing capacity of the soft clay and the loose sand. As a conclusion, these easily available waste materials can be effectively and economically used in the construction of stone columns for soil improvement.

Keywords: Crushed bricks, crushed concrete, improvement, loose sand, modification, soft clay, stone column, waste material and settlement.

ÖZ

Günümüzde hızlı nüfus artışı ve ekonomik gelişme, bina yapmak için gerekli olan iyi durumdaki arazi bulunmasını zorlaştırdı. Genellikle karşılaşılan zemin problemleri, yumuşak killerde aşırı oturmalar, düşük taşıma kapasitesi ve tamamen suya doymuş gevşek kumlarda sıvılaşmadır. Bu tür problemleri azaltmak için teknik ve ekonomik açıdan zemin iyileştirme alternatifleri en iyi seçenek haline gelir. Son yıllarda zemin iyileştirme yöntemleri önemli gelişmeler göstermiş ve inşaat projelerinde kullanımları yıllar içinde artmıştır. Çeşitli zemin iyileştirme yöntemleri arasında taş kolon uygulaması, en pratik ve ekonomik zemin iyileştirme tekniklerinden biri olarak kabul edilmektedir. Taş kolonlar zayıf zeminin taşıma kapasitesini arttırmak ve yumuşak killerin sıkışabilirliğini azaltmak için kullanılır. Bu çalışmanın amacı taş kolonun yumuşak kilin sıkışması üzerindeki etkinliğini değerlendirmek; gevşek kumda yüksek taşıma kapasitesi için oturma ve yoğunluğuna olan etkisini araştırmak. Çalışma aynı zamanda taş kolon yapımı için en etkili ve ekonomik materyalin seçimi için kurallar sağlıyor. Çalışmada farklı inşaat alanlarından atık maddeler seçilmiştir: ezilmiş tuğla ve ezilmiş atık beton, taş kolonlar bu geri dönüştürülmüş malzemelerle oluşturulmuştur. Kırma taş üçüncü bir taş kolon malzemesi olarak kullanılmıştır. Tek taş kolon ve gurup taş kolon takviyeli güçlendirilmiş ve güçlendirilmemiş toprağın yük-yerleşim tepkisi aynı yükleme koşulunda belirlendi. Seçilen atıkların taş kolon yapımında kullanılması umut vericidir. Yumuşak kil ve gevşek kumun sıkışabilirlik ve taşıma kapasitesinde çok iyi bir gelişme sağladılar.

Sonuç olarak, kolayca bulunabilinen bu mevcut atık maddeler zemin iyileştirme için taş kolon yapımında etkin ve ekonomik olarak kullanılabilir.

Anahtar Kelimeler: Ezilmiş tuğla, ezilmiş atık beton, iyileştirme, gevşek kum, modifikasyon, yumuşak kil, taş kolon, atık madde ve oturma.

I DEDICATE MY DISSERTATION WORK TO MY FAMILY

AND MANY FRIENDS.

A SPECIAL FEELING OF GRATITUDE TO MY LOVING

PARENTS, WHOSE WORDS OF ENCOURAGEMENT AND

PUSH FOR TENACITY RING IN MY EARS.

ACKNOWLEDGEMENT

I would like to thank my supervisor Prof. Dr. Zalihe Sezai who has been more than generous with her expertise and precious time. Special thanks go to her for her countless hours of reflecting, reading, encouraging, and most of all patience throughout the entire process.

Special thanks go to Civil Engineering Staff at Eastern Mediterranean University in North Cyprus for their academic and scientific support throughout my study of M.Sc. especial Prof. Dr. Özgür Eren, Prof. Dr. Tahir Çelik, Prof. Dr. Osman Yilmaz, Assoc.Prof.Dr. Khaled Marar.

A special thanks to Deanery of Graduate Studies at Engineering Faculty for their administrative and academic support.

A special thanks goes to Eng. Ogun Kılıç who supports and helps me in testing stage.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

c	Cohesion
C_c	Compression index
C_s	Swelling index
C_u	Coefficient of uniformity
C_v	Coefficient of consolidation
e	Void ratio
e_{max}	Maximum void ratio
e_{min}	Minimum void ratio
G_s	Specific gravity
m_v	Compressibility coefficient
SP	Poorly graded sand
W_{op}	Optimum moisture content
$\rho_{d(max)}$	Maximum index density
$\rho_{d(max)}$	Maximum dry density
$\rho_{d(min)}$	Minimum index density
σ	Normal stress
σ_p'	Preconsolidation pressure

LIST OF ABBREVIATIONS

ASTM	American society for testing and materials
CBR	California bearing ratio
MDD	Maximum dry density
OMC	Optimum moisture content
PI	Plasticity index
PL	Plastic limit
LL	Liquid limit
UCS	Unconfined compressive strength
USCS	Unified soil classification system
W	In situ water content
DMM	Deep Mixing Method
DJM	Dry Jet Mixing method

Chapter 1

INTRODUCTION

1.1 General background

Soil has always been one of the most important governing parts of design in any construction projects in the world. Construction projects become more complex and difficult to accomplish with any kind of problematic soils such as soft clays with very high compressibility, expansive soils with high volume change and loose sands likely to liquefy during earthquakes. During design, all these threats should be considered and the foundation design should be done accordingly so that the foundation failures will not occur due to improper foundation design. One of the ways of dealing with such problems is to modify the existing ground conditions by applying some modification techniques so that no foundation failure will occur in construction.

Within the scope of this study, the ground modification technique stone column which is a very effective and an economical alternative to deep modification techniques will be used for the improvement of loose sand and soft clay present in North Cyprus and the existing poor ground conditions will be improved.

1.2 Cyprus geology

Cyprus island with 9,251 km^2 area is the largest island in the Mediterranean sea. The North Cyprus zone is occupying around 3,299 km^2 of total area (Atalar & Das, 2009). The zone of North Cyprus consists of sedimentary rocks, ranging in age from the Upper Cretaceous to the Pleistocene (Geological Survey Department). Its main constituents are bentonitic clays, marls, chalks, cherts, limestones, calcarenites, evaporites and clastic sediments (Geological Survey Department). The Famagusta region in North Cyprus consists of calcareous sands and sandstones, marly sands, and gravels, which correspond to the upper portion of the Plio-Pleistonece to recent deposits (Cyprus Geological Heritage Educational Tool). The lower part of these deposits, which form the base of the aquifer, is a sequence of blue-grey marls of Pliocene age (Cyprus Geological Heritage Educational Tool).

In history, Cyprus Island has faced a lot of natural disasters like earthquake (Atalar & Das, 2009). In North Cyprus, there are also soils with poor soil conditions such as; loose gravel and sand, soft clay soils, expansive soils, etc. (Malekzadeh & Bilsel, 2012; Abiodun & Nalbantoglu, 2015). These types of soils result in high compressibility and consolidation settlement in soft clays and liquefaction problem in loose sands.

1.3 Problem statement

As aforementioned, highly compressible soft silty clays are widespread around the Island. North Cyprus is located on coastal strip of the island and the soft clays are usually subjected to settlement problems. Similarly, the loose sands exist especially on the coastline of the island and produce an unacceptable risk of liquefaction problem. Stone column application is considered as one of the effective way to enhance the properties of problematic soils. Stone column is one of the modification techniques that can help to solve the problems in soft clays, loose sand and strengthens the soils against settlement, low bearing capacity and liquefaction problems (Maduro et al., 2004, Castro et al., 2014; Ali et al., 2014). The purpose of using stone columns in problematic soils is similar to concrete or steel piles. Both of them work to develop more dense and strong soils so that the settlement and the liquefaction problems are prevented.

In the past ground modification applications, concrete elements such as concrete piles, sheet piles and retaining walls in embankment were used for the improvement of the site conditions (Li et al., 2017). These methods though still in use but they are very old, very expensive and they need difficult technology to apply. Some of these procedures include deep excavations, concrete mixing and insulation to improve embankment settlement (Shi et al., 2017; Kitazume & Terashi, 2013). Most of the applications of concrete piles have become burdensome for construction companies and the researchers are trying to use easier implementation techniques such as stone column to improve the ground conditions. Stone column applications enable the construction companies to improve the ground conditions with low cost easy application and handling.

Many researchers studied the effects of stone columns on different soil types such as soft compressible clays, loose sands and they found the stone columns to have positive effects on the improvement of the bearing capacity and reducing the compressibility of soft clays (Killeen & McCabe, 2014; Sivakumar et al., 2004 Lorenzo & Bergado 2004; and Murugesan & Rajagopal 2010). For the formation of the stone columns, different materials such as; crushed stones, sandstones and lime powder were used as column materials (Abiodun & Nalbantoglu, 2015). These filler materials played different roles in the mechanical and chemical improvement of the soils (Broms, 2000).

1.4 Thesis aim

In the present study, the stone columns application will be used for the improvement of both soft silty soil and the loose sand to reduce the risk of compressibility and consolidation settlement in soft silty soil and the bearing capacity and liquefaction problem in loose sand. In the study, different filler materials will be used in the installation of the columns. These materials are the waste by products in the construction sites. These are the old crushed waste concrete and crushed bricks. These kinds of waste materials are usually considered as by product materials resulting during the production of construction materials such as bricks or demolition of the old buildings: crushed waste concrete which cannot be reused as concrete (Rahman et al., 2015). These crushed waste concrete are heavy pieces which cannot be removed easily from the construction site and they form danger in the construction site. In the previous studies, Indraratna et al., 2015 found out that, sand and crushed stones columns were very effective in improving the mechanical properties of highly compressible clays.

In the present study, series of tests will be conducted on soft silty soil and loose sand to evaluate the effectiveness of stone columns produced by waste materials: crushed waste concrete and bricks on settlement and bearing capacity of these soils. A test tank will be designed to simulate the field conditions of natural and reinforced soils by stone column and the test results will be compared and discussed. The single and group of stone columns will be formed to evaluate the effectiveness of the stone columns.

The behavior of the filler materials in the stone column under different loading conditions will be analyzed in terms of strength, settlement , and stiffness of the stone columns.

1.5 Objectives of studies

The objectives of this study include the followings:

- To enhance the stability of soft silty soil and loose sand by using stone column technique.
- To use different types of waste as filler materials for formation of the stone columns.
- To recycle the waste materials such as crushed bricks and waste concrete on construction sites and use them in the construction of the stone columns for soil remediation.
- To study and compare the behavior of soft silty soil and loose sand with and without stone columns formed by different filler materials.
- To emphasize the benefits of using stone columns techniques instead of using costly methods such as concrete elements.
- To study and compare the soil behavior with the group of stone columns and the single stone column, and conclude on the degree of improvement.

1.6 Outline of thesis

This study includes the following chapters:

Chapter 1 Introduction

Chapter 1 presents an introduction to the research. It includes a background, Cyprus geology, the aim of the study and objectives of this study. Background information of the thesis is outlined.

Chapter 2 Literature review

Chapter 2 presents the literature review and the previous studies on the stone columns. It describes the theoretical backgrounds which have been used in the application of the stone columns in highly compressible soils.

Chapter 3 Materials and methods

Chapter 3 shows the materials section and describes the properties of each material used in this study. The methodology section describes the model test tank and the construction of the stone columns in the tank.

Chapter 4 Results and discussion

This chapter presents and discusses all the test results obtained from the laboratory study. The behavior of stone column within different filler materials is discussed.

Chapter 5 Conclusion and recommendations

Chapter 5 summarizes the obtained results and discusses the behavior of silty soil and sand reinforced with stone columns. This chapter also presents the conclusion and the recommendations for further studies.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

The biggest section of the earth´s crust includes a lot of different soil types, such as, sand, till and clay. These different kinds of soils make up two different sorts of ingredients such as particles and pores. The particles are the solid part and the pores are filled with gas, water or both. The relationships between the volumes of all these different components have a huge influence on the geotechnical characteristics and the properties of the soil such as; density, porosity and water content. On the other side, There are a lot of factors that have impacts on the soil behavior; such as the form of the particles, texture, and grain size distribution.

2.2 General characteristics of cohesion less soil and clay

Generally speaking, clay is considered as a soft soil. It is a very widespread soil on the earth. It has a grain size less than 0.002 mm. Both sand and clay have varied density values. Table 2.1 shows mass density for different types of poorly graded soil and well graded soil (Ismail & Teshome, 2011).

Table 2.1: Mass density of clay, silt and sand (Ismail and Teshome, 2011)

Type of Soil	*Mass density ρ (Mg/m³)**			
	Poorly graded soil		*Well-graded soil*	
	Range	*Typical value*	*Range*	*Typical value*
Loose sand	1.70–1.90	1.75	1.75–2.00	1.85
Dense sand	1.90–2.10	2.07	2.00–2.20	2.10
Soft clay	1.60–1.90	1.75	1.60–1.90	1.75
Stiff clay	1.90–2.25	2.00	1.90–2.25	2.07
Silty soils	1.60–2.00	1.75	1.60–2.00	1.75
Gravelly soils	1.90–2.25	2.07	2.00–2.30	2.15

Sallfors (2001) stated that contacts between the particles in clay are considered indirect contact. Because of poor contact between clay particles and grains size distributions; clays have lower strength, less permeability and they are exposed to deformation more than other soils. Furthermore due to their mineralogical formations, clays may have attraction force between clay particles. Figure 1 describes the molecular attraction between each clay particles.

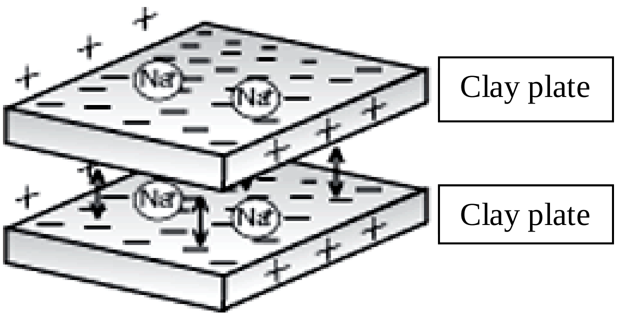

Figure 2.1: Molecular attraction between clay particles (Moritz, 1995)

When clay is exposed to high compressional forces, it becomes more dense, and the compressibility becomes more lower than original case. When it comes to excavation work in a clay layer, vertical and horizontal defect will occur. All these problems lead to challenges to implement a construction projects such as, buildings, roads, railways and bridges on a ground that contains a deep layers of clay. Piles, sheet piles and slope stability parameters are considered as geotechnical and practical solutions to face all these problems.

2.3 Structures of clay

2.3.1 Bond attraction between clay particles

The force bond between general soils is critical, but in clay cases are different. Clays in typical state it has a negative sign (-) on the plat faces and it has a positive sign (+) cover all edge surface and corner also. During the time attractions between the edge surface and flat faces will increase and become more close to each other. Some bond attraction happened between all the faces at this time the structure of clay becomes more rigid and stable (Biczok and Szilvassy, 1964).

2.3.2 Structure of flocculated clay particles

Some clay includes flocculated particles; this kind of particles can give the suitable consistency to the bonds attraction, make it fairly stable and increase the stiffness of the particles, as shown in Figure 2.2 below. The degree of contact between the flocculated particles is high due to harmony of geometric shape (Kezdi, 2013).

Figure 2.2: Structure of clay with flocculated particles (Kezdi, 2013)

2.3.3 Structure of (sand – coarse) clay

According to Kie (1966), natural clays may involve a lot of grains content such as sand and coarse particles. The distance between sand and coarse particles is not short and it contains a lot of voids. Clay particles play important role as a filler material. When this kind of clay is subjected to compressional loading, the loads will transmit to all particles to make it more dense, and the gaps between particles will be removed as shown in Figure 2.3. Where's; 1- coarse stone and 2- fine sand stone.

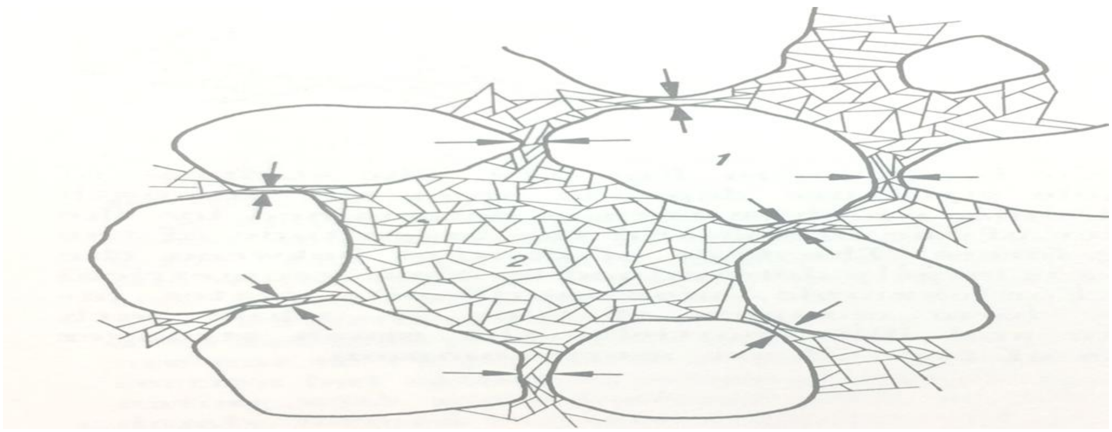

Figure 2.3: Structure of clay with sand - coarse particles (Kie, 1966)

2.4 Soft clay properties

Nowadays, soft clay can be represented as a well known division of problematic soils, which are commonly encountered under the form of deposited sheets in coastal regions. There are several problems that are faced when dealing with the study of soft clays such as; field investigation, behavior of soil, consistency of geotechnical structures and ground improvement solutions. Table 2.2 shows some properties of soft clay.

Table 2.2: General properties of soft clay (Klai et al., 2009)

Sample	Water content, ω (%)	Specific gravity	Unit weight (kN/m³)	W_L (%)	W_p (%)	I_C (%)	I_P (%)
1	40	2.62	17.4	46	27	0.31	19
2	52	2.5	16.1	55	50	0.52	5
3	44.3	2.53	18	51	41.5	0.70	9.5
4	65	2.32	17.6	65	50	0.40	15

Where's,

w: water content, W_L: Liquid limit, W_P: Plastic limit, I_C: Compaction index, I_P: Plasticity index.

To study the behavior and characteristics of soft clays, it requires determining their geotechnical properties. Henceforth, it is needed to implement laboratory tests on extracted samples either from cored specimens or remolded specimens. Soft clay is a suspicious soil because of its high compressibility and weak strength substratum. Then, designing foundation on soft clay is required a comprehensive study especially for both the short term behavior and for the long term behavior (Bouassida and Klai, 2012).

2.4.1 Compression properties of clay

Reul and Gebreselassie (2006) stated that there are changed volumes in clay resulted from several cases:

1) The percentage of soil swelling or shrinkage is considered as independent of loading on the soil. The factors like the value of precipitation or the variation in duration time are the main circumstances which changes the prosperities of clay.

2) The loading process and unloading status produce settlement and heavy cases.

During the loading on the clay, the original shape of the soil will be changed because of compressibility and total volume of voids will reduce. In case of saturated soil, the total load will be carried firstly by water and it will develop a pressure on the soil pores. Final stage of the loading system will transfer to the original structure of soil. Figure 2.4 describes the changing of total stress in clays during one dimensional consolidation.

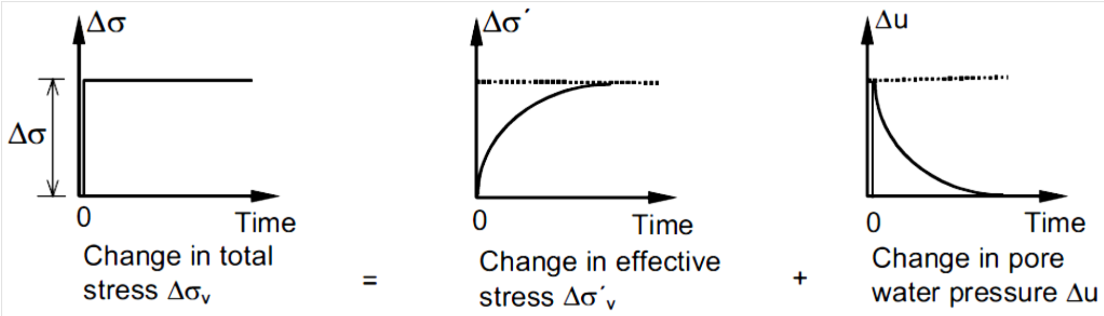

Figure 2.4: The Changing of total stress applying on pore pressure (Mitchell, 1993)

2.4.2 Shear strength of cohesive soil

The shear strength of cohesive soil is dependent on two parameters, which are cohesion(c) and the internal friction angle (ϕ). To evaluate the shear strength parameters the direct shear test or triaxial test can be performed on clays. The most appropriate test for cohesive soils is the triaxial test because of the control of the drainage conditions. The cohesion (c) for normally consolidated clays is approximately equal to zero. But, the cohesion for overconsolidated clays is greater than zero (Das, 2008).

2.5 Ground improvement techniques in soft clays

2.5.1 CCSG pile composite foundation in soft clay

Concrete cored sand gravel pile composite foundation (CCSG) is considered as a new type of composite foundation, for improving and treatment of the soft clay ground. This kind of composite foundation technology has been exceedingly used to improve and enhance the characteristics and properties of soft clay soil (Yu et al., 2013).

CCSG piles are consisted of sand-gravel shell and concrete cored pile, which is prefabricated and has low grade concrete. The distance between these composite piles is filled by soil. The composite pile is a new type of composite foundation, which is used during the time and has been put forward in the recent years. This foundation is used as low grade concrete piles like the vertical drainage body and cushion as the horizontal drainage body, depending of the idea of controlling and differentiating post construction settlement, as shown in Figure 2.5.

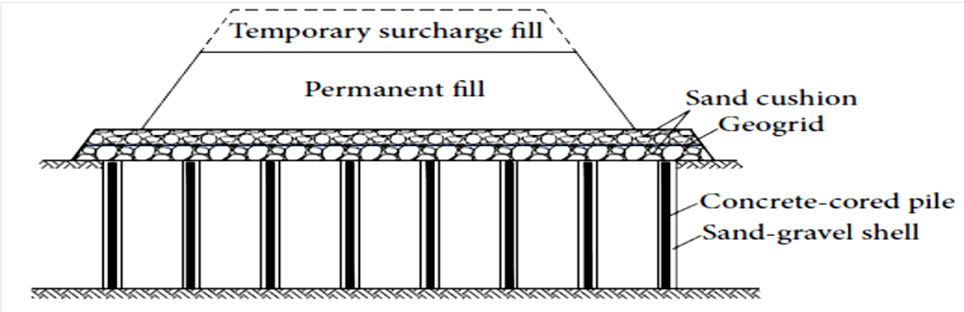

Figure 2.5: Schematic diagram of section. (Yu et al., 2013)

This new form of technology has a lot of advantages. Using the concrete cored sand gravel shell like the vertical drainage body, leading to accelerate the consolidation process between the piles and soil during the preloading period and through the construction implementations (Yu et al., 2013).

2.5.2 Reinforcement by sand piles

Sand piles can be considered as normal alternative between the common types of reinforcement by stone columns and vertical drains of sand. It has diameter less than 30 cm. Sand piles have been used in some countries. Figure 2.6 shows the procedures of penetration of sand piles in soft clays. The most important part after the installed network of sand piles is to improve the structure by adding a 40 cm thickness blanket over the sand piles networks, to distribute the load over the piles, make more uniform settlement and support the horizontal drainage of collected water from the sand piles to make it as vertical drains of filler materials (Bouassida et al., 2012).

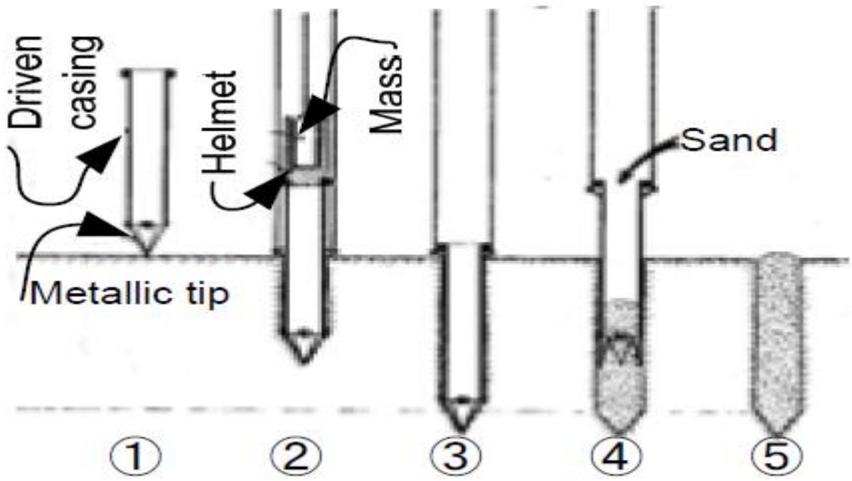

Figure 2.6: The formation of sand piles in soft clay (Magnan, 1983)

2.5.3 Deep mixing method

Deep mixing, DM is one of the most important method, which is formed through chemical reactions between reagent and soil Zheng et al., (2009).. In situ soil mixing (SM) technology can be subdivided into two general methods:

Deep Mixing Method (DMM).

Dry Jet Mixing method (DJM).

The main purposes of deep soil mixing are settlement reduction, increasing of stability, prevention of sliding, application as retaining structure, vibration reduction, liquefaction mitigation and remediation of contaminated ground (Holm 2001).

According to Han (2005) in DM technique, columns can be subjected to shearing, bending, rotation, tension failure, or combination of these four modes, depending on soil conditions, column strength, and design configurations. Figure 2.7 shows flexural and tension failure zones at different locations of the embankment.

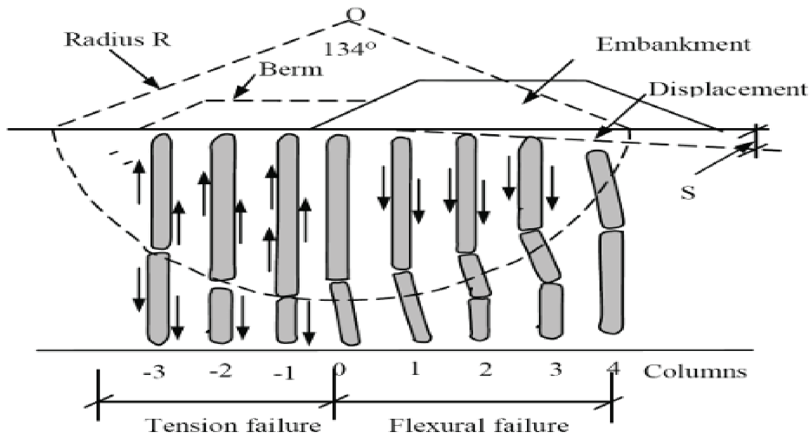

Figure 2.7: Possible Failure Modes of Columns (Broms, 1999)

Depending on the conditions of the soil; such as conditions of the underground, stability of the foundation and cost of the treatment, different patterns of column installations are used. These patterns include: single columns, group of column, secant columns and tangent columns Figure 2.8 described these patterns.

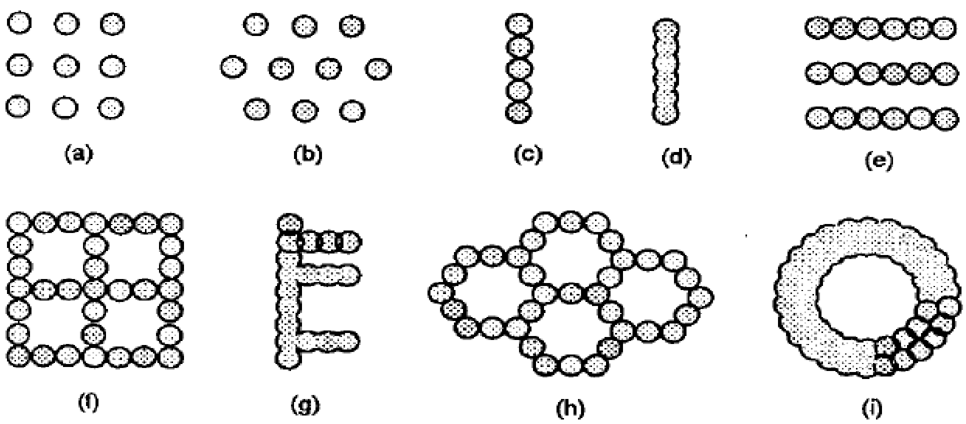

Figure 2.8: Different patterns of deep soil mixing (Guetif, 2007)

2.6 Stone columns for soil improvement

Stone columns are considered as one of the effective way to support the soft clay. There are a lot of advantages for this technique such as; reducing the degree of the settlement, developing the bearing capacity and improving the stiffness of the soil. The purpose of the stone columns is to modify the properties and characteristics of the surrounding natural clay and levelling the different elevations (Castro et al., 2014).

The level of support of a soft soil by stone columns is affected by such factors as; the nature of column materials (crushed stones, gravel and other filler materials in soft soil) and the degree of cohesion and the rigidity. The densification degree of the materials in the soft clay has affected some aspects such as; the process of installation of stone column into soft clay, by using vibrocompacted method and the consolidation operations in the soft soil before starting the final loading operation. Instantly after installing the column, the pores in the soil will carry all the high pressures, so the surrounding materials will help to develop the soft soil to resist the pressures (Guetif, 2007).

Generally speaking, stone columns are an important part for transferring the loads. In general cases, the diameter of stone column is not less 75 cm and not larger than 100 cm. Stone columns usually sit on solid and hard layer or bedrock, but sometimes floating columns are also installed. Usually when single column is used, it will not occur any effect in reducing the settlement. Using of stone columns as foundations, require group stone columns installed in the same area with uniform distribution and equal spaces between each other. Figure 2.9 described the group of stone columns (Zahmatkesh and Choobbasti, 2010).

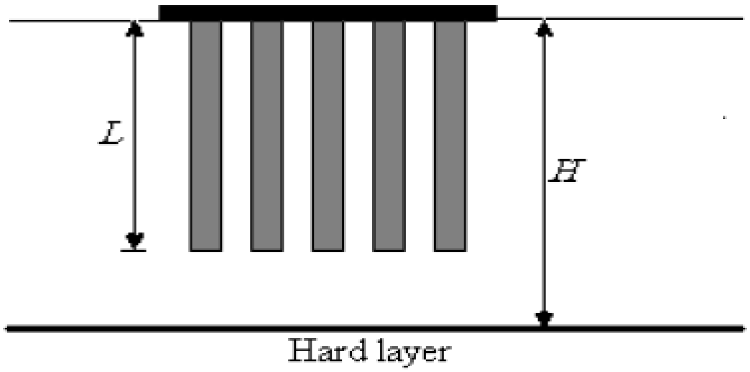

Figure 2.9: Modeling of group of stone columns (Zahmatkesh & Choobbasti, 2010)

2.6.1 Single columns

Broms, (1991) reported that, the ultimate bearing capacity of a single column is governed either by the shear strength of the surrounding soil (shear failure) or by the strength of the column materials (column failure). In case of soil failure, the ultimate bearing capacity of a single column depends both on the skin friction resistance along the surrounding surface of the column and on the bottom resistance. The short term ultimate bearing capacity of a single column can be expressed as:

$$Q^{col} = \pi . d . lc + 2.25 . \pi . d^2$$

Where:

Q^{col}= bearing capacity of column

d = the diameter of the column.

lc = the length of the column.c_u = the average undrained shear strength of the surrounding soil.

2.6.2 Group of columns

Broms, (1991) presented that similar to single columns, the ultimate bearing capacity of a column group is governed either by the shear strength of the untreated surrounding soil and the shear strength of the column materials. The total bearing capacity of a group of columns can be written as:

$$Q^{group} = 2Cu.lc.(B + L) + (6\ to\ 9)Cu.B.L$$

Where;

Q^{group}= bearing capacity of group of columns

B and *L* are the width and length of the locally loaded area.

lc = the length of the column.

c_u = the average undrained strength of the surrounding soft soil.

2.7 Stone column arrangement

2.7.1 Simulation of stone columns

Previous studies in the literature made a lot of simulation for stone columns (Sexton et al., 2016). The axisymmetric that based on cell unit makes the distance between columns more uniform and the loading that applied on cells is more homogenous. Figure 2.10 shows this kind of grids. This method depends on using the area replacement ratio. This ratio is described below.

$$\text{Area replacement ratio, } RR = \frac{1}{g}\left(\frac{Dc}{s}\right)$$

Where;
RR: replacement ration
s: column spacing
Dc: column diameter
g: grid ratio

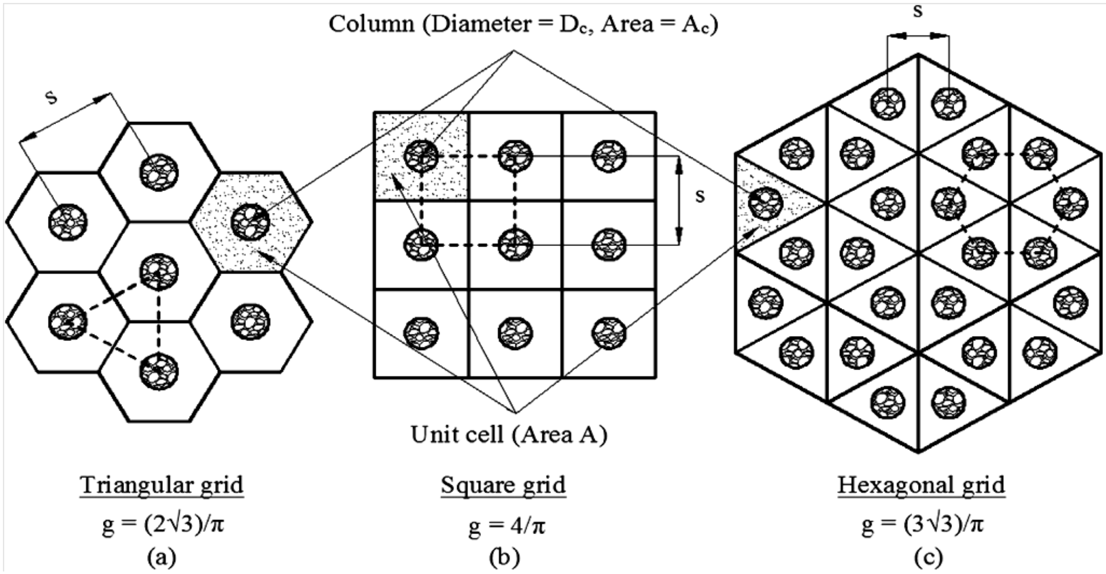

Figure 2.10: Simulation of stone columns (Sexton et al, 2016)

2.7.2 Configuration of stone columns

Columns spacing of triangle and square patterns

In triangular e and square patterns, each column acts as a separated cylindrical element with a radius of influence (Re) given in equation below.

Re = C.S

where S is the constant distance from center to center of each column and C is a constant having values 0.525 for triangular pattern and 0.564 for square patterns. For most practical cases, the influenced diameter may be assumed to be equal to the actual column spacing (Balaam and Booker. 1981). Figure 2.11 shows the radius of influence (Re) of the square and triangular pattern.

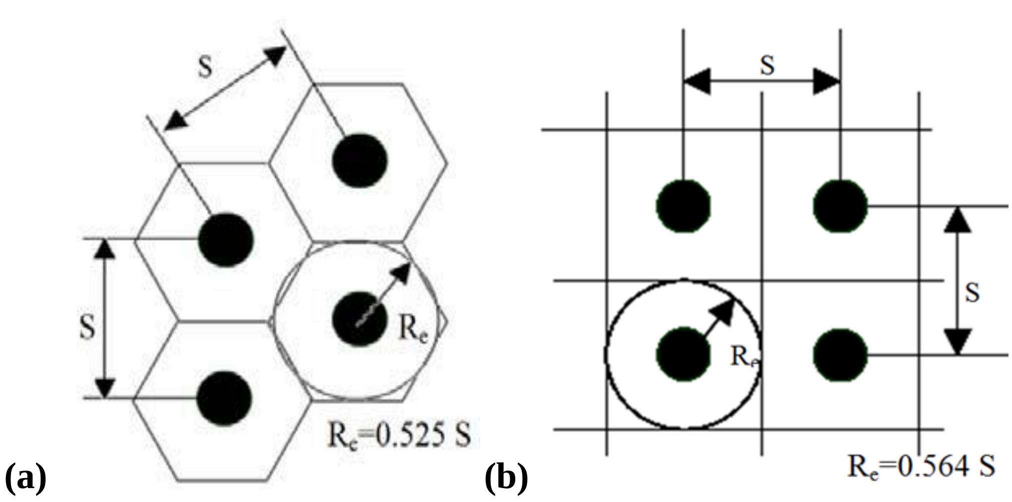

Figure 2.11: Plan (a)Triangular pattern (b) square pattern (Balaam and Booker, 1981)

Columns spacing of concentric ring

This method is concerned on centric stone column with concentric ring. This ring is divided by symmetrical axis in each direction which formed a geometrical simulation. Figure 2.12 illustrates the concentric rings: (a) stone columns grid with respect to a reference column; and (b) calculation of concentric ring dimensions. (Elshazly et al., 2008).

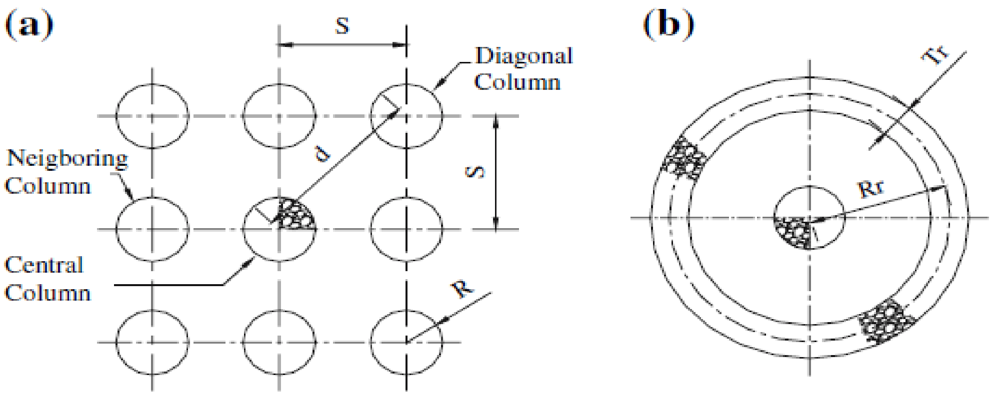

Figure 2.12: The illustration of concentric rings (Elshazly et al., 2008)

2.8 Load transfer mechanism in the stone column application

One of the techniques available for improvement of the mechanical prperties of soft clay is the replacement of some of the clay soil with crushed rock or gravel to form an array of stone columns under the foundation. The granular material is stiffer than the soft clay so that the columns act as piles transmitting the foundation loads to greater depth with load transfer occurring by a combination of shaft resistance and end bearing. The granular material has a high permeability by comparison with the clay so that the column act as drains reducing the path length for consolidation of the soft clay under the foundation and hence speeding up the consolidation of this material Figure 2.13 shows the load transfer in stone column (Wood & Hu, 1997).

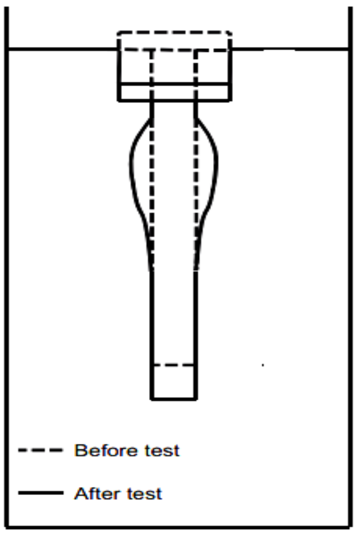

Figure 2.13: Load transfer in stone column (Ali et al., 2014)

2.9 The influence of the installation of stone columns

Installation of columns can be done by different types of techniques such as: deep vibration or hydraulic equipments like vibrocompaction or vibroflotation (Priebe, 1995, Castro et al., 2014). The changes can also be from the nature of surrounding soil. Installation of stone columns can make the soft soil more dense due to the pressure loading (Slocombe et al., 2004).

2.10 Floating stone columns

Stone column is considered as an effective way to resist the settlement behaviour and to improve the time of consolidation. In addition, floating columns are mainly used in construction sector due to some factors such as: cost, excavator's limitation and end bearing capacity (Ng et al., 2014).

Various methods exist to measure the degree of settlement and consolidation of stone columns. Priebe (1995) discovered the most common way to calculate the settlement of stone columns in the ground. This method is summarized by using a unit cell notion, which considers the stone columns system in rigid state, while the soil part as a parameter.

Rao and Ranjan (1985) prepared equation by using equivalent modulus to estimate the settlement of soft clay under the floating columns. Japan Institute of Construction Engineering JICE (1999) suggested a way to measure the settlement in soft clay layers include floating stone columns by using equation below.

$$\alpha = \frac{Ac}{A}$$

where; α: the settlement, Ac: area of column, A: total influence area.

2.11 Plate load test

Venkatramaiah, (1995). Plate load test is an in-situ load bearing test and it is considered as the main approach to investigate the settlement characteristics of soft clays . It is used to determine the bearing capacity and settlement of soil under a given loading condition in the field. Generally, it depends on the rigid plate level to foundation surface. This test determines the settlement according to the loads that can be applied for each time. The settlement degree can be observed by using two or three dial gages. There are two kinds of loads that can be applied either gravity load or dead weight by using hydraulic jack. The test set-up is shown in Figure 2.14. Where's, D_f = depth of foundation and b_p = diameter of plate.

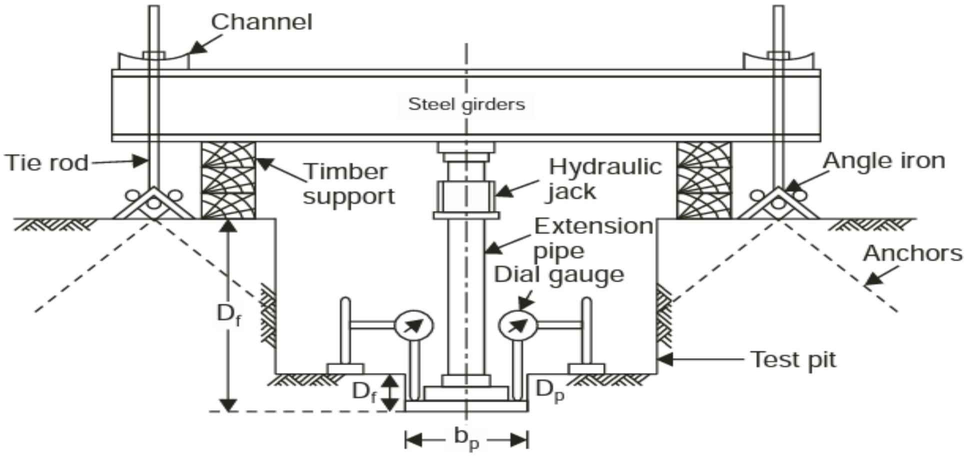

Figure 2.14: Plate load test set – up

Chapter 3

MATERIALS AND METHODS

3.1 Introduction

In this study, series of tests were performed to study the effect of stone columns on the settlement of soft clay and beach sand. Different kinds of waste materials were used in the construction of the stone columns. This chapter will describe the physical properties and the mechanisms that were used in experimental study. The method of analysis that were used in the previous research (Chenari et al., 2017; Zahmatkesh & Choobbasti, 2010; Malarvizhi & Ilamparuthi., 2004; Isaac & Girish 2009; Ali., 2010) were also studied and an appropriate methodology was developed in this study.

This chapter summarizes the techniques that were used during testing. The properties of the soils before stone column application were studied so that the natural properties of the soils were introduced. Two types of different soil are used in this study; the first one is loose sandy soil and the second one is soft silty clay. These types of soils are considered to be the most problematic soils in North Cyprus (Malekzadeh & Bilsel 2012; Mirsalehi 2013; Abiodun & Nalbantoglu 2015; Onochie & Rezaei 2016). Standard test procedures were used to determine the properties of the soils used in this study. The main test that was performed on both soils is the plate load test. This test was performed in order to investigate the settlement of soft silty clay and the bearing capacity of the loose sand reinforced with the stone columns.

Stone columns application is performed by using different types of construction waste materials. This application is used for increasing the bearing capacity and improving the settlement behavior of soils. The stone columns systems that were used in this study are single and group of stone columns. The design of the stone columns: diameter, spacing, height, loading, etc. have been studied from the previous studies (Babu, 2013; Ellouze, 2017; Kadhim, 2015; Castro, 2017) in order to simulate the most effective soil model for field application. The design details of the tests include; soil and materials preparation, layer compaction, stone columns insulation, surface leveling and model tank preparation. All the physical and mechanical tests in this study had been carried according to American Society for Testing and Materials (ASTM) standers.

3.2 Soil samples extraction

Soil samples in this investigation are extracted from two different locations: Tuzla and Glapsides Beach by using two different ways of excavation. For soft clayey soil which existed below 5 m in Tuzla region, big excavator was used to take the sample Figure 3.1 shows the sample extraction mechanism. On the other hand Glapsides Beach sand was taken near the surface below approximately 50 cm.

Figure 3.1: Extraction of soft clayey soil from Tuzla.

3.3 Materials

The soils that were used in this study are taken from Tuzla region and the Glapsides Beach in Famagusta, North Cyprus. Tuzla soil is very soft and it has a very high compressibility characteristic whereas Glapsides Beach sand exists in loose saturated state and it has a bearing capacity problem. It is also known that Cyprus is in a seismically active zone (Erhan, 2009; Atalar & Das, 2009) and in fully saturated loose sands, liquefaction can be a serious problem. Due to these problems *in* Tuzla and the Glapsides regions, the aforementioned soils were decided to be studied in the present study.

The Glapsides beach sand is taken from the depth of approximately 50 cm from the surface. The soft clayey silt exists below 5 m from the ground surface in Tuzla region. This soft soil was excavated from a depth of approximately 6 m to 7 m below the ground surface

3.3.1 Soft soil

Figure 3.2 shows the location of soft soil taken from Tuzla region. Stone column applications have been applied on soft soils to improve the stability of such soils (Guetif et al., 2007; Zahmatkesh & Choobbasti, 2010). Table 3 describes the physical properties of soft clayey silt used in this study.

Figure 3.2: Location of soft soil in Tuzla.

Table 3.1 : Physical properties of soft soil

Soil index properties	Values
In situ bulk density (g/cm^3)	1.74
In situ dry density (g/cm^3)	1.18
Specific gravity	2.75
In situ water content (%)	48
Maxim dry density (g/cm^3) (1)	2.14
Optimum moisture content (%) (1)	21
Liquid limit (%) (2)	60
Plastic limit (%) (2)	33
Plasticity index (%) (2)	27
Classification (3)	CH
Compression index Cc (4)	0.36
Expansion index, Cr	0.16
Preconsolidation pressure, $\sigma p'$ (kPa)	60

1 According to ASTM D 698 – 07

2 According to ASTM D 4318

3 According to ASTM D 2487 - 00 (Unified Soil Classification System)

4 According to ASTM D 2435-04

3.3.2 Loose sandy soil

Loose saturated sands are considered to be one of the problematic soils in geotechnical engineering. If such soils exist in seismically active regions, they are liable to liquefaction and settlements during strong ground motion.

In this study, loose saturated sand is collected from Silver beach, Famagusta North Cyprus. Figure 3.3 shows the location of loose sand sample. Series of tests were conducted in order to determine the physical properties of this sand. Insitu density and insitu water content tests were performed on site and the rest of other tests were conducted in the soil mechanics laboratory. Table 3.3 shows the physical properties of loose sand used in this study.

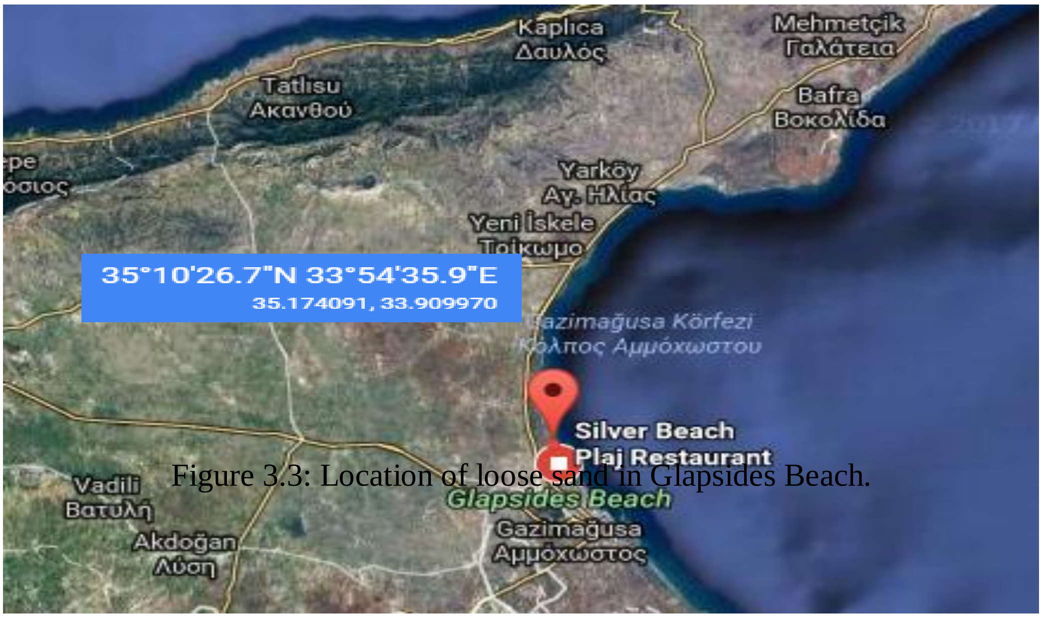

Figure 3.3: Location of loose sand in Glapsides Beach.

Figure 3.3: Location of loose sand soil.

Table 3.2 : Physical properties of sand.

Soil index properties	Quantities
In situ bulk density g/cm^3	1.6
Specific gravity (1)	2.6
Maxim dry density g/cm^3 (2)	1.82
Minimum dry density g/cm^3 (3)	1.49
Relative density %	25
Water content %	13.5
Maximum void ratio (2)	0.7
Minimum void ratio (3)	0.4
In situ void ratio	0.625
Classification (4)	SP
Group name	Poorly graded sand
Coefficient of curvature, Cc	1.135
Coefficient of uniformity, Cu	1.351

1 According to ASTM D 854

2 According to ASTM D4253 - 16

3 According to ASTM D4254 - 16

4 According to ASTM D 2487 - 00 (Unified Soil Classification System)

The particle size distribution curve of the sand is given in Figure 3.4.

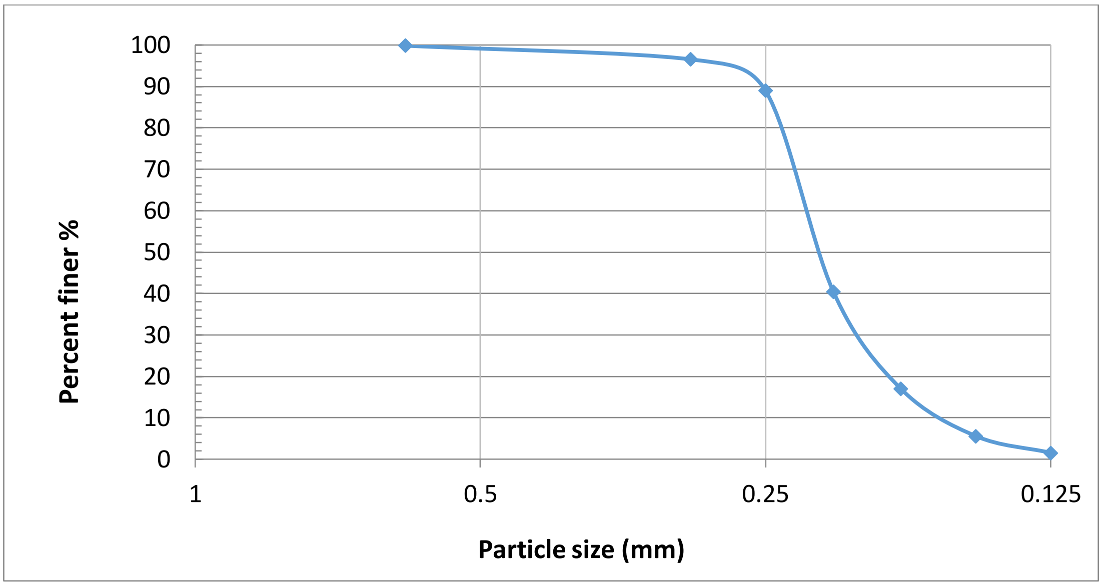

Figure 3.4: Loose sand analysis

3.4 Stone column concept

Stone column materials are considered as a method for reducing the settlement and increasing the bearing capacity of the soil. Stone column techniques depend largely on the kind of filler materials such as; stone, sand or rocks. Different types of materials are used as a stone column material in this study. The properties of these materials used in the study are different; each one has specific characteristics like strength and stiffness. Two types of stone column design were used: single and group of stone columns. Stone columns are generally carried out using different methods of replacement such as; the vibro replacement technique, the wet method and the dry method (Keller Far East, 2002; ICE, 2009). In the study, different factors related to stone column application have been studied; different dimensions of the stone columns, different arrangement pattern of stone column, etc. Both single and group of stone columns were used in the study.

3.5 Stone column materials

In this study, different types of filler materials were used as stone column materials. The reinforcing materials are chosen entirely from the *waste* products generated in the construction industry in North Cyprus. Due to the demolishing of old buildings, lots of waste materials such as steel, concrete and bricks are being generated and usually these waste materials cannot be reused in the construction and disposal of these waste materials is very difficult. This study tries to find a way of using these waste materials as a filler material in the construction of the stone columns. The type of waste materials used in this study are the old crushed waste concrete and the broken bricks existing on many construction sites in North Cyprus.

3.5.1 Crushed waste stone

Crushed stone (Stone) is one of the type of filler materials used in this study. Usually, this material is used in the construction projects especially in concrete works, as base layer for foundation and finishing works. Crushed waste stone used in this study is collected from different construction sites existing as a waste construction material. Figures 3.5 and 3.6 show the particle size distribution curve and sample of crushed stones, respectively.

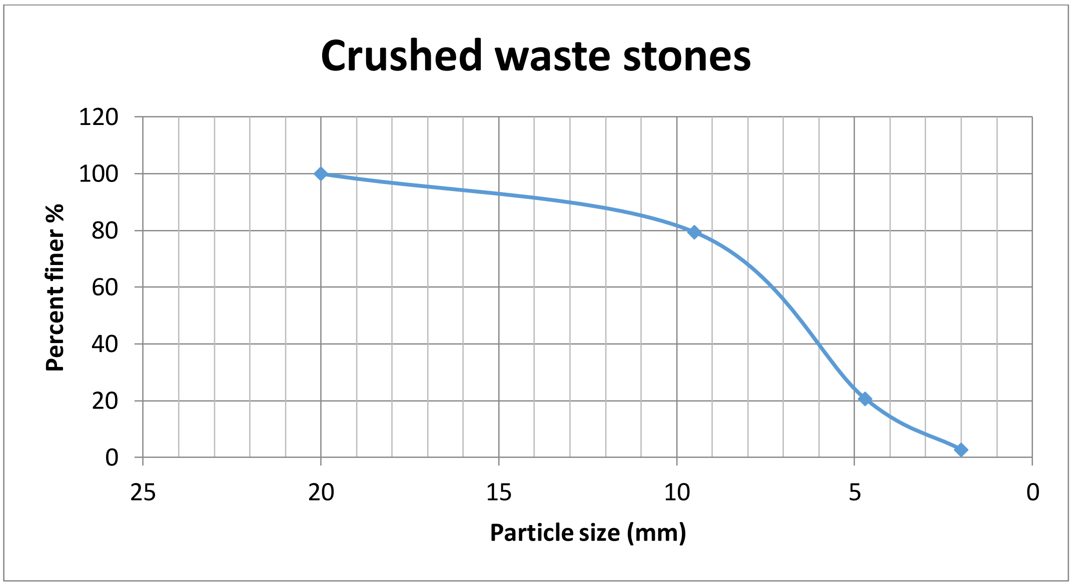

Figure 3.5: Particle size distribution curve of the crushed waste stone

Figure 3.6: Sample of crushed waste stones

3.5.2 Crushed bricks

Brick is one of the most important elements in construction projects. Bricks are used mainly to built the inernal and external walls in the structures. There are alots of broken bricks which are existing as waste material on construction sites. Figure 3.7 shows some sample of crushed bricks.

Figure 3.7: Sample of crushed bricks

Huge amounts of bricks are exposed to crushing due to different reasons such as; during transportation , extending the pipes through the bricks, during demulation work and bad manufacturing of the bricks. Crushed bricks can not be used again in wall construction. Figure 3.8 shows the particle size of the crushed bricks used in this investigation.

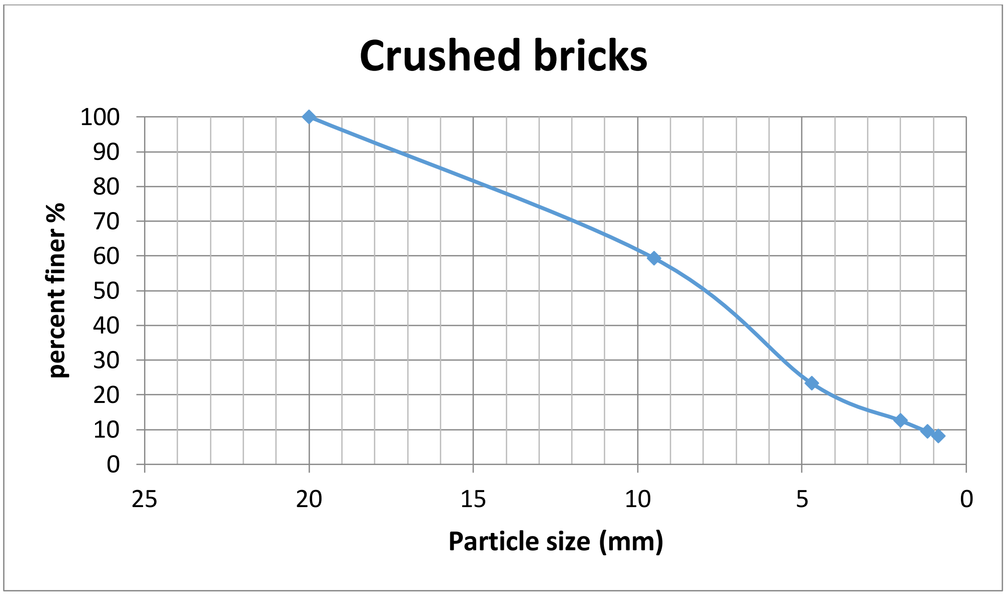

Figure 3.8: Particle size analysis of the crushed bricks

3.5.3 Crushed waste concrete

Recycled crushed waste concrete materials with high compressive strength are selected in this study because there are considerable amount of crushed exist in North Cyprus as a waste material. It is predicted that crushed waste concrete will work well in the stone column application. This kind of waste is very heavy and it is very difficult to be transported for disposal. Also, very large area is needed for the storage of this waste material. The crushed waste concrete in this investigation was collected from an old buildings that were demolished due to time and environmental conditions. These buildings were no longer able to work as structural elements. The collected waste concrete blocks were broken into small pieces. Figures 3.9 and 3.10 show the particle size distribution curve and the crushed waste concrete sample that is used in this study, respectively.

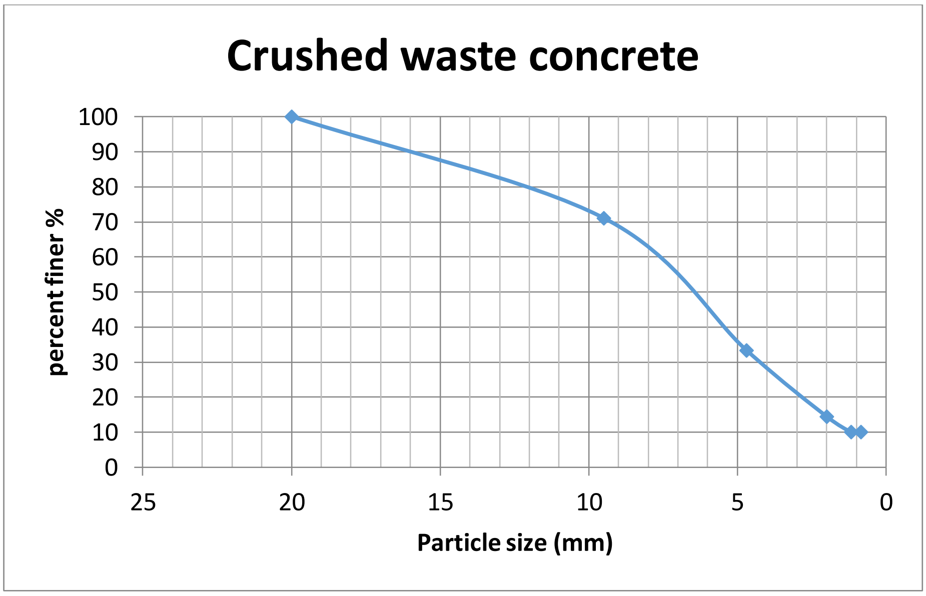

Figure 3.9: The particles size distribution curve of the crushed concrete


Figure 3.10: Sample of the crushed waste concrete

3.6 Methods: Test preparation

The test tank that was used in this study has cylindrical shape. The diameter of the test tank used for testing the loose sand is 40 cm diameter and the length is 40 cm. Figure 3.10 shows the steel tank used for the loose sand. The test tank that was used for clay has 25 cm diameter and 35 cm length as described in Figure 3.11. The dimensions of the test tanks are chosen according to the principles suggested by (Meyerhof & Sastry, 1978; Bowels, 1988). (Meyerhof & Sastry, 1978; Bowels, 1988) They stated that the failure zone of the stone column extends about 1.5 times the diameter of the stone column and 2 times the diameter of piles over the depth of stone column.

To evaluate the settlement rate in the test tank, free spaces should be provided (Indraratna & Redana, 1995). The test tank should have enough space between the failure wedges around the stone columns and the surface of test tank (Malarvizhi & Ilamparuthi, 2004). In this study, in the preparation of the soil sample in the test tank, the tank is divided into three layers; in the first layer, the coarse stone was placed for drainage in 10 cm, in the second layer, the test soil sample (soft soil or loose sand) was compacted and placed in 25 cm and then on top of the soil sample, a model footing was placed in the third layer. Figure 3.10 shows the corresponding layers of the test tank.

Figure 3.11: Model test tank

3.7 Sample preparation in the laboratory test tank

In this investigation, in order to simulate the natural conditions of the soil in the field, all the test samples were prepared at the in situ density of the studied soils. As it is known, during the extraction of the soil samples, the soil properties such as; void ratio, density, are changed due to the disturbance of the soil. Because of this reason, in situ density and water content of the soil in the field were determined during soil extraction. ASTM D 2937 method was used to determine the in situ density of the soil in the field.

The in situ density of the loose sand was found to be 1.6 g/cm^3. By using this density value, the amount of sand required to fill the test tank in the laboratory was calculated and the calculated amount of sand was compacted into the test tank.

According to the calculations, the amount of sand required to fill the test tank at the predetermined density value was 50.24 kg.

To get the specific degree of compaction, before testing. Small cylindrical model was used to determine the number of blows required for placing the sand at the required density. The weight of the small mold used in this study was 2943.4 g. The length and the diameter of the mold were 13.5 cm and 10.3 cm, respectively. The sand was placed in three layers in the mold, and specific number of blows were applied for each layer of sand starting from 0 to 10 blows. For each case, the weight and the density of soil were measured and calculated to determine the optimum numbers of blows that should be applied on the sand in the test tank. Table 3.3 described the data obtained for each case. Figure 3.12 shows the relationship between density of soil and the number of blows.

Table 3.3: Number of blows and the density of the sand.

Weight of sand in the test tank (g)	Bulk Density (g/ cm^3)	Number of Blows (N)
1324.9	1.47	0
1354.0	1.50	2
1400.5	1.54	4
1444.4	1.58	6
1462.9	1.63	8
1507.6	1.67	10

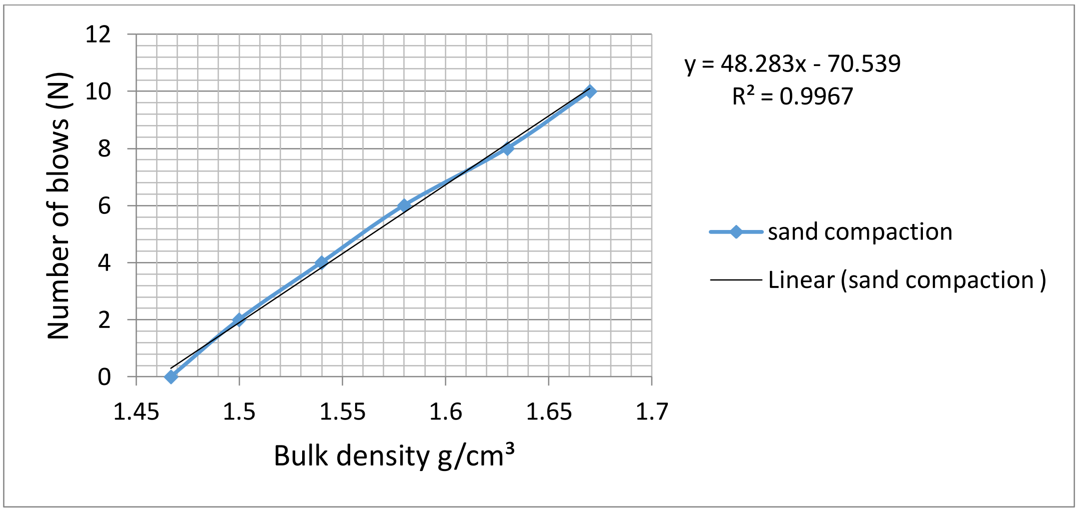

Figure 3.12: The relationship between density of sand and the number of blows

In Figure 3.12, the number of blows that should be applied to 50.24 kg of sand in the test tank was found to be 7. The same method for determining the number of blows for soft soil was used and the number of blows for that soil was determined to be 5.

3.8 Preparation of test tank

In the preparation of the sand and the stone columns in the test tank, some field conditions were considered and adapted in order to simulate the actual field conditions in the laboratory. These were friction between the test tank and soil, number of layers, the stone columns installation and spacing, etc. Some of these conditions were described below.

3.8.1 Oiling of the test tank

Enough care was given to oil the test tank in order to eliminate the frictional force between the wall of the test tank and soil sample. A thin coat of grease was applied for all the cases where both single and group of columns were installed. This coat was applied on the inner surface of the test tank in order to work well for reducing the friction.

3.8.2 Base layer

For enabling the drainage of pore water and forming a hard layer (Zahmatkesh & Choobbasti, 2010) for the stone columns, a base layer was provided at the bottom of the test tank. This layer contained crushed stone having particle sizes between 5 - 20 mm. The height of this layer was 10 cm. Zahmatkesh & Choobbasti, 2010 stated that stone columns should be extended until the hard layer. Figure 3.13 shows the base layer in the test tank.

Figure 3.13: Base layer of test tank

3.8.3 Soil sample preparation in the test tank

The second layer in the test tank is occupied by soil samples (soft clay or loose sand). The centre of the tank was marked and a PVC pipe of 50 mm diameter was placed at the centre of the tank. Around this pipe the soil was compacted. The calculated amount of soil according the field density was divided into three equal amounts and then they were compacted in three layers in 25 cm thickness with specific number of blows as specified in Figure 3.12. Figure 3.14 shows the preparation of soil sample in the test tank as described by Ng & Tan, (2014). They stated that soil should be well compacted in the test tank according to the in situ bulk density and water content values to simulate the natural field conditions.

Figure 3.14: The compacted soil sample in the test tank

3.8.4 Stone column preparation in the test

Dimensions of stone columns

The dimensions of stone column that are used in this study were selected carefully to fulfill the design requirements of the stone columns. In all the experiments in this study, 5 cm diameter and 25 cm height of stone columns were used in order to produce the full limiting axis stress on the column (Isaa & Girish, 2009). According to Isaa & Girish, 2009. l/d ratio (length of column/diameter of the column) should be minimum 4.5 so that full limiting axial stress on the stone column is developed. Figure 3.15 shows the length of the layers in the test tank.

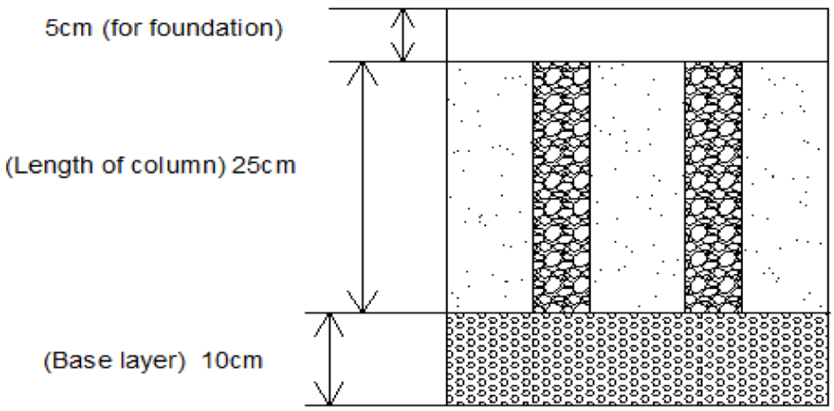

Figure 3.15 The dimensions of the layers in the test tank

Single and group of stone columns

In this study, two types of stone columns were used; single column and group of columns. Single column case was used for both soft clay and loose sand beds. In all cases, the center point of steel tank was taken as datum point to determine the distance between the stone columns. Two sheets were used to determine the specific location of single and group of columns. These sheets were used to fix the position of stone columns and to keep the equal distance between the columns. Figure 3.16 described the pattern of stone column. PVC pipes were used as frame to keep the dimensions of column uniformly.

Figure 3.16: The pattern of single and group of stone columns

Spacing between stone columns

The center to center spacing between the columns in the test tank was constant for all cases. The spacing was taken to be 3 times the diameter of the column (Isaa & Girish, 2009). Enough space was provided between the edges of the tank and the stone columns so that there would not be any interface with the failure zone (Rao & Madhira, 2010). The pattern of stone columns that was used in this study was square. The square pattern was formed by marking the center of steel tank and then placing the pipe of stone column at the center of the tank.

Oiling of the PVC pipe

A layer of oil was applied around the inner and outer surface of the PVC pipe for easy extraction of the pipe from the soil. This enabled the pipe to be withdrawn without any disturbance to the surrounding soil.

Installation of stone columns in the test tank

In this study, two methods; one for the loose sand and one for the soft soil were applied for the installation of stone columns in the test tank. For the loose sand, the center point of the steel test tank was first determined and then the PVC pipe over the base layer was placed before adding the loose sand into the test tank. Figure 3.17 showed the installation process of the stone column.

Figure 3.17: Installation of a single stone column into the test tank

Slight grease was applied on both inner and outer surface of the pipe for easy withdrawal without any disturbance to the surrounding soil. Required stone column material was carefully charged in the tube in three layers to achieve required density. The PVC tube was withdrawn to certain level and charging of stones for the next layer was continued. The operations of charging of stones, compaction and withdrawal of tubes were carried out simultaneously.

The filler materials of stone column were then carefully charged into the pipe. The filler material was divided to three equal amounts. Each amount was placed and compacted into the PVC pipe by using 12 mm diameter steel rod until the required amount of density (1.5 g/cm^3 was achieved. According to Malarvizhi & Ilamparuthi, 2004), this density of the stone column material should be taken very close to the surrounding soil's density. When the stone column was filled completely in the PVC pipe, and the required density was achieved, then the loose sand was placed around the pipe and compacted uniformly in three equal layers. Figure 3.18 showed the process of installation of loose sand for group of columns.

Figure 3.18: Installation process of single and group of columns in the test tank

All the stone columns were fixed to be vertical during the insulation of soil sample. The upright position of the PVC pipe was achieved with the aid of a water balance. Figure 3.19 showed the pipe and the water balance.

Figure 3.19 The vertical stone column

The second method of stone columns installation was for soft clayey silt sample. For this soil, the base layer of crushed stone was first placed at the bottom of the test tank. The soft clay soil was placed gently and compacted into the test tank with steel rammers. To achieve the same density of clay in each test, the clay was placed in five equal layers of 4 cm thickness in the tank. The surface of the test tank was mobilized, and then the single pipe was pushed gently into the center of the clay bed until it reached to the bottom of the soil layer. Then the pipe was pulled out of the tank and the soft clay was realized from the pipe. Then the hole in the test tank was filled with stone column materials and compacted. All the similar procedures that were mentioned for the loose sand such as; oiling of the tank, compaction of the soil, etc. were also followed in soft clayey silt. Figure 3.20 showed the stone columns and the soft soil in the test tank.

Figure 3.20 The stone columns and the soft clay in the test tank

Extraction of PVC pipes from the test tank

After placing the PVC pipes and filling them with the column materials, the surface of the test tank was trimmed, and then the PVC pipes were lifted up vertically in order to prepare the sample to the test.

Figure 3.21: Extraction of stone columns

After extraction of all the pipes of the stone columns, the surface of the test tank was leveled and the soil was left until 24 hours to develop a good contact between the filler materials of stone columns and soil particles in the test tank. Figures 3.21 and 3.22 showed the last stage of the test tank before loading.

Figure 3.22: Test tank before loading

3.3.5 Loading system

Two types of loading systems were used in this investigation; the first one was for loose sand sample and the second one was for the soft clay. After the preparation of the loose sand tank, small circler foundation with specific dimensions suggested by Malarvizhi & Ilamparuthi, 2004 was used in the test.The dimensions of the foundation were 12 cm diameter and 5 cm thickness. According to Malarvizhi and Ilamparuthi, 2004, the diameter of the loading plate in the test tank should be equal to 2.3 times the diameter of the single column.

Loose sand sample

To obtain the load deformation curve of the loose sand, the compression machine (hydraulic jack) shown in Figure 3.23 was used for loading. The vertical load was applied on the single and group of the stone columns. The applied loads and the deformation values were taken with a computerized system by the machine.

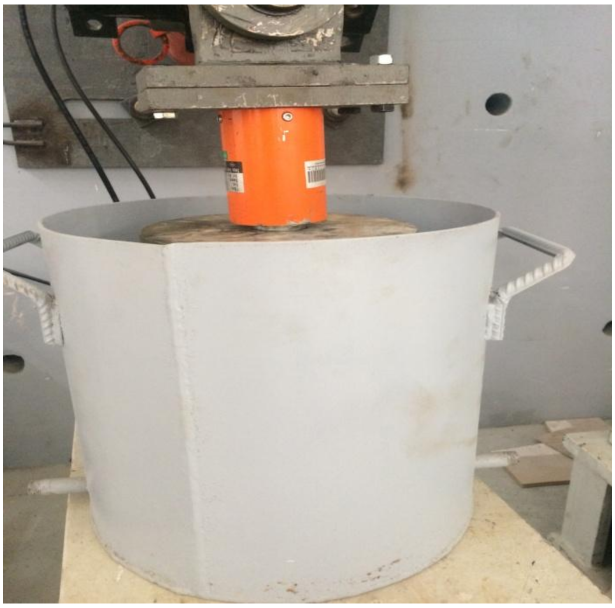

Figure 3.23: Soil sample under the vertical loading

Two dial gauges were fixed on the top of the foundation to measure the settlement of the soil under the applied loads. Figure 3.24 showed the foundation with sensitive settlement gauges. The loading was applied with a rate of 0.48 mm/min.

Figure 3.24: Sensitive settlement gauges fixed on the circular foundation

The processes of the loading system were started from zero load. The load was increased gradually until the foundation became submerged. The date was obtained in tabular form giving the amount of applied loads, time and the average settlement between the two deformation gauges. Figure 3.25 showed the test tank after loading.

Figure 3.25: Loose sand sample after loading process

Loading of soft clay

The mechanisms that had been used with soft soil were different from the previous method. Because of the low permeability of highly compressible soft soil, the settlement measurement was hard to investigate in short time interval. The method that was chosen in this study was similar to the method that was suggested by Malarvizhi & Ilamparuthi, (2004). According to this method, the loads were increased gradually in short time interval and the settlement values were recorded by deformation gages.

The loading was conducted by using a cylindrical tank with 20 cm diameter and 30 cm height with two drainage outlets. After the installation of the stone columns and the soft soil, a thin steel foundation plate with 15 cm diameter was placed on the surface of the prepared soft soil. The loads were then applied on a small cylinder which was placed over the center of the steel foundation plate. Figure 3.26 showed the test set up for soft clay.

For the soft soil, for all testing, the loading was started from 50 Newton steel disc loads and increased until 250 Newton. 5 hours were needed to apply the whole loads to the soil samples. The loads were increased hourly by 50 Newton as Malarvizhi & Ilamparuthi, (2004). The settlement of the soil was noted after one hour before increasing the load on the specimen.

Figure 3.26: The loading system of soft clay

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Introduction

In this section, all the experimental results obtained in this study were presented and discussed. This chapter described the behavior of natural soil: loose sand and soft clay reinforced with different types of column materials such as; crushed bricks, crushed waste concrete and crushed stones. The tested soils were analyzed with and without stone columns by performing load-settlement tests for analyzing settlement and compressibility of the soft clay and the loose sand. The CBR tests were also performed to investigate the penetration resistance of the same soils reinforced with stone columns with different column materials and the results were presented in this section.

4.2 Physical properties of the tested soil: Loose sand and soft clay

The physical properties and the particle size distribution curve of the loose sand were presented in Chapter 3. The results of the hydrometer test performed on the soft clay were given in Figure 4.1.Hydrometer test was performed according to ASTM D 422 – 63. From figure 4.1 silt content was found to be 32 % and clay content was 62%. The clay content makes up the biggest part of the soil. According to the unified soil classification system, the soil was classified as CH: inorganic clay of high plasticity.

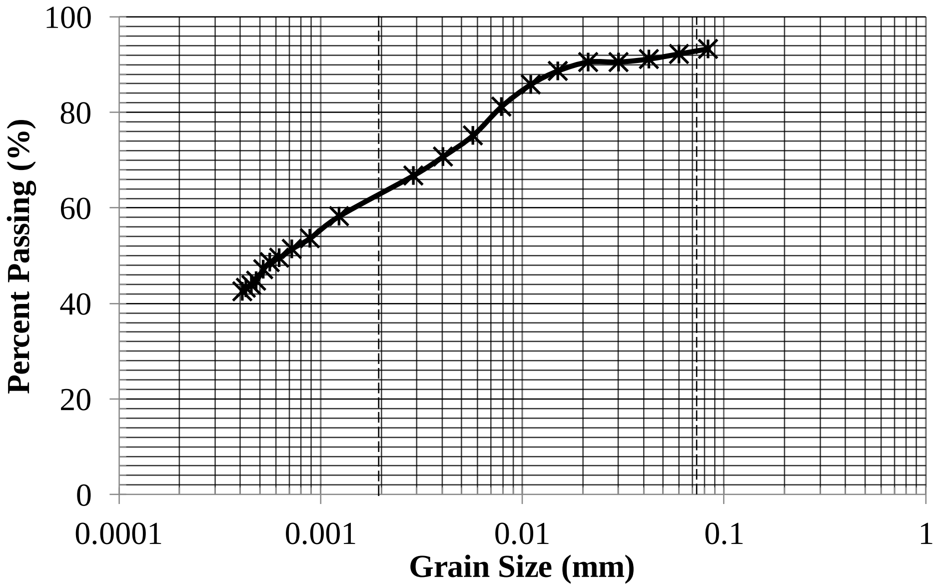

Figure 4.1: Grain size distribution of soft clay soil by hydrometer analysis

The standard Proctor compaction curve of natural soft clay was given in Figure 4.2. and the compaction characteristics of the soil were determined. The maximum dry density of the soft clay was found to be 2.14 g/cm³ and the optimum moisture content was obtained to be 21.0 %.

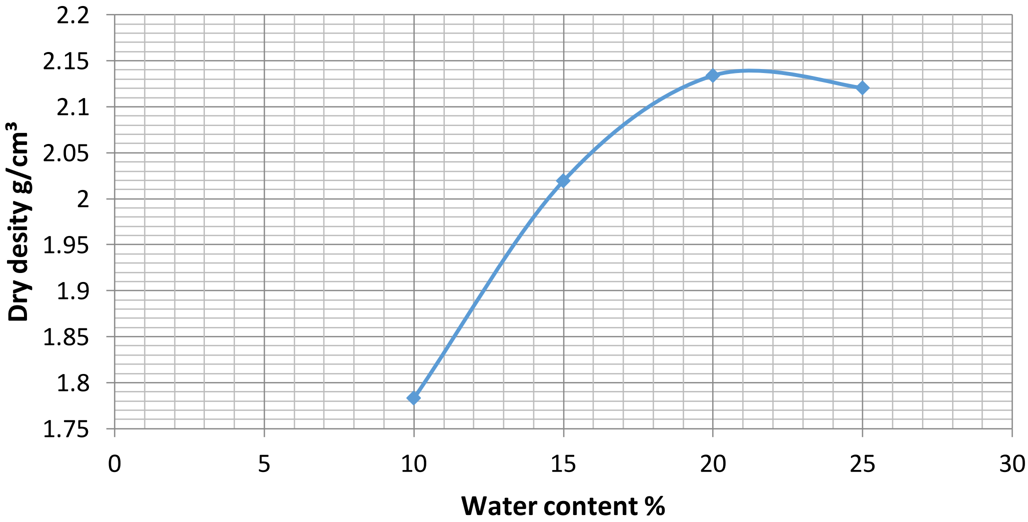

Figure 4.2: Standard Proctor Compaction curve of natural clay soil

4.3 Effects of single stone column on settlement behavior of loose sand

This section will study the behavior of loose sand soil supported with and without single stone column under laboratory plate load test. Settlement behaviors were observed for each sample at different stage of loading. The loading system was started from low pressure (0 kN) to high pressure (until failure of soil).

4.3.1 Behavior of natural soil under laboratory plate load test

Figure 4.3 shows the unreinforced natural loose sand soil under the loading system starting from zero to 4 kN. The applied load was increased gradually. In the first stage of loading between 0-2 kN, small amount of settlement value was observed. after this loading stage, the settlement was increased dramatically. The ultimate load was observed to be 4 kN. At this value the soil failed to resist the applied loads.

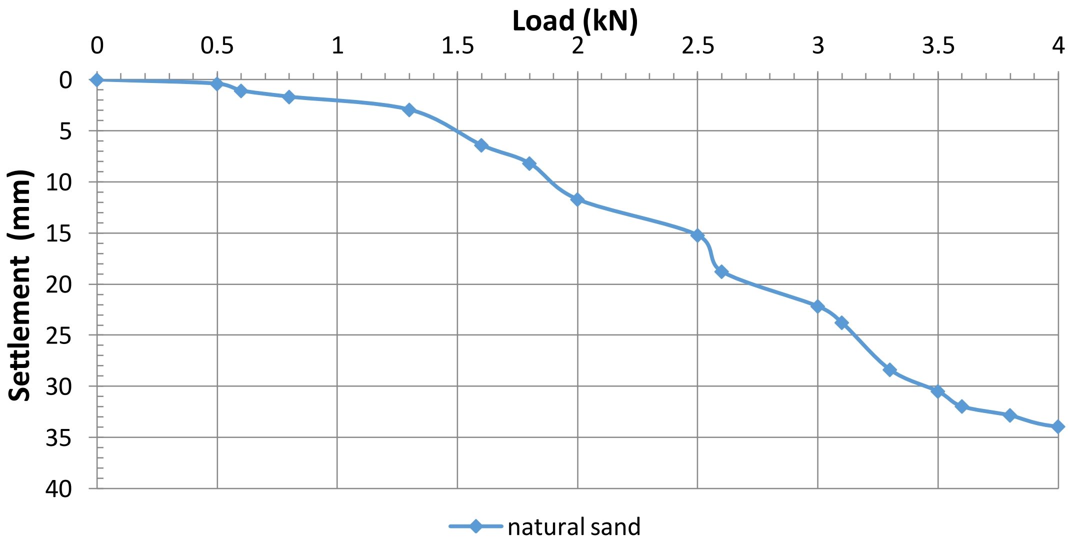

Figure 4.3: Settlement behavior of natural loose sand

4.3.2 Natural loose sand reinforced with single stone column formed by crushed bricks

Figure 4.4 showed the load-settlement curves of the natural loose sand and the sand reinforced with single stone column formed by the crushed bricks.

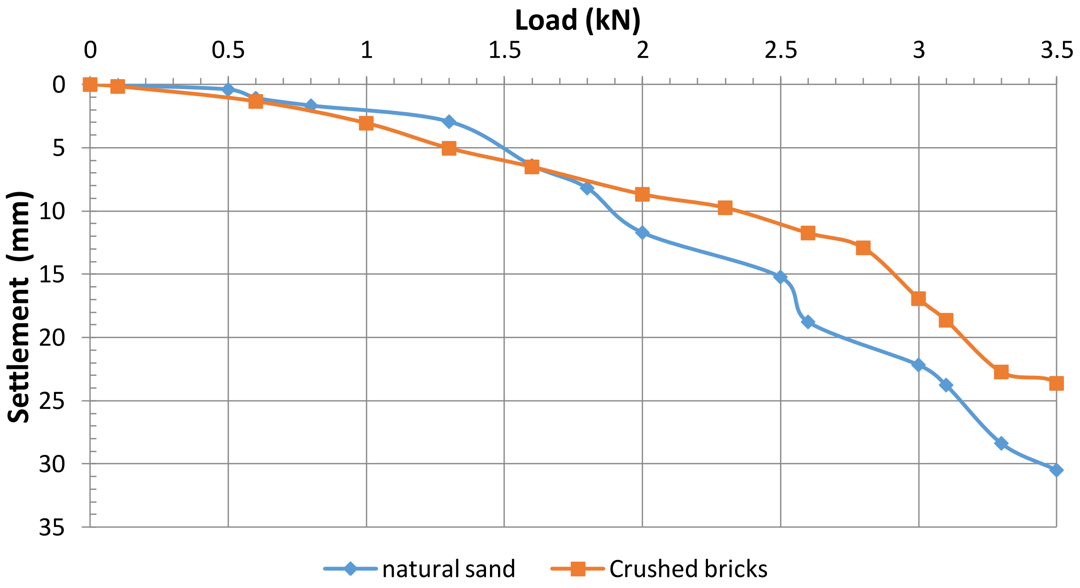

Figure 4.4: Settlement behavior of loose sand reinforced with crushed brick column

Figure 4.4 showed that crushed bricks did not cause a noticeable improvement in the settlement behavior of soil sample. The settlement of soil was increased gradually unit 3 kN, and then the settlement remained unchanged until 3.5 kN at around 28 mm settlement. Then an increase in the settlement of the soil started until the end of loading. The flattening of the curve between 3 kN and 3.5 kN load can be due to the irregular shape of the crushed brick particles and the spacing between them. At the start of loading, as the load was increased gradually, these spaces were filled and closed and a good interlocking between the brick particles was achieved so that no settlement of the soil was observed. Then, with the increase in loading, this interlocking was overcome and the settlement of the soil continued until the ultimate load as illustrated in Figure 4.4.

4.3.3 Natural loose sand reinforced with single stone column formed by crushed waste stone

Figure 4.5 showed the settlement of natural loose sand and the sand reinforced with crushed waste stone . The figure indicated that at the first stage of loading: from zero to 4 kN, there was a continuous increase in settlement of soil sample from zero to 30 mm. Compared with the natural sand, the settlement behavior of the sand with reinforcement was improved due to the higher resistance of the crushed stone to the applied loads.

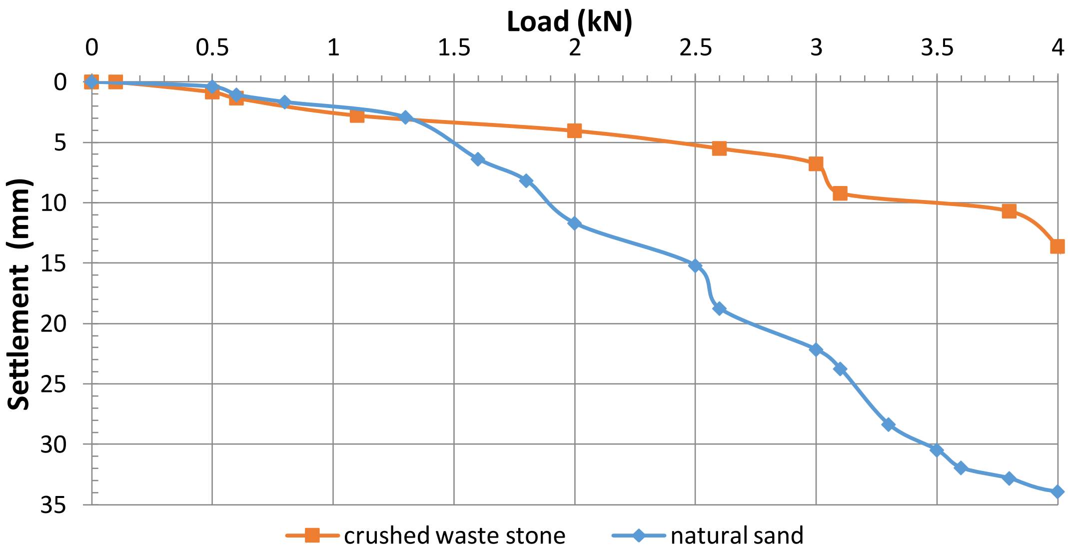

Figure 4.5: Settlement behavior of loose sand sample with crushed stone

4.3.4 Natural loose sand reinforced by stone column formed with crushed waste concrete

Figure 4.6 showed the settlement behavior of loose sand reinforced with single stone column with crushed waste concrete. The figure indicated that compared with the other column materials (crushed waste stone and crushed bricks), crushed waste concrete resulted in the best improvement in the load-settlement behavior. The load carrying capacity of the sand was increased more than 100% as described in the figure below.

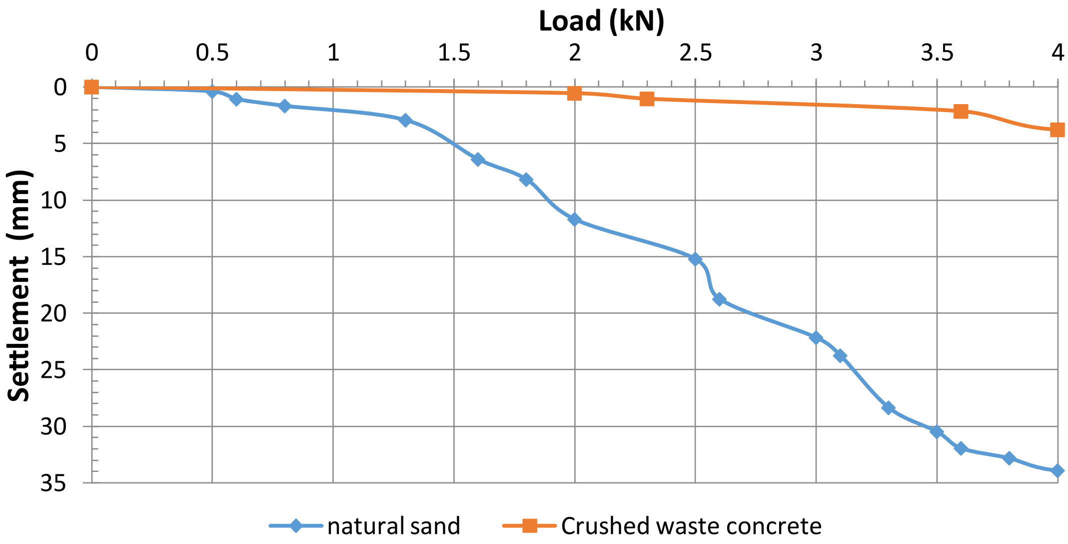

Figure 4.6: Settlement behavior of loose sand sample with crushed waste concrete

4.3.5 Comparison of load-settlement behavior of loose sand with different stone column materials

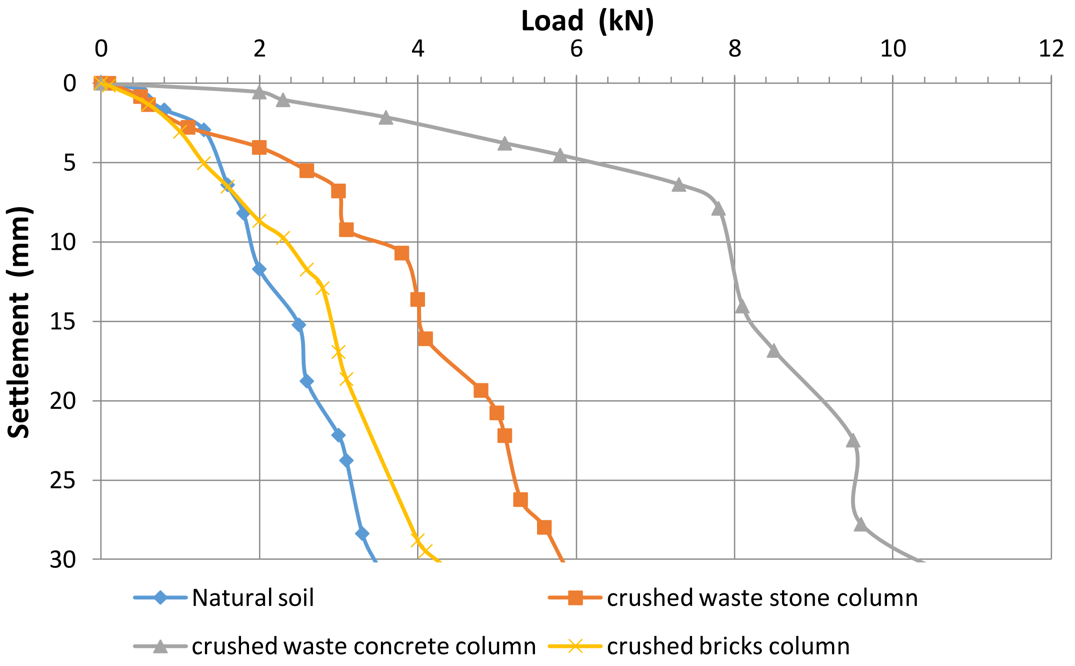

Figure 4.7: Load-settlement behavior of sand with single column by waste materials

Figure 4.7 illustrated the load-settlement behavior of loose sand reinforced with different types of waste materials. As shown in the figure, the superior performance of soil was obtained for the sand sample reinforced by the crushed waste concrete column. The sand sample reinforced by the crushed waste concrete gave the lowest settlement value. 25 mm settlement for the same soil was obtained at around 9 kN loading whereas for the natural loose sand, the same amount of settlement was obtained under approximately 3 kN loading. Table 4.1 showed the loads required for 25 mm settlement for each type of reinforcing stone column material.

Table 4.1. Load required for 25 mm settlement

Material	Load (kN)
Natural soil	3.1
Crushed bricks	3.9
Crushed stone	5.8
Crushed concrete	9.9

4.4 Effects of single stone column on settlement behavior of soft clay reinforced with different stone column materials

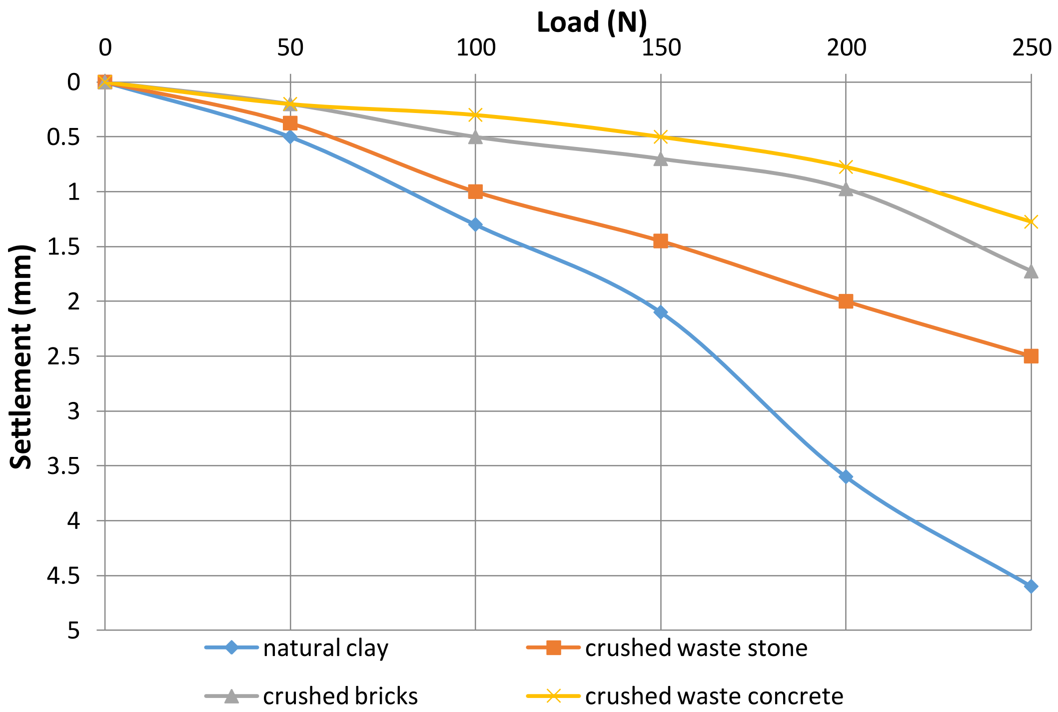

Figure 4.8: Single stone column reinforced soft clay with different column materials

Figure 4.8 compared the test results of reinforced soft clayey silt by using three different types of waste materials. All the samples were subjected to the same loading. The loads on the soil sample were increased in each 30 minutes. Figure 4.8 indicated that natural gave the highest settlement under 250 N loading. Stone columns formed by using crushed bricks and waste concrete played the strongest role for the settlement improvement of soft clay. As shown in Figure 4.8, crushed waste concrete resisted the settlement and achieved the highest performance due to the concrete's higher stiffness and capacity to the applied loads.

4.5 Behavior of loose sand with group of stone columns

In this section, the settlement behavior of the reinforced sand with group of stone columns were studied and the test results were discussed. In the group of stone column application, the same techniques and the loading system that were used in the single stone column application were applied. The obtained test results were analyzed and compared with each other.

4.5.1 Natural loose sand reinforced by crushed bricks as group of stone columns

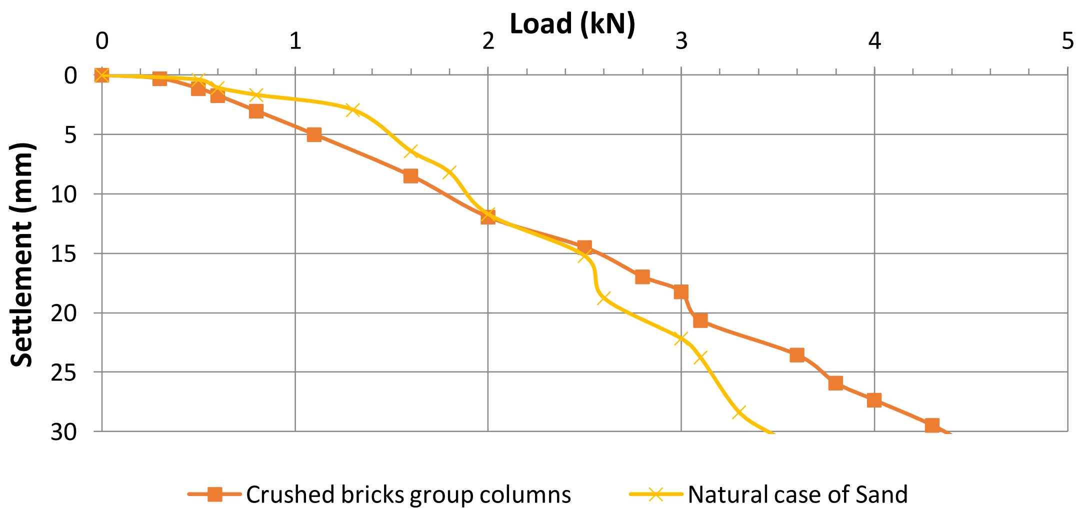

Figure 4.9: Loose sand sample reinforced by group of crushed bricks columns

Figure 4.9 showed the natural sand and the loose sand reinforced with group of crushed bricks columns. From the figure, it can be seen that the settlement of soil reinforced with group of crushed bricks columns increased constantly from zero to 30 mm. There seemed to be no significant improvement with the single column behavior. On the other hand, the settlement behavior of the natural sand was significantly improved with the group of stone column application.

4.5.2 Natural loose sand reinforced by crushed waste stone as group of stone columns

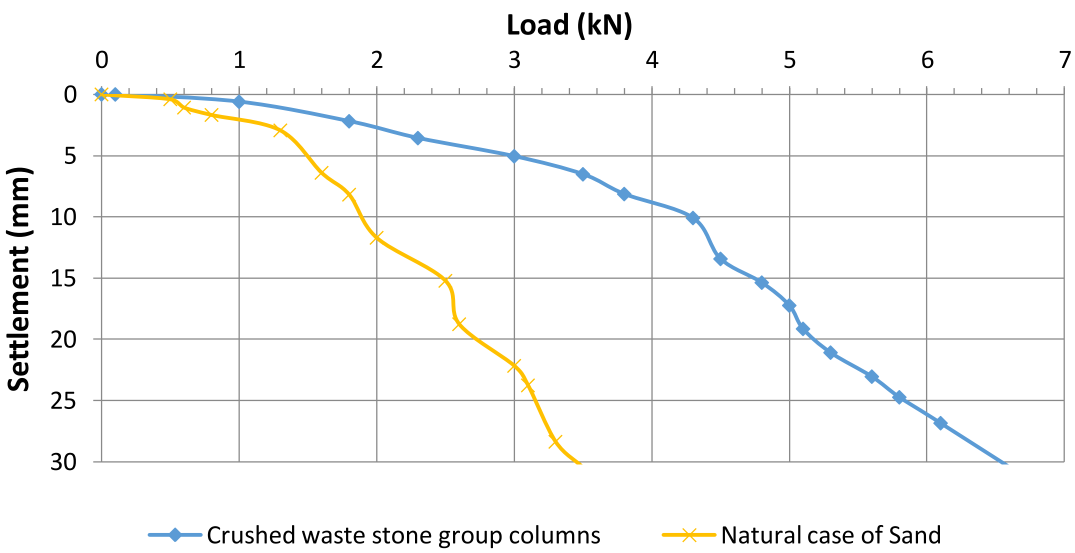

Figure 4.10: Loose sand sample reinforced by group of crushed waste stone columns

Figure 4.10 illustrated the behavior of loose sand sample reinforced with group of stone columns which were formed by crushed stone waste materials. The figure indicated that there was a gradual increase in the settlement values as the loading was increased.

4.5.3 Natural loose sand reinforced by crushed waste concrete as group of stone columns

Figure 4.11 shows the load-settlement curve for loose sand sample reinforced by group of crushed waste concrete columns. Using crushed waste concrete as group of stone columns gave the greatest reduction in the settlement behavior of loose sand. Starting from the beginning of loading, the settlement increased slightly until 7 kN loading. After that loading, the rate of increase in settlement increased. This behavior could be explained due to the breakage of the crushed waste concrete particles after some load application. In this case, 7 kN loading. After the cracking of these small concrete blocks, settlement of the stone columns accelerated until rearrangement of the concrete particles and regaining its strength. After the crushed waste concrete particles distributed evenly and settled down, the resistance to loading was regained as shown in Figure 4.11.

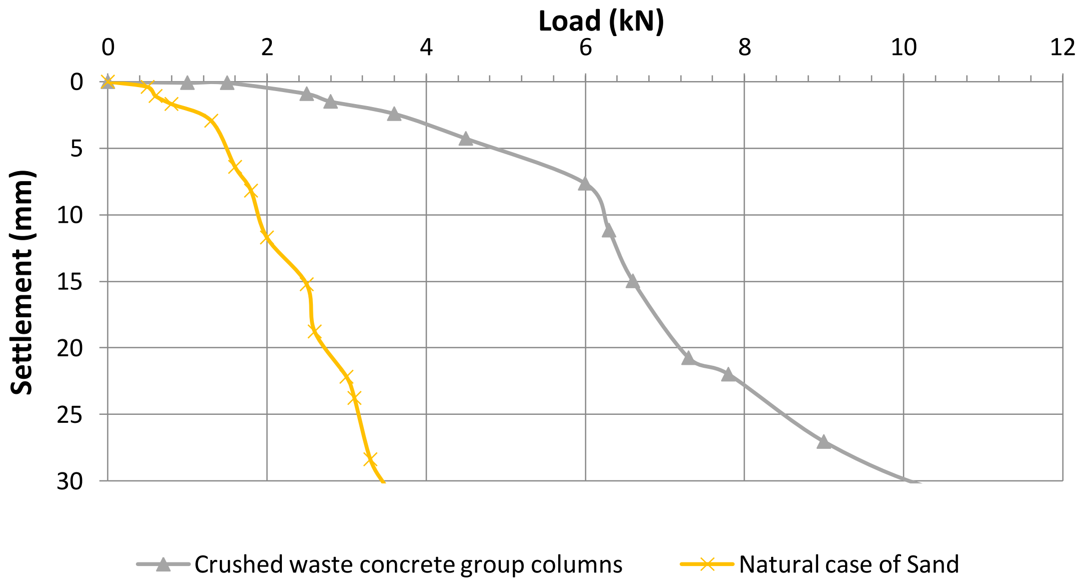

Figure 4.11: Loose sand sample reinforced by group of crushed waste concrete

4.5.4 Comparison of the settlement behavior of loose sand reinforced with different materials of groups of stone columns

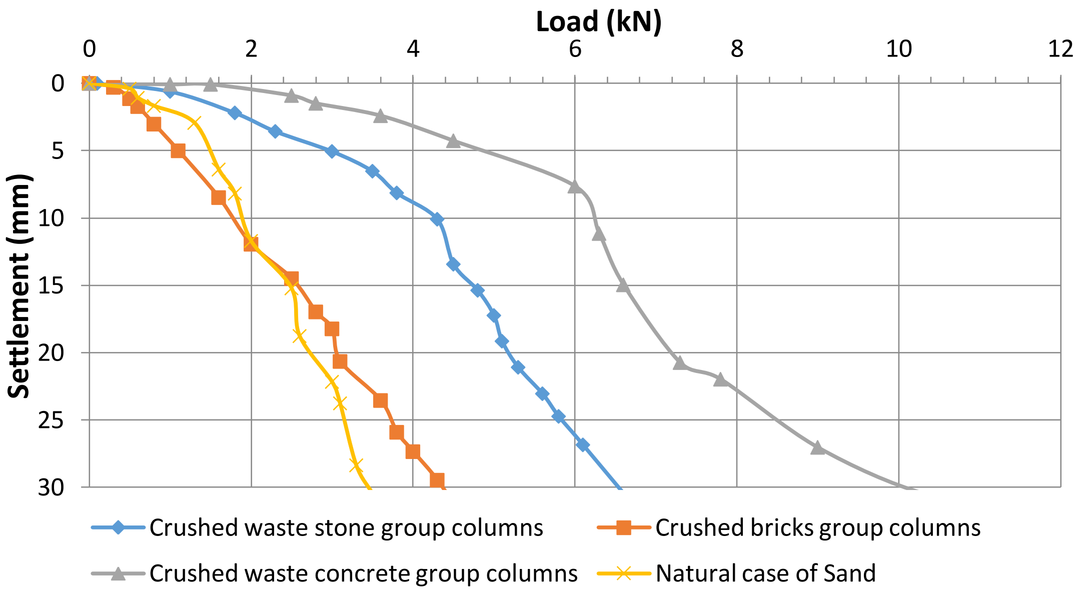

Figure 4.12: Loose sand reinforced with different groups of stone columns

Figure 4.12 shows the comparison of the load-settlement curves of loose sand reinforced with different materials of groups of stone columns. The figure indicated that crushed brick columns were not effective in reducing the settlement behavior of loose sand. It gave similar curve as natural soil. On the other hand, using crushed stone and crushed waste concrete stone columns, the performance of sand was improved and the peak load carrying capacity of the sand was increased Table 4.2 showed the load required for 25 mm settlement.

Table 4.2. Load required for 25 mm settlement

Materials	Load (kN)
Natural soil	3.1
Crushed bricks	4.8
Crushed stone	5.3
Crushed concrete	10

4.6 California Bearing Ratio (CBR) for natural and single stone column reinforced loose sand

The California Bearing Ratio, CBR can be calculated by using equation given below. The CBR of the soil can be determined as the ratio of the unit load needed to provide a penetration depth of 2.54 mm of the penetration piston to the standard unit load, 6900 kPa required to obtain the same depth of penetration on a standard sample of crushed stone. Figure 4.13 showed the CBR test results for natural soil. In Figure 4.13 showed the CBR test results for natural soil. the unsoaked CBR value of the natural loose sand soil was determined to be 2.69% which was a very low value for a subgrade material. According to (Asphalt Institute, 1970) classification system, the soil with CBR number between 0-3 is defined to be very poor for the use of subgrade material.

$$CBR\ \% = \frac{Stress\ on\ piston\ (test\ unit\ load)}{standerd\ stress\ (standerd\ unit\ load)} \times 100$$

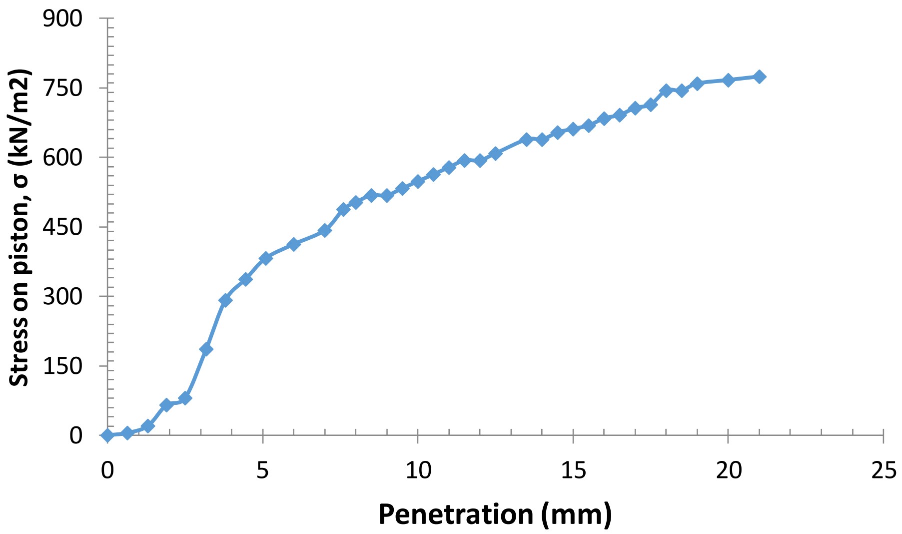

Figure 4.13: California bearing ratio test results for natural soil

4.6.1 CBR test for loose sand improved with crushed bricks

Figure 4.14 shows the effect of single stone column filled with crushed bricks on the CBR value. The CBR value for loose sand sample improved with crushed bricks was found to be 4.58%. The result indicated that the CBR value was increased from 2.69 % to 4.58%. By the increase in the CBR number with crushed bricks waste materials, the soil as a subgrade was classified as poor to fair.

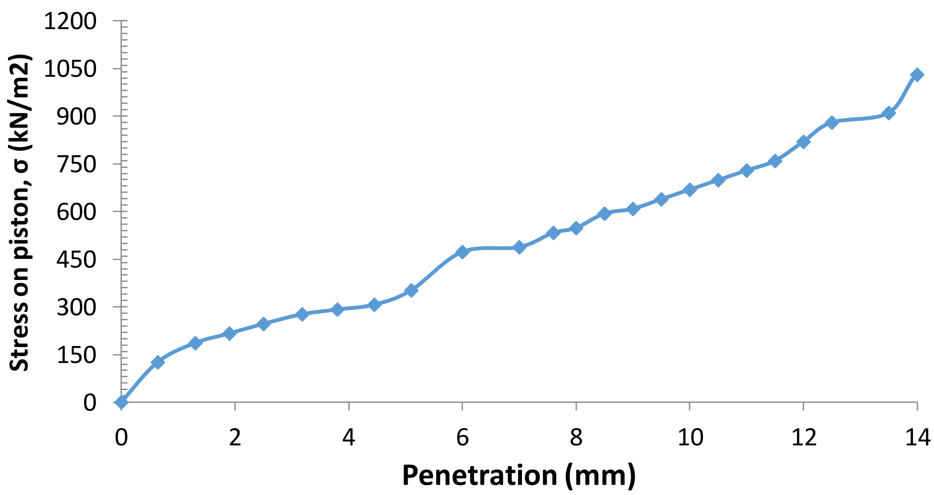

Figure 4.14: California bearing ratio test results for natural soil with crushed bricks

4.6.2 CBR test for loose sand improved with crushed waste stone

Figure 4.15 shows the CBR curve for the natural sand reinforced with crushed waste stone. The figure indicated that the penetration resistance of loose sand was improved by crushed stone. The highest performance was achieved with the application of the crushed stones. The obtained CBR value was determined to be 7.36%. According to (Asphalt Institute, 1970), the soil with CBR number between 7-20 is defined to be fair for the use of a subgrade material.

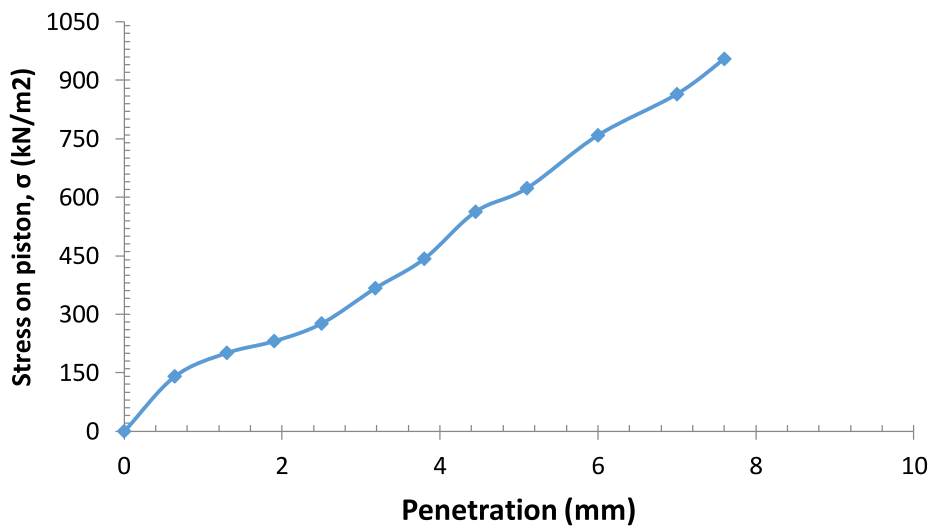

Figure 4.15: California bearing ratio test for natural soil with crushed waste stone

4.6.3 CBR test for loose sand improved with crushed waste concrete

Figure 4.16 illustrated the performance of loose sand soil when it was treated with crushed waste concrete column. Test result indicated that the CBR value for this soil was found to be 5.02%. The value of penetration was similar to the natural soil reinforced with crushed stone.

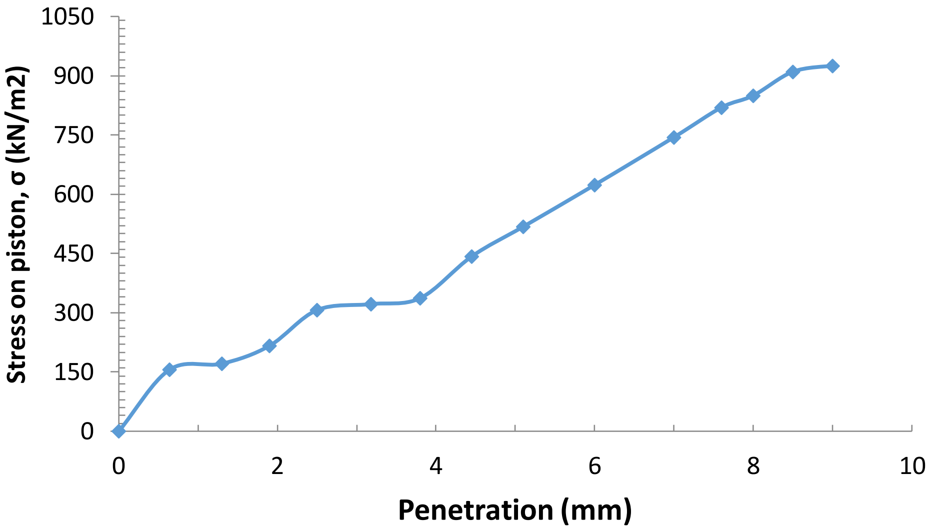

Figure 4.16: California bearing ratio curve for sand with crushed waste concrete

4.6.4 CBR curves of natural loose sand reinforced with different types of waste materials

Figure 4.17 shows the CBR curves obtained for different stone column materials. The figure indicated that the maximum value of CBR was obtained in loose sand sample reinforced with crushed stone. The CBR value for loose sand treated with crushed waste concrete was less than the CBR of soil sample treated by crushed stone. However, the results for both types of column materials: crushed stone and waste concrete proved to increase the load bearing capacity of the loose sand. The California bearing ratio increased from 2.69 % to 5.02 % and 7.3 % with crushed waste concrete and crushed stone stone column applications, respectively. The use of waste materials for the stone column application seemed to be encouraging for the improvement of the load bearing capacity and penetration resistance of the loose sand. The increased CBR values are promising especially in pavement engineering projects.

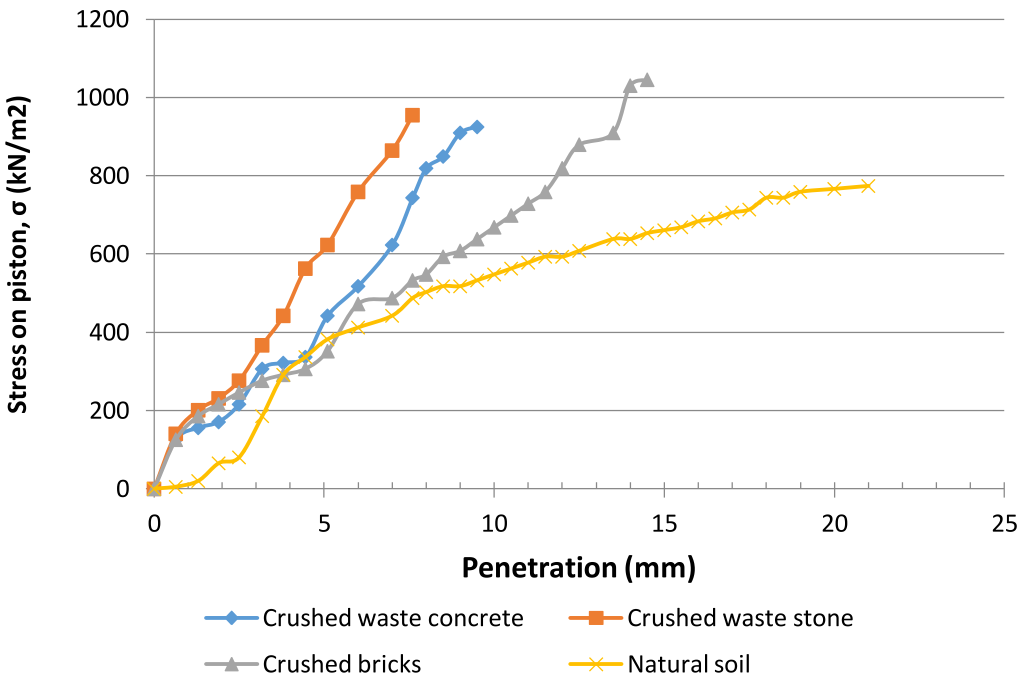

Figure 4.17: CBR curves for natural soil reinforced with different waste materials

4.7 California Bearing Ratio (CBR) test on Soft clay reinforced with single stone columns

4.7.1 CBR test for natural soft clay soil

Figure 4.18 shows the penetration behavior for natural soft clay under the applied stresses. The CBR value obtained for natural soil was found to be 0.92 % which presented a very poor soil condition.

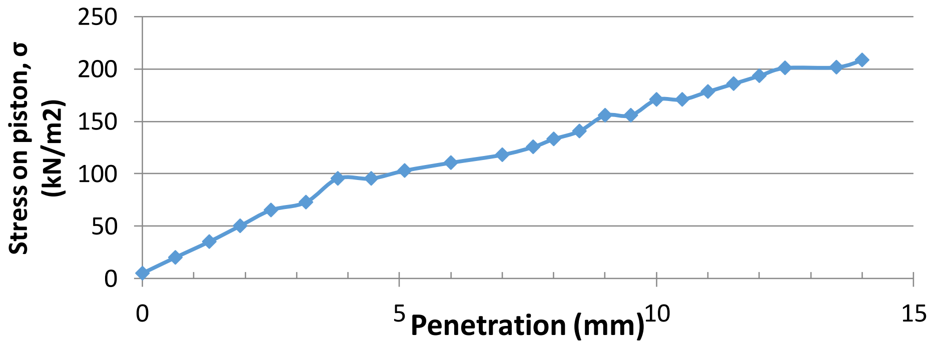

Figure 4.18: CBR curve for natural soil

4.7.2 CBR curve for soft clay improved with crushed bricks

Figure 4.19 showed the CBR curve obtained for the soft soil reinforced with crushed bricks. As it can be seen in the figure, little amount of improvement was achieved for this soil sample. The obtained CBR value was determined to be 1.6 %. Due to the low bearing resistance of the crushed brick particles, slight improvement in the penetration resistance of the soft clayey silt was achieved.

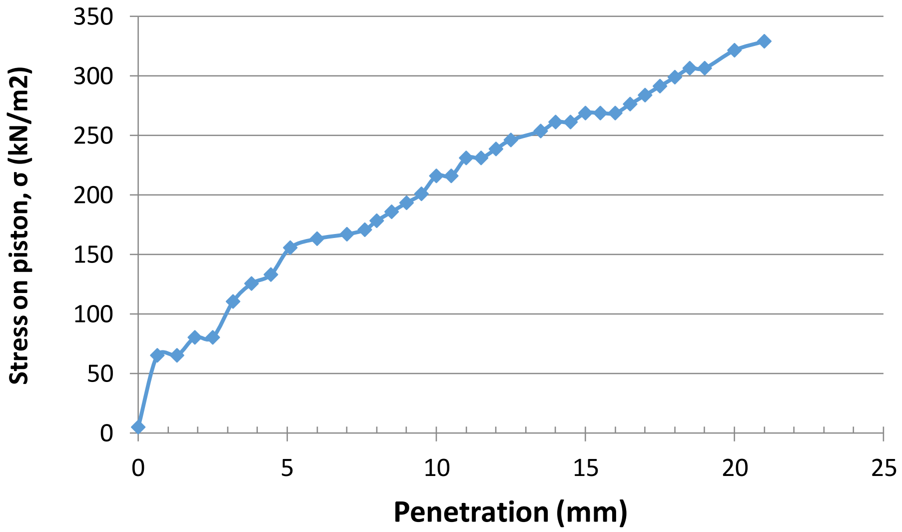

Figure 4.19: CBR curve for natural clay with crushed bricks

4.7.3 CBR curve for soft clay improved with crushed waste stone

Figure 4.20 described the effect of using crushed stone column on the penetration resistance of the soft soil. The test result indicated that there was not much improvement in the penetration resistance of soft soil with crushed stones. This could be explained due to the gaps and the insufficient contact area between the crushed stone particles to resist penetration. The obtained CBR value was around 1.38 %.

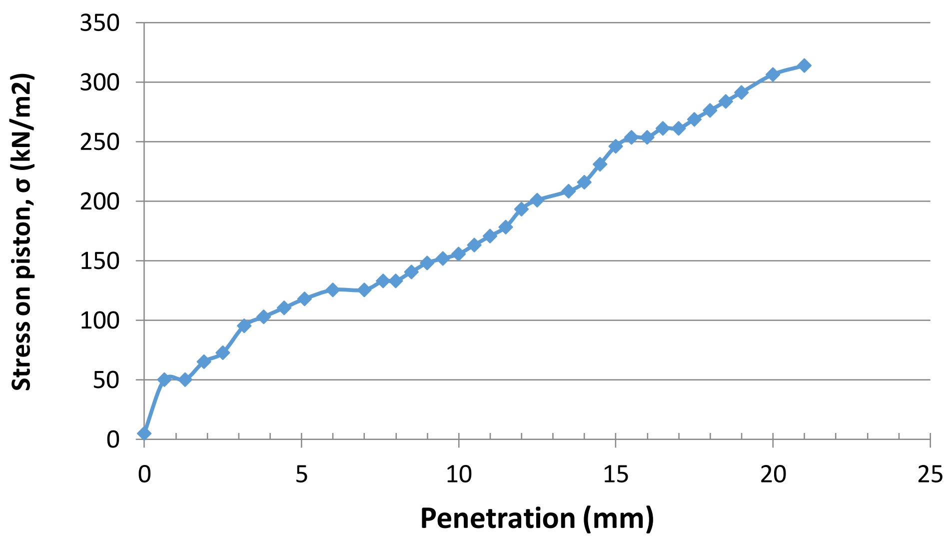

Figure 4.20: CBR value for natural clay with crushed stone

4.7.4 CBR curve for soft clay improved with crushed waste concrete

Figure 4.21 showed the CBR curve for natural clay reinforced with crushed waste concrete. In this figure, better performance of the penetration resistance was achieved. The CBR value obtained for the soft clay reinforced with crushed waste concrete was 3.13 %. This was the highest value among the other materials used for the reinforcement of the soft soil.

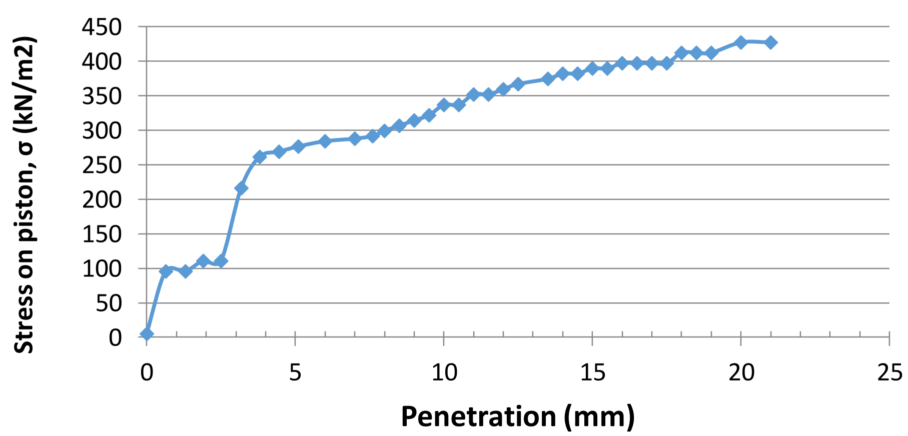

Figure 4.21: CBR curve for natural clay with crushed waste concrete

4.7.5 CBR curves of natural soft clay with different types of waste materials

Figure 4.22 showed the CBR curves for natural soft clayey silt reinforced with different stone column materials. As aforementioned, the maximum CBR value was obtained for the stone column formed with crushed waste concrete materials. Crushed waste concrete column increased the penetration resistance of the soft soil.

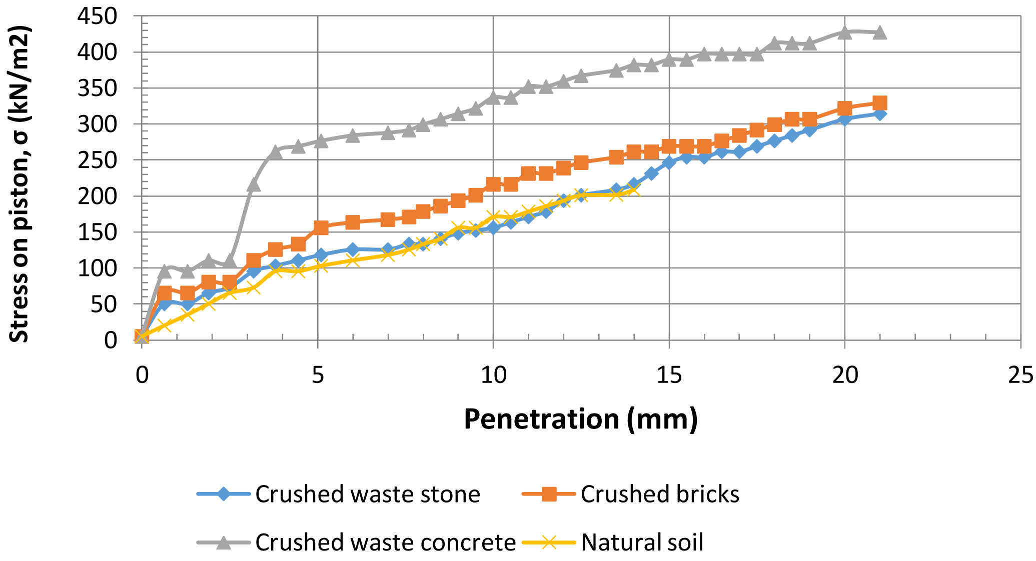

Figure 4.22: CBR curves for soft clay reinforced with different waste materials

Chapter 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

From the results of the experimental work carried out on the engineering properties of natural and reinforced sandy and soft clay soils, the following conclusions can be made:

- For both loose sand and soft clay, the stone columns application has a very good effect on the engineering properties of the problematic soils. Using different types of construction waste as soil improvement materials improved the mechanical and engineering properties of such soils.
- Construction waste materials considered as problems in different sites have been converted into a usable beneficial material in soil remediation. By using these materials in soil improvement, the amount of waste will be reduced in nature.
- By using crushed bricks, crushed stone and crushed waste concrete in the improvement of the loose sand, crushed waste concrete resulted in the best improvement in the load-settlement behavior and the load carrying capacity. The ultimate load was reached after 10 kN loading.
- The CBR value for loose sand sample improved with crushed bricks was found to be 4.58% whereas the CBR value for soil improved by crushed waste concrete was 5.02%. The highest performance in the CBR value was

achieved with the application of the crushed stones. The obtained CBR value was determined to be 7.36%.

- For soft clay soil, stone columns formed by using crushed bricks and waste concrete played the strongest role for improving the settlement behavior.
- The CBR values for reinforced soft clay are 1.6%, 1.38% and 3.1% for crushed bricks, crushed stone and crushed waste concrete, respectively. Crushed waste concrete due to its higher stiffness and capacity to the applied loads was found to be more effective in improving the CBR value of the soft clay.
- The increased CBR values of the stone column reinforced soils are promising especially in pavement engineering projects.
- The use of construction waste materials in stone column application seemed to be promising for improving the load bearing capacity and penetration resistance of the loose sand and soft clay. These waste materials which are found in large quantities in nature, can be effectively and economically used in soil remediation.

5.2 Recommendations

Literature review indicated that lots of investigations have been done on the stone column application. Specially, the effect of dimensions of stone columns, effective area and pattern of stone column on the load bearing capacity and compressibility of problematic soils.

In this investigation, different construction waste materials available in huge amount in nature were used as stone column materials and the performance of these materials were investigated on the engineering behavior of soft clay and loose sand. For further studies, different types of waste materials and sizes of particles could be considered. Different column diameters and pattern of stone columns could be tested.

In addition, for testing load-settlement behavior of soft clay soil, different loading system could be used to measure the settlement more accurately.

REFERENCES

Abdulla, A., & Kiousis, P. (1997). Behaviour of cemented sands testing. *International journal of numerical and analytical methods in geomechanics*.

Ahnberg, H. (2006). Strength of Stabilized Soils: A Laboratory Study on Clays and Organic Soils Stabilized with Different Types of Binder, *Swedish Deep Stabilization Research Center, and Linköping, Sweden, Report No. 16*.

Abiodun A.A and Nalbantoglu Z. (2015). Lime pile techniques for the improvement of clay soils. *Canadian Geotechnical Journal. Vol. 52, No. 6.*

Ali, K., Shahu, J. T., & Sharma, K. G. (2010). Behaviour of reinforced stone columns in soft soils: an experimental study. *In Indian Geotechnical Conference.*

Ali, K., Shahu, J. T., & Sharma, K. G. (2014). Model tests on single and groups of stone columns with different geosynthetic reinforcement arrangement. *Geosynthetics International.*

Atalar, C., & Das, B. M. (2009). Geotechnical properties of Nicosia soils, Cyprus. *In Proceedings.*

Babu, MR Dheerendra, Sitaram Nayak, and R. Shivashankar. "A critical review of construction, analysis and behaviour of stone columns." *Geotechnical and Geological Engineering.*

Balaam, N. P. and Booker, J. R., Analysis of rigid rafts supported by granular piles. Int. J. for Num. and Anal. *Methods in Geomech., 1981.*

Biczok, I., & Szilvassy, Z. (1964). Concrete corrosion and concrete protection.

Bouassida, M., & Klai, M. (2012). Challenges and Improvement Solutions for Tunis' Soft Clay. *International journal of GEOMATE: geotechnique, construction materials and environment.*

Bowels, J.E., Foundation Analysis and Design, 4th Edition, *McGraw Hill,1988.*

Broms BB (1991) Deep compaction of granular soils. *Foundation engineering handbook.*

Broms, B. B. (2000, June). Lime and lime/columns. Summary and visions. *In Proceedings of the 4 th International Conference on Ground Improvement Geosystems: Keynotes Lecture.*

Castro, J. (2017). Groups of encased stone columns: Influence of column length and arrangement. *Geotextiles and Geomembranes.*

Castro, J., Karstunen, M., & Sivasithamparam, N. (2014). Influence of stone column installation on settlement reduction. *Computers and Geotechnics.*

Chenari, R. J., Fard, M. K., Chenari, M. J., & Sosahab, J. S. Physical and Numerical Modeling of Stone Column Behavior in Loose Sand. *International Journal of Civil Engineering.*

Cyprus Geological Heritage Educational Tool. Retrieved from: http://www.cyprusgeology.org/english/4_3_2_aquifers.htm

Ellouze, S., Bouassida, M., Bensalem, Z., & Znaidi, M. N. (2017). Numerical analysis of the installation effects on the behaviour of soft clay improved by stone columns. *Geomechanics and Geoengineering.*

Elshazly, H., Elkasabgy, M., & Elleboudy, A. (2008). Effect of inter-column spacing on soil stresses due to vibro-installed stone columns: interesting findings. *Geotechnical and Geological Engineering.*

Erhan G. (2009). Assessment of Liquefaction/Cyclic Failure Potential of Tuzla Soils. Master of Science Thesis in civil Engineering, *Eastern Mediterranean University, North Cyprus.*

Guetif, Z., Bouassida, M., & Debats, J. M. (2007). Improved soft clay characteristics due to stone column installation. Computers and Geotechnics.

Han J., Huang J, Porbaha A. (2005). "2D numerical modeling of a constructed geosynthetic-reinforced embankment over deep mixed columns." *Contemporary Issues in Foundation Engineering , ASCE Geotechnical Special Publication No. 131.*

Retrievedfrom:http://www.moa.gov.cy/moa/gsd/gsd.nsf/dmlSediments_en/dmlSediments_en?OpenDocument#) H-Y Fang (ed), Chapman & Hall.

Indraratna, B., Ngo, N. T., Rujikiatkamjorn, C., & Sloan, S. W. (2015). Coupled discrete element–finite difference method for analysing the load-deformation behaviour of a single stone column in soft soil. *Computers and Geotechnics.*

International, c. e. (2009). ICE. Netherland. Retrieved from: www.ice-holland.com.

Isaac, D. S., & Girish, M. S. (2009). Suitability of different materials for stone column construction. *EJGE.*

ISMAIL, A., & TESHOME, F. (2011). Analysis of deformations in soft clay due to unloading.

Ivan Jackson Maduro, P.E., Carlos Rodriguez Molina, P.E., Luis Vazquez Castillo, (2004). The Use Of Stone Columns On Settlement And Liquefaction Susceptible Soils. *Fifth International Conference On Case Histories In Geotechnical Engineering.*

Jaki J (1944) The coefficient of earth pressure at rest. *Journal of Society of Hungarian Architects and Engineers, Budapest, Hungary.*

Japan Institute of Construction Engineering (JICE), 1999. Flexible Foundation, Foundation Structure Part, *Design Code for Flexible Box Culvert – II (Chapter 4).San-kaidouPress,Tokyo, (in Japanese).*

Kadhim, S., Parsons, R. L., & Han, J. (2015). Stability Analysis of Embankments Supported by Geosynthetic Encased Stone Columns. *In IFCEE 2015.*

Keller, F. E. (2002). Vibro-Stone column. *Courtesy of Keller Foundation.*

Kezdi, A. (2013). Soil physics: selected topics *(Vol. 25). Elsevier.*

Kie, T. (1966). Determination of the Rheological Parameters and the Hardening Coefficients of Clays. *In Rheology and Soil Mechanics*

Killeen, M. M., & McCabe, B. A. (2014). Settlement performance of pad footings on soft clay supported by stone columns: *A numerical study. Soils and Foundations.*

Kitazume, M., & Terashi, M. (2013). *The deep mixing method (p. 410). Balkema: CRC Press.*

Li, X., Cai, G., Liu, S., Puppala, A. J., Zheng, J., & Jiang, T. (2017). Undrained Shear Strength and Pore Pressure Changes Due to Prestress Concrete Pile *Installation in Soft Clay. International Journal of Civil Engineering, 1-11.*

Lorenzo, G., and Bergado, D. (2004). "Fundamental parameters of cement-admixed clay - New approach." J. *Geotech. Geoenviron.*

Magnan, J. P. (1983). Theory and practice of vertical drains. *Tech. et Documentation.*

Malarvizhi, S. N., & Ilamparuthi, K. (2004). Load versus settlement of clay bed stabilized with stone and reinforced stone columns. *Proceedingns of GeoAsia–2004, Seoul, Korea.*

Malekzadeh M., and Bilsel H. (2012). Effect of Polypropylene Fiber on Mechanical Behaviour of Expansive Soils. *Electronic Journal of Geotechnical Engineering.*

Meyerhof, G.G. and Sastry V.V.R.N, "Bearing capacity of piles in layered soils", part I and II, *Canadian Geotechnical Journal, 15.*

Mirsalehi, S. (2013). Simulation of the Numerical Behavior of Stone and Geosynthetic Encapsulated Sand Columns in Tuzla area (Doctoral dissertation, *Eastern Mediterranean University (EMU)).*

Mitchell JK (1993) Fundamentals of soil behaviour. 2nd ed., John Wiley & Sons

Moritz, L. (1995). Geotechnical properties of clay at elevated temperatures *(Vol. 47). Swedish Geotechnical Institute.*

Murugesan, S., and Rajagopal, K. (2010). "Studies on the behavior of single and group of geosynthetic encased stone columns." J. *Geotech. Geoenviron.*

Ng, K. S., & Tan, S. A. (2014). Design and analyses of floating stone columns. *Soils and Foundations.*

Onochie, K. K., & Rezaei, A. (2016). Special Considerations in Design of Foundation in Problematic Soils.

Priebe, H.J.,1995.The design of vibro replacement. *GroundEng.*

Properties of soil, Properties of soil appendix C (n.d.). Retrieved from: https://www.sefindia.org/forum/files/appc_soil_properties_718.pdf

Rahman, M. A., Imteaz, M. A., Arulrajah, A., Piratheepan, J., & Disfani, M. M. (2015). Recycled construction and demolition materials in permeable pavement systems: geotechnical and hydraulic characteristics. *Journal of Cleaner Production.*

Rao, B.G.,Ranjan,G.,1985.Settlementanalysisofskirtedgranularpiles.J. *Geotech.Eng.*

Rao, L., & Madhira, M. (2010, December). Evalution of optimum spacing of stone columns. *In Indian Geotechnical Conference. GEOtrendz. December.*

Reliable method for determining the plastic limit. Moreno-Maroto, J. M., & Alonso-Azcárate, J. (2015).

Reul, O., & Gebreselassie, B. (2006). Excavations and foundations in soft soils. *Springer Science & Business Media.*

Reul, O., & Gebreselassie, B. (2006). Excavations and foundations in soft soils. *Springer Science & Business Media.*

Sallfors, G. (2001): Jordmateriallara-Jordemekanik. 3:rd edition. Chalmers University of Technology, *Goteborg, {Sweden}, {2001}.*

Scherzinger T (1991) Materialverhalten von Seetonen - Ergebnisse von Laboruntersuchungen und ihre Bedeutung für das Bauen in weichem Baugrund. P.hD. thesis, *Institut fur Bodenmechanik und Felsmechanik der University Fridericiana in Karlsruhe, Heft 122.*

Sexton, B. G., McCabe, B. A., Karstunen, M., & Sivasithamparam, N. (2016). Stone column settlement performance in structured anisotropic clays: the influence of creep. *Journal of Rock Mechanics and Geotechnical Engineering.*

Shi, W., Chen, Q., Nimbalkar, S., & Liu, W. (2017). A new mixing technique for solidifier and dredged fill in coastal area. *Marine Georesources & Geotechnology.*

Sivakumar, V., McKelvey, D., Graham, J., and Hughes, D. (2004). "Triaxial tests on model sand columns in clay." *Can. Geotech. J.*

Slocombe, B. C., Bell, A. L., & Baez, J. I. (2004). The densification of granular soils using vibro methods. *In Ground and Soil Improvement. Thomas Telford Publishing.*

Venkatramaiah, C. (1995). Geotechnical engineering. *New Age International.*

Wood, D. M., & Hu, W. (1997). Mechanisms of load transfer deduced from failure modes of model stone column foundations. In Proceedings of *the International Symposium on Deformation and Progressive Failure in Geomechanics, Nagoya*

Yu, J., Cai, Y., Qi, Z., Guan, Y., Liu, S., & Tu, B. (2013). Analytical Analysis and Field Test Investigation of Consolidation for CCSG Pile Composite Foundation in Soft Clay. *Journal of Applied Mathematics, 2013.*

Zahmatkesh, A., & Choobbasti, A. J. (2010). Investigation of bearing capacity and settlement of strip footing on clay reinforced with stone columns. *Australian Journal of Basic and Applied Sciences.*

Zahmatkesh, A., & Choobbasti, A. J. (2010). Settlement evaluation of soft clay reinforced by stone columns, considering the effect of soil compaction.International. *Journal of Research and Reviews in Applied Sciences.*

Zheng, G., Liu, S. Y., & Chen, R. P. (2009). State of advancement of column-type reinforcement element and its application in China. *In Proceedings of the US-China Workshop on Ground Improvement Technologies.*