Numerical Analysis of load – Settlement Response of StoneColumn Reinforced Silty Sand Soil At Adama City Using a Plaxis 3D Model

Jemila Dita Haji

A Thesis Submitted to the Department of Civil Engineering,

School of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Civil Engineering (Specialization in Geotechnical Engineering)

Office of Graduate Studies

Adama Science and Technology University

May, 2024

Adama, Ethiopia

Numerical Analysis of load – Settlement Response of StoneColumn Reinforced Silty Sand Soil At Adama City Using a Plaxis 3D Model

Jemila Dita Haji

Advisor

Argaw Asha (PhD)

A Thesis Submitted to the Department of Civil Engineering,
School of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Civil Engineering (Specialization in Geotechnical Engineering)

Office of Graduate Studies
Adama Science and Technology University

May, 2024
Adama, Ethiopia

DECLARATION

I declare that this MSc. thesis entitled "**Numerical Analysis of load – Settlement Response of Stone Column Reinforced Silty Sand Soil At Adama City Using a Plaxis 3D Model** "is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Jemila Dita Haji ________________ ____________

Name of Student Signature Date

`

RECOMMENDATION OF ADVISOR

I, the advisor of this MSc thesis, hereby certify that I have closely advised the student while developing this thesis and read the draft entitled "**Numerical Analysis of load – Settlement Response of Stone Column Reinforced Silty Sand soil At Adama City Using a Plaxis 3D Model**" prepared under my guidance by Jemila Dita Haji Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Argaw Asha (PhD)	__________________	______________
Advisor	Signature	Date

APPROVAL OF BOARD OF EXAMINERS

I , the advisors of the thesis entitled "**Numerical Analysis of load – Settlement Response of Stone Column Reinforced Silty Sand soil At Adama City Using a Plaxis 3D Model**" and developed by Jemila Dita Haji, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Argaw Asha (PhD)	___________________	______________
Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Jemila Dita Haji have read and evaluated the thesis entitled "**Numerical Analysis of load – Settlement Response of Stone Column Reinforced Silty Sand Soil At Adama City Using a Plaxis 3D Model**" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Civil Engineering (specialization in Geotechnical Engineering).

________________________	____________________	______________
Chairperson	Signature	Date
________________________	____________________	______________
Internal Examiner	Signature	Date
________________________	____________________	______________
External Examiner	Signature	Date

Final approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

________________________	____________________	______________
Department Head	Signature	Date
________________________	____________________	______________
School Dean	Signature	Date
________________________	____________________	______________
Office of Postgraduate Studies, Dean	Signature	Date

ACKNOWLEDGEMENT

First, I would like to thank the almighty Allah for all the blessings I have received and the strength he gave me through my life and during my research work. I would like to express my sincere appreciation and deep gratitude to my advisor, Dr. Argaw Asha, who devoted time and effort to this research project. I am extremely grateful for all his support, encouragement, and advice throughout my studies.

I would like to thank all the staff in the consulting office for providing me with secondary data and material.

I would like to express my appreciation to my friend, especially Engineer Saliha Mohammed, for her support during my thesis work, and my appreciation also goes to my classmate, especially Bereket Bogale, for her kind assistance and support.

I am greatly indebted to my family for their prayers and support of my ideas. I wish to also appreciate all my friends and all my staff, especially Buzayo Asafe, Shimelis Ragasa, and Salih Abdela, for their kind assistance and support.

Finally, I am also thankful to all those who are not mentioned here but have helped and supported me in order to achieve this research work successfully.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS, SYMBOLS AND ABBREVIATION

FEM	Finite Element Modelling
H	Layer Thickness
KN/M	Kilo Newton per Meter
KN	Kilo Newton
KPa	Kilo Pascal
L	Length of Stone Column
L/D	Length to Diameter Ratio
N	Number of columns
N	Northing
n	Stress concentration factor
PVD	Prefabricated vertical drain
S	Centre to Centre Spacing
S/D	Spacing over Diameter Ratio
SPT	Standard Penetration Test
S	Stone Column Spacing
UDL	Uniformly Distributed Load
OMC	Optimum Moisture Content
USCS	Unified Soil Classification System
2D	Two Dimensional
3D	Three Dimensional
A	Area of stone column
AASHTO	American Association Society of Highway and Transport Organization
Ap	Total area with in unit cell
A_r	Area Replacement ratio

ASTM	American Society for Testing and Materials
BSI	British Standard Methods of Test for Soil
B	Footing Size
D	Diameter of stone column
De	effective Diameter
Ec	Modulus Elasticity of Concrete
E	Easting
Es	Modulus Elasticity of soil
FEM	Finite Element Method
Ø	Friction Angle

ABSTRACT

Construction of civil engineering projects requires a load bearing soil. Soil from Adama city up to critical depth is generally classified as loose silty-sand soil. Infrastructures constructed on this kind of soil fail well before their designed lifespans. It becomes highly important to increase the strength of such soil in order to reduce damage and maintenance costs. Therefore, finding environmentally safe, low-cost, readily available, and long-term ground improving materials is imperative. The application of stone columns as ground improvements beneath building foundations plays a crucial role. The study employed advanced finite element software, Plaxis 3D, to evaluate the impact of several factors such as the magnitude of the imposed load on the designated isolated footing varying from 1400KN to 3000KN, length to diameter ratio of stone column and spacing between the stone columns on settlement reduction. The study comprises three different spaces (S) that were taken in relation to the columns' diameter (D), which are (S/D= 2, 2.5, and 3) as well as different arrangements of stone columns. These arrangements include a single column at the center and four columns at the corners with one at the center without maintaining specific column spacing, all while considering L/D ratios of 5 and 10 in order to determine the most effective values. The analysis is performed using a powerful finite element based program Plaxis 3D to examine the effects of various parameters. The results showed that the improved settlement value is primarily dependent on the number, spacing, diameter, and L/D ratio of the stone column on the given soil. According to the study, when the axial load increased from 1400KN to 3000KN, the settlement increased from 40.45mm to 79.67mm, indicating that the decision to use isolated footings to sustain the load was effective at limited maximum load. As a result of incorporating stone columns, the settlement was reduced from 40.45mm to 27.3mm and 79.67mm to 36.48mm respectively. Settlement improvement becomes a more pronounced effect with a longer diameter and length of the stone column. Based on the data, it can be concluded that settlement values in this soil decrease with an increase in column number and L/D as well as a decrease in the optimum stone column spacing. Stone columns enhance soil drainage by establishing vertical pathways for water flow, leading to a decrease in pore water pressure. This highlights the importance of stone columns as a viable method for ground improvement in soil with high settlement tendencies.

Keywords: *Plaxis 3D, Settlement, stone column, Ground Improvement, L/D, Column Spacing*

CHAPTER ONE
INTRODUCTION

1.1.Background

The formulation of foundations and embankments on loose soils presents a formidable challenge for geotechnical engineers owing to the unfavorable settlement and bearing capacity behavorble. Various methods of ground enhancement are applied to address the challenges linked with the substantial compressibility and low shear strength of loose soils. Historically, granular reinforcements have been a prevalent solution for enhancing soft soils in foundation applications. Burbach used sand piles for the first time in 1839 in Bayonne (France) instead of wood piles that rapidly degraded as groundwater levels fluctuated (Dhouib A., et al, 2004). The stone column technique is commonly employed on a global scale. It has proven to be effective in enhancing the engineering characteristics of soils. Numerous instances have been documented showcasing the benefits of this methodology. Throughout the past two decades, notable advancements have been made in connection to this technique, particularly with respect to construction machinery and materials. Ground improvement methodologies are utilized to enhance and modify unfavorable ground conditions to ensure that construction projects can fulfil performance criteria in a cost-effective manner. Typically, ground improvement focuses on enhancing soil layers, although in certain instances, it may extend to improving rock layers as well. When a poor ground exists at a project site, geotechnical engineers use ground improvement techniques to "fix" the poor ground problems (Terashi, et al., 2000).

Soil enhancement through the use of stone columns is widely practiced, particularly for softer soil types, owing to their effectiveness and minimal environmental repercussions. Stone columns consist of vertical boreholes in the earth, which are filled with gravel and compacted using a vibrator. This technique entails inserting vertical stone columns into the ground at a specified depth beneath the ground surface. Consequently, a layer of compacted gravel can be placed on top of the columns in preparation for the construction of new foundations. The inclusion of gravel, which has a higher strength, stiffness and permeability than the natural soft soil, improves the bearing capacity and the stability of embankments and natural slopes, reduces total and differential settlements, accelerates soil consolidation and reduces the liquefaction potential (J. Castro, 2014).

The stone column method is quick to construct and can be done at any time of the year (Samuel T. et al, 2019). More recently stone columns have also been deployed beneath small isolated pad or strip foundations at low or moderate loading conditions. Stone columns are most appropriate for sandy soil conditions. A higher quantity of stone columns is essential for soils with silt layers. One benefit of stone columns is the elimination of the need for dewatering or excavation during the construction process, resulting in a comparatively brief construction duration. Several factors affect its efficiency in improving the mechanical properties of the soil, and the most important of these factors are the spacing, length, and diameter of the stone columns (J. Castro, 2014). The stone columns mitigate the impact of liquefaction in the future by compacting the soil and incorporating stones into it to enhance its strength, resulting in the formation of a rigid composite soil structure. Through this process, the non-liquefiable upper soil layer is fortified and thickened to minimize the occurrence of deformations, inclinations, and uneven ground settlement arising from liquefaction of the lower soil strata. As a result, stone columns can also provide the soil with an increased drainage path, reducing excess pore water pressure that can lead to liquefaction, thus reducing the consequences of liquefaction (Luehring R et al, 2001).

This research analyzed the influence of the diameter, length, and spacing of the stone columns on settlement and ground bearing capacity utilizing finite element analysis like PLAXIS 3D. The investigation delves into the potential of this method to enhance load-bearing capacity and diminish settlement by examining the impact of modifying these diverse parameters within a specified loose soil for the incorporation of stone columns. This task is executed through the utilization of PLAXIS 3D, a three-dimensional finite element software. Within the research locale, there is a widespread distribution of silty-sand to silty-clay deposits extending to significant depths, showcasing feeble strength and high compressibility. Thus, fortifying the existing strength attributes of such soil via the integration of ground stone columns emerges as exceedingly crucial. A stone column, comprising compacted granular material within lengthy cylindrical cavities, is employed as a strategy to ameliorate the strength and consolidation traits of soft clays. The load-bearing capacity of a stone column is ascribed to the frictional characteristics of the stone mass, the cohesion and frictional attributes of the surrounding soils, as well as the flexibility or rigidity features of the foundation transmitting stresses to the enhanced ground. Hence, this study endeavors to scrutinize the repercussions of numerical modeling analysis of stone column-reinforced silty sand soil on compressibility (settlement reduction) characteristics. Subsequently, subsequent to identifying the indices and engineering properties of both materials through the assistance of collated secondary data from consulting firms, a thorough analysis of settlement reduction in the designated soil due to the inclusion of stone columns in the sampled soil, employing numerical techniques, was meticulously examined. Lastly, the research findings and prospective avenues are delineated.

1.2.Statement of the problem

The in-situ soils are not usually suitable for supporting the desired structures such as buildings, dams and bridges. Every day, it is becoming difficult to find good construction sites for the structures. Soil from the study area is considered as problematic soil for various civil engineering projects; hence, such problematic soil should be removed and replaced by another selected material or it should be stabilized by using physical or chemical means. Particularly, in the study area considerable research is not yet sufficiently done on improving or enhancing the strength properties of selected soil by using effective, environmentally suitable and easily available materials such as stone column. As a result, a corrective measure should be made to mitigate the problem while taking into account the construction quality, cost, and duration by employing an economical soil (ground) improvement techniques.

The need for the modification of the problematic soils is increasing each day. Different types of ground modification techniques have been developed in the previous years. The type of modification technique that will be applied on soil depends on the type of the problematic soil existing on site. Stone column application has its advantage among the other modification techniques. It is much simpler than many other techniques and it is cost effective. When compared to others, using stone column is not expensive, stone column not only increase the bearing capacity rather it reduces settlement of foundation soil by densifying the soil component, improve drainage condition.

The stone column technique is applied either by a replacement or a displacement method. Owing to improve the mechanical treatment of soft cohesive soils and to quicken construction, the acceleration of the consolidation rate is very important. Among many methods for ground reinforcement, stone column reinforcement is applied worldwide. Based on the stiffness of stone columns, they work similar to piles as good as vertical drains. The primary objective of stone column reinforcement is to enhance the load-bearing capacity of soft cohesive soil and facilitate the acceleration of the consolidation rate in said soil, thereby reducing the duration of the settlement process. Guetifet et al. (2007) documented that the enhancement of soft soil through the implementation of stone columns can be attributed to three key factors. First and foremost, this process entails integrating a stronger columnar material (such as crushed stones, gravel, etc.) into the less compacted soil. Secondly, it includes the compaction of the surrounding soft soil during the installation of the stone columns. Lastly, it functions as vertical drains. Therefore, the introduction of stone columns into feeble soils goes beyond a mere substitution process, as it can lead to alterations in both the material characteristics and the stress state within the treated soil mass. In the current investigation, a numerical evaluation of the load-settlement behavior of stone column-reinforced silty sand soil in Adama city was conducted using a Plaxis 3D Model. The study applied finite element analysis by subjecting static loads to examine the impact of settlement reduction under various conditions, with subsequent discussion of the findings. A three-dimensional representation of ground reinforcement through stone columns was developed, and the outcomes of the finite element analysis concerning settlement analysis for each case of stone column inclusion were deliberated.

1.3.Research Questions

1. Can the use of ground stabilization techniques such as inclusion of stone column, improves the vertical deformation properties of the given soil used as a building foundation material?
2. To what extent can ground stone columns improve the engineering properties of silty sand soil when analyzed using a numerical model?
3. How do different length-to-diameter ratios and centre to centre spacing of stone columns impact settlement reduction in silty sand soil, as analyzed using the Plaxis 3D numerical model?

1.4.Objectives

1.4.1.General Objectives

The general objective of this thesis is to study the effect of inclusion of stone column to improve settlement characteristics of loose soil using Stone column as ground improvement material supported with numerical modeling with Plaxis 3D software.

1.4.2. Specific Objectives

1. To investigate the potential application of ground stone columns to enhance the settlement properties of the given soil using numerical model.
2. To assess the magnitude and scope of the vertical deformation enhancement characteristics of the designated soil by reinforcing the selected soil with stone columns under different conditions.
3. To analyse the suitability behaviour of stone column with different centre to centre spacing and application of different length to diameter ratio on the basis of their settlement behaviour using 3D numerical model.

1.5. Significance of the study

A structure built on problematic soil will undergo a large settlement. To make the soil more appropriate for structures, soil can be stabilized by the physical or chemical improvement techniques. Modification of soft soil with a stone column is a promising physical ground improvement technique; it improves bearing capacity and reduces the settlement characteristics of the soil. The majority of construction projects have been undertaken inside the proposed study areas. Engineers face challenges due to the presence of low bearing soil. These soils have low bearing capacity and high compressibility characteristics. In order to use these soils suitable for construction, making remedial measures on the available soil to achieve the specified objectives are necessary. Hence ground improvement needs to be applied. Additionally, the current construction method (removing and replacing) is very time-consuming and expensive. Therefore, the result from the study plays a crucial role, since application of stone column is cost effective and easily available material than others. The study can also be used to develop a soil stabilization manual, as it will have a customized nature to meet the soil stabilization requirements for future development programs.

1.6.Scope and limitation of the study

1.6.1. Scope of the study

Basically, the study focuses on improving the settlement property through reducing the high compressibility characteristics of the available loose soil by using stone column as a ground improvement material. Hence, in order to achieve the objectives of the research purely analytical method was followed. The section is divided into two stages. The first phase involves the collection of representative secondary data from the consultation firms (see appendix 2) as well as the identification of engineering properties of the stone column and concrete based on the collected secondary data. secondly, by using the optimum amount in terms of number, length, L/D ratio of stone column and properly spacing of stone column inclusion inside the soil volume; analysis of settlement reduction properties and bulging characteristics using plaxis 3D numerical model were carried out both before and following the inclusion of stone column. Finally, the results and findings of the research will be analyzed, organized and presented.

1.6.2 Limitation of the study

- As part of this study, a numerical model of the effect of stone columns on silty sand soil was used only for shallow foundations, such as isolated but to examine the overall impact of stone columns on bearing capacity and settlement reduction, deep foundations should also be considered.
- This study applied stone columns on soil without encasing them with geosythetic material, however a comparative study with and without encased stone columns would be ideal to see for further lateral deformation and bulging reduction.
- In this study, the effect of stone column inclusion in silty sand soil as a bearing capacity improvement and settlement reduction was examined using numerical model such as PLAXIS 3D, however if fully functional model testing laboratory experiment is available it would be better to conduct laboratory test and see its effect as a comparative study.

1.7. Thesis organization and outline

The study was organized mainly into five chapters. The first chapter introduces the background, the statement of the problem, the objectives, and the scopes of the study are outlined. The second chapter was mainly a literature review that stated the study's matter. It describes the theoretical background and the application of the stone columns in the given problematic soils. This section covers reviews on the concept of stone column as a soil improving material; design philosophy of stone column inclusion as a foundation support; design considerations; method of analysis; settlement reduction capacity of stone column reinforced soil; parametric studies; finite element modeling of isolated footing before and following treating with stone column; soil distribution in the study area; and research gaps were covered. The methodology for the study is presented in the third chapter, which includes the input subsoil, stone column, and footing material parameters, along with the suggested constitutive behavior that controls them. Additionally, a numerical model used for the study is explained. The fourth chapter relied on the presentation, analysis, interpretation of results and discusses the behavior of stone column reinforced problematic soil in full scale three-dimensional finite element analyses. Finally, the fifth chapter provides the conclusions and recommendations of this study based on the numerical analysis and in the end, the list of references are given.

CHAPTER TWO

LITERATURE REVIEW

2.1. Introduction

Stone columns were first noted in 1830, in France, where they were used to improve the foundation of an ironworks situated over soft estuarine deposits (Moreau et al, 1935). This method was reappeared in 1933, in Germany, as a by-product of a compaction method for granular material (Hughes and Withers, 1974). Due to the need to treat soft clay deposits during the late 1950s, stone column as a ground improving method was further developed (Greenwood, 1975). Nowadays, due to the sophisticated equipment and advanced technology, stone columns can be installed to even deeper deposits with lengths of over 30 m (Black et al., 2007). In modern industry, the application of stone columns is more than improving soft cohesive soil, but it is also used to reduce the possible liquefaction of cohesionless soil under seismic loading (Adalier et al., 2003).

It is common for structures such as buildings, storage tanks, warehouses, earthen embankments, etc., to settle excessively or have stability problems on weak soils. To support structures, weak soil must be strengthened in order to have sufficient shear strength and compressibility to carry loads. Solving or reducing encountered problems may require ground or soil improvement. The ground conditions can be improved by using various methods such as stone columns, jet grouting, compaction grouting, short piles, dynamic compaction, lime stabilization and the like, but this research proposal mainly focuses on stone columns as an improvement material on silty sand soils. To improve soft soils for a foundation of an embankment or structure, stone columns, also called aggregate piers, are widely used. This is a vertical borehole filled with compacted gravel in the ground.

The performance of weak/soft clay can be enhanced by using a variety of geotechnical methods of construction. Ground improvement techniques are being used as a result of urban and industrial development, as well as an increasing demand for buildings on soft clay soils.

Stone columns play a critical role in soil stabilization and are ideal for improving soft clays, silts, and loose silty sands. They are a cost-effective method for improving the ground. In Ethiopia, infrastructure development requires more land since it is a developing country. In order to construct with the limited amount of land available, it is necessary to develop soils with low shear strength, low bearing capacity, and high compressibility. It is more effective to use stone columns for stabilizing large areas of soil mass. When the load is applied, the excessive pore water pressure is rapidly drained. In soft soils, stone columns acted as rigid elements that carried higher shear stresses, reducing settlement and improving deformability and strength. It has been proven that stone column techniques improve slope stability, increase bearing capacity, reduce differential and total settlements, reduce liquefaction property of sands, and increase settlement time (Singh I. et al, 2019). This method was initiated in France in 1830‟s and is widely used especially in Europe since 1950‟s. The column consists of compacted pebbles or crushed stones compacted by a shaker. The installation of stone columns is said to be one of the most cost-effective and environmentally friendly ways to improve weak soil deposits (Srijan et al, 2021).

An underground surface can be improved with stone columns, which are a network of compacted stones that reinforce the soil. Among the reasons for the use of stone columns is the partial replacement of compressible soil with more suitable materials such as stone aggregate, sand, and other granular materials which are more capable of providing support. These substitutes also act as reinforcement material, hence increasing overall strength and stiffness of the soft soil (A.P. Ambliy et al, 2007). Weak soil, which has very low shear strength and high compressibility to support structures require strengthening to be capable of carrying loads from structures. Stone columns are ideally suited for structures (Mokhtari et al, 2012), because:

- Cost effective: stone columns are cost-effective solution for ground improvement compared to other method.
- Time efficient: the installation of stone column is relatively quick process.
- Flexibility: stone columns can be installed in variety of soil type and conditions, making them a versatile solution.
- Environmental benefits: stone columns are environmentally friendly as they require minimal excavation and have a low carbon footprint.
- Increased load bearing capacity: Stone columns are significantly increasing the load bearing capacity of soil, making them ideal for stabilizing.
- Long-lasting: stone columns are durable and long-lasting.

It is commonly found that soil from the study areas exhibit excessive deformation with a low bearing capacity. The application of soil improvement methods plays an important role in minimizing the risks associated with such situations. In this thesis, numerical analysis were carried out using environmental friendly and easily available ground improvement techniques that are used to minimize the problematic characteristics of soil with the help of secondary data collected from a consulting office (illustrated in appendix 2). Compared to chemical and physical stabilizers, there are very few studies that use stone columns to improve the soil in the study area. The literature study reveals researchers investigating static and dynamic properties of given soil, comparing field and laboratory studies, and stabilizing the soil with different additives. In the review, several shortcomings are noted regarding the common practice of adding chemical additives to tropical soils, since most of these additives are not made from waste products or demolished materials, but rather are obtained directly from manufacturers, which make them more expensive to use. As a result, it is crucial to implement materials that are readily available, cost-effective and environmentally friendly material as a means to improve problematic soils.

2.2. Methods for Stone Column Installation

No matter what kind of methods or tools are used, stone columns are normally installed using this procedure: initially a cylindrical cavity is created and sustained underground, and then granular materials are gradually filled in and compacted while the supports are extracted. This granular fill usually consists of gravel or crushed stone. Selecting the construction method mainly depends on the site conditions and the availability of the construction equipment and the filling materials (Abdulrasool, 2016). The construction of stone columns can be categorized into three methods.

2.2.1. Construction of stone column by vibro-replacement method

In this method, a hole is formed by jetting a probe down to the desired depth using water or oil. The key feature is that the material in the probe or case is flushed out in the liquid flows and replaced by granular material. Figure 2.1 shows a schematic illustration of the vibro-replacement method. Replacement method involves replacing in-situ soil with stone column materials. A vibratory probe (vibroflot), accompanied by a water jet, is used to create the holes for the columns. This technique is suitable when the ground water level is high, and the in-situ soil is relatively soft (Ambily and Gandhi et al. 2007). When fines content in the soil exceeds

15 to 20% (Refer to graph 2.8), the soil is replaced by stones or gravel which is poured in stages; a process called vibro-replacement. At each stage the aggregates are vibrated into a dense state. The column-soil composite formed reduces the settlement and the compressibility of the ground as well as increasing the bearing capacity, the stiffness and the shear strength of the soil (**Charles et al, 2002**)

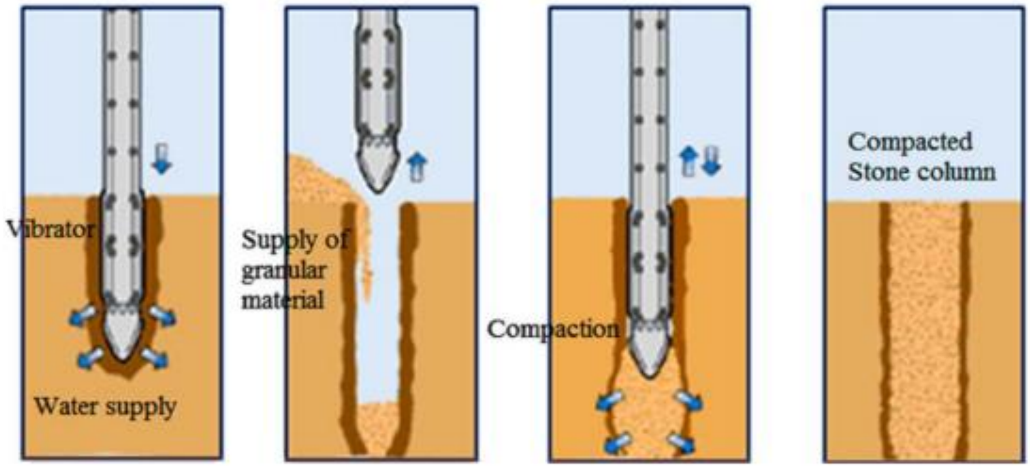


Figure2.1 Vibro-replacement (Dheerendra Babu et al., 2012)

2.2.2. Construction of stone column by vibro-displacement method

In vibro-displacement method, compressed air rather than liquid (water or oil) is used to assist the penetration of the probe into the ground. The soil underground is forced to form a cavity rather than being removed while making the borehole. The diameter of the stone column using this method is usually smaller than that of vibro-replacement method. The vibro-displacement procedure is shown in **Figure 2.2** A technique called "Vibro composer" (Dheerendra Babu et al., 2012). Displacement method is utilized when the water table is low and the in-situ soil is firm. It involves using a vibratory probe, which uses compressed air, to displace the natural soil laterally (Ambily and Gandhi et al. 2007).

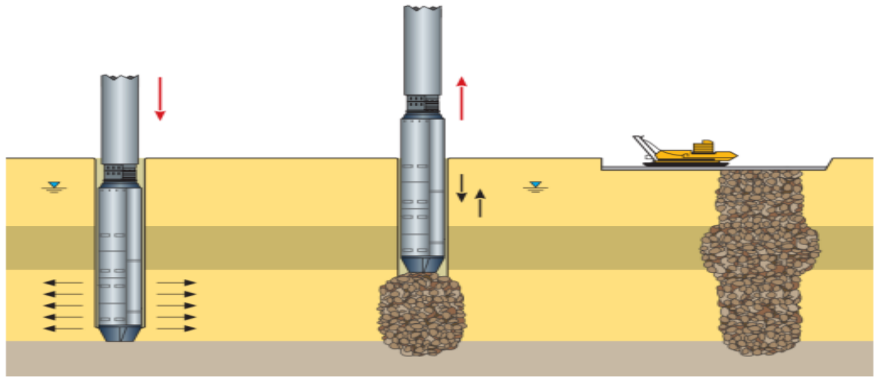


Figure 2.2 Vibro-replacement (Dheerendra Babu et al., 2012)

2.2.3. Construction of stone column by rammed stone column method

The rammed stone column is an old-fashion method where stone column is installed in several stages. The compaction of granular materials in the pre-bored holes is achieved through heavy falling weight rather than vibration. The rammed stone column is cost effective due to the low requirement of equipment, but it may be relatively slow and uneconomical when the target depth exceeds 12-15m. Besides, it is not appropriate for improvement of sensitive soils. A sketch is presented below in Figure 2.3.

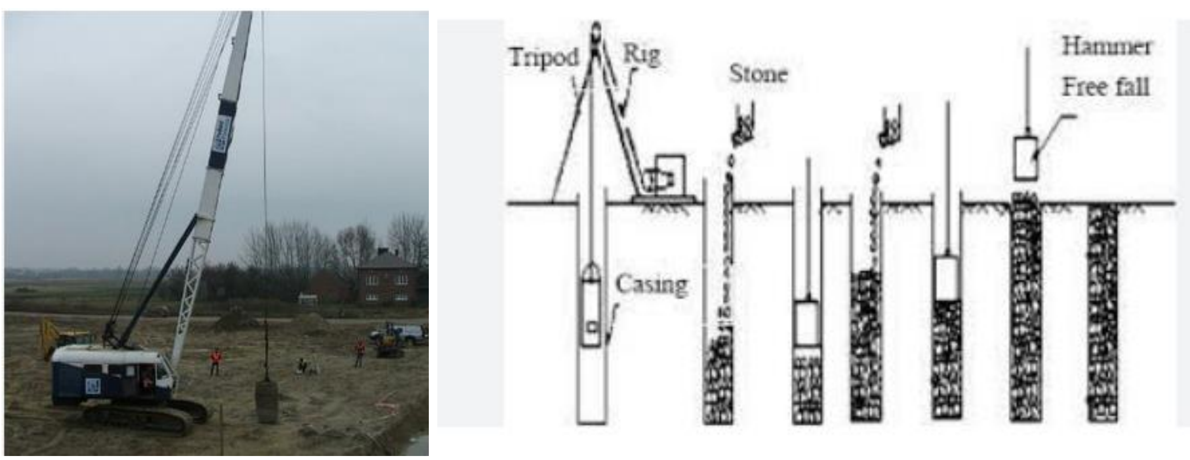


Figure 2.3 Rammed stone column (Dheerendra Babu et al., 2012)

Stone columns are continuous columns of compacted aggregate that are typically formed using a vibratory probe or ramming probe to create vertical inclusions of high stiffness, shear strength and improved drainage characteristics. Stone columns typically range in diameter between 18 and 42 inches (Dheerendra Babu et al., 2012)**.** When a vibratory probe is used to form the hole in which the stone column is constructed, the elements are referred to as vibratory stone columns. In this method, creation of hole in the ground and compaction of granular fill backfilled in the hole is done mechanically using a mechanical unit called vibrofloat. Stone columns may be constructed using vibrofloat either by Wet process, which is suitable for soft to firm soil with high water table condition where borehole stability is questionable, or by dry process which is suitable for soils of relatively high initial strength with low water table, where the hole can stand of its own upon extraction of the probe, such as unsaturated fills.

If separate drilling equipment is used to create the hole in which the stone is placed, then the elements are commonly referred to as aggregate stone column. The process of installation where soil is taken out during boring is called non displacement type of installation. The bored rammed stone columns are used in cohesive soils. In this technique, a casing pipe is used to remove the cohesive soil protecting the sides of the bore, thus minimizing disturbance to the surrounding soil. The stones are laid into the bore and rammed to a larger diameter as the casing pipe is withdrawn. These columns achieve their strength by the lateral restraint offered by the surrounding soil. It is therefore very essential that the shear strength of the surrounding soil not be reduced by the construction of the stone column. Hence, the stone column technique could be adopted in clays of low sensitivity. These columns also act as drainage paths to accelerate settlements under loading. If the soil is laterally displaced while making the hole due to driving of a tube or a casing, it is the displacement type of boring (Dheerendra Babu et al., 2012).

The key factors for designing and calculating a stone column project is the improvement design (i.e., depth, diameter, and the spacing of stone columns), loading intensity and type, footing dimension and ground water table, and stone column and soil properties. Except for stone column properties, all others are not highly complicated to measure or correlate from design or soil investigation reports. On the other hand, there have always been debates on the properties of stone columns among researchers and designers in the field of ground improvement and more importantly, on the stiffness of the executed columns (Keller, 2017). Two main technologies exist for installing stone columns, namely top- and bottom-feed methods (sometimes referred to as wet or dry methods, respectively). The methods are schematically shown in Figure 2.4.

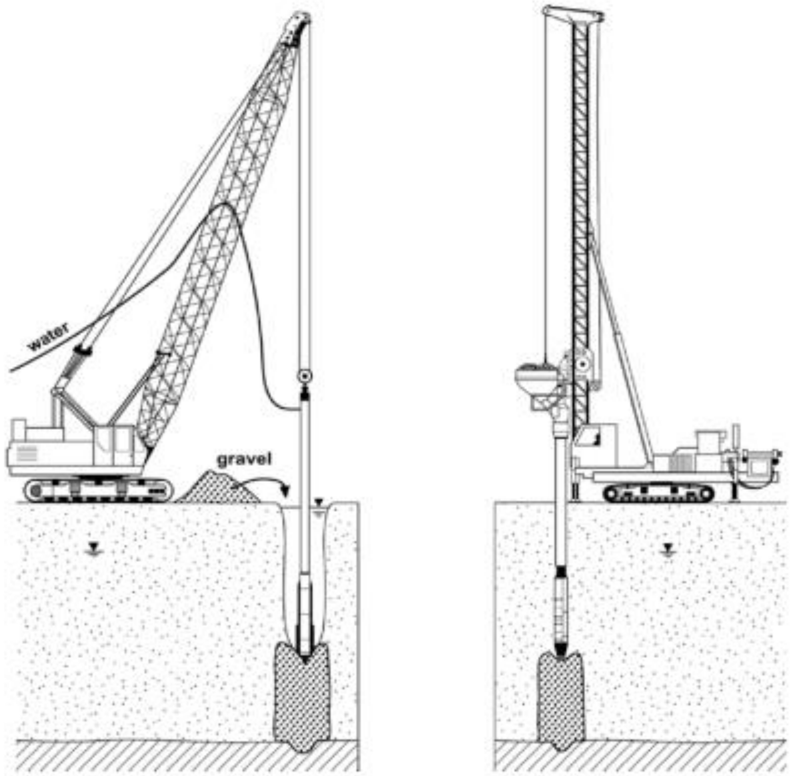


Figure 2.4 Stone column installation (stone Feeding) methods (Keller, 2017)

Stone columns are installed using either top or bottom feed systems. In either case, primarily hole of required diameter was augured. Auger was inserted into the soil bed by rotating it manually at the centre of the tank. Care was taken so that the disturbance of the soil surrounding the bore hole will be minimized (Charles, 2002). In the wet method, a depth vibrator is suspended from a crane. The vibrator penetrates the ground using electric power and a high-pressure jet of water. By vibration and high water jet pressure, the soil surrounding the vibrator is liquefied assisting in penetration and creating a cavity around the vibrator and its holding tube. The cavity is then filled with aggregates while the vibrator is at its maximum depth. Next, the stone column is formed in steps in which the aggregate is laterally pressed into the soil by pushing the vibrator downward. Regarding the dry process, the vibrator and the extension tube are equipped with a channel through which aggregates can reach the tip of the vibrator by the pressurized air. When the vibrator is penetrated down to the design depth, the aggregates are fed into a funnel and transported through the channel. During the withdrawal steps, aggregates run from the vibrator tip into the created annular space and then are compacted and pressed into the surrounding soil during the following re-penetration step. Construction of stone columns is generally carried out in one of two ways: either through a replacement or a displacement method. When using the displacement or dry method, native soil is displaced laterally by a vibratory probe that is powered by compressed air to move it laterally. It is suitable for use in areas where the groundwater level is low and where the in situ soil is fairly hard. In the replacement or wet method, native soil is replaced by stone columns in a regular pattern where the holes are constructed using a vibratory probe accompanied by a water jet. Figure 2.5 - 2.7, shows the installation of stone column both replacement and displacement methods under dry and wet conditions.

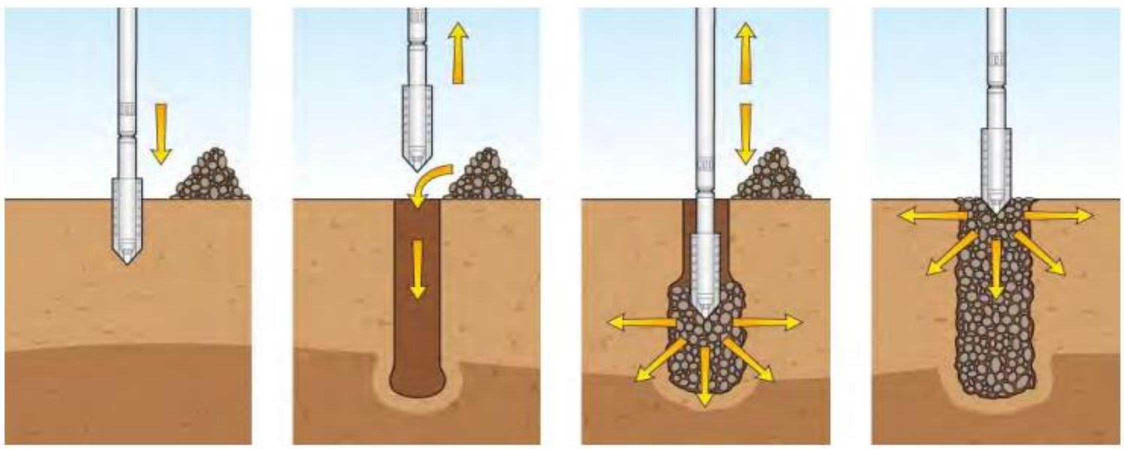


Figure 2.5 Dry – top - feed method process schematic (BRE, 2000).

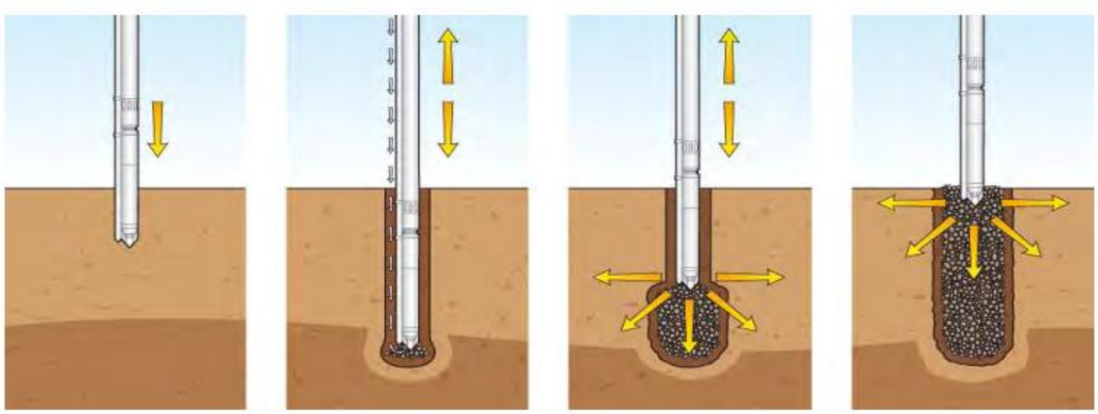


Figure 2.6 Dry – Bottom - feed method process schematic (BRE, 2000)

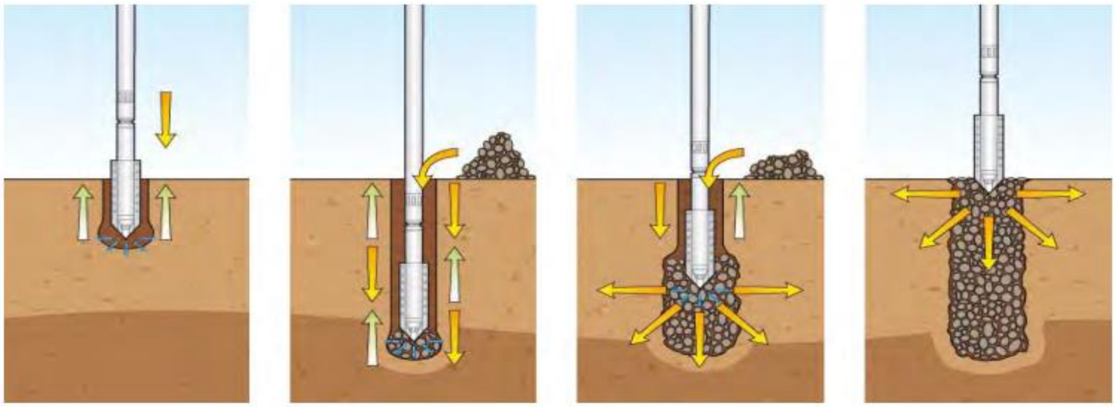


Figure 2.7 Wet - top - feed method process schematic (BRE, 2000)

As shown in Figure 2.8, the vibro- replacement cab is applicable for fine-grained and coarse-grained material whereas vibro-displacement is just applicable in coarse-grained soils. Based on several case studies the vibro techniques can be used for a wide range of soils (refer to Figure 2.8) and for various projects and applications such as landfills, embankments, highways, airports, railways, slope stability and bridge abutments (McKelvey, D., et al, 2004).

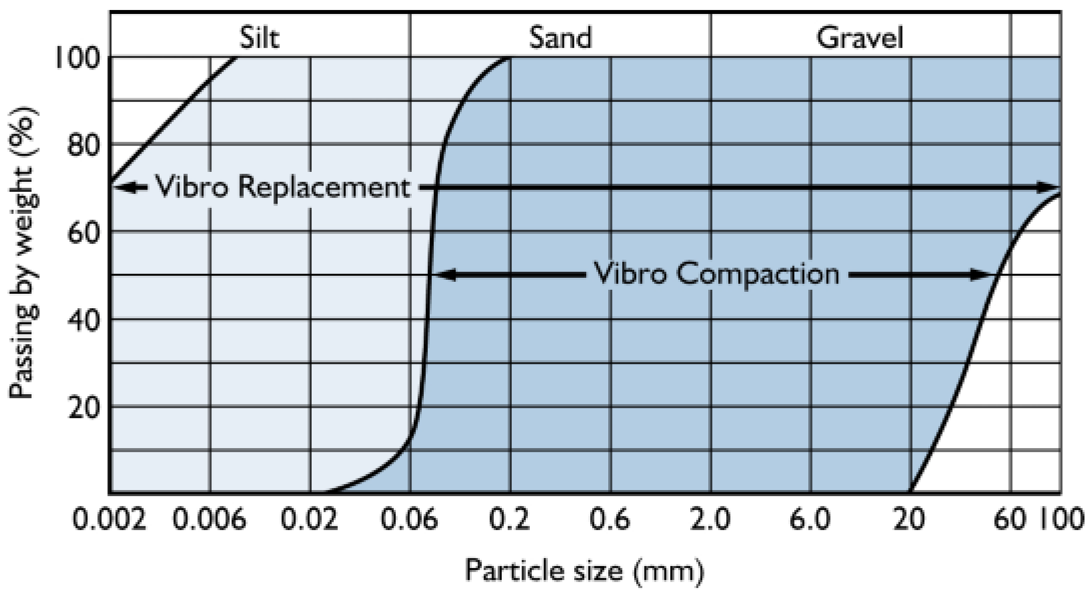


Figure 2.8 Applicability of Vibro-Compaction and Vibro-Replacement (Keller Far East, 2002)

2.3. Application and usage of stone column

A substantial amount of time and money can be saved if structures can remain stable on a natural foundation, but most natural soils are not capable of bearing load or meet serviceability requirements when new infrastructure is built. To avoid these problems, it would be necessary to improve the ground properly (Indraratna et al., 1992). There are a number of factors to be considered when selecting ground improvement methods, including the site conditions, the types of structures, and the budget. Currently, four methods are commonly used in practice (Sivakumar et al., 2004):

- Pile installation is efficient and usually saves time, although it is costly;
- Embankment- or vacuum-associated vertical drains may speed up consolidation, but they always take a lot of time;
- A chemical stabilization process involves mixing lime, cement, or other chemicals with soft clay with high water content; it is not environmentally friendly and can sometimes delay the construction decision;
- Stone columns which increase the overall stiffness and shear strength of soft ground (Black et al., 2007).

Regardless of the limitation in the application, stone columns usually provide a relatively cost-effective and environmentally friendly option compared to other ground improvement methods. The principal concept of stone column is replacing some of the original soft clay with an array of compacted columns made of a coarse granular material such as gravel. To some extent, stone columns act as piles that ‘shoulder’ the load from surrounding soil and serve as vertical drains that allow excess pore pressure to dissipate. This method increases the bearing capacity, reduces total and differential settlements, accelerates consolidation, improves stability, and enhances the control of liquefaction (Guetif et al., 2007, McCabe et al., 2009).

Stone column improves the shear strength of the subsoil to increase the bearing capacity. It improves the stiffness of subsoil to decrease settlements. It has the ability to carry very high loads since columns are ductile. It is more economical than piling (Karun. et al, 2013). Rapid consolidation of subsoil is facilitated in stone column. Immediate increase of shear strength and friction angle of treated soil occurs. There is no waiting period after installation unlike PVD. Embankment construction can begin soon after installation. When installed in a uniform grid pattern it ‘homogenizes’ variable soil properties, thereby reducing the potential for differential settlement.

Application of stone column is normally used in different civil engineering constructions such as embankments slopes, deep excavations and under smaller constructions like pipelines (Dheerendra Babu et al., 2012). Stone columns have been used as an effective technique for improving the engineering behaviour of soft clayey grounds and loose silt deposits. The soil improvement via stone columns are achieved from accelerating the consolidation of weak soil due to shortened drainage path, increasing the load carrying capacity and/or settlement reduction due to inclusion of stronger granular material (Ayadat T, Hanna AM, 2008). It is used to increase the soil's shear strength and to increase its resistance to liquefaction. Nowadays the application of stone columns in civil engineering projects is more effective than other methods, since the material is easily available, cost effective and environmentally friendly. Some of the advantages of application of stone column as ground improvement are stated below (Mokhtari *et al*, 2012):

- It is possible to build heavier structures without the risk of settlement or failure with stone columns when the soil is weak or compressible.
- Stone columns can reduce settlement by consolidating and densifying soil, providing structures with a stable foundation.
- By stabilizing slopes and embankments, stone columns prevent soil erosion and landslides.
- Stone columns can increase soil strength and stiffness in earthquake-prone areas, preventing soil liquefaction.
- Stone columns can improve the drainage of foundation soils, reducing the risk of water damage and erosion.
- Stone column method is often a cost-effective solution compared to other ground improvement methods, such as deep foundation systems.
- Stone columns are an environmentally friendly solution, since they reduce the need for excavation and landfilling of soil, thereby preventing natural disturbances.

2.4. Design Considerations

Whenever assessing the suitability of stone columns for a given site and foundation system, it is necessary to first evaluate the performance of the unimproved ground and then determine if the stone columns can provide the desired results based on improved bearing capacity, density, and settlement reduction Basically, stone columns can be designed as follows (Hughes et al, 1974):

- Assess the load carrying capacity of stone columns.
- Determining the stone column length, diameter, which is a critical part of the design process, is determined from evaluation of the settlement calculations. Stone column diameter and spacing are determined from contractor experience.
- Determine the area replacement ratio (stone column area divided by tributary area of stone column) necessary to provide the required reduction of settlement.
- Estimate the settlement for the proposed loading conditions for the unimproved ground using conventional settlement calculations.

Prediction of the stone column diameter and spacing which is the critical part of the design process is mostly based on contraction experience. Column diameter, are predicted empirically. Commonly; construction methods (wet or dry method, top or bottom feed), vibratory probe characteristics, and characteristics of the strata in which the stone columns will be installed are some of the factors that affect the spacing and column diameters (Makhtari et al, 2012). According to Taube et al, (2002), diameter of stone column ranges from 24 to 36 inches is typically best suitable in case of dry installation method, whereas for wet installation methods diameter of stone column are typically larger by a factor of approximately 20 to 40 per cent. Figure 2.8 below shows plan of stone column arrangements. As shown from the figure inclusion of stone column in the form triangular and square patterns are commonly used arrangements.

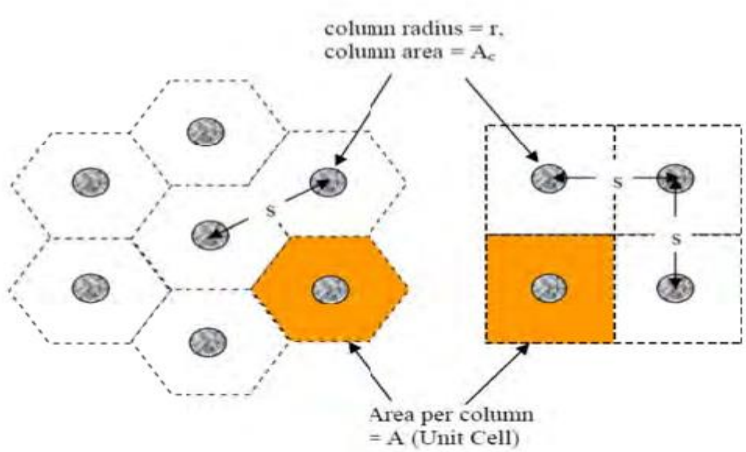


Figure 2.9 Plan of stone column, triangular and square pattern (Taube et al, 2002)

While stone columns will transmit some load to the soil by shear stresses (along the column-soil interface) and end bearing (at the column base), the predominant load-transfer mechanism (unless the column is very short) is lateral bulging into the surrounding soil. The relevant column stresses are depicted in Fig. 2.9 The passive resistance of the surrounding soil dictates the column performance under load. Generally, the column bulging will be greatest close to the top of the column where the overburden pressures are lowest.

2.5. Design parameters to be considered

2.5.1. Stone Column Diameter

Installation of stone columns in soft cohesive soils is basically a self- compensating process that is softer the soil, bigger is the diameter of the stone column formed. Due to lateral displacement of stones during vibrations/ramming, the completed diameter of the hole is always greater than the initial diameter of the probe or the casing depending upon the soil type, its undrained shear strength, stone size, characteristics of the vibrating probe/rammer used and the construction method. Diameter usually varies from 800 to 1500 mm (Karun. et al, 2013). Stone columns vary in diameter depending on several factors, including the device used, how the device is adapted to the site's soil, how deep the soil is penetrated, and the amount of energy used (power output, vertical force, and running time).

Different layers may have different resistances to penetration, so a column's diameter may vary over its length. In most cases, dry method columns are between 50 and 80 cm in diameter (P. Aguado et al., 2013)

2.5.2. Filler material

Filler Materials of Stone Columns require important specifications to enable to reinforce the weak soil and thus strengthen it. Filler materials consider an important parameter in designing stone columns. Natural aggregates have been utilized in construction projects for a long time. But at present, the world is moving towards sustainable construction and reusing recyclable materials if possible. In addition, it is getting harder to find sand and gravel from natural sources. Consequently, considering sustainable options as alternatives is the best solution. There are three important factors when choosing filler materials, such as availability, suitability, and economy. Researchers are studying the possibility of using sustainable and recycled materials and their effect on improving weak soil properties (Ghazavi et al. 2013; Siva Gowri Prasad et al. 2016; Zahmatkesh et al. 2010). It was agreed by many researchers who evaluated the effectiveness of filler materials and found their positive effect significantly in improving soil properties (George et al. 2016; Nazaruddin et al. 2013; Palaniappan et al. 2013; Prasad et al. 2015). The column material size is chosen based on the ratio of the column diameter (D) to the column material size (d). The range of D/d value lies in 4.72–62.5(Pandey et al. 2022).

2.5.3. Pattern arrangement

Triangular and square arrangements of stone columns are taken into consideration because they are the two most common types of vertical drain arrangement. Stone columns should be installed preferably in an equilateral triangular pattern which gives the densest packing although a square pattern may also be used. A typical layout of the patterns is shown in Figure below.

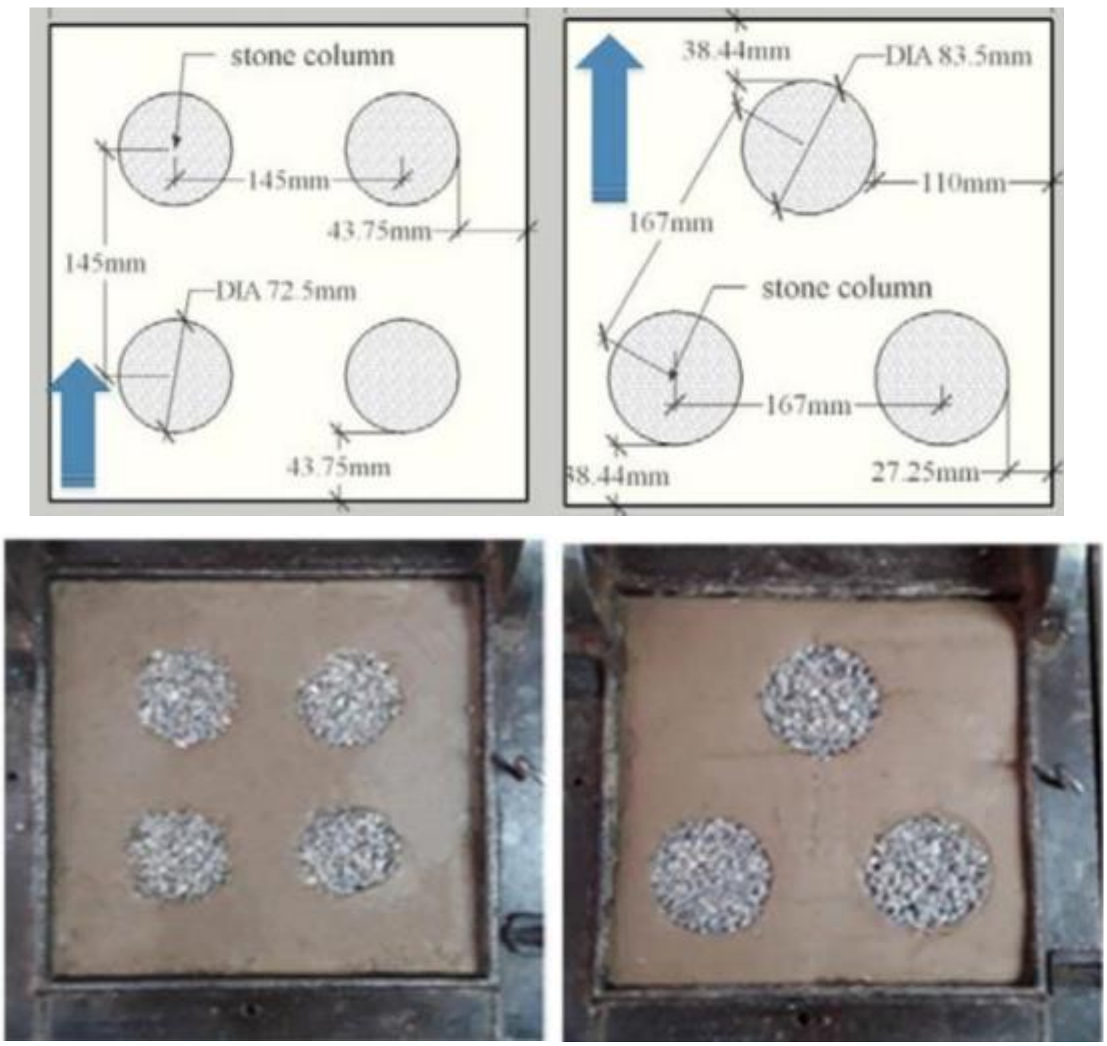


Figure 2.10 Rectangular and Triangular pattern arrangement of stone column installation (Asllani M. et al., 2019)

Grouped stone columns are generally arranged in a square or triangular pattern. The area of surrounding soil for each stone column can be closely approximated as an equivalent circle to allow an axial symmetry condition. This equivalent circle has an effective diameter (de) of 1.05, and 1.13 times the spacing between stone columns (s) for the triangular and the square patterns respectively (Castro, 2017). The stone column spacing generally ranges from two to three times the stone column's diameter depending on the soil condition, the applied load, the construction method, the permissible settlement and the required degree of improvement (Aguado et al, 2011). Ambily and Gandhi (2007) revealed that, no significant improvement was observed beyond this spacing range. This is in agreement with the work presented by Prasad et al. (2012).

2.5.4. Spacing

The design of stone columns should be site specific and no precise guidelines can be given on the maximum and the minimum column spacing. However, the column spacing may broadly ranges from 2 to 3 times column diameter, depending upon the site conditions, loading pattern, column factors, the installation technique, settlement tolerances, etc. For large projects, it is desirable to carry out field trials to determine the most optimum spacing of stone columns taking into consideration the required bearing capacity of the soil and permissible settlement of the foundation. Settlement value is highly influenced by the diameter and spacing of the holes. Srijan et al. (2021) found that a larger diameter with a lower spacing significantly reduced settlement. The design load and amount of improvement determine the spacing of stone columns in order to provide the desired foundation, reliable stone column factors, soil tolerance, and the process of installation and site circumstances. Srijan and Gupta (2021) stated that according to a practical validation, shows, closer spacing is required in isolated footing as compared to larger rafts. Generally, as seen from literatures the spacing of stone column inclusion vary between two or three times to that of stone column's diameter.

2.5.5. Area Replacement ratio

Area replacement ratio is defined as the ratio of area of the stone pile (Ap) to the total area within the unit cell (A): $\boldsymbol{A\mathrm{r} = A_P/A}$

Where:

Ar= area replacement ratio, A=area of the stone pile and Ap=the total area within the unit cell

An area replacement ratio of 0.25 or higher is needed for treated ground for stone columns in order to significantly improve in bearing capacity (Dheerendra Babu et al. 2013).

2.5.6. Stress Concentration factor

The stress concentration factor (n), due to externally applied load, is defined as the ratio of average stress in the stone column to the stress in the soil within the unit cell. The value of stress concentration factor generally lies between 2.5 and 5 at the ground surface.

2.5.7. Failure Mechanism

Stone columns may fail through different failure mechanisms if the necessary precautions are not taken. Single stone column or stone columns group, loading condition, column length (i.e., floating or end bearing), the strength of the surrounding soil, column material, and the encasement are the parameters defining the failure modes of stone columns. Failure modes of stone column groups depend on the loading type and lateral spreading (Pandey et al. 2022). Figure below shows failure modes of grouped stone column.

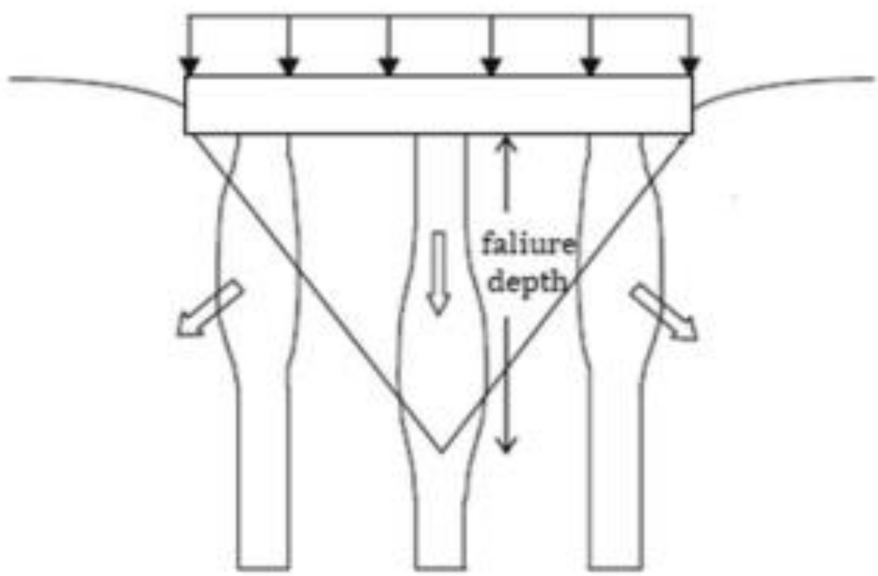


Figure 2.11 Failure mechanism of grouped stone column (Wood D.M. et al, 2000)

Effect of surrounding soil to identify ordinary or encased stone column application

Ordinary stone columns are widely used in clayey soils with undrained shear strength ranging from 15KN/m^2 to50 kN/m^2 to improve; the bearing capacity, reduce the settlement and increase the consolidation settlement speed (Barksdale and Bachus 1983). In very soft soils, with undrained shear strength lower than or equal to15 kN/m^2, the lateral support provided by the soil is not sufficient, and ordinary stone columns may fail due to excessive bulging. In these situations, encasing stone column with high stiffness geosynthetics provides extra lateral support to the stone column (Miranda et al. 2017; Tandel et al. 2017).

2.6. Review of Previously Conducted Study

One of the most common techniques for improving soft soils for the foundation of embankments or structures is stone columns, also known as granular piles or aggregate piers (Vahedian, A., et al, 2014). Ground improvement by a stone column was believed to be a cost-effective method. Stone column involves improving weak soils by installing vertical boreholes in the ground, filled upwards with aggregates and compacted by a vibrator. Stone columns have been widely applied when dealing with soft soil to enhance its bearing capacity, decrease settlements, improve the stability of slopes, reduce the liquefaction under cyclic loads, and accelerate consolidation times (Jorge C., 2017). Nowadays, they are globally used in many soil types and loading conditions because of their ease of construction and cost effectiveness compared to the other improvement techniques. Moreover, stone columns can be considered environmentally satisfactory due to using recycled materials instead of the traditional aggregates in stone column construction (Moayed et al, 2017). The mode of failure of stone column mainly depends on its use (single or grouped), column length, loading condition, strength of surrounding soil and column filling material (Pandey et al. 2022). A number of experimental and numerical studies were conducted on stone columns to investigate the modes of failure. A study conducted by Hu (1995) revealed that stone columns can be bulged, punched, sheared and bent. Bulging was observed in the lower length of the central column while it remained in the upper length of the outer columns. In stone columns, general shear failure was the predominant mode of failure. Finite-element analysis performed by Wood et al. (2000) supports these observations. Stone columns failed in conical areas below the foundation, according to the researchers. Figure 2.12 shows the failure mechanisms of the stone columns group.

Barksdale and Bachus (1983) have conducted finite element analyses to give non-linear solutions to settlement and stress concentration of stone columns reinforcing soft cohesive soils. From the analysis, they reported that soil shear strength did not influence the settlement since the soils which have modulus of elasticity greater than 1100 KN/m^2 did not fail by an interface or soil failure. In non-linear analyses, the effect of interface was found to be very little as increasing the settlements; therefore, the effects of interface elements, having able to model the no slip, slip or separation using Mohr-Coulomb failure criteria, were ignored.

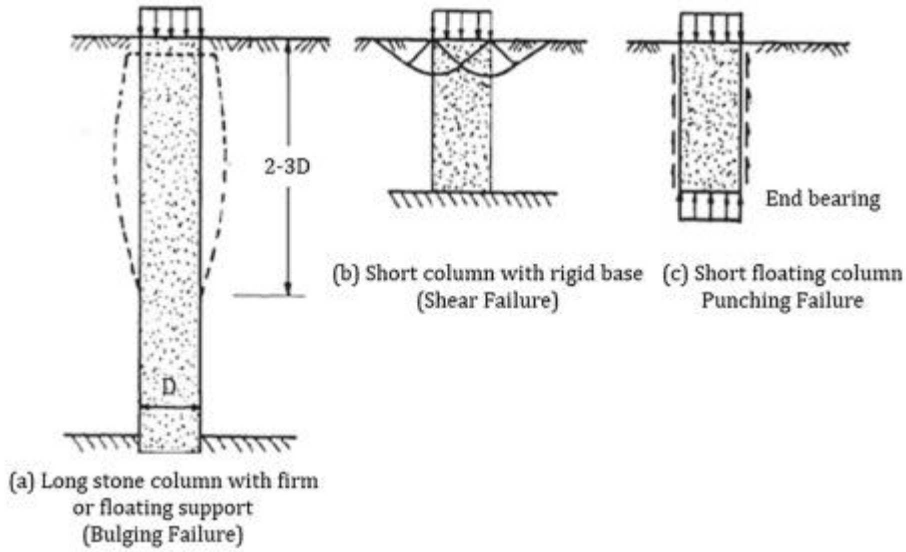


Figure 2.12 Modes of failure of single stone column in soft soil (Barksdale et al, 1983)

McKelvey et al. (2004) conducted a series of laboratory tests on consolidated clay soil to examine the failure mechanisms in stone columns group. They reported that the deformation of the central stone column was uniform, while the perimeter columns deformed away from the adjacent columns. A review of recent laboratory, numerical, and field studies on the behaviour of stone columns in different types of soils was presented. A summary table that provides a concise overview of recent research efforts is also presented. Table 2.1 summarizes how researchers conducted their models, which weak soil was improved, what the geometry of columns was, how loading was applied and the main findings which were drawn from their studies. The previously mentioned parameters and their effect on the performance of columns are thoroughly discussed in the following tables.

Table 2.1 list of previously conducted related works

Reference	**Lab/ Numerical**	**Soil type**	**Fill material**	**Single/ Group Column**	**D (mm)**	**L/D**	**Main Conclusion**

Saxena and Roy(2022)	Numerical	Clay	Crushed Pebble Gravel	Single column	25	2,3, 4,6 and 9	Settlement was found to decrease with increasing angle of internal friction
Ashour et al(2022)	Lab	Soft clay	Crushed basalt	Single	28	6	Stone column improved the threshold cyclic stress of the soft soil by about 15% and reduced the strain by more than double
Awn and Abbas (2020)	Field	Soft soil	Stones with bentonite in %	Group	250	4	Stone column mixed with 40% bentonite decreased by settlement 55% to untreated soil and the optimum length of stone column was found to be 1/3 of soil layers
Andreou et al(2008)	Lab	Clay	Sand Gravel	Group	20	10	The bearing capacity of soft clay reinforced with drained sand was twice that for undrained column. As the confining pressure increases, the improvement in the shear strength was more noticeable in the soil improved with sand column.

Elsawy in 2013 analysed the behaviour of clay and geogrid encased stone columns beneath embankment loading using consolidation analysis and found that the bearing capacity of the foundation increased along with excess pore water pressure reduction.

Das, et al., (2013) has carried out the study on the stone column to improve the load capacity of sandy silt soil with clay in naturally consolidated state. Load test were conducted in compression testing machine for single unencased stone column in sandy soil with clay (i.e., sand = 37.29%, silt = 33.00% and clay = 29.71%) encased (with Geotextile) stone column on layered soil. In case of un encased stone column load carrying capacity increases with the increasing diameter of stone column but in unencased and encased layered soil load carrying capacity decreases with the increasing the diameter of stone column. Also, stone columns under proper conditions can greatly decrease the time required for primary consolidation.

Eied M. M. et al., (2014) mention 3-D numerical model to represent the soil and the stone column under the foundation. The numerical model is based on finite element (ABACUS-program). Comparative study is performed to determine the suitable analysis to evaluate the behavior of the stone columns group below foundation. The numerical results are calibrated with in situ-measurements

YogendraTandel et al., (2015) analyses the behavior of stone column by the numerical modelling of a small group of laboratory- modelled reinforced stone columns. The study is carried out considering parameters like area replacement ratio, stiffness of reinforcement material and reinforcement length. The performance of reinforced stone column group is discussed in terms of bearing ratio, settlement ratio, stress concentration factor and lateral deformation. The results of numerical analyses indicate that area replacement ratio and stiffness of geosynthetic are the governing parameters for enhancing the performance of reinforced stone column. The performance of partial reinforced stone column is close to that of a fully reinforced stone column.

Fattah (2012) evaluates the use of stone column ground improvement for embankment construction on soft soils. The results show that stone columns can significantly improve the stability and reduce the settlement of embankments on weak soils. The study also highlights the importance of proper design and construction techniques for achieving optimal performance.

Lofty Fayed in 2018 examines the effect of stone column diameter on soil improvement through numerical modelling and laboratory testing. The results show that increasing the diameter of stone columns can improve the load-bearing capacity and reduce settlement of weak soils. However, the study also highlights the importance of considering other factors such as soil type and column spacing in the design process.

In 2021 Al-kazzaz, investigates the influence of stone column spacing on settlement reduction in soft soils. The results show that decreasing the spacing between stone columns can significantly reduce settlement. However, the study also highlights the trade-off between reducing settlement and increasing construction costs.

Jorge Castro (2014) describes 2D and 3D finite element analyses that study the performance of groups of stone columns beneath a rigid footing. Those numerical analyses show that the number of columns and their arrangement have a small influence on the load-settlement curves. This paper proposes a new simplified approach to study groups of stone columns, which involves converting all the columns of the group beneath the footing in just one central column with an equivalent area. This simplified model is used to conclude that, for settlement reduction, there is a column critical length in a homogeneous soil around twice the footing width, and high area replacement ratios beneath a rigid footing are less efficient.

Micheál M. Killeen et al, (2014) mention a 3-D finite element analysis in conjunction with an elastic–plastic soil model is used to identify the effect of variables in the design process and interactions between them: these include column arrangement, spacing, length, and Young's modulus of the column material. A simplified method is proposed to relate the settlement of small groups to a reference unit cell settlement predicted by current analytical approaches.

In general, as seen from the previous works, Stone column ground improvement techniques enhance the load-bearing capacity of weak soils and reduce settlement. This technique involves laying vertical columns of compacted crushed stones in the soil in order to improve its properties. According to the literature review above, recent studies on stone column ground improvement have yielded some interesting results. As a result of the literature review, stone column ground improvement is effective at improving load-bearing capacity and reducing settlement of weak soils. In order to achieve optimal performance, various factors, such as soil type, column spacing, and diameter, must also be taken into account during the design process.

CHAPTER THREE

METHOD AND NUMERICAL MODELLING OF STONE COLUMN

3.1. Introduction

The purpose of this section is to create a numerical model to simulate a small group of stone columns that support a rigid footing on soft soil. A description of the study area was provided. A realistic boundary condition is adopted, including restraints, the ground water table, applied loads, and the method used to install columns. Using secondary data from the study area, a material parameter is calibrated for the soil profile. Additionally, a material parameter is presented for stone columns. Furthermore, this section describes the study area and the process undertaken to attain the general and specific objectives of the study. To accomplish these objectives, several steps were followed. First, a detailed literature review was conducted to gain a deep understanding of stone column application on settlement reduction for shallow foundation rested on loose soil.

Relevant parameters, methods, and the effects of these parameters on the settlement of the structure were investigated in detail. Next, representative data were gathered from geotechnical design offices, companies specializing in geotechnical investigations, and government agencies concerned with these matters. Taking into account the depth and number of boreholes and the extent of the area covered, the research area where weak soil could be found was determined based on the collected data. Parameters used as input for numerical modeling of the foundation system using Plaxis 3D were identified. A numerical model was then developed for stone column inclusions on selected soils for a variety of parameters. On the basis of the model's output, results and discussions were made. In the end, conclusions and recommendations were drawn. In **Figure 3.2,** the flow chart of this research is shown more clearly.

3.2. Description of study area

Adama is located in eastern Showa, Oromia Region of approximately 90 km away from the capital city Addis Ababa. It is located at 8°33’35’’N - 8°3’46’’ N latitude and 39°11’57’’ E – 39°21’15’’ E longitude. The town is among one of the fast-growing towns in industries. According to the master plan of the town, different construction activities have been carried. The major economic activities in the city are trade, urban agriculture, and investment such as hotel, factories, flour and food complex, food oil production, micro and small-scale enterprises and other informal business activities like street trade and the like. The town is the hub of a vast region of immense economic potentials accessible by means of railway and expressway. Due to these facts, the urbanization is rapid in the different directions of the town and investors are attracted to invest in the town and the nearby areas. Currently, many civil engineering structures such as roads, bridges, Industry Park and multistory buildings including international hotels and commercial centers are under construction in the town. On the other hand, the town has been vulnerable to geological hazards like erosion and associated landslides, ground fissure and flooding during rainy season. The soil in the area is predominantly loose silt-sandy soil, which is known for its low bearing capacity and high susceptibility to settlement.

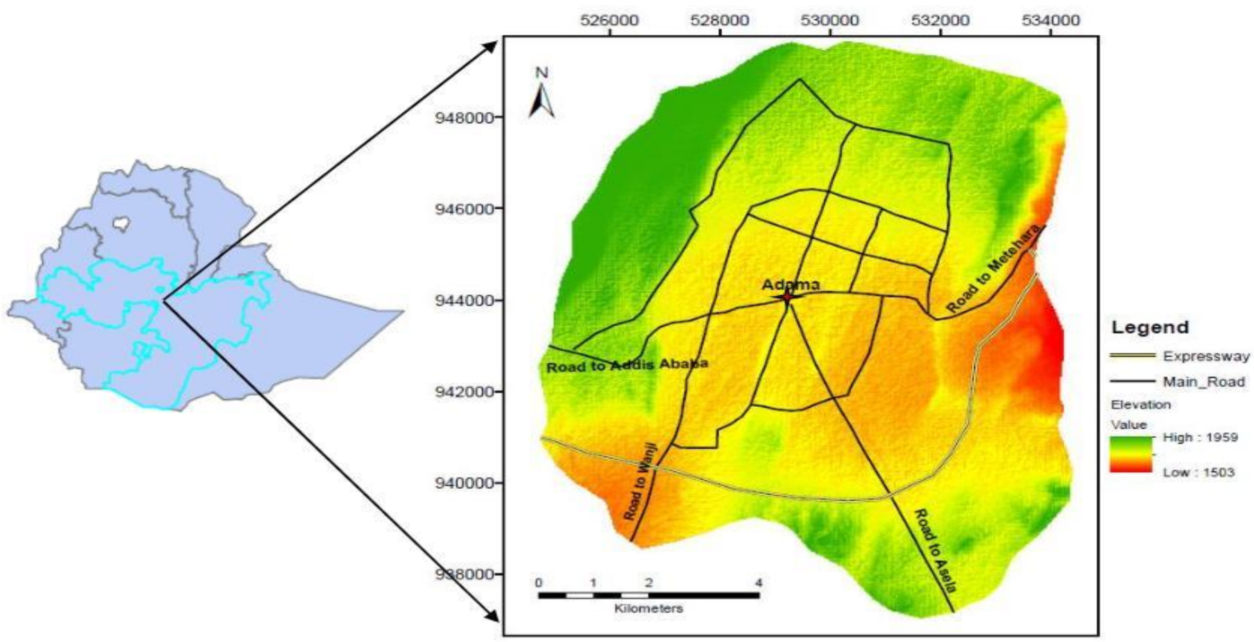


Figure 3.1 1Location map of Adama Town

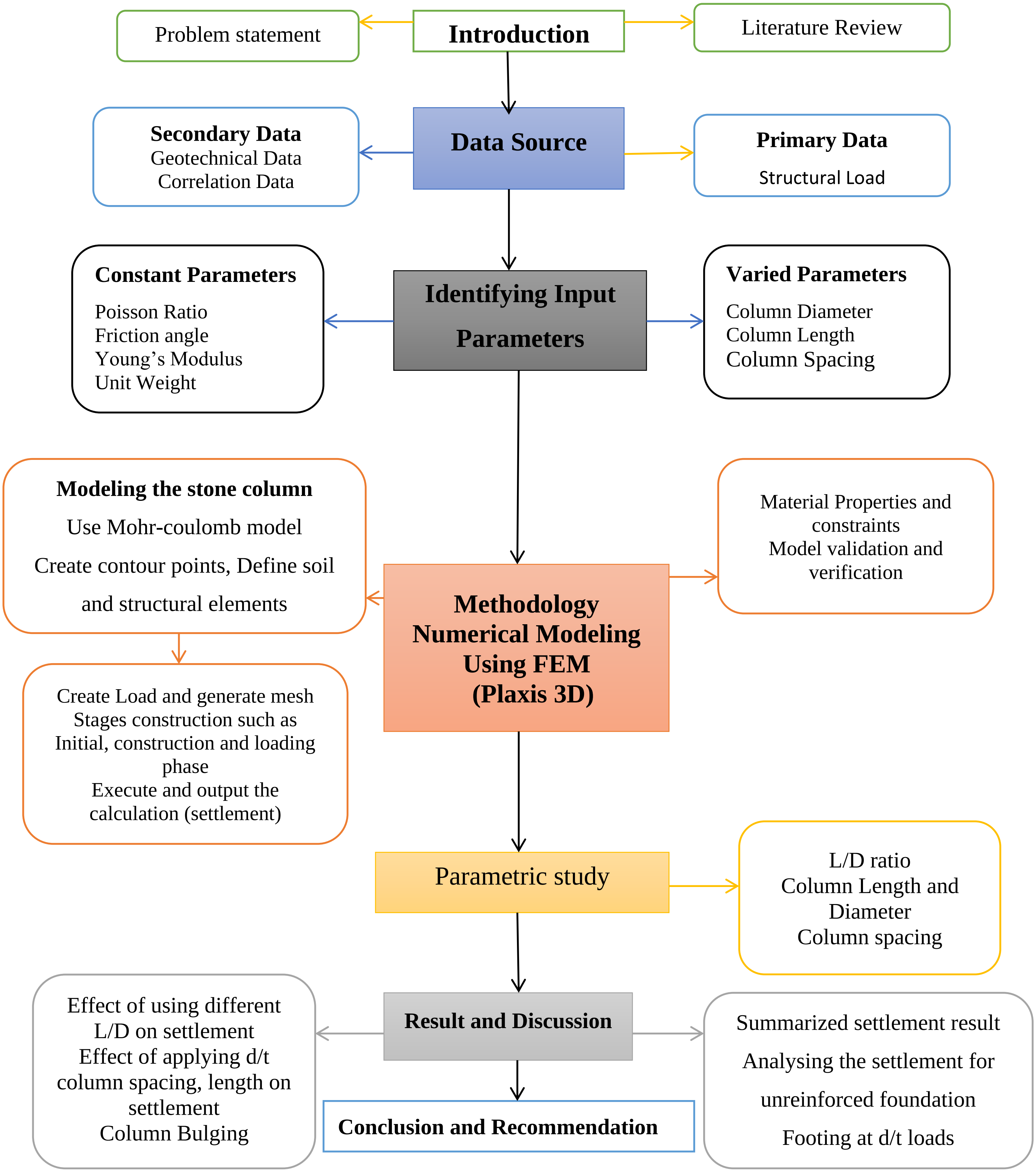


Figure 3.2 Research methodology Flow Chart

3.3 Development of Finite Element Numerical Model using PLAXIS 3D

In this research paper, a comprehensive analysis and parametric study of stone column application on loose soil were conducted using the powerful finite element-based software called PLAXIS 3D CONNECT Edition V20. The selection was made on various parameters from the components of the effect of stone column inclusion system; some were kept constant, while others were varied based on their effects on the response of the Footing, soil and stone column interaction. The parameters that were varied include column diameter, column spacing, column length, and number of stone column. The material properties of both soil and structural elements were kept constant throughout the study.

3.3.1The soil Parameters

This research examined the dominant characteristics of loose soil obtained from geotechnical investigation offices. Modelling the soil as an Elastoplastic Mohr-Coulomb medium was used to represent material non-linearity. For the Adama town soil, a single-layer model was developed from 2 borehole data, with the primary type being a non-plastic silty sand soil. These boreholes extended to 13m from the ground surface. In their report, subsurface water was not encountered in all boreholes during the course of drilling. As a result, the water table was not considered for this study.

Geotechnical parameter for the layer was sourced from the collected data, and missing information was estimated using empirical equations derived from the Standard Penetration Test. (SPT) values of the boreholes. Empirical relationships based on the SPT N value are commonly employed because of their simplicity and usefulness in estimating various parameters like cohesion, angle of friction, Poisson's ratio, shear wave velocity, and bearing capacity (Kumar R. et al, 2016). SPT is a widely used method for general soil characterization. Young's modulus, cohesion, angle of friction, and Poisson's ratio of layers were not given in the soil investigation report. Therefore, Young's modulus of layers has been determined using Appendix 2 as reported in USCS (Kézdi & Rétháti, 1974; Obrzud & Truty, 2012). Cohesion, angle of friction, and Poisson's ratio were determined using a correlation equation developed by Kumar R. et al. (2016).

3.3.2 Development of Stone Column Material Parameters

The stone column material chosen to be installed in the clay soil in order to improve its strength and stiffness is crushed stone used for construction purpose especially aggregate for concrete production. Its properties were acquired from Adama to Awash expressway project Profile for CEG Consulting Engineering Groups, Stone Crushing and Screening Plant (2021) and, its properties were calibrated with international standards, which focused on stone column materials. A summary of the parameters developed for the stone column is presented in Table 3.1.

Table 3.1 Soil and stone column properties adopted for all subsequent finite element analysis

Soil Parameter	Stone Column	Soil
Material Model	MC	MC
Depth	6m	9m
Drainage condition	Drained	Drained
Bulk Unit weight (KN/M3)	19	18
Saturated Unit weight (KN/M3)	20	19
Modulus of Elasticity, E (mPa)	80	35
Friction Angle (^{0})	42	32
Dilatancy Angle	12	2
Poisons Ratio	0.3	0.4

3.3.3 Development Material Parameters for selected footing type

In the present study, a square footing and column were considered. C25/30 concrete grade and S-400 steel were used with a Poisson’s ratio of 0.15 for concrete. The size of the footing was evaluated using load and bearing pressure thus an isolated footing with a square size of 2.5m by 2.5m with 0.8m thickness for all footing types were selected. In all footing types, the cross-sectional dimension of the column was selected as 0.4 m by 0.4 m. For the given footings, the column had a load carrying capacity of 1400KN and 3000KN respectively were considered. **Figure 3.3** shows a three-dimensional view of inclusion of a single column loading on a given footing.

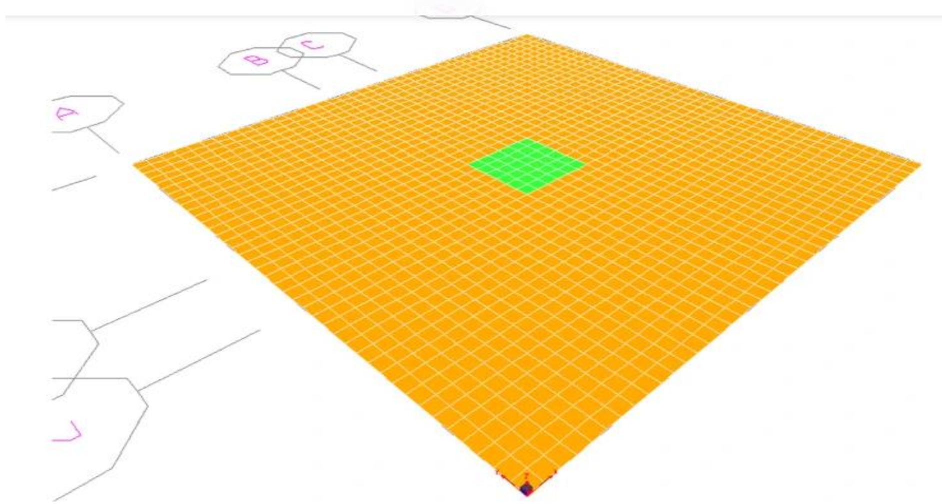


Figure 3.3 3D view of stone column loading as uniformly distributed load (UDL) on footing

The structure model applied in this study is a reinforced concrete isolated footing. The rigid footing was assumed as perfectly rough and modeled as a very stiff plate that produces uniform settlements. A typical parameter values for the reinforced concrete material were assumed for the footing as per the general property of concrete structure as shown in Table 3.2. A linear elastic model was used to simulate the footing material.

Table 3.2 Material properties of footing

Concrete Parameter	Values
Material behavior	Impermeable
Young's Modulus, E (kpa)	$30x10^6$
Unit Weight (KN/M3)	24
Poison's ratio	0.15

3.3.4 Finite Element Mesh and Boundary Conditions

The accuracy of the finite element model depends not only on the level of sophistication of the material model, but also on the boundary condition of the domain, on the number and type of the elements in to which the domain is discretized and other modeling issues.

The structural model comprises a soil continuum featuring undisturbed boundary conditions, a square isolated footing foundation, an interface component, and a uniformly distributed load (UDL) of 224kPa from a 1400KN point load for footing type 1. In addition, a load of 480KPa from a 3000KN point load is applied for footing type 2, with the provided dimensions of the footing being 2.5m by 2.5m. In the context of this particular study, the soil is represented by a typical excavation zone with a width of 5B (12.5 m) and a length of 5L (12.5m), where B and L correspond to the width and length of the chosen isolated footing (2.5m by 2.5m). The excavation's depth is determined as 2B + 2/3(Length of the maximum stone column), which in this case is 9m, as illustrated in figure 3.4. These parameters are utilized for modeling the excavation area using Plaxis 3D. Figure 3.4 shows the typical finite element mesh used in the present study. According to the design office report, water was not encountered in all boreholes while drilling the subsurface. Consequently, the water table was not considered, and a drained analysis was employed for this study.

The code for finite elements Plaxis 3D was used to create the entire 3D model. This code automatically generates the finite element mesh using a triangulation procedure, but global and local mesh refinements may be defined to ensure a good quality of the mesh (Brinkgreve et al., 2008). Soil and stone columns were modelled as a continuum element consisting of 10-noded tetrahedral elements. At the excavation edge, the model's lateral soil domain boundaries were set at a distance equal to twice the width and were limited against horizontal movement while allowing vertical movement of the soil. In a stone column, the pressure bulb was created with a size up to double the width, whereas in a group of stone column inclusion, it was formed at two-thirds of the stone column length as shown in Figure 3.5 below. Consequently, the bottom soil boundary had a vertical distance equal to twice the footing width plus two-thirds of the column length, and it was limited in both horizontal and vertical movements.

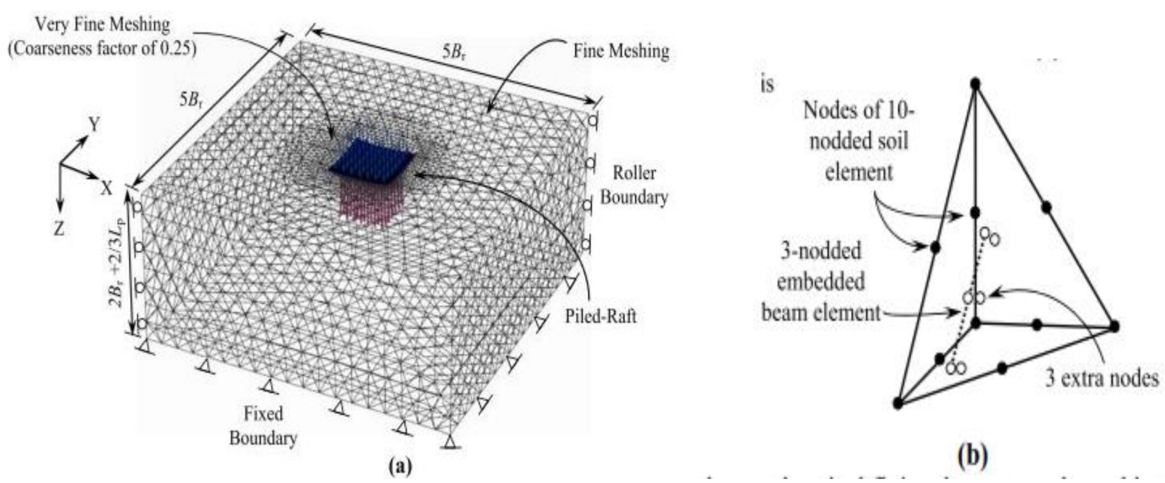


Figure 3.4 (a) Boundary and typical finite element mesh used in the parametric study, and (b) and (b)10-node tetrahedral element with 3-node embedded beam element

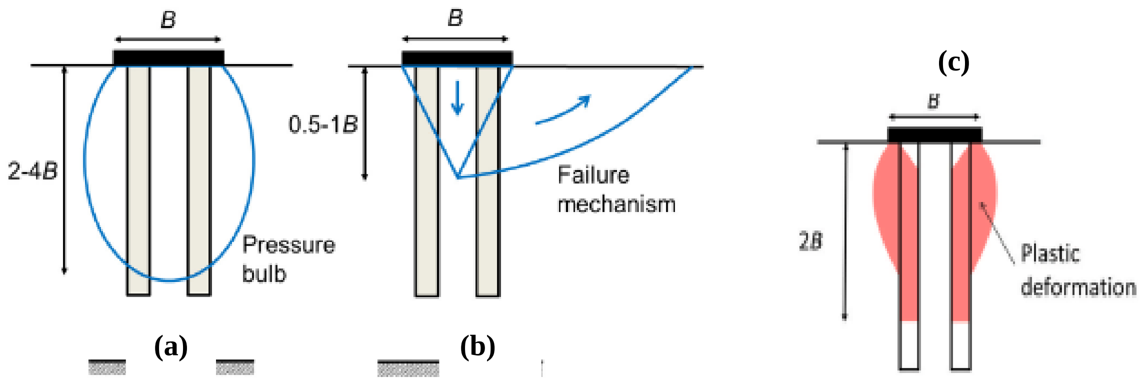


Figure 3.5 Justification of critical column length in a homogeneous soil layer: (a) Settlement reduction in elastic materials linked to pressure distribution; (b) Bearing capacity; (c) Settlement reduction in elasto-plastic materials related to plastic deformation. (J. Castro, 2017)

The examination of a unit or group of stone column inclusion on the given soil consists of three phases, including the initial phase, the construction phase, and the loading phase. During the initial phase, which involves setting up the initial geometry configurations and the corresponding stress field, the soil domain was activated. In the construction phase, the stone column-footing geometry was activated, while in the loading phase, the applied load was activated and executed. Preliminary analysis of the footing without stone column under the imposed load revealed that the chosen lateral boundaries of the soil domain were adequate, as the observed area of plastic strain developed in the soil was equal to the footing width (Br) laterally from the footing edge.

3.3.5 Modeling the stone column

A key benefit of the Mohr-Coulomb model, widely used in the modelling of geotechnical works, is that it requires a few input parameters, and these parameters can all be obtained from standard soil tests. In the Mohr-Coulomb model, soil was represented by 10-node tetrahedral elements as well as elastic perfectly plastic elements as shown in Figure 3.4. A variety of parameters were required for this modelling, including cohesion, the internal friction angle, the Young's modulus, and the Poisson's ratio. Mohr-Coulomb failure criteria indicate that soils fail when their mobilized shear stress exceeds their shear strength. The soil domain was analyzed using constant material parameter values to simplify the analysis process. Column and pad of the footing were modelled as area (shell) elements, having six degrees of freedom at each node, as specified by Vishwakarma et al (2017) for modelling a concrete slab.

Load transferred from the column was treated as a concentrated point load. However, the load is uniformly distributed (UDL) over the cross-sectional area of the column in the mathematical model. In finite-element modelling, the plate (shell) is discretised and the soil was modelled as a spring with equivalent stiffness.

The footing was designed using triangular plate elements. Upon meshing, these plates consist of 6-node triangular plate elements, each having six degrees of freedom. The stone column was modeled as embedded beam elements. Inclusion of stone columns using various diameter to length was analyzed in soils using the bottom feed system. These embedded beams are composed of beam components combined with unique interface elements that facilitate interaction with the surrounding soil. Once meshed, these beam elements transform into 3-node line elements with six degrees of freedom for each node, including three translational and three rotational movements. Killen, M. (2012) conducted preliminary checks on the influence of interface elements upon the settlement performance of various configurations of columns beneath a 3m square footing. He had clearly showed that a similar variation of settlement improvement factors with column length was observed for column modeled with and without interface elements. Since columns are highly interlocked with the surrounding soil, thus it is appropriate to model the column-soil interface in the subsequent numerical modeling by omitting interface element.

The footing and stone column maintain an elastic state due to their modulus of elasticity being higher than the soil's, leading to the footing and column material being considered linearly elastic. A rigid connection connects the column and footing. In this analysis, the interface element is represented by the interface reduction factor (R_{inter}), which signifies the interface element's strength as a percentage of the adjacent soil's shear strength. The pile-soil interface technique used is illustrated in Figure 3.6. Figure 3.6(a) and (b) respectively illustrate the "no slip" and "slip" conditions between the soil and pile elements.

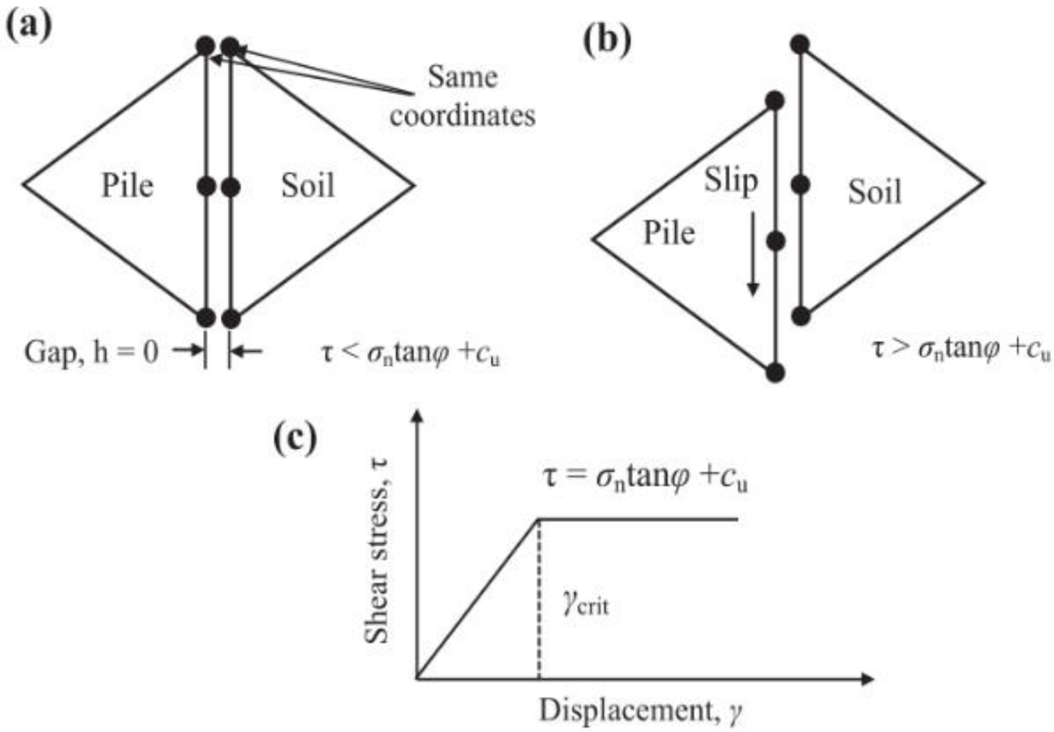


Figure 3.6 stone column-soil interface modeling technique (a) no slip, (b) slip, and (c) Coulomb frictional law (Jeong et al., 2004)

Interface elements are available in PLAXIS 3D foundation to model the interaction between smooth and rough surfaces i.e. between stone column and the soil. Interface elements can simulate gap and slip displacements, which are normal and parallel to the interface, respectively. The loss of strength at the interface is modeled with a reduction factor (R_{inter}), which relates the interface strength to the soil strength through friction angle (ϕ) as:

$$tan\varphi_i = R_{inter} tan\varphi_{soil} \leq tan\varphi_{soil}$$

According to the Plaxis 3D manual, sand and concrete interface recommendations range from 0.8-1, whereas clay and concrete recommendations range from 0.7-1. Modelling soil-stone column interactions was done using node pairs instead of single nodes in 3-node line elements. One node in each pair is part of the beam element, while the other is a point in the 10-node wedge element belonging to the soil element. The primary reason for introducing interface elements is to simulate displacement discontinuity between the structural elements and the soil mass. In the finite element formulation, the coordinates of each pair of nodes are identical, signifying that the interface element has zero thickness (h = 0) (Figure 3.6(a)).

The Mohr-Coulomb failure criterion is followed by interface elements, and when the soil's shear stress is equal to its yield shear strength ($\tau_f = c + \sigma_n \tan\phi$ slippage occurs at the interface (Figure 3.6(b)). Elastic shear behavior exists until the shear stress reaches a critical value (γ_{crit}), after which the shear displacement increases without an accompanying rise in shear stress (Figure 3.6(c)). The primary purpose of introducing interface elements is to simulate displacement discontinuity between structural elements (stone column) and the soil mass.

3.4 Mesh Sensitivity Analysis

A mesh sensitivity analysis was conducted to investigate the effect of element number on the accuracy of the finite element model. The number of columns, column size, and column spacing are varied under pad footings in subsequent parametric studies. Using two different footing sizes, mesh sensitivity analysis was conducted to compare the accuracy of medium and fine meshes against very fine meshes. The vertical displacement was examined for the mesh sensitivity analysis as the settlement performance of the stone column is the primary focus of this thesis work. It is possible to influence the results of the finite element model by changing the number of elements. In order to examine this effect on stone column inclusions, five different finite element meshes were tested on a biased mesh system with varying element sizes and numbers.

Table 3.3 Effect of the number of elements on maximum settlement

Trial Number	Mesh Coarseness	Number of Elements	Maximum Settlement (m) for 3000KN load
1	Very Coarse	1640	0.06987
2	Coarse	2967	0.07177
3	Medium	7896	0.07578
4	Fine	19720	0.07877
5	Very Fine	50,381	0.07967

Figure 3.5 and Table 3.3 shows that the maximum central settlement increases with an increase in elements until it reaches 19,720 elements. Once the maximum central settlement reaches this point, the number of elements has almost no impact. As a result, the fourth trial model was selected for further analysis. The soil domain was covered with a fine mesh, while the structural

components were covered with a mesh that was considerably finer. Its coarseness factor between fine and very fine mesh is 0.09%, which indicates that the element size in this very fine mesh is 0.09% times smaller than that in the fine mesh.

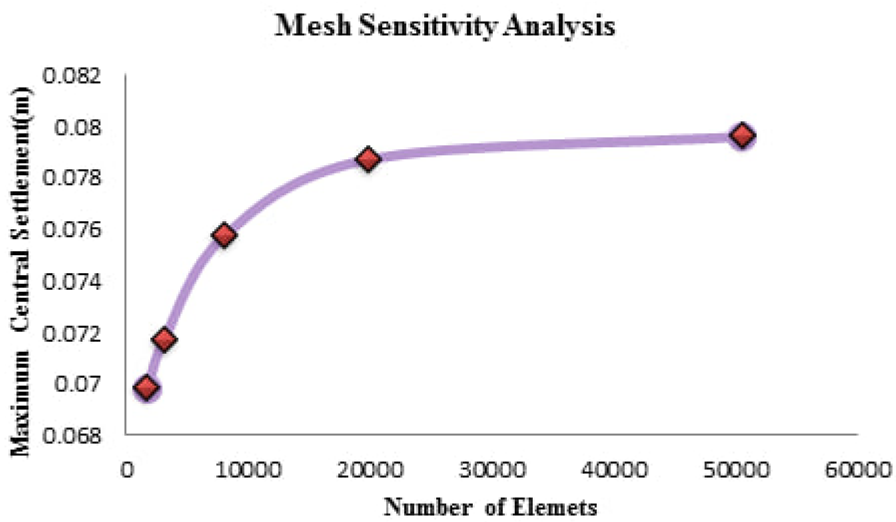


Figure 3.7 Effect of mesh coarseness on maximum central settlement

As shown in Figure 3.7, an example of a finite element mesh, for the case of 3000KN load applied, can be seen. The use of a finer mesh gave slightly higher settlements, but the differences were negligible. Mesh sensitivity analyses were performed to confirm the accuracy of the mesh.

3.5 Model Validation

In this research, the validity of the modeling approach was tested by comparing the numerical findings to existing literature. A study of the application of stone columns to selected homogeneous soil layer is presented in this thesis. In order to achieve the objectives, isolated footing types F1 with square measures of 2.4m by 2.4m, with a footing thickness of 0.8m were selected. The footing rests on several circular stone columns with length to diameter ratios of 5 and 10, fully embedded in homogeneous silty sand soil layer. The stone columns are evenly spaced beneath the footing, with varying sizes between them. In order to simulate loading, a uniform vertical load was applied to the foundation surface.

All of the subsequent numerical modeling analyses were performed using a small strain formulation and a staged construction process was modeled. Work planes are horizontal planes (x-z planes) at a certain vertical level (y-level) in which geometry points and lines and, in particular, structures and loads can be identified. Every model in PLAXIS 3D, before the beginning of any calculation phase, starts with the initial phase. The initial phase consists of the soil clusters only in which not all other structural parts are activated. Therefore, this stage calculates the stresses and deformations due to the soil clusters only by means of gravity loading. A series of Finite Element Analysis conducted using PLAXIS 3D Foundation code to examine the effect of key design parameters upon the settlement performance of stone columns. The key design material parameters and considerations are illustrated in Table 3.1 and 3.2. In addition, the preliminary checks for sensitivity analysis have also dictated.

Figure 3.8 compares the load-settlement behaviour of the stone column reinforced soil generated by the current numerical model analysis with the Plaxis results generated by Mohanty P. (2015). It can be seen from the figure that the present numerical study's results are in good agreement with those of previous numerical studies.

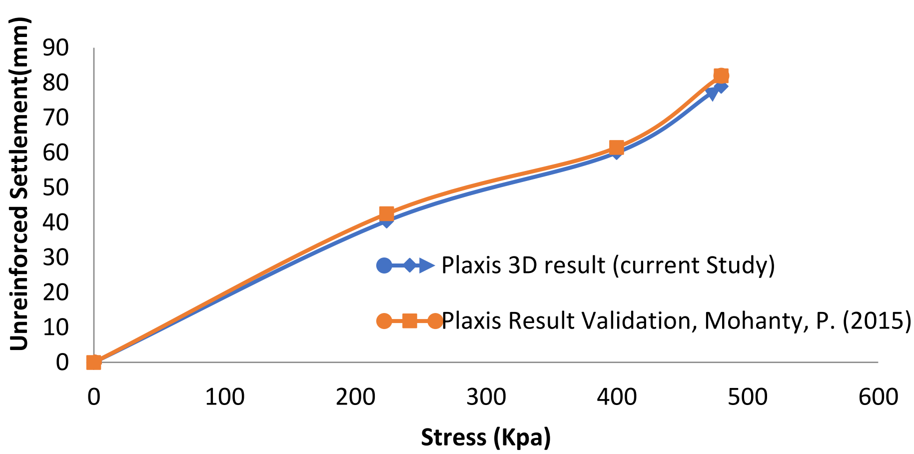


Figure 3.8 Comparison of the current study's results and previous numerical studies on load-settlement behavior of the given soil before reinforcing with stone column

CHAPTER FOUR

RESULT AND DISCUSSION

4.1. Introduction

With PLAXIS 3D, 42 Finite Element Analyses were conducted to analyse the settlement behaviour of stone columns in several configurations. The purpose of this study is to verify the effectiveness of stone columns and to better understand the behaviour of stone columns in problematic soils. Parametric studies focused mainly on the settlement performance of stone columns under working loads. This is because the design of foundation on weak soil is usually governed by settlement rather than bearing capacity criteria, due to its high compressibility (Priebe, 1979).

The study considered variables like column diameter, spacing, length, number, and a square footing size and thickness. To evaluate the interaction effects of the stone column for drained soil conditions, two types of a square isolated footing were taken into account. In order to minimize the storage and time required for numerical computations, smaller foundation dimensions were considered in this study, along with the general dimensions commonly used by most researchers and standards. Figure 4.1 shows an example of stone column inclusion with the provided footing size considered in the present parametric study for different numbers of columns and their spacing. Table 4.1 and Table 4.2 summarize the foundation and soil parameters, as well as the geometric configurations of the footing-column model used in the parametric analysis, respectively. A detailed result of the analysis is presented in this chapter along with details on the influence of key design parameters, analysis of the results of the numerical modelling as well as the discussion of the outcomes.

Table 4.1 Material properties used in the parametric analysis

Parameters	Soil	Stone Column	Concrete
FE Model	Elasto-Plastic	Elastic	Elastic
Young's Modulus, E (Mpa)	35	80	$30X10^3$
Poisons Ratio, ν	0.4	0.3	0.15
Cohesion, C	Cohesionless	-	-

Friction Angle, Ø, (°)	32	42	-
Unit weight, γ, kN/m3	18	19	24
Dilatancy Angle	2	12	-

Table 4.2 Geometric configuration

Footing Types	Parameters	Values
F – 1	Axial Load	1400KN and 3000KN
	Length (m)	2.5
	Width (m)	2.5
	Thickness (m)	0.8
F – 2	Axial Load	3000KN
	Length (m)	2.5
	Width (m)	2.5
	Thickness (m)	0.8
Stone columns configuration under selected isolated Footings	Stone column total number	40
	Stone column L/D ratio	5 and 10
	Typical Stone column configuration arrangements for each trial for Footing type 1 and 2 while subjected under the load of 1400KN and 3000KN	L/D=10, D=0.4, L=4 , n=1
		L/D=10, D=0.6, L=6 , n=1
		D/L=10, D=0.4, L=4 , n=5
		D/L=10, D=0.6, L=6 , n=5
		D/L=10, D=0.4, L=4 , n=5, S=2D
		D/L=10, D=0.6, L=6 , n=4, S=2D
		D/L=10, D=0.4, L=4 , n=4, S=3D
		D/L=10, D=0.6, L=6 , n=4, S=3D
		D/L=10, D=0.4, L=4 , n=5, S=2.5D
		D/L=10, D=0.6, L=6 , n=4, S=2.5D
		D/L=5, D=0.4, L=2 , n=1
		D/L=5, D=0.6, L=3 , n=1
		D/L=5, D=0.4, L=2 , n=5
		D/L=5, D=0.6, L=3, n=5

		D/L=5, D=0.4, L=2 , n=5, S=2D
		D/L=5, D=0.6, L=3 , n=4, S=2D
		D/L=5, D=0.4, L=2 , n=4, S=3D
		D/L=5, D=0.6, L=3 , n=4, S=3D
		D/L=5, D=0.4, L=2 , n=5, S=2.5D
		D/L=5, D=0.6, L=3 , n=4, S=2.5D

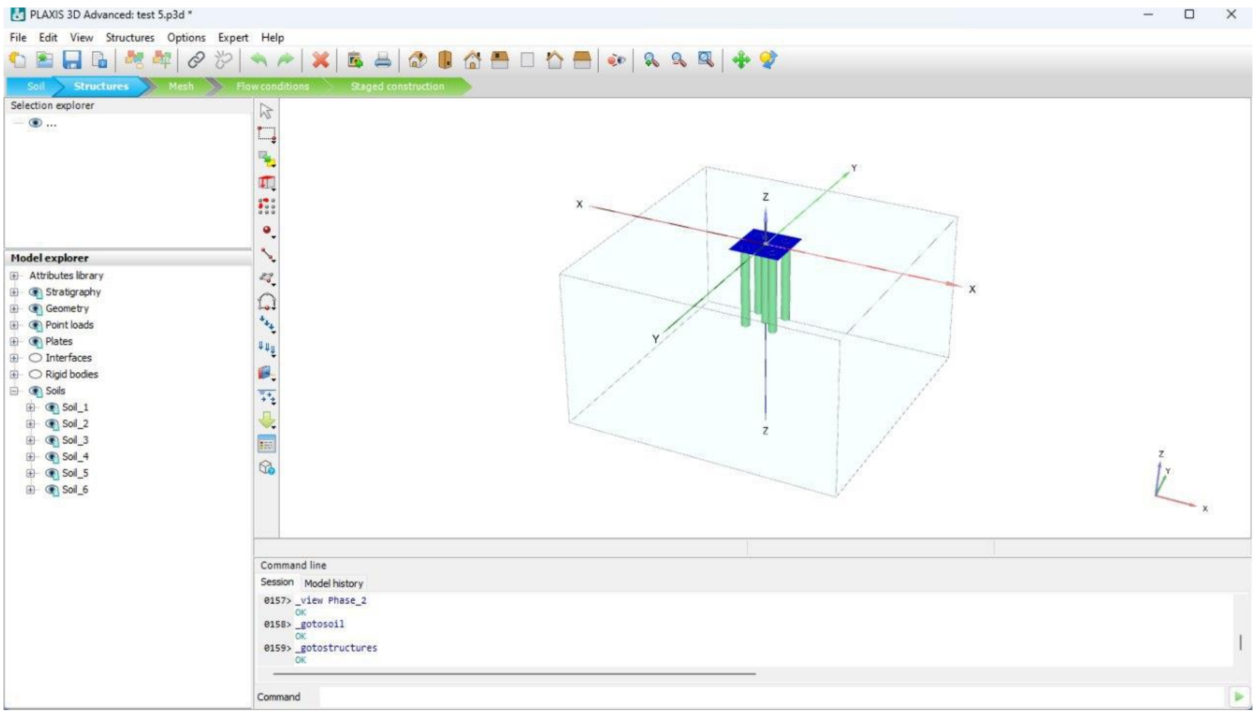


Figure 4.1 sample of modelling of stone column inclusion on a given soil

4.2 Settlement results obtained using a numerical model by Plaxis 3D at different conditions

In Table 4.2, the amount of settlement obtained under various conditions is shown by varying the spacing of stone columns, the number of columns, and the ratio of column lengths to column diameters. According to the table, settlement decreases as column diameter, length, and number increase, whereas settlement increases as column spacing (S/D) increases up to optimum values. The effect of spacing is greater with the larger column's length. This is due to an increase in the soil confinement and an increase in the concentration of stresses in the stone columns. For column diameter which is 0.6m and at an applied axial load of 1400KN, with a short length of columns (L/d=5), the improvement in the soil settlement is 17.18%, 20.15%, and 20% for spacing (S/D = 2, 2.5, and 3), respectively, over untreated ones. The corresponding rate of improvement is 30.28%, 32.51%, and 32.01% with long columns (L/d=10). As shown in the table the increase in the stone column number occupies a decrease in the axial settlement. This is due to the increase in the confinement and the replacement of soil with stone column. In general, it can be said that there is a relative improvement in the settlement values of the soil, coinciding with the establishment of columns in the given problematic soil. This results from the transfer of stresses and sharing the load to the stone columns as a result of the strength of the material composing the columns with respect to the low strength of the soil (Fattah, M.Y, 2016).

Table 4.3 Settlement results of soil with stone column inclusion subjected to an applied load of 1400KN and 3000KN respectively, using Plaxis 3D numerical model

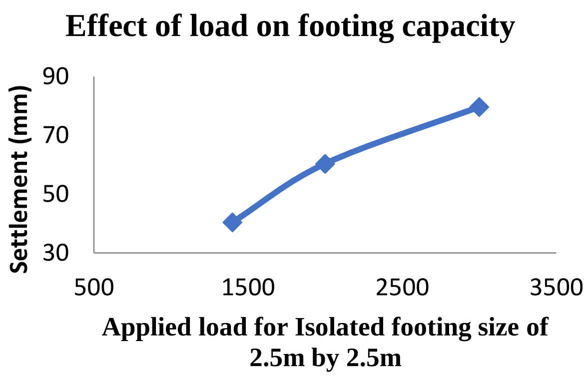
L/D	D	Settlement (mm)									
		Applied Load(1400KN)(224KPa)					Applied Load(3000KN)(480KPa)				
		S/D= 2	S/D = 2.5	S/D= 3	1 column	5 column	S/D= 2	S/D= 2.5	S/D= 3	1 column	5 column
5	0.4m	36.8	37.9	37	39.44	35.6	62.4	68.7	66.2	76.54	59.71
10		33.1	33.0	34.2	38.3	32.37	54.5	54.1	57.8	71.25	57.6
5	0.6m	33.5	32.3	32.1	39.1	31.44	54.4	50.9	49.9	72.59	48.48
10		28.2	27.3	27.5	34.1	26.4	42.4	39.9	39.98	52	36.48

4.3 Analysing the settlement properties of unreinforced foundation Footing

The purpose of this study was to examine the behaviour of square isolated footings when imposed with uniformly distributed vertical loads of 224kPa for footing type one and 244.14Kpa for footing type two, with varying thicknesses at 0.8m. Optimal axial load sustain capacity of selected footing type with no stone column reinforcement should be evaluated before investigating the effect of stone column inclusion. In order to achieve this, an isolated footing with a 0.8m thickness and, square footing size of 2.5m by 2.5m with varying axial loads of 1400KN, 2000KN, and 3000KNKN was selected and the effect of applying different loads on settlement was investigated using the PLAXIS 3D numerical model.

Figure 4.2 shows that the maximum settlement becomes increased as the load from superstructure being increased, which added more load to the soil. Therefore, isolated footings may have limitations in supporting maximum loads. Alternative foundation types may prove more appropriate in situations involving heavy loads or larger structures. In the context of tall or high-rise structures, the relatively small size of isolated footings may not offer sufficient support against potential settlement or tilting. This limitation makes them less suitable for such projects A.A. Beena (2024). The choice of foundation type, including isolated footings, should align with the project's requirements, considering load distribution, soil characteristics, and structural stability. A balanced understanding of the advantages and disadvantages ensures informed decision-making in selecting and implementing isolated footings for diverse construction projects.

Therefore, application of stone column for selected footing types limited to magnitude of axial loads comes from superstructure, number of storeys. Based on the analysis and previous works (K.S. Watts et al, 2000*)*, the application of stone column in this study is mainly deployed beneath isolated pad at low or moderate loading conditions.



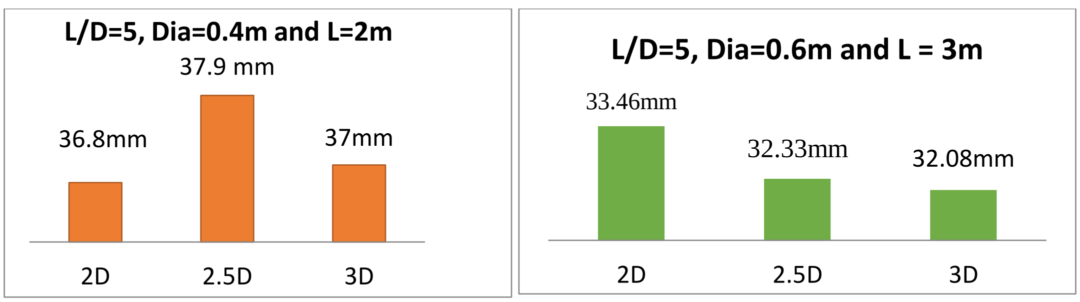
Load (KN)	Settlement (mm)
1400	**40.45**
2000	**60.34**
3000	**79.67**

Figure 4.2 Effect of application of different load on treated soil

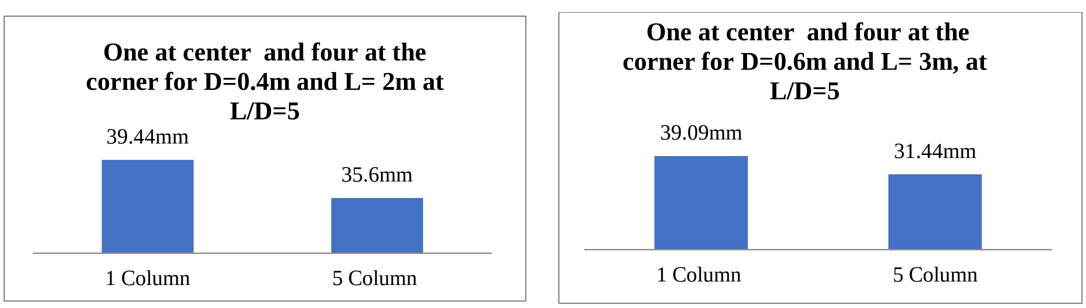
4.4 Study of the effect of incorporating stone columns into footings for columns bearing 1400KN of axial load

In the study, the load-settlement relationship was studied in order to determine how selected foundation systems would perform before and after stone columns were incorporated. The paper presents numerical simulations to investigate the settlement reduction caused by stone columns. The finite element code Plaxis 3D connect edition V20 was used to develop a numerical model that could help to understand the influence of the changes in the state of soil due to column installations. To represent the distributed load, an isolated footing with a thickness of 0.8m and a dimension of 2.5m by 2.5m was used with the properties listed in Table 3.1 and 3.2. The spacing, length to diameter ratio and stiffness of the stone column along with size and thickness of the footing allow for a full arching of the load, which can be considered as a rigid. Crushed stone is used as column backfill and common properties were chosen for the numerical model (see Table 3.1). In order to reproduce the soil-column interaction, a linear elastic-perfectly plastic soil model based on the Mohr-Coulomb yield criterion was selected.

Figure 4.1 illustrates the effect of inserting a stone column below a footing whose dimensions are 2.5 m by 2.5 m and 0.8 m thick, imposed with an axial load of 1400 KN for a variety of centre-to-centre spacing and length-to-diameter ratios. The results of numerical analysis at different stone column diameters and lengths for footing one on the settlement were summarized in Figure bellows. Based on the results shown in the figure 4.3 and 4.4, settlement decreased as the number, length, and diameter of stone columns increased. According to figure 4.3 and 4.4 (A, B, C and D), settlement decreases as L/D increases. According to the figure, the settlement reduction obtained for L/D=5 is quite small compared to the displacement when L/D = 10. Consequently, parameters such as spacing, diameter, and length can be combined to optimize stone column design.

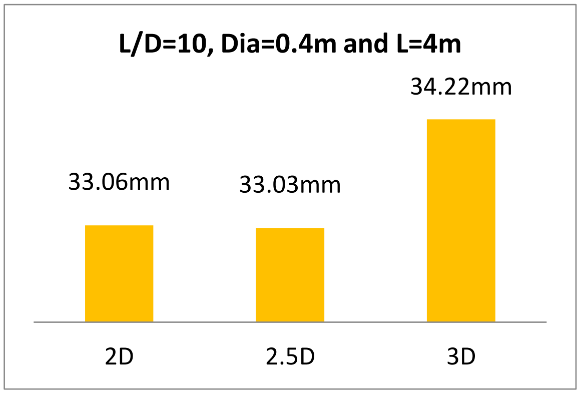


A/Settlment Vs spacing for D(0.4m),L/D=5 **B**/ Settlment Vs spacing for D(0.6m),L/D=5

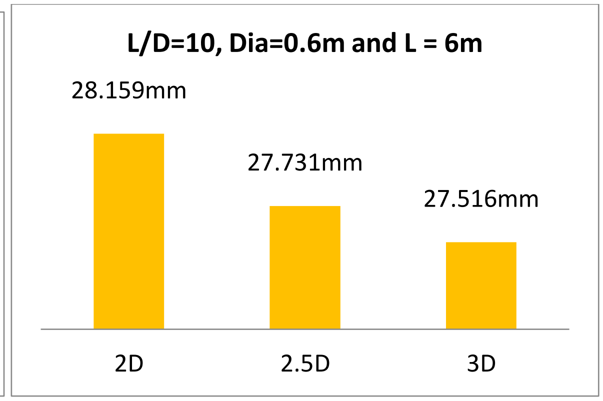


C/Settlement Vs Number of columns for D=0.4m **D**/ Settlement Vs Number of column for D=0.6m

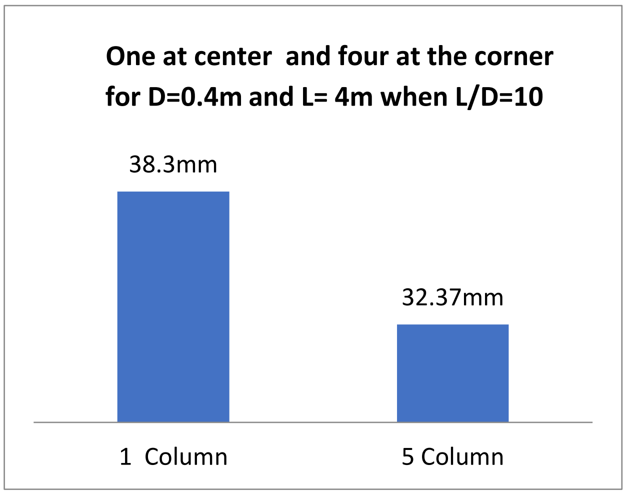
Figure 4.3 Determination of settlement values for the 1400KN axial load application when L/D = 5 and Diameter of 0.4m and 0.6m with the column spacing of 2D, 2.5D and 3D and 1,5 number of column inclusion



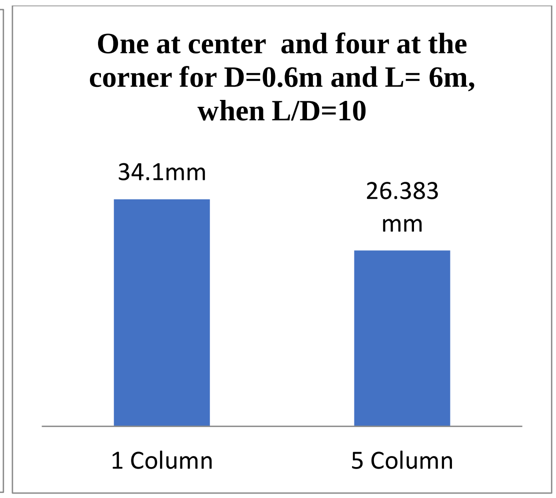
A/Settlment Vs spacing for D(0.4m),L/D=10



B/ Settlment Vs spacing for D(0.6m),L/D=10



C/Settlement Vs Number of columns for D=0.4m

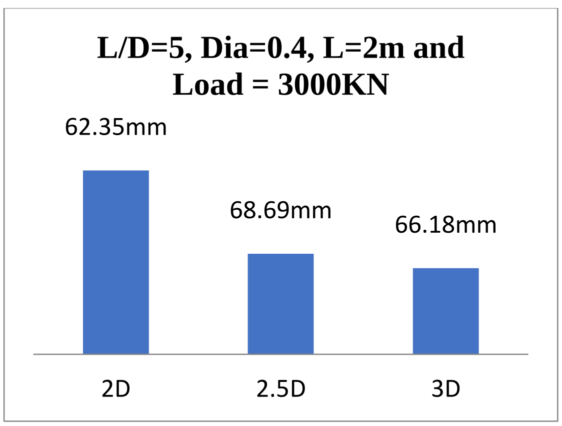


D/ Settlement Vs Number of columns for D=0.6m

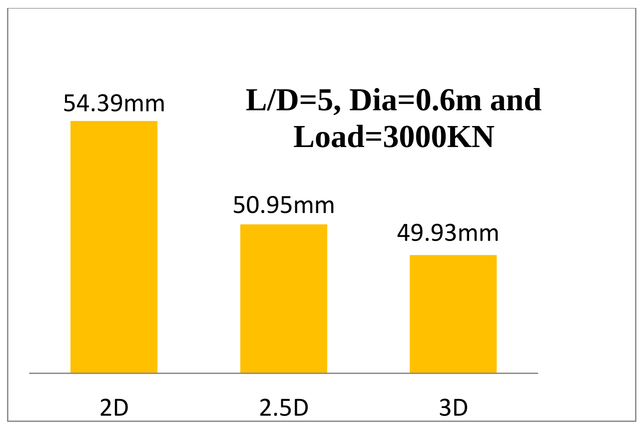
Figure 4.4 Determination of settlement values for the 1400KN axial load application when L/D = 10and Diameter of 0.4m and 0.6m with the column spacing of 2D, 2.5D and 3D and 1,5 number of column inclusion

4.5 Analysis of the effects of incorporating stone columns into the footings for axial column loads of 3000KN

This study aims to understand the effect of stone column inclusion on loose soil and to identify the parameters that have a dominating effect on load sharing and settlement reduction. Attempts were made to account for nonlinear behaviour of soil and column materials. Based on this objective, numerical analysis results were compared at different loading conditions and stone columns' effects on settlement reduction were clearly analysed. A stone column inserted under a footing with similar dimensions, spacing, and length-to-diameter ratios to section 4.3, but with a 3000KN axial load, is illustrated in Figure 4.5 and 4.6. According to figure 4.5 and 4.6, the settlement of the soil increases with increasing load and shows a continuous deformation (settlement) at more or less constant load (pressure). This response indicates that the material selected for stabilization (loose soil) falls under a compressible layer. For a given load, the stone column stabilized bed shows a similar settlement response, but it is less and decreases as column length increases and spacing decreases up to optimum column spacing. As a result, the load carrying capacity and stiffness of the soil are improved through stone column stabilization, and the length, number and spacing of the columns play an important role in reducing settlement. For an applied pressure, the numerical analysis shows that settlement is reduced when stone column length is increased. The higher the L/D ratio is, the lesser the settlement. An extensive parametric study was carried out to understand the influence of L/D ratio and column spacing on settlement reduction. As shown in Figure 4.5 (C and D) and 4.6, the effect of variant spacing between the stone columns taken as a ratio (S/D) on the attitude of loose soil with a circular cross-section has a diameter of 0.4m and 0.6m respectively.

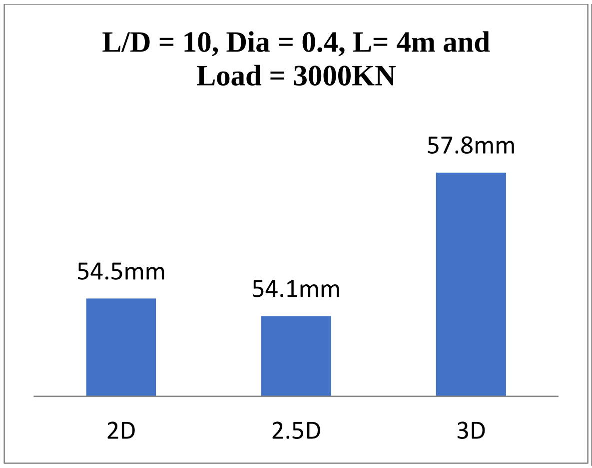


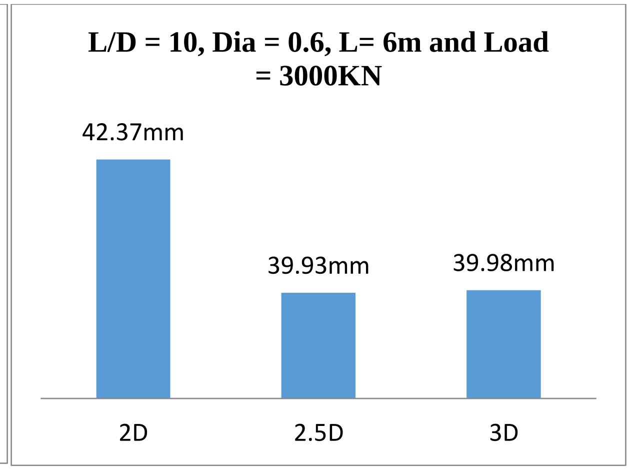
A/Settlment Vs spacing for D(0.4m),L/D=5



B/ Settlment Vs spacing for D(0.6m),L/D=5

Figure 4.5 Determination of settlement values for the 3000KN axial load application when L/D = 5and Diameter of 0.4m and 0.6m with the column spacing of 2D, 2.5D and 3D and 1,5 number of column inclusion



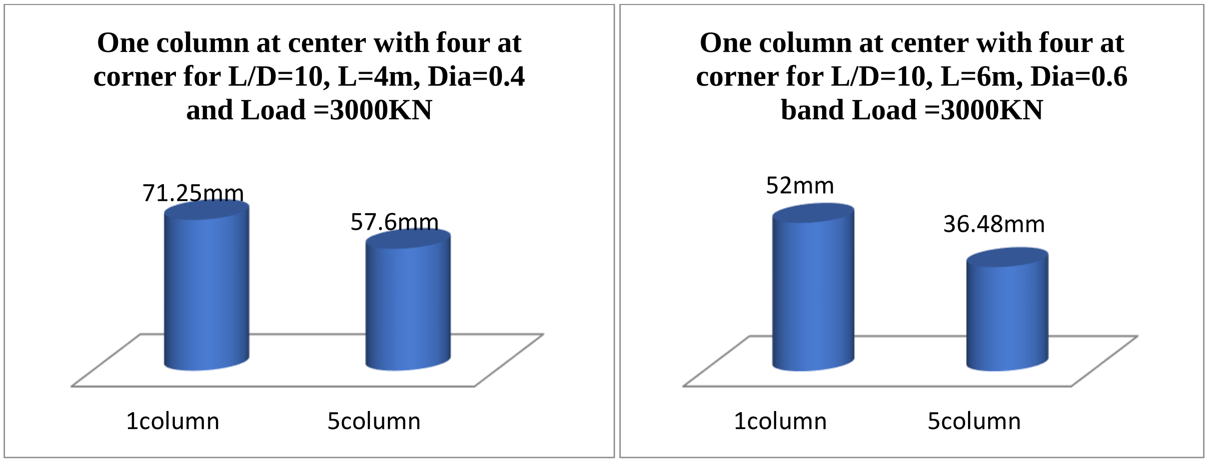


A/ Settlment Vs spacing for D(0.4m),L/D=10 **B**/ Settlment Vs spacing for D(0.6m),L/D=10

Figure 4.6 Determination of settlement values for the 3000KN axial load application when L/D = 10 and Diameter of 0.4m and 0.6m with the column spacing of 2D, 2.5D and 3D respectively

In this study a systematic 3D finite element analyses were conducted to clarify the most important parameters and the influence of the number of columns and their position beneath a rigid footing. The stone column geometry significantly affects the behaviour of soft soils reinforced by stone columns (Mohtasham and Khodaparast 2018). Moreover, the failure mechanism of stone columns is mainly influenced by the stone column geometry and the properties of surrounding soil. The number of stone columns has also a major effect on the performance of the improved soil layer. It can be defined as the ratio of the stone column area after compaction to the total area within the unit cell. A study was conducted on the significance of stone column inclusion on the given soil using different L/D ratios and spacing for 2D, 2.5D and 3D, using diameters of 0.4m and 0.6m for comparison with other options. The effect of randomly incorporating one stone column in the centre, one at the centre along with four in the corners as shown in figures 4.2(c &d) and 4.3(c &d) were investigated to see if there is any further possible settlement reduction on the original soil due to the applied load.

Figure 4.7 illustrates settlement values with L/D=10, loading the foundation with 3000KN and having the stone column diameters of 0.4 m and 0.6 m respectively with different arrangements of stone columns, including only one centre column, and one at centre column with four corners. As seen from the Figure for all cases taking D=0.4m and D = 0.6m while L/D = 10; the study indicated that the settlement values of five stone column arrangements decreased by 19.16% and 29.85% (from 71.25mm and 52mm to 57.6mm and 36.48mm), respectively, when compared with only a single column arrangement. This is an agreement with the results of the research performed by previous studies. The more loose soil replaced by the stone column, the higher the area replacement ratio and the greater the positive effect on the system performance (Shahu et al. 2000). It could be more economical to add columns rather than increasing length (Miranda et al. 2021).



A/Settlement Vs Number of columns for D=0.4m B/ Settlement Vs Number of columns for D=0.6m

Figure 4.7 Determination of settlement values for the 3000KN axial load application when L/D = 10 and Diameter of 0.4m and 0.6m with the column number of 1 and 5 respectively

At 480Kpa (3000KN) distributed load, Figures 4.8 - 4.11, were shows that the settlement value decreases with increasing L/D ratio from 5 to 10 for the provided certain centre to centre spacing such as 2D, 2.5D and 3D.

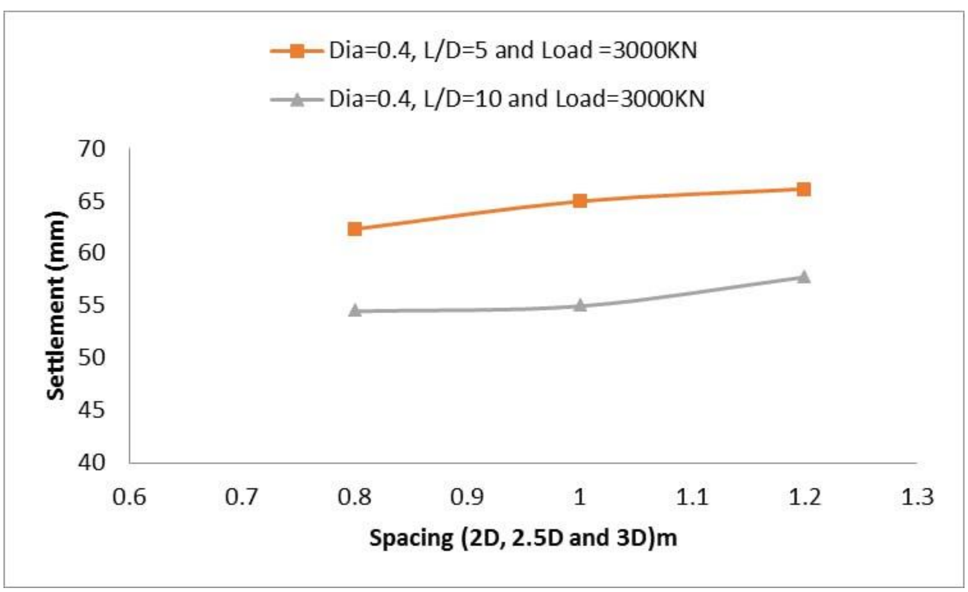


Figure 4.8 Determination of settlement values for the 3000KN axial load application when L/D = 10 and Diameter of 0.4m and 0.6m with the column number of 1 and 5 respectively

According to figure 4.8, when the L/D value for 2D, 2.5D and 3D spacing is increased from 5 to 10 while the diameter is taken as 0.4m, the settlement decreased by 12.5%, 15.38%, and 12.71 % (from 62.35mm, 65mm and 66.18mm to 54.52mm, 55mm, and 57.77mm) respectively as a result of the applied load of 3000KN. It is evident from the preceding that the rate of improvement in settlement with varying column spacing is a function of the length (L/D). There is a consistent decrease in settlement with decreasing (S/D) values. This is a result of soil confinement, friction, stiff materials, and a larger area replacement ratio, which all reduce settlement. It was found by Said et al. [18] that the settlement of the soft soil decreased as the area replacement of the given soil by stone column increased. For low L/D ratios (such as 4 in this study), the load is transferred to the soil through friction and end bearing. Whenever friction reaches its limit, the end bearing capacity is unable to carry the load, which leads to the stone column being punched into the stratum below (Hughes and Withers, 1974, Black et al., 2007). With larger L/D ratios (6), loads are unlikely to transfer to the bottom of the column due to increased friction with depth. For increased L/D ratio, there is no punching because the displacement of the footing is absorbed by compression and lateral deformation of the stone column at the upper position (Wood et al, 2000).

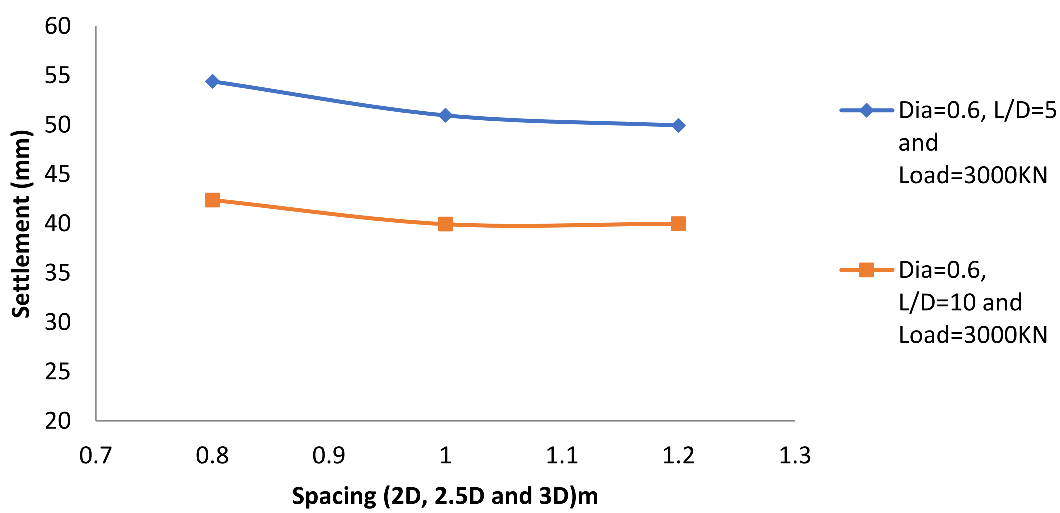


Figure 4.9 Relationship between settlement versus column spacing for 3000KN axial load and diameter is 0.6m and when L/D is 5 and 10 respectively

Figure 4.10 illustrates how settlement can be minimized with different L/D ratios when applying 1400KN and 3000KN axial loads while retaining equal stone column diameter and spacing. With an increase in L/D from 5 to 10, the analysis at S/D 2.5 indicates a reduction in settlement from 37.9mm to 33.9mm when using axial loads of 1400 KN and 65mm to 55mm when using 3000 KN. The result demonstrated that as the length and diameter of the stone column become increased then settlement becomes significantly reduced.

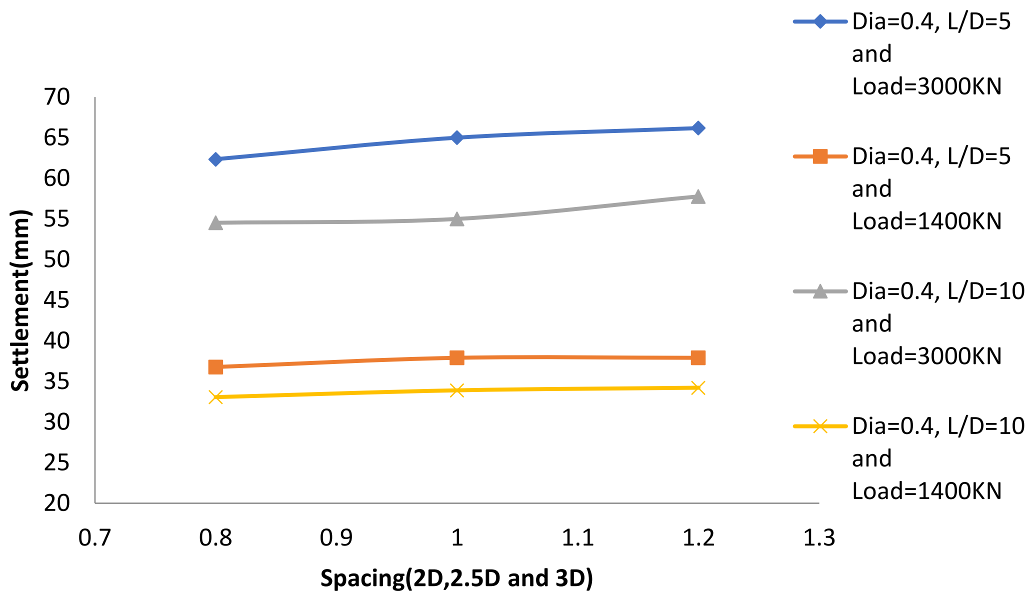


Figure 4.10 Relationship between settlement versus column spacing for 1400KN and 3000KN axial load and diameter is 0.4m and when L/D is 5 and 10 respectively

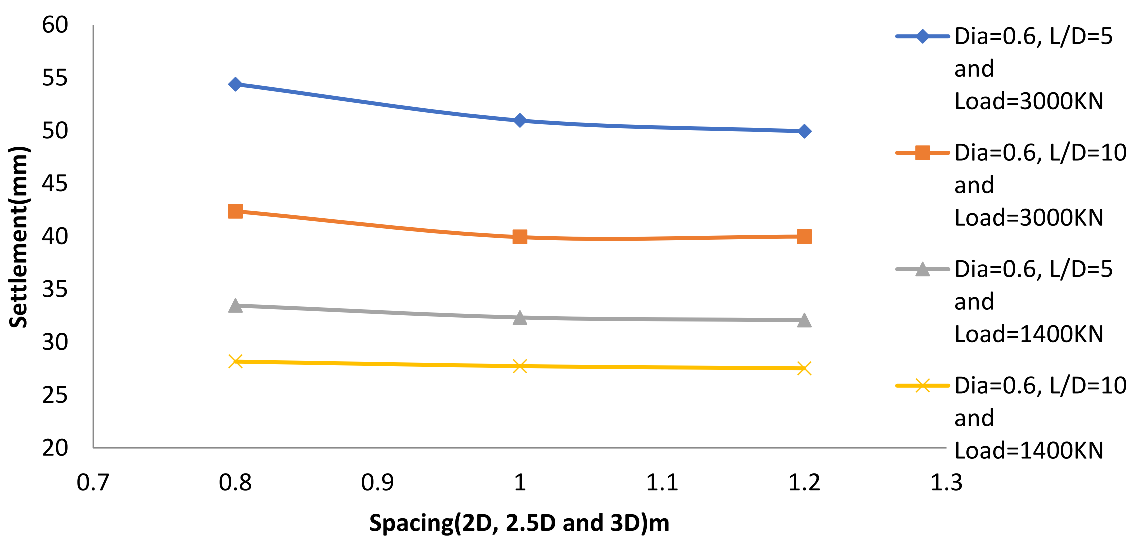


Figure 4.11 2Relationship between settlement versus column spacing for 1400KN and 3000KN axial load and diameter is 0.6m and when L/D is 5 and 10 respectively

From Figure 4.11 it can be seen that as the diameter increases from 0.4m to 0.6m, the analysis at S/D is 2.5 and L/D is 10, the result shows that there is further reduction in settlement from

55mm to 39.93mm. The result shows that settlement is further reduced when the diameter increases.

4.5.1Effect of column positioning beneath a rigid footing on settlement reduction

Additionally, the parametric study focuses on the effect of column spacing, or more specifically, the relative position of columns under the footing, on settlement reduction. According to Aguado et al. 2011, the spacing between stone columns is generally two to three times its diameter, depending on the soil condition, the applied load, the construction method, the settlement permitted, and the degree of improvement required. Ambily and Gandhi (2007) found that no significant improvement was observed beyond this spacing range. Those findings are consistent with those presented by Prasad et al. (2012).

In figure 4.12, inclusion of stone columns on a given are shown with spacing (S) of 2D and 2.5D, diameter (D) of 0.4m and L/D ratio of 10 at an applied load of 3000 KN respectively. As shown from the figure, the study used stone column application with the spacing of 2D and 2.5D where D is the diameter of the stone column which is taken as 0.4m. It is important to note that for both cases, the number of stone columns was 5, which indicates that changing the spacing between the columns does not change the area coverage, but only changes the column's position beneath the foundation footing.

Accordingly, the reduced settlement results for 2D and 2.5D spacing with D=0.4m, L/D=10, and an applied load of 1400KN and 3000KN using footing size of 2.5m by 2.5m were 33.06mm, 33.03mm, and 54.52mm and 54.07m (refer to Table 4.3) , respectively. As seen from the result, the settlement improving performance of inclusion of equal amount of stone column but varying the column spacing brings approximately similar results. The results suggest that changing the spacing between stone columns, while maintaining the same number of columns, does not affect settlement performance of stone column inclusions in soil (Jorge Castro et al, 2021). Barksdale and Bachus (1983) stated that area replacement ratio less than 10% did not show any considerable improvement in the characteristics of soft soil, and greater than 35–40% was not economical.

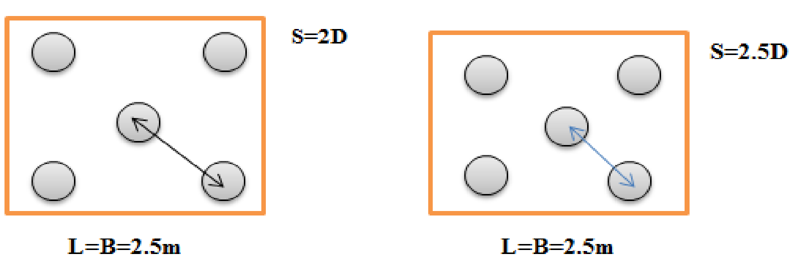


Figure 4.1 Variation of column relative position in the 3D model

4.6 Effect of load increment on stone column lateral deflection (bulging)

Different experimental and numerical studies investigated the modes of failure in stone columns group. A study performed by Hu (1995) revealed that stone columns could fail by bulging, punching, shearing and bending. The predominant mode of failure in stone columns group was general shear failure. Figure 4.14 shows images of lateral deformation of single and grouped stone columns when subjected to 1400K and 3000KN. As seen from the graph the observations are in agreement with Wood et al. (2000), who proved that bulging occurred at the lower lengths of the central columns while it remained at the upper lengths of the outer columns. The failure mechanism for a stone column loaded over its diameter in homogeneous soil is bulging when L/D is greater than 3, and local shear failure when L/D is less than 3. According to figure 4.13, when a stone column reinforced by homogeneous soil has a length to diameter ratio of 4, or greater, bulging failure occurs at a depth equivalent to 2 to 3 stone column diameters. Nevertheless, there is numerical and experimental evidence that bulging can occur in shallower depths (Pitt et al. (2003); Murugesan and Rajagopal (2006)).

Bulging deformation is considered an indicator of stone column bearing capacity. Increasing the bulging deformation will decrease the bearing capacity of the stone column. Figure 4.13 and 4.14**,** shows the bulging deformation in the case of the column area loaded. This study did not investigate the determination of numerical values for lateral deformation of stone columns; however, as shown from the figure, the maximum bulging occurs at a depth approximately equal to the diameter of the conventional stone column beneath the selected footing.

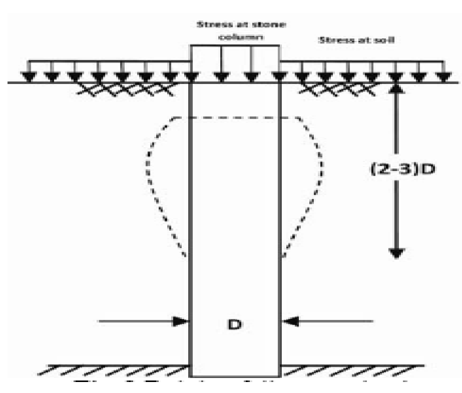
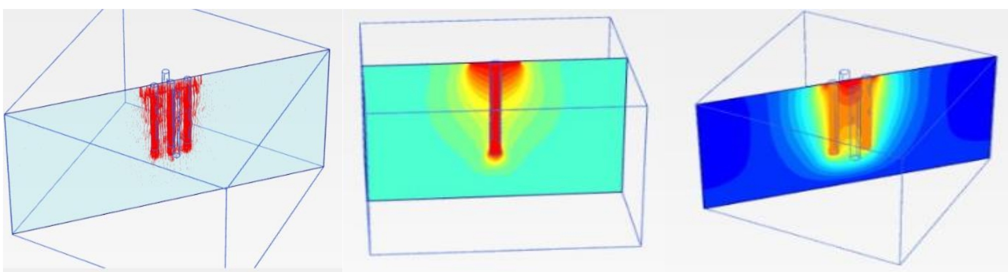


Figure 4.13 Bulging failure mechanism

As shown in the figure below stone column bulges at their upper part with a length of two or three times the column’s diameter. Das and Pal (2013) found that when a stone column is installed in layered soil, the entire bulging occurs in the top weak layer due to its small lateral confinement. The researchers found that the failure of stone columns group took place in conical area below the foundation. Figure 4.14 A; and B shows an image for single and grouped stone column inclusion lateral deformation while subjected at axial load of 3000KN. As seen from the figure the bulging of the stone columns in a group is not similar to that in a standalone condition. Even if the analysis of lateral deformation was not the aim of this paper, yet as shown from the figure 4.14 as the load increased then bulging becomes increased and it is possible to decide that the lateral extent of stone column Bulging is mainly influenced by applied load, column arrangement and L/D ratio. From literatures, the main factor influencing the value of maximum bulging is the amount of the axial load applied on the stone columns. The results of the analysis indicated that by increasing the axial load on top of the stone columns, the value of maximum bulging was increased.



A/Lateral deformation due to 1400KN load application

B/Lateral deformation due to 3000KN load for single column

C/Lateral deformation due to 3000KN load for grouped column

Figure 4.14 Image that shows lateral deformation due to application of different loads

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Structures built on problematic soil can experience extensive settlement. To make soil suitable for construction, both physical and chemical improvements can be made. Stone columns are a promising physical ground improvement technique that enhance the bearing capacity and settlement characteristics of problematic soils. This study investigated the performance of silty sand soil reinforced with stone columns using 3D finite element analysis with PLAXIS software. Several configurations were studied, including stone columns with length/diameter (L/D) ratios of 5 and 10, and centre-to-centre spacings of 2D, 2.5D, and 3D, under axial loads of 1400kN and 3000kN. Based on the key findings the following conclusions are drawn:

- Effect of L/D Ratio: Increasing the L/D ratio from 5 to 10 reduced settlement values significantly. For a 3000kN load, settlement values decreased from 54.4mm, 50.95mm, and 49.93mm to 42.4mm, 39.9mm, and 39.98mm, respectively, as L/D ratio increased.
- Column Spacing: Settlement values for different spacings (2D, 2.5D, 3D) showed that the optimal spacing was 2.5D. Settlement reduction was not strictly sequential, indicating other factors influence improved settlement values.
- stone column arrangement without maintaining column c/c spacing: it showed better settlement reduction compared to regularly spaced columns. For a 3000kN load with an L/D ratio of 10, randomly spaced columns yielded a settlement of 36.48mm compared to 42.4mm for 2D spacing.
- Column Diameter: Increasing the diameter of stone columns improved load-carrying capacity. For a 1400kN load with an L/D ratio of 10, settlement values were 33.1mm, 33mm, and 34.2mm for 0.4m diameter columns, reduced to 28.2mm, 27.3mm, and 27.5mm for 0.6m diameter columns.
- Load and L/D Ratio: Higher L/D ratios significantly improved settlement values. For a 3000kN load, settlements improved from 33.5mm, 32.3mm, and 32.1mm with an L/D ratio of 5, to 28.2mm, 27.3mm, and 27.5mm with an L/D ratio of 10.

- Number of Columns: Increasing the number of stone columns reduced settlement further. For a 3000kN load, settlement decreased from 52mm for one column to 34.48mm for five randomly inserted columns.
- Bearing Capacity: As spacing decreased, bearing capacity increased. Optimal spacing was found to be 2.5D, with no significant improvement beyond this range.
- Bulging Failure: To avoid bulging failure, especially in clayey soils, the length of stone columns should not exceed 2-3 times their diameter.

5.2 Recommendations

- The study basically focuses numerical analysis whereas performing of laboratory experiments and validates the numerical results obtained from PLAXIS 3D using different soil types and loading conditions can be studied.
- The full-scale analysis of stone column performance in three-dimensional and two-dimensional analyses for comparison of the results within the consolidation process can be studied.
- A number of parameters were not taken into account when studying stone columns in problematic soil. These parameters include the effect of recycled aggregates as column filling material replacing traditional aggregates, the effect of horizontal reinforced stone columns, the effect of using unreinforced and reinforced sand layer over encased stone columns, the optimum design of encased stone columns, and the effects of loading, water quantities and collapsible soil characteristics.
- The encased stone column has an advance over the ordinary stone column as it reduces bulging due to that it provides a lateral confining to the column which gives it more stiffness to resist the surrounding conditions of the soil and the time rate of consolidation increases which reduces settlement. The encased stone column technique enhances strength and decreases deformation.

REFERENCES

A.A., Beena (2024). Isolated footing: a comprehensive guide to buildings. https://www.bricknbolt.com/blogs-and-articles/isolated-footing-guide-advantages-disadvantages.

A. P. Ambily, & Shailesh, R, Gandhi (2007). Behavior of Stone Columns Based on Experimental and FEM Analysis. 10.1061/_ASCE_10900241_2007_133:4_405.

Aguado, P., P. Berthelot, & L. Carpinteiro (2011). Recommendations for the design, calculation, construction and quality control of stone columns under buildings and sensitive structure. Rueil-Malmaison, France: French Committee for Soil Mechanics and Foundations (CFMS): 32.

Al-Kazzaz, Zeena & Al-Obaydi, Moataz (2021). Effect of Spacing between Stone Columns on the Behavior of Soft Soil. E3S Web of Conferences. 318. 01006. 10.1051/e3sconf/202131801006.

Andreou P., Frikha W., Frank R, Canou J., Papadopoulos V., & Dupla J. (2008). Experimental study on sand and gravel columns in clay. Ground Improvement 161(GI4):189–198.

Ashour S., Ghataora G., & Jefferson, I. (2022). Behaviour of model stone column subjected to cyclic loading. Transp Geotech.

Aslani, M., Nazariafshar, J. & Ganjian, N. (2019). Experimental Study on Shear Strength of Cohesive Soils Reinforced with Stone Columns. Geotech Geol Eng **37**, 2165–2188

Awn, S. & Abbas, J. (2020). Improvement of soft soil by stone column treated with bentonite. Key Eng Mater 857:283–291.

Ayadat, T. & Hanna, A., M. (2008). Soil improvement by internally reinforced stone columns. Ground Improvement 161(GI2):55–6.

Babu, M., Nayak, S. & Shivashankar, R. (2012). A Critical Review of Construction, Analysis and Behaviour of Stone Columns. Geotechnical and Geological Engineering. 31. 10.1007/s10706-012-9555-9.

Baraksdale, R., D. & Bachus, R., C. (1983). Design and construction of stone columns. Federal Highway Administration, Vol.1, School of Civil Engineering, Georgia Institutes of Technology, Atlanta.

Baruah, Darin & Sahu, A. (2015). Comparative Study of Load Deformation Behaviour of Silty Clay Bed Reinforced with Stone Column of Different Depth and Gradation.

BRE (2000). Specifying Vibro Stone Columns. K. Watts. Garston: Building Research Establishment: 38.

Brinkgreve, R. B. J & Broere, W. (2008). PLAXIS 3D Foundation Manual, Version 1.1.

Charles, J. A. (2002). Ground improvement: the interaction of engineering science and experience-based technology. Géotechnique 52 (7): 527–532.

Das, P. & Pal, S.K. (2013). A Study of the Behavior of Stone Column in Local Soft and Loose Layered Soil. EJGE.

Dhouib, A., Magnan J.-P., & Guilloux, A. (2004). Procédés D'amélioration des Sols Historique, Méthodes de Reconnaissance, Applications et Données Économiques. Volume 2. Presses de l'ENPC/LCPC; Paris, France: pp. 577 598. ASEP-GI. (In French).

Eied, M. M., Helmy, H. M., & El-Kaissouny, M., G. (2014). "Numerical Analysis of Ground Improvement by Group of Ordinary and Encased Stone Columns" Journal of American Science; 10.

Elsawy, M. (2013). Behaviour of soft ground improved by conventional and geogrid-encased stone columns, based on FEM study. Geosynthetics International, 20. 276-285. 10.1680/gein.13.00017.

Fattah, M.Y., Zabar, B.S. & Hassan, H.A. (2016). Experimental analysis of embankment onordinary and encased stone columns. International Journal of Geomechanics, 16(4), p.04015102.

Fattah, Mohammed & Al-Jamaily, Nagham & Salman, F. (2012). Improvement of the Behaviour of Embankment on Soft Soil by Stone Columns. Proceedings of the International Conference on Ground Improvement and Ground Control, Edited by Buddhima Indraratna, Cholachat Rujikiatkamjorn and Jayan S. Vinod. 677-683. 10.3850/978-981-07-3559-3.

Fayed, A. L., T. M. Sorour, H. F. Shehata. (2018). Study of the Behavior of Floating Stone Columns in Soft Clay Formations Using Numerical Modeling.

In Frikha, W., S. Varaksin, A. & Viana da Fonseca (eds). (2017). Soil Testing, Soil Stability and Ground Improvement. GeoMEast,. Sustainable Civil Infrastructures, Springer, Cham.

George, C., & C. PavanKumar. (2016). “Studies on Natural Geotextile Reinforced Quarry Waste Column For Improving Soft Soil Ancy Genu.” International Journal of Science, Engineering and Technology Research.

Ghazavi, Mahmoud, & Javad Nazari Afshar. (2013a). “Bearing Capacity of Geosynthetic Encased Stone Columns.” Geotextiles and Geomembranes 38:26–36. doi: 10.1016/J.GEOTEXMEM.2013.04.003.

Hu, W. (1995). Physical Modelling of Group Behaviour of stone column foundation. PhD Thesis, University of Glasgow Glasgow.

Hughes, J.M.O. & Withers, N.J. (1974). Reinforcing of soft cohesive soils with stone columns, Ground Engineering, Vol. 7, No.3, 42-49

J. Castro, (2014). Numerical Modelling of Stone Columns beneath a Rigid Footing. Comput. Geotech., 60, Pp. 77-87.

Jeong, S., Lee, J., & Lee, C. J. (2004). Slip effect at the pile–soil interface on drag load. Computers and Geotechnics, 31(2), 115–126.

Jorge Castro, (2017). “Modeling Stone Columns.” Journal of Materials 10(7).

K.S. Watts. *(2000).* An instrumented trial of vibro ground treatment supporting strip foundations in a variable fill Géotechnique.

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

Kézdi, Á., & Rétháti, L. (1974). Handbook of soil mechanics (Vol. 1). Elsevier Amsterdam.

Kumar, R., Bhargava, K. & Choudhury, D. (2016). Estimation of Engineering Properties of Soils from Field SPT Using Random Number Generation. INAE Lett **1**, 77–84.

Luehring, R., Snorteland, N., Mejia, L., & Stevens, M. (2001). “Liquefaction mitigation of a silty dam foundation using vibro-stone columns and drainage wicks: a case history at salmon lake dam.” Proceedings of the 21st USSD annual meeting and lecture. Denver, CO.

McKelvey, D., Sivakumar, V., Bell, A., & Graham, J. (2004). Modelling Vibrated Stone Columns in Soft Clay. Proc Inst Civ Eng, Geotech Eng, 157(GE3):137–149. https://doi.org/10. 1680/geng.2004.157.3.137.

Micheál, M., Killeen, Bryan, A., & McCabe. (2014). “Settlement performance of pad footings on soft clay supported by stone columns: A numerical study.” Soils and Foundations; 54 (4):760–776.

Mokhtari, Masoumeh & Kalantari, Behzad. (2012). Soft Soil Stabilization using Stone Columns. —A Review. 17.

MOREAU, N. & MOREAU, M. (1935). Foundations. Emploi du Sable. Annales des ponts et chausses. Memoires**,** 171-214.

Murugesan, S., & Rajagopal, K. (2006). Geosynthetic-encased stone columns: Numerical evaluation. Geotextiles and Geomembranes, Vol. 24, pp. 349–358.

Nav, M., Rahnavard, R., & Noorzad, A., & Napolitano, R. (2020). Numerical evaluation of the behavior of ordinary and reinforced stone columns. Structures. 25. 481-490. 10.1016/j.istruc.2020.03.021.

Nazaruddin, A., M. Shakri, & M. Hafez. (2013). "A Laboratory Study on Bearing Capacity of Treated Stone Column." Electronic Journal of Geotechnical Engineering.

Obrzud, R., & Truty, A. (2012). The Hardening Soil Mode. A Practical Guidebook Z Soil, PC, 100701 reports, revised 31.01.

P., Mohanty, & M., Samanta. (2015). "Experimental and numerical studies on response of the stone column in layered soil." Int. J. Geosynth. Gr.Eng., vol. 1, no. 3, p. 27, 2015.

Palaniappan, K., & S. Prabhu. (2013). "Improving Soft Clay Soil Using Fly Ash As Material Of Column." International Journal of Engineering Research & Technology (IJERT).

Pandey, B., Rajesh, S., & Chandra, S. (2022). Performance of soft clay reinforced with encased stone column: a systematic review. Int J Geosynth Ground Eng 8(40):1–14. https://doi.org/10.1007/s40891-022-00387-x.

Pitt, J., M., & White, D., J. (2003). Highway application for rammed aggregate piles in Iowa soils. Iowa Department of Transportation, Final Report, PLAXIS BV.

Pradip, D., & Sujit, K., P. (2013). A Study of the Behavior of Stone Column in Local Soft and Loose Layered Soil. EJGE Vol.18, pp.1777-17786.

Prasad, A., Kazemian, S., Kalantari, B., & Huat, B. B. K. (2012). A behavior of reinforced vibrocompacted stone column in peat. Pertanika Journal of Science and Technology, 20(2), 221–241.

Priebe, H,.J. (1995). The Design of Vibro Replacement. Ground Engineering, December, pp. 31-37.

Rudrabir, G. & Kashliwal, A. (2008). Ground Improvement Techniques – with a Focused Study on Stone Column. Dept. of Civil Engineering, VIT University.

Samuel, T., M., Freeda, C., .C, & Brema, J. (2019), Analysis on the Performance of Stone Columns with Different Materials in Soil Stabilization. International Journal of Engineering and Advanced Technology (IJEAT) ISSN: 2249 – 8958, Volume-8, Issue3.

Saxena, S., & Roy, L. (2022). Suitability analysis of stone column materials with PLAXIS. Eng Technol Appl Sci Res 12(2):8421–8425.

Siva, G., Prasad, S., & P., V., V., Satyanarayana. (2016). "Improvement of Soft Soil Performance Using Stone Columns Improved with Circular Geogrid Discs." Indian Journal of Science and Technology 9(30):1–6. doi: 10.17485/IJST/2016/V9I30/99186.

Srijan, & A., K., Gupta. (2021). IOP. *Conf. Ser.: Earth Environ. Sci.* **796** 012021**DOI** 10.1088/1755-1315/796/1/01.

Taube, M.G. & Herridge, R.J. (2002). Stone Columns for Industrial Fills. The 33rd Ohio River Valley Soil Seminar (ORVSS).

Terashi, M., & Ilan, Juran. (2000). "Ground Improvement - State Of The Art." Paper presented at the ISRM International Symposium, Melbourne, Australia.

Vahedian, A., Mahini, S., & Aghdaei, S. (2014). "A short state of the art review on construction and settlement of soft clay soil reinforced with stone column." Int. J. Eng. Tech. 6, 420-425.

Vishwakarma, R., J., & Ingle, R., K. (2017). Simplified approach for the evaluation of critical stresses in concrete pavement. Struct Eng Mech 61(3):389–396.

Wang, G. (2009). Consolidation of Soft soil foundations reinforced by stone columns under time dependent loading. J. Geotech. Geoenviron. Eng., 135, 1922–1931. [**Google Scholar**] [**CrossRef**].

Wood, D., Hu W., & Nash, D. (2000). Group effects in stone column foundations: model tests. Geotechnique 50(6):689–698.

Y. S. Hong, C. S. Wu, & Y. S. Yu. (2016). "Model test on geotextile encased granular columns under 1-g and undrained conditions." Geotext. Geomembr., vol. 44, no. 1, pp. 13-27, 2016.

Yogendra, T., Mohsin J., Chandresh, S. & Atul D. (2015). "Numerical analyses of laboratory modeled reinforced stone column." Current Science, VOL. 108, NO. 1354 7, 10 APRIL.

Zahmatkesh, A., and A. Choobbasti. (2010). “Settlement Evaluation of Soft Clay Reinforced By Stone Columns, Considering the Effect of Soil Compaction.” International Journal of Research & Reviews in Applied Sciences 3:159–66.

APPENDIX

Apendix-1: Outputs From Etabs And Plaxis 3d Software's

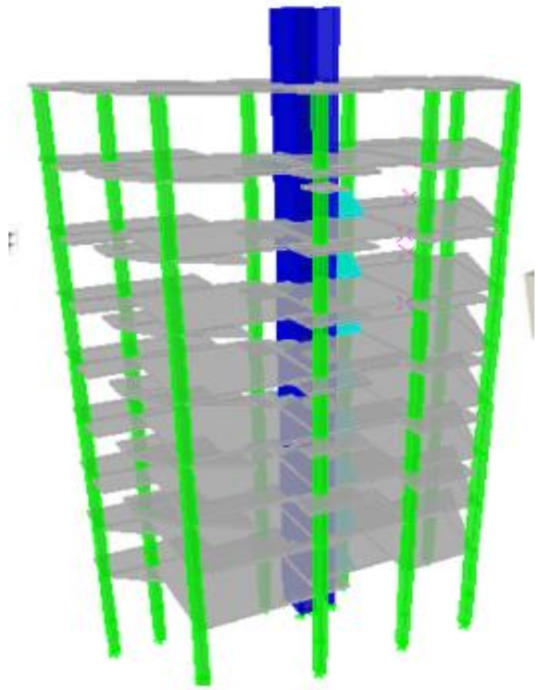


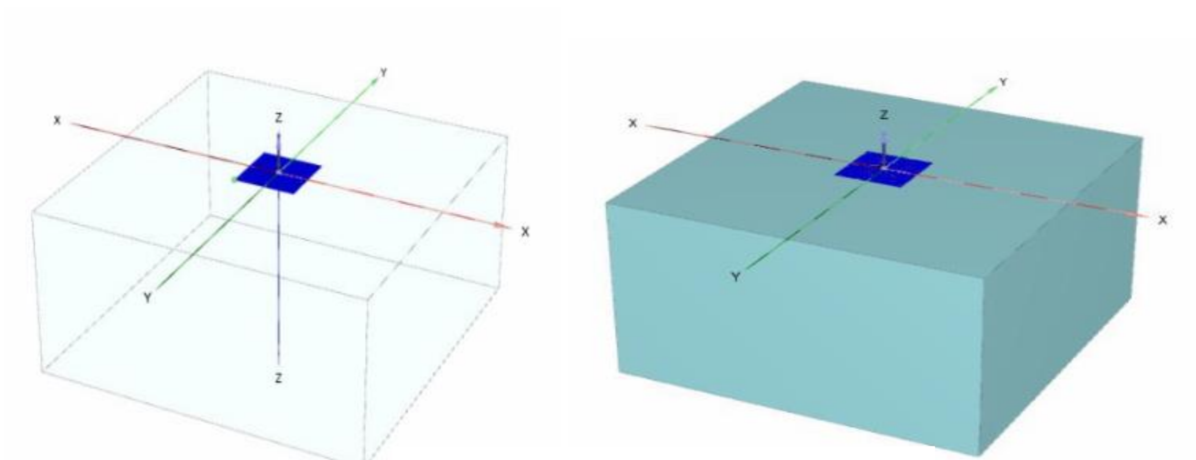
Figure A-1.1: Design B+G+7 Building Using ETABS software

Figure A-1.2: Selected 2.5m by 2.5m Isolated Footing for the Plaxis 3D analysis

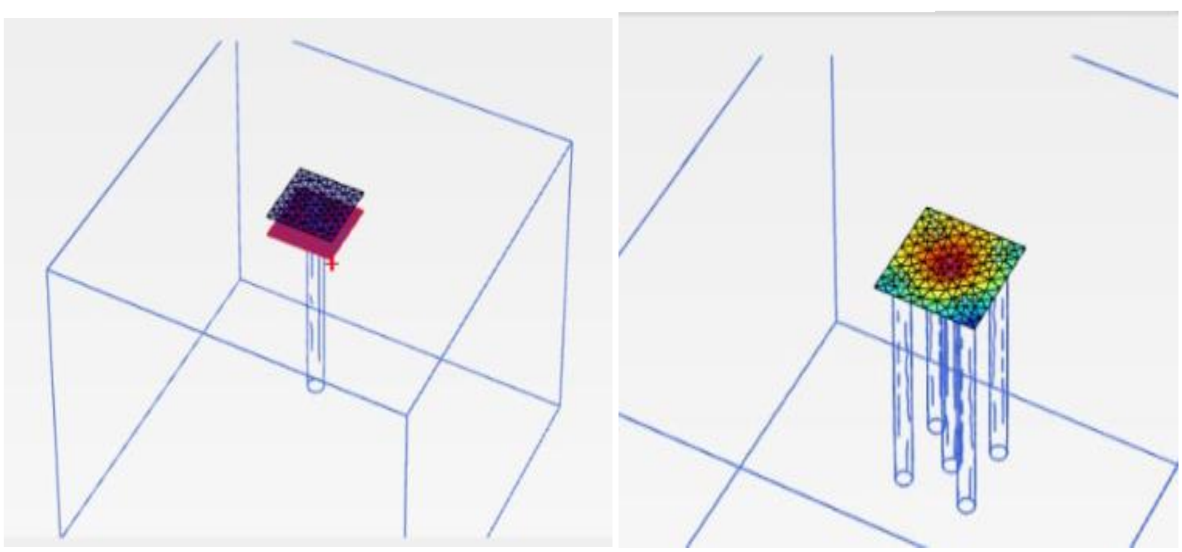
To reduce the number of footing to be analyzed and grouping the obtained loads is very important. For this study only a square isolated footing with 2.5m by 2.5m was selected and categorized load group is as shown in below table

Table A-1.1: Selected Footing type and Load categorization from ETABS Analysis

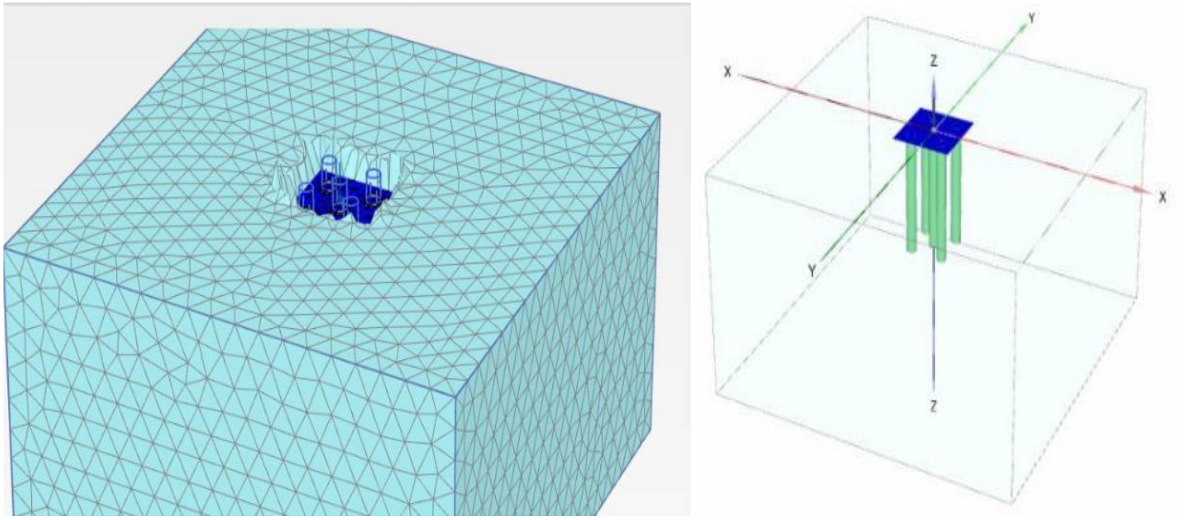
Footing type	Fz (Load Ranges) KN	Mx (KN-M)	My (KN-M)	Kinds (footing types) No	Maximum Load selected, KN
F-1	1250-1400	-0.176 to 2.849	-1.109 to 0.307	5	14000
F-2	1400-2000	0.672 to 0.885	0.823 to 0.924	9	2000
F-3	2000-3000	-2.137 to -1.784	-70.82 to -7.753	12	3000



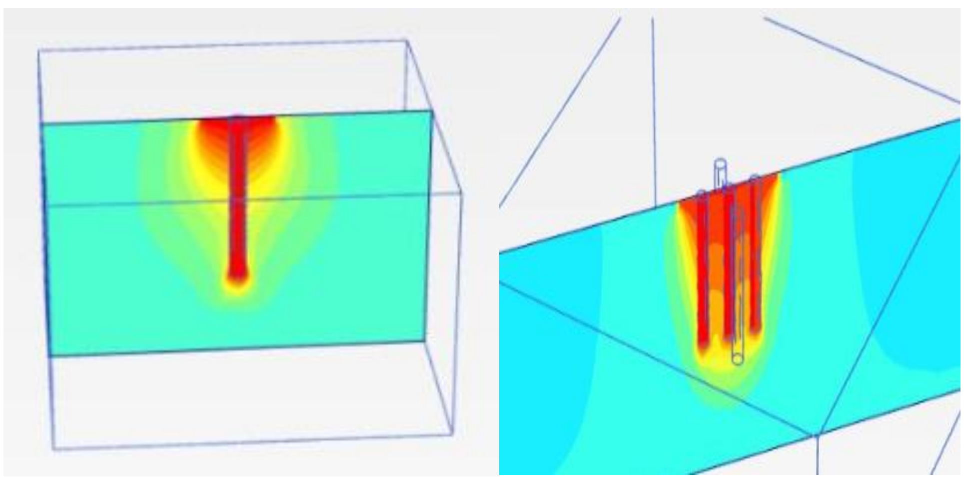
Soil and foundation structure model



Single and grouped stone column Model



Mesh generation and modelling the structure including foundation and stone column



Single and grouped stone column vertical and lateral deformation

Appendix – 2: Soil data, empirical equations and standard values through correlations

A-2.1: Tolerable maximum settlement of the building as per EBCS

Criterion	Isolated Footing	Mat Foundation
Angular Distortion (δ/l)	Cracking = 1/300	
For Clay soil	75mm	75mm – 125mm
For Sand Soil	50mm	50mm – 75mm

A-2.2: Typical values of soil Young's modulus for different soils according to USCS (MPa) For sand soil at different condition

USCS	Description	Loose	Medium	Dense
GW, SW	Gravels/Sand well-graded	30-80	80-160	160-320
SP	Sand, uniform	10-30	30-50	50-80
GM, SM	Sand/Gravel silty	7-12	12-20	20-30

A-2.3: Typical values of soil Young's modulus for different soils according to USCS (MPa) for sand soil at different condition

GM, SM	Sand/Gravel silty	7-12	12-20	20-30	
USCS	**Description**	**Very soft to soft**	**Medium**	**Stiff to very stiff**	**Hard**
ML	Silts with slight plasticity	2.5 - 8	10-15	15 -40	40 - 80
ML, CL	Silts with low plasticity	1.5 - 6	6-10	10-30	30 -60
CL	Clays with low-medium plasticity	0.5 - 5	5-8	8-30	30 - 70
CH	Clays with high plasticity	0.35 - 4	4-7	7-20	20 - 32
OL	Organic silts	-	0.5 -5	-	-
OH	Organic clays	-	0.5 -4	-	-

A-2.4: Measured and adjusted SPT N values

BH	Depth of N count	N count	Cn	N55	Wtd. Average
1	1.5	17	1.8833	17	13.4
	3.0	17	1.3317	16	
	5.0	15	1.0316	12	
	7.0	20	0.8718	14	
	9.0	17	0.7689	11	
	11.0	20	0.6955	11	
	13.0	24	0.6397	13	
2	1.5	17	1.8833	17	14.7
	3.0	19	1.3317	18	
	5.0	18	1.0316	15	
	7.0	21	0.8718	14	
	9.0	23	0.7689	14	
	11.0	21	0.6955	12	
	13.0	24	0.6397	13	

The SPT/300mm will be adjusted for different factors before employing them for design. The N-values are converted to N_{60}' standard energy ratio value according to Bowles (Bowles, 1988).

$$N'_{60} = C_N \times N \times n_1 \times n_2 \times n_3 \times n_4$$

Where N'_{60} = adjusted N

C_N = adjustment for overburden pressure $(p''_o/p'_o)^{1/2}$

p'_o = overburden pressure

p''_o = reference overburden pressure (95.76 kPa or 1.0 kg/cm^2)

n_1 = E_r/E_{rb} (where E_r is average energy ratio that depends on the drill system and E_{rb} is the standard energy ratio). E_r is taken as 45 and E_{rb} as 55

n_2 = Rod length correction

Rod length > 10 m = 1,

Rod length 6-10 m = 0.95,

Rod length 4-6 m = 0.85,

Rod length 0-4 m = 0.75

n_3 = sampler correction (1.00 in our case)

n_4 = borehole diameter correction (1.00 in our case)

A-2.5: Laboratory test result for the given soil

BH-ID	Depth (m)	Sieve Analysis (mm)				Atterberg Limits		Unified Soil Classification
		4.75	2.00	0.425	0.075	LL	PI	
BH-1-1	3.45-4.00	99.64	96.84	85.07	76.35	NP	NP	ML
BH-1-2	13.45-14.00	98.76	97.78	85.92	69.07	NP	NP	ML
BH-2-1	5.45-6.00	95.71	93.71	86.14	74.85	NP	NP	ML
BH-2-2	9.45-10.00	99.84	98.21	92.39	77.54	NP	NP	ML

A-2.6: Correlation equation for cohesion (C), angle of internal friction (f), and Poisson's ratio (v) using SPT N value (R. Kumar et al., 2016).

$C = -2.2049 + 6.484N$ N = 2 - 30 (Cohesive soil)

$C = -16.5 + 2.15N$ N = 10 - 30 (Intermediate soil)

$\varphi = 7N$ for N<=4

$\varphi = 27.12 + 0.2857N$ for N=4 to 50

$v = 0.2 + 0.01N$ N= 0 - 20 loose granular soil

$v = 0.2 + 0.005N$ N= 20 - 50 dense granular soil

$v = 0.15 + 0.0167N$ N= 0 - 6 Soft Clay

$v = 0.125 + 0.0125N$ N= 6 - 30 stiff clay

Penetration Resistance and soil properties on the Basis of SPT N values (Peck et al, 1974)

ABSALAT	ABSALAT DESIGN AND BUILD PLC	Sheet 1 of 1
	Title: BOREHOLE LOG SHEET	BH ID No: BH-1

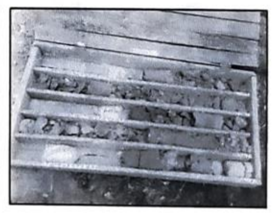
Project: Geotechnical Inv. of 2B+G+10+T Mixed Use Building
Client: Ene Getahun Tesfaye
Location: Adama, Oromia, Ethiopia
BH Coordinates (UTM- Adindam Datum)
Easting: #####
Northing: #####

Ground Elevation: ####
BH Inclination: Vertical
Flushing System: Water
Date started: 12/06/2023
Date completed: 14/06/2023
Total depth drilled(m): 15

Depth	Core run(m)	TCR(%)	RQD(%)	Casing Dia(mm)	Hole Dia.(mm)	AFS(%)	SPT N-values /300mm	Sampling		Field Description of Soil/rock	Graphic Log	GWL
0.00												
	0.50	100			108							
1.00	0.50	100										
	0.50	100					1.50					
							6/8/9					
2.00	0.45	100					1.95					
3.00	1.00	100					3.00					
							6/7/10	3.45				
	0.45	100					3.45					
4.00	0.55	100			89			4.00				
5.00	1.00	100					5.00					
							2/2/3					
	0.45	100					5.45					
6.00	0.55	100										
7.00	1.00	100					7.00			Grayish to grayish brown, medium dense, non plastic clayey sandy SILT with trace of gravel		
							7/9/11					
	0.45	100					7.45					
8.00	0.55	100										
9.00	1.00	100					9.00					
							8/8/9					
	0.45	100					9.45					
10.00	0.55	100										
11.00	1.00	100					11.00					
							9/10/10					
	0.45	100					11.45					
12.00	0.55	100										
13.00	1.00	100					13.00					
							8/11/13	13.45				
	0.45	100					13.45					
14.00	0.55	100						14.00				
15.00	1.00	100							15.00			
16.00												

Core Photographs

Depth 0.00 - 5.00



Depth 5.00 - 10.00

Depth 10.00 - 15.00

Consultant: ____________
Subcontractor: ____________
Supervisor: ____________
Logged By: Nurilign K.
Approved By: ____________

Drilling Method: Dry boring
Type of Rig: ROTARY
Bit Type: Tungsten Carbide, Diamond
Bit diameter(mm): 108, 89

BH = Borehole
N = Blows/30cm
CPT = Cone Penetration Test
USCS = Unified Soil Classification System
RQD = Rock Quality Designation
TCR = Total Core Recovery
AFS = Averge Fracture Spacing
Rc = Rock core

Rock sample
Undisturbed sample
Disturbed sample
Static groundwater level

REMARK ____________

ABSALAT	ABSALAT DESIGN AND BUILD PLC	Sheet 1 of 1
	Title: BOREHOLE LOG SHEET	BH ID No: BH-2

Project: Geotechnical Inv. of 2B+G+10+T Mixed Use Building
Client: Ene Getahun Tesfaye
Location: Adama, Oromia, Ethiopia
BH Coordinates (UTM- Adindam Datum)
Easting: #####
Northing: #####

Ground Elevation: ####
BH Inclination: Vertical
Flushing System: Water
Date started: 12/06/2023
Date completed: 14/06/2023
Total depth drilled(m): 15

Depth (m)	Core run(m)	TCR(%)	RQD(%)	Casing Dia(mm)	Hole Dia.(mm)	AFS(%)	SPT N-values /300mm	Sampling	Field Description of Soil/rock
0.00					108 (0.00–4.00)				0.00–0.70: Dark grayish, stiff to hard, non plastic clayey sandy SILT with trace of gravel
0.50	0.50	100							
1.00	0.50	100							
1.50	0.50	100					1.50 / 6/8/9 / 1.95		
1.95	0.45	100							
3.00	1.00	100					3.00 / 6/9/10 / 3.45		
3.45	0.45	100							
4.00	0.55	100			89 (4.00–15.00)				
5.00	1.00	100					5.00 / 6/8/10 / 5.45	5.45–9.45	
5.45	0.45	100							
6.00	0.55	100							
7.00	1.00	100					7.00 / 7/9/12 / 7.45		0.70–15.00: Grayish to grayish brown, medium dense, non plastic clayey sandy SILT with trace of gravel
7.45	0.45	100							
8.00	0.55	100							
9.00	1.00	100					9.00 / 9/11/12 / 9.45	9.45–10.00	
9.45	0.45	100							
10.00	0.55	100							
11.00	1.00	100					11.00 / 10/10/11 / 11.45		
11.45	0.45	100							
12.00	0.55	100							
13.00	1.00	100					13.00 / 11/11/13 / 13.45		
13.45	0.45	100							
14.00	0.55	100							
15.00	1.00	100							15.00
16.00									

Core Photographs

Depth 0.00 - 5.00

Depth 5.00 - 10.00

Depth 10.00 - 15.00

Consultant:
Subcontractor:
Supervisor:
Logged By: Nurilign K.
Approved By:

Drilling Method: Dry boring
Type of Rig: ROTARY
Bit Type: Tungsten Carbide, Diamond
Bit diameter(mm): 108, 89

BH = Borehole
N = Blows/30cm
CPT = Cone Penetration Test
USCS = Unified Soil Classification System
RQD = Rock Quality Designation
TCR = Total Core Recovery
AFS = Averge Fracture Spacing
Rc = Rock core

Rock sample
Undisturbed sample
Disturbed sample
Static groundwater level

REMARK