ADDIS ABABA UNIVERSITY

AAU/AAIT SCHOOL OF GRADUATE STUDIES

MASTER'S THESIS

GUIDELINE FOR THE SELECTION OF SAFE AND ECONOMICAL TYPES OF REINFORCED CONCRETE FOUNDATION FOR DIFFERENT BUILDINGS CONSTRUCTED ON EXPANSIVE SOIL OF ADDIS ABABA

BY HAILEMARIAM GIRMA

OCTOBER 2016

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A thesis submitted to the school of Graduate studies of Addis Ababa University, Institute of Technology, AAiT in partial fulfillment of the requirements of the Degree of Master of Science in Civil and Environmental Engineering.

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ADDIS ABABA

OCTOBER 2016

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ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my advisors, Professor Alemayehu Teferra and Dr. Henok, for their outstanding cooperation, constructive suggestion, valuable guidance, and his encouragement offered to throughout this research work.

I would like also to express my deepest gratitude to EiABC soil laboratory Head (Dr. Kassahun), EiABC soil laboratory staff (Ato Geremew/Assistant Head/, Ato Abey and Ato Mesfin), Addis Ababa city Housing Construction and Development Project Office geotechnical engineering staff (Ato Yebeltal and Ato Mesfin/Head/) who supported me in providing all available geotechnical investigation soil reports and AAU's, Science Faculty Computational Program staff (Ato Dagem Yosef and Ato Elias Girma) who introduced me to Visual Basic and assisted me in developing software program. My thanks go to all senior AAU/EiABC's staff and friends (Ato Woyech B. and Ato Wendimu) who are engaged in foundation design works for the information and research materials that were required.

My heartfelt gratitude goes to my son Amanuel and my wife Rahel Azale for their sacrifices and encouragement that enabled me to attain this level.

ABSTRACT

The selection of safe and economical types of reinforced concrete foundation is one of the challenges for professionals in current designing practice, and this issue is more complex for foundation design for different buildings that are intended to be constructed on expansive soils of Addis Ababa. Beside the concern of swelling pressure of expansive soils, the availability of precise foundation software, cost of construction, and variability of foundation design factors with uniqueness of the project are also among the factors that brought extra challenges on professionals to select the safest and economical foundation in different localities of Addis Ababa.

In this research work, an attempt is made to develop a simple software using Programming language, MATLAB 2011, and visual basic ultimate studio 2015 for handling the above issues by applying seven main reinforced concrete foundations such as footing foundations, slab foundations such as slab-on-ground, uniform mat and ribbed mat foundations, straight bored pile, single and double-under-reamed pile foundation for different buildings ranging from one story to sixteen stories under four grouping. The expected input for this software are superstructure loads, swelling pressure, allowable/safe bearing capacity (based on UCS values and N-values from SPT readings), depth of moisture fluctuation and foundation determining factors like aspect ratio for dimensional factor and aspect ratio of load factor.

With this research, it is believed that a considerable time would be saved in geotechnical investigation. A suitable guideline for the selection of safe and economical types of reinforced concrete foundation for different buildings constructed on expansive soil of Addis Ababa is proposed.

NOTATIONS

A_p = Area of pile base

A_s = Surface area of pile shaft

a_v = Coefficient of compressibility

B = Width of footing or smaller dimension of mat foundation

c = Cohesion

C_c = Compression Index

C_v = Coefficient of Consolidation

D_s = Diameter of straight Pile shaft

D_u = Pile bulb diameter

e = Void Ratio

E_u = Undrained Young's Modulus

E' = Drained Young's Modulus

Δe = Change in Void Ratio

F_s = Free Swell

f_s = skin friction

G_s = Specific Gravity

G = Group of Story level (G_1, G_2, G_3 & G_4)

I_s = Swelling Index

K = coefficient of later earth pressure

K_o = Earth pressure at rest

K_s = Modulus of subgrade reaction

$L_L = W_l$= Liquid Limit

OCR = Over Consolidation Ratio

m_v = Coefficient of volume compressibility

NMC = W= Natural Moisture Content

$P_L = W_p$= Plastic Limit

$P_I = W_l – W_p$= Plastic Index

P = Building loads

Q_{ult} = Ultimate bearing Capacity

Q_{all} = Allowable bearing Capacity

q_u= Unconfined compressive strength

Q_s = Skin resistance of pile

Q_{sup} = Contact Pressure of the building

σ_s = Save bearing Capacity

Q_p = Point resistance or end bearing resistance

q_p = tip ultimate bearing capacity of the soil

S_L = Shrinkage Limit

ϕ = Angle of Internal friction

ϕ' = Effective angle of Internal friction

P_s = Swelling Pressure

S_c = Consolidation settlement

S_i = Immediate settlement

S_s = Secondary Settlement

UCS = Unconfined Compressive Strength

X = Aspect ratio of plan dimension = L/H=longest building width over height of building

Y = Aspect ratio of Loads = the ratio of building loads over safe bearing Cap.

Z= Depth of moisture fluctuation

γ_w = Unit weight of water

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CHAPTER ONE

1. INTRODUCTION

1.1 . GENERAL

Soils that exhibit volume change due to change in soil moisture are referred to as expansive or swelling soils. Expansive soils are principally residual soils. In case of Ethiopia, they are derived from the weathering of basic volcanic rocks which cover most of the Ethiopian plateau like Addis Ababa [25].

Soils that exhibit volume changes usually possess a considerable percentage of montmorillonite clay mineral which has an octahedral sheet sandwiched between two silica sheets. When this mineral is exposed to moisture, water is absorbed between interlayering lattice structures and exert an upward pressure. This upward pressure, known as swelling pressure, causes most of the damages associated with expansive soils.

The built up pressure is usually responsible for cracking of buildings when uplift pressure/swelling pressure is greater than contact pressure or superstructural loads. Since damages of structures caused by expansive soils have been reported from different areas of Addis Ababa, theses damages include buildings, roads, factories, hydraulic structures etc. Based on the previous reports, damages were caused by lack of proper identification and classification of expansive soils and improper design of the foundations of the damaged structures [1].

Damages due to expansive soils could occur in any type of building unless and otherwise proper measures are taken. These measures are moisture control, soil stabilization and structural measures. In this research, the structural solutions will be explained in depth for different building types and how to select the best types on foundations in terms of safety and economic considerations for the proposed building type constructed on expansive soil.

1.2 . PURPOSE OF THE RESEARCH

This research provides a guide line for the selection and design of different foundations for buildings constructed on expansive clay soil areas of Addis Ababa.

The guide line which is provided in this paper can significantly reduce the risk of undesirable and severe damages to many structures founded on expansive soils.

1.3 . THE RESEARCH BACK GROUND

In Ethiopia, a lot of damages have been occurring due to expansive soils. Although there is not an organized economic survey, it is assumed that most of the economic loss due to failures associated with civil engineering constructions are attributed to expansive soils. Low level of understanding of the mechanisms of heaving and the measures required to counter such problem associated with underestimating of swelling pressures by foundation designers, inadequate use of safety associated with the conservative design, and improper soil investigations and interpretations of soil parameters have contributed for most of the failure caused by expansive soil area in Ethiopia [11].

In Addis Ababa, it has been noticed that expansive soils cover large parts of the city where recent fast construction activities are carried out. During the past decades, rapid expansion of the city lead to the construction of various structures, particularly cost efficient buildings in the central as well as all around periphery of Addis Ababa. The existence of expansive soils in this area has caused structural damages on light buildings, asphalt pavement and buried utility lines.

1.4 . OBJECTIVE OF THE RESEARCH

The Geotechnical Engineer who is engaged in designing the foundation of different structures, investigates subsurface conditions and assesses risks posed by site conditions to overcome uncertainties in designing safe and economical foundations. The designer should obtain all the possible information about the problems confronting him/her, to determine what course of actions are open to him/her, to study various alternatives that might be used to support the structure, to visualize the probable action of those alternatives, to estimate their approximate costs, to decide upon the relative feasibility of their construction, to choose the best foundation, and the last but not least, to justify to his project initiators about the nature of the problems and the reason for his recommendations.

A. GENERAL OBJECTIVES

The general objective is to prepare a general guideline for the selection of different reinforced concrete foundation types for different areas of Addis Ababa based on safety and economic considerations. That is to develop a software which facilitates the selection of best option among the various reinforced concrete foundations for a proposed building type and soil profile conditions.

B. SPECIFIC OBJECTIVES

The specific objectives are: -

- Determination of the swelling pressure of expansive soil of Addis Ababa and incorporating the swelling pressure and depth of moisture fluctuations as an input for the selection of foundation type as an output.
- Assessment of the extent of damages caused by swelling characteristic of the soil and provisions of different heave protection mechanisms especially structural measures in the selection of foundation types on buildings that are constructed on expansive soil.

1.5 . SCOPE OF THE RESEARCH

This research work primarily addresses both the general and specific objectives by developing a software for simple selection of different reinforced concrete foundation on expansive soil of Addis Ababa with determination of swelling pressure as input for the software in comparison to presumed design bearing resistance under vertical loading and soil properties. As per the continuation of this research work following the previous researchers, the study involves collecting soil test data from different selected sites of expansive soil coverage, data from previous research works and data from different concerned office to fulfill the requirement of this research work.

1.6 . ORGANIZATION OF THE RESEARCH

This paper consists of seven chapters. The first chapter covers the introduction of the entire paper concepts in precise manner and it discusses the purpose of this research, the background of the study, objective and scope of this research. The second chapter is devoted to literature review appropriate to the research topic. The third chapter specifically comprises data collection and analysis which presents the summarized data from the laboratory results and other related laboratory results from other researches which are important for preparation of software development and determination of design parameters. In the fourth chapter, the determination of design parameters for both shallow foundation (i.e. footing foundation & slab type foundation) and deep foundations (i.e. mainly straight bored pile and under-reamed pile) are presented here. Foundation design and analysis with cost comparison are included in fifth chapter which clearly presents the algorithm of the proposed software. Finally, chapter six and seven incorporate the discussions about how to select foundation type using this software and general conclusion and recommendations respectively.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. INTRODUCTION

Expansive soils are primarily clays. Clays are fundamentally very different from silts, sands, and gravels. The mechanical properties of silts, sands and gravels depend on such properties as the size, shape, texture, and gradation of the particles. Clay soils on the other hand, comprise of extremely small plate like particles, having extremely large specific areas (m^2/g). For small size particles, the electrical forces acting on the surface of the particles are much greater than the gravitational force. Furthermore, the surfaces of the plate-like clay particles have inherent electrical charges. As the specific surface area (SSA) of clay particles increases, the importance of the charged surface properties of the clay particles becomes increasingly prominent.

Particle size alone does not determine clay mineral. Probably the most important grain property of fine-grained soils is the mineralogical composition [9]. The three most important groups of clay minerals are montmorillonite, illite, and Kaolinite. Since montmorillonite clay mineral has SSA of $800m^2/g$, illite has $80m^2/g$ and Kaolinite has only $15m^2/g$. Montmorillonite is the clay mineral that is mostly present in expansive soil. When these minerals are exposed to moisture, water is absorbed between the inter-layering lattice structures and exerts an upward pressure, which is the cause for most damages associated with expansive soil because montmorillonite clays can swell to more than 15 times their original volume when going from a dry state to fully saturated liquid limit state [9].

2.2. EXPANSIVE SOIL PROPERTIES

2.2.1. ORIGIN OF EXPANSIVE SOILS

The origin of expansive soils is related to a complex combination of conditions and processes that result in the formation of clay minerals having a particular chemical makeup which, when in contact with water, expands [9]. The conditions or processes which determine the clay mineralogy include composition of the parent material and degree of physical and chemical weathering to which the materials are subjected.

The constituents of the parent material during the early and intermediate stages of the weathering process determine the type of clay formed. The nature of the parent material is much more important during these stages than after intense weathering for long periods of time.

The parent materials that can be associated with expansive soils are classified into two groups [9]. The first group comprises of the basic igneous rocks such as basalts, gabbro and volcanic glass which have low silica, generally about 45% to 25% and rich in metallic base such as pyroxenes, amphiboles and olivine. Here the feldspar and pyroxene minerals of the parent rocks decompose to form montmorillonite which is the predominant mineral of expansive soil [9] [5]. The second group comprises the sedimentary rocks that contain montmorillonite as a constituent including shale, limestone and clay stones which break down physically to form expansive soils [9]. The expansive soil of Ethiopia are derived from both groups [5].

The weathering process by which clay is formed includes physical, biological and chemical process. The most important weathering process responsible for the formation of montmorillonite is the chemical weathering which includes hydrolysis, hydration, oxidation, carbonation and solution of parent rock mineral which generally consists of ferro-magnesium mineral, calcic feldspars, volcanic glass, volcanic rocks and volcanic ash. Chemical weathering of parent rock in high rainfall climatic conditions is mainly form primary minerals. The primary minerals are altered through chemical weathering processes into secondary minerals.

2.2.2. CLAY MINERALOGY

Clay minerals are composed of two basic structural units, namely tetrahedral and octahedral. Silica tetrahedral consists of a silica atom surrounded by four oxygen atoms forming a tetrahedron. When each silica atom is shared by two tetrahedral through repeated linkage, a **silica sheet** is formed. The alumina octahedron consists of an aluminum atom surrounded octahedraly by four oxygen atoms and two hydroxyl ions. Each aluminum atom is shared by two octahedrons through repeated linkage that is called an **alumina sheet** [9].

On the basis of their crystalline arrangements, the three most important groups of clay minerals are montmorillonite, illite and kaolinite. From the mineralogical standpoint, the magnitude of expansion depends upon the amount of clay minerals present, their exchangeable ions, the electrolyte content of the aqueous phase and the internal structure.

2.2.3. SWELLING CHARACTERISTICS AND SWELLING PRESSURE

2.2.3.1. SWELLING CHARACTERISTICS OF EXPANSIVE SOIL

As the name indicates, the main characteristics of an expansive soil is that it swells on wetting and shrinks on drying [16]. The swelling potential of such a soil is measurable and is determined in the laboratory. Different swelling tests are conducted in the laboratory. The most common ones are the free swell, percentage swell and swelling pressure tests.

Free Swell Test may be considered as a measurement of volume change in clay upon saturation and it is a simple test to estimate the swelling potential of expansive clay. It consists of placing a known volume of dry soil in water and measuring the increase in volume. The difference between the final and initial volume, expressed in percentage of initial volume is the free Swell. It is a very crude test and had been used in early days when refined testing methods were not available. If the free swell is less than 50%, the soil may not cause considerable damage to lightly loaded structures whereas the soils having free swell about 100% can cause considerable damage.

$$F_s = [(V_f - V_o)/V_o]*100\% \qquad (2.1)$$

Where:-

F_s = free swell (%)

V_f = final volume/soil volume after swelling, cm^3, and V_o = Initial volume, $10cm^3$

Percentage Swell Test is more accurate methods and is conducted in the laboratory with undisturbed samples in one dimensional consolidation test apparatus. Percentage swell is defined as the vertical expansion of swelling soil expressed in percentage of the initial height of the sample.

Swelling Pressure Test is more accurate methods and is conducted in the laboratory with undisturbed samples in one dimensional consolidation test apparatus. The swelling pressure is the pressure required to keep the volume of a swelling soil sample constant. In other words, swelling pressure is the vertical pressure required to prevent volume change of laterally confined sample when it is allowed to take in water [4].

Generally, the swell pressure of a soil is the external pressure that needs to be placed over a swelling soil to prevent volume increase, while the swell potential of an expansive soil is the magnitude of heave of a soil for a given final moisture content and loading condition. There are different ways to recognize expansive soils in the field before constructing a foundation.

Table 1 gives limits of free swell, percentage swell, and swelling pressure for different degrees of expansiveness of swelling soils. Most expansive soils found in Addis Ababa have free swell and swelling pressure amounting to values above 100% and 1kP/cm^2 respectively [16].

Table 1:- Free Swell, Percentage Swell and Swelling Pressure limits [5]

Degree of Expansiveness	Free Swell (%)	Percentage Swell (%)	Swelling Pressure (kP/cm^2)
Low or none	< 50%	Less than 1	Less than 0.2
Medium	50 to 100%	1 to 5	0.2 to 1.0
High	>100%	Greater than 5	Greater than 1.0

2.2.3.2. FACTORS AFFECTING SWELLING CHARACTERISTICS AND SWELLING POTENTIAL OF EXPANSIVE SOIL

As a definition, swell potential of a soil is expressed as the percentage of swell of laterally confined sample which has been soaked under a surcharge of 1 psi (7kPa). In other words, the term swelling potential is generally used to indicate the amount of vertical swell (expressed as per cent of initial thickness) obtained under a particular surcharge (7kPa) [4].

The factors influencing the **swelling characteristics** or the shrink-swell potential of a soil can be considered in three different groups.

A. **Soil characteristic** that influence the basic nature of the internal force field. These includes clay mineralogy, soil water chemistry, soil suction, plasticity, soil structures and fabrics and dry density.

B. The **environment factor** that influence the changes that may occur in the internal force system. These include initial moisture condition, moisture variation, climate (i.e. ground water, drainage and manmade water source, vegetation, permeability and temperature).
C. **State of stress**, which include stress history, surcharge load and soil profile.

Moreover, from laboratory investigations, factors influencing the **swelling potential of expansive soil** have been found to be initial moisture content, initial dry density, degree of saturation, thickness of soil strata and the surcharge load.

A. The percentage swell, or heave is noted to decrease by increasing moisture content and degree of saturation, this implies that **pre-wetting** on expansive soil will reduce the amount of heave.
B. The percentage swell is observed to decrease by increasing the surcharge load and by decreasing the initial dry density of soil, from this it can be concluded that by **increasing the pressure under a foundation**, heaving will be reduced.
C. Furthermore, the amount of heave decreases with the decrease in thickness of the swelling soil stratum, this implies that **removing part of the expansive soil** or **lower the foundation deeper** than normally needed for stable soils will reduce the amount of heave.
D. The dry density is an important factor in determining the magnitude of volume change. If the initial dry density of the soil is high, then swell potential or swelling pressure of expansive soil will be high. The reason is that higher densities result in closer particles spacing, and therefore causing greater particle interaction.

2.2.3.3. DETERMINATION OF ACTIVE ZONE DEPTH

Active zone depth is defined as the depth of soil beneath a structure that is contributing to actual heave that takes place at some point at the surface at any particular time. The depth of the active zone is limited by the depth of expansive soil and by the depth at which the overburden pressure is equal to the swell pressure. Therefore, the depth at which the overburden pressure equals to the swell pressure provides a method for estimating maximum possible active zone depth [27].

Even though the soil may have the potential to swell and shrink below the depth of the active zone, volume changes will not take places because the water content of the soil is constant. Besides, since the water content distribution does not change with time below that zone, the soil should be either stabilized or removed down till that active zone depth, otherwise the foundation must extend to a depth that exceeds that of the active zone if the replaceable depth of moisture fluctuation is uneconomical [11].

2.2.4. PREDICTION OF HEAVE, DAMAGE DUE TO HEAVE AND METHODS OF PREVENTING HEAVE DAMAGE

2.2.4.1. PREDICTION OF HEAVE

Among many prediction methods in use today, evaluation of soil volume changes by direct measurements of swelling pressure with a consolidometer is the most widely used method for predicting heave. In swell-consolidation method, an undisturbed sample is allowed to absorb water under a load of 7kPa and is put aside to fully expand and reach equilibrium. Then it is consolidated by increasing the applied pressure in intervals following the conventional consolidation test procedure. The load increment is continued until the sample reaches its initial volume (zero volume change). The load corresponding to zero volume change is taken as swelling pressure [4]. In other words, the pressure required to prevent the specimen to its initial void ratio (height) is used to define the swelling pressure.

Moreover, most of the structural damages occur when the swelling pressure is greater than the foundation pressure or contact pressure. Assessing the swelling pressure is an important task in dealing with expansive soil.

2.2.4.2. RECORDED DAMAGES ON BUILDINGS CONSTRUCTED ON EXPANSIVE SOIL OF ADDIS ABABA

Based on previous recorded damaged buildings constructed on expansive soil areas of Addis Ababa, it has been found out that 67% of the buildings built in these areas show severe damage that might be due to improper structural design, surface and sub-surface drainage, watering of plant during landscaping near foundations and/or from giving little or no attention to the expansive nature of expansive soils.

Data on observed damages of buildings constructed on expansive soils of Addis Ababa is analyzed on different types of foundations and presented in Table 2 [1].

Table 2:- Number of damaged buildings and type of foundation system [1]

Types of Foundation	No of Building	No of Damaged Buildings	%age of Damaged building (%)
Stiffened Mat	7	1	1.45
Footing Foundation	26	13	18.84
Masonry Foundation	57	50	72.46
Pile Foundation	3	2	2.90
Wall Foundation	3	3	4.35

2.2.4.3.METHODS OF PREVENTING HEAVE DAMAGE

In order to minimize the danger of damages to buildings because of heave and shrinkage, the following methods have been used: - namely moisture control, soil stabilization and structural measures [3, 9].

A. **Moisture Control** is made to prevent surface water which may seep into a building foundation by providing moisture barriers above such as horizontal and vertical barriers around the foundation soil, and adequate surface and sub-surface drainage system because the main cause of heaving and shrinkage is the fluctuation of moisture under and around the structure in specified area.

B. **Soil Stabilization** is made to minimize the swelling potential of expansive soil by one or more of the following methods, namely: - soil replacement, pre-wetting, compaction control and chemical treatment.

With Soil Replacement Method, all of the swelling soil is removed and replaced with non-swelling soil. This method is recommended for cases where the thickness of expansive soil is small, less than 2.5m. It is the simplest and easiest solution for slabs and footings founded on expansive soils and it provides the safest method for slab-on-ground construction.

With Pre-Wetting Method, the soil is flooded to achieve swelling prior to commencement of construction. This method, however, has disadvantage in reducing bearing capacity of foundation soil by reducing the shear strength of the soil. It is successful if the depth of active zone is not large. It has been effectively used for stabilizing soil beneath floor slabs, pavements. However, its application for building foundations is still questionable and risky.

With Compaction Control Method, the upper soil is scarified and re-compacted to low soil density. This reduces the swelling property and heave of the expansive soil. The main advantage of using this approach is that the swelling potential can be reduced without the negative effects caused by introducing excessive moisture into the soil. The draw-back with this method is that the low density compaction will result in low bearing capacity of subgrade of foundation soil.

With Chemical Treatment Method, it is the process of mixing additives like lime, cement, and other chemicals to expansive soils, so as to retard their potential expansiveness. Lime will reduce plasticity and hence the swelling potential of the soil, it is often used successfully in the construction of highways and airports. Meanwhile, the action of cement is to reduce the liquid limit, plastic index and the potential volume change, it is mainly used in highway constructions. However, use of lime and cement stabilization for foundation soils are not advised because one may require to treat considerable depth. Also its long term durability is not known.

C. **Structural Measures** is the most effective and widely used method. In this method, one of the following measures is employed.

Design the Building as Rigid Unit: - A rigid building is one which is free from uneven displacement which might cause structural damage. Rigidity of a building can be achieved by providing adequate reinforcement to foundation, beams, slabs and walls in such a manner that all of these will result in a monolithic form of building. This method is recommended for light and compact buildings. Mat foundations can be used under this category because they can be referred as structural slab-on-ground and stiffened slab to prevent the possibility of differential heave.

Providing Flexibility to Building: - A flexible building is one which allows differential movement to occur between its members without itself being damaged. Flexibility can be achieved by providing the building into small rigid compartments with flexible joints. This method is recommended for long buildings.

Providing Deep Foundations: - Here piles are used as a solution so that the pile should be placed in non-swelling stable zone (i.e. greater than 3.5m depth). The bottom of piles should be enlarged (under-reamed) to increase bearing and anchoring capacities of the piles. Piles should be protected from tension failure by either decreasing pile diameter, or increasing loading on the pile as high as possible, or by reinforcing pile for tensile force due to soil heave, or by providing pile with sleeve (of weak spongy material) in order to isolate pile shaft from soil.

2.3. FOUNDATION TYPES AND POSSIBBLE STRUCTURAL SOLUTIONS

2.3.1 GENERAL FOUNDATION CONCEPTS

The lowest artificially built part of a structure which transmits the load of the structure to the ground is called foundation [26]. The foundation of a structure is always constructed below ground level so as to increase the lateral stability of the structure.

Since the function of foundation is to transfer the load of the superstructure to the underlying soil formation without overstressing the soil, a safe foundation design provides a suitable safety factor against shear failure of the soil and excessive settlement. The soils limiting shear resistance is referred to as ultimate bearing capacity (Q_{ult}) of the soil. For design purposes an allowable bearing capacity (Q_{all}) is obtained by dividing the ultimate bearing capacity with a suitable factor of safety. The safe bearing capacity of the soil must not be exceeded; otherwise excessive settlement may occur, resulting in damage to the building and its service facilities.

Moreover, ground movement beneath a structure's foundations, which is the main issue of this paper, can occur due to shrinkage or swell of expansive soils due to climatic changes, mineralogical composition of the soil, or frost expansion of soil.

2.3.2 REINFORCED CONCRETE FOUNDATION CLASSIFICATION ON EXPANSIVE SOIL

2.3.2.1 SHALLOW FOUNDATIONS

The foundations provided immediately beneath the lowest part of the structure, near to the ground level are known as shallow foundations which implies that sallow foundations can transfer the super structural loads to the ground very near surface rather than deeper depth or to sub-surface [26]. It shall be designed with adequate bearing and structural capacity and with tolerable settlements. The purpose of this type of foundations is to distribute the structural loads over a considerable base area at the foundation bed.

Shallow foundations are applied when the soil beneath the foundation is strong enough to sustain the load of the building, hence generally shallow foundations on Expansive soil are further classified as footing foundations and slab foundations [9].

2.3.2.1.1. FOOTING FOUNDATION TYPES ON EXPANSIVE SOIL

Footing foundation is an enlargement at the bottom of columns/bearing walls that distribute the applied structural loads over a sufficiently large soil area. The footing foundation consists of concrete slab/pad under each structural columns and continuous slab under load bearing walls. This type of foundation is often used in small to medium size structures with moderate to good soil conditions.

However, footing foundations can be successfully placed on expansive soil provided that a sufficient dead-load pressure is exerted on the foundation, or the structure is rigid enough so that differential heaving will not cause cracking [9].

Hence, this type of foundation is not recommended in areas where the anticipated heave in the soil is high. Therefore, the use of footing foundation in expansive soils should be restricted to soils having relatively low swelling potential. When sufficient dead load pressure of superstructure is exerted on the foundation, the swelling pressure of the soil can be suppressed or restricted as long as the dead load pressure is greater or equal to the swelling pressure. This can be achieved by using small footing dimension to concentrate the load pressure, but professionals should take care in order not to exceed the bearing capacity of the soil. If the swelling pressure of the soil exceeds the bearing pressure of the soil, the use of this principle is not successful [10].

A footing can also be used where the top layers of expansive soil have small thickness and/or the active zone of the area is at shallow depth so that the footing foundation can be placed on the stable layer (zone) at shallower depth [10].

Generally, footing foundations can be successfully placed on expansive soil provided one of the following criteria are met; if sufficient dead-load pressure is exerted on the foundation, if the structure is rigid enough so that differential settlement can be reduced, and/or if swelling potential of the foundation soils can be eliminated or reduced [9].

Under footing foundation types, the well-known types of footing such as isolated, combined, strap and strip footing can be used within the limits of the above footing applications.

2.3.2.1.2. SLAB FOUNDATION TYPES ON EXPANSIVE SOIL

I. SLAB-ON-GROUND

A slab-on-ground/slab-on-grade is a concrete slab placed directly on the ground with little consideration given to its structural requirements. These slabs are constructed either with or without reinforcement.

The unreinforced slabs are generally constructed in residential houses or where a light floor load is expected. The limits of the length of the unreinforced slab are based upon the amount of shrinkage cracking control desired. Whereas a lightly reinforced slab is normally reinforced with a temperature control as a prime design factor. The choice between the two types depends upon the subsoil conditions as well as the loading conditions.

Slab-on-ground construction on expansive soil will always pose a cracking and heaving problem unless the subgrade soils are treated or replaced. In construction of building such as warehouse and storage areas, special design is required to maintain the structural integrity of the building.

Figure 1:- Slab-on-ground/Slab-on-grade foundation

II. MAT/RAFT FOUNDATIONS

Mat foundations are also known as raft foundations which are heavily reinforced concrete foundations that usually cover the entire plan area of the building to distribute the loads over a large area. Mat/raft foundations are thickened concrete slabs that support a number of columns or walls. Mats are reinforced with both positive and negative steel, adequately reinforced to resist moments in orthogonal directions. They are rigid elements that distribute column and wall loads over a larger area, thus reducing the magnitude of the vertical stress on the foundation soil. They do not only decrease the stress but also produce a more uniform settlement profile and subsequently reduces differential settlement [23].

Mats may be preferred over spread footings on strata that are erratic or have low bearing capacities. Mats are usually more economical than footings when the total base area required for individual footings exceeds about one-half of the area covered by the structure.

Mats can be used to create deep basements, distribute column loads more uniformly and provide basement slabs (water barrier). Mats may be used when the foundation soil has a low bearing capacity or large differential settlements are anticipated. The use of mat foundation may also be advantageous where the foundation is below water table and there is need to eliminate water infiltration into basement of a building.

Mat foundation is generally classified as ribbed mat and uniform/solid mat.

i. **Uniform Mat Foundation/Solid Mat** are sometimes referred to as structural slab-on-ground. The slab should be designed to resist both the negative and positive moments as a result of structural loading and heaving of the soil [9]. Normally mat foundations are reinforced both at the bottom and top [3]. This is because the exact contact pressure distribution under the mat is not known. It has however, limitations as pointed out by previous researchers [10].

ii. **Ribbed Mat Foundation** is reinforced concrete mat with a grid of underlying cross beams supporting the slabs that has been successfully used as foundation for even relatively loaded structures on expansive soils because heavy beams running in both direction to resist column loads and the soil pressure transferred to the beams from the mat. In ribbed foundation systems, the differential swell is the controlling factor governing the success of such construction. If the soil beneath the slab is to swell uniformity, no distortion would be caused in the slab. Distortion occurs when the supporting soil swells non-uniformly or differentially [9] [10]. Ribbed mats are frequently used in practice because they are economical than uniform mats.

2.3.2.2 DEEP FOUNDATIONS

Deep foundations transfer loads from structures to an available firm stratum at deeper distance below the ground surface. These foundations are used when the required bearing capacity of shallow foundations cannot be obtained, settlement of shallow foundations is excessive, and shallow foundations are not economical. Moreover, for safeguarding against the ground movements effectively, the best remedy is to anchor the structure at a deeper depth where the volumetric change of the soil due to seasonal moisture variation is constant or negligible.

Deep foundations are not only used to anchor structures against uplift forces but also used to assist in resisting lateral and overturning forces. It is necessary be required for special situations such as expansive or collapsible soil and soil subject to erosion or scour. Generally, deep foundations are commonly used under the following circumstances: -

i. When one or more upper soil layers are highly compressible and too weak to support the load transmitted by the superstructure, deep foundations are used to transmit the load to underlying bedrock or a stronger soil layer. When bedrock is not encountered at a reasonable depth below the ground surface, the resistance to the applied structural load is derived mainly from the frictional resistance developed at the soil-pile interface.
ii. In many cases, expansive and collapsible soils may be present at the site of a proposed structure. These soils may extend to a great depth below the ground surface. Expansive soils swell and shrink as their moisture content increases and decreases, and the pressure, of the swelling can be considerable.

Generally, for safeguarding against the seasonal ground movements effectively, the best remedy is to anchor the structure at a depth where the volumetric change of the soil due to seasonal and other variations is negligible. This can be achieved in expansive soils by using either straight bored piles or under-reamed piles. The method can be economical in areas where considerable heave can be expected and the additional cost can be balanced against the saving in the future maintenance. Straight bored piles or under-reamed piles can be used depending on the soil conditions. Straight bored piles are used in shallow expansive soils, single under-reamed piles for light structures in deep layers of expansive soils and double under-reamed piles for foundations of heavier structures in deep layers of expansive soils [3] [9] [10].

I. STRAIGHT BORED PILE FOUNDATION

For the straight bored piles, if the combined effect of the weight of the dead load and the skin friction does not balance the uplift force due to swelling, the whole pile may be lifted and cause structural damage to the building. One may estimate the total uplifting force using equation 2.2.

$$\mathbf{U=\pi*D*f*u*h} \quad (2.2)$$

Where: -

D=diameter of pile

u=swelling pressure

h=depth of pile in the active zone

f=coefficient of uplift between concrete and soil.

According to Chen [9], the value of f may be taken as 0.15 and the value of swelling pressure acting on the pier for soils with high degree of expansion is about $490kN/m^2$ and for soils with medium degree of expansion is about $245kN/m^2$.

The critical factor which should be considered is the tension force produced within the pile as the result of the swelling pressure. This force is more critical on under-reamed piles located in deep layers of expansive soils.

II. UNDER-REAMED PILE FOUNDATION

Under-reamed piles are bored cast-in-situ concrete piles having bulb shaped enlargement near base. These piles are commonly recommended for providing safe and economical foundations in expansive soils and other types of soils having poor bearing capacity. In these types of foundations the structure is anchored to the ground at a depth where ground movement due to changes in moisture content is negligible. A pile having one bulb is known as single under-reamed pile. It is seen that the load bearing capacity of the pile can be increased by increasing the number of bulbs at the base. In such cases the pile is named as multi-under-reamed pile. The increase in the bearing capacity of the pile can also be achieved by increasing the diameter and the length of the pile.

Buildings founded on expansive soils often crack due mainly to differential ground movements as a result of alternative swelling and shrinkage of the soil due to changes in its moisture content. With a view to meet this movement effectively, the best remedy is to anchor the structure at a depth where the volumetric change of the soil due to seasonal and other variations is negligible. Under-reamed piles have been economically achieved this anchorage both at shallow and deep layers of expansive soils.

CHAPTER THREE

3. DATA COLLECTIONS

3.1. GENERAL

Nowadays, due to the result of accelerated growth of Ethiopia, the majority of building construction are now executed in most of expansive soil coverage areas of Addis Ababa even if cost of construction on such soil types is expensive due to their susceptibility to damage that is caused by swelling characteristics of such soil types and even damages could more sensitive specially for low rise/light weight building such as residential building, warehouses, and small office building.

Not only the residential buildings (G+0 to G+2), but also medium rise buildings are also susceptible to damage caused by expansive soil because of less attention given to the swelling pressure. In this research, swelling pressure in the design and analysis of foundation is considered.

Available soil data are collected from research works and other sources that have relevance to the current research. In addition to the secondary data, the author has undertaken his own tests at specific sites.

3.2. LOCATION AND GEOTECHNICAL CHARACTERISTICS OF EXPANSIVE SOILS

3.2.1. LOCATION OF THE RESEARCH AREAS

The locations of the areas investigated are present in Fig.2. The area of Addis Ababa that are covered in this research project are **Bole-airport**/Hotel site/, **Gerji**/Korea Hospital/, **CMC**/Access real estate/, **Summit**/summit 2 condominium/, **Bole-Arabessa**/project 15 construction site/, **Yeka-Ayat-**II/Kiber-Demena church/, **Megenagna**/opposite to AMCE/, **Bole-Bulbula**/left side of the road when driving from Bole Michael to Bulbula/, **Mekanissa-Jemo**/in front of Haile Garment or Rivera Hotel/, **Goffa**/Goffa Gabrael/, and Akaki/Tirunesh-Beijing Hospital/. The required data/samples from those locations are collected and analyzed in the laboratory.

Moreover, important data for this paper work have also been collected from past research works, A.A City government-Housing Development project office, and EiABC's/Ethiopian institute of Architecture, Building Construction and City planning/ soil laboratory records.

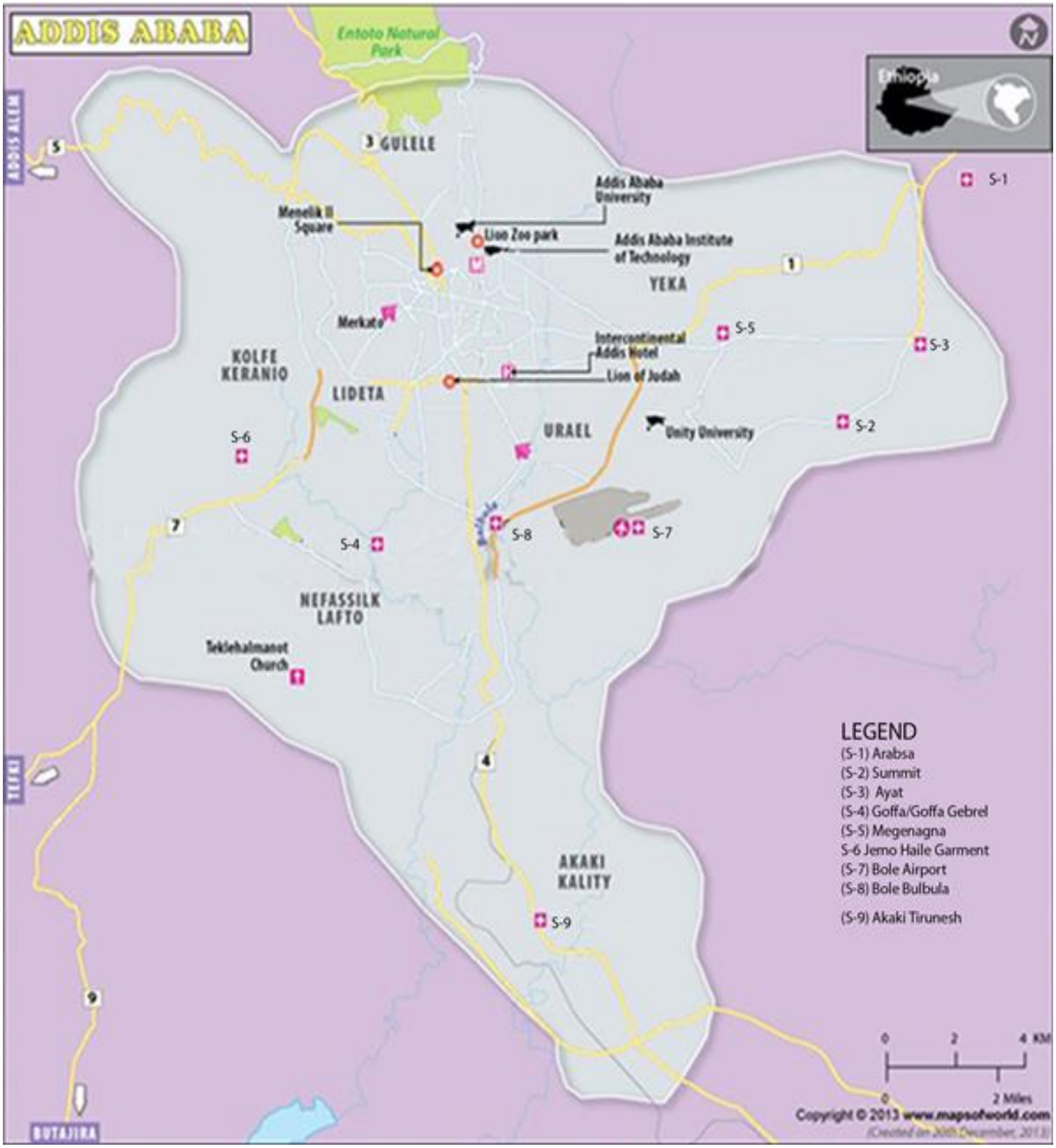

Figure 2:- Google Map of Addis Ababa showing location of the Research area

3.2.2. LABORATORY TEST RESULTS

The summarized laboratory results of the selected tests such as Atterberg limit, grain-size analysis, swelling potential according to Eq. 3.1 [5], free swell, swelling pressure, unconfined compressive strength, and natural moisture content are presented here in Table 3 to show all relevant result that determine the selection of safe and economical type of foundation for expansive areas of those localities in Addis Ababa.

$$\mathbf{S = 0.23P_I - 3.12} \qquad (3.1)$$

Where S = Swelling Potential

P_I = Plasticity Index

Table 3:- Summary of laboratory test results on selected study area [*Laboratory test has been performed by EiABC's Soil Laboratory Staffs under my close follow up but the selected results which exhibits the properties of Expansive soil has been collected for this paper work*]

Site No	Locations	L_L (%)	P_L (%)	P_I (%)	Swelling Potential (%)	Deg. Expansiveness	Free Swell (%)	Swelling Pressure	UCS, Qu (kPa)	Cu (KPa)	NMC (%)
S1	Arabessa	115	45	69	13	V. High	205	391	231	115	46
S2	Summit	97	47	50	8	V. High	155	296	160	80	45
S3	Ayat	88	38	50	9	V. High	175	334	188	94	43
S4	Goffa	91	48	43	7	High	91	174	148	74	45
S5	Megenagna	103	38	64	12	V. High	100	191	155	77	43
S6	Jemo-Mek	74	38	36	5	High	90	172	137	69	46
S7	B. Bulbula	73	38	35	6	High	165	315	168	84	43
S8	B. Air Port	102	40	62	11	V. High	195	357	161	80	42
S9	Akaki	68	34	34	5	High	78	148	94	47	30

3.2.3. SUMMARY OF COLLECTED DATA

Available data as reported by earlier researchers are tabulated in Table 4 and Table 5 below.

Table 4:- The Range of Values of Laboratory Test Results of Addis Ababa Expansive Soils by Various Researchers [10].

RESEARCHERS	L_L (%)	P_L (%)	P_I (%)	Clay Content (%)	Free Swell (%)	Swelling Pressure (KPa)	Shrinkage Limit	Specific Gravity
Yehaise H. 2001	98-104	27-33	69-72	10-14	70-110	-	-	2.63-2.85
Solomon Y. 1983	87-115	15-35	72-90	40-70	90-170	94-235	-	-
Alemayehu & Solomon 1986	87-123	15-35	68-93	40-70	90-170	94-251	8-13	2.48-2.78
Alemayehu T. & Mesfin L. 1999	89-120	-	55-90	50-80	23-90	-	-	-
Mesfin Kassa 2005	93-100	25-27	57-73	70-75	97-114			
Afework Sisay 2004	102-116	42-62	46-71	60-	60-120	-	7-28	2.37-2.75
Tekelu Daniel 2003	79-121	25-50	38-84	48-82	64-140	-	-	-
Legesse (2004) & Daniel (2003)	96-109	24-48	55-77	45-80	75-140	108-420	3-10	2.76-2.85
Ayenew & Mesfen (2011)						150-450		
H/Mariam G. 2015	68-122	34-48	34-74		78-205	148-390		

Moreover, for the pile design due to limitation of the field SPT test data, some practical data are incorporated in Table 5.

Table 5:- Soil test results with borehole logs [10]

Site	Depth (m)	SPT Value	Depth (m)	L_L (%)	P_L (%)	P_I (%)	Free Swell (%)	Specific Gravity
Ayer Tena	0.00-1.50		2.70	53.10	31.35	21.75	40.00	2.51
	1.50-6.10	17						
	6.10-12.00	>50						
Mekanisa	0.00-2.20		2.70	110.1	45.45	64.26	100.00	2.62
	2.20-9.00	8 -14.0						
	9.00-10.00	41						
Kirkos	0.00-1.60		3.00	97.00		64.00	200.00	
	1.60-5.00	10						
	5.00-6.00	21						
	6.00-10.00							
Lideta	0.00-2.00		3.00	79.10	38.41	40.69	90.00	2.49
	2.00-7.20	10-16.0						
	7.20-15.00							
Kality	0.00-3.00	7	2.80	88.90	44.73	44.17	120.00	2.45
	3.00-8.00	11						
	8.00-10.30	>50						
Bole	0.00-3.00	9.0-11	3.00	98.00	49.06	48.94	140.00	2.65
	3.00-6.50	13						
	6.50-7.90							
	7.90-10.00							

CHAPTER FOUR

4. DETERMINATION OF DESIGN PARAMETERS

4.1. GENERAL

Since structural solutions are the most effective way of minimizing or eliminating heave damages of the structures due to swelling characteristics of the soil underneath the foundations, these solutions start with the determination of some important parameters from soil test in the laboratory or in the field. These are cohesion (c), angle of internal friction (ϕ), depth of ground water table, swelling potential of the soil, unit weight of the soil (γ) and N-values of standard penetration test (SPT) value [4]. These values, in combination with the reaction from the super-structural load and certain given factor of safety are used to determine the safe/allowable bearing capacity of the soil for both shallow and deep foundations. The bearing capacity determination can be done both for initial and final conditions.

A Software has been developed for the selection of foundation types on expansive soil of Addis Ababa by giving due consideration to the swelling pressure and comparing it with either contact pressure for shallow foundation or skin resistance for deep foundation.

4.2. DETERMINATION OF DESIGN PARAMETERS FOR SHALLOW FOUNDATIONS

4.2.1. DESIGN PARAMETERS FOR FOOTING FOUNDATIONS

i. **Based on analytic equation**

In general**,** the ultimate bearing capacity of the soil under a footing may be computed using the following equation: -

$$Q_{ult}= C*N_c d_c S_c i_c + (q)*N_q\, d_q S_q i_q + (0.5\gamma B)*N_\gamma d_\gamma S_y i_y \quad (4.1a)$$

Q_{ult} = Ultimate bearing capacity of footing

c = Cohesion

B = Width of footing

q = γ'D =Effective surcharge at the base level of the footing.

γ' = effective unit weight of soil

N_c, N_q, N_γ = Bearing capacity factor

S_c, S_q, S_γ = Shape factors

d_c, d_q, d_γ = Depth factors

i_c, i_q, i_γ = Inclination factors

Noting that c = 0.5q_u, Meyerhof's bearing capacity equation for initial (ϕ_u) condition becomes

$$Q_{ult} = C^*N_c d_c S_c i_c + (q)^*N_q d_q S_q i_q \qquad (4.1b)$$

The allowable bearing capacity, Q_{all} is obtained by dividing Q_{ult} by a reasonable safety factor.

$$Q_{all} = Q_{ult}/F.S \qquad (4.2)$$

For initial conditions, according to EBCS 7-1995 [13], the bearing capacity equation is: -

$$R_d = (2+\pi)^* c_u s_c + q \ \ldots\ldots\ldots\ldots \text{with } c_u = c_{uk}/_{\gamma m} \qquad (4.3)$$

Where

R_d = the design bearing resistance

q = the design total over burden pressure at the level of the foundation base

c_u = the design value of the undrained shear strength

c_{uk} = the characteristic undrained shear strength

$_{\gamma m}$ = the safety factor for the ground property = 1.7

S_c= the design value of the dimensionless shape factor due to cohesion =1.2 for a square footing

ii. Bearing Capacity determination for footing foundation from UCS/Unconfined Compressive strength/

For the determination of bearing capacities, the following ranges of unconfined compressive strength (q_u) for clays and silty clays is recommended and as quoted in [3].

Table 6:-Correlation between the number of blows of the SPT and Consistency [3]

No of blows of SPT(N_{30})	CONSISTANCY		UCS, (q_u) (kN/m^2)
	Descriptions	Ic	
0-2	Slurry	0.00 - 0.50	0-25
2-4	Soft	0.50 - 0.75	25-50
4-8	Medium		50-100
8-15	Stiff	0.75 - 1.00	100-200
15-30	Semi hard	1.0 - Ws	200-400
>30	Hard	W_S – W = 0	>400

Note that consistency Index could be determined using equation 4.4 as follows:-

$$I_c = (w_l - w) / I_p \tag{4.4}$$

Where $I_p = w_l - w_p$ = plasticity index,

w = moisture content

w_l = liquid limit

w_p = plastic limit.

Using the above range of values in conjunction with the borehole log description in Table 7, the shear strength parameters for the sites considered are determined. The undrained cohesion, c_u is obtained from the value of unconfined compressive strength, q_u. The shear strength parameters determined and used for design are shown in Table 7.

Table 7:- Shear Strength parameters used for design [10]

SITE	Description of soil (from bore logs)	Initial condition (Unconfined Compression)		Final condition (Consolidated-drained Condition)		Remarks
		c_u (kPa)	ϕ_u (deg)	c' (kPa)	ϕ' (deg)	
Ayer Tena	Stiff to hard Silty clay	150	0	0	30	Medium Expansive
Mekanisa	Medium stiff to stiff grey plastic clay	50	0	0	22	Highly Expansive
Kirkos	Stiff moderately plastic clay	75	0	0	22	Highly Expansive
Lideta	Medium stiff, light brownish to grey expansive silty clay	50	0	0	25	Highly Expansive
Kality	Medium plastic clay	50	0	0	24	Highly Expansive
Bole	Stiff brownish plastic silty clay	75	0	0	23	Extremely High Expansive

iii. From N-values of SPT data, Meyerhof proposes [8]

$$Qp = q_p * Ap \qquad (4.5)$$

Where:-

$$q_p = (40*N)*(L_b/B) < (400*N) \qquad (4.6)$$

N = Average of the SPT numbers in a zone of about 8B above to 3B below of the pile tip.

L_b/B = average depth ratio of point to point bearing stratum, may be less than the actual L/B in stratified soils and B = width or diameter of the pile

Generally, one should take care for different values of bearing capacity for the design of the foundations. The smaller value of the bearing capacity determined is used for the sake of safety among values from different methods of bearing capacity determination.

The next parameter that needs to be determined is the swelling pressure of the soil. For the purpose of this research, values of swelling pressures are taken from previous research works as presented in Table 8.

Table 8: - Design parameters for isolated footing and wall foundations

Site	Descriptions of Soil	Q_{all} (Meyerhof) (kPa)	Q_{all} (ESCP) (kPa) [12]	Swelling pressure (from previous works) (kPa)
Ayer Tena	Stiff to hard silty clay	320	375	50
Mekanisa	Medium stiff to stiff plastic clay	120	160	108
Kirkos	Stiff moderately plastic clay	170	215	125
Lideta	Medium stiff, light brownish to grey expansive silty clay	118	150	205
Kality	Medium stiff, grey silty clay with some sand	120	160	108
Bole	Stiff brown plastic silty clay	170	214	300

4.2.2. DESIGN PARAMETERS FOR SLAB-ON-GROUND

Most of the slab-on-ground foundation types are employed for case, where the swelling potential is considered to be minimal. These slabs are constructed with minimum reinforcement. It should be emphasized that the function of slab-on-ground foundation is to resist small amount of heave that might occur beneath a slab foundation.

4.2.3. DESIGN PARAMETERS FOR MAT FOUNDATIONS

A. Bearing Capacity of Mat Based on Conventional Method

The mat foundation must be designed to limit settlements to a tolerable amount and must be stable against a deep shear failure, which may result in either a rotational failure or a vertical (or punching) failure. The ultimate bearing capacity of the soil under a mat may be computed using the following equation [8]:-

$$Q_{ult} = C*N_c d_c S_c i_c + \gamma D N_q d_q S_q i_q + 0.5\gamma B N_\gamma S_\gamma i_\gamma d_\gamma \quad (4.7)$$

Where :-

B = least mat dimension and D = depth of mat

The allowable soil pressure is obtained by applying a suitable factor of safety, where the Terzaghi or Hansen bearing capacity factor can be used. The allowable bearing capacity, Q_{all} is obtained by dividing Q_{ult} by a reasonable safety factor.

Since mat foundations typically provide a bridging effect over intermittent soft or erratic spots in the soil, mats are usually not sensitive to differential settlement. Hence the allowable bearing value to be used for design of mat foundation may be somewhat higher than that for spread (isolated) footings.

B. Bearing Capacity of Mat Based on Penetration Result

Based on standard penetration test (SPT), the allowable bearing capacity for an allowable settlement of 50mm may be estimated from [16]: -

$$Q_{all.} = \frac{N_{55} K_d}{F_2} \quad (4.8)$$

Where, $F_2 = 0.08$,

N_{55} = Statistical average of the blow count in the stratum under SPT

$K_d = 1 + 0.33(D/B) < 1.33$

In designing the Mat foundation, the modulus of sub-grade reaction (k_S) needs to be determined while using this software. k_S is a conceptual relationship between soil pressure and deflection that is widely used in the structural analysis of foundation members.

Bowles [8] has suggested for approximate ks, from the allowable bearing capacity as: -

$$k_S = 40*(F.S)*Q_{all} \quad (4.9)$$

Where: -

k_S = Modulus of subgrade reaction

Q_{all} = allowable bearing capacity

F.S = factor of safety used for computation of the allowable bearing capacity varying from 3 to 6. Taking F.S =3.

$$k_S = 40*(F.S)*Q_{all} = 120*Q_{all} \quad (4.10)$$

4.3. DESIGN PARAMETERS FOR DEEP FOUNDATIONS

Deep foundation is installed in the ground to transfer the structural loads to the soil at some significant depth below the base of the structure if the expansive soil is present at the site of a proposed structure. To overcome the problems of shallow foundation, pile foundations may be considered as alternative when piles are extended beyond the active zone. Here, the design parameters for straight piles and under-reamed piles will be discussed.

4.3.1. DESIGN PARAMETERS FOR STRAIGHT PILES

In the computation of design values for piles, the general formula to be used for cohesive soils, including expansive clays, depends on pile resistance development that comes from skin resistance and end bearing resistance. Hence the general formula for the ultimate resistance of pile could be:-

Q_{ult} (Ultimate Resistance) = Skin Resistance + Point/end bearing Resistance

$$Q_{ult} = Q_S + Q_P = fs*As + q_p*Ap \quad (4.11)$$

Where: -

$$Q_S = f_s*A_s = \text{Skin Resistance} \quad (4.12)$$

$$Q_P = q_p*A_p = \text{Point /end bearing/ Resistance} \quad (4.13)$$

A. DETERMINATION OF THE POINT RESISTANCE, Q_P

Point Bearing/Resistance of Pile Based on Bearing Capacity Equation

The soil parameters may be derived from laboratory tests on undisturbed samples but more often from unconfined compression. In general, the point capacity is computed as [8]:-

$$Qp = A_p*q_p \quad (4.14)$$

$$q_p = c*N'_c d_c S_c + \eta*q'*N'_q\, dqSq + 0.5*\gamma' B_p* N'_\gamma*S_\gamma \quad (4.15)$$

Where:-

c = Cohesion of soil beneath pile point (or undrained shear strength s_u)

q_p = tip ultimate bearing capacity of the soil beneath pile tip

Q_p = Ultimate pile tip capacity

B_p = Width/base of pile point (usually used only when point is enlarged), otherwise it can be neglected so N'_γ term in equation is neglected if base is too small.

N'_c = Bearing capacity factor for cohesion adjusted for shape and depth When ϕ= 0 we have C= Su and N'_c = 9. And Use $d_c = 1+0.4*\tan^{-1}(L/B)$

N'_q = Bearing capacity factor (may include overburden effects) and Use $d_q = 1+2*\tan\phi\,(1-\sin\phi)^2 \tan^{-1}(L/B)$

N'_γ = Bearing capacity factor for width/base of foundation= N_γ since it is not affected by depth

q' = effective vertical stress (overburden pressure) at pile point where $q' = \gamma L$ = effective vertical (or overburden) pressure at pile point

η = 1 for all except for the method of Vesic. For Vesic, use $\eta = (1+2K_o)/3$ where Ko = at rest earth pressure coefficient

S_γ = Shape factor

Neglecting the N_γ term as for cohesive soils, the effect of friction in the soil is zero, and making adjustment for pile weight; Bowel has suggested the following equation [8]

$$q_p = (c*N'_c d_c + \eta*q*(N'_q - 1)\, d_q) \qquad (4.16)$$

This equation gives the value N'q=1 for c = s_u and ϕ= 0, the ultimate pile point capacity is [8]

$$Qp = A_p q_p = A_p\,(9\, s_u) \qquad (4.17)$$

Point Bearing/Resistance of Pile Based On Penetration Test (SPT) Datas

From Mayerhof [8] based on Penetration Test (SPT), the point resistance is as indicated below.

$$Qp = Ap*((40*N55)*Lb/B) < Ap*(380*N55)\ldots\ldots\ldots\ldots kN \qquad (4.18)$$

Where:-

Q_P = point resistance in kN

A_P = Area of pile base

N_{55} = Statistical average of the SPT numbers in a zone of about 8B above to 3B below of the pile point.

B = width or diameter of the pile

L_b/B = average depth ratio of point to point bearing stratum, may be less than the actual L/B in stratified soils.

L_b = Penetration depth in the point-bearing stratum, Min. L_b=B

According to Shioi and Fukuri, [8] Pile tip resistance is computed as:-

$$Q_p = q_p*A_p = (3*S_u)*A_p \qquad (4.19)$$

The value of Q_P is in MPa.

B. DETERMINATION OF THE SKIN RESISTANCE, Q_s

Estimating the skin resistance of piles in clay is difficult as compared to sand due to the presence of several variables. Two methods, λ and α are proposed [8, 6].

i. The λ method

Vijayvergiya and Focht as quoted by Bowles [8] assumed that the displacement of soil caused by pile driving results on a passive lateral pressure at any depth and that the average unit skin frictional resistance of a pile for over consolidated clays is:-

$$f_{av} = \lambda * (\sigma_p + 2*Su) \text{ ……….in units of Su} \qquad (4.20)$$

where: -

σ_p =mean effective vertical stress for the entire embedment length, L, σ_p = (A1 + A2 + A3+…)/L where A1, A2, A3… are vertical effective stress distribution areas on the piles

$c_U = S_U$ = mean undrained shear strength (ϕ= 0)

λ = coefficient that changes with the depth of penetration of the pile as per Table 11.

Table 9:-Variation of λ with pile embedment length, L [8]

L (m)	0	5	10	15	20	25	30	35	40	50	60	70	80	90
λ	0.5	0.336	0.245	0.2	0.173	0.15	0.136	0.132	0.127	0.118	0.113	0.11	0.11	0.11

Thus, the total frictional resistance of the pile in cohesive/clay soil may be calculated as:-

$$Qs = p*L*f_{av} \quad (4.21)$$

Where p = perimeter of the pile section, L = pile length and f_{av} = unit frictional resistance

Care should be taken in obtaining the values of σ_p (summation of vertical effective pressure on pile divided by total embedment length of pile) and c_u (weighted average) in layered soil.

ii. The α method [14]

According to α method, the unit skin resistance in clayey soils can be represented by the equation:-

$$fs = \alpha * c_u \quad (4.22)$$

Where α = empirical adhesion factor that depends on σ_p/c_u where σ_p = summation of vertical effective pressure on pile divided by total embedment length of pile and c_u is the cohesion.

$$Qs = \Sigma f*p*\Delta L \quad (4.23)$$

Where f = unit friction, p = perimeter of the pile section and L = pile length.

Both the α and λ method are widely accepted by foundation designers. Hence in this research both methods are used. Whichever gives smaller value shall be used for design.

4.3.2. DESIGN PARAMETERS FOR UNDER-REAMED PILES

The ultimate bearing capacity of an under-reamed pile in direct bearing is determined from [28]:-

$$Q_{ult} = A_p*N*C_p + \alpha*C*A_s \quad (4.24)$$

Where:-

A_p= Area of pie base (X-sectional area of under-reamed bulb) and A_s = Surface area of pile shaft excluding the upper shrinkage crack zone.

N = bearing capacity factor = 9 for expansive and other clayey soils

C = Average undisturbed shear strength of the soil along the pile length

C_p = Undistrubed shear strength of the soil at the pile base

α = Reduction factor, α = 0.5 for double and multi-under-reamed piles and α =1.0 for the portion between the first and the last under-reams.

Generally, the straight and bored piles, if the combined effect of the weight of the dead load and the skin friction does not balance the uplift force due to swelling, the whole pile may be lifted and resulted in structure damage to the building [3]. In order to check the uplift in the pile when the expansive soil acts in tension to pull the pile out, the uplifting force will be determined according to [6] as;

$$\text{Uplift force} = F_u = (\pi * D * Z_a) * K_s * P_s \qquad (4.25)$$

Where:-

D = Diameter of pile

Z_a = Depth of Active Zone

K_s = Uplift coefficient = 0.15

P_s = Swelling Pressure

F_u = Uplifting Force

CHAPTER FIVE

5. SELECTIONS OF FOUNDATION TYPES AND COST COMPARISONS

5.1. GROUPING OF SAMPLE BUILDING FOR THE SELECTION OF DIFFERENT FOUNDATION TYPES

Nowadays most buildings on expansive soil areas of Addis Ababa are both low rise-light weight and high rise-heavy weight buildings. This research work mainly incorporates building structures ranging from (G+1) to (G+16) to address the demand of most project initiators.

This study is a continuation of previous related findings that had grouped the buildings according to aspect ratio for dimensions factor which is the ratio of longest building's width to the height of the building (i.e. X= L/H) [10]. In this research, these buildings are also grouped based on aspect ratio for loads factors ($Y=\mathbf{Q_{sup}/Q_{all}}$) which is the ratio of building's contact pressure ($\mathbf{Q_{sup}}$) over the allowable or safe bearing capacity ($\mathbf{Q_{all}}$) of the foundation soil in addition to the aspect ratio for dimensions factor. Other inputs which are required in addition to the two aspect ratios are the swelling pressure/swelling characteristics of these expansive soil, depth of moisture fluctuation, skin resistance, other functional requirements and cost of construction are considered as input for the selection of safe and economical types of reinforced concrete foundation on expansive soils of Addis Ababa.

Grouping of the proposed buildings with their contact pressure which is super-structural loads over contact area and building height could be considered as: -

Group 1 = $\mathbf{G_1}$ includes G^{+1} to G^{+4} building which has a building height of $3m \leq H \leq 15m$ and a contact pressure of $35\ kPa \leq Q_{sup} \leq 175\ kPa$.

Group 2 = $\mathbf{G_2}$ includes G^{+5} to G^{+8} building which has a building height of $15 < H \leq 27m$ and a contact pressure of $175\ kPa < Q_{sup} \leq 315\ kPa$.

Group 3 = $\mathbf{G_3}$ includes G^{+8} to G^{+12} building which has a building height of $27 < H \leq 39m$ and a contact pressure of $315\ kPa < Q_{sup} \leq 455\ kPa$.

Group = $\mathbf{G_4}$ includes G^{+13} to G^{+16} building which has a building height of $39 < H \leq 51m$ and a contact pressure of $455\ kPa < Q_{sup} \leq 595\ kPa$.

The reason why this research work includes the aspect ratio of loads factor in addition to the previous researchers' aspect ratio of dimensions factor as an additional grouping parameter could be to address how functional requirement for the different building would affect the selection of foundation types. This can be justified as with the same building height, the pressure that is transferred to foundation soil may vary due to purpose of the building. Moreover, aspect ratio for load factor, which needs contact pressure and allowable bearing pressure, can have easy and reliable access for inputs that are required for simple manipulation of the prepared software because contact pressures are collected from related professionals/structural Engineers rather than buildings' height and length that are collected from Architects or project initiator.

5.2.GUIDELINE FOR THE SELECTION OF DIFFERENT FOUNDATION TYPES

The developed software considers only the ranges of X between 0.35 to 2.8 because compartmentation should be required when X is greater than 2.8 and minimum functional floor area is also required to limit the lowest values of X to be 0.35. Moreover, using the value of Y which comprise the contact pressure with allowable bearing pressure, one can easily differentiate at least the proposed foundation would be either shallow foundation type when Y is less or equal to one or deep foundation type when Y is greater than one when the contact pressure is greater than the safe bearing capacity of the soil. However, this is not generally implying that low-rise buildings may always be founded on shallow foundations and high rise buildings may necessarily be founded on deep foundation, but rather to say the governing inputs to classify main foundation types are contact pressure and allowable bearing capacity of the soil which should be collected carefully to reach on a remarkable result. Using additional inputs such as depth of moisture fluctuation, swelling pressure, skin resistance and the other details, one can easily select the safest and economical foundation types on expansive soil of Addis Ababa.

Based on the facts for provision of aspect ratio for load factor, here we can use any building type with proposed location instead of using similar building in every site. In each site, seven different types of reinforced concrete foundations are designed for the range of buildings mentioned above. Under shallow foundations such as footing, the three slab foundation types such as slab-on-grade, uniform mat and ribbed mat foundation are considered. Under deep foundations such as straight shaft, single and double under-reamed pile foundation have been incorporated. This selection could be done in order to check the structural appropriateness of the foundation alternatives.

5.3. FOUNDATIONS' COST COMPARISONS

While in selecting the appropriate type of foundations based on safety issues, the cost issue is also addressed in the selection of foundation types. The prepared software has incorporated the cost issues by having aspect ratio for load factors that would balance the expected foundation decisions which are not only fulfill the safety issues but also incorporates the preliminary cost considerations as well. Moreover, the cost of moisture control for shallow foundation is also incorporated in this software as economical consideration, this can be achieved by comparing the moisture fluctuation depth with two times the depth of foundation. Similarly, in order to control heave in deep foundation selection, the swelling pressure is compared with only the skin resistance for both safety and economical reason.

If one requires detail cost issues of the expected foundation type, it is better to prepare excel sheet for checking detail cost issues for both single and mixed safety issues together with detailed foundation design on expansive soils of Addis Ababa.

5.4. SOFTWARE DEVELOPMENT

5.4.1. GENERAL

In general, using the inputs like longest width of building plan (L), building height (H), contact pressure (Q_{sup}), allowable/safe bearing capacity of the soil (Q_{all}), swelling pressure (P_s), depth of moisture fluctuation (Z), functional requirement and cost of construction, the software developed in this study is used to select the best foundation alternative in terms of safety and economy for any building types with their proposed soil profile conditions which are collected from different genuine and reputable geotechnical laboratories.

A user friendly software is developed using Visual Basic Studio 2015 for having an output based on those collected inputs for safety and preliminary project cost determination. When the Software is started, the window which says "Foundation Recommendation for Expansive Soil" will appear. This window contains different menu like File, Edit, View and Help. File menu contains New, Import, export and Exit. Edit menu helps the user to copy, cut, paste, select all, deselect, and cear all inputs from the dialog box. View menu helps the user to adjust the main window by Normal view, minimized view or to close the window. Under help, user can access user guide and about the software.

5.4.2 PROGRAM ALGORITHM FOR SOFTWARE DEVELOPMENT

In writing the programming codes for developing the software, the Select Case…End Select Control Structure is used in MATLAB 2011.

By using the aspect ratio for dimensions' factor and loads factor of different buildings as a variable, cases are sequentially checked for which a given Y is less than or equal to or greater than one which determine at least the expected foundation would be either shallow foundation or deep foundation categories. The cases are continuing for checking specific foundation type by having inputs such as depth of moisture fluctuation, depth of expected foundation, swelling pressure, skin friction and groupings. The program flow chart for algorithm of the proposed software is presented below.

After the users enter all the input data in the prepared dialog box, the output will be visible with the safest and economical foundation type with its all inputs and calculated results when the user clicks "analyze data".

FLOW CHART FOR PROGRAM ALGORITHM

Figure 3:- **Program algorithm flowchart for software development (Appendix 1)**

CHAPTER SIX

6. DISCUSSIONS

6.1. DISCUSSION ON LABORATORY RESULTS and FOUNDATION RECOMMENDATIONS

Based on the summarized laboratory results (Table 10) which are an input for running the prepared software program for the selection of safe and economical type of foundation, an attempt would be made to clarify the following issues: -

Table 10: -Summary of Laboratory results of different areas under this paper study.

Site No	LOCATIONS	L_L (%)	P_L (%)	P_I (%)	Swelling Potential (%)	Degree of Expansiveness	Free Swell (%)	Swelling Pressure	UCS, Qu (kPa)	Cu (kPa)	NMC (%)
S1	Bole Arabessa	115	45	69	13	V. High	205	391	231	115	46
S2	Bole Summit	97	47	50	8	V. High	155	296	160	80	45
S3	Bole Ayat	88	38	50	9	V. High	175	334	188	94	43
S4	Goffa	91	48	43	7	High	91	174	148	74	45
S5	Megenagna	103	38	64	12	V. High	100	191	155	77	43
S6	Jemo/Mekenissa	74	38	36	5	High	90	172	137	69	46
S7	Bole Bulbula	73	38	35	6	High	165	315	168	84	43
S8	Bole Air Port	102	40	62	11	V. High	195	357	161	80	42
S9	Akaki/Tirunesh	68	34	34	5	High	78	148	94	47	30

i. The ranges of the values of the swelling pressure of expansive soil of Addis Ababa on such selected site vary from 148kPa to 391kPa which are higher in comparison with the presumed designed bearing resistance of the soft to medium cohesive clay soil [Appendix 2], hence the governing factor in design of foundation on such areas could be swelling pressure as equivalent to the bearing capacity of the soil. Ignoring swelling pressure in design of foundation is not acceptable to the safety and economic consideration of the foundation types in Expansive soil of Addis Ababa.

ii. When we see the degree of expansiveness of such expansive soil areas such as Bole Arabessa, Summit, Ayat and Bole Airport are under the category of very high degree of expansiveness, but Goffa, Jemo, Akaki and Bole are under the category of high degree of expansiveness.

Hence using shallow foundation on areas of very high degree of expansiveness, extreme care should be taken and additional heave protection other than structural measure are also required to avoid structural distress due to pressure that comes from these highly expansive soil. Moreover, foundation design on soil with high degree of expansive also needs mixed heave protection specially if there is shallower moisture fluctuation depth when compared to depth of foundation.

iii. Based on the test result on natural moisture content, the unconfined compressive strength and undrained shear strength of soil from under this research areas are purely cohesive clay soil. Hence designers who are engaged in geotechnical investigations and foundation design should be aware of such soil property to recommend project initiators to incorporate prior solution before damage may occur.

6.2. DISCUSSION ON FOUNDATION SELECTION USING PREPARED SOFTWARE

The output of the research has indicated the following points: -

i. Footing foundation is the safest and economical foundation type when the building is categorized as group G_1 and the swelling pressure of the soil is less than the contact pressure. Otherwise economical moisture control is required to use footing foundation for the soil having swelling pressure higher than the contact pressure under similar building group because the additional cost for moisture control could be compensated with the saving for future maintenance. If there is uneconomical to increase the depth of footing to the bottom of the active zone or to control moisture for footing foundation to carry buildings under group G_1, the conditions forced to select uniform mat foundation rather than footing foundation to protect building's structures from differential movement.

ii. The result for the slab foundation type shows that ribbed mat foundation has more stiffness when higher swelling pressure is greater than the building's contact pressure under building group G_2 and if there is a difficulties of controlling moisture in that specific area. Here the ribbed mat foundation can be more preferable than uniform mat foundation to provide additional stiffness for thin concrete slab foundation with ribbed beams where the soil possesses large amount of movements. Whereas uniform mat foundation is the safest and economical selection of foundation types if swelling pressure from expansive soil of

Addis Ababa is less than contact pressure of the building under group G_2 by providing the economical moisture mechanism for either the moisture fluctuation depth is higher or less than the depth foundation. Moreover, if there is a shallower depth of expansive soil below foundation level that cause very high swelling pressure, the economical decision could be using uniform mat foundation together with removal of expansive soil and replacement by a granular fill material instead of using ribbed mat foundation because the sum of confining pressure created by fill material and contact pressure from the building exceeds the previous swelling pressure.

iii. The result for the deep foundation for building group G_2 is the safest and economical selection rather than any shallow foundation options when the soil has very high swelling pressure and if there is uneconomical moisture control mechanism for ribbed mat foundation. Hence we can select straight shaft pile if the given high swelling pressure is less than the skin resistance, otherwise double under-reamed piles are the safest and economical option to resist uplift force when the swelling pressure is still greater than the skin resistance of the pile.

iv. The result of deep foundation for building group G_3 or G_4 has given straight shaft pile or under-reamed piles for both safety and economical considerations where buildings are founded in deep layers of expansive soil. When the swelling pressure is less than the skin resistance of the pile, straight shaft pile is economical than the under-reamed piles. If the deep layers of expansive soil have carried building under group G_3, single under-reamed piles are more economical than double under-reamed piles even if the swelling pressure is greater than the skin resistance of the piles. Otherwise double under-reamed piles are the safest foundation option when the deep layers of expansive soil have carried building under group G_4.

v. For economical considerations, non-structural heave protections like moisture controls are also be included in development of the software in addition to structural foundation options which can placed on or within the given moisture fluctuation depth to resist differential volume changes and/or to prevent uplift of the supported buildings.

vi. However, the depth of moisture fluctuation has given a significant difference in selection of shallow foundation types on expansive soil, the provision of moisture control for foundation selection can bring similar result based on safety considerations if the moisture fluctuation depth is either higher or lower than depth of foundation.

vii. If light weight building has been founded on the soil that has very high swelling pressure due to shallower depth of moisture fluctuation when compared to building's contact pressure, deep foundation is more economical than provision of moisture controls because piles with sufficient length can develop upholding force which resist the uplifting forces due to swelling of expansive soils in the upper zone.

viii. Generally, if the aspect ratio for dimension factor is between 0.35 and 2.8 and the proposed building is group under G_1 or G_2, it can be concluded that footing foundation could be selected if the swelling pressure is less than or equal to 175kPa, uniform mat foundation could be selected if the swelling pressure varies between 175 to 315kPa and ribbed mat foundation could be selected if the swelling pressure is greater than 315kPa. However, if the swelling pressure is greater than or equal to 315kPa with above similar conditions, deep foundation is more economical than ribbed mat foundation when the cost of moisture control is high to use ribbed foundation.

CHAPTER SEVEN

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. CONCLUSIONS

As per the prepared software and collected laboratory test results on specific localities of Addis Ababa, the following point may be concluded: -

- The developed software with particular application provides a simple, quick, and accurate selection of safe and economical types of reinforced concrete foundation for different buildings constructed on expansive soils of Addis Ababa.
- The developed software is also important to study how the depth of moisture fluctuation can affect the result in selection of foundation types on Expansive soil and economical provision of moisture control can solve the problem of swelling soil.
- Foundation selection on expansive soil of Addis Ababa where the swelling pressure ranges from 148kPa to 391kPa shall comply with the design criteria that prevent the uplift of the supported structure and resist the force exerted on the foundation due to volume changes.
- Generally, the guidance and information provided in this study can be an essential tool for users in the selection of economical foundation during geotechnical investigations for light and heavy multi-story buildings constructed on expansive soil of Addis Ababa to reduce the risk of undesirable and severe damages, and moreover it helps to avoid future maintenance cost of the buildings.

7.2. RECOMMENDATIONS

The program developed provides for quick selection of safe and economical foundations type in expansive soils of Addis Ababa. To extend the program and to be used as an industrial software for the selection and design of foundations, it is recommended to include structural design and provision of other required soil parameters.

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Appendix 1:- FLOW CHART FOR PROGRAM ALGORITHM

Appendix 2:- PRESUMED DESIGN BEARING RESISTANCE UNDER VERTICAL STATICAL LOAD [EBCS-7, PAGE 72]

ETHIOPIAN BUILDING CODE STANDARD FOR FOUNDATIONS

Table 6.3 Presumed Design Bearing Resistances* under Vertical Static Loading

Supporting Ground Type	Description	Compactness**or Consistency***	Presumed Design Bearing Resistance (KPa)	Remarks
Rocks	Massively crystalline igneous and metamorphic rock (granite, basalt, gneiss)	Hard and sound	5600	
	Foliated metamorphic rock (slate, schist)	Medium hard and sound	2800	
	Sedimentary rock (hard shale, siltstone, sandstone, limestone)	Medium hard and sound	2800	These values are based on the assumptions that the foundations are carried down to unweathered rock
	Weathered or broken-rock (soft limestone)	Soft	1400	
	Soft shale	Soft	850	
	Decomposed rock to be assessed soil			
Non-cohesive Soils	Gravel, sand and gravel	Dense Medium dense Loose	560 420 280	Width of foundation *(B)* not less than 1 m
	Sand	Dense Medium dense Loose	420 280 140	Ground water level assumed to be depth not less than *B* below the base of the foundation.
Cohesive soils	Silt	Hard Stiff Medium stiff Soft	280 200 140 70	
	Clay	Hard Stiff Medium stiff Soft Very soft	420 280 140 70 Not Applicable	

* The given design bearing values do not include the effect of the depth of embedment of the foundation

** Compactness: dense: $N > 30$,
medium dense: N is 10 to 30
loose: $N < 10$, where N is standard penetration value

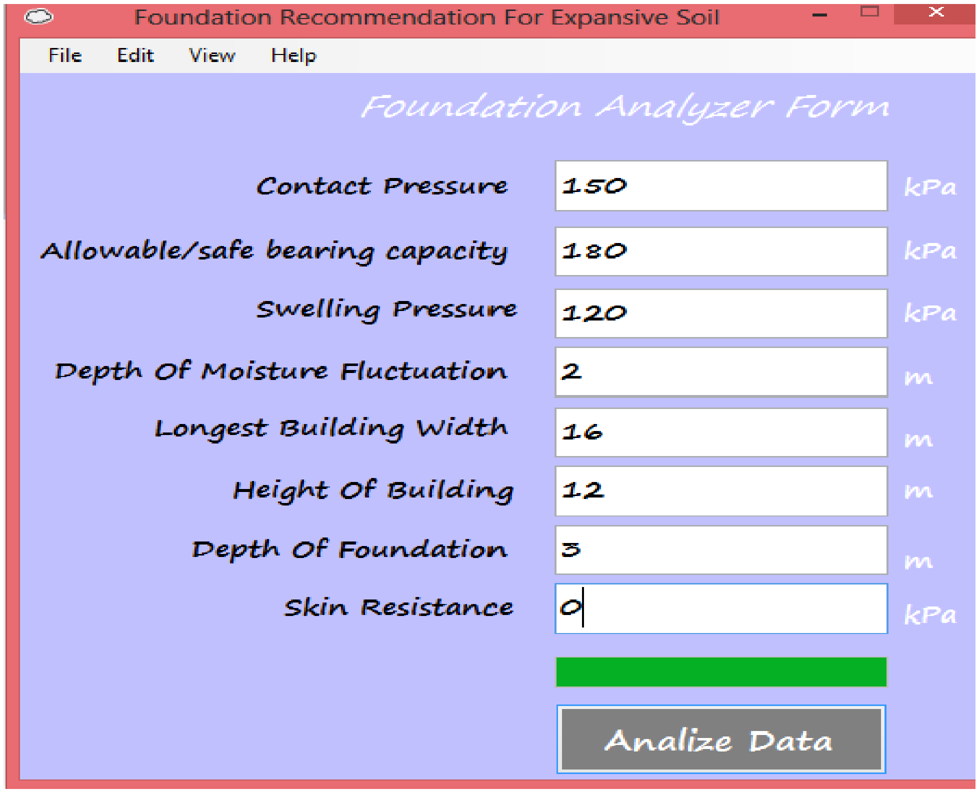
*** Consistency: hard: $q_u > 400$ kPa,
stiff: = 100 to 200 kPa
medium stiff: $q_u = 50$ to 100 kPa
soft: $q_u = 25$ to 50 kPa, where q_u is unconfined compressive strength

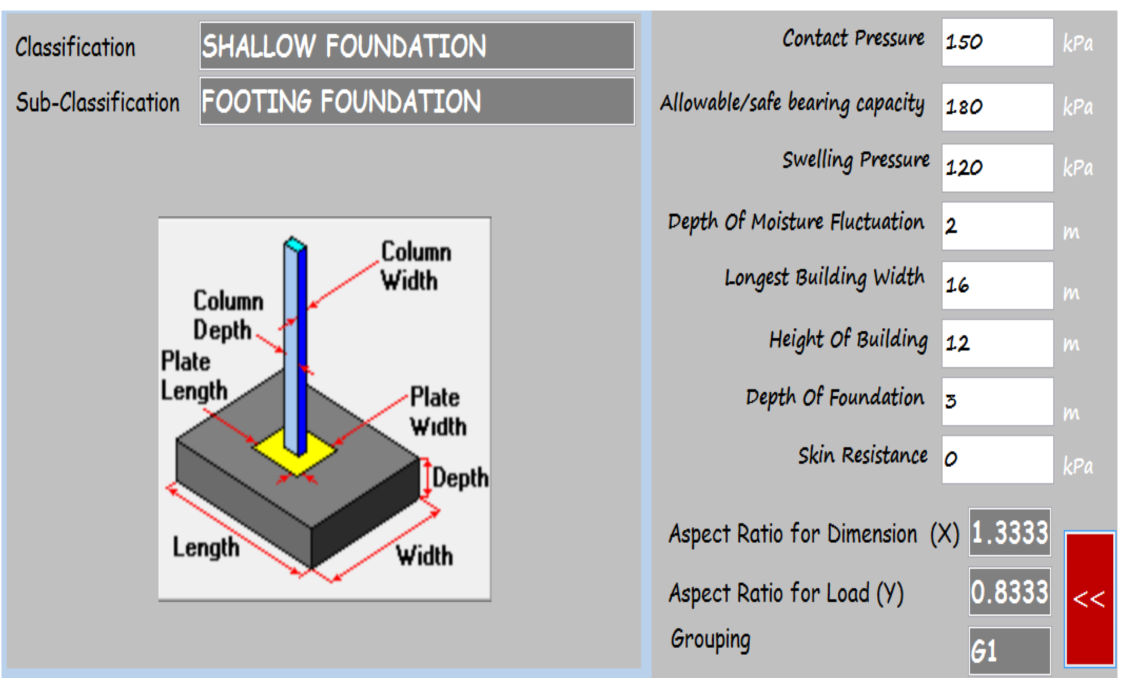
Appendix 3:- SUMMARY OF LABORATORY RESULT [EIABC LABORATORY]

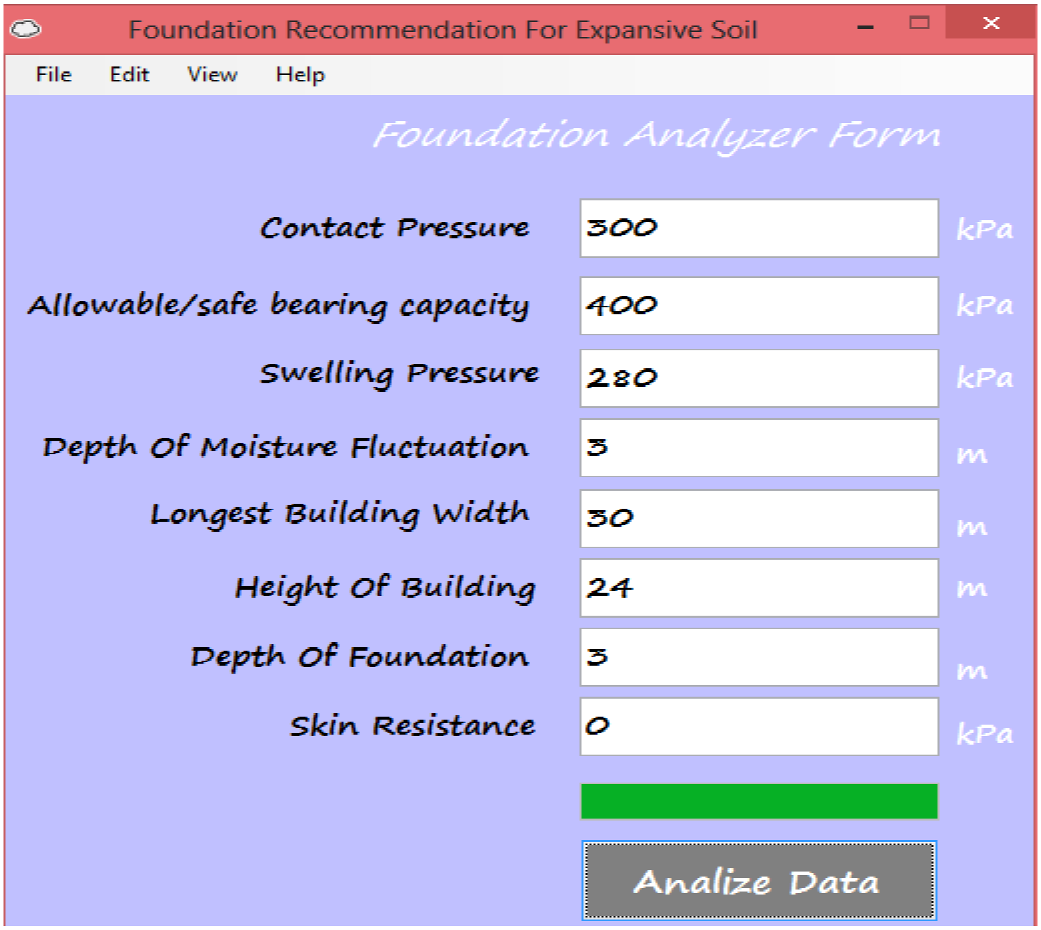
This Appendix 1 contains the following representative laboratory test results are attached with this research paper with their all necessary input and output which are shown clearly.

- **A. One dimensional swell-consolidation tests**
- **B. Unconfined Compression tests**
- **C. Free Swell Tests**
- **D. Atterberg Limits**

Appendix 4: - SOFTWARE'S OUTPUT FOR FOUNDATION RECOMMENDATION AMONG DIFFERENT REINFORCED CONCRETE FOUNDATION S (*Using Visual Basic Studio 2015*)



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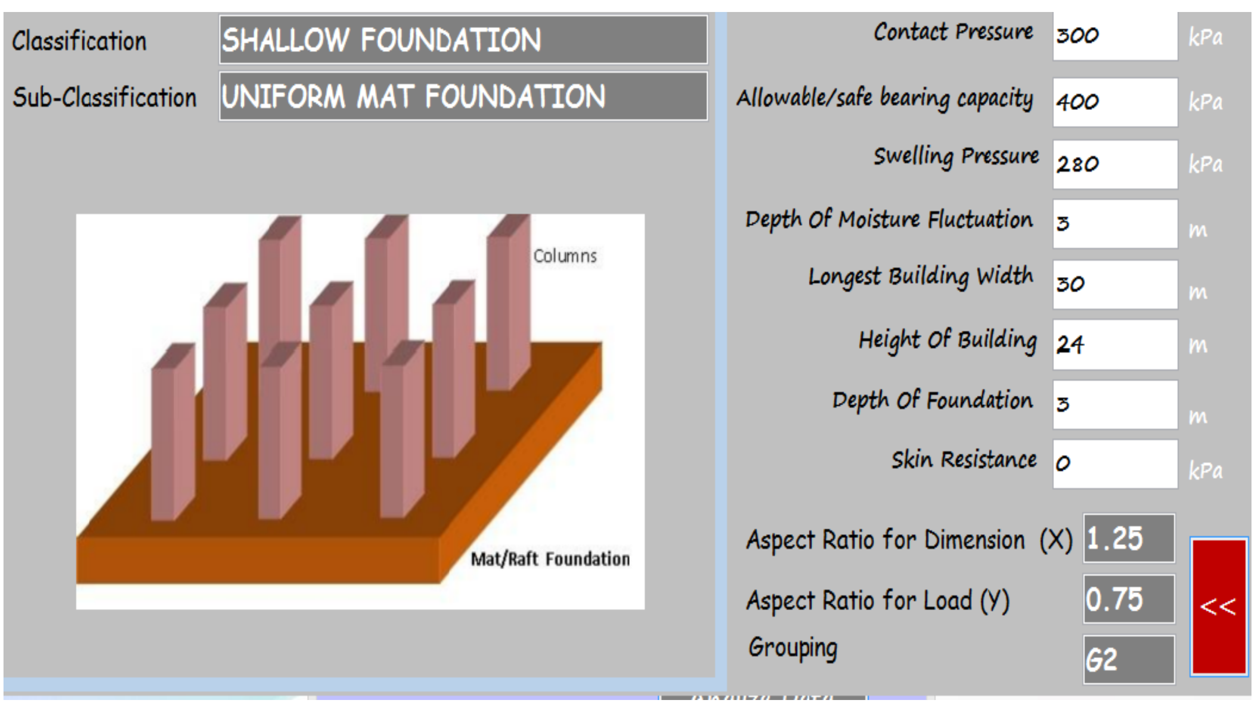
File
Edit
View
Help
Foundation Analyzer Form
Contact Pressure
300
kPa
Allowable/safe bearing capacity
400
kPa
Swelling Pressure
280
kPa
Depth Of Moisture Fluctuation
3
m
Longest Building Width
30
m
Height Of Building
24
m
Depth Of Foundation
3
m
Skin Resistance
0
kPa
Analize Data


Classification
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Sub-Classification
UNIFORM MAT FOUNDATION
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Mat/Raft Foundation
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Allowable/safe bearing capacity
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kPa
Swelling Pressure
280
kPa
Depth Of Moisture Fluctuation
3
m
Longest Building Width
30
m
Height Of Building
24
m
Depth Of Foundation
3
m
Skin Resistance
0
kPa
Aspect Ratio for Dimension (X)
1.25
Aspect Ratio for Load (Y)
0.75
Grouping
G2
<<


Foundation Recommendation For Expansive Soil
File
Edit
View
Help
Foundation Analyzer Form
Contact Pressure
300
kPa
Allowable/safe bearing capacity
400
kPa
Swelling Pressure
350
kPa
Depth Of Moisture Fluctuation
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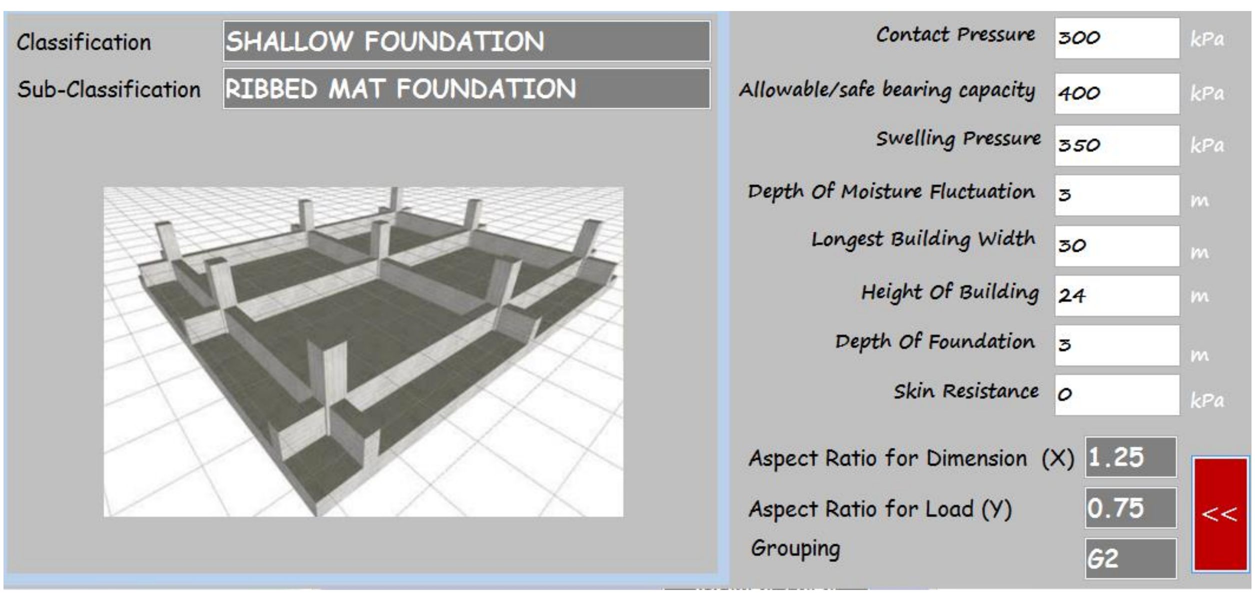
m
Longest Building Width
30
m
Height Of Building
24
m
Depth Of Foundation
3
m
Skin Resistance
0
kPa
Analize Data


Classification
SHALLOW FOUNDATION
Sub-Classification
RIBBED MAT FOUNDATION
Contact Pressure
300
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Allowable/safe bearing capacity
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kPa
Swelling Pressure
350
kPa
Depth Of Moisture Fluctuation
3
m
Longest Building Width
30
m
Height Of Building
24
m
Depth Of Foundation
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Aspect Ratio for Load (Y)
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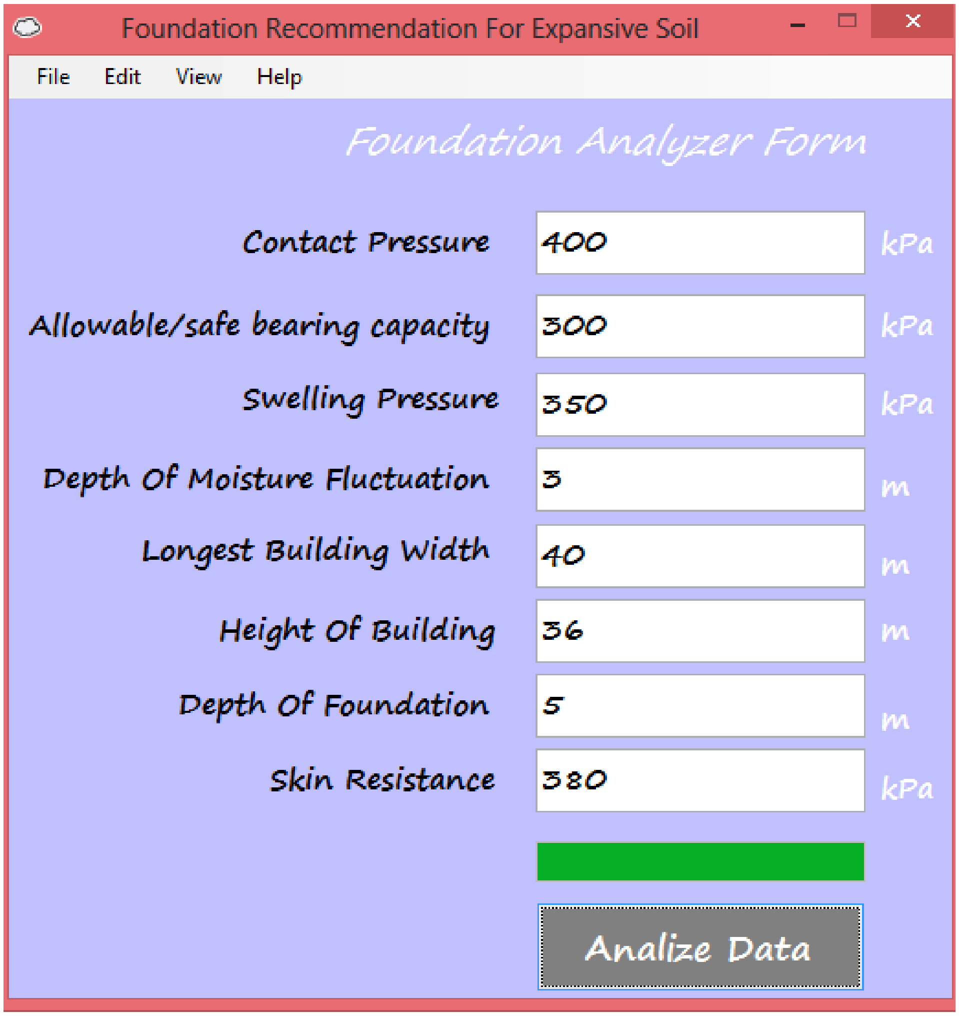
Grouping
G2
<<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Allowable/safe bearing capacity
300
kPa
Swelling Pressure
350
kPa
Depth Of Moisture Fluctuation
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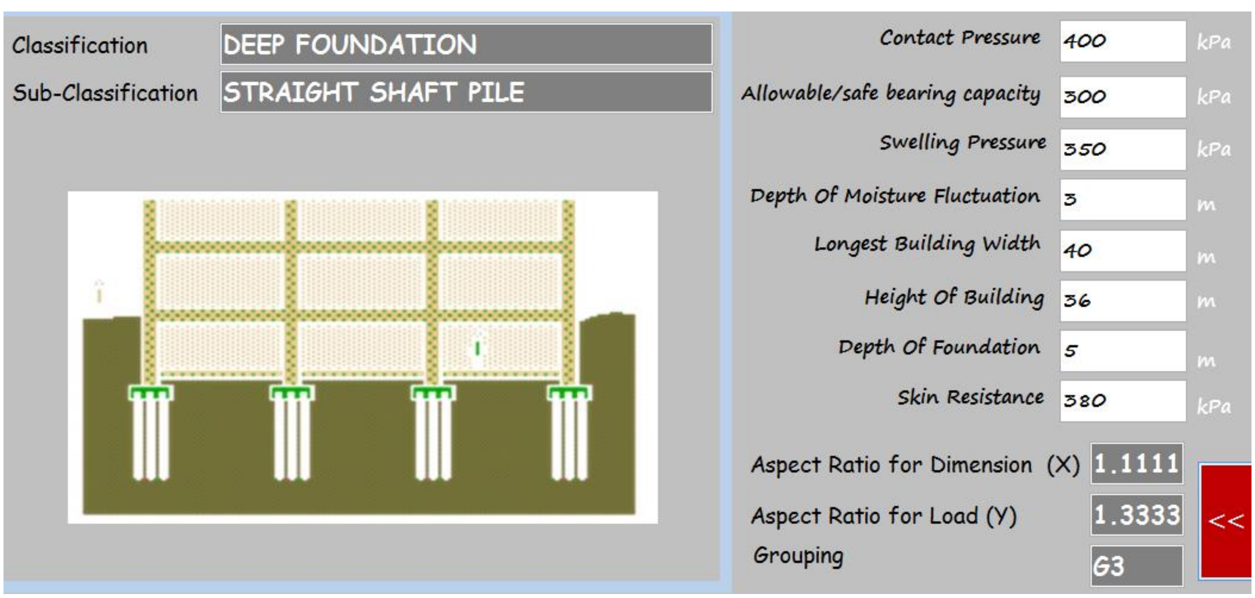
Height Of Building
36
m
Depth Of Foundation
5
m
Skin Resistance
380
kPa
Analize Data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DEEP FOUNDATION
Sub-Classification
STRAIGHT SHAFT PILE
Contact Pressure
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Allowable/safe bearing capacity
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kPa
Swelling Pressure
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kPa
Depth Of Moisture Fluctuation
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m
Longest Building Width
40
m
Height Of Building
36
m
Depth Of Foundation
5
m
Skin Resistance
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kPa
Aspect Ratio for Dimension (X)
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Aspect Ratio for Load (Y)
1.3333
Grouping
G3
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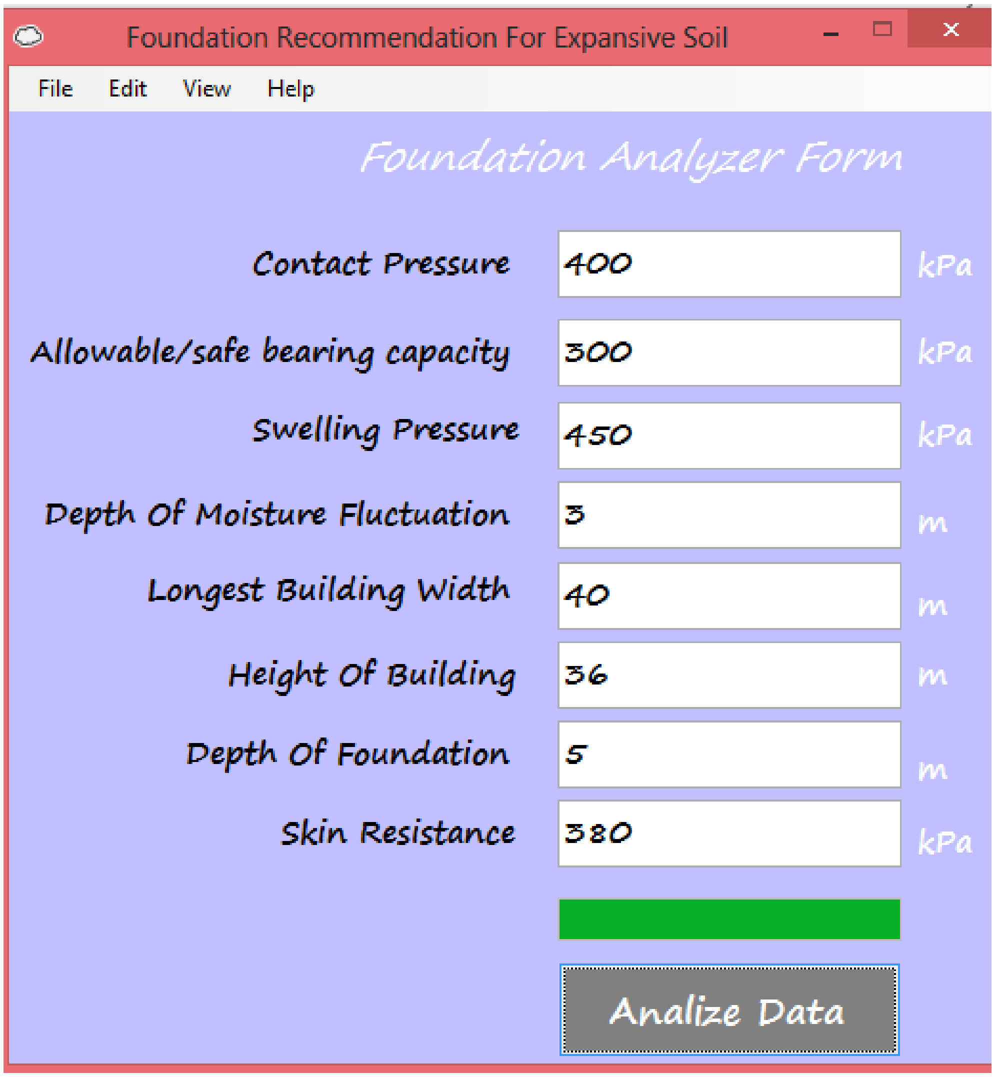
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Foundation Analyzer Form
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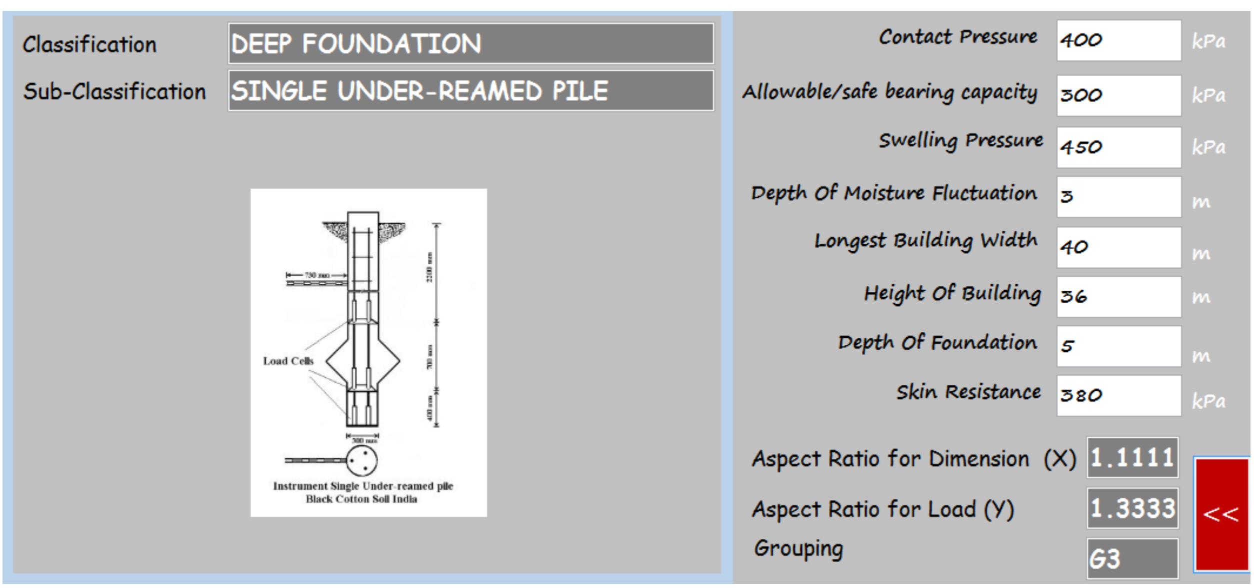
kPa
Allowable/safe bearing capacity
300
kPa
Swelling Pressure
450
kPa
Depth Of Moisture Fluctuation
3
m
Longest Building Width
40
m
Height Of Building
36
m
Depth Of Foundation
5
m
Skin Resistance
380
kPa
Analize Data


Classification
DEEP FOUNDATION
Sub-Classification
SINGLE UNDER-REAMED PILE
Load Cells
Instrument Single Under-reamed pile
Black Cotton Soil India
Contact Pressure
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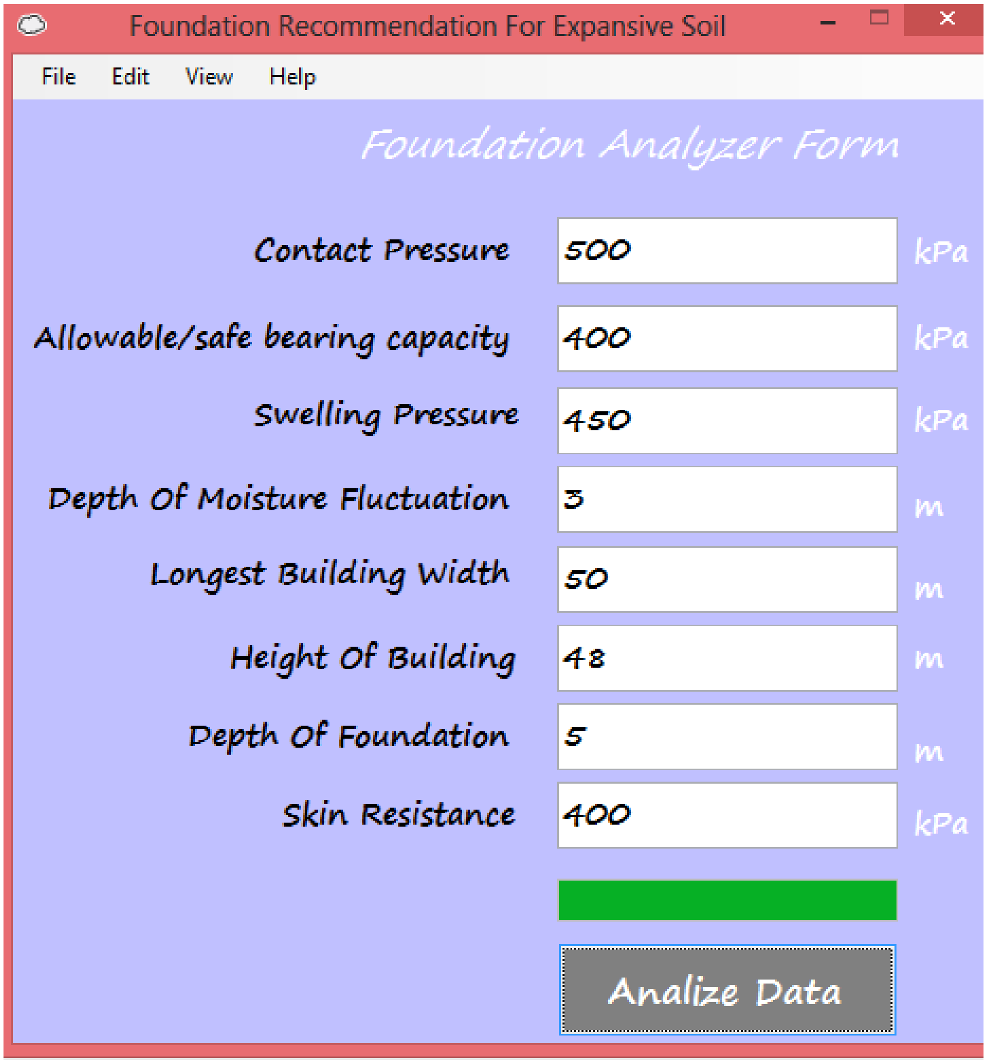
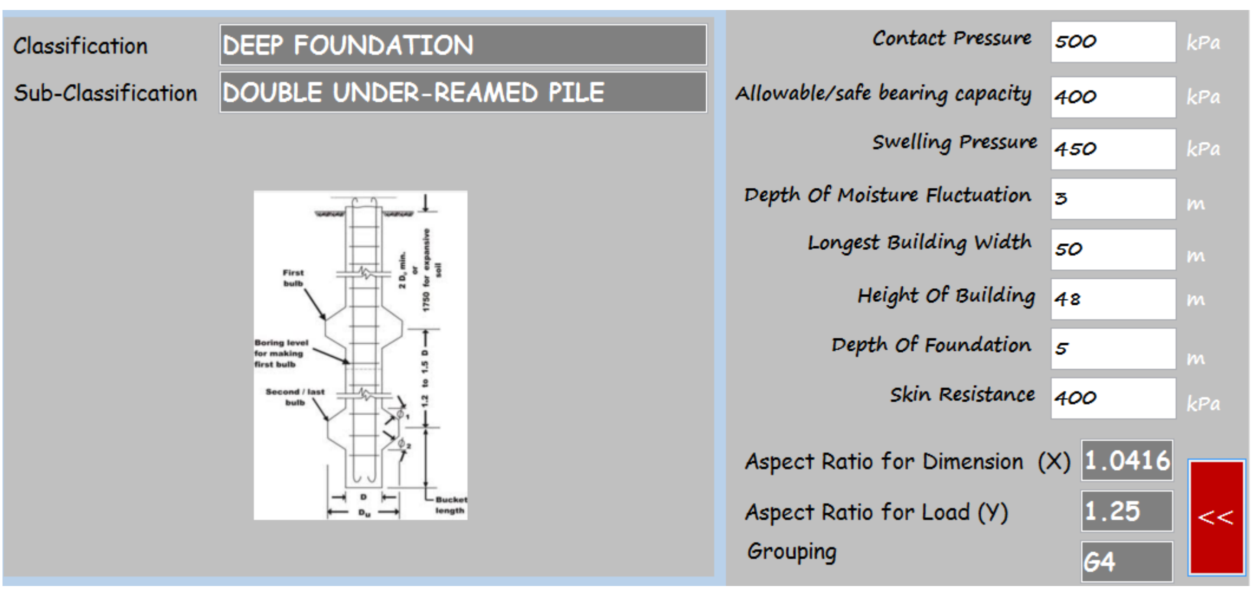
kPa
Allowable/safe bearing capacity
300
kPa
Swelling Pressure
450
kPa
Depth Of Moisture Fluctuation
3
m
Longest Building Width
40
m
Height Of Building
36
m
Depth Of Foundation
5
m
Skin Resistance
380
kPa
Aspect Ratio for Dimension (X)
1.1111
Aspect Ratio for Load (Y)
1.3333
Grouping
G3
<<


Foundation Recommendation For Expansive Soil
File
Edit
View
Help
Foundation Analyzer Form
Contact Pressure
500
kPa
Allowable/safe bearing capacity
400
kPa
Swelling Pressure
450
kPa
Depth Of Moisture Fluctuation
3
m
Longest Building Width
50
m
Height Of Building
48
m
Depth Of Foundation
5
m
Skin Resistance
400
kPa
Analize Data


Classification
DEEP FOUNDATION
Sub-Classification
DOUBLE UNDER-REAMED PILE
First bulb
Boring level for making first bulb
Second / last bulb
Bucket length
Contact Pressure
500
kPa
Allowable/safe bearing capacity
400
kPa
Swelling Pressure
450
kPa
Depth Of Moisture Fluctuation
3
m
Longest Building Width
50
m
Height Of Building
48
m
Depth Of Foundation
5
m
Skin Resistance
400
kPa
Aspect Ratio for Dimension (X)
1.0416
Aspect Ratio for Load (Y)
1.25
Grouping
G4
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