SIMULATION OF PLATE LOAD TEST USING FINITE ELEMENT METHOD

Abenezer Gebremariam Midksa

A Thesis Submitted to 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 (Geotechnical Engineering)

Office of Graduate Studies

Adama Science and Technology University

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Approval sheet

I, the advisor of the thesis entitled **"Simulation of Plate Load Test Using Finite Element Method"** and developed by **Abenezer Gebremariam Midksa**, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Srikanth Vadlamudi (Ph.D.)	____________________	_______________
Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by **Abenezer Gebremariam Midksa** have read and evaluated the thesis entitled **"Simulation of Plate Load Test Using Finite Element Method"** 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).

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Declaration

I hereby declare that this Master Thesis entitled **"Simulation of Plate Load Test Using Finite Element Method"** 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.

Abenezer Gebremariam Midksa	______________________	_______________
Name of the student	Signature	Date

Recommendation

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled **"Simulation of Plate Load Test Using Finite Element Method"** prepared under my guidance by **Abenezer Gebremariam Midksa** submitted in partial fulfillment of the requirements for the degree of Mater's of Science in Civil Engineering (Specialization in Geotechnical Engineering). Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Srikanth Vadlamudi (Ph. D)	________________________	________________
Major Advisor	Signature	Date

ACKNOWLEDGEMENT

I would like to express my sincere and deepest gratitude to my advisor Dr Srikanth vadlamudi for his critical comments, suggestions in guiding and supervising throughout all my research work. Also, I would like to extend my deepest appreciation for Adama Science and technology university civil engineering staff member for their hard work and all their support throughout my studies.

Above all I am very thankful to the Almighty God, who is always with me in each and every step of my life. I thank God for everything He did and made education compatible with the rest of my life. Finally, I would like to express my deepest gratitude to my parents, my friends and all who contributed to this research work in one way or another.

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ABBREVATONS

B: Least Lateral Dimension or Width of plate (m)

D: Least Lateral Dimension or diameter of plate (m)

C: Cohesion of Soil (kN/m^2)

Φ: Angle of Internal Friction of Soil (Degree)

Ψ: Dilatancy Angle of Soil (Degree)

γ: Bulk Density of Soil (kN/m^3)

γ_{dry}: Dry Density of Soil (kN/m^3)

γ_{sat}: Saturated Density of Soil (kN/m^3)

E: Youngs Modulus of Elasticity of Soil (kN/m^2)

v: Poisson Ratio of Soil

D_f: Foundation Depth (m)

K_o: Earth Pressure Coefficient at Rest

σ_v: Total Vertical Pressure (kN/m^2)

σ_h: Total Horizontal Pressure (kN/m^2)

D_w: Depth of Water Table below Ground Surface (m)

ACRONYMS

FEA:	Finite Element Analysis
FEM:	Finite Element Method
CPT:	Cone penetration test
SPT:	Standard penetration test
N:	Number of blows of standard penetration test
FPLT:	Field plate load test
CPLT:	cyclic plate load test
2D:	Two Dimension
3D:	Three Dimension
PDE	Partial differential equation

ABSTRACT

The Plate Load test is one of the most important tests for obtaining soil information, particularly in regard to foundation design. In this thesis the 2D and 3D model was employed in the interpretation of plate load tests using CONNECT Edition V20.02 PLAXIS 2D and 3D. Additionally, a parametric study of the effects of key parameters such as loading plate diameter, plate roughness, elastic modulus and angle of internal friction of soil on the test results was conducted. For both two-dimensional models and three-dimensional models, two material models were used i.e., linear elastic for plate and Mohr-Coulombs for soils. Finally, determined numerically analysis result using 2D and 3D plaxis were compared against actual filed testing data. It has been observed that Numerical simulations in both PLAXIS 2D and PLAXIS 3D is an efficient way to evaluate the load-settlement behavior of plate load test and gives the best convergence to test results. And also, the result of three-dimensional model is better as compared to the two-dimensional model results. Moreover, the plate diameter, plate roughness, elastic modulus and friction angle of soil can have a significant effect on test results i.e., settlement increases proportionally with the increase size of the plate dimensions, settlement is higher when the loading plate is smooth than those with a rough plate, Settlement decreases proportionally with the increase of the elastic modulus of soil located below the base of the plate up to depth two times of plate width (2B) and settlement have no significant change with the increase of the modulus of elasticity of soil below depth greater than two times plate width (2B), increase in friction angle of a soil increase in resistance for a given settlement, Settlement decreases significantly with increase cohesion of soil, Increasing values of the dilatancy angle of soil from (ψ = 0 to ψ = ϕ) increase in the resistance force and Increasing of Poisson's ratio decreases gradually the settlement.

Key words: plate load test, Finite Element Method, Load-Settlement curves, Simulation

1 INTRODUCTION

1.1 Background

Due to rapid growth of urbanization, constructions of civil structures are increasing tremendously. For the civil structures, design and analysis of foundation plays a vital role. The calculation of Ground-foundations interaction is one of the most interesting problems for geotechnical engineers and researchers, and has been one of the challenging issues in geotechnical engineering since late nineteenth century. In a country like Ethiopia which is developing at high growth rate and which needs many constructions works in the future, geotechnical investigation on the engineering properties of the supporting material is very essential.

Soil is the most important material which is used for construction of engineering structures; therefore, it is necessary to understand and study the behavior of the soil under loads and the factors that affect it (Waheed & Asmael, 2018). Field Plate loading test (FPLT) is one of the most applicable in situ geotechnical tests which is employed to figure out the base soil strata`s elasticity modulus, bearing capacity, coefficient of base reaction and etc. especially when the foundation material is such that it is practically impossible to collect undisturbed samples for foundation testing (Atarigiya & Ofori-addo, 2019). Although the test is performing all around the world, However, there are several limitations associated with performing the plate load test; It is exceedingly time-consuming and expensive.

Nowadays, the numerical simulation of structures is one of the most popular approaches widely used in geotechnical and structural analysis. Numerical analysis provides immediate and suitable solutions for various field problems which can be used for similar type of field problems that arise in the future as well. During the past few years, there has been an obvious trend towards developing finite element techniques as they give very reliable and accurate solutions to complex engineering problems.

In comparison with other materials, soil has a more complex material due to the nature of their components; In practice, engineers are looking for less difficult methods to simplify computations for base soil strata`s elasticity modulus, bearing capacity, coefficient of base reaction and etc. analysis since experimental analysis is time intensive and widely used solutions like limit equilibrium are no longer relevant. As a result, computer systems based on the finite element approach have gotten a lot of attention in recent decades as a strong tool for addressing complicated problems.

This master thesis aims to study the plate load tests numerically using Mohr-Coulomb's soil models and finite element method-based programs CONNECT Edition V20.02 PLAXIS 2D and CONNECT Edition V20.02 PLAXIS 3D, which are commercially available and widely used in geotechnical engineering in order to simulate plate load test. Different relevant reports of investigations and load tests are collected and studied. The appropriate parameters required are identified and extracted to be used in Mohr-Coulomb's soil model which is the constitutive model used for numerical study of plate load test. Then discussed and compared field plate load test with numerical simulation of such a test in similar conditions. Finally, differences and difficulties in the results interpretation with their possible reasons are discussed.

1.2 Statement of the Problem

When the foundation material is such that it is nearly difficult to gather undisturbed samples for foundation testing, plate load tests can represent satisfactory findings in determining the elasticity modulus, bearing capacity, coefficient of base response, and other soil stratum properties. And it usually performed in different projects. However, the cost of running this test and the time it takes is one of the difficulties that engineers faced in current geotechnical practices. So, in this study the possibility of applying a finite element model to simulate the plate load test is examined in order to compare results with actual plate load tests and to use the model as one alternative for determining elasticity modulus, bearing capacity, coefficient of base reaction and etc. of soil strata`s, at least for preliminary design purposes.

1.3 Objective of the study

1.3.1 General objective

The main objective of the present study is to conduct finite element analysis for plate load test using both two- dimensional and three-dimensional analyses

1.3.2 Specific objective

- To validate the FEM model with actual plate load test results
- To compare the result of analysis using PLAXIS 2D and PLAXIS 3D
- To conduct Parametric studies

1.4 Significance of the Study

This study contributes in the creation of a plate load test model that uses finite element analysis and Mohr-coulomb failure criteria to simulate plate load test. As a result, by employing finite element models to estimate the overall behavior of the field plate bearing test, the cost and time required to conduct the plate load test is reduced.

1.5 Scope of the study

The scope of this study is to simulating plate load tests with two-dimensional and three-dimensional finite element software and comparing the results to Field plate load test results to determine the validity of the finite element models used to predict the overall behavior of the field plate load test.

Required data was obtained from various soil investigation and design reports of the separate projects, as well as linked soil characteristics, in order to meet the above-mentioned study objectives. And the major results and findings of this study are thus applicable for the particular project sites and other comparable soil conditions.

1.6 Limitation of the Study

The study has the following limitations:

- Few correlations are available in the literature in terms of SPT N value for soil but there is no clear explanation for selection of these correlations.
- Due to the unavailability of soil investigation and plate load test data only two project areas were adopted in this research.

1.7 Organization of the thesis

The content of this thesis is organized in to six chapters: The first chapter provides general introduction with the research objectives, scope and significance of the study. The second Chapter tried to point out the major works done related to this matter. It also reviewed case studies and thesis reports done on PLAXIS and their results are discussed. Chapter three presents methodology, material parameters, soil profile and plate load test data adopted for modeling. The fourth Chapter is focus on numerical modeling of plate load test, geometry, mesh, boundary condition, following that plaxis model has been developed and analysis steps were presented. The fifth Chapter is analysis result and parametric study. In this chapter results are presented and compared. It also gives a brief description procedure and the geometrical input for the model in the software mentioned and influence of key parameters is also furnished. The last chapter, Chapter six, discusses the conclusions derived from this study and limitations in the analyses and recommendations for future work.

2 LITERATURE REVIEW

2.1 Introduction

Soil medium has very complex and erratic mechanical behavior, because of the Nonlinear, stress dependent, anisotropic and heterogeneous nature of it. Field Plate Load Test (FPLT) is one of the important tests especially in obtaining the necessary information about the soil with particular reference to design of foundation which has certain limitations (Bowles, 1996).

Predicting Ground-foundations interaction is highly significant as it is a prerequisite for any design and the failure mechanism of soil beneath footing. During the last three decades, several experimental and analytical research have been done to assess the Ground-foundations interaction. Aside from this, numerical approaches such as boundary element and finite element methods were employed extensively to study the system due to their high accuracy and capacity to tackle complicated issues. However, both of these powerful numerical methods require a considerable amount of engineering judgment and computation cost to completely solve the physical problem. Because of these reasons, researchers in this area have focused on simplified and economical models to characterize the problem.

The elasticity modulus, bearing capacity, coefficient of base reaction and etc. of soil is most usually determined by experimental (Field Plate Load Test) or by empirical methods. with the current rapid development of numerical analysis, the use of finite element method is attracting engineer's attention towards using this method as one option. And the study of numerical methods to solve geotechnical problems are increasing tremendously such as finite element method (FEM) (Sloan & Rondolph, 1982)**,** (Griffiths, 1989) and the finite difference method (Frydman & Burd, 1997)**.** Different constitutive models are used to simulate the soil with different structure interaction following the development of more and more comprehensive constitutive models to describe the complex behavior of geo-material under different loading conditions (Hashiguchi, 1989) (Collins & Kelly, 2002)**.**

Elasto-perfectly plastic model with Mohr- Coulomb failure criterion, usually named as Mohr-Coulomb model, is widely used in finite element analysis of geotechnical engineering, due to its simplicity and sufficiently accuracy. The failure envelope, being dependent on the major and minor principal stresses is defined by cohesion, c and internal frictional angle, ϕ. And a constant stiffness is used in this model.

2.2 Plate loading tests

Field Plate Load Test (FPLT) is one of the most commonly employed and suitable methods for determining bearing capacity, elasticity modulus, coefficient of base reaction and etc. of foundation soils especially when the foundation material is such that it is practically impossible to collect undisturbed samples for laboratory testing and also the penetration tests such as Standard Penetration Test (SPT) and other cone tests (i.e., CPT, SCPT etc.) cannot be performed.

Plates, round or square, varying in size and thickness are employed for the test. The load on the plate is applied by making use of a hydraulic jack. The reaction of the jack load is taken by a cross beam or a steel truss anchored suitably at both the ends. The settlement of the plate is measured by a set of three dial gauges of sensitivity 0.02 mm placed 120^o apart. The dial gauges are fixed to independent supports which remain undisturbed during the test (Murty, 2007).

Figure 2.1 Diagram of plate load test

A diagram of plate load test is shown in Figure 2.1. For the load test to be performed, a ditch of depth D_f is excavated which should be not less than 4 to 5 times the size of the plate. If the water table is above the level of the foundation, the water is carefully pumped out and kept it at the level of the foundation. A suitable bearing plate is selected and placed on the soil at the bottom of the pit, and incremental load on the bearing plate is applied. After the application of an incremental load, enough time is allowed for settlement to occur. When the settlement of the bearing plate becomes negligible, another incremental load is applied. In this manner a load-settlement plot can be obtained as shown in Figure 2.2.

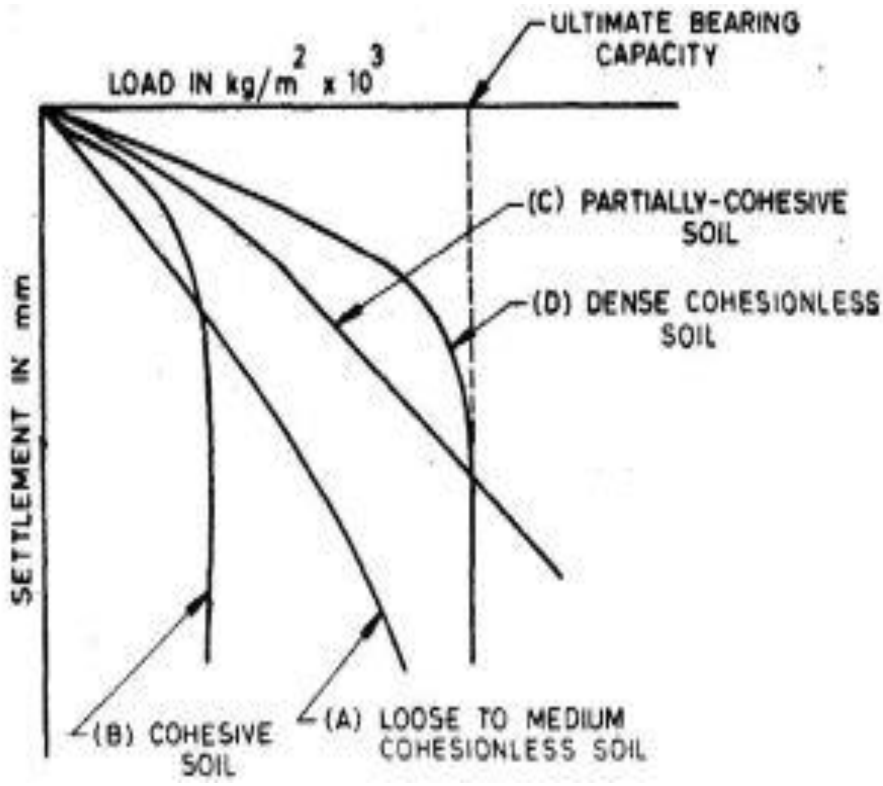

Figure 2.2 Load – Settlement plot

- **Curve A:** This type curve is obtained in case of loose to medium cohesion less soil (i.e., 15 < N < 30). This type of curve shows no clear point of failure.
- **Curve B:** This type curve is obtained in case of cohesive soil. As the load increases the curve leans toward settlement curve.
- **Curve C:** This type curve is obtained in case of partially cohesive soil (i.e., C-ϕ soil). This type of curve also does not show a clear point of failure.
- **Curve D:** This type curve is obtained in case of dense cohesionless soil (i.e., N > 30). This type of curve is common in case of dense sand or gravel deposits.

2.3 Basics of Finite Element Analysis

Finite element analysis is a method of solving continuous problems governed by differential equations by dividing the continuum into a finite number of parts (elements), which are specified by a finite number of parameters (Zienkiewicz et al., 2005). FEM subdivides a large problem into smaller, simpler, parts, called finite elements. The simple equations that model these finite elements are then assembled into a larger system of equations that models the entire problem. FEM then uses variational methods (mathematical analysis that deals with maximizing or minimizing functional i.e., a function from a vector space into its underlying scalar field, or a set of functions of the real numbers) from the calculus of variations to approximate a solution by minimizing an associated error function.

The subdivision of a whole domain into simpler parts has several advantages:

- Accurate representation of complex geometry
- Inclusion of dissimilar material properties
- Easy representation of the total solution
- Capture of local effects

FEM is best understood from its practical application, known as Finite Element Analysis (FEA). FEA as applied in engineering is a computational tool for performing engineering analysis. It includes the use of mesh generation techniques for dividing a complex problem into small elements, as well as the use of software program coded with FEM algorithm. In applying FEA, the complex problem is usually a physical system with the underlying physics expressed in either PDE or integral equations, while the divided small elements of the complex problem represent different areas in the physical system.

As described on (Potts et al., 2001)**,** the finite element method involves the following steps.

Element discretization: this is the process of modeling the geometry of the problem under Investigation by assemblage of small regions, termed finite elements. These elements have nodes defined on the element boundaries, or within the element.

Primary variable approximation: a primary variable must be selected (e.g., displacements, stresses etc.) and rules as to how it should vary over a finite element established. This variation is expressed in terms of nodal values. In geotechnical engineering it is usual to adopt displacements as the primary variable.

Global equations: Combine element equations to form global equations

$$\{M_d\} = [K_G]\{\Delta d_G\} \tag{2.1}$$

Where $[K_G]$ is the global stiffness matrix, $\{\Delta d_G\}$ is the vector of all incremental nodal displacements and $\{M_d\}$ is the vector of all incremental nodal forces.

Boundary conditions: Formulate boundary conditions and modify global equations. Loadings (e.g., line and point loads, pressures and body forces) affect $\{M_d\}$, while the displacements affect $\{\Delta d_G\}$

Solve the global equations: The global Equations (2.1) are in the form of a large number of simultaneous equations. These are solved to obtain the displacements $\{\Delta d_G\}$ at all the nodes. From these nodal displacements secondary quantities, such as stresses and strains, are evaluated.

2.3.1 Modeling by Plaxis

PLAXIS is a 2D finite element package for the analysis of deformation and stress of the soil and soil-structure interaction problems. Geotechnical applications require constitutive models for the realistic simulation of the non-linear and time dependent behavior of soils. PLAXIS has the required features to deal with numerous problems encountered in most geotechnical structures.

PLAXIS 3D Foundation is a family member of PLAXIS, which is a special purpose three-dimensional finite element computer program used to perform deformation analyses for various types of foundations in soil and rock. The program allows for a fully automatic generation of 2D and 3D finite element meshes, which enables users to quickly generate a true three-dimensional finite element mesh based on a composition of horizontal cross sections at different vertical levels.

In the present study finite element analysis has been carried out using CONNECT Edition V20.02 PLAXIS 3D & 2D software.

PLAXIS software program consists of four basic components, namely Input, Calculation, Output and Curves. In the Input program the boundary conditions, problem geometry with appropriate material properties is defined. The problem geometry is the representation of a real three-dimensional and two-dimensional problem and it is defined by work-planes and boreholes. The model includes an idealized soil profile, structural objects, construction stages and loading. The model should be large enough so that the boundaries do not influence the results. Boreholes are points in the geometry model that define the idealized soil layers and the groundwater table at that point. Multiple boreholes are used to define the variable soil profile of the project.

During mesh generation soil layers are interpolated between the boreholes so that the boundaries between the soil layers coincide with the boundaries of the elements and Mesh dimensions should be appropriately defined, to prevent the effects of boundary conditions.

The mesh element size can be adjusted by using a general mesh size varying from very coarse to very fine and also by using line, cluster and point refinements.

PLAXIS allows for a fully automatic generation of finite element mesh. The generation of the mesh is based on a robust triangulation procedure, which results in “unstructured” meshes. These meshes may look disorderly, but the numerical performance of such meshes may yield better results than for regular structured meshes.

Very fines mesh should be avoided in order to reduce the number of elements, thus to reduce the memory consumption and calculation time. The program does not allow entering a new structural element or a new soil cluster after the mesh is generated. If a new element or cluster is added to the geometry model, the mesh generation should be repeated with the new input.

After defining the model geometry and generation of mesh, initial stresses are applied by using either K_o-procedure or gravity loading. The initial stresses in the soil are affected by the weight of the soil and history of the soil formation. Stress state is characterized by vertical and horizontal stresses. Initial vertical stress depends on the weight of the soil and pore pressures; whereas initial horizontal stresses are related to the vertical stresses multiplied by the coefficient of lateral earth pressure at rest. The K_o - procedure may only be used for horizontally layered geometrics with a horizontal ground surface and, if applicable, a horizontal phreatic level. In the present study the K_0-procedure has been used.

In this analysis the effect of ground water table is not taken into account. If it would have been taken into account then the initial stress would have been calculated by effective stress consideration. As the effect of ground water table is not considered it has been done by the total stress consideration only.

$$\sigma_h = K_o\sigma_v \qquad (2.2)$$

where K_o is based on Jacky’s formula (1944) which is written as:

$$K_o = 1- \sin\phi \qquad (2.3)$$

PLAXIS program has convenient procedures for automatic load stepping and for the activation and deactivation of loads and parts of the geometry (Staged Construction). Staged construction is a very useful type of loading input. In this special PLAXIS feature it is possible to change the geometry and load configuration by deactivating or reactivating loads, volume elements or structural objects as created in the geometry input. Staged construction provides an accurate and realistic simulation of the various loading, construction and excavation processes. This option can also be used to reassign material data sets to clusters or structural elements.

As mentioned above the construction stages are defined by activating or deactivating the structural elements or soil clusters in the work-planes and a simulation of the construction process can be achieved. In every construction step, the material Properties, geometry of the model, loading condition and the ground water level can be redefined. During the calculations in each construction step, a multiplier that controls the staged construction process (ΣM_{stage}) generally starts at zero and is expected to reach the ultimate level of 1.0 at the end of the calculation phase. (*CONNECT Edition 20.04 PLAXIS 3D-Reference Manual*, 2020)

2.3.2 Mohr coulomb soil model

Plaxis describes the mechanical behavior of soils and rocks as a stress-strain relationship using constitutive models. Different soil models are incorporated in the software such as the HB model, the Mohr coulomb model, soft soil model, hardening soil model, soft soil creep model, and jointed rock model. The feature also enables the use of self-programmed or user-defined constitutive models.

Elasto-perfectly plastic model with Mohr- Coulomb failure criterion, usually named as Mohr-Coulomb model, provides a failure criterion of soil material using a critical combination of normal and shear stress. And is widely used in finite element analysis of geotechnical engineering, due to its simplicity and sufficiently accuracy. The failure envelope, being dependent on the major and minor principal stresses is defined by cohesion, c and internal frictional angle, ϕ. In the MC model a constant stiffness is used. The model involves five parameters, i.e., young's modulus, E, Poisson's ratio, ν, cohesion, c, internal friction angle, ϕ, and dilatancy angle, ψ.

2.4 Related studies

Different researchers are developing a finite element model to simulate and analyze the field plate load test. Some of related studies are outlined below:

Khanal (2013) studied back-calculate the plate load tests using advanced soil models in PLAXIS 2D in order to gather experience on soil behavior and constitutive models. For this, extensive study of literature with full-scale load tests was carried out. Both tests on clay and sand were the theme interest. To examine the plate loading tests, he used three case studies were selected which are case study on clay till from Sweden, case study on saprolite soil from Portugal and case study on sand from Texas A&M, USA. And, the load-settlement responses of vertically loaded footings placed on both sands and clay were analyzed using the finite element method. The numerical analysis was performed using PLAXIS 2D. The soil profiles and parameters used in the analysis were based on either in situ tests or laboratory tests. He was used The Hardening Soil model as a material model to analyze the soil behavior. Finally, he was concluded that the load-settlement curves obtained from finite element analysis were compared with those from plate-load tests are well fitted.

Fu et al., (2009) Conducted Discrete Element Simulations of Shallow Plate-Load Tests. He was simulated Shallow plate-load tests using a two-dimensional discrete element procedure together with parameters calibrated from a series of biaxial compression experiments on aluminum rods. In the study the deformation and force transmission characteristics within ground materials were investigated first, and then attentions were focused on studying the influences of the interparticle friction coefficient, the roughness of the loading plate, and the size of loading plate on the testing results, including the ultimate bearing capacity, the deformation behavior, and the failure mode. He was also analyzed the well-known scale effect in plate-load tests from the perspectives of both continuum mechanics and discrete element method simulations. Finally, the result was proven that the nonlinear strength behavior of the materials beneath the foundation is a possible source of the scale effect; however, this effect may be counterbalanced by the boundary restriction effect in laboratory experiments.

Zhang & Zhou, (2020) they were developed a 3D-finite element model using Plaxis 3D software to simulate the plate load tests and compared the finite element results with those obtained from experimental tests. For the study Twenty-seven plate load tests were carried out on three different types of subgrade soils which are collected from different sites in Kerbala city and tested under static load under three degrees of compaction. The experimental results were verified numerically using the finite element method. In the numerical simulation, the Mohr-Coulomb model was used to represent the behavior of soil. finally, the numerical and experimental results were analyzed and compared and the results showed a good agreement with experimental work, also showed the possibility of using Plaxis 3D in the simulation of the static plate load test.

Naeini & Taherabadi, (2015) conducted three-dimensional simulation of PLT, investigated by using finite element code, and compares the results obtained from site studies with the results of the numerical modelling. During verification, it was found that a constant number must be used to be multiplied in the modulus of elasticity as an input of finite element code (ABAQUS). This constant is estimated to be 3. Then, the obtained constant was used to estimate the Ks of another site and the results show that the relation has sufficient accuracy in soft soils but it cannot be reliable in coarse one. Also, the goal of their research was to explore the ability of numerical modeling to evaluate the value of Ks without performing some plate load tests, was achieved.

Ziaiemoayed et al. (2017) Investigated analysis of plate load test results in the case of loose and dense sandy soil to investigate the effects of chamber dimension on plate load test results. FLAC3D was used investigated the results of FPLT test numerically. The experiments conducted on $30 \times 30 cm^2$ plate load tests with $1 \times 1 \times 1\ m^3$ chamber show that the boundary conditions have no significant effect on the results and thus they are applicable to in situ conditions.

Lee & Salgado (2000) analyzed the FPLT test numerically using 3D finite element program ABAQUS, to study the size effects of plate resistance for sand soil at different relative densities. They compared the experimental and numerical results and found a good agreement with a maximum error of 20% between the results.

Teodoru & Toma (2009) Studied A numerical simulation of plate loading test, in order to underlines the size effect on settlements and derived values of geotechnical parameters. The study was based on the comparison between the results obtained by Finite Element Method (FEM) using the Mohr-Coulomb soil model and by some observations from literature. The obtained numerical results revealed that the subgrade reaction coefficient is strictly dependent on parameters like size of the loaded area and loading magnitude, and thus completely general and generic, and not a fundamental material property of soil that can somehow be determined rationally, as often one claims to be.

3 METHODOLOGY

3.1 Method of the study

The aim of this research work is to model the plate load tests using FEM in order to gather experience on soil behavior and constitutive models and this section consists of the research methods used to achieve the study's general and specific aims. This research started with unstructured literature review during proposal preparation: to get an in-depth knowledge of the subject area attributed to the plate load test and numerical method; to assess the level of existing knowledge and identify gaps to select thesis topic; and identify suitable research methods for data collection and analysis. Conceptual and contextual literature reviews were followed once the main research work is started.

In pursuance of the presented objectives, the following methods were employed:

- A thorough review of current literature and theories was conducted to gain a better knowledge related to the study area.
- Collection of soil parameters from investigation reports done in the lab and from field tests, and gathering actual plate load test data are the first and foremost steps required to start this study. Different correlation techniques are also used to determine soil parameters that are not included in the soil investigation report.
- Once we get all the required soil parameters, The finite element analysis was performed using CONNECT Edition 20.04 PLAXIS 2D and CONNECT Edition 20.04 PLAXIS 3D. For both investigations, two primary finite element material models were incorporated they are Linear elastic and Mohr-Coulomb model.
- Discussed about the comparison of field test and finite element analysis based on the output of PLAXIS 2D and 3D results.
- Finally, conclusion and recommendation were given on all over the research results.

The data necessary for this study are from Addis Geosystem plc (AGS) and other acknowledged publications. The entire procedure is summarized on the flow algorithm below (Figure 3.6):

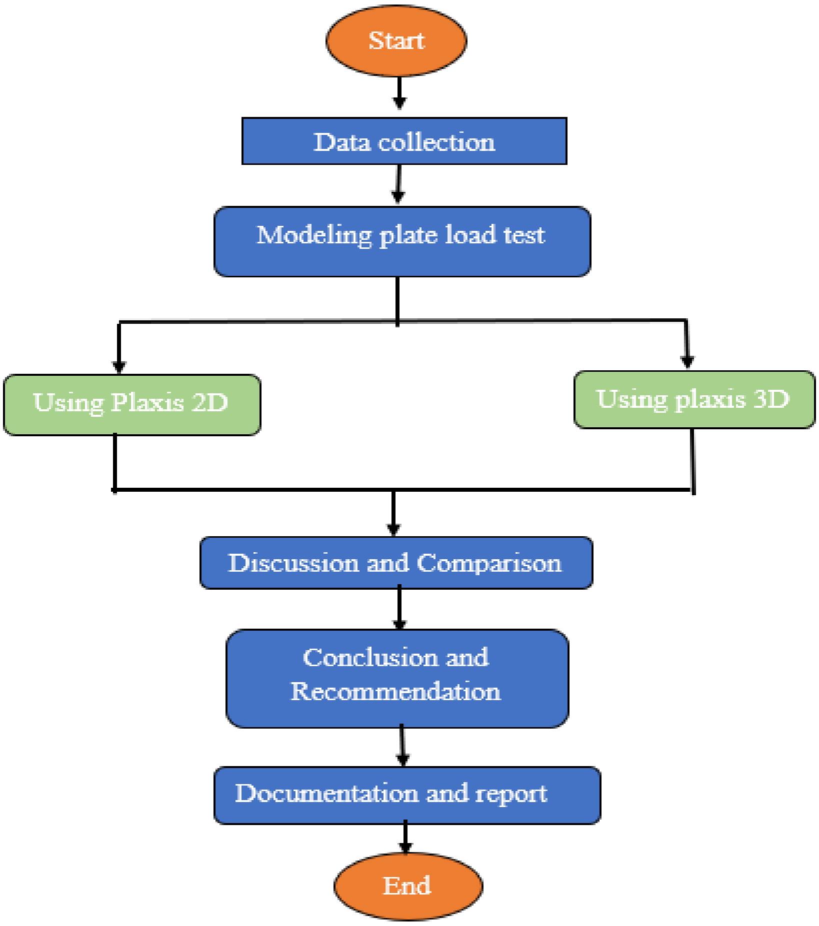

Figure 3.3.1 General flow of work

3.2 Reports used for the study and analysis

In this research study numerical modeling of different plate load test using FEM are modeled in layered soil profile. The soil parameter used in the modelling and plate load test data are incorporated from geotechnical site investigation reports.

A geotechnical site investigation is the process of gathering information and assessing the site's conditions in order to design and construct foundations for various structures such as buildings, dams, and bridges.

Soil investigation and detailed material report data are the basic input, for the FEM analysis of different geotechnical problems. Most of geotechnical reports that are usually available and/or used in current design and construction practices are commonly done with the intention of determining only the basic soil parameters like cohesion and angle of internal friction. However other important parameters should be determined to get sufficient input parameters for the FEM model.

Availability of such soil data is the main factor governing the selection of the study area of this thesis. Two different sites are selected with sufficient data and high-quality plate load tests for this study in various areas of the country, namely:

- Effluent Treatment Plant Project (Sebeta Town, Oromia region)
- Potash Evaporation Pond Design project (Dallol, Afar Region)

3.2.1 Effluent Treatment Plant Project (Sebeta Town, Oromia region)

The investigation work carried out for a proposed Effluent Treatment Plant in Oromia Region, Alemgena, Jemo-Furi Railway station area. The Geotechnical Investigation was carried out for Repi Soap and Detergent PLC and Addis Geosystem plc was carried out the soil investigation task to determine the engineering properties of soil and nature of the subsurface geological material.

Figure 3.2 Partial view of the proposed Effluent Treatment Plant site.

Core drilling of three boreholes up to a depth of 12m, and along with in situ and laboratory tests has been conducted. Accordingly, the following engineering geological layers have been identified.

1. Top soil (soft, dark, silty clay with grass roots)
2. Very stiff to hard, light brown, silty clay

Ground water was encountered in all the three boreholes at 1.9m, 2.2m and 2.6m depth in BH-1, BH-2 and BH-3 respectively. The summarized soil properties of those layers are shown in Table 3.1

Table 3.1 Description of soil strata (Effluent Treatment Plant Project), (obtained from the soil investigation report by Addis Geosystems plc)

Soil type	soft, dark, silty clay with grass roots at the top.	Very stiff to hard, light brown, silty clay
Layer Thickness (m)	2.3	15.7
Adjusted N value	11	17
Bulk unit weight (γ) (kN/m^3)	17	18
Dry unit weight (γ_{dry}) (kN/m^3)	13.83	13.73
Friction angle (ϕ) (°)	5	10
Cohesion (c) (kN/m^2)	20	27

The Cyclic Plate Load Test was conducted to measure in-situ determination of Bearing Capacity and Settlement of foundation at proposed foundation level when subjected to the designed test load and the test was performed according to methods and procedures described in ASTM - D1194. The test was carried out at one location in a test pit excavated manually having a plan dimension of 8.0 m X 3.0 m and 1.5m depth from NGL. A 600mm diameter and 25mm thick plate was used in the test. A wheel loader weighing about 17.5 Tones was used as reaction load. Two cycles i.e., unloading at interval of 1kg/cm2 load increment was adopted while just unloading gradually at the end of the test was adopted for the plate load test. The load vs settlement curve of the plate load test is shown in Fig. 3.2.

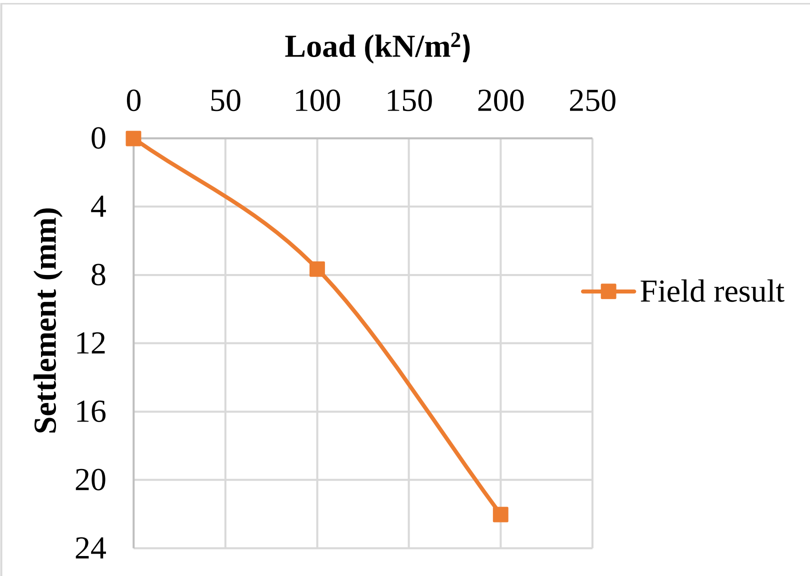

Figure 3.3 Load –settlement graph, Effluent Treatment Plant Project (from test reports by Addis Geosystems plc)

For further reference on loading test data and borehole log sheets, refer Appendix A

3.2.2 Potash Evaporation Pond Design (Dallol, Afar Region)

Ground Investigation works carried out for Design of Evaporation Pond in Yara Dallol's Potash Development project located in Afar National Regional State of Ethiopia. The purpose of the ground investigation was to explore and evaluate the surface and sub-surface conditions of the proposed Evaporation Pond area, in order to provide Geotechnical design parameters for the design and construction of evaporation ponds for the potash Mining project. Addis Geosystem plc. had carried out the soil investigation task.

Figure 3.4 Close and distant view of Evaporation Pond site

Sixteen boreholes to maximum depth of 20m each were drilled to identify subsurface conditions and 15 test pits (TP-100 to TP-114) excavated to maximum depth of 3m. And generally, three distinct geotechnical layers have been encountered in the boreholes which are repeated at different depths from borehole to bore hole. These layers include

1. Halite,
2. Silty clay/Clayey silt and
3. sandy silt/Silty sand

Ground water was encountered in all test pits and boreholes with water level ranging between 0.10m to 0.80m depths from surface. the summarized soil properties of those layers are shown in Table 3.2 to Table 3.4.

Table 3.2 Description of soil strata at TP-100 (Potash Evaporation Pond Design project), (obtained from the soil investigation report by Addis Geosystems plc)

Soil type	Soft, dark grey Silty CLAY with some very thinly bedded halite and few halite crystals	Dense, dark grey to light grey, thinly bedded crystalline HALITE interlayered with soft, dark grey, thickly laminated silty clay which mostly coats the halite
Layer Thickness (m)	1.7	7.3
SPT N value	5	40

Table 3.3 Description of soil strata at TP-108 (Potash Evaporation Pond Design project), (obtained from the soil investigation report by Addis Geosystems plc)

Soil type	Dense, dark grey to light grey, medium to coarse grained crystalline HALITE interlayered with firm dark grey very thinly bedded Silty CLAY and thin layers of gypsum/anhydrite.
Layer Thickness (m)	9
SPT N value	46

Table 3.4 Description of soil strata at TP-112 (Potash Evaporation Pond Design project), (obtained from the soil investigation report by Addis Geosystems plc)

Soil type	Dense to very dense, light grey to dark gray thinly bedded crystalline HALITE with soft to firm, dark gray, very thinly bedded Silty CLAY.	Firm to stiff, dark grey Silty CLAY with some halite crystals.	Dense to very dense, light grey to dark gray thinly bedded crystalline HALITE with soft to firm, dark gray, very thinly bedded Silty CLAY
Layer Thickness (m)	1.6	0.8	6.6
SPT N value	40	33	40

Plate load test was carried out to replace field CBR test as it was not available. The test was carried out as per the test procedures described in ASTM D-1194 (Standard Test method for Bearing Capacity of Soil for static load and spread footing). The test was conducted at 15 test pit location at natural ground level (TP 100 – TP 114). A 300mm diameter and 25mm thick plate was used in the test and an excavator weighing about 41.5 Tons was used as reaction load. The testing load ranges between 75 to 325Kpa. In this study I was allocated three of them, i.e., plate load tests at TP-100, TP-108 TP-112. The load vs settlement curve of the plate load test is shown in Fig. 3.3, Figure 3.4 and Figure 3.5

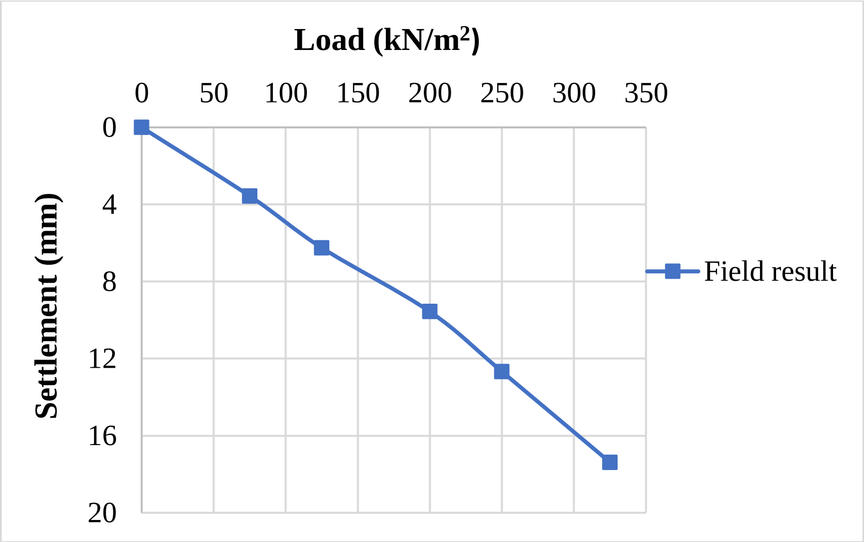

Figure 3.5 Load –settlement graph of TP-100, Potash Evaporation Pond Design project (from test reports by Addis Geosystems plc)

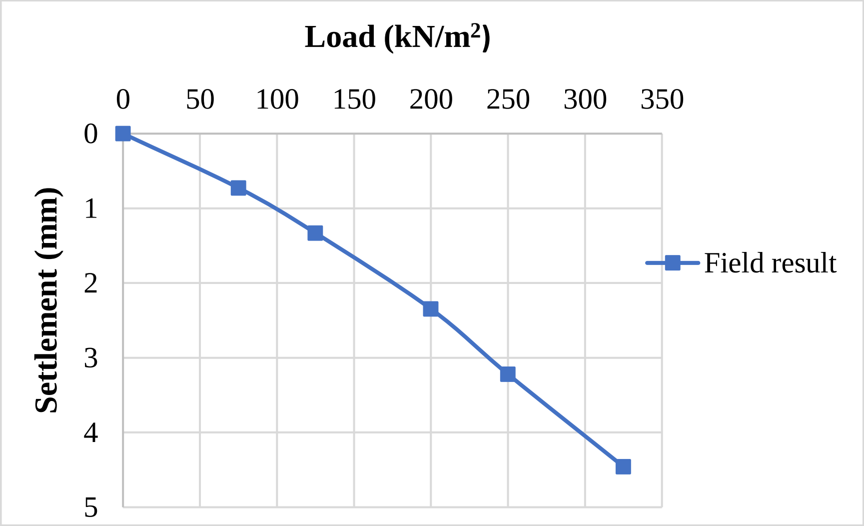

Figure 3.6 Load –settlement graph of TP-108, Potash Evaporation Pond Design project (from test reports by Addis Geosystems plc)

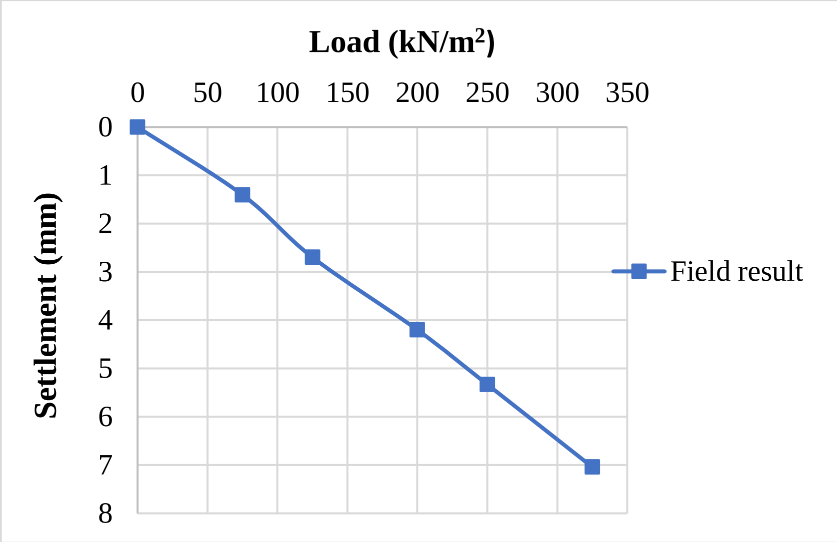

Figure 3.7 Load –settlement graph of TP-112, Potash Evaporation Pond Design project (from test reports by Addis Geosystems plc)

For further reference on loading test data and borehole log sheets, refer Appendix B

3.3 Correlation and Determination of basic Soil Parameters

The soil investigation results, that have been obtained and are used in this study are tabulated and shown in the preceding sections. However, almost all the above data are not complete in terms of the requirement of soil parameters for the numerical analysis. Usually, only basic soil parameters are likely to be obtained from geotechnical reports. Parameters necessary for the numerical analyses in this study have been determined in two ways; by taking directly from the field and laboratory test results and the remaining, perhaps most of the parameters which could not be obtained directly from the laboratory tests, have been indirectly derived by using empirical correlations based on the recommendations of different literature, international geotechnical codes and standards.

3.3.1 Modulus of elasticity (E)

The modulus of elasticity E is a basic parameter that describes the load-settlement behavior of soils and governs the results of settlement related problems. The use of a practical and reasonable stiffness values representing the in-situ conditions is of great importance in finite element analysis for better simulation of the actual condition of the soil. Several methods are available for estimating the modulus of elasticity of a soil as described**.** the modulus of elasticity values which could not be obtained directly from the laboratory tests, will be indirectly derived by using the following empirical correlations methods

I. Empirical formulas of modulus of elasticity equations by several test methods based on the adjusted SPT N_{55} value for different types of soil specified in (Bowles, 1996)

For sand

$$E = 500(N+15) \tag{3.1}$$

$$= 7000(N)^{1/2} \tag{3.2}$$

$$= 6000(N) \tag{3.3}$$

For gravely Sand

$$E = 600(N + 6), \text{ for } N < 15 \tag{3.4}$$

$$E = 600(N + 6) + 2000, \text{ for } N > 15 \tag{3.5}$$

For clayey sand

$$E = 320(N+15) \tag{3.6}$$

For Silts, sandy silt, or clayey silt

$$E = 300(N+6) \tag{3.7}$$

Where, $N= N_{55}$

Thus, correcting for field procedures, and on the basis of field observations, it appears reasonable to standardize the field SPT number as a function of the input driving energy and its dissipation around the sampler around the surrounding soil. SPT N-Value obtained from field test is corrected by using the following formula by Skempton, (1986)

Where,

$$N60 = \frac{E_H C_B C_S C_R\, N}{0.6} \quad \text{(Skempton, 1986)} \quad \text{`} \tag{3.8}$$

N_{60} = Corrected SPT N-value for field procedures

E_H = Hammer efficiency (Table C.1)

C_B = Borehole diameter correction (Table C.1)

C_S = Sampler correction (Table C.1)

C_R = Rod length correction (Table C.1)

N = Measured SPT N-value in field

This correction is to be done irrespective of the type of soil.

Table 3.5 modulus of elasticity value for Effluent Treatment Plant Project

Layer Thickness (m)	Description	SPT. (N_{cor} - values)	modulus of elasticity (E) (kN/m^2)
2.3	soft, dark, silty CLAY with grass roots at the top.	11	5100
15.7	Very stiff to hard, light brown, silty CLAY	17	6900

The modulus of elasticity (E) has been determined using Equation 3.7, since is applicable for Silts, sandy silt or clayey silt of each soil layer.

Table 3.6 modulus of elasticity value for TP-100 (Potash Evaporation Pond Design project)

Layer Thickness (m	Description	SPT. (N_{cor} - values)	modulus of elasticity (E) (kN/m^2)
1.7	Soft, dark grey Silty CLAY with some very thinly bedded halite and few halite crystals	5	3435
7.3	Dense, dark grey to light grey, thinly bedded crystalline HALITE interlayered with soft, dark grey, thickly laminated silty clay which mostly coats the halite	37	13899

The modulus of elasticity (E) has been determined using Equation 3.7, since is applicable for Silts, sandy silt or clayey silt of each soil layer. And SPT N-value corrected based on equation 3.8.

Table 3.7 modulus of elasticity value for TP-108 (Potash Evaporation Pond Design project)

Layer Thickness (m	Description	SPT. (N_{cor} - values)	modulus of elasticity (E) (kN/m^2)
9	Dense, dark grey to light grey, medium to coarse grained crystalline HALITE interlayered with firm dark grey very thinly bedded Silty CLAY and thin layers of gypsum/anhydrite.	42	15534

The modulus of elasticity (E) has been determined using Equation 3.7, since is applicable for Silts, sandy silt or clayey silt of each soil layer. And SPT N-value corrected based on equation 3.8.

Table 3.8 modulus of elasticity value for TP-112 (Potash Evaporation Pond Design project)

Layer Thickness (m)	Description	SPT (N_{cor} - values)	modulus of elasticity (E) (kN/m^2)
1.6	Dense to very dense, light grey to dark gray thinly bedded crystalline HALITE with soft to firm, dark gray, very thinly bedded Silty CLAY.	37.	13899
0.8	Firm to stiff, dark grey Silty CLAY with some halite crystals	30	11610
6.6	Dense to very dense, light grey to dark gray thinly bedded crystalline HALITE with soft to firm, dark gray, very thinly bedded Silty CLAY.	37	13899

The modulus of elasticity (E) has been determined using Equation 3.7, since is applicable for Silts, sandy silt or clayey silt of each soil layer. And SPT N-value corrected based on equation 3.8.

3.3.2 Shear Strength Parameters

Shear strength parameters, namely, angle of internal friction (ϕ’) and cohesion (c’) are determined mostly from the direct shear test result that are taken from samples obtained from shallow depth. But for layers, where laboratory test results are not available, are estimated using different correlations techniques.

3.3.2.1 Cohesion (C’)

- Correlation method provided by Daniel (2001) has been used to determining cohesion of soil.

$C = -2.2049 + 6.484N$ for cohesive soils (Kumar et al., 2016) 3.9

$C = -16.5 + 2.15N$ for intermediate soils (Kumar et al., 2016) 3.10

Where N is uncorrected number of blows

3.3.2.2 Internal friction (ϕ’)

Correlation method provided by Daniel (2001) has been used to determining angle of internal friction

$\phi = 27.12 + 0.2857N$, N value (range 4to50) (Kumar et al., 2016) 3.11

Where N is uncorrected number of blows

3.3.3 Saturated and Unsaturated Unit Weight Determination

The saturated unit weight is determined Correlation method provided by B.Peck et al., (1974). And the Bulk unit weight is determined from Figure C.1 which are given by Bowles, (1977).(Caltrans Geotechnical manual, 2021)

For cohesive soil

$\gamma_{sat} = 16.8 + 0.15N_{60}$ (kN/m^2) (B.Peck et al., 1974) 3.12

3.3.4 Poisson’s Ratio, ν

Poisson's ratio is a characteristic that represents a material's volume change in a direction perpendicular to the load application. It's the proportion of axial compression to lateral expansion in soils. For most clay, (Bowles, 1996) recommends a Poison's ratio of 0.4 to 0.5, and 0.2 to 0.4 for medium to dense cohesiveness less soil. As a result, for the numerical analysis of this study, typical values of 0.4 and 0.3 were used from Table C.2 given by (Bowles, 1996).

3.3.5 Dilatancy angle (ψ)

As an attempt to improve the result of the analysis the value of the angle of the dilatancy, ψ, for clays are ($\psi \approx 0$) and for non-cohesive soils (sand, gravel) with the angle of internal friction $\phi > 30°$ the value of dilation angle was estimated as $\psi = \phi - 30°$.

3.4 PLAXIS Software and Procedure

The two-dimensional and three-dimensional finite element program PLAXIS is used to simulate the plate load test. To carry out a finite analysis using PLAXIS the software requires the following parameters to model the problem; which are excavation width & depth, plate dimension, soil and interface properties such as material model type, unit weight, young's modulus, Poisson's ratio, cohesion, friction angle, dilatancy angle and interface reduction factor. A finite element mesh has been created and the material properties and boundary conditions are specified. To set up a FEM, geometry model composed of points, lines and other components has been created in the XY-plane for PLAXIS 2D and XYZ-plane PLAXIS 3D. The finite element mesh was generated in PLAXIS after the material properties and boundary conditions are assigned. For the generation of mesh, it is advisable to set the Global coarseness to fine. Then finally the initial conditions are generated and simulation is followed by one or more further analysis stages, each of which is coupled with a specific procedure that specifies the kind of analysis to be conducted.

3.4.1 Inputs

Foundation soil:

In this project, two case studies was done from different places. For the first case from Ethiopia, Oromiya Region, Alemgena area, Sebeta Woreda, 08 Kebele, around Jemo-Furi Railway Station, black cotton soil at the top and expansive silty CLAY soil; for second case from Dallol, Afar Region, Danakil Depression, Ethiopia, it is Halite, Silty CLAY/Clayey SILT and sandy SILT/Silty SAND soil. The Mohr - coulomb soil model was used to represent the soil for all cases.

Plate:

The PLAXIS program allows for elastic or Elasto-plastic material behavior in plate or footing elements. In these cased, elastic plate elements are used. Different sizes of footings or plates are used according to the case studies.

Loading:

The distributed load A is applied vertically in the plate for the simulation of bearing capacity and settlement of the plate.

Interfacial strength:

The purpose of interface element is to simulate the relative friction between plate and soil. According to (*CONNECT Edition 20.04 PLAXIS 3D-Reference Manual*, 2020) the roughness of the interaction is modeled by selecting an appropriate value for the strength reduction factor (R_{int}) in the interface. If there is no relative sliding between the soil and plate, $R_{int} = 1$. If the deformation or sliding of plate is more than the soil body, $R_{int} < 1$. $R_{int} = 1$ is used in the model.

3.4.2 Procedure and Simulation

The procedures in numerical simulation for steel plates from different case studies are done by excavating to the foundation level and placing the plate above it. During construction stage, the plate and load are activated. The incremental load is applied on the plate and performing staged construction by increasing load with each step increment until failure and extracting settlement contour at the founding level a pressure-settlement curve can be attained to ultimately evaluate the bearing capacity and subgrade coefficient for that set of soil parameters and plate system.

3.5 Comparison between PLAXIS 2D & 3D results with field measurements

The output obtained from numerical simulation of the plate load test using PLAXIS 2D & 3D is analyzed and plotted in load-settlement curve is compared with measured load-settlement curve in the field.

4 FINITE ELEMENT MODELING

4.1 Introduction

In this chapter numerical modeling procedure of different plate load test in layered soil profile are presented. Finite element method could be used to simulate the plate load test. Selecting an appropriate constitutive model has a significant influence on the accuracy of the solutions. In the analysis plaxis software (i.e., two dimensional and three-dimensional) used and for modeling two material models were used i.e., linear elastic for plate and Mohr-Coulombs for soils.

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. And in order to have good modeling it is necessary to carry out preliminary check that is sensitivity analysis such as mesh, geometry distance to the boundary to ensure the accuracy of numerical modeling.

4.2 Model generation using PLAXIS

To simulate plate load test, an attempt was made using numerical modeling and analyze using finite element software packages CONNECT Edition V20.02 PLAXIS 2D and PLAXIS 3D. The input techniques, mesh generation, and analysis steps of a PLAXIS model used in this work are depicted below.

4.2.1 Geometric modeling

External boundaries are an artificial representative of real forces, extensions and conditions that define the solution of a finite element model. It is not possible to include real natural extension of a mass of soil or some events applied on it, so finite element code (PLAXIS) enables the user to substitute the reaction of these extensions and events as a restraint, displacements and forces at the boundary. Consequently, the user can quantify these effects and assign them to the studied model with minimum effect on the accuracy of this model. Positions of boundary restraints can significantly affect finite element simulation results. Because the reaction forces and displacement created at these borders can affect the impact of applied forces on the zones of interest. So, to avoid any restriction that reflected on the accuracy of the finite element model, a user should select the location of this boundaries to be sufficient distant from any zone of interest, but at the same time the user should consider them not to be exceedingly far, costing more time in the analyzing process.

Practically the sensitivity analysis was carried out on the model for both side and bottom boundary. The plate and the soil make up the model. The diameter of the plate, D, defines the rest of the geometry.

Because findings in plate settlement assessments done with closer limitations have been influenced by the distance between the symmetry axis and the vertical outer boundary, it should be equal to or greater than $50 \times$ radius of loading plate in horizontal direction and $60 \times$ radius of loading plate in vertical direction in order to reduce an effect of boundary conditions (Fengier et al., 2013). This restriction will be applied in every example studied, and it is especially important because the geometry size has a significant impact on plate settling findings.

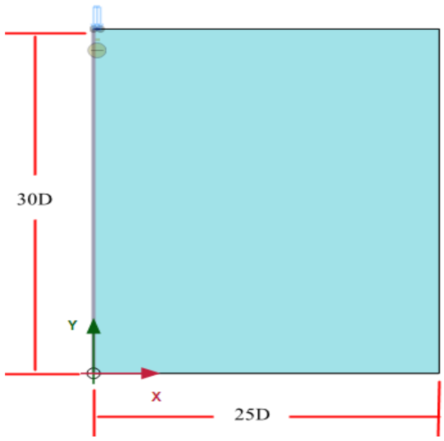

Figure 4.1 Geometry of the model (PLAXIS 2D).

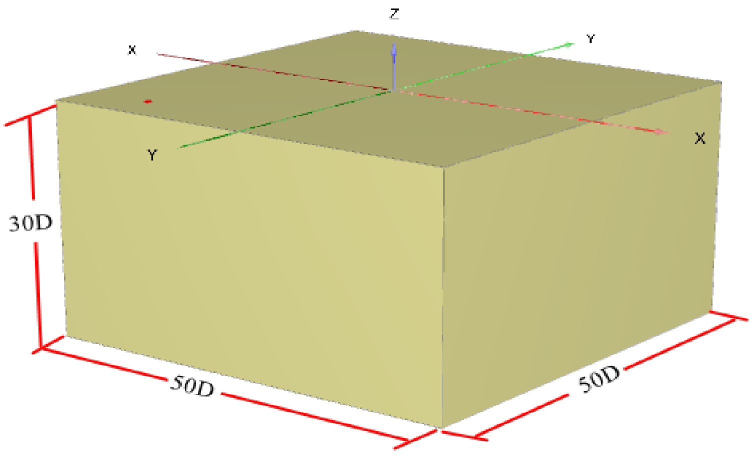

Figure 4.2 Rectangle and soil block (PLAXIS 3D).

The acceptance of geometry of the model was assured by varying horizontal and vertical boundaries in terms of plate diameter (D) for the same applied load and the following result obtained

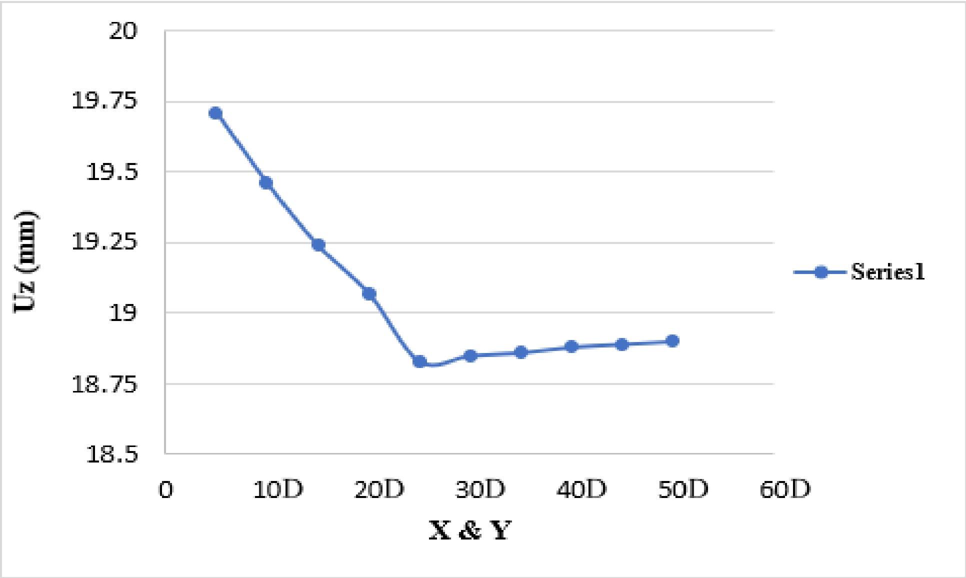

Figure 4.3 Settlement versus horizontal boundary in terms of D

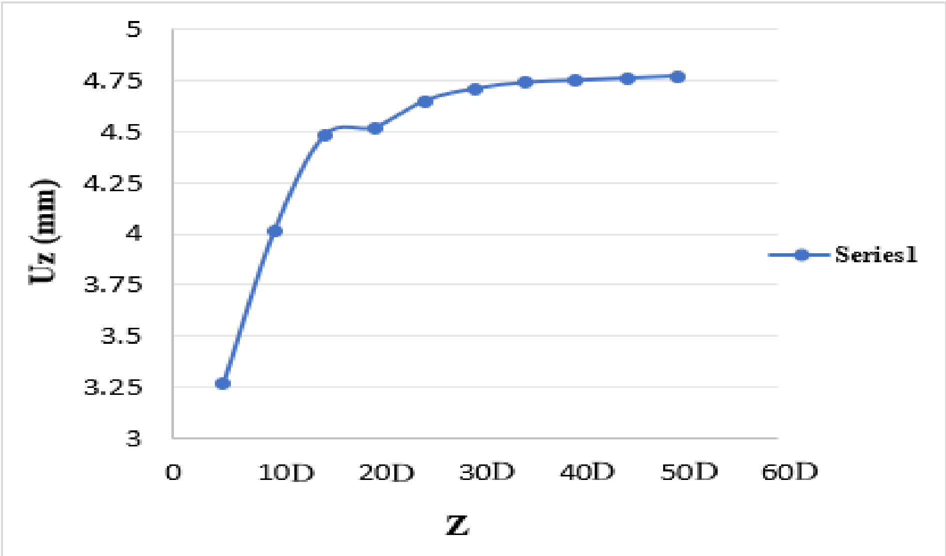

Figure 4.4 Settlement versus vertical boundary in terms of D

From figure 4.3 and 4.4 it is concluded that the distance between the symmetry axis and the vertical outer boundary, should be equal or higher than 25D and the distance between the surface and the rigid layer, should be equal or higher than 30D. It is observed that plate settlement results have been affected when analyses performed with closer limits.

4.2.2 Boundary Condition (fixities)

To depict the actual situation, appropriate boundary conditions (both essential and natural) must be applied during modeling. Fixities, loads, and regulated displacements were all part of this and default boundary conditions are automatically applied in plaxis.

Plaxis 2D

The geometric boundaries were horizontally constrained on the left and right sides ($u_x = 0$ and u_y = free) and entirely fixed ($u_x = u_y = 0$) at the bottom of the geometry in the models.

Plaxis 3D

- Vertical model boundaries with their normal in x-direction (i.e., parallel to the yz-plane) are fixed in x-direction ($u_x = 0$) and free in y- and z-direction.
- Vertical model boundaries with their normal in y-direction (i.e., parallel to the xz-plane) are fixed in y-direction ($u_y = 0$) and free in x- and z-direction.
- Vertical model boundaries with their normal neither in x- nor in y-direction are fixed in x- and y-direction ($u_x = u_y = 0$) and free in z-direction.
- The model bottom boundary is fixed in all directions ($u_x = u_y = u_z = 0$).
- The 'top surface' is free in all directions.

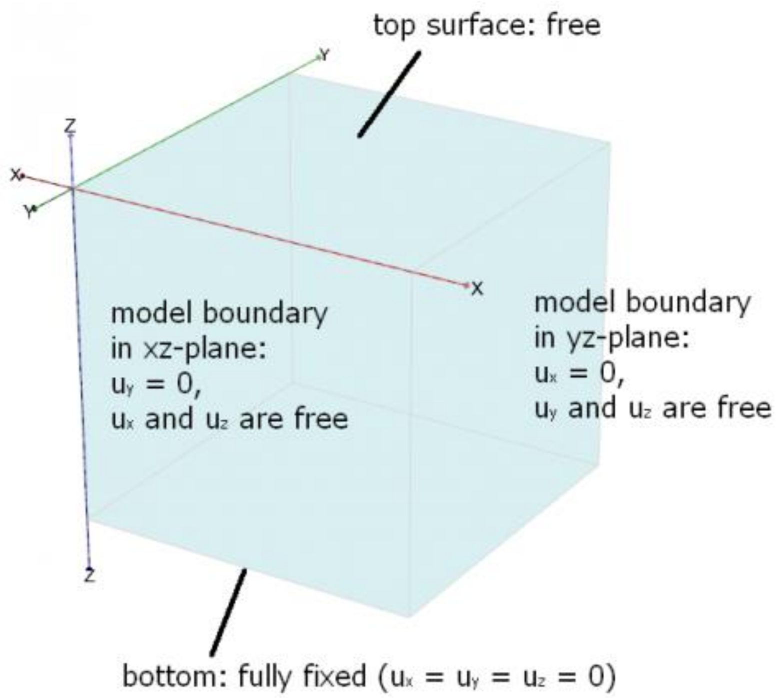

Figure 4.5 Boundary condition in plaxis 3D

4.2.3 Material Modeling

Plaxis distinguishes between soil data sets and loading plates data sets. Table 4.1, Table 4.2, Table 4.3 and Table 4.4 shows the soil properties of each project site used for modelling. And the properties of the loading plate are presented in Table 4.5. The Mohr coulomb soil model for soil and linearly elastic model for plate was used for this study.

Table 4.1 Summary of soil input parameters for Effluent Treatment Plant Project

Soil type	soft, dark, silty CLAY with grass roots at the top.	Very stiff to hard, light brown, silty CLAY
Material depth(m)	2.3	9.7
Model	MC	MC
Adjusted N value	11	17
Bulk unit weight (γ) (kN/m^3)	17	18
Dry unit weight (γ_{dry}) (kN/m^3)	13.83	13.73
Saturated unit weight (γ_{sat}) (KN/m^3)	18.27*	18.03*
Friction angle (ϕ) (°)	5	10
Cohesion (c) (kN/m^2)	20	27
Poisons ratio (ν)	0.3*	0.3*
Dilatancy angles (ψ)	0*	0*
Modulus of elasticity, (E) (kN/m^2)	5100*	6900*
$R_{interface}$	1.0*	1.0*

The entry * indicates indirectly derived by using charts, tables and empirical correlation

Table 4.2 Summary of soil input parameters for Potash Evaporation Pond Design project (TP-100)

Soil type	Soft, dark grey Silty CLAY with some very thinly bedded halite and few halite crystals	Dense, dark grey to light grey, thinly bedded crystalline HALITE interlayered with soft, dark grey, thickly laminated silty clay which mostly coats the halite
Material depth(m)	1.7	7.3
Model	MC	MC
SPT N value	5	40
Adjusted N_{60} value	5	37
Bulk unit weight (γ) (kN/m^3)	16.9*	20.42*
Saturated unit weight (γ_{sat}) (KN/m^3)	17.55*	22.3*
Friction angle (ϕ) (°)	28.5*	38.5*
Cohesion (c) (kN/m^2)	30*	69.5*
Poisons ratio (ν)	0.3*	0.3*
Dilatancy angles (ψ)	0*	8.5*
Modulus of elasticity, (E) (kN/m^2)	3435*	13899*
$R_{interface}$	1.0*	1.0*

The entry * indicates indirectly derived by using charts, tables and empirical correlation

Table 4.3 Summary of soil input parameters for Potash Evaporation Pond Design project (TP-108)

Soil type	Dense, dark grey to light grey, medium to coarse grained crystalline HALITE interlayered with firm dark grey very thinly bedded Silty CLAY and thin layers of gypsum/anhydrite.
Material depth(m)	9
Model	MC
unadjusted N value	46
Adjusted N value	42
Bulk unit weight (γ) (kN/m^3)	20.42*
Saturated unit weight (γ_{sat}) (KN/m^3)	23*
Friction angle (ϕ) (°)	40*
Cohesion (c) (kN/m^2)	82.4*
Poisons ratio (ν)	0.3*
Dilatancy angles (ψ)	10*
Modulus of elasticity, (E) (kN/m^2)	15534*
$R_{interface}$	1.0*

The entry * indicates indirectly derived by using charts, tables and empirical correlation

Table 4.4 Summary of soil input parameters for Potash Evaporation Pond Design project (TP-112)

Soil type	Dense to very dense, light grey to dark gray thinly bedded crystalline HALITE with soft to firm, dark gray, very thinly bedded Silty CLAY	Firm to stiff, dark grey Silty CLAY with some halite crystals.	Dense to very dense, light grey to dark gray thinly bedded crystalline HALITE with soft to firm, dark gray, very thinly bedded Silty CLAY
Material depth(m)	1.4	1.6	6
Model	MC	MC	MC
uncorrected N value	40	33	40
corrected N value	37	30	37
Bulk unit weight (γ) (kN/m^3)	20.42*	20*	20.42*
Saturated unit weight (γ_{sat}) (KN/m^3)	22.3*	21.3*	22.3*
Friction angle (ϕ) (°)	38.5*	36.5*	38.5*
Cohesion (c) (kN/m^2)	69.5*	54.45*	69.5*
Poisons ratio (ν)	0.3*	0.3*	0.3*
Dilatancy angles (ψ)	8.5*	6.5*	8.5*
Modulus of elasticity, (E) (kN/m^2)	13899*	11610*	13899*
$R_{interface}$	1.0*	1.0*	1.0*

The entry * indicates indirectly derived by using charts, tables and empirical correlation

Table 4.5 summary of material properties of the loading plate

Parameters	Name	Steel plate	Unit
Diameter	D	300,600	Mm
Thickness	d	0.025	M
Elastic modulus	E	200	GPa
Poisson's ratio	v	0.33	
Type of behavior	Type	Elastic, isotropic	
Unit weight	γ	78.5	kN/m^3

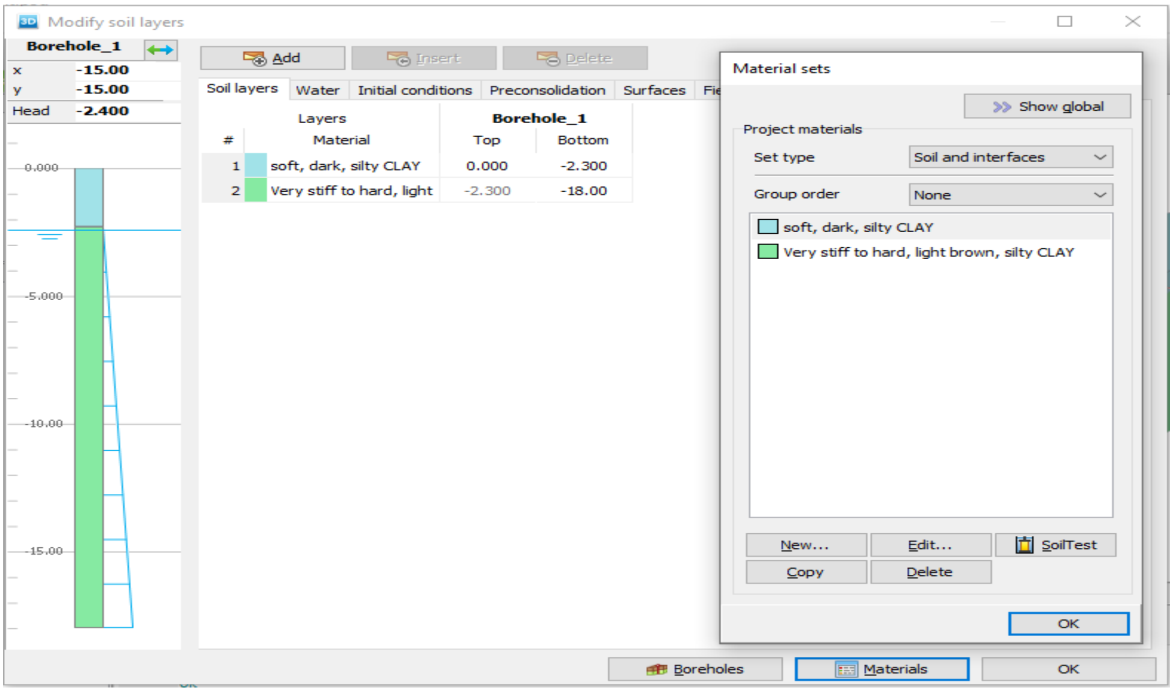

Figure 4.6 Borehole and Soil Parameters Definition

4.2.4 Mesh Generation

The finite element numerical approach is based on the discretization of a continuous into finite elements, with each element's behavior or actions described and then connected to represent the continuum. Different sorts of elements, such as a beam, shell, or solid, as well as different types of forms, such as triangular, quadrilateral, and tetrahedral, can be employed in FE discretization, depending on the nature of the project. The 4th order 15-node triangular element for 2D model and 10-node tetrahedral element for 3D model were used in this study. In general, decreasing element size and increasing the order of interpolation improves the accuracy of the answer (i.e., quadratic is more accurate than linear). However, when the element size decreases and the sequence of interpolation increases, the computation time increases (*CONNECT Edition 20.04 PLAXIS 3D-Reference Manual*, 2020).

A mesh sensitivity analysis was used to explore the impact of the number of elements on the accuracy of the finite element model. Here, one of the models is chosen, and the influence of mesh size adjustments on model output outcomes is compared. The mesh size is very coarse, coarse, medium, fine and very fine.

Table 4.6 Effect of the mesh size changes on the 75 kN/m^2 and 325 kN/m^2 of the load displacement (PLAXIS 3D)

Settlement for 75 kN/m^2 load	**Settlement for 325 kN/m^2 load**	**Mesh size**
4.35 mm	19.65 mm	Very course
4.29 mm	19.64 mm	course
4.28 mm	19.48 mm	Medium
4.15 mm	18.67 mm	fine
3.98 mm	17.61 mm	Very fine

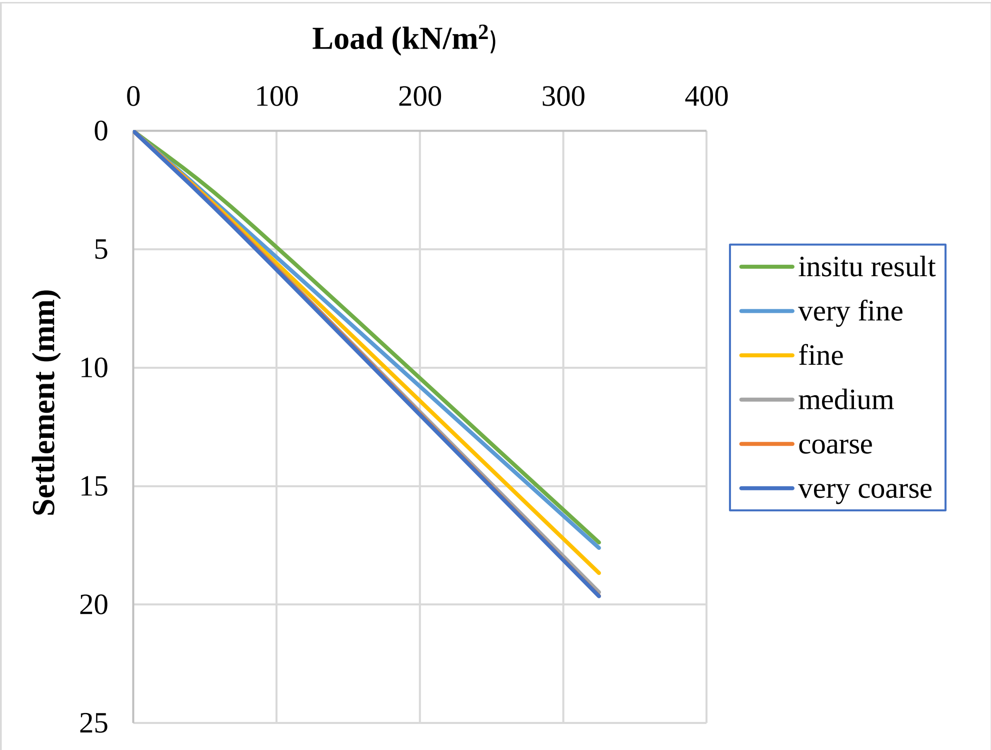

Figure 4.7 Effect of the mesh size changes

From Figure 4.8 it is concluded that very fine mesh size has better accuracy compared to field test, but has longer computational time and memory consumption. so, in order to avoid such difficulty, I was used fine mesh size for all the subsequent FEA.

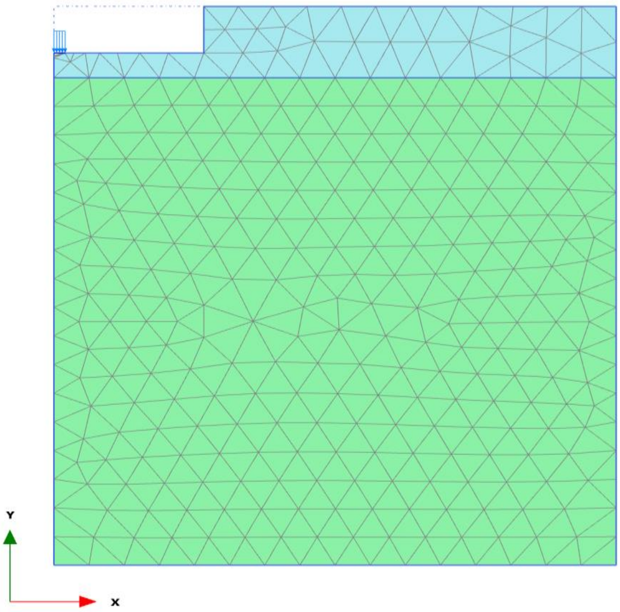

Figure 4.8 PLAXIS 2D finite element mesh generation

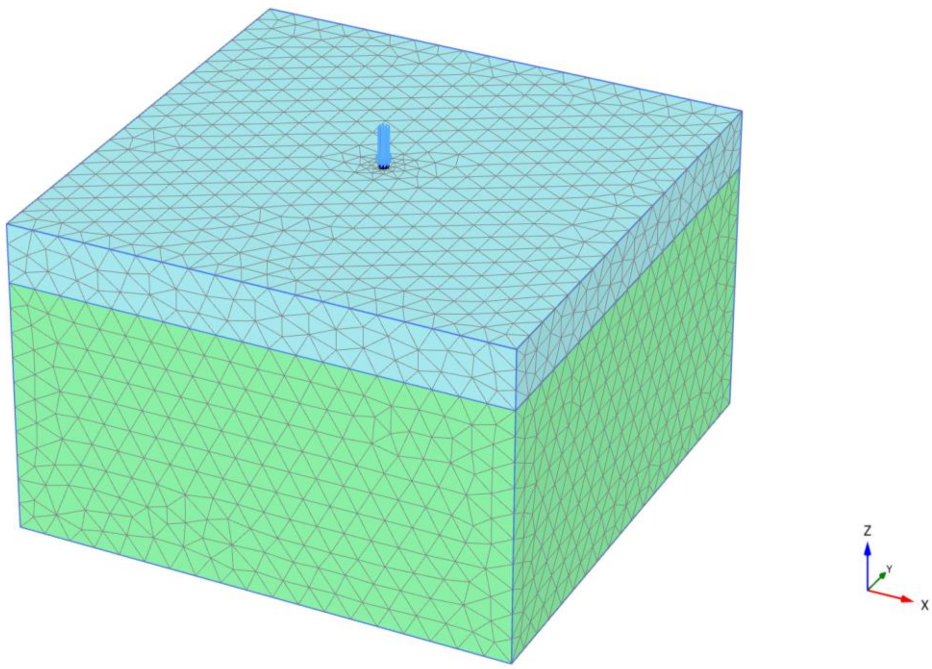

Figure 4.9 PLAXIS 3D finite element mesh generation

4.2.5 Analysis Steps

The general analysis step, which can be used to analyze linear and or non-linear response, is selected for the analysis, (*CONNECT Edition 20.04 PLAXIS 3D-Reference Manual*, 2020)**.**

The initial step and the analysis step are two types of analysis steps. Plaxis adds a separate initial phase at the start of the model step that allows you to declare boundary conditions and predefined fields. The analysis phase is followed by one or more further analysis stages, each of which is coupled with a specific procedure that specifies the kind of analysis to be conducted. Different analytical processes were used in this work to imitate actual plate loading tests, as shown below:

1. Initial stress condition (geostatic condition)

The actual in situ stress initial condition of the soil mass is simulated in this step. Equilibrium condition of the internal stress is checked here.

2. Excavation:

In this step soil excavation for the plate to be installed are modelled and simulated by deactivating the corresponding finite elements in the model. When the elements are deactivated in the analysis, the contribution of mass and stiffness of that element is removed from the global Mass and Stiffness matrix. The excavated soil above the foundation level was removed in this step-in order to account the relief pressure.

3. Plate installation:

In this step installation of the test plate and interface is simulated by putting in place finite elements representing the plate at the location where the preceding step performed removal of soil elements.

4. Loading:

In this step the test loads are applied in incremental manner to simulate the actual plate load test procedures.

5 RESULT DISSCUTION AND PARAMETRIC STUDY

5.1 Presentation of results

In order to see if a finite element model could be used to simulate the plate load test and to determine the validity of the finite element models used to predict the overall behavior of the field plate bearing test a total of eight finite element modeling has been carried out for plate load test at Effluent Treatment Plant Project and Potash Evaporation Pond Design project using PLAXIS 2D and PLAXIS 3D. some of those model results are given below:

5.1.1 Finite Element Analysis result of a plate load test Using PLAXIS 2D

5.1.1.1 Effluent Treatment Plant Project

The tests were conducted using diameter of 0.6m steel plate. Due to this the geometry dimension of the model is 15m in horizontal and 18m in vertical direction.

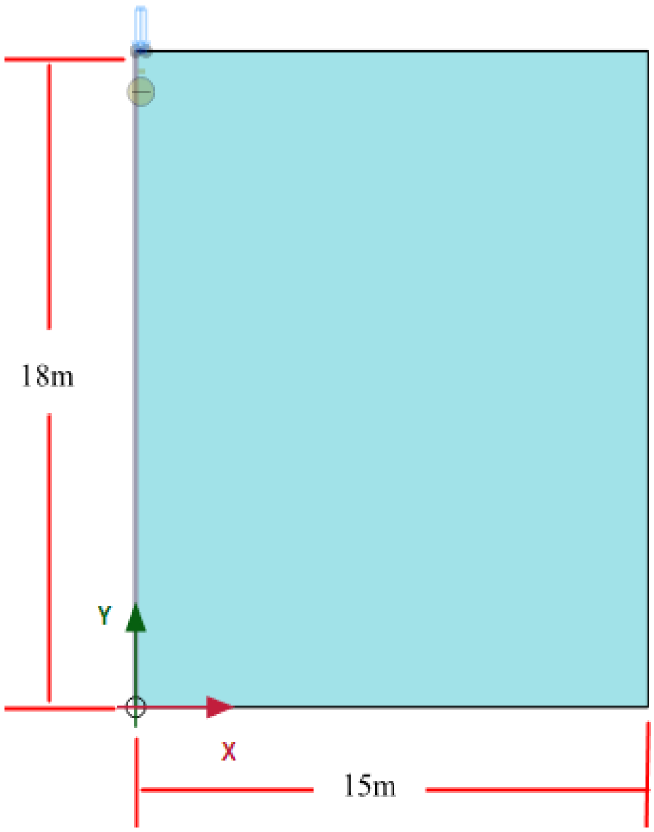

Figure 5.1 Geometry of the model, D=0.6m.

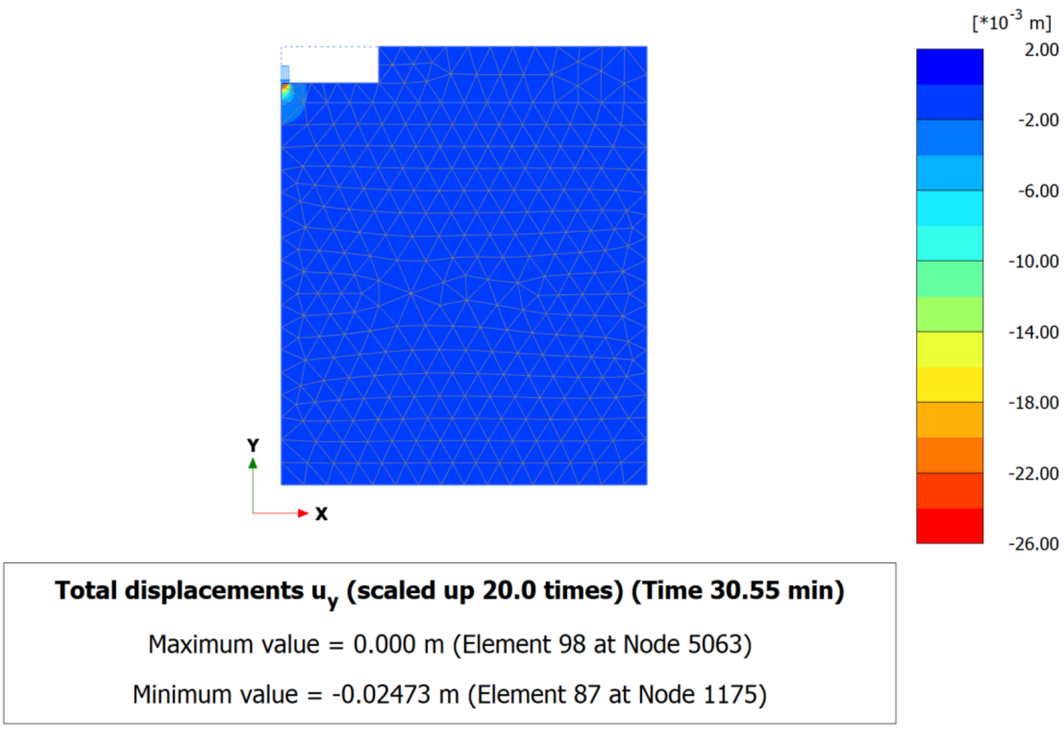

Figure 5.2 Settlement contours of Effluent Treatment Plant Project soil for maximum test load

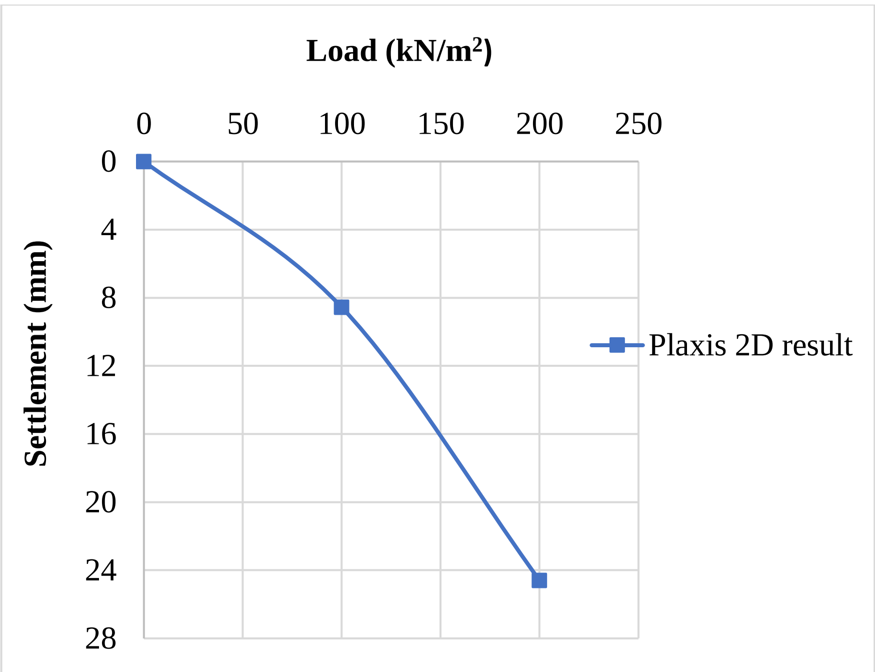

Figure 5.3 load-settlement curve from 2D FEA for Effluent Treatment Plant Project

5.1.1.2 Potash Evaporation Pond Design project

The tests were conducted using diameter of 0.3m steel plate. Due to this the geometry dimension of the model is 7.5m in horizontal and 9m in vertical direction.

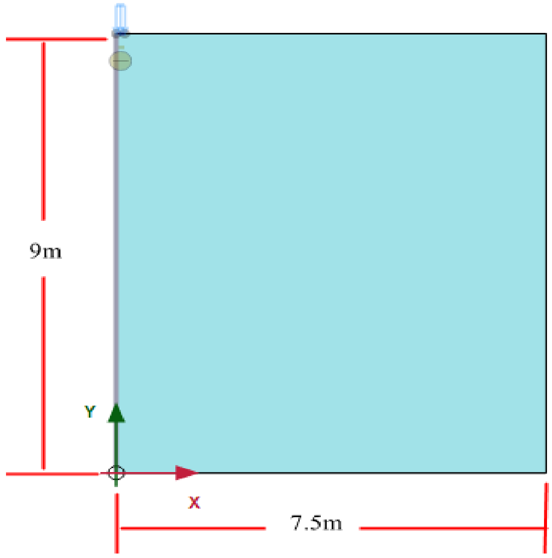

Figure 5.4 Geometry of the model, D=0.3m.

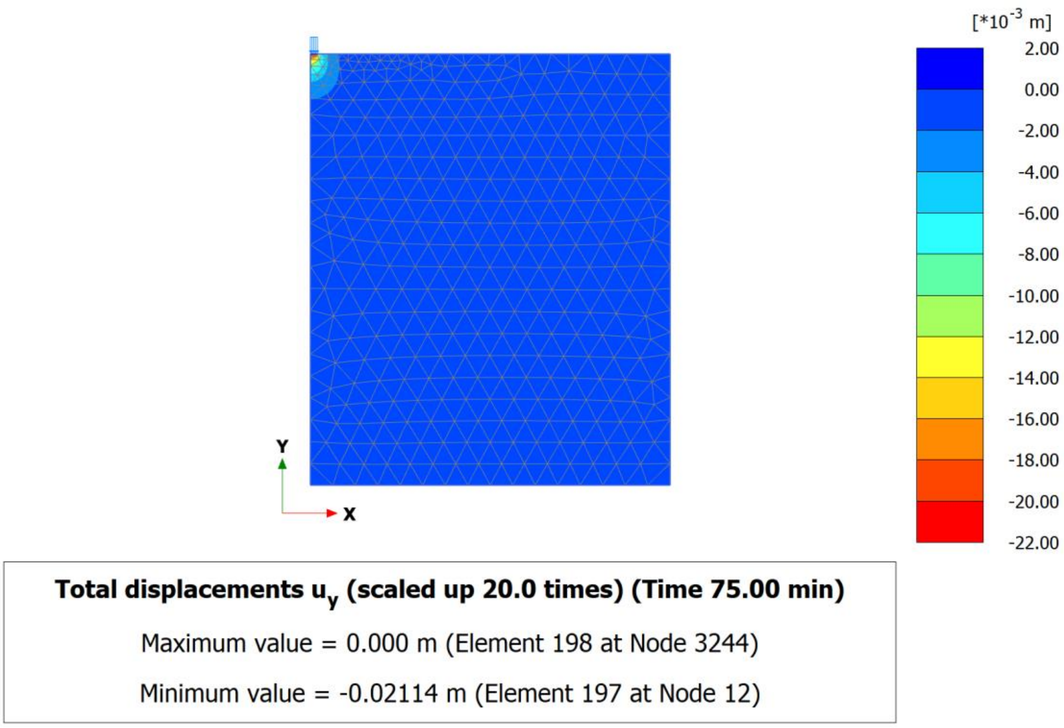

Figure 5.5 Settlement contours of Potash Evaporation Pond Design project @ TP-100 soil for maximum test load

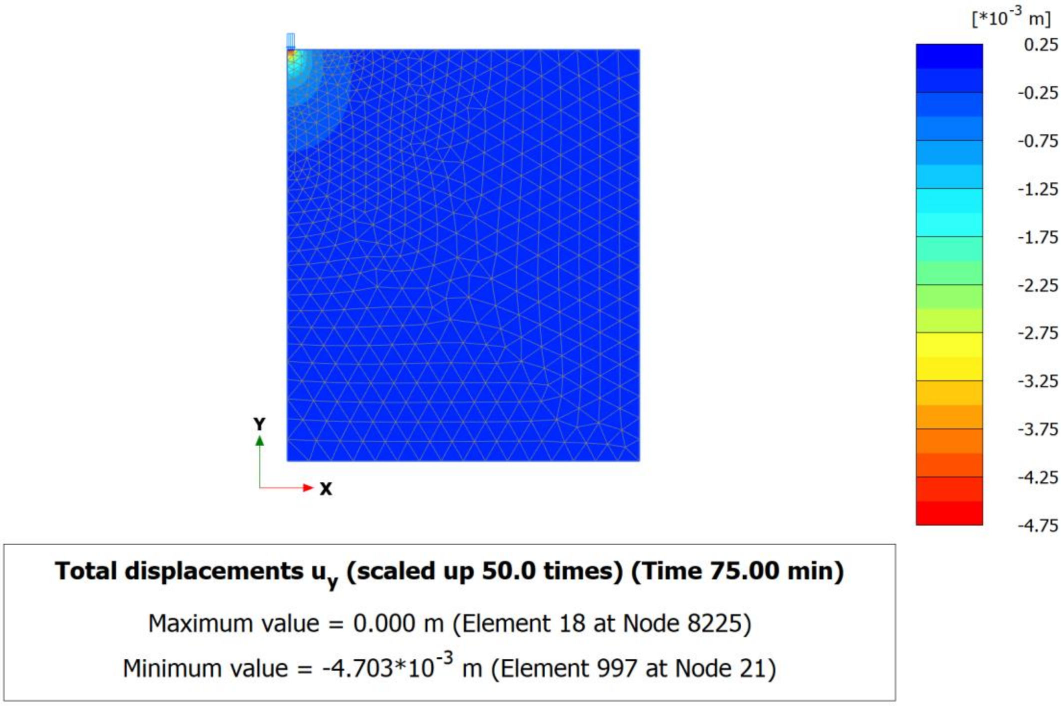

Figure 5.6 Settlement contours of Potash Evaporation Pond Design project @ TP-108 soil for maximum test load

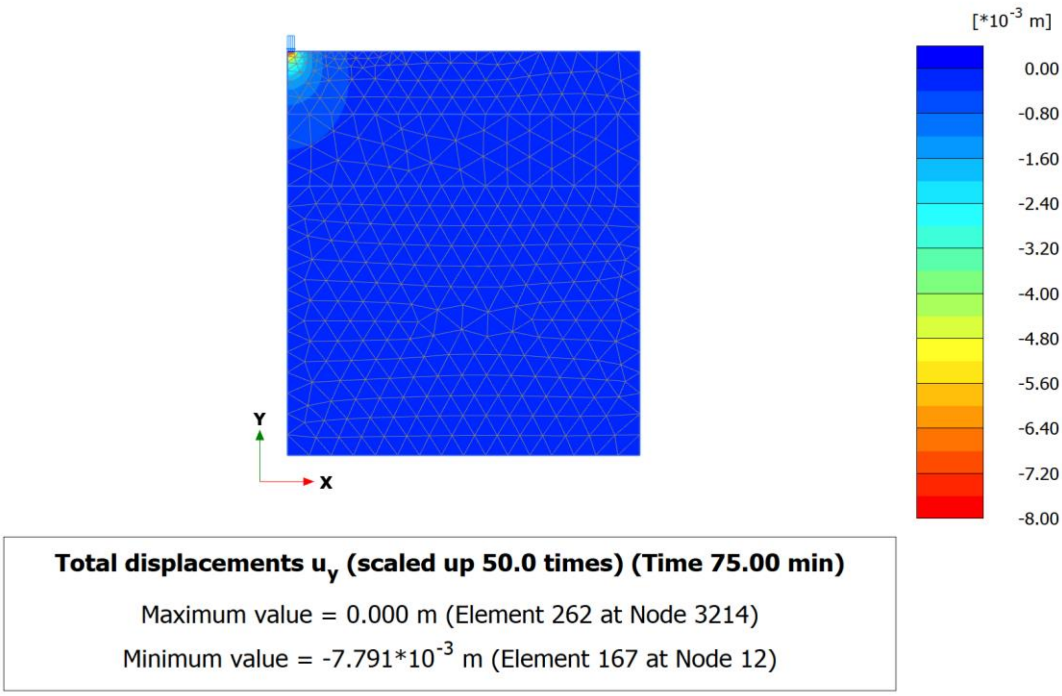

Figure 5.7 Settlement contours of Potash Evaporation Pond Design project @ TP-112 soil for maximum test load

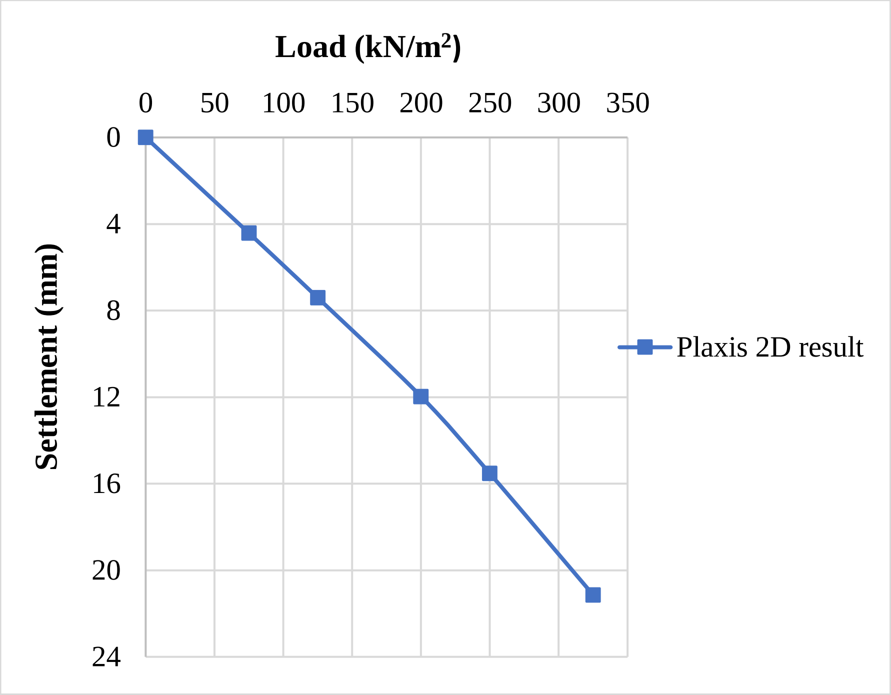

Figure 5.8 load-settlement curve from 2D FEA for TP-100, Potash Evaporation Pond Design project

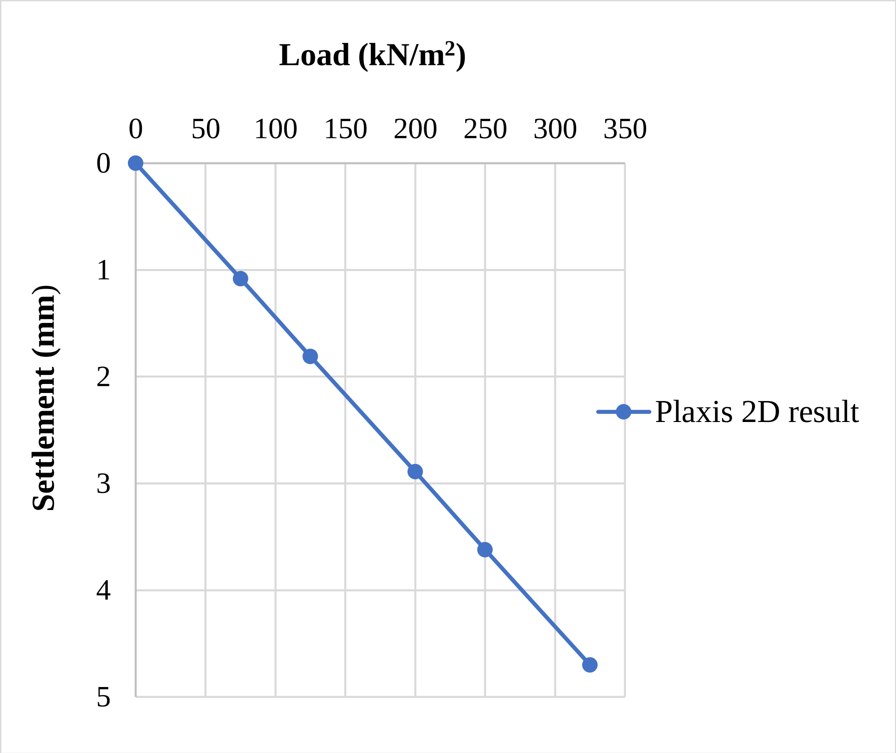

Figure 5.9 load-settlement curve from 2D FEA for TP-108, Potash Evaporation Pond Design project

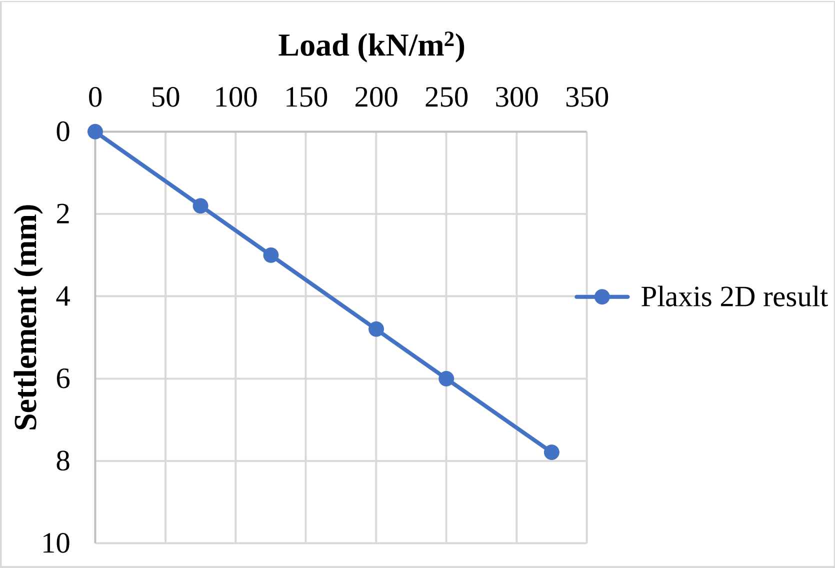

Figure 5.10 load-settlement curve from 2D FEA for TP-112, Potash Evaporation Pond Design project

5.1.2 Finite Element Analysis result of a plate load test Using PLAXIS 3D

5.1.2.1 Effluent Treatment Plant Project

The tests were conducted using diameter of 0.6m steel plate. Due to this the geometry dimension of the model is 30m in horizontal (X and Y) direction and 18m in vertical direction.

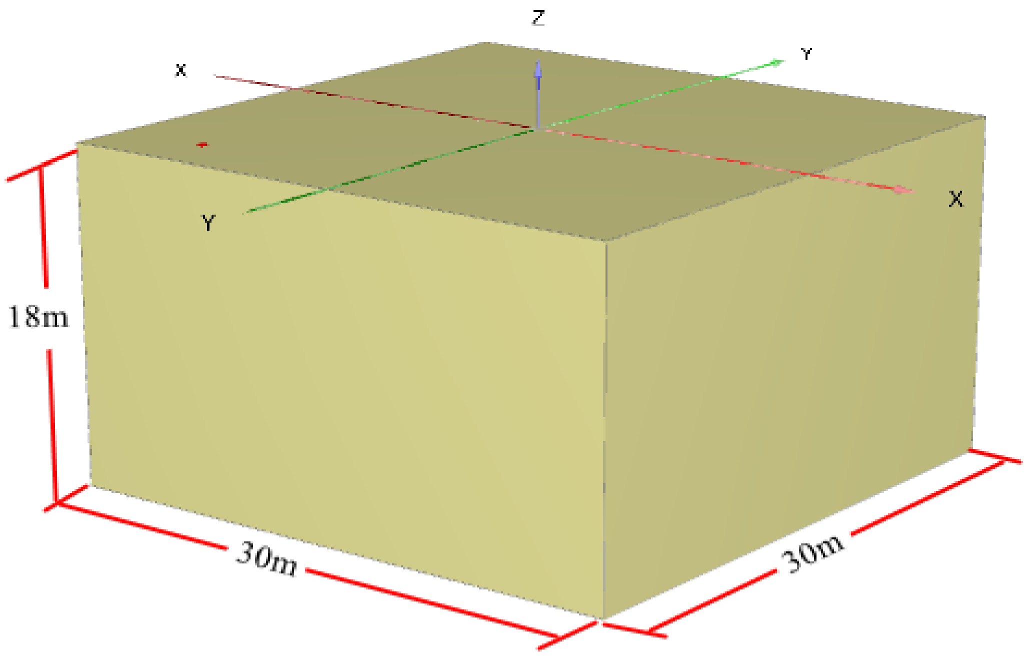

Figure 5.11 Geometry of the model, D=0.6m.

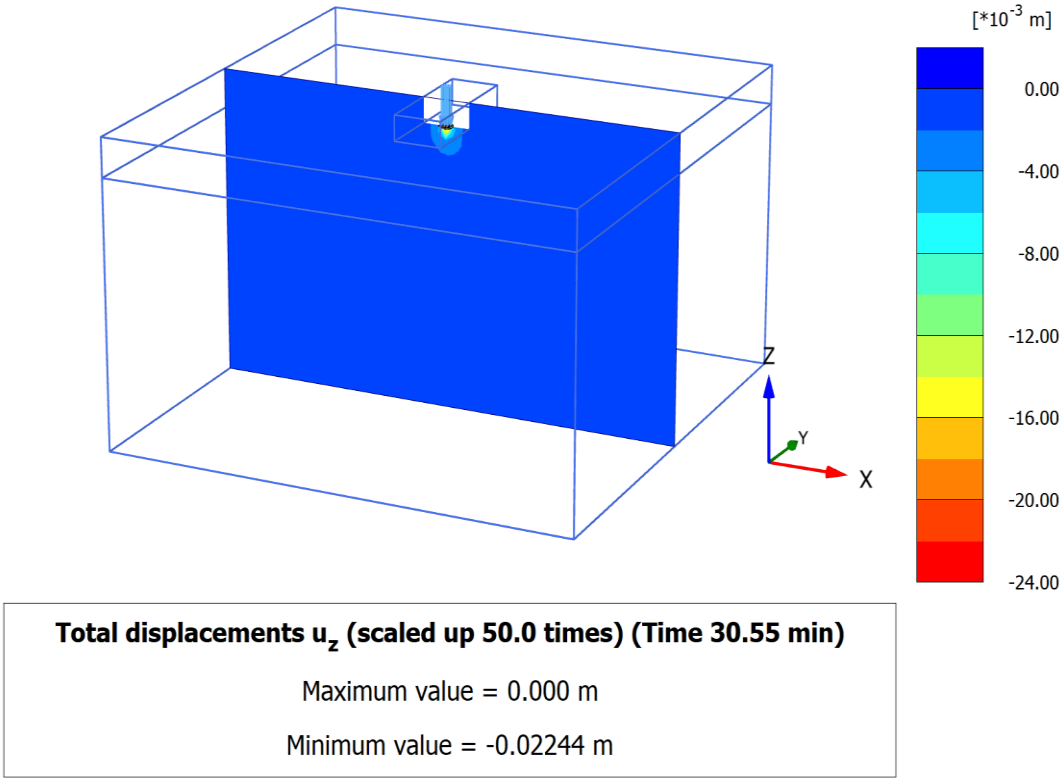

Figure 5.12 Settlement contours of Effluent Treatment Plant Project soil (cross section) for maximum test load

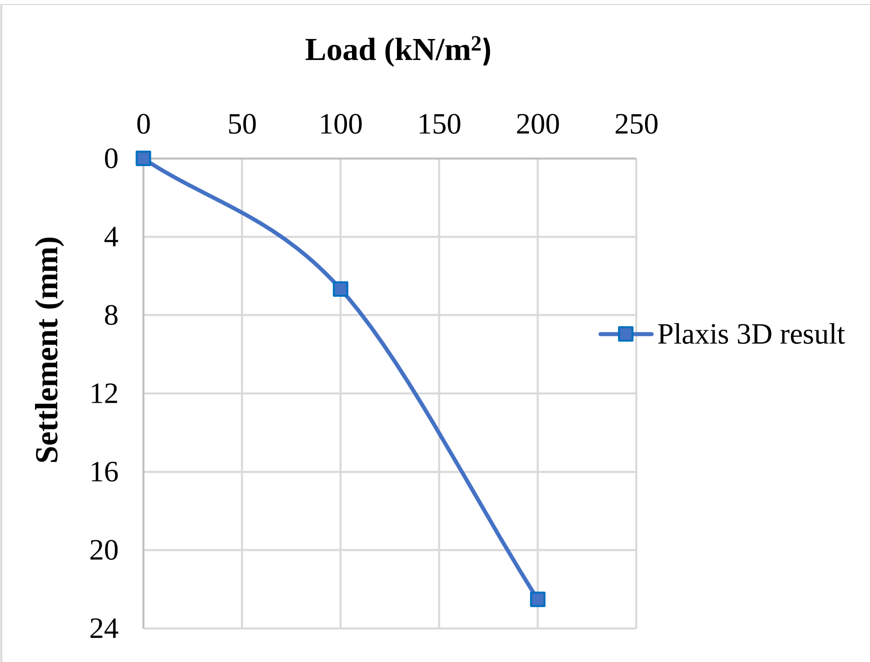

Figure 5.13 load-settlement curve from 3D FEA for Effluent Treatment Plant Project

5.1.2.2 Potash Evaporation Pond Design project

The tests were conducted using diameter of 0.3m steel plate. Due to this the geometry dimension of the model is 15m in horizontal (X and Y) direction and 9m in vertical direction.

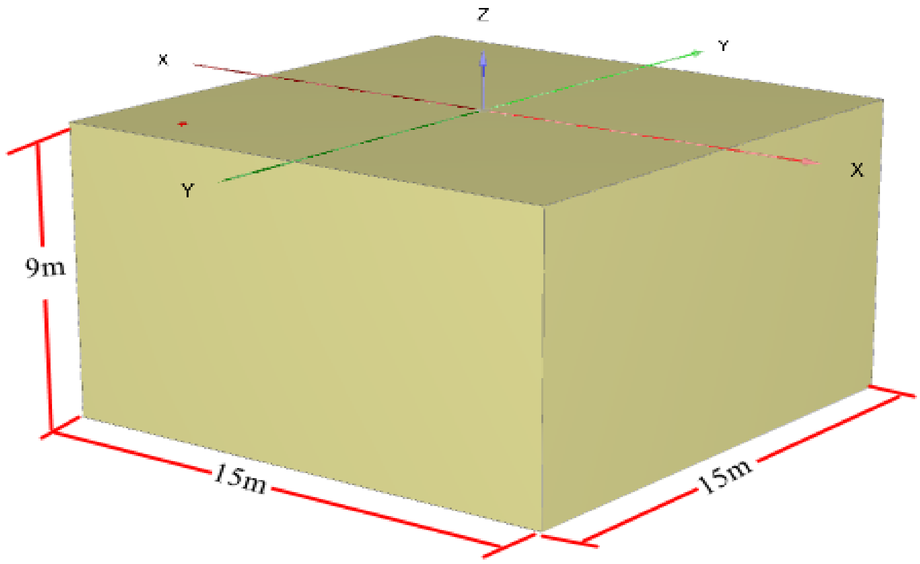

Figure 5.14 Geometry of the model, D=0.3m.

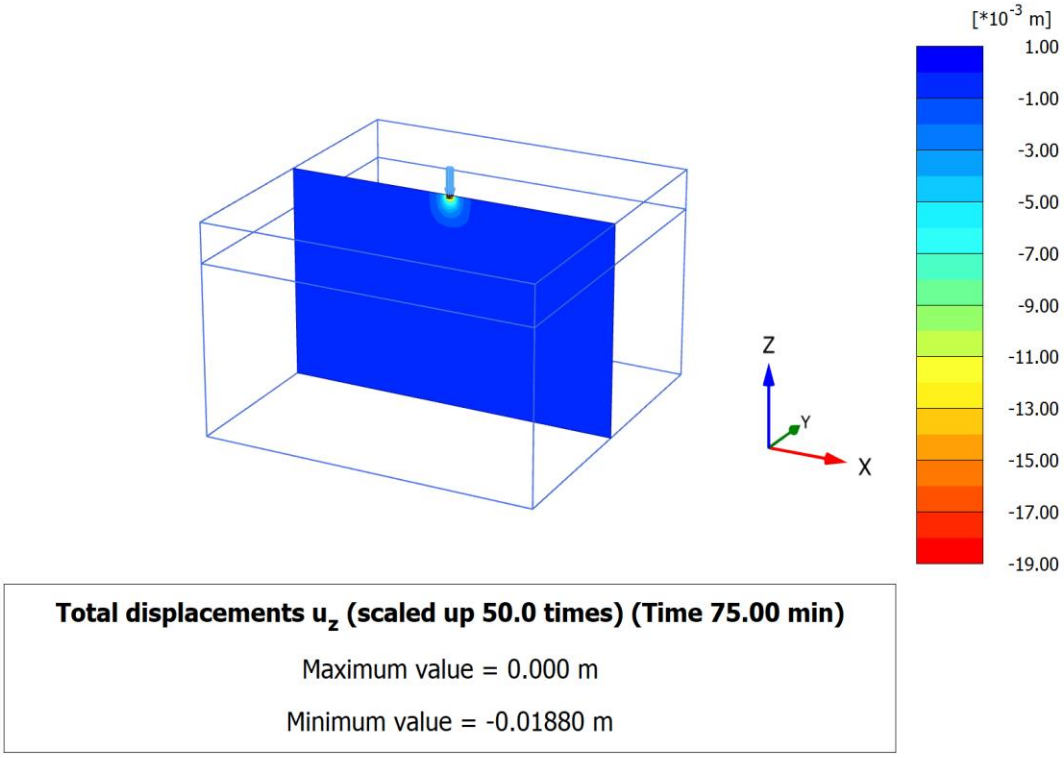

Figure 5.15 Settlement contours of TP-100 soil (cross section) for maximum test load

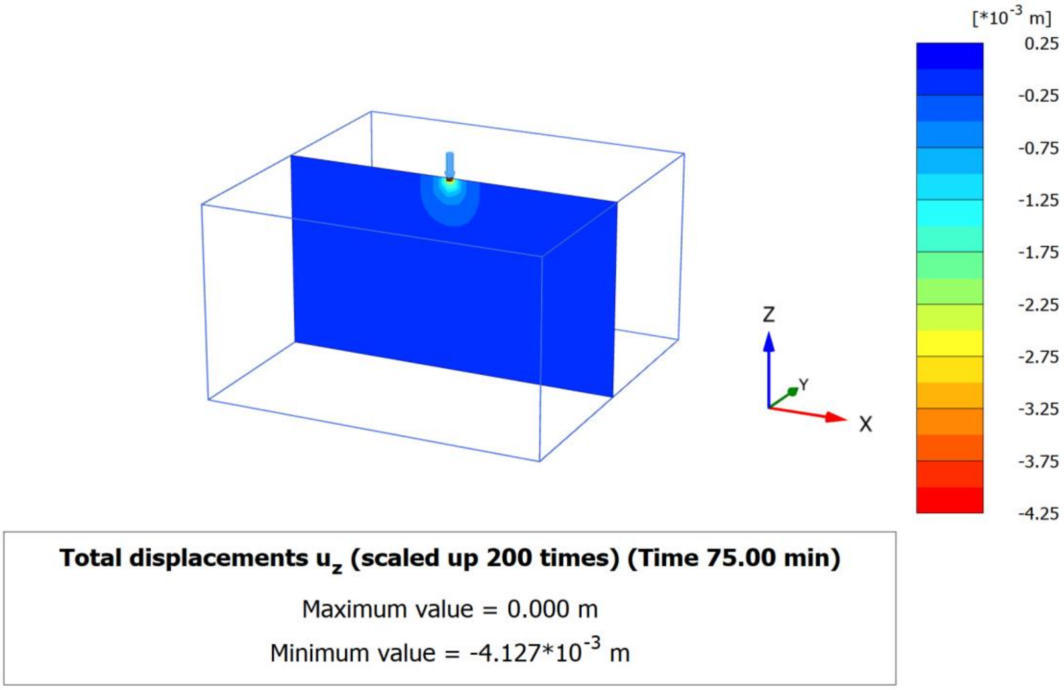

Figure 5.16 Settlement contours of TP-108 soil (cross section) for maximum test load

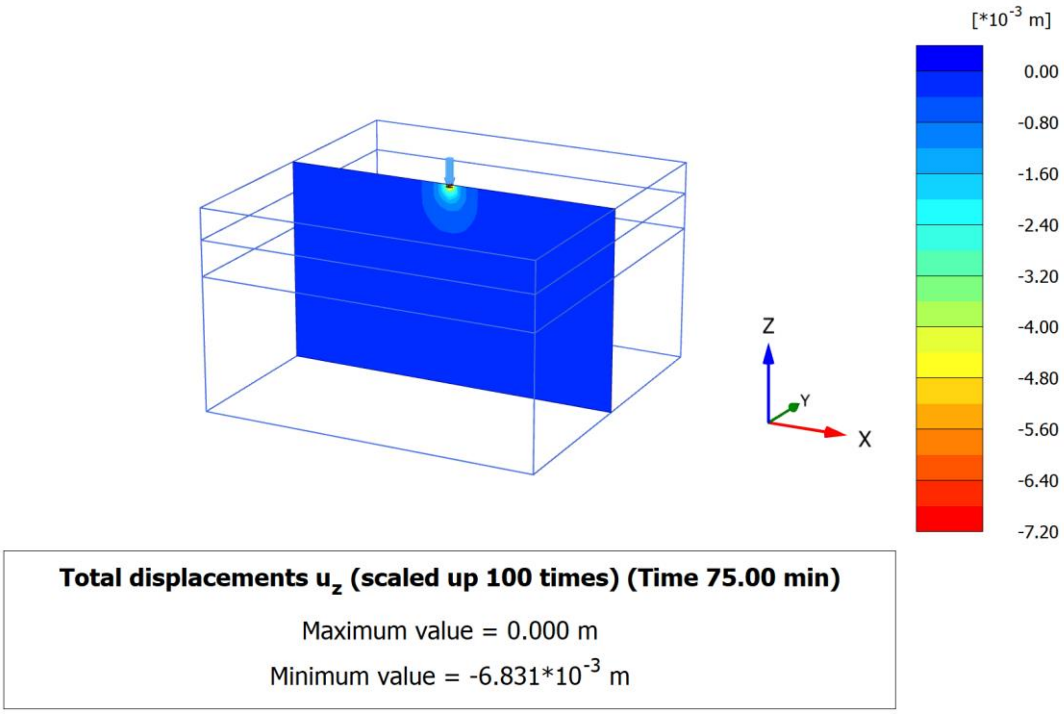

Figure 5.17 Settlement contours of TP-112 soil (cross section) for maximum test load

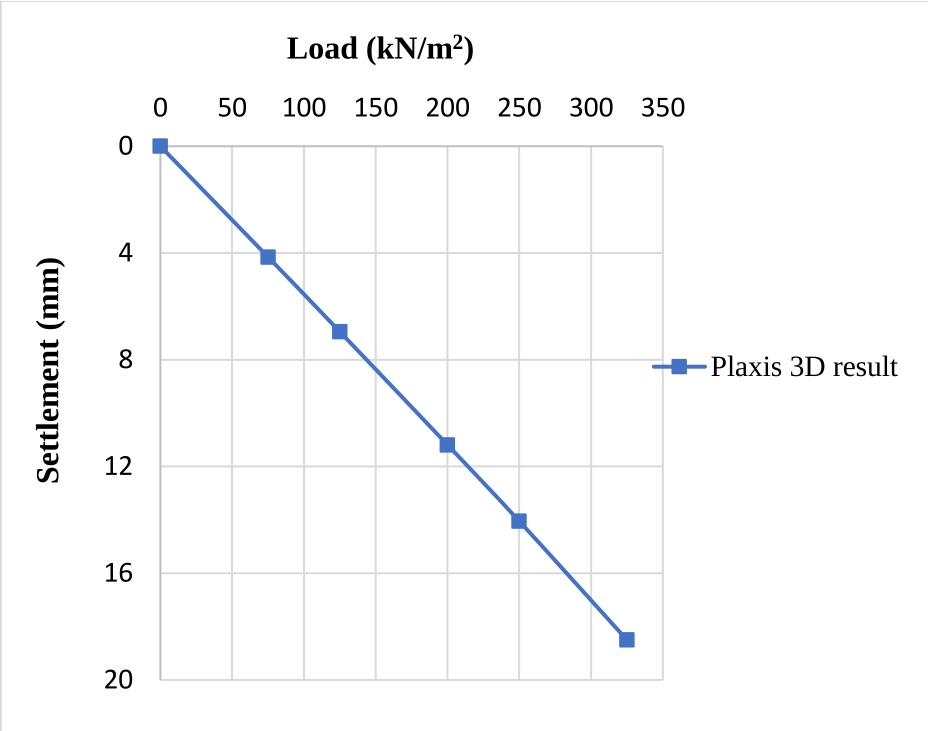

Figure 5.18 load-settlement curve from 3D FEA for TP-100, Potash Evaporation Pond Design project

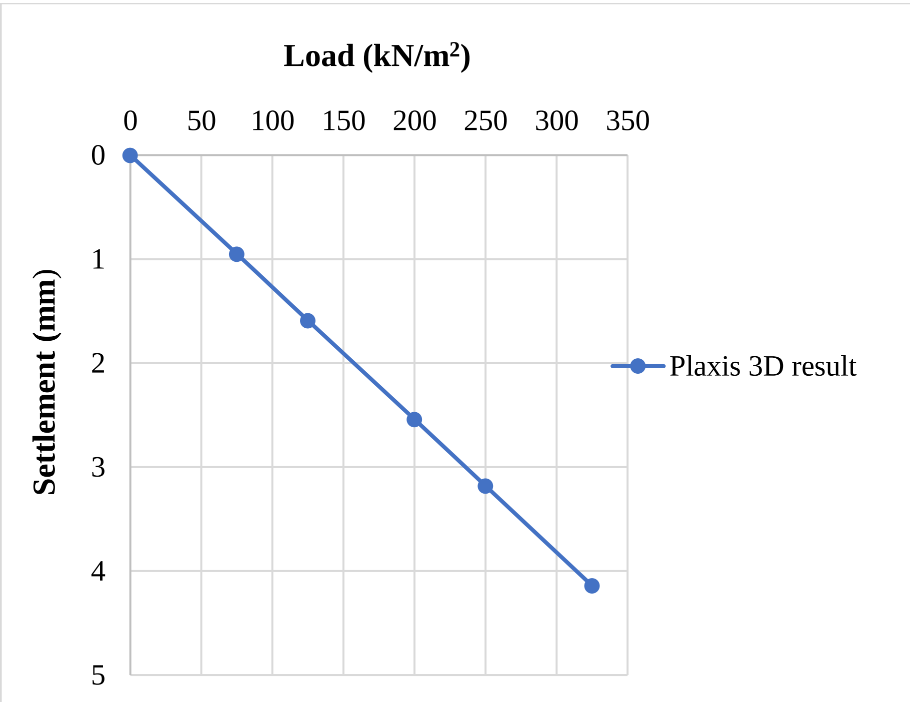

Figure 5.19 load-settlement curve from 3D FEA for TP-108, Potash Evaporation Pond Design project

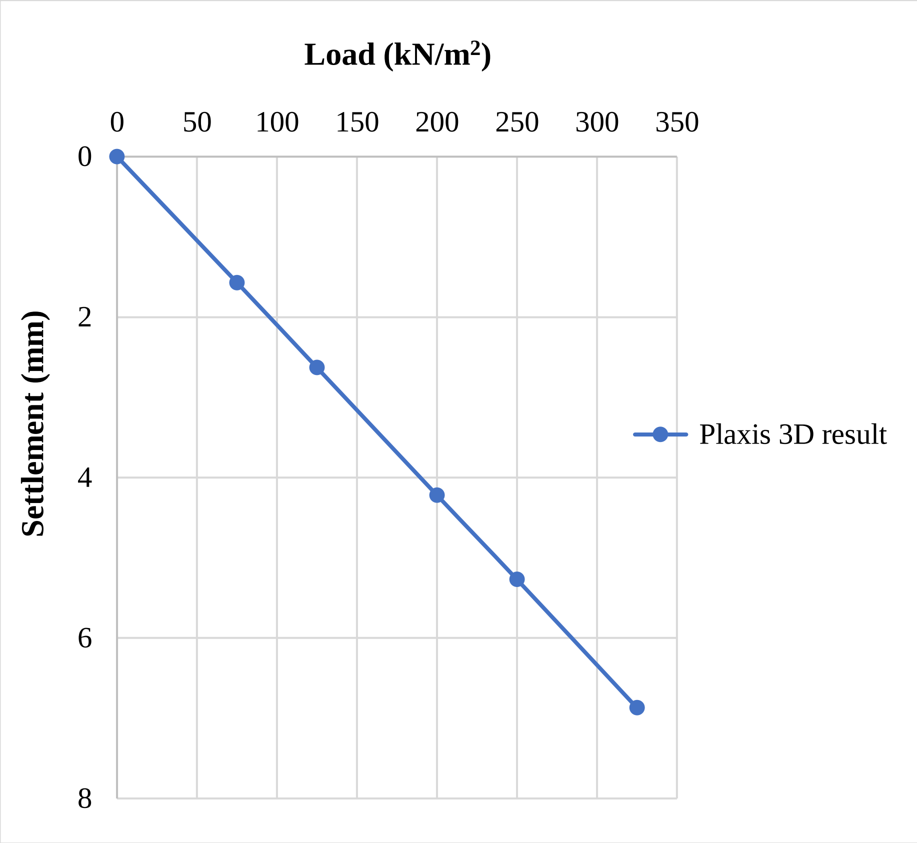

Figure 5.20 load-settlement curve from 3D FEA for TP-112, Potash Evaporation Pond Design project

5.2 Validation of FEM Result

The validation is carried out to evaluate the efficiency analysis of the numerical results using the program for predicting the behavior of the experimental data. The case study for validation was selected from the field tests performed by Addis geosystem plc. And to carry validation the load-settlement response obtained from both PLAXIS 2D and 3D numerical analysis is compared with experimental test, shown in Figure 5.21 to Figure 5.24 and Comparison of finite element analysis results with field plate load test was made basing on vertical settlement corresponding to maximum, shown Table 5.1.

5.2.1 Effluent Treatment Plant Project

Plate is loaded up to 200 KN/m^2 load. The stage wise loading is applied by load increments of 100 and 200 kN/m^2 at the plate and the observed settlement for the corresponding loads was plotted.

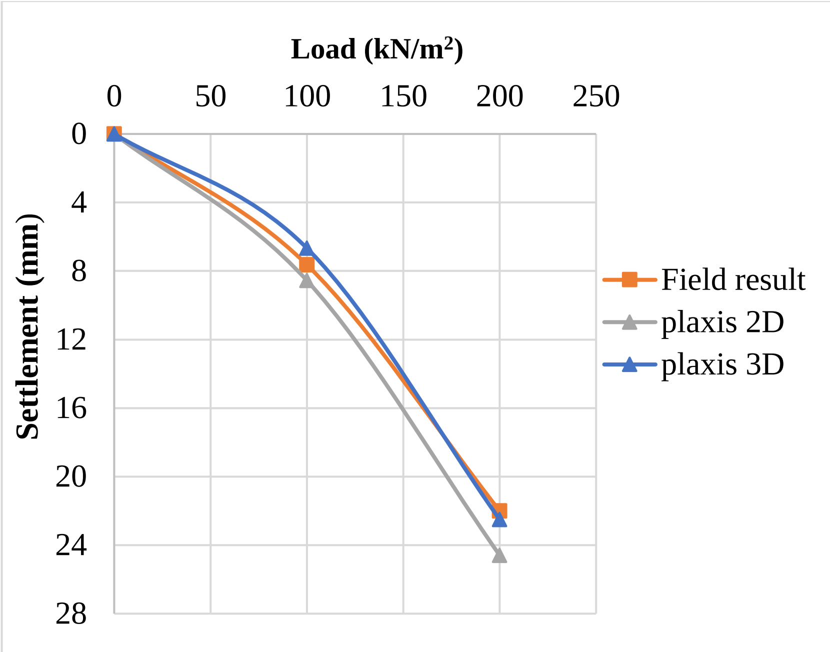

Figure 5.21 The load-settlement response of experimental test and finite element analysis of the Effluent Treatment Plant Project

5.2.2 Potash Evaporation Pond Design project

Plate is loaded up to 325 kN/m^2 load. The stage wise loading is applied by load increments of 75,125,200,250 and 200 kN/m^2 at the plate and the observed settlement for the corresponding loads was plotted.

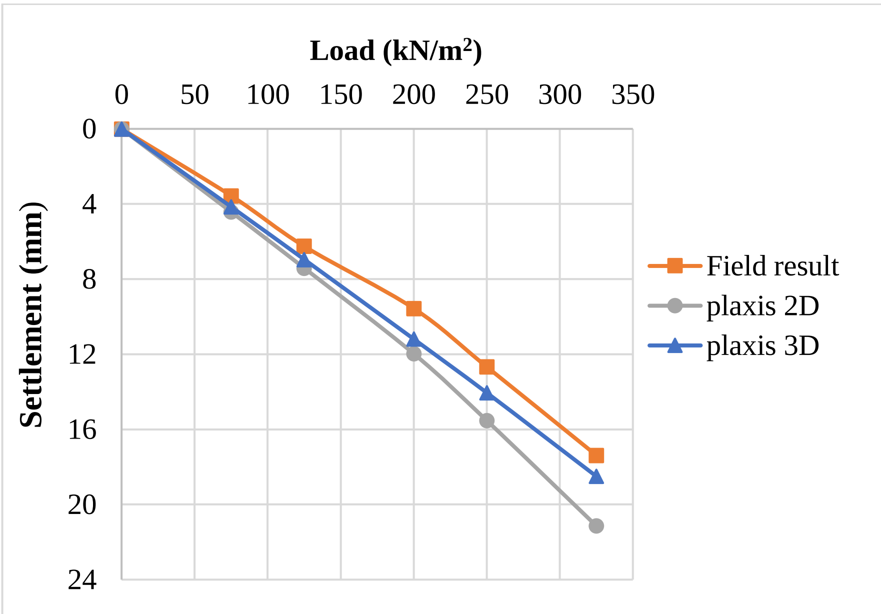

Figure 5.22 The load-settlement response of experimental test and finite element analysis of the Potash Evaporation Pond Design project, @TP-100)

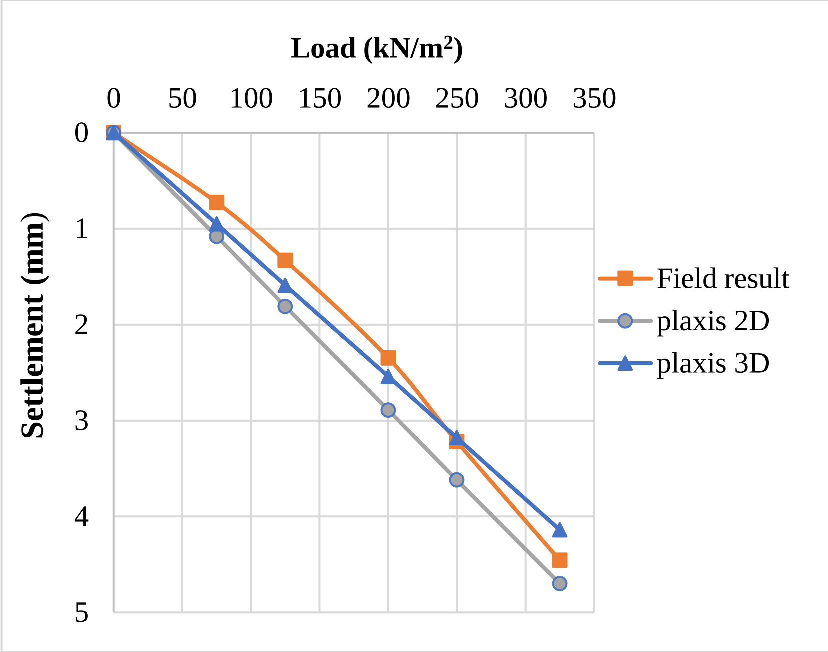

Figure 5.23 The load-settlement response of experimental test and finite element analysis of the Potash Evaporation Pond Design project, @TP-108)

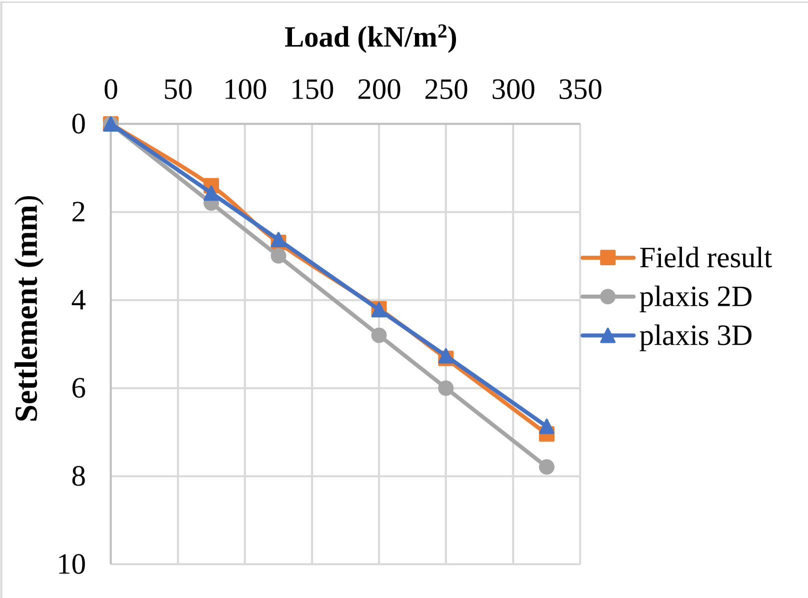

Figure 5.24 The load-settlement response of experimental test and finite element analysis of the Potash Evaporation Pond Design project, @TP-112)

From the above load settlement plot (Figure 5.21 to Figure 5.24), It can be seen that the experimental and the numerical curve are more or less similar for the plate load test investigated.

Comparison of finite element analysis results with field plate load test was made basing on vertical settlement corresponding to maximum test load (ultimate load up to which the plate load test was carried out) 200 kN/m^2 for Effluent Treatment Plant Project and 325 kN/m^2 for Potash Evaporation Pond Design project and presented in a tabular form as shown in Table 5.1

Table 5.1 Comparison of vertical settlement 2D, 3D and field test

<table>
<tr><th colspan="2" rowspan="2">project</th><th colspan="3">Vertical settlement (mm)</th><th rowspan="2">Difference (%) of plaxis 2D with field result</th><th rowspan="2">Difference (%) of plaxis 3D with field result</th></tr>
<tr><th>Field result</th><th>Plaxis 2D analysis</th><th>Plaxis 3D analysis</th></tr>
<tr><td colspan="2">Effluent Treatment Plant</td><td>23.12</td><td>24.6</td><td>22.12</td><td>6.01</td><td>-4.52</td></tr>
<tr><td rowspan="3">Potash Evaporation Pond Design</td><td>TP-100</td><td>17.38</td><td>21.14</td><td>18.5</td><td>17.79</td><td>6.05</td></tr>
<tr><td>TP-108</td><td>4.46</td><td>4.7</td><td>4.14</td><td>5.12</td><td>-7.73</td></tr>
<tr><td>TP-112</td><td>7.04</td><td>7.79</td><td>6.87</td><td>9.63</td><td>-2.47</td></tr>
</table>

As it is shown in Table 5.1, the difference value obtained from the finite element analysis and field plate load test for the Effluent Treatment Plant project is 6.01 % and -4.52 % using plaxis 2D and 3D respectively. From the same table, difference value obtained from the finite element analysis and field plate load test for the Potash Evaporation Pond Design project at TP-100, TP-108 and TP-112 are 17.79 %, 5.12 % and 9.63 % respectively using plaxis 2D and 6.05 %, -7.73 % and -2.47 % respectively using plaxis 3D. Here the positive %age difference value shows that the percentage increase in Plaxis with that of field result and the negative values shows that increase in field result than that of the Plaxis.

The result of the two – dimensional and three – dimensional models are close to field test results. thus, the results of the Plaxis program fit with measured results and the finite element results is validated. For all plate load test, numerical analysis results obtained using PLAXIS 3D shows a closer result towards the actual load test as compared with the other results obtained using PLAXIS 2D. It is very clear that the above correlation techniques and FEM analysis models i.e., Linear Elastic & Mohr- Coulomb models are the best models to predict realistic load- settlement behavior of plate load test. But it is necessary to perform more analyses of static plate load test to give general recommendation.

5.3 Parametric study

The results of plate-load tests are influenced by many factors, including the soil modulus of elasticity, soil internal angle of friction, cohesion of soil, dilatancy angle of soil, Poisson ratio of soil, plate size and roughness of the loading plate. However, studying the effects of these factors is not so easy in field tests. In this thesis study the effect of variation of the such parameters on the load-settlement behavior of plate load test is conducted and the results are shown below.

5.3.1 Effect of Plate Size

Plate load test at Potash Evaporation Pond Design project, TP-100 has been chosen to carry out this study to evaluate the influence of plate loading test size on the finite element analysis of soil. In each numerical test, the plate size was allowed to fluctuate while the other factors were maintained constant to isolate the influence of size. Five finite element calculations were done to expand the connection between applied pressure and settlement, as shown in Figure 5.36, and different values of plate size were explored in order to study the influence of plate size on the soil. This parameter has been set to diameter 0.3m,0.4m,0.5m,0.6m, and 0.7m.

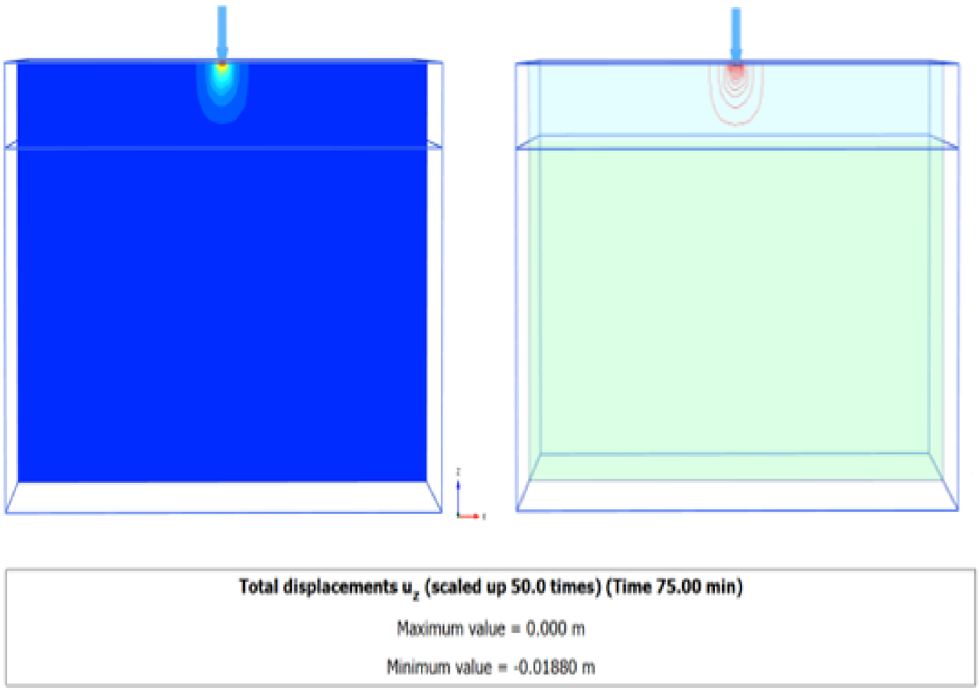

Figure 5.25 Distribution of deformations in soil for D=30cm

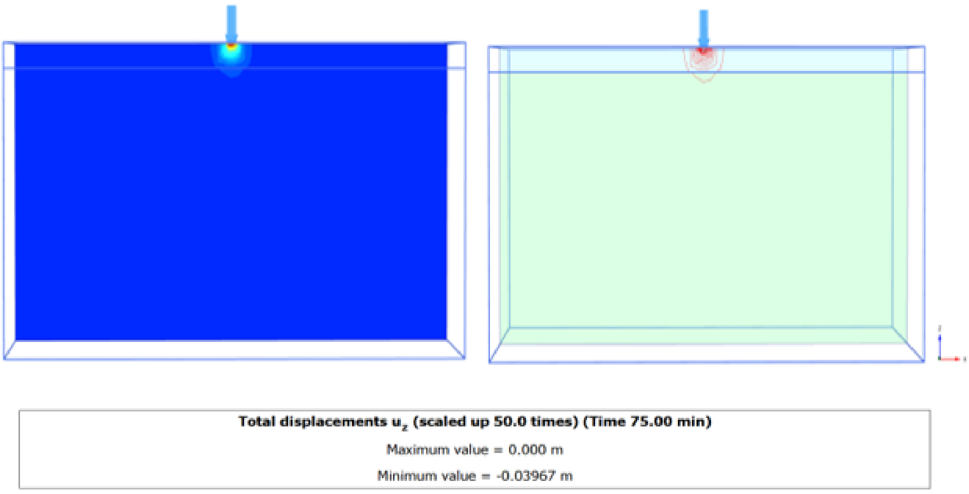

Figure 5.26 Distribution of deformations in soil for D=70cm

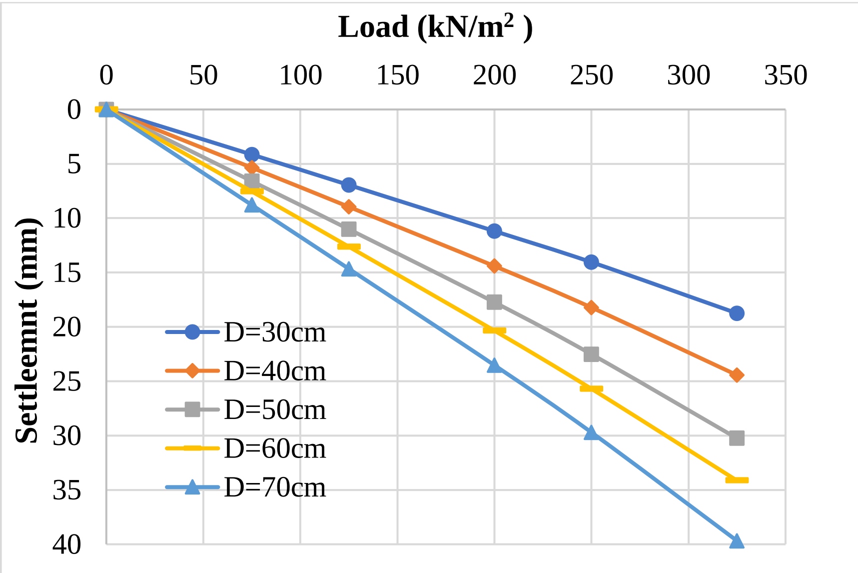

Figure 5.27 Relationship between load & settlement for different plate size

Figure 5.27 presents the relationship between load and settlement for different plate dimension under same load per unit area and soil condition. It is observed from the above figure that for large plate diameters, settlement increases proportionally with the size of the plate dimensions.

Figure 5.25 and Figure 5.26 show the Distribution of deformations in soil obtained from the numerical investigation at maximum testing load using different plate dimension and it observed that the larger the plate size, the larger the deforming soil mass beneath the plate, which results in larger settlements. It is thus imperative that the size of plate is chosen carefully taking into account the site-specific project requirements.

5.3.2 Effect of Plate Roughness

Not only the interparticle friction coefficients but also the friction between the loading plate and underlying granular particles has an appreciable influence on the test results. Interface element is used to simulate the relative friction between plate and soil. According to (CONNECT Edition 20.04 PLAXIS 3D-Reference Manual, 2020) the roughness of the interaction is modeled by selecting an appropriate value for the strength reduction factor (R_{inter}) in the interface.

The interface strength i.e., R_{int} varies between 0 to 1, 0 represents smooth interface (i.e., no shear strength is developed), and 1 represents rigid interface (i.e., no relative displacement between the layers). In practical (on field), the interface lies between the 0 and 1. The R_{int} is evaluated in the laboratory using direct shear test or may be decided based on the type of the soil (engineering judgment helps).

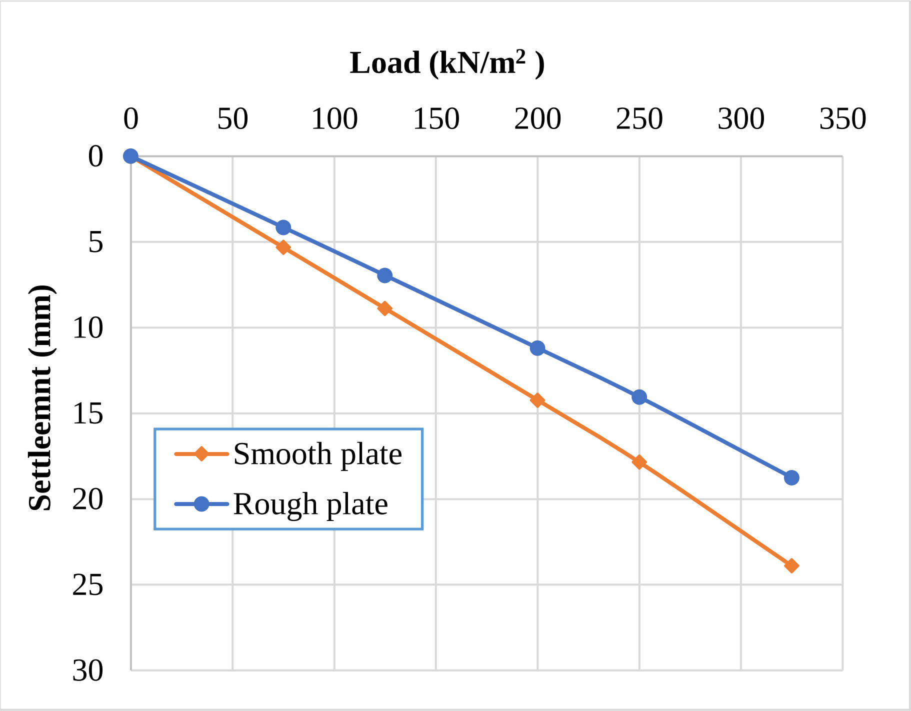

Figure 5.28 Comparison of FEM results based on smooth and rough plates

Figure. 5.28 compares the numerical results obtained from FEM plate-load tests performed with smooth and rough plates. It can be seen that the settlement is higher when the loading plate is smooth than those with a rough plate. And in numerical modelling, it is necessary to take into account the coefficient of strength reduction in the interface in order to correctly simulate moving contact between the structure and the soil.

5.3.3 Effect of Soil Modulus of Elasticity

Parametric study on the FEM analysis has been carried out by varying modulus of elasticity of the soil layers. For this study only the analysis done using 3D plaxis has been considered on selected plate load test i.e., TP-100 Potash Evaporation Pond Design project. The effect of changing the soil modulus of elasticity on the load settlement response is shown in Figure 5.29.

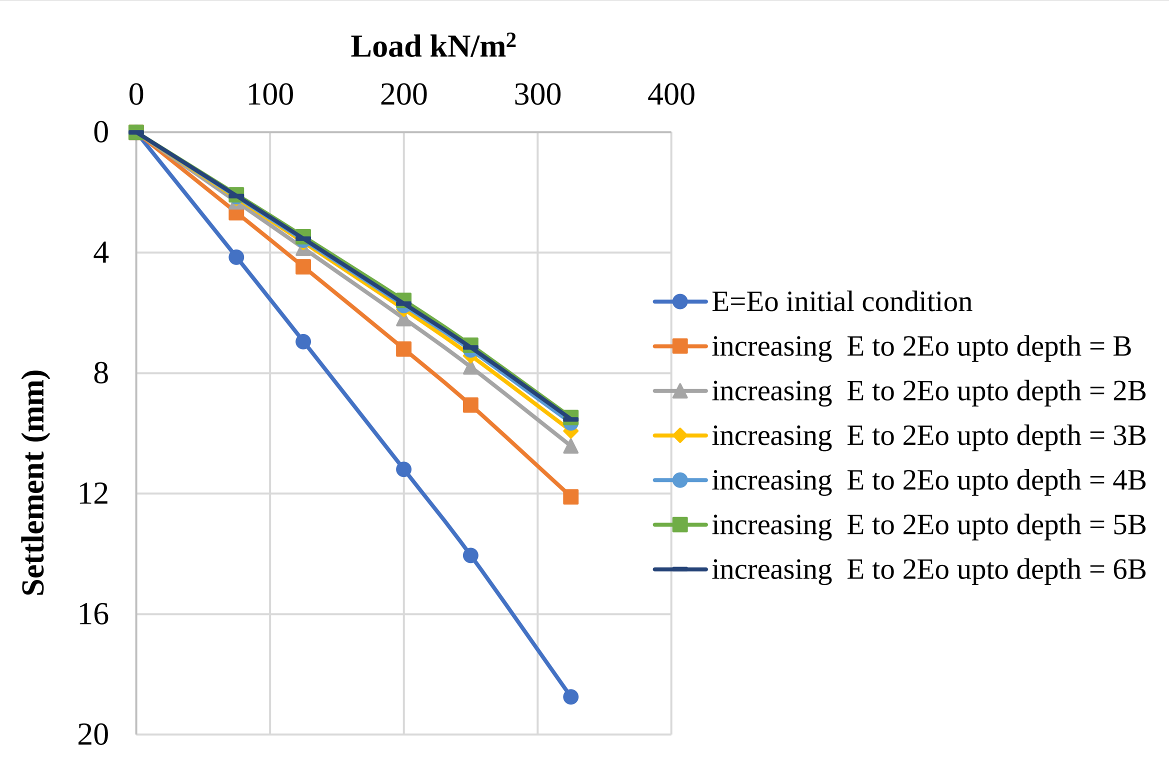

Figure 5.29 Effect of elastic modulus of soil below of bottom of plate (2E)

Figure 5.29 presents the relationship between load and settlement for varying parameter modulus of elasticity of the soil located below the base of the plate up to depth six times of plate width (6B) under same load per unit area and other soil condition. It is observed from the above Figure that for modulus of elasticity, settlement decrease proportionally with the increase of the elastic modulus of soil located below the base of the plate up to depth two times of plate width (2B) and settlement have no significant change with the increase of the modulus of elasticity of soil below depth greater than two times plate width (2B). this result shows that increasing elastic modulus of soil located below depth greater than two times plate width (2B) from the base of plate do not contribute much to load settlement behavior of plate load test and demonstrates that the FPLT results can determine the character of soil located within a depth of less than two times the width of the bearing plate.

5.3.4 Effect of Soil Angle of Internal Friction

Effect of friction angle of a soil, ϕ, on the load settlement graph of a soil model was seen by varying values of the friction angle as ϕ, 1.2ϕ, 1.5ϕ and 2ϕ. For this study only the analysis done using 3D plaxis has been considered on selected plate load test i.e., Effluent Treatment Plant project. The result is presented in Figure 5.30 below.

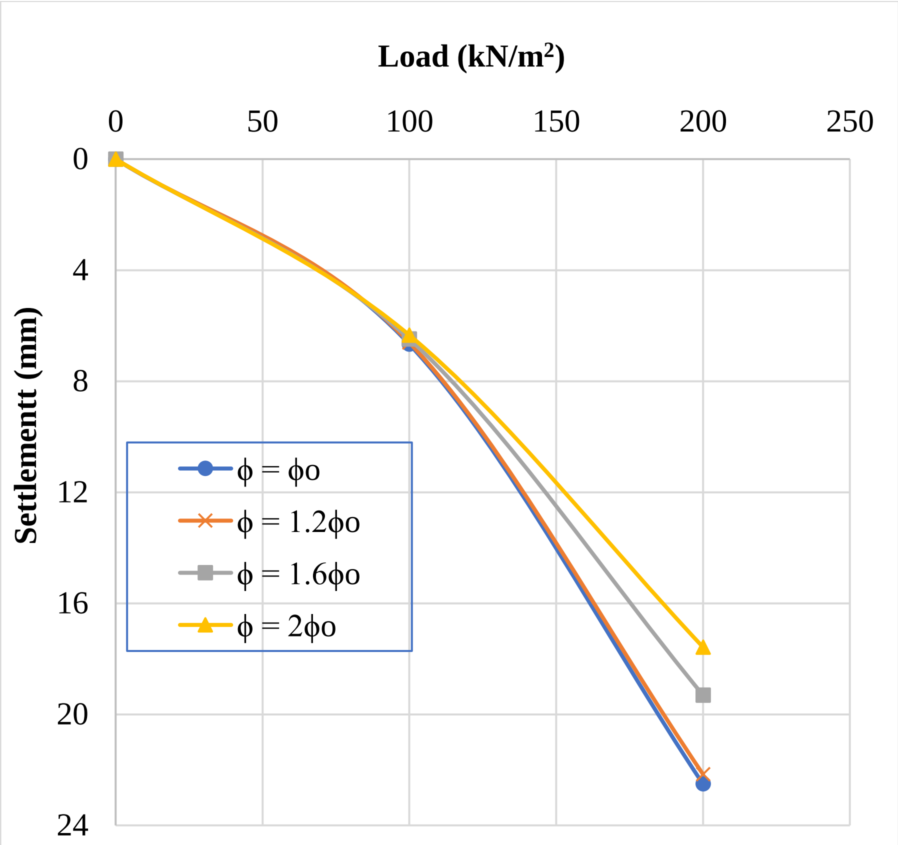

Figure 5.30 influence of angle of internal friction on the load settlement relationship

Figure 5.30 Presents the relationship between load and settlement for varying parameter internal friction angle. It is observed that increasing the friction angle of a soil increase in resistance for a given settlement. The nature of the graph in the elastic deformation remains the same for all the cases of ϕ taken for the parametric study.

5.3.5 Effect of Soil Cohesion

Effect of cohesion of a soil, C, on the load settlement graph of a soil model was seen by varying values of the cohesion as Co, 1.5Co and 2Co. For this study only the analysis done using 3D plaxis has been considered on selected plate load test i.e., Effluent Treatment Plant project. The result is presented in Figure 5.31 below.

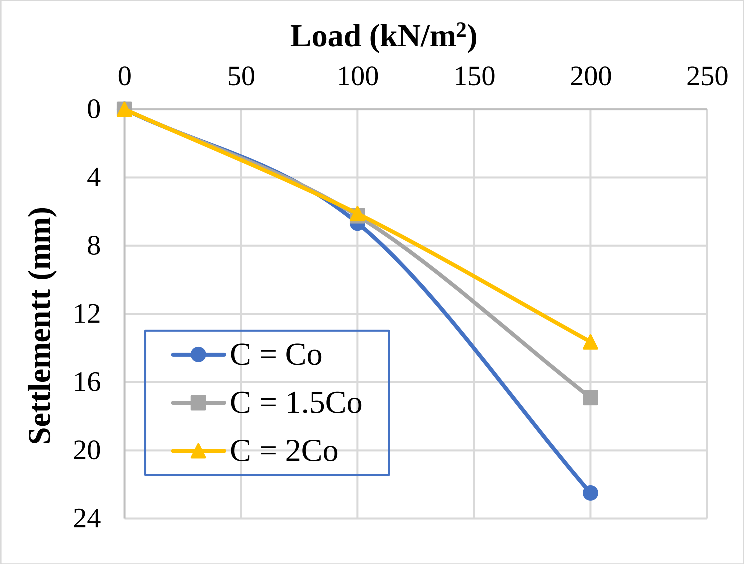

Figure 5.31 Influence of cohesion of soil on the load settlement relationship

The effect of variation soil cohesion on load against the settlement curve is shown in Figure 5.31, and it is obvious that the settlement decreases significantly with variation cohesion of soil from (C = Co to C = 2Co).

5.3.6 Effect of Soil Dilatancy

Effect of soil dilatancy, ψ, was assessed by examining the load settlement response for varying soil dilatancy. To study this, plate load test TP-100 from potash evaporation pond design project is taken. Different values of ψ, ranging from ψ = 0 to ψ = ϕ has been taken and the corresponding effect on load settlement curve is shown in Figure 5.32.

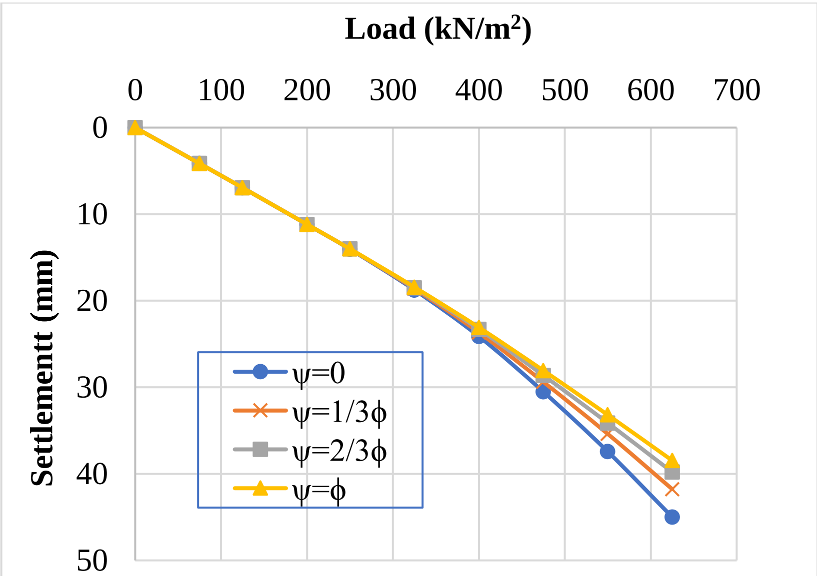

Figure 5.32 Influence of dilatancy angle of soil on the load settlement relationship

Figure 5.32 present the effect of variation soil dilatancy angle on load against the settlement curve, it is observed that resistance for a given settlement in the non-dilatant soil ($\psi = 0$) decreased, which means varying values of the dilatancy angle of soil from ($\psi = 0$ to $\psi = \phi$) increase in the resistance force.

5.3.7 Effect of Soil Poisson's Ratio

The effect of Poisson's ratio of soil on the load settlement response of plate load test was seen by varying values of the Poisson's ratio of soil from (0.25 to 0.4). For this study only the analysis done using 3D plaxis has been considered on selected plate load test i.e., Effluent Treatment Plant project. The result is presented in Figure 5.33 below

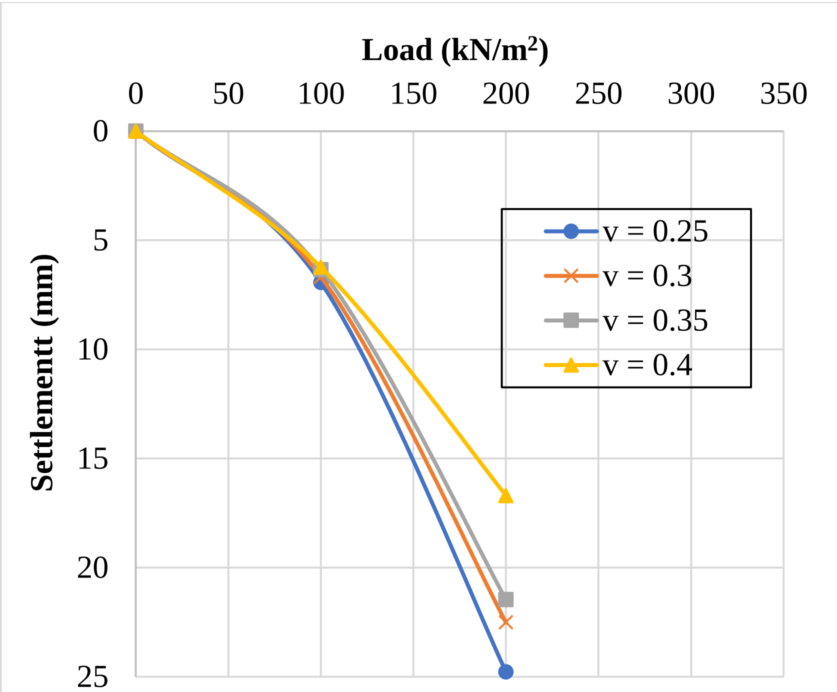

Figure 5.33 Influence of Poisson's ratio of soil on the load settlement relationship

The effect of Poisson's ratio of soil on the load settlement response of foundation is shown in Figure 5.32, it was observed that the effect is slight at small settlements of the plate, whereas it showed significant effect at large settlements. It seems that increasing of Poisson's ratio from (0.25 to 0.4) decrease gradually the settlement.

6 CONCLUSION AND RECOMMENDATION

6.1 Conclusions

It has been shown that it is possible to simulate load-settlement behavior of field plate load. This has been implemented using the PLAXIS 2D and PLAXIS 3D software packages. The following are some general conclusions made from the findings:

- Numerical simulations of plate load test in both PLAXIS 2D and PLAXIS 3D is an efficient way to evaluate the load-settlement behavior and gives the best convergence to test results.
- The models incorporated in FEM which are Mohr-Coulomb for soils and linear elastic for plate perfectly validated/simulated the plate load test results.
- Understanding and selection of the appropriate material model and input parameters for FEM are extremely important and will badly affect the results if not given proper consideration.
- It is concluded that the distance between the symmetry axis and the vertical outer boundary, should be equal or higher than 25D and the distance between the surface and the rigid layer, should be equal or higher than 30D. It is observed that settlement results have been affected when analyses performed with closer limits.
- The results observed with plate load test models in PLAXIS 3D are comparably better as of PLAXIS 2D models.
- FEA plate-load tests with different sizes of loading plates show that proportional increase in the settlement with increasing a plate width. The larger the plate size, the larger the deforming soil mass beneath the plate, which results in larger settlements.
- The settlement is higher when the loading plate is smooth than those with a rough plate.
- Settlement decreases proportionally with the increase of the elastic modulus of soil located below the base of the plate up to depth two times of plate width (2B) and settlement have no significant change with the increase of the modulus of elasticity of soil below depth greater than two times plate width (2B). This result shows that increasing elastic modulus of soil located below depth greater than two times plate width (2B) from the base of plate do not contribute much to load settlement behavior of plate load test and demonstrates that the field plate load test results can determine the character of soil located within a depth of less than two times the width of the loading plate.

- Increasing the friction angle of a soil increase in resistance for a given settlement. The nature of the graph in the elastic deformation remains the same for all the cases of ϕ taken for the parametric study.
- Settlement decreases significantly with increase cohesion of soil.
- Increasing values of the dilatancy angle of soil from ($\psi = 0$ to $\psi = \phi$) increase in the resistance force i.e., resistance for a given settlement in the non-dilatant soil ($\psi = 0$) is small,
- Increasing of Poisson's ratio decreases gradually the settlement. The effect is slight at small settlements of the plate, whereas significant effect at large settlements.

6.2 Recommendation

This study addresses a number of issues and draws several useful conclusions. However, there are some limitations in the analyses and unresolved issues that merit further investigation. These limitations are presented here, together with some recommendations for future work.

- The majority of soil characteristics necessary for numerical analysis in this study are collected by correlation approaches described in various literatures. Only a few parameters are directly derived from the test results. This is owing to a lack of appropriate laboratory and field test findings for the various soil layers at various depths. This might be cited as a severe disadvantage in this study. A better FEM simulation result might have been produced if most soil characteristics were acquired directly from laboratory and field test data.
- Other FEM software like Abaqus, ANYSIS, and so on can be used for analysis.
- Other than Mohr-Coulomb model, advanced soil models such as Hardening Soil model, Soft Soil Creep model and user defined models can be used.

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APPENDIX

Appendix - A Sub soil profile, Bore log data and FPLT data for Effluent treatment plant project

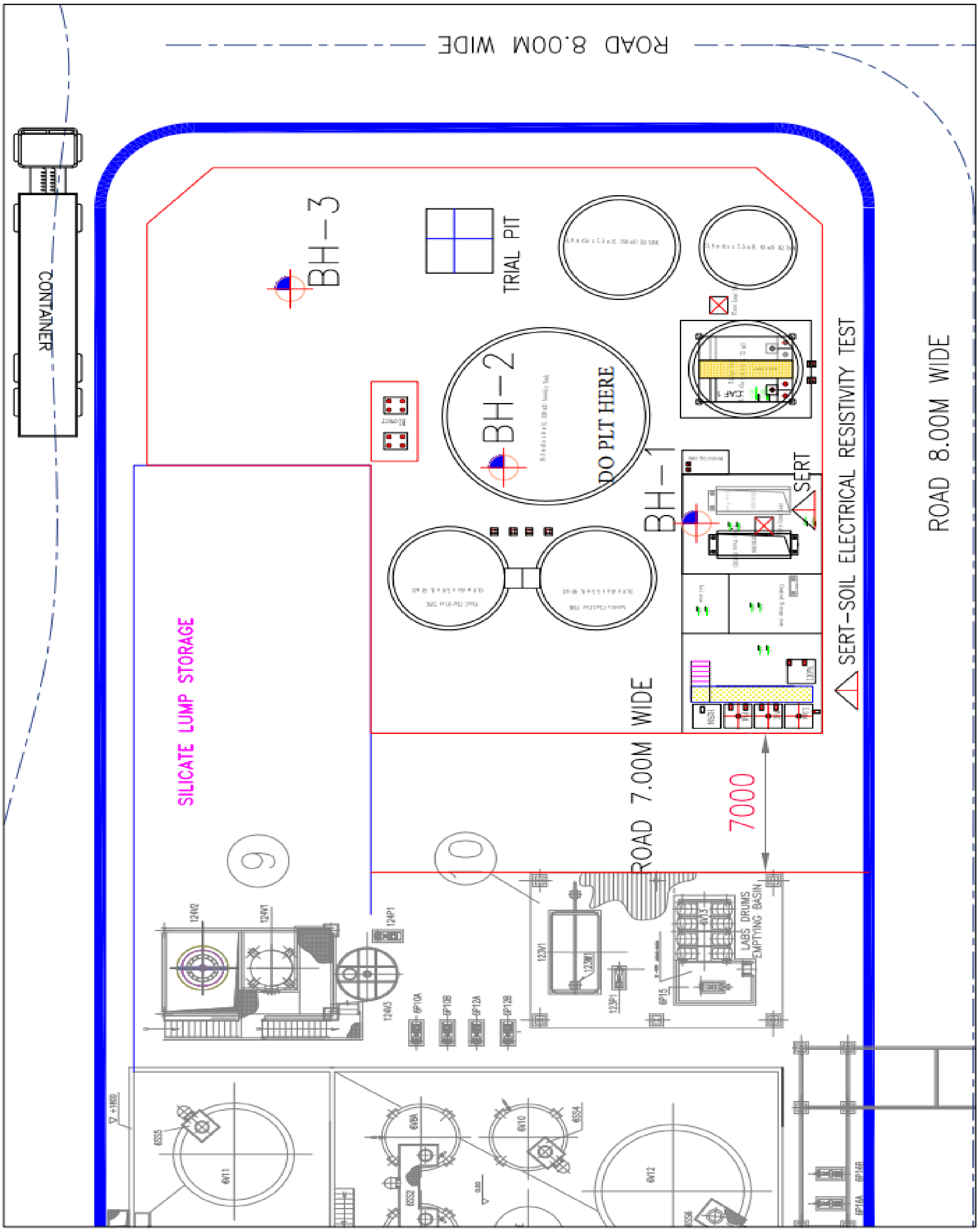


Figure A.1 Site Plan Showing Location of boreholes, test pits, and CPLT Locations of Effluent Treatment Plant Project.

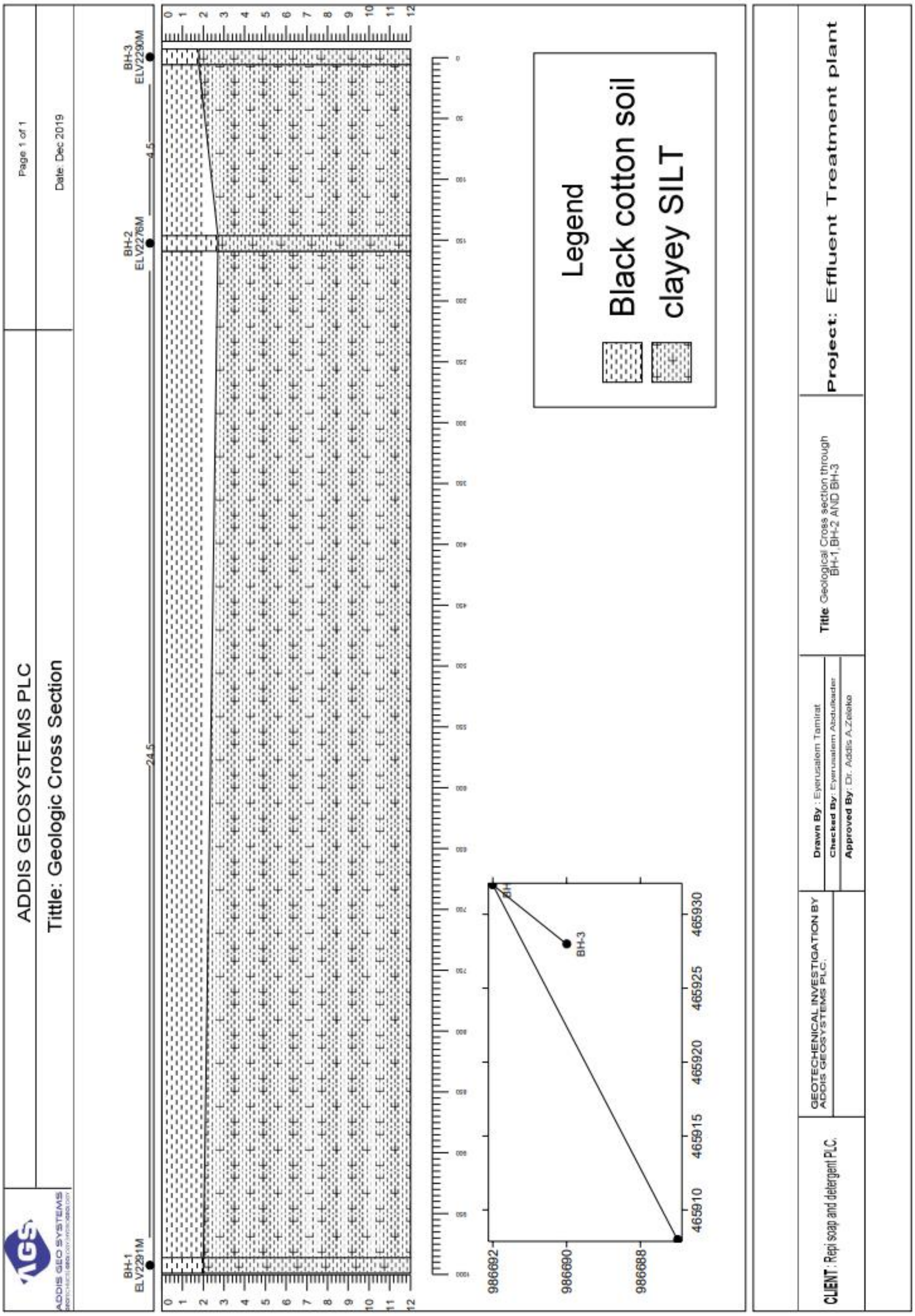


Figure A.2 geological cross section of Effluent Treatment Plant Project.

ADDIS GEOSYSTEMS PLC.	SHEET 1 of 1
Tittle: BOREHOLE LOG SHEET	BH No: 2

PROJECT: Effluent Treatment plant (ETP)
LOCATION: Alemgena
CLIENT :Repi Soap and Detergent PLC.
DATE STARTED: 28/11/2019
DATE COMPLETED: 29/11/2019

BORING TYPE : Rotary coring
GROUND WATER LEVEL : 2.20m
BH COORDINATES : N-0986692, E-0465432
BH ELEVATION :2290m
INCLINATION : Vertical. TOTAL BH DEPTH 12m

Hole Diameter (mm)	Sample Record	SPT/DPT N_value	Strata Description	Run Length Depth (m)	TCR (%)	RQD (%)	Remark
89			soft,dark silty CLAY (Black cotton soil)	0.4	100	-	
				1.5	100	-	
		9		1.95	100	-	
				2.5	100	-	
	UD			2.7	100	-	
			very stiff to hard, light brown, clayey SILT/ silty CLAY	3	100	-	
		16		3.45	100	-	
				4	100	-	
	UD			4.3	100	-	
				4.5	100	-	
		20		4.95	100	-	
				5.5	100	-	
	UD			5.91	100	-	
				6	100	-	
		35		6.45	100	-	
				7.5	100	-	
		21		7.95	100	-	
				8.5	100	-	
	UD			8.8	100	-	
				9	100	-	
		28		9.45	100	-	
				10	100	-	
				10.3	100	-	
				10.5	100	-	
		28		10.95	100	-	
				11.5	100	-	
	UD			11.8	100	-	

Depth (cm): 0 1 2 3 4 5 6 7 8 9 10 11 12

Legend

BH	BOREHOLE	DS	DISTURBED SOIL SAMPLE
(Nc)	CONE PENETRATION TEST	UD	UNDISTURBED SOIL SAMPLE
SPT	STANDARD PENETRATION TEST	RK	ROCK SAMPLE
N	BLOWS/30cm	R	REFUSAL
W	WATER SAMPLE		
NGL	NATURAL GROUND LEVEL		
RQD	ROCK QUALITY DESIGNATION		
TCR	TOTAL CORE RECOVERY		
▼	STATIC GROUND WATER LEVEL		

LOGGED BY : Nigusse Yirgu Date:30/11/2019
DRAWN BY: Eyerusalem Tamirat Date:01/12/2019
APPROVED BY : Dr.Addis A.Zeleke Date:01/12/2019

Figure A.3 Borehole log data for working plate load test, Effluent Treatment Plant Project

ADDIS GEOSYSTEMS PLC
SOIL AND MATERIAL TESTING LABORATORY

ADDIS GEO SYSTEMS

Project :- **Effluent Treatment Plant**
Client :- **Repi Soap and Detergent Plc**
Location :- **Oromiya Alemgena Area**
Test type :- **Various**

1.Soil Sample

Sr No	BH No	Depth (m)	Sample Type	Soil Description	% Pass Sieve No-200	Specific gravity	NMC (%)	Free Swell, %	Unit weight, gm/cc		Atterberg Limit, %			Direct Shear		UCS (kg/cm^2)	Swelling pressure Kpa	Consolidation, Cc
									Bulk Unit Weight	Dry Unit Weight	LL	PL	PI	C(kPa)	Φ(°)			
1	BH-1	2.50-2.80	Undisturbed	MH(A-7-5)	88.10	2.50	33.14	90.00	1.70	1.28	83.00	49.10	41.70	_	_	_	_	_
2	BH-1	5.5-5.85	Undisturbed	_	_	_	_	_	_	_	_	_	_	27.11	11	_	63	0.32
3	BH-1	11.5-11.80	Undisturbed	ML/A-4	95.60	2.40	42.17	_	2.05	1.44	_	_	_	_	_	_	_	0.29
4	BH-2	2.50-2.70	Undisturbed	MH(A-7-5)	88.40	2.45	41.30	80.00	1.75	1.24	82.4	40.4	42	_	_	_	67.44	_
5	BH-2	4.00-4.30	Undisturbed	_	_	_	25.53	60.00	1.67	1.33	_	_	_	_	_	202.1	_	_
6	BH-2	5.50-5.90	Undisturbed	_	_	_	_	_	_	_	_	_	_	25	11	_	58.45	0.26
7	BH-2	8.50-8.80	Undisturbed	ML/A-4	97.7	2.44	33.82	85.00	1.67	1.25	60.7	47.5	13.2	33	9.04	_	_	_
8	BH-2	11.5-11.80	Undisturbed	ML/A-4	96.00	2.53	32.53		1.97	1.49	_	_	_	_	_	_	_	0.24
9	BH-3	1.50-1.80	Undisturbed	ML/A-4	96.50	2.45	22.35	60.00	2.10	1.72	_	_	_		_	_	_	_
10	BH-3	3.50-3.80	Undisturbed	_	_	_	_	_	_	_	_	_	_	23.57	10.3	134.71	_	_
11	BH-3	5.00-5.30	Undisturbed	ML/A-4	95.20	2.55	39.33	_	1.84	1.32	_	_	_	_	_	_	_	0.22
12	BH-3	8.00-8.30	Undisturbed	ML/A-4	96.00	2.45	27.44	_	1.72	1.35	_	_	_	_	_	_	_	0.23
13	BH-3	9.5-9.80	Undisturbed	ML/A-4	94.10	2.50	23.95	80.00	1.97	1.59	_	_	_	_	_	_	_	0.25
14	BH-3	11.00-11.30	Undisturbed	_	_	_	43.47	_	1.95	1.36	_	_	_	_	_	_	_	0.28
15	PIT-1	1.00	Undisturbed	ML/A-4	96.50	2.45	30.42	60.00	1.79	1.37	_	_	_	_	_	_	_	_
16	PIT-1	1.5	Undisturbed	ML/A-4	94.90	2.50	_	_	_	_	_	_	_	_	_	_	_	_
17	PIT-1	1.30-1.50	Undisturbed	ML/A-4	94.60	2.40	29.21	90.00	1.67	1.29	65.7	42.7	23	_	_	_	_	_

Note :- 1. Grain Size Distribution, Four Direct Shear and Consolidation Graphs of test results are drawn and attached here with

2. NMC= Natural Moisture Content

Tested By :- Habtamu Asefa
Date :- 23/12/2019
Signature :- ______________

Checked By :- Helen Amdemichael
Date :- 23/12/2019
Signature :- ______________

Approved By :- Eyerusalem Abderkadir
Date :- 23/12/2019
Signature :- ______________

Addis Geosystem Plc Tel.+251 1 1631773 / 1 18060 1071 Fax: +251 116634415 Email:addisss@ethionet.et/Web:www.addisgeosystems.Com

Figure A.4 Laboratory Test Results, Effluent Treatment Plant Project

CYCLIC PLATE LOAD TEST (CPLT)

Client: Repi Soap and Detergent PLC
Project: Effluent Treatment Plant
Location: Oromiya Region, Alemgena area
Test Pit Location: CPLT
Depth of Pit: 1.5m from NGL
Material Type: Soft, dark, silty CLAY with grass roots at the top

GPS Co-ordinate: N=0986891, E=0466015
Weather Condition: Sunny
Plate Size: Dia 600mm*25mm
Reaction Load: 34 Ton (34000Kg)
Dial Guage accuracy: 0.01m
Testing Standard: ASTM D1194 and British Standard (BS1377-9)
Date of Test: January 02, 2020

cycle	Applied pressure			Applied time, min		Dial Reading Division			Dial Reading, mm			Average Settlement, mm	Remark
	kg/cm^2	kpa	t/m^2	interval	total	Dail, No 1	Dail, No 2	Dail, No 3	Dail, No 1	Dail, No 2	Dail, No 3		
loading	0	0	0	0.00	0.00	0	0	0	0.00	0.00	0.00	0.00	ok
	1	100	10	0.15	0.15	768	743	556	7.68	7.73	5.56	6.89	ok
	1	100	10	15.00	15.15	780	860	652	7.8	8.6	6.52	7.64	ok
unloading	0	0	0	0.25	15.40	420	620	581	4.2	6.2	5.81	5.34	ok
loading	2	200	20	0.15	15.55	2520	2065	1913	25.20	20.65	19.13	21.66	ok
	2	200	20	15.00	30.55	2520	2150	1933	25.20	21.50	19.33	22.01	maximum allowable settlement of 25mm
unloading	0	0	0	0.25	30.80	2340	2065	1266	23.40	20.65	12.66	18.90	ok

Figure A..5 Plate load test data, Effluent Treatment Plant Project

Appendix - B Sub soil profile, Bore log data and FPLT data for Potash Evaporation Pond design project

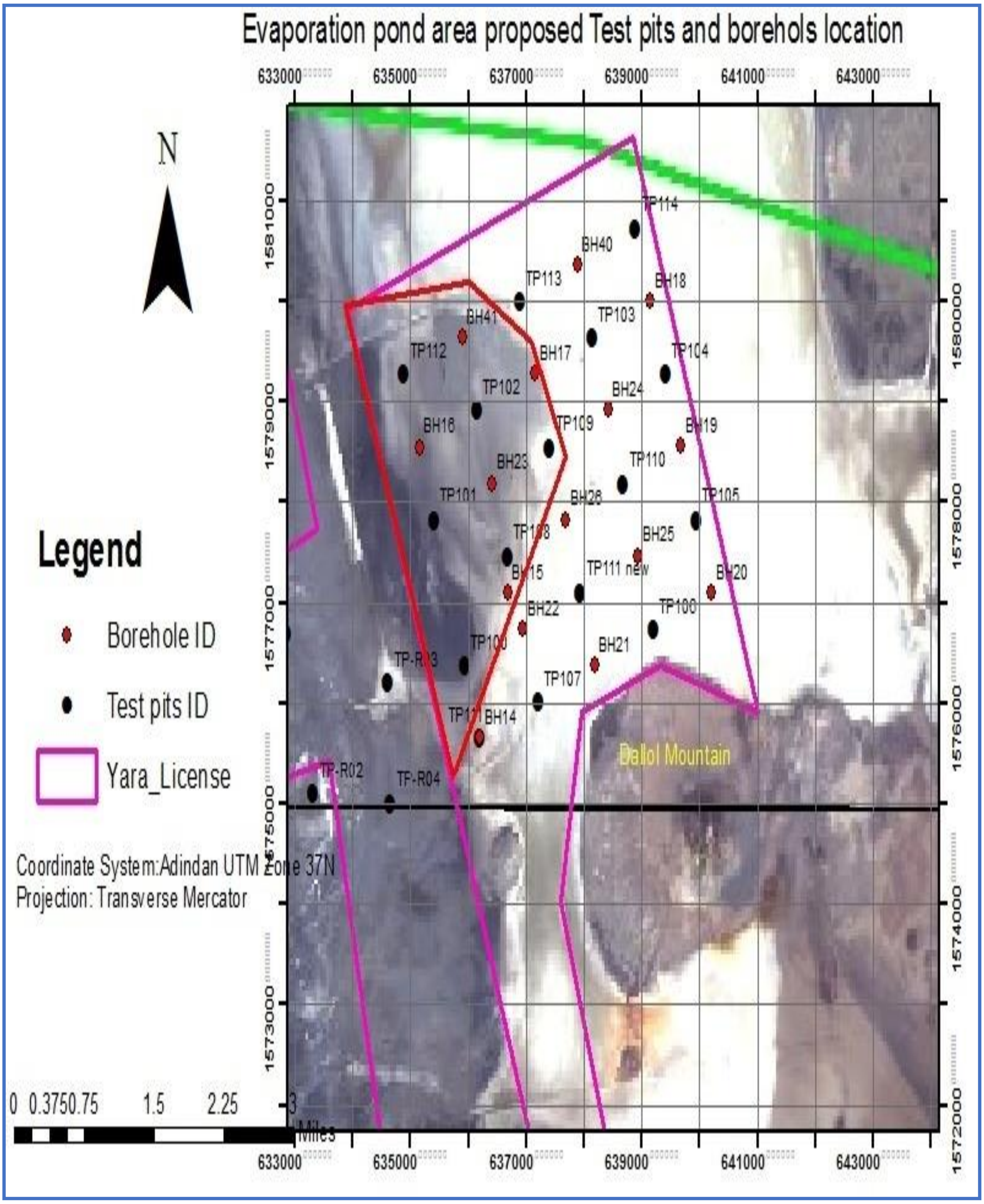


Figure B.6 Site Plan Showing Location of boreholes, test pits, and FPLT Locations of potash evaporation pond design project

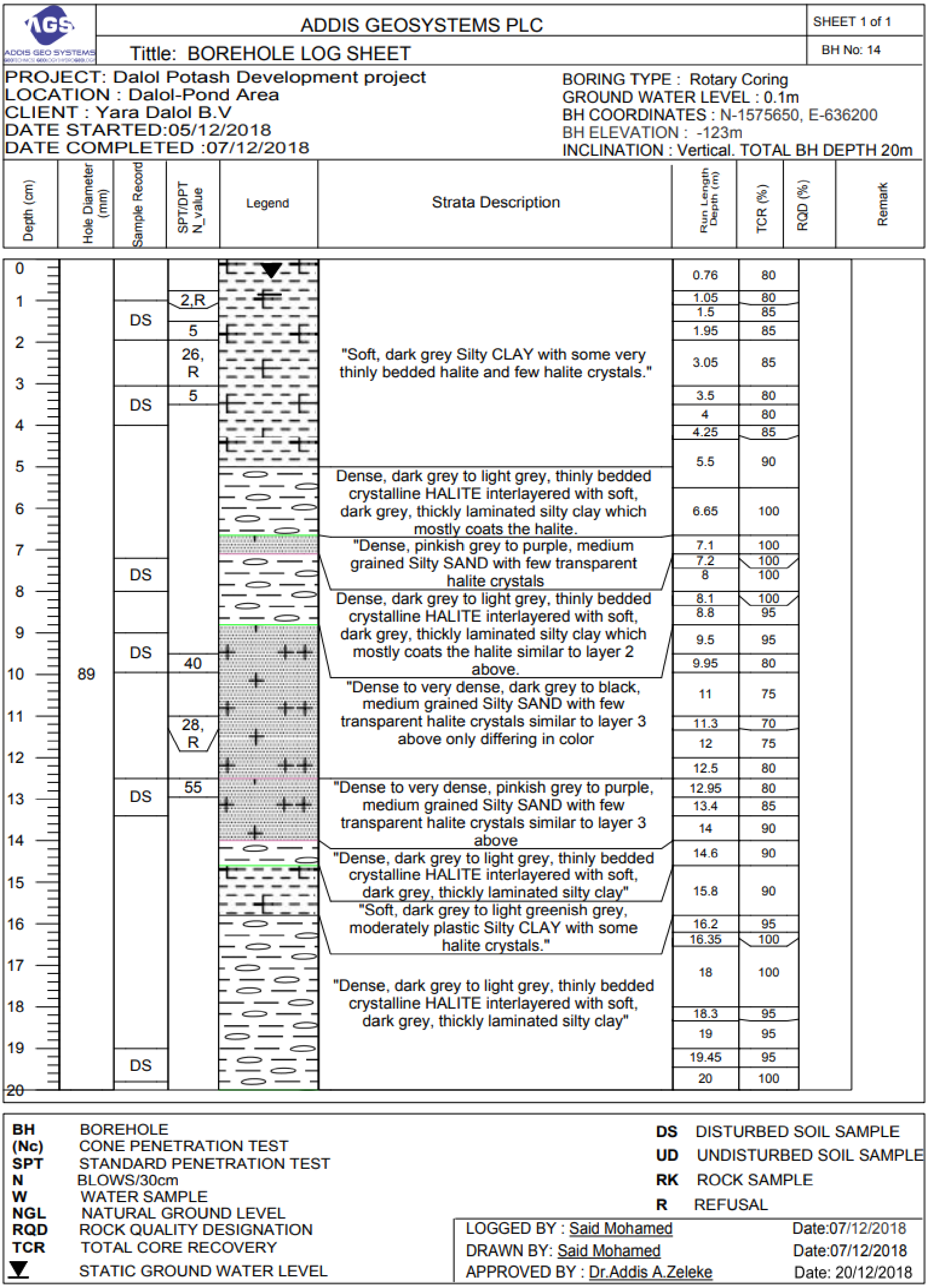


Figure B.7 Borehole log data for working plate load test, potash evaporation pond design project

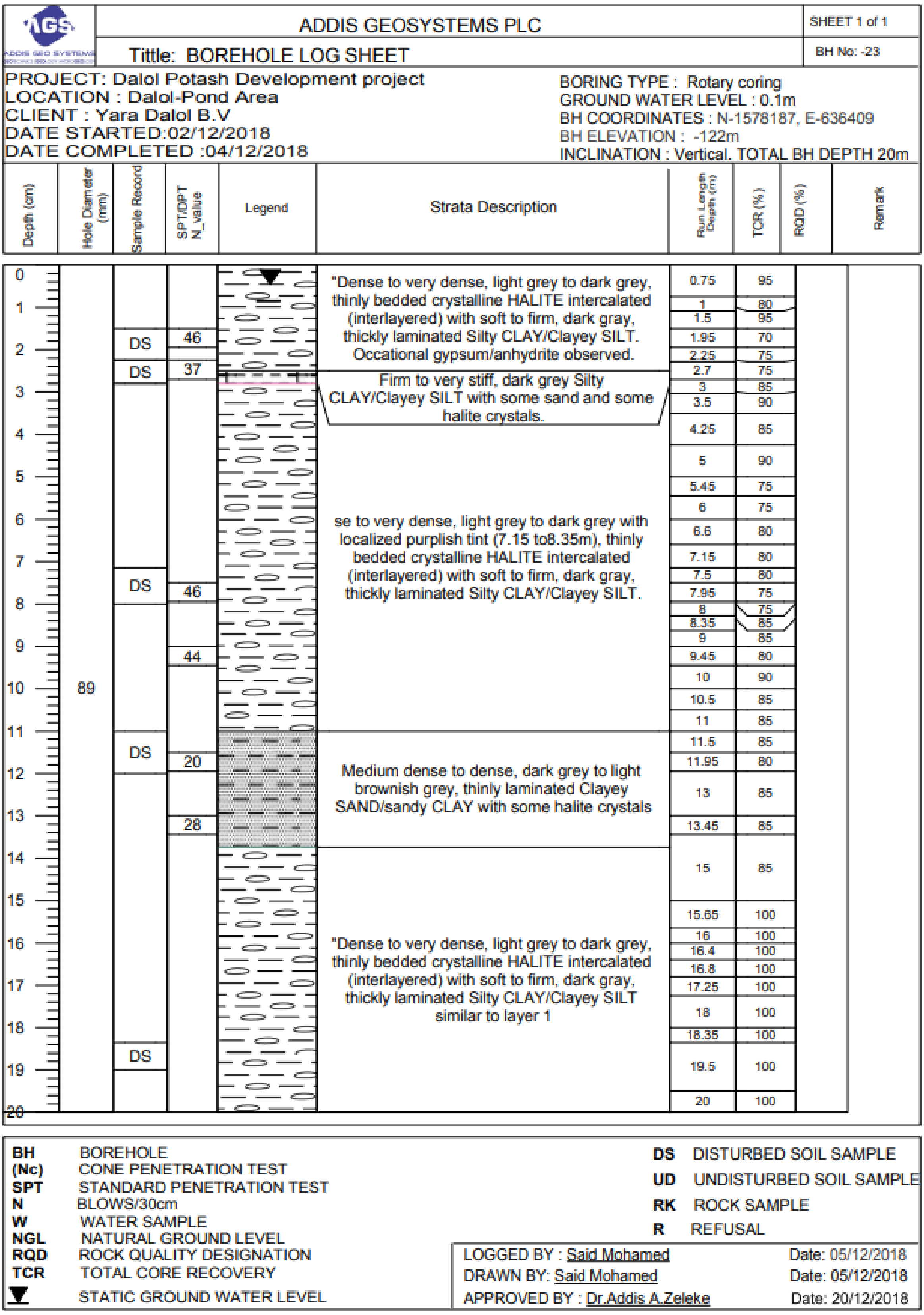
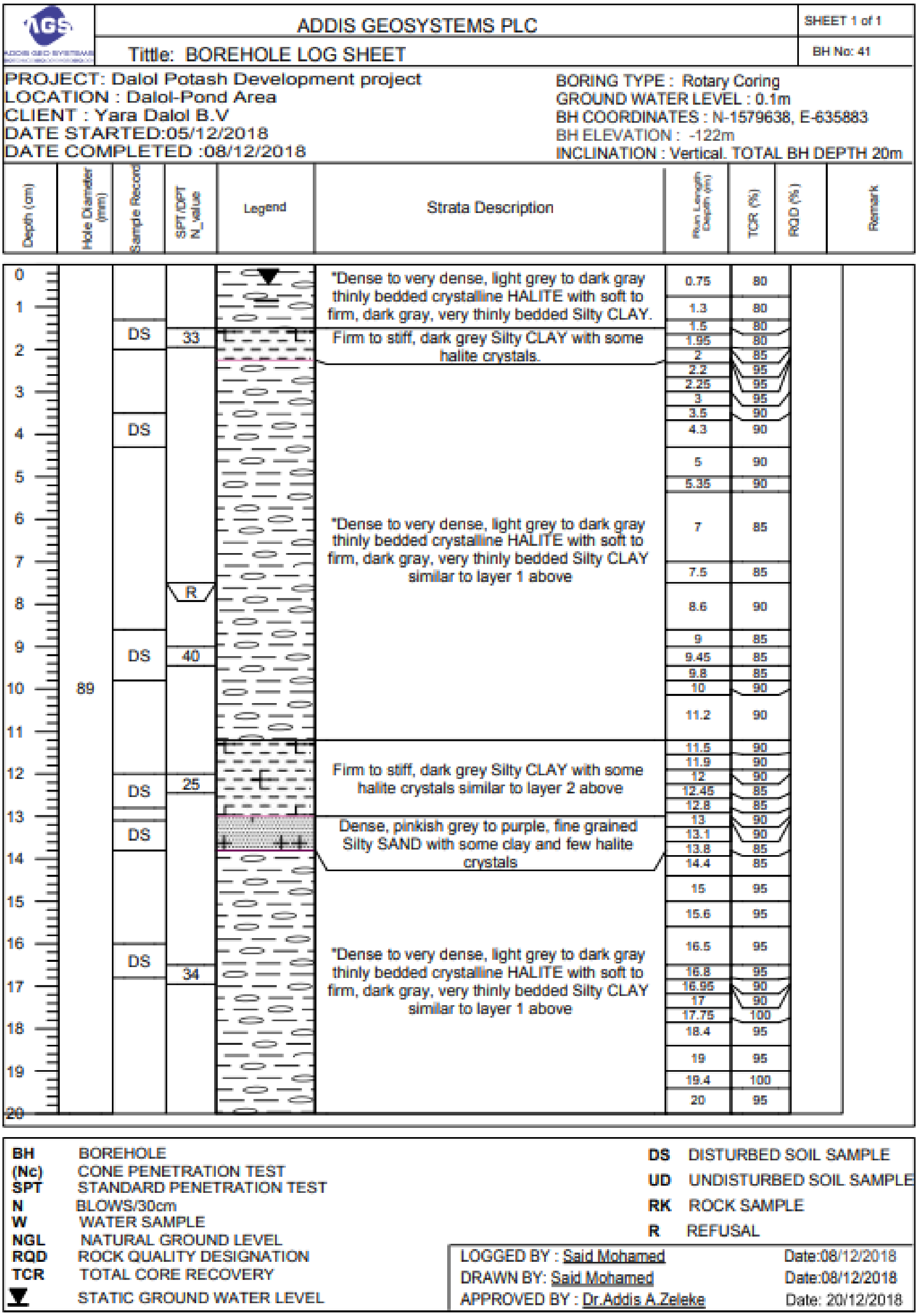


Figure B.8 Borehole log data for working plate load test, potash evaporation pond design project



ADDIS GEOSYSTEMS PLC

Tittle: BOREHOLE LOG SHEET

SHEET 1 of 1

BH No: 41

PROJECT: Dalol Potash Development project
LOCATION : Dalol-Pond Area
CLIENT : Yara Dalol B.V
DATE STARTED:05/12/2018
DATE COMPLETED :08/12/2018

BORING TYPE : Rotary Coring
GROUND WATER LEVEL : 0.1m
BH COORDINATES : N-1579638, E-635883
BH ELEVATION : -122m
INCLINATION : Vertical. TOTAL BH DEPTH 20m

Depth (m)	Hole Diameter (mm)	Sample Record	SPT/DPT N_value	Strata Description
0–1.5	89			"Dense to very dense, light grey to dark gray thinly bedded crystalline HALITE with soft to firm, dark gray, very thinly bedded Silty CLAY.
1.5–2.2		DS	33	Firm to stiff, dark grey Silty CLAY with some halite crystals.
2.2–11.2		DS; DS	R; 40	"Dense to very dense, light grey to dark gray thinly bedded crystalline HALITE with soft to firm, dark gray, very thinly bedded Silty CLAY similar to layer 1 above
11.2–13		DS	25	Firm to stiff, dark grey Silty CLAY with some halite crystals similar to layer 2 above
13–13.8		DS		Dense, pinkish grey to purple, fine grained Silty SAND with some clay and few halite crystals
13.8–20		DS	34	"Dense to very dense, light grey to dark gray thinly bedded crystalline HALITE with soft to firm, dark gray, very thinly bedded Silty CLAY similar to layer 1 above

Run Length Depth (m)	TCR (%)	RQD (%)	Remark
0.75	80		
1.3	80		
1.5	80		
1.95	80		
2	85		
2.2	95		
2.25	95		
3	95		
3.5	90		
4.3	90		
5	90		
5.35	90		
7	85		
7.5	85		
8.6	90		
9	85		
9.45	85		
9.8	85		
10	90		
11.2	90		
11.5	90		
11.9	90		
12	90		
12.45	85		
12.8	85		
13	90		
13.1	90		
13.8	85		
14.4	85		
15	95		
15.6	95		
16.5	95		
16.8	95		
16.95	90		
17	90		
17.75	100		
18.4	95		
19	95		
19.4	100		
20	95		

BH BOREHOLE
(Nc) CONE PENETRATION TEST
SPT STANDARD PENETRATION TEST
N BLOWS/30cm
W WATER SAMPLE
NGL NATURAL GROUND LEVEL
RQD ROCK QUALITY DESIGNATION
TCR TOTAL CORE RECOVERY
STATIC GROUND WATER LEVEL

DS DISTURBED SOIL SAMPLE
UD UNDISTURBED SOIL SAMPLE
RK ROCK SAMPLE
R REFUSAL

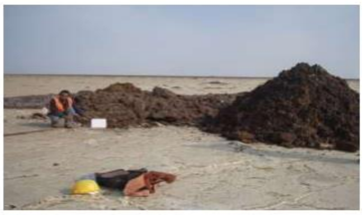
LOGGED BY : Said Mohamed Date:08/12/2018
DRAWN BY: Said Mohamed Date:08/12/2018
APPROVED BY : Dr.Addis A.Zeleke Date: 20/12/2018

Figure B.9 Borehole log data for working plate load test, potash evaporation pond design project

ADDIS GEOSYSTEMS PLC
TEST PIT LOG SHEET

Project	Yara Dallol Potash project-Geotechnical investigation			
Test Pit	No	Coordinates		Elevation(m)
	TP 100 *Relocated position*	E: ~~635936~~ E: 636,310	N: ~~1576374~~ N: 1,576,499	-121
Structure	*Evaporation Pond*			
Date	Excavation started: 08-12-2018	Excavation completed: 09-12-2018		
Excavation Method	Excavator	Logged by: Kumneger Molalign		
Ground water	0.90m depth			

Depth (m)	Formation Description	Legend	Sampling Depth(m)
0.00-1.70	Soft to firm, light brown to dark grey moderately plastic very thinly bedded Silty CLAY/Clayey SILT with thin layers of halite and gypsum/anhydrite.		BD samples:
1.70-3.00	Dense, dark grey to light grey coarse grained thinly bedded crystalline HALITE with thinly laminated dark grey silty CLAY. NB: Relocated due to muddy site		0.00-1.20 1.20-3.00 SC sample 0.00-0.15 0.80-0.95



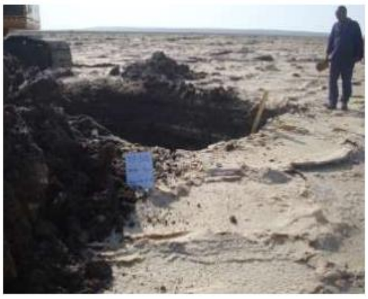
BD: Bulk disturbed sample
SC: sand cone sample
Picture: Top: Test pit site picture
Bottom: Test pit face picture

Figure B.10 Test pit log with site and test pit face picture (TP-100)

ADDIS GEOSYSTEMS PLC
TEST PIT LOG SHEET

Project	Yara Dallol Potash project-Geotechnical investigation			
Test Pit	No	Coordinates		Elevation(m)
	TP 108	E: 636672	N: 1577462	-120
Structure	*Evaporation Pond*			
Date	Excavation started: 07-10-2018	Excavation completed: 07-10-2018		
Excavation Method	Excavator	Logged by: Kumneger Molalign		
Ground water	@3m			

Depth (m)	Formation Description	Legend	Sampling Depth(m)
0.00-3.00	Dense, dark grey to light grey, medium to coarse grained crystalline HALITE interlayered with firm dark grey very thinly bedded Silty CLAY and thin layers of gypsum/anhydrite.		BD samples: 0.00-0.70 0.70-3.00



BD: Bulk disturbed sample
SC: Sand cone samples
Picture: Top: Pit site picture
Bottom: Test pit face picture

Figure B.11 Test pit log with site and test pit face picture, (TP-108)

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TEST PIT LOG SHEET

Project	Yara Dallol Potash project-Geotechnical investigation			
Test Pit	No	Coordinates		Elevation(m)
	TP 112	E: 634906	N: 1579284	-120
Structure	*Evaporation Pond*			
Date	Excavation started: 06-10-2018		Excavation completed: 06-10-2018	
Excavation Method	Excavator		Logged by: Kumneger Molalign	
Ground water	Starting from 2m depth			

Depth (m)	Formation Description	Legend	Sampling Depth(m)
0.00-1.00	Dense to very dense, light grey to dark grey, medium to coarse grained thinly bedded crystalline HALITE interlayered with very thinly bedded Silty CLAY and thin layers of gypsum/anhydrite.		BD samples: 0.00-1.20 1.20-3.00
1.40-3.00	Firm to stiff, light brown to dark grey moist silty CLAY interlayered with dense, light grey very thinly bedded crystalline HALITE		SC sample 0.00-0.15 0.90-1.05

BD: Bulk disturbed sample
SC: Sand cone sample
Picture: Top: Test pit site
Bottom: Test pit face picture

Figure B.12 Test pit log with site and test pit face picture (TP-112)

PLATE LOAD TEST DATA RECORDING SHEET

Client:	Yara Dallol B.V	GPS Co-ordinate:	E: 634906, N: 1579284
Project:	Potash Developmnet Project	Weather Condition:- Sunny	Sunny
Location:	Dallol - Crescent area	Design Load: 125KPa	125KPa
Test pit Location:	TP 112	Plate Size:	Dia 300mm *25mm
Depth of Pit:	At natural ground level (NGL)	Dial Guage accuracy:	0.01mm
Soil Description:	Halite	Testing Standard:	ASTM D1194-94
		Date of Test:	16-Nov-18

Cycle	Reaction Load KN	Applied Pressure Kpa	Elapsed Time (min)	Dail Reading Division G1	G2	G3	Average Settlement, mm	Remark
Loading		75	0.15	0.21	0.83	0.11	0.38	
			1.00	1.25	0.89	1.15	1.10	
			2.00	1.29	0.91	1.19	1.13	
			4.00	1.36	1.01	1.27	1.21	
			8.00	1.41	1.05	1.33	1.26	
			15.00	1.56	1.15	1.50	1.40	
		125	0.15	2.55	2.10	2.45	2.37	
			1.00	2.61	2.15	2.50	2.42	
			2.00	2.64	2.20	2.55	2.46	
			4.00	2.70	2.26	2.61	2.52	
			8.00	2.77	2.32	2.68	2.59	
			15.00	2.87	2.41	2.81	2.70	
		200	0.15	4.12	3.59	4.02	3.91	
			1.00	4.17	3.64	4.06	3.96	
			2.00	4.20	3.67	4.10	3.99	
			4.00	4.26	3.72	4.16	4.05	
			8.00	4.33	3.76	4.23	4.11	
			15.00	4.42	3.84	4.34	4.20	
		250	0.15	5.37	4.79	5.28	5.15	
			1.00	5.43	4.85	5.34	5.21	
			2.00	5.44	4.86	5.35	5.22	
			4.00	5.46	4.88	5.38	5.24	
			8.00	5.50	4.91	5.42	5.28	
			15.00	5.54	4.96	5.49	5.33	
		325	0.15	6.72	6.19	7.70	6.87	
			1.00	6.81	6.21	7.72	6.91	
			2.00	6.85	6.24	7.76	6.95	
			4.00	6.89	6.24	7.82	6.98	
			8.00	6.93	6.24	7.84	7.00	
			15.00	6.97	6.24	7.91	7.04	

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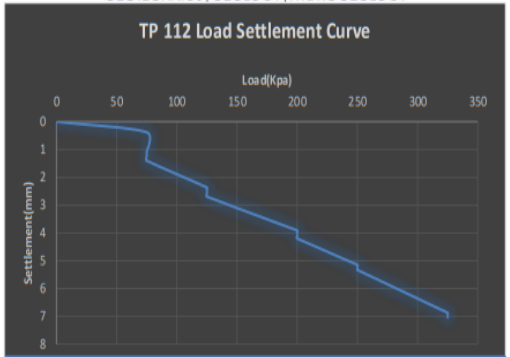


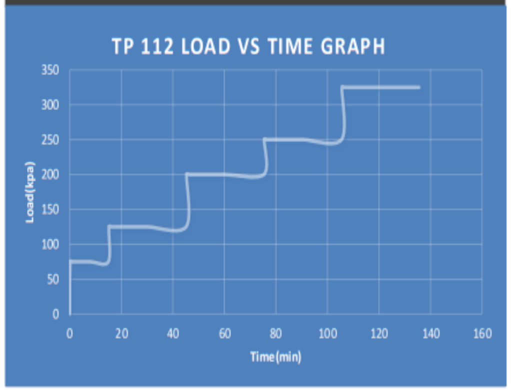
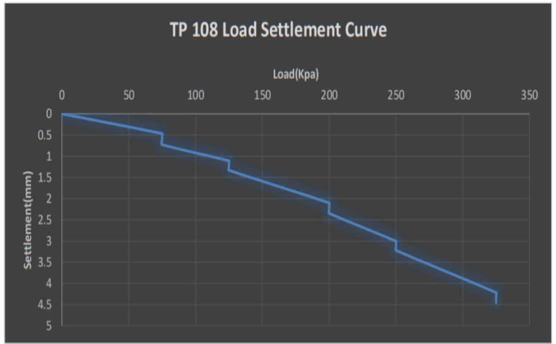


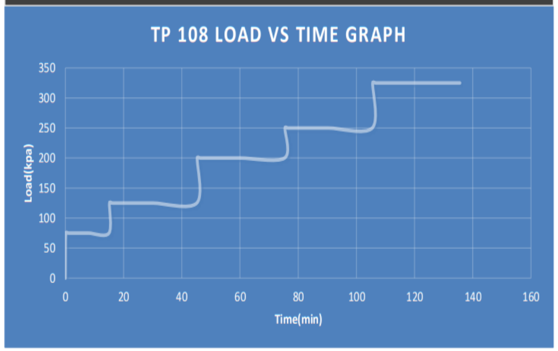
Figure B.13 Plate load test data for TP-100, Potash Evaporation Pond Design project

PLATE LOAD TEST DATA RECORDING SHEET

Client:	Yara Dallol B.V	GPS Co-ordinate:	E: 636684, N: 1577459
Project:	Potash Developmnet Project	Weather Condition:- Sunny	Sunny
Location:	Dallol - Crescent area	Design Load: 125KPa	125KPa
Test pit Location:	TP 108	Plate Size:	Dia 300mm *25mm
Depth of Pit:	At natural ground level (NGL)	Dial Guage accuracy:	0.01mm
Soil Description:	Halite	Testing Standard:	ASTM D1194-94
		Date of Test:	22-Nov-18

Cycle	Reaction Load	Applied Pressure	Elapsed Time (min)	Dail Reading Division			Average Settlement,	Remark
	KN	Kpa		G1	G2	G3	mm	
Loading		75	0.15	0.36	0.54	0.49	0.46	
			1.00	0.39	0.56	0.52	0.49	
			2.00	0.41	0.60	0.54	0.52	
			4.00	0.44	0.64	0.58	0.55	
			8.00	0.50	0.72	0.66	0.63	
			15.00	0.58	0.82	0.78	0.73	
		125	0.15	0.94	1.22	1.16	1.11	
			1.00	0.98	1.25	1.21	1.15	
			2.00	0.99	1.28	1.22	1.16	
			4.00	1.03	1.32	1.26	1.20	
			8.00	1.07	1.38	1.32	1.26	
			15.00	1.14	1.45	1.40	1.33	
		200	0.15	1.85	2.26	2.19	2.10	
			1.00	1.92	2.31	2.25	2.16	
			2.00	1.95	2.34	2.29	2.19	
			4.00	1.98	2.37	2.32	2.22	
			8.00	2.03	2.43	2.37	2.28	
			15.00	2.09	2.50	2.45	2.35	
		250	0.15	2.72	3.17	3.12	3.00	
			1.00	2.76	3.20	3.16	3.04	
			2.00	2.78	3.23	3.19	3.07	
			4.00	2.82	3.28	3.22	3.11	
			8.00	2.86	3.33	3.28	3.16	
			15.00	2.92	3.39	3.35	3.22	
		325	0.15	3.87	4.40	4.38	4.22	
			1.00	3.94	4.45	4.45	4.28	
			2.00	3.97	4.48	4.47	4.31	
			4.00	4.01	4.52	4.50	4.34	
			8.00	4.05	4.57	4.55	4.39	
			15.00	4.10	4.65	4.62	4.46	





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Signature		
Name		
Date		

Figure B.14 Plate load test data for TP-108, Potash Evaporation Pond Design project

PLATE LOAD TEST DATA RECORDING SHEET

Client:	Yara Dallol B.V	GPS Co-ordinate:	E: 636310, N: 1576499
Project:	Potash Developmnet Project	Weather Condition:-	Sunny
Location:	Dallol - Crescent area	Design Load:	125KPa
Test pit Location:	TP 100NEW	Plate Size:	Dia 300mm *25mm
Depth of Pit:	At natural ground level (NGL)	Dial Guage accuracy:	0.01mm
Soil Description:	Halite	Testing Standard:	ASTM D1194-94
		Date of Test:	8-Dec-18

Cycle	Reaction Load	Applied Pressure	Elapsed Time (min)	Dail Reading Division			Average Settlement, mm	Remark
	KN	Kpa		G1	G2	G3		
Loading		75	0.15	2.46	2.57	2.48	2.50	
			1.00	2.48	2.60	2.50	2.53	
			2.00	3.48	3.62	3.53	3.54	
			4.00	3.48	3.62	3.54	3.55	
			8.00	3.48	3.64	3.54	3.55	
			15.00	3.48	3.65	3.56	3.56	
		125	0.15	5.06	5.28	5.21	5.18	
			1.00	5.08	5.31	5.23	5.21	
			2.00	5.08	5.33	5.25	5.22	
			4.00	6.08	6.34	6.28	6.23	
			8.00	6.08	6.34	6.28	6.23	
			15.00	6.08	6.36	6.31	6.25	
		200	0.15	8.64	8.98	8.92	8.85	
			1.00	8.67	8.98	8.93	8.86	
			2.00	8.67	8.99	8.95	8.87	
			4.00	9.67	9.01	9.96	9.55	
			8.00	9.67	9.02	9.98	9.56	
			15.00	9.67	9.03	9.99	9.56	
		250	0.15	11.33	11.75	11.73	11.60	
			1.00	11.34	11.78	11.73	11.62	
			2.00	12.41	12.79	12.76	12.65	
			4.00	12.41	12.80	12.79	12.67	
			8.00	12.41	12.81	12.79	12.67	
			15.00	12.41	12.81	12.79	12.67	
		325	0.15	15.94	15.46	15.47	15.62	
			1.00	15.97	15.47	15.47	15.64	
			2.00	15.98	15.48	15.51	15.66	
			4.00	17.98	17.50	17.51	17.66	
			8.00	17.08	17.55	17.51	17.38	
			15.00	17.08	17.55	17.51	17.38	

Company	Addis Geosystems plc	Yara Dallol B.V
Signature		
Name		
Date		

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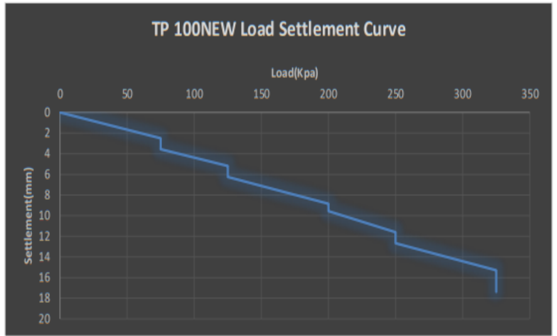

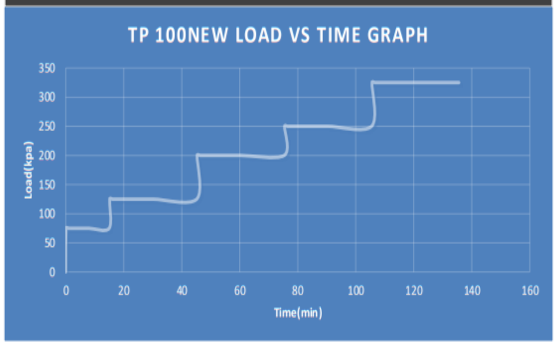

Figure B.15 Plate load test data for TP-112, Potash Evaporation Pond Design project

Appendix - C Some informative tables and figures

Table C.1 Correction table for field procedure of SPT N-value

SPT Hammer Efficiencies (BNBC 2015 Table 6.D.4)		
Hammer Type	**Hammer Release Mechanism**	**Efficiency, E_H**
Automatic	Trip	0.70
Donut	Hand dropped	0.60
Donut	Cathead+2 turns	0.50
Safety	Cathead+2 turns	0.55-0.60
Drop/Pin	Hand dropped	0.45
Borehole, Sampler and Rod Correction Factors (BNBC 2015 Table 6.D.5)		
Factor	**Equipment Variables**	**Correction Factor**
Borehole Dia Factor, C_B	65 – 115 mm (2.5-4.5 in)	1.00
	150 mm (6 in)	1.05
	200 mm (8 in)	1.15
Sampler Correction, C_S	Standard sampler	1.00
	Sampler without liner (not recommended)	1.20
Rod Length Correction, C_R	3 – 4 m (10-13 ft)	0.75
	4 – 6 m (13-20 ft)	0.85
	6 – 10 m (20-30 ft)	0.95
	>10 m (>30 ft)	1.00

Table C.2 Typical range of values for Poisson's ratio (Bowles, 1996)

Type of soil	**μ**
Clay, saturated	0.4 - 0.5
Clay, unsaturated	0.1 - 0.3
Sandy clay	0.2 - 0.3
silt	0.3 - 0.35
Sand, gravelly sand Commonly used	-0.1 - 1.00 0.3 - 0.4
rock	0.1 - 0.4 (depend somewhat on type of rock)
loess	0.1 - 0.3
ice	0.36
concrete	0.15
steel	0.33

Figure C.16 Correlation between SPT and bulk unit weight after Bowles,1977 (Caltrans Geotechnical manual, 2021)