BSc Thesis

Numerical simulations of the tip behavior of an earthworm robotic probe for soil monitoring purposes

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Preface

This thesis project of the bachelor marks a remarkable journey in my academic career, that has given me both the challenges and the rewards of expanding my knowledge. The research report that is displayed in this report is the outcome of many hours reading literature, simulating scenarios, doing experiments or analysis, and more importantly, executing things that I've learned throughout the years of programme.

During the high school year, my interest in this field was encountered, as I was passionate about structures, objects, and how they are made or built. Furthermore, I had eager to focus on technical subjects, which pushed me on choosing this field of study. The journey has had many obstacles, especially during the beginning, but each barrier has helped me grow and make me stronger for future situations.

I am more than thankful to my supervisors, Floriana and Ilya, who have been very helpful and encouraged me a lot throughout the project. Their insights assisted me in obtaining important aspects of the study. Moreover, their patience and availability, or willingness to help me understand concepts, has inspired me to work with desire and enthusiasm on the project.

Furthermore, I want to thank my family for their support and the motivation they gave me to achieve this. I consider them as the most important thing in my life, and I hope to make them happy with my achievements in life.

Finally, this thesis is a result of many factors that have contributed to me in different ways, and I hope that I have made everyone feel delighted or content in this journey. To everyone who has been a part of it, I appreciate everything you have done!

Ralf Idrizi

June, 2024

Abstract

The industry of construction is increasing rapidly day by day, and the actual needs of people are expanding. Many developments in this field during the years have helped engineers simplify the process of construction. These developments tend to offer multiple benefits in terms of environmental sustainability, time efficiency, and cost. This report is focused on evaluating the best dimensions of a robotic probe, that tends to investigate the soil properties by using sensors. The robotic probe mimics the behavior of the earthworm, in order to tackle the penetration resistance caused by different types of soil compositions.

The analysis in the report assesses the geometry of the probe tip by using COMSOL, a software capable of simulating geotechnical scenarios, and gives an overview of which dimensions of the tip are the most suitable and effective in terms of penetration resistance by analyzing three prototypes that are taken into account, each of them having a different tip height or aspect ratio, where the aspect ratio signifies the division of tip height against the diameter of the probe.

The report begins by outlining the context and research motivation, also noting the benefits of this study to the current construction works. Following that, a literature review is carried out to explain in more detail the methods or theories implemented to apply the research. Moreover, the research dimensions, including the objective and questions, that are answered after the results are carried out, are set. Afterward, a methodology including how the simulations in COMSOL and experiments are performed is given.

After executing the results, each alternative is described, and the effect that the physical properties have on the final outcome is analyzed by implementing a sensitivity analysis, where it is observed that various inputs have a significant effect on the final outcome, and for this reason, considerable attention should be given when collecting the input data. Furthermore, the results are accomplished both in elastic and plastic behavior, where elastic assumes a linear stress-strain relationship, while plastic also takes into account other parameters defining plasticity. The linear elastic behavior is then compared to the experimental observations, where it is seen that the error is approximately 15 %, as the simulations underestimate the experimental results. Following that, it is observed that the aspect ratio of 4 is the most suitable option, while the differences between the prototypes are not large. After describing every outcome, and pointing out the best dimensions achieved during the analysis, the report is summed up with a conclusion and discussions regarding the final results, and future research recommendations.

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1 Introduction

In today's world where many challenges are being faced, the necessity to provide new technologies and raise effectiveness is increasing. Soil monitoring is one of the fields where new developments are needed to make the process more efficient, in terms of cost and time, and for this reason, many tools to do so have been invented. Among these tools, non-invasive burrowing equipment plays a considerable role in today's practices of soil monitoring. In contrast to the traditional method, which could damage the soil and provide wrongful outcomes, the necessity to create new ways to provide the soil properties and give better insights is becoming crucial.

One relevant example would be the earthworm-inspired robotic probe. The earthworm is characterized by its burrowing skills in soil, such as penetrating difficult terrains (Sharma et al., 2017). Motivated by this creature, the burrowing mimics its characteristics to navigate and move through the soil without causing significant disruption or damage. This method could simplify the task by minimizing the environmental impact and increasing the accuracy of results related to underground soil monitoring.

In this research, the results of soil monitoring by implementing the robotic probe are simulated by using COMSOL and comparing the results with experimental data. In the following chapters, a more detailed description of the case and its applications is followed by an analysis of how to improve the efficacy of the outcomes that are given.

2 Context

The motivation behind this research is the proposal of the Robotic lab and the Soil Micro Mechanics chair of the University of Twente to collect data for the design of an earthworm-inspired robotic probe.

The use of invasive methods for soil monitoring can result in a number of problems related to the environment or other variables while using non-invasive tools would bring a lot of benefits to the field. For instance, minimal disturbance would be achieved, and the nature of the soil would be kept in its natural state, which would make the soil exploration more accurate. Furthermore, these tools would be more efficient in terms of cost and time, whereas the invasive equipment would require more labor and more time to be placed in the study area. These considerations bring the necessity to develop non-invasive equipment for soil monitoring, and in this case, the probe whose tip is analyzed in this report.

Second, since the probe needs to be adjusted to the specific type of soil and studied for the best burrowing strategies, concepts from the field of soil mechanics are a primary source of information for the study. Two of the major theories that were analyzed and adapted to the research are the Mohr-Coulomb theory and Cone Penetration Testing, which show the main dynamics of penetration of rigid elements in the soil. These theories were chosen due to the similarities and applications that these objects have regarding the robotic probe in terms of rigid penetration. Following that, the principles of Mohr-Coulomb's theory are discussed, as critical soil properties can be derived from them.

Furthermore, the COMSOL Multiphysics software is used to simulate the scenarios, which display a plot of displacements and stress distribution, according to the input corresponding with the designs that are created. This allows for determining the various dimensions of the earthworm-inspired robotic probe to the specific soil conditions, and predicting performance or optimizing the characteristics of the probe.

The scope of research encompasses several domains because conducting and analyzing this research requires the production of connections across several fields, such as soil-mechanics knowledge, and the use of COMSOL to reach a conclusion and fill in the gaps of the current knowledge. A broader aspect of the focus of this research and the motivation behind it is given in Section 2.1.

2.1 Research Motivation and Problem Statement

The reason for being inspired by earthworms relies on the ability that this animal has to burrow through the soil by using peristaltic locomotion, a characteristic of earthworms. The earthworm movement is identified by two phases, specifically the contraction and expansion of different sections of the body simultaneously, specifically called peristalsis locomotion. This action is caused by the contractions of an earthworm's body, which create a wave throughout its shape (Collier, 1938). The movement allows this creature to navigate through difficult terrains without creating significant disturbance to the soil when compared to traditional drilling techniques. For this reason, the attributes of the earthworm inspired an effective solution for soil exploration operations.

The University of Twente has been investigating the opportunities of designing, fabricating, and testing a robotic earthworm, where many examples have been set. During the years, 4 prototypes have been developed, where each of these were tested in a specific soil, and then analyzed based on the overall performance. For instance, the probes were classified according to the difficulty of manufacturing, the needed pressure to penetrate, the anchoring, etc. An overview of the current prototype is shown in Figure 1 (Anselmucci et al., 2021).

Following that, the robotic probe could be optimized at a higher level, in order to achieve more realistic results. For this reason, numerical simulations using the COMSOL software are needed to be carried out, to assure a faster way of evaluating the

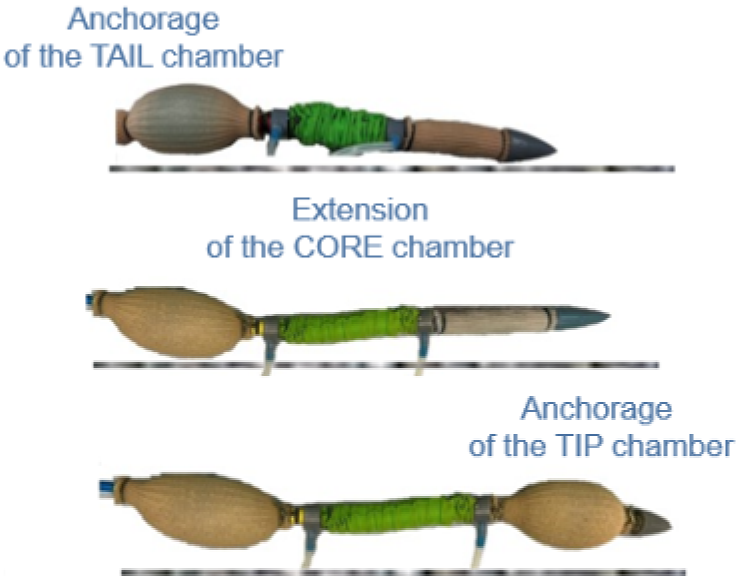

Figure 1: The prototype developed at UT in the main phases of action, such as the anchorage and extension

outcomes of soil monitoring by the robotic earthworm. Moreover, the simulations could bring an innovative strategy to assess the soil properties. Due to this, a comparison of simulation results to experimental observations would fill in gaps in the current knowledge in this field. An overview of the main aspects, terms, or tools that are addressed and used in this report is introduced in Section 3.

3 Literature review

3.1 Soil exploration importance and methods

Over the years, many methods have been used to acquire soil characteristics, and most of them have the same objective and procedure. Soil exploration is important due to the relevance that it contains in every construction project, where it checks if the quality is within the requirements, and evaluates the characteristics of the equipment that should be used to start constructing. Another reason to do a soil exploration is to collect soil from the field of expertise and test it in a laboratory, for a detailed analysis of its properties, such as the shear strength, moisture, etc. (Das, 2020).

The methods that have been used largely during the years, mostly consist of invasive ways of monitoring soil properties. For instance, the boring methods have been applied widely. This process consists of drilling a hole with mechanical equipment, where the soil samples are disturbed or collected to go through laboratory tests. Another known strategy is the Standard Penetration Test, where a standard split-spoon sampler is used. The sampler is made up of a steel tube, which is responsible for collecting the soil samples, and then the samples are sent to the laboratory, similarly to the boring method. Following these, the Cone Penetration Testing (CPT) is also practiced during monitoring. This method involves a cone-shaped device that is driven through the soil. More information about this method is given in Section 6.

As discussed above, the majority of strategies to be used in this field are invasive. For this reason, the necessity to produce new strategies, which would be more efficient and accurate comes up. In the next section, literature about the pros and cons of the robotic earthworm is given.

3.2 Robotic earthworm characteristics

The importance of monitoring the soil is closely related to the quality of buildings. Several methods have been used to complete this action, while there are always new attempts to create a more effective method to fulfill the monitoring. A few examples and literature that are relevant to the topic to be discussed are shown below.

According to Karipoth et al., the deformable nature of robotic earthworms is very helpful to the field of investigation and can be adapted to different terrains. Moreover, the sensors make it possible to achieve feedback from time to time, which could help in providing insights into the deformation of its movement. Following that, earthworm-robotics have the ability to operate automatically in challenging environments, different from the other non-invasive rigid methods.

On the other hand, there are a number of drawbacks regarding the usage of this method

(Karipoth et al., 2021). For instance, the probe needs to be maintained by power supplies during the operations of soil monitoring. Securing a lightweight and long-lasting power supply would be challenging. Additionally, the probe may be prone to damage occurring due to the harsh environments. For this reason, the robotic shape should offer durability and resistance.

Due to the difficulties that can be faced during the making up of probes, the demand to find an easier way of testing the prototype arises.

3.3 Simulations by using COMSOL

To begin with, today's world is moving towards new technologies that simplify daily tasks, and create a more effective strategy to deal with problems. One of these examples is the simulations. With a variety of goods, simulations are widely being chosen to estimate specific phenomena, including the soil mechanics aspects. Physical experiments or tasks, always have a closer connection to the real values. However, the simulations could evaluate the results in a much faster time, with the help of simulation models. Furthermore, one can play with values and change the ranges of inputs, allowing users to analyze the behavior of an event in different scenarios. Moreover, it would be cheaper in operating costs to perform simulations, due to the nonnecessity of using equipment to execute experiments.

One of the software models to apply geomechanics simulations is COMSOL. This software is capable of modeling different cases and determining the soil behavior by using the Mohr-Coulomb model. Additionally, displacement plots can be carried out, and failure criteria of specific materials can be deduced. An option of the output coming from COMSOL is shown in Figure 2. The data for each plot is then imported into Excel.

The simulations in this research paper are expected to be run via COMSOL, and more information about the technicalities and specifics of the software are given in the following chapters.

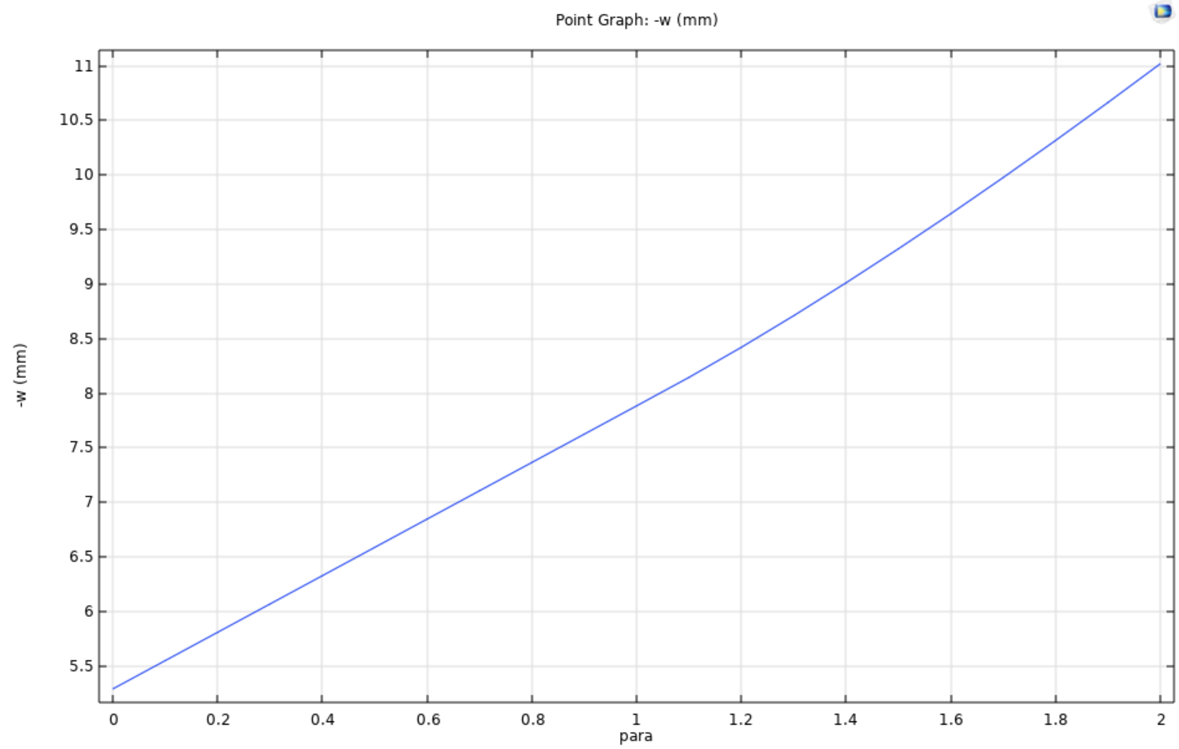

Figure 2: Displacement plot in COMSOL (“COMSOL: Multiphysics software for optimizing designs”, n.d.), where -w represents the displacement, while para is related to the load, specifically para 1 equals 100 kPa

4 Research dimensions

The research will analyze the rigid penetration of the robotic probe tip, in order to fill the gaps in current knowledge and contribute to the study area by introducing more optimized designs or an easier way to check the validity of designs by simulations. An overview of the research objective and questions is described below.

4.1 Research objective

As also described in the introduction and context, the aim of this research is to simulate an earthworm-inspired robotic probe tip, which will be able to explore and collect data about the soil or other buried objects, to find the best burrowing strategies to deal with penetration resistance, by using COMSOL, a software that is used to study the physical interactions of real world's model.

4.2 Research questions

The research questions that are answered during this research are as follows:

Question 1: What are the key characteristics of an earthworm-inspired robotic probe that influence the effectiveness in navigating and burrowing in a specific type of soil?

- How does the overall design of the probe tip contribute to efficient burrowing?
- In which ways is the design of the probe tip influenced by the soil properties?

Question 2: Are the outputs in terms of penetration resistance of the numerical simulation comparable with the experimental data?

- How sensitive are the simulation results to variations in input parameters related to the used soil in the lab or probe tip design, and how can we optimize this information to achieve more realistic results?
- Are there challenges or limitations while using COMSOL to simulate soil interactions?

5 Research framework

As mentioned before, literature on Mohr-Coulomb principles, CPR(Cone Penetration Resistance) testing, and experiments on finding parameters are conducted in order to analyze the behavior of soil based on theory and practice. The theory helps in checking the dynamics of the soil penetration tool, and the design that it should have. This phase leads to the design of the robotic probe tip. There are three specific designs, differing in tip length. This decision is taken to validate the probe tip in different dimensions and inspect its performance in a specific type of soil. For this reason, three aspect ratios are taken into account, where the aspect ratio represents the division of the tip length with probe diameter. By finishing the design, the input dimensions are then carried out in COMSOL. Following that, COMSOL software is able to predict the vertical displacement or stress distribution of the probe tip in soil. This procedure is considered and applied for each design, where different results are conducted and discussed. Afterwards, the outcomes of the simulation are compared to experimental data, which are found by experiments carried out in the lab, that are conducted by another colleague(Tekin, 2024). Then, a sensitivity and uncertainty analysis is performed to make room for improvement and try to bring the simulation closer to reality. Finally, the research is summed up with a discussion and conclusion about the outcomes and improvements performed in the analysis. An overview of the processes that occur during the research is shown in Figure 3.

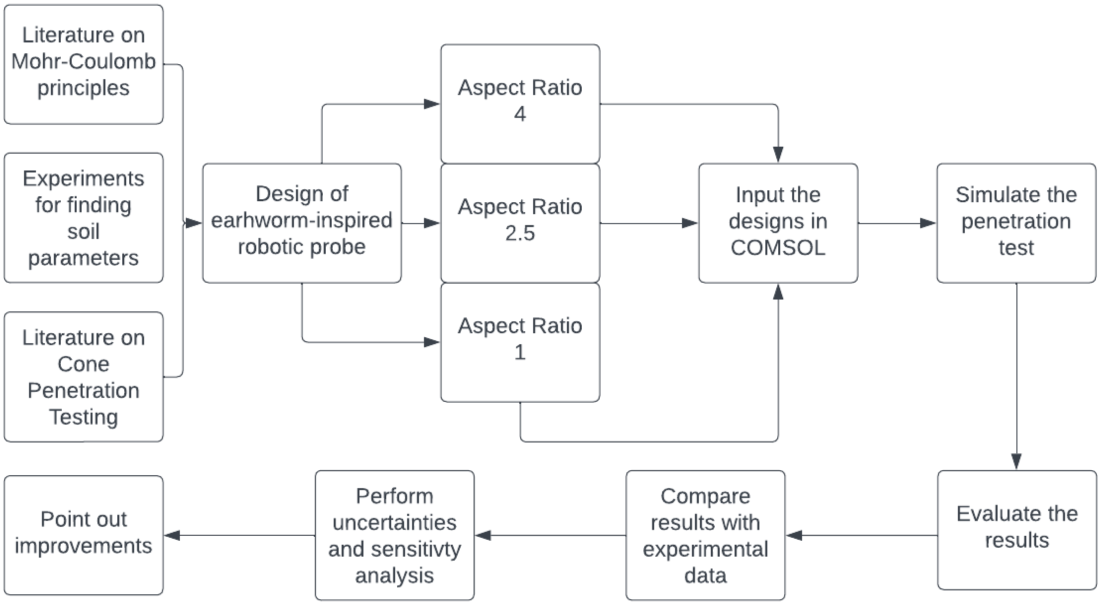

Figure 3: A flowchart describing the proposed research framework

6 Theoretical approach

In order to fulfill the needs of the research, and answer the questions that were raised, a theoretical background is necessary. As was explained in the research framework, a literature review on soil mechanics and cone penetration testing needs to be carried out. To validate the simulation, various formulas and explanations from the theory are used to assume the values inputted in the software.

There are many ways of monitoring the soil, and each of them has its own benefits or drawbacks. However, the objective is the same, to determine the soil properties. In this section, aspects of theory that help in achieving knowledge on the methods that fit the research objective are discussed.

6.1 Mohr-Coulomb's theory

To begin with, the Mohr-Coulomb theory is one of the principle theories of this research. The Mohr-Coulomb failure theory describes the shear strength of materials or soils under different conditions of stress, and it expresses it to be dependent on normal stress, friction angle, and cohesion, as is shown in Equation 1:

$$\tau = c + (\sigma Tan\phi) \tag{1}$$

, where τ represents the shear strength, σ shows the normal stress, c the cohesion value and ϕ gives the friction angle. Moreover, the plane of shear stress, according to the normal stress, is shown in Figure 4.

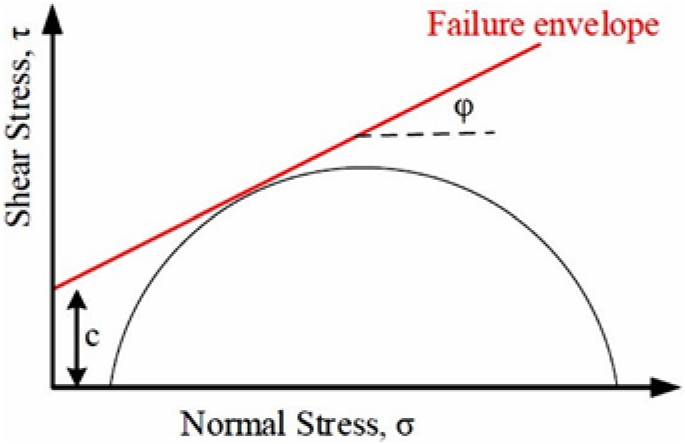

Figure 4: Mohr-Coulomb failure plane (Giwangkara et al., 2020)

When it comes to the simulations, COMSOL can calculate the stress at specific points of the model, and this could be compared to the failure line of Mohr-Coulomb, which would lead to understanding if failure is likely to occur. Furthermore, the relationships that are set via this theory, would help in finding the shear strength of the material that will penetrate the soil.

On the other hand, the two other properties of the equation, specifically the friction angle(ϕ) and the cohesion value (c), are found by laboratory testing or can be obtained from the Unified Soil Classification System(USCS), where cohesion describes the strength of material particles to stay attached, while the angle of internal friction represents the frictional shear resistance of the soil (Ediger, 2021).

6.2 Cone penetration testing

Another way of collecting or monitoring soil properties is by doing a cone penetration test. The method is applied by pushing the cone penetrometer toward the soil, which makes it possible to determine the cone end resistance q_c (Das, 2020). Over the years, this method has been used widely due to the simplicity it offers, as no boreholes are needed to do the soil monitoring. However, it is not possible to undergo a laboratory test after doing the cone penetration testing. Furthermore, a correlation has been distinguished by experimenting, where the soil friction angle is calculated by cone end resistance q_c(Pa), and vertical effective stress σ_0(Pa), by the equation below (Kulhawy and Mayne, 1990):

$$\phi = tan^{-1}[0.1 + 0.38log(\frac{q_c}{\sigma_0})] \tag{2}$$

It should be noted that the equation above is applicable only for sandy soils.

On the other hand, other relationships including the shear strength in undrained conditions have been derived from the observations, as seen in the equation below (Anagnostopoulos et al., 2003):

$$c_u = \frac{q_c - \sigma}{N_k} \tag{3}$$

where c_u represents the undrained shear strength, σ equals the total vertical stress, while N_k shows the bearing capacity factor that is approximately 18.3 for each type of cone dimension.

The equations shown above are not used during the calculations, but they give insights into how the penetration is related to the soil properties. By having the undrained shear strength of soil, its stability of it can be analyzed, and evaluated in terms of engineering applications. For this reason, the cone penetration testing helps show an example of how the soil is monitored by implementing this technique. This strategy could also be used for the penetration of the robotic probe in this case, as the simulations could lead to a correlation between the shear strength, vertical total stress, or other parameters, such as the friction angle, etc.

7 Methodology

7.1 Simulation Setup

In this section, the process of simulation is described, including the specifications of the soil properties that are implemented in COMSOL.

To begin with, three designs are imported to COMSOL. As mentioned, the change in design considers the different tip shape geometries and different aspect ratios. Furthermore, it should be noted that the simulation focuses on the rigid nature of the design. The designs that are intended to be made are inserted in COMSOL, by importing their geometry and shapes. A similar shape to the one that is simulated is shown in Figure 5.

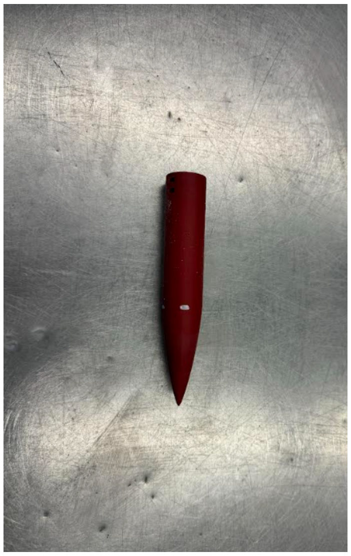

Figure 5: The shape of probe used for soil exploration

Afterwards, the material, and soil properties are inserted into the software. This includes the soil density, friction angle, and other characteristics, that are conducted from the experiments in the lab. Three experiments are executed, including the void ratio experiment, sieving, and direct shear test. An explanation of each is given in the simulation development. Following that, the physics interfaces are selected, where the main focus of the research is on solid mechanics, as the objective is to analyze the soil interaction and behavior with the element or probe. Then, the boundary conditions are set. This step specifies the parts that are wanted to be investigated, by identifying the locations of the soil domain, where it is desired to check the behavior over stress or force. Additionally, the fixed constraints should be noted. These constraints specify the objects that don't displace over the simulation. In this case, it is the base of the soil domain, as this boundary needs to stay fixed during the penetration. A more detailed description of the COMSOL components that were used in the simulations can be found in Appendix D. After importing the main characteristics, such as the dimensions of the probe, the tip of the probe, and the soil domain, the display will be similar to Figure 6. More information about the dimensions of the soil domain and tip are shown in Appendix E.

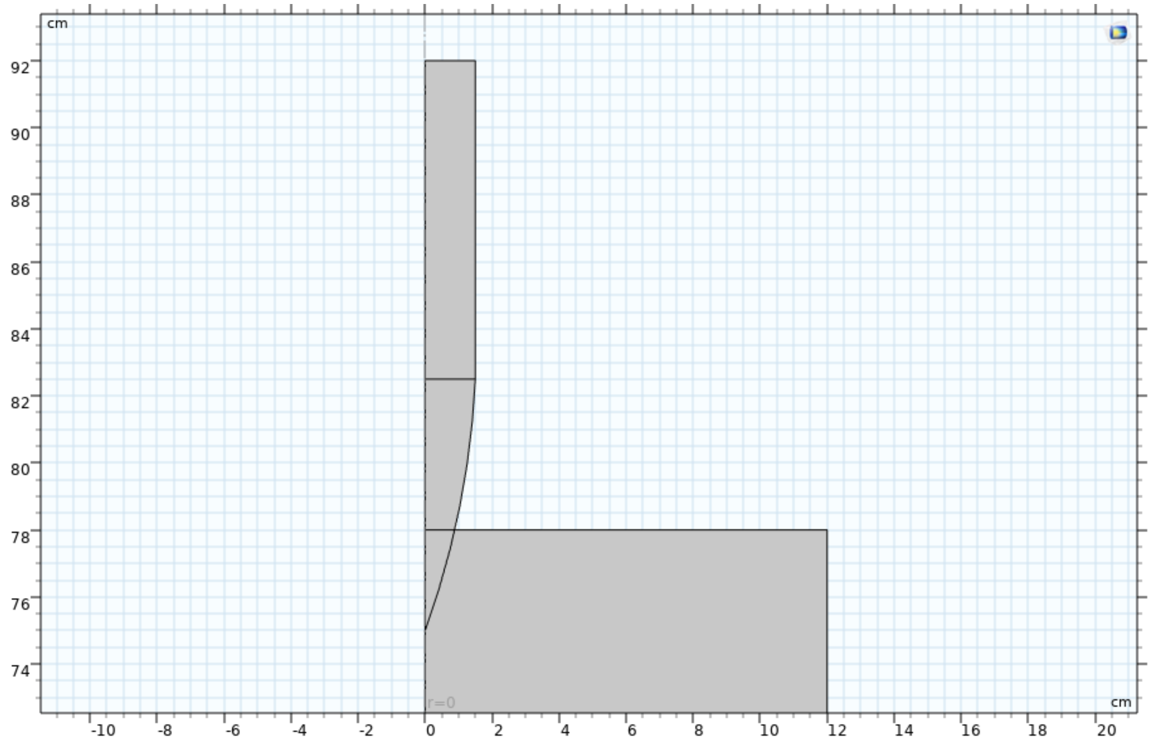

Figure 6: The setup of probe and boundary conditions in COMSOL by being based on the real dimensions

After evaluating the designs that were created similar to the cone penetrometer and prototypes in the lab, characterized by a different diameter or length, an analysis of the results focusing on the differences in shapes that were inputted in the software is carried out. For instance, COMSOL offers information about the von Mises stress and reaction forces, as seen in Figure 7, which gives then statistics or data about the stress exerted in soil. A more detailed explanation of the von Mises stress is given in the Simulations section.

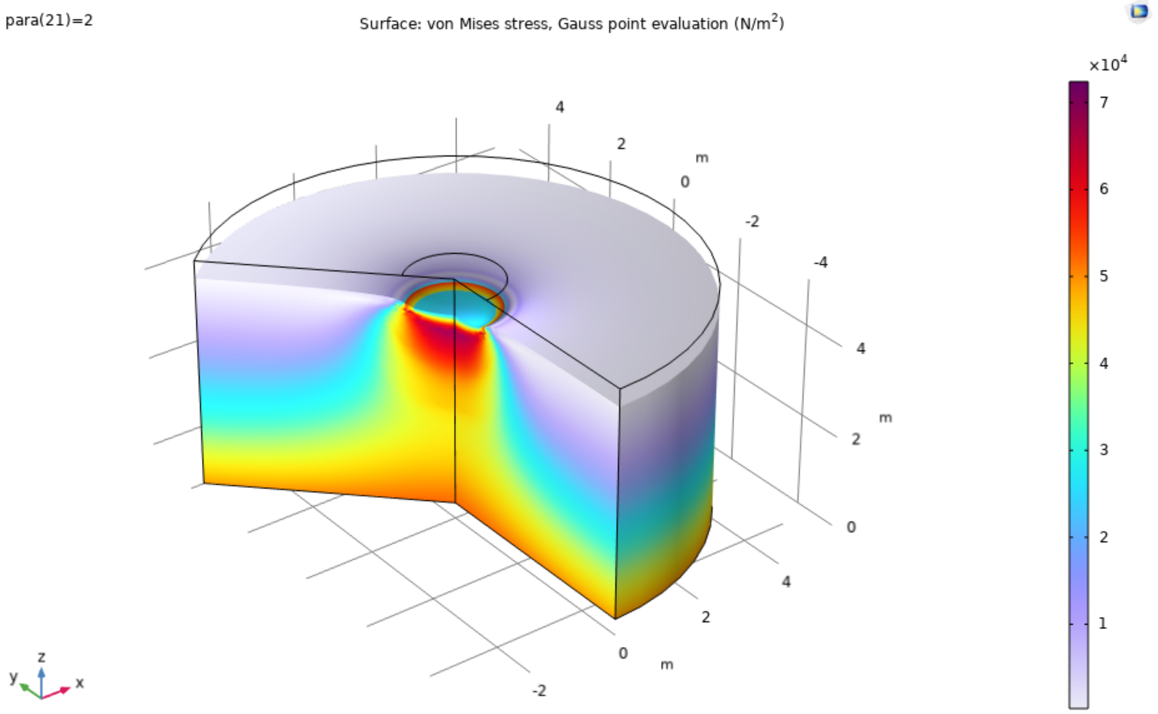

Figure 7: A 3D configuration of the von Mises stresses experienced in the simulation, where the color bar represents the level of magnitude

Figure 7 shows the distribution of stress in soil by a penetration simulation, where the colors show the level of the magnitude, as dark red signifies the maximum value of the stress. The display is shown in 3D to have a better preview of the COMSOL output. The information observed from the software is crucial to analyzing the behavior of different shapes in soil monitoring. Other displays of the stress appearance are shown in Appendix F.

7.2 Comparison to the experimental results and verification of results

After simulating every case that was introduced in the previous section, the results are compared to experimental observations. As mentioned before, three of the prototypes or designs used during experiments are similar to the designs that were simulated via COMSOL, to make a fair comparison. The comparison is done by displaying graphical visualizations of the results observed from the simulations and experiments, such as the shear strength, friction coefficient, or cohesion. Following that, a verification and validation process is carried out to check the uncertainties or limitations that are obtained from the simulations. Moreover, a sensitivity analysis follows up to provide information about the changes in outcomes that are affected by different inputs.

8 Simulation development

In order to simulate the situations that were analyzed in this report, various parameters are first obtained experimentally. As explained previously, the designs are different, while the soil conditions for the experiments should be the same. Three important variables are carried out, and these values are then implemented in COMSOL. Specifically, the void ratio, mesh size, cohesion, and friction angle are investigated. The section below provides a description of the experiments that were conducted to carry out the aforementioned parameters.

8.1 Collection of soil properties experimentally

8.1.1 Void ratio

The void ratio is a crucial parameter that represents the volume of voids to the volume of solids in a soil sample. This parameter gives an understanding of the permeability or porosity of the soil. To quantify the value, an experiment was performed.

Firstly, a bucket with a known volume was measured for the weight and dimensions. Then, the bucket was filled with dry sand, which was taken from the soil that was used for the probe penetration. This bucket was then weighted again, and the new mass was subtracted from the one with the empty bucket. The new mass was divided by the density of the sand, in order to achieve the volume of solids. Then, the maximum void ratio was calculated by using Equation 4:

$$e = \frac{V_v}{V_s} \tag{4}$$

where e, V_v, and V_s represent respectively the void ratio, volume of voids, and volume of solids. Afterward, the bucket was placed in the shaking machine for five straight minutes. The shaking machine is displayed in Figure 8.

Figure 8: Shaking machine used to carry out the void ratio experiment

After the process of shaking the bucket filled with sand, a space was created from the top of the bucket. This height is measured and the new volume of voids is calculated by multiplying the height with the base of the rectangular bucket. Finally, the minimum void ratio is found by using the same equation. This process is done three times, in order to increase the accuracy. The average of each is shown in Table 1, while the calculations are displayed in Appendix A.

Minimum void ratio(e_{min})	Maximum void ratio(e_{max})
0.306	0.521

Table 1: The minimum and maximum void ratio of sand used to derive the experiments

8.1.2 Particle Size Distribution

As mentioned earlier, a particle size analysis by conducting a sieving experiment is carried out. The equipment is shown in Figure 9.

Figure 9: The sieving equipment used to conduct the Particle Size Distribution

This experiment is important as it gives an idea of the particle size of the soil, and increases the optimization of simulations by implementing the values in software.

In order to run the experiment, the dry sand that was used for the experiments of the probe tip penetration was collected and put in the mesh sieves. The screens were placed on top of one another, where the upper sieve would have larger openings. Then, by using the machine, the sample passed through the sieves, and at the end of the sieving process, each sieve was measured in weight. This process was conducted three times, in order to increase the accuracy of the results, and the average weight of each mesh screen was taken into account. The distribution of the dry sand is shown in Figure 10, while the values regarding the weights specific to the diameter of particles are shown in Appendix B. Figure 10 shows that the dry sand is a finer soil, as there is a higher percentage of smaller particles.

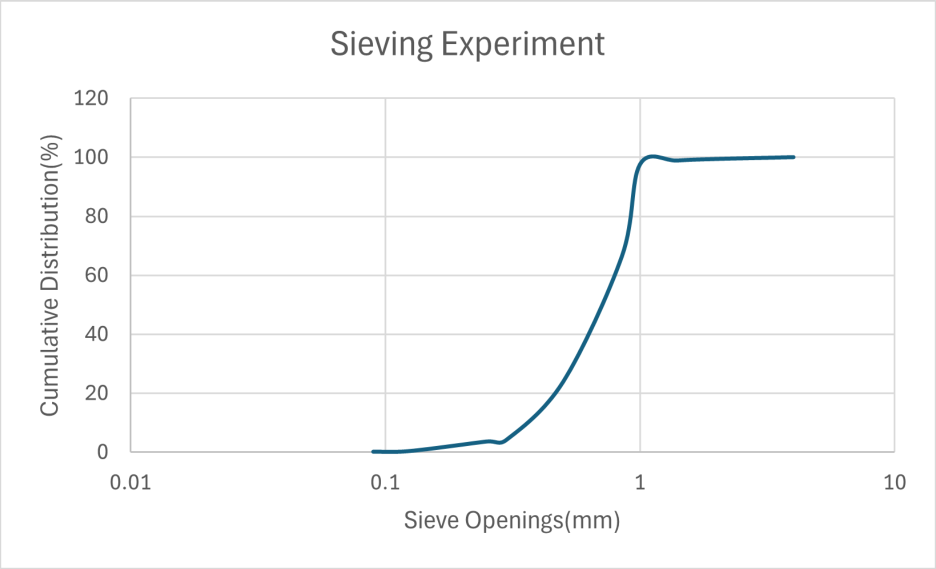

Figure 10: Particle Size Distribution

The importance of carrying out a sieving analysis lies in the relationship that the particle size distribution has with the other variables, such as the void ratio, or cohesion and friction angle. Soils with different particle size distributions can behave differently under load, causing also distinct outcomes. Following that, the sieving experiment directly affects the porosity and permeability of soil that can be added as properties in the software. Finally, the necessity of conducting this analysis is mostly to state the soil nature, as the changes in particle size distribution could lead to different outcomes in future research. The same can be said for the void ratio calculation.

8.1.3 Shear Resistance

Other important factors that are taken into account while doing the simulations are specifically the cohesion and friction angle of the soil sample. As explained earlier, these characteristics are important in determining the shear stress of the soil. The experiment used to find the values is the direct shear test. The equipment is shown in Figure 11.

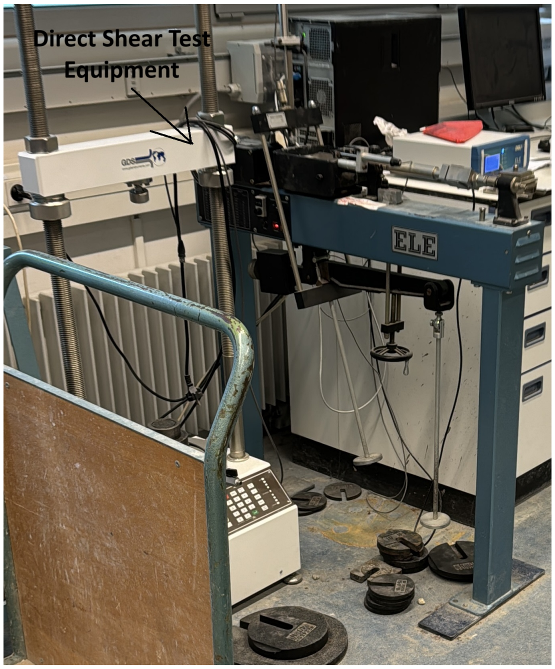

Figure 11: The direct shear test equipment highlighted by the arrow

Three different normal stresses were placed in the equipment, to determine the peak shear stress for each trial. Then, these points were plotted in a graph, and a trendline was drawn. The results of the normal and shear stresses, including the equation describing the cohesion and friction angle are shown below. The graph is given in Figure 12.

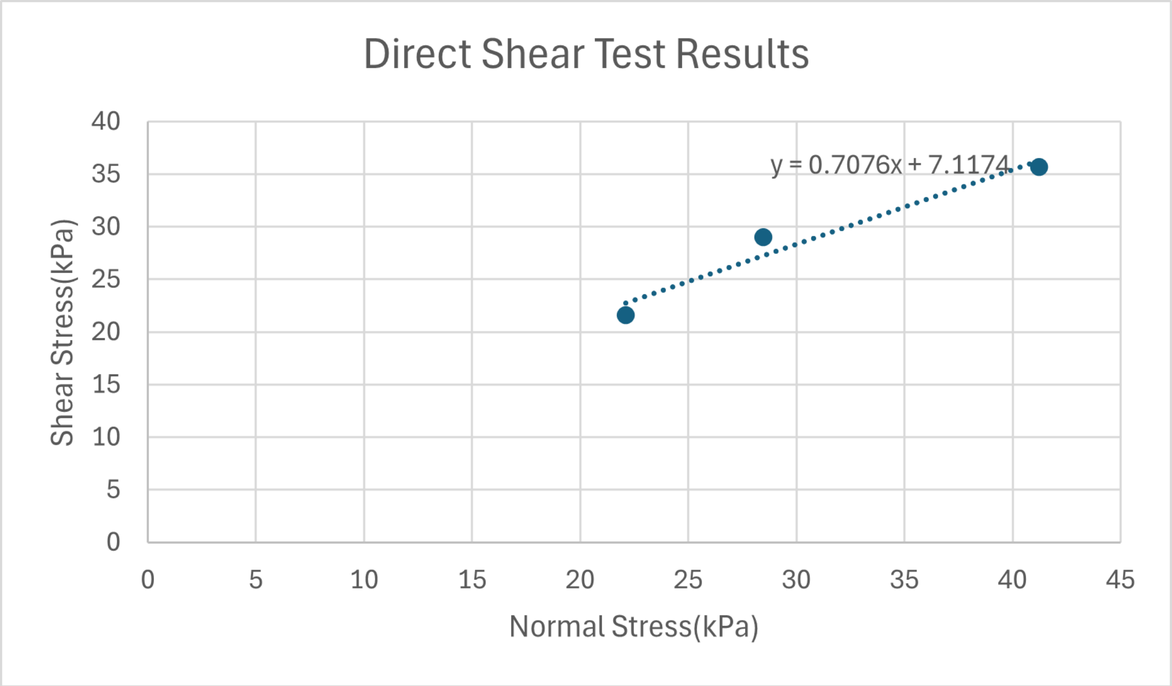

Figure 12: The normal and shear stresses derived by the experiments, including the failure plane highlighted by the trendline

The equation provides the cohesion, which is the point where the x-coordinate equals 0. For this reason, the cohesion amounts to approximately 7.1 kPa. When it comes to the friction angle, the gradient shows the tangent of the angle. In this case, the angle is approximately 35.3°. A more detailed overview of calculations is shown in Appendix C.

9 Results

9.1 Numerical outputs

As discussed in the Methodology section, the simulations are carried out in COMSOL. The rigid behavior of the probe is tested in different bulk densities, in order to check the performance of each tip ratio with respect to the soil properties. Firstly, the characteristics of the dry sand and probe are implemented, including the found values from the experiments. The simulations consider two different scenarios of soil, specifically the linear elastic behavior, where the stress and strain relationship are linear, and the elastoplastic behavior that takes into account the plasticity of the soil.

Three different geometries were built, each differing in tip height to diameter ratio, specifically the ratios of 1, 2.5, and 4 were taken into account. After building the geometries, the material properties were inputted, and then the physical properties of each were implemented. The simulations are displacement-driven. This means that a prescribed displacement was given to the whole probe, to make it easier to compare the results to the experimental ones. After that, a mesh was applied to both the soil and probe. The mesh is responsible for dividing the geometry into smaller elements, increasing the accuracy of the model. In this case, the soil is parted in extremely fine elements, in order to accurately consider the nature of dry sand during simulations. An overview of the model builder in COMSOL is shown in Appendix D.

9.1.1 Linear Elastic Behavior

After importing the properties of materials, the simulations are computed. The software provides the stress needed to displace the probe in the desired distance, specifically 20 cm, which is similar to the displacement made by the machine in the laboratory. An overview of the stresses for each probe is given in Table 2.

-	Bulk Density		
Aspect Ratio	$1200kg/m^3$	$1500kg/m^3$	$1800kg/m^3$
1	116 kPa	195 kPa	274 kPa
2.5	184 kPa	309 kPa	435 kPa
4	266 kPa	448 kPa	630 kPa

Table 2: Simulation results in different densities, showing the stress experienced per each aspect ratio

The stresses above define the output of von Mises stress that is exerted in each probe tip. Von Mises stress is a representation of the stress state caused by the probe in a single or scalar value. In this case, the probe is only subjected to a load in one direction, which allows the von Mises stress to be equal to the equivalent stress state.

Furthermore, the vertical stress is observed in COMSOL, and it appears that the same value is observed, allowing the calculations to be dependent on these stresses. The maximum stress is found to be around the tip, which is logical as that part faces the largest contact with the soil.

As can be seen above, the tip ratio 1 exerts the lowest stress in soil. One of the factors that contributes to this is the shearing area of the specific probe, as it makes it easier for the stress to be distributed throughout the probe. For this reason, when converting the stress to load, the formula below is used:

$$\sigma = \frac{F}{A} \tag{5}$$

Due to this, the contact areas for each probe are accounted for. The contact areas represent the area where the force is exerted or distributed. The procedure to find the area was by being based on the experiments, as two specific values were captured from the experiments, specifically being the pressure and the force. By dividing the force with pressure, the area on which the force is applied can be found. Furthermore, the area on which the stress is distributed is also checked by the Measure option in COMSOL, by selecting the tip domain and conducting the area of the probe tip shown in Figure 6. Then, the average vertical stress of the selected area is calculated, and the area is multiplied by the vertical stress. Moreover, in order to verify the chosen method to calculate the force, the reaction forces for each design were considered. The forces needed to push the probe are given in Table 3.

-	Bulk Density		
Aspect Ratio	$1200 kg/m^3$	$1500 kg/m^3$	$1800 kg/m^3$
1	174 N	292.5 N	411 N
2.5	163.76 N	275.01 N	387.15 N
4	159.6 N	268.8 N	378 N

Table 3: Simulation results in different densities, showing the force experienced per each aspect ratio

The results show that the best ratio when it comes to the lowest force needed to displace the object is the third probe, specifically an aspect ratio of 4. This shows that less force is needed to push the probe to the desired position. A large factor contributing to this is that the force is applied in a lower contact area, and the penetration is more efficiently managed. Moreover, the steeper probe displaces less soil vertically, which translates into requiring less overall force.

Furthermore, an analysis is carried out by changing the diameter of the probe and keeping a constant tip height while setting the bulk density as 1540 $\mathrm{kg\,m^{-3}}$, similar to the one used during the experiments. The simulations are done in the same ratios as above, and the results in Table 4 are achieved.

Aspect Ratio	Force to displace to 20 cm(in N)
1	333.2
2.5	288.36
4	286.8

Table 4: Numerical results relating to the change in diameter in geometry of the probe

It is displayed that the probe with the smallest diameter possesses the best outcome, as it requires the lowest force to be displaced 20 cm downward in the soil domain. However, it should be noted that the stress in soil when displacing this probe is the largest, while the relatively small contact area plays an important role in decreasing the force needed.

9.1.2 Elastoplastic Behavior

As mentioned previously, the elastoplastic behavior is analyzed during the simulations, where the input of the direct shear test is imported, specifically the cohesion and friction angle. In this case, the pressure that displaces the probe remains constant, and the displacement of each probe ratio is evaluated. The results are shown in Table 5.

Aspect Ratio	Displacement in cm
1	19.212
2.5	19.224
4	19.25

Table 5: Displacement results in dry sand

The displacement outcomes show that a higher distance is achieved by using the probe with a ratio of 4, meaning that it would be more effective on choosing it instead of the other alternatives. However, the difference is not large within the options.

In order to check the efficiency of probes, simulations were also done in a different soil. The clay properties were implemented, including the cohesion and friction angle. In this case, the displacement of each probe per 100 kPa is compared. The procedure of implementing the geometry of shapes and other physical characteristics remains the same as in the previous simulations. The results are present in Table 6.

Tip height- Diameter Ratio	Displacement in mm
1	5.345
2.5	5.415
4	5.4025

Table 6: Displacement results in clay

The results show that a higher displacement is achieved with a ratio of 2.5. Clay is considered as a more resistant soil when compared to dry sand, which can also be distinguished by the increase of Young Modulus, which represents the stiffness of soil. This means that the second probe performs better in stiffer soils.

9.1.3 Investigation of the Boundary conditions

When implementing the simulations, the specifics of boundaries are imported from the experimental setup. A more detailed explanation of the dimensions of the boundary radius and probe size is shown in the following section. In order to know the effect that these boundaries have on the stress in soil, simulations regarding the diameter of the boundary are carried out. This is done by changing the radius manually in COMSOL and evaluating the stresses in each case. Each probe is chosen to apply the simulations, as it is expected that the effect of boundaries influences each probe in the same direction. A plot describing the relationship between the boundary conditions and stress is shown in Figure 13.

The plot shows that after expanding the radius of the soil domain to 28 cm, the change in stress is not significant. This shows that having a radius of 28 cm would better estimate the stress in soil, as the stress is no longer influenced by the soil container dimensions.

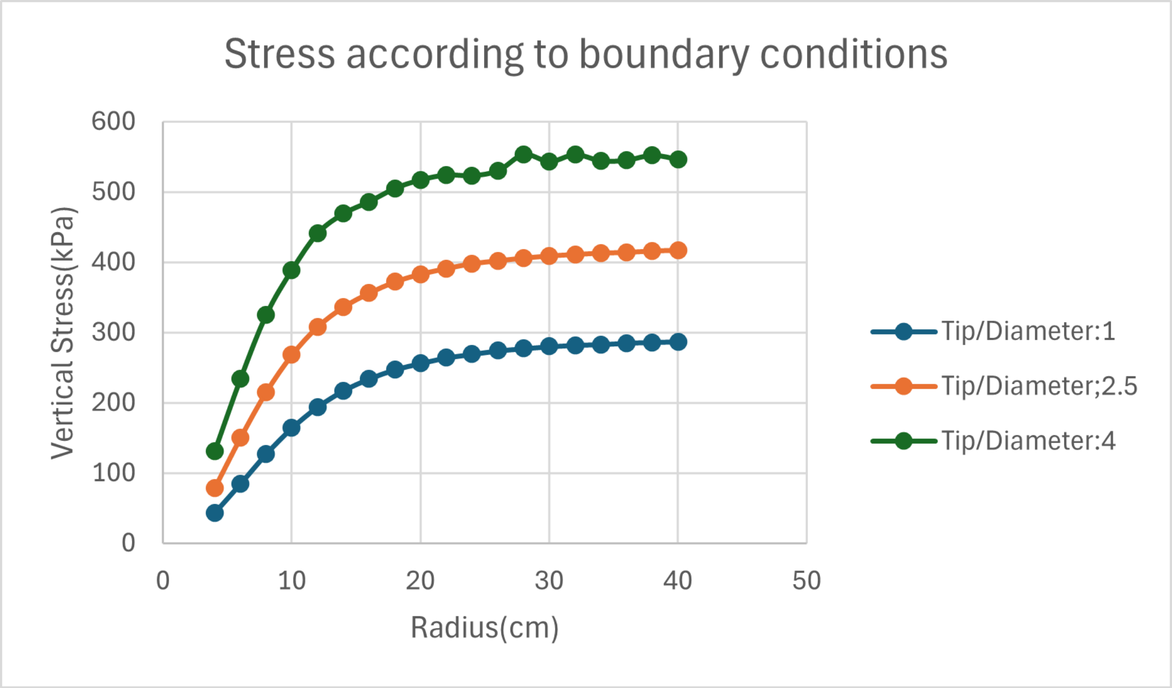

Figure 13: The relationship of stress and radius of boundary domain

9.1.4 Final validation

In order to check the validity of the simulations, experiments were carried out(Tekin, 2024). Each probe is assessed in the same displacement as used in COMSOL. An overview of the test setup is shown in Figure 14.

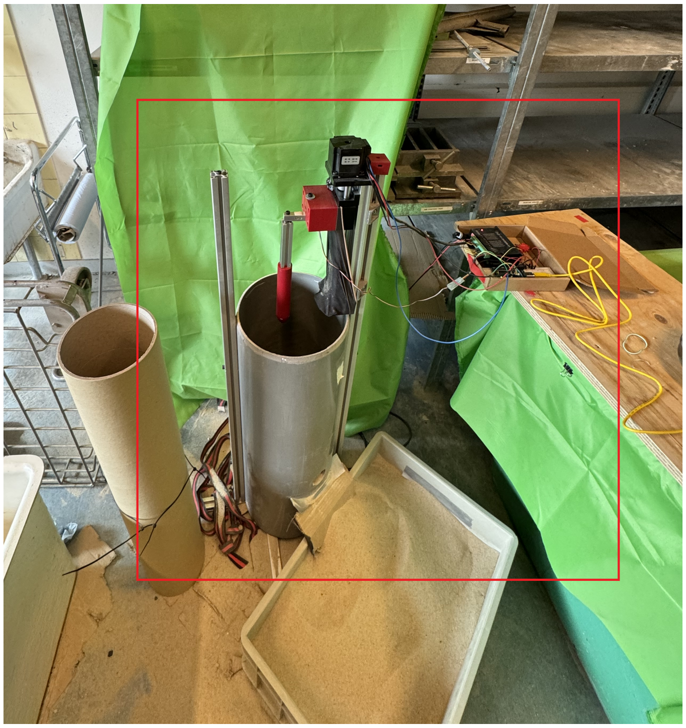

Figure 14: The experimental setup of the penetration experiment highlighted within the red rectangle

The sand that is shown above is the same as the one used for finding the physical properties mentioned previously, such as cohesion, friction angle, void ratio, etc. The basket is filled per each experiment carried out, in order to remove the effects that pre-consolidated soil would cause on the results. The bulk density chosen to execute the experiment is 1540 $\mathrm{kg\,m^{-3}}$. The experiments are performed three times per probe, and the average force for each is observed, to increase the accuracy of the results. The results comparing the experimental and simulation observations are shown in Table 7.

Aspect Ratio	:1	:2.5	:4
Experimental Results	382.76 N	379.98 N	371.1 N
Numerical Results	306 N	288.36 N	281.4 N

Table 7: Experimental vs Numerical observations

As can be seen from Table 7, the simulations underestimate the forces needed for the probe to reach 20 cm. Many factors and uncertainties could contribute to this issue, and a more in-depth analysis of the problems that could appear during simulations is described in the Sensitivity analysis section. Furthermore, a plot showing the values in Table 7 is shown in Figure 15.

On the other hand, both the simulations and experiments show that the aspect ratio 4 between the tip height and diameter of the probe is considered to be the best option, as it requires less force. However, the difference is not that large within the options. Finally, it appears that the simulations are comparable to the experiment in terms of showing the most efficient probe version, while there is a difference in the value of forces, which can be related to uncertainties regarding the experiments or the model used to conduct numerical simulations.

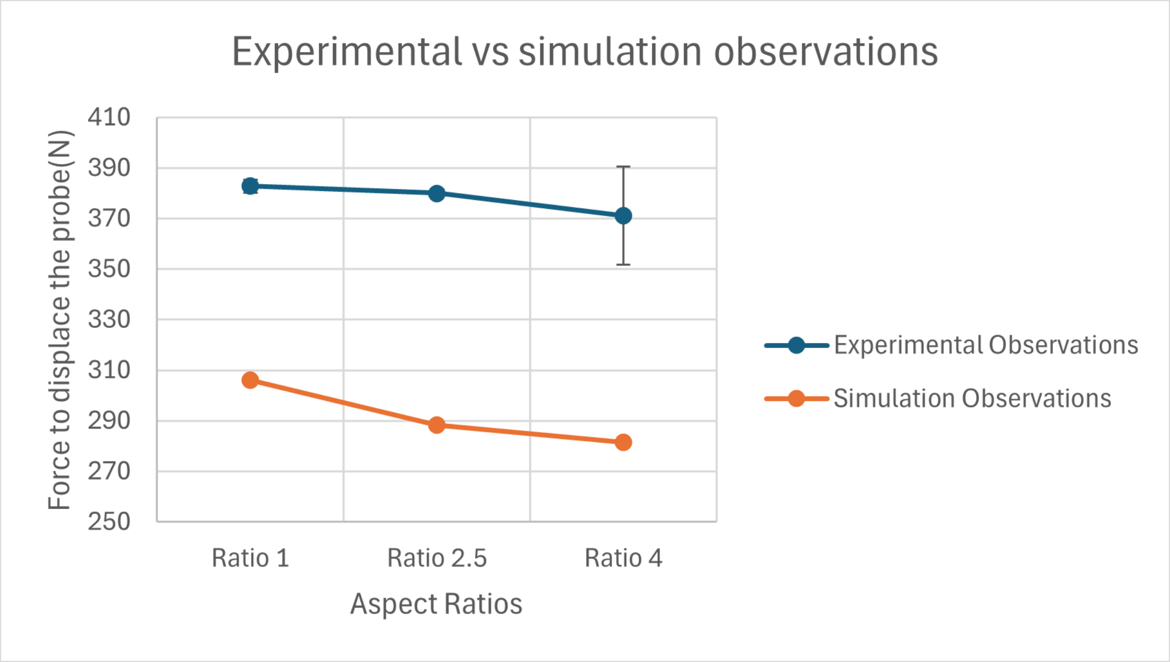

Figure 15: The results of numerical simulations and experimental observations per each aspect ratio, including the standard deviation

The x-axis shows the aspect ratios, while the y-axis shows the force required to displace the probe to 20 cm. Moreover, the graph also displays the standard deviation of the outcomes, as can be said that the aspect ratios of 1, and 2.5 have an insignificant error, while the aspect ratio of 4 has a higher uncertainty.

9.2 Sensitivity and uncertainty analysis

After implementing the simulations, and comparing them to the experimental observations, a sensitivity analysis is needed to be accomplished. Furthermore, the sensitivity study would answer one of the research questions, on the importance of parameters in terms of perceiving realistic results when compared to experiments.

Firstly, a sensitivity analysis is performed on the inputs that are given for the calculation of the force, as described in the Simulation Results section. The two considered parameters are Young's Modulus and bulk density. The analysis is done manually by changing each dimension in a specific quartile, such as 25% or 50% while keeping the other values constant. Moreover, a random probe is selected to perform the investigation, as it is expected that the probes have the same behavior in terms of changing the input dimensions. The plot below gives an overview of the density of parameters.

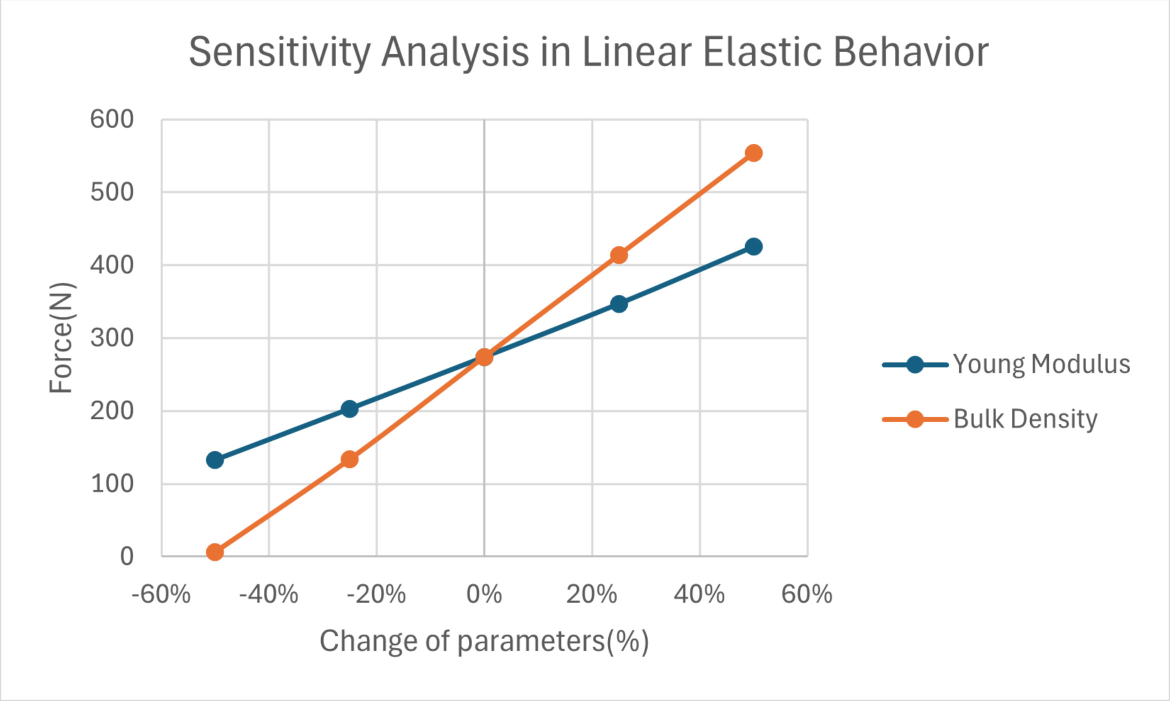

Figure 16: Sensitivity analysis on Linear Elastic Material considering the Young Modulus and Bulk Density

The graph clearly describes that the bulk density has a higher impact on the final outcome. For this reason, high importance should be given to this value, as it could lead to unrealistic results.

Another analysis is done considering the cohesion, and friction angle, which were accounted for when calculating the displacement in dry sand and clay, where the plasticity behavior of soil was taken into consideration. The same procedure is followed, where the plot in Figure 17 describes the behavior of displacement in terms of the aforementioned parameters.

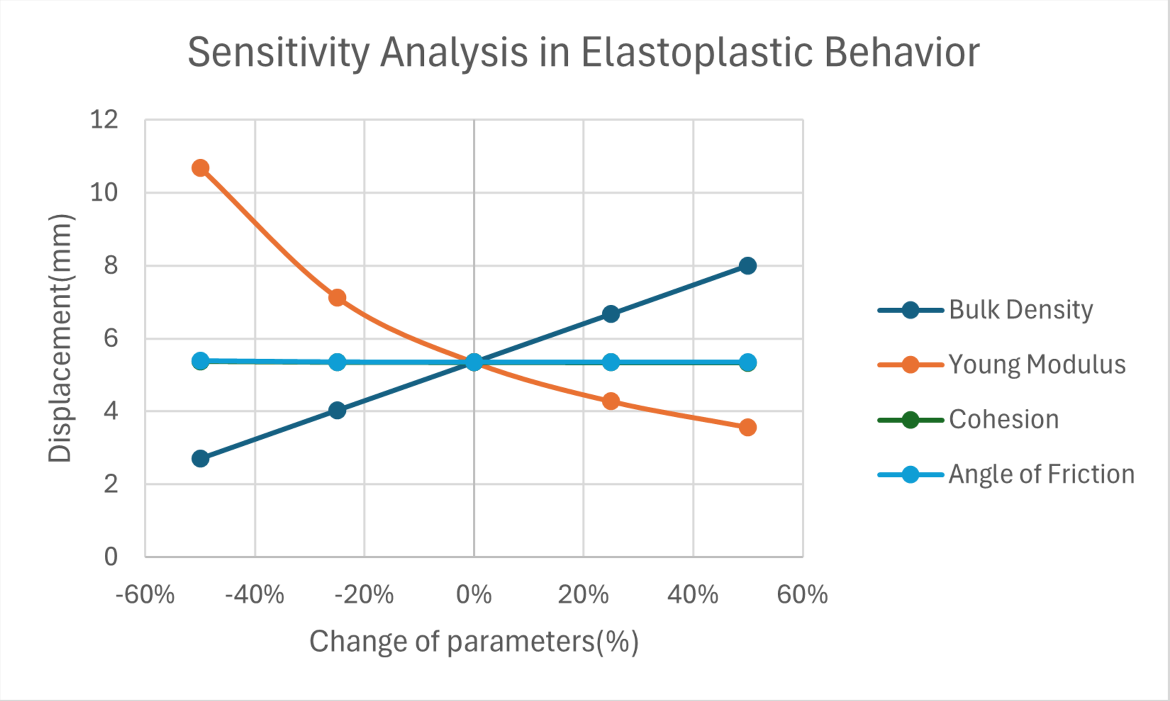

Figure 17: Sensitivity analysis on elastoplastic behavior of soil

The plot suggests that the cohesion and friction angle have an insignificant role in the outcome when compared to Young's Modulus and bulk density. However, considerable notability should be given to each value, in order to get a realistic result. Furthermore, it is shown that when applying the elastoplastic material behavior to the soil, a strange nature of density with respect to the displacement is observed. However, when checking the reaction force with regard to the density, it is noticed that limitations are present. The increase in density also increases the reaction force, while the reaction force should stay constant in order to have a fair comparison. When changing the other variables such as Young's Modulus, there is no difference in the reaction force. For this reason, it should come to an agreement that the bulk density does not represent the actual behavior of soil in terms of elastoplasticity. Furthermore, it is also observed that when reducing the void ratio by 20 %, there is an increase in displacement specifically by 10 %. However, in theory, the decrease in the VOID ratio should provide a more resistant soil. For this reason, a technical explanation of the limitations of COMSOL is explained in Appendix G.

10 Discussion

The analysis showed that the simulations can be considered pragmatic, as the results are close to reality. For instance, the simulations and experiments result all in one conclusion that the tip: diameter ratio of 4 would be the most efficient solution in terms of penetration resistance.

Following that, the difference in forces needed to displace the probe was not large. For this reason, the context of the usage that the probe is connected to is significant on which option to choose. For example, one could choose the ratio of 1, as the stress is distributed in a larger area, and the stress in the soil is less when compared to the other choices. This could help in not disturbing the soil, which could remove any risks of damaging the soil microstructure.

On the other hand, there were unexpected results during the sensitivity analysis. When executing the changes in the final outcome with regards to Young's Modulus, it was observed that with the increase of this parameter, the displacement would be higher, while the increase of Young's Modulus would mean that the soil is stiffer, which translates to a higher penetration resistance soil. Furthermore, there could also be limitations in terms of the simulations. In real life, the soil could have unpredictable behavior due to unexpected particles that can be found in the soil.

To sum up, the simulations could be a good foundation for analyzing the behavior of soil. However, future research should focus on giving a better estimation of the penetration resistance in terms of other behaviors, such as focusing only in the plastic deformation or adding extra parameters. For instance, COMSOL provides a variety of parameters that could be crucial in evaluating the stress in soil, or force needed for displacement. This would provide a more time-efficient solution to determine the soil properties and would reduce the cost needed to experiment. Finally, the studies could advance more by going deeper in inspecting the relation of stress to other properties present in COMSOL.

11 Conclusion

To begin with, the analysis and simulation development tended to answer the research questions and expand the knowledge on this subject. The analyzed probe would be very beneficial to the future construction industry, introducing an innovative option that can achieve soil properties. For this reason, the study aimed to find the best geometry that could help in achieving the objective.

Firstly, it was achieved that the lowest force needed to displace the probe in dry sand is reached when the tip aspect ratio is 4. Furthermore, when exerting the same force, this specific option would penetrate the most. However, it should be noted that the differences between the aspect ratio of 4 and 2.5 were insignificant, while the aspect ratio of 1 underperforms.

On the other hand, when implementing the elastoplastic conditions, it turned out that the ratio of 4 would perform the best in dry sand, while the ratio of 1 had the least efficient results. This analysis was also carried out by implementing clay characteristics, where it was pointed out that the aspect ratio of 2.5 performs the best. Several factors related to the physical properties of clay could be affecting it. Clay is a more cohesive soil when compared to sand, and has a lower contact area that would minimize the adhesive forces that resist penetration, making it easier to penetrate.

After reviewing the simulations, the comparisons to the experimental observations turned out to be similar. For example, the same outcome on checking which option would be more suitable was achieved. To mention, the experiments showed that the aspect ratio of 4 is the ideal choice. Following that, the differences between the forces needed to displace the probe to 20 cm downward for each aspect ratio, were not large, the same as it was achieved during the simulations. However, there was a slight difference when comparing the experimental observations with numerical simulations in the magnitude of force, specifically by approximately 15%.

The differences in values were analyzed by applying the sensitivity analysis, where it was observed that two of the most influential soil parameters are Young's Modulus and bulk density. Moreover, the cohesion and friction angle are considered to be less significant in terms of the final outcome. For this reason, one should give a high consideration in evaluating the aforementioned parameters, due to the effect they have on the result, by researching more about them or trying to derive them experimentally.

Finally, the validation of simulations with the experimental data showed the benefits and drawbacks of each option, by considering many situations, where it should be pointed out that the ratio of 4 was the most efficient solution in low-stiffness soils, specifically soils implying low Young's Modulus, while the ratio of 2.5 would be better in terms of higher stiffness soils. Additionally, the choice would also depend on the goal of the study and the area where it would be executed.

12 Future Perspectives

As also mentioned earlier, this study analyzed many aspects related to the simulations and their comparison to experimental observations. As it was observed, there was a similarity between the experimental observations and numerical simulations, while there would also be room for improvement by reducing the error. For instance, future studies could dive further into the COMSOL limitations and try to solve them. Furthermore, upcoming researchers should also give a high consideration of the inputs that are implemented in COMSOL, as the Sensitivity Analysis showed that the change of parameters could lead to high uncertainties regarding the outcome.

For this reason, the main aspects that a future researcher should take into account when analyzing this study, is to understand the COMSOL calculations in terms of the changes in parameter or geometry and seek to include more variables related to the soil properties in the input, such as the shear modulus, compression index or other characteristics, in order to have a closer outcome or result to the reality.

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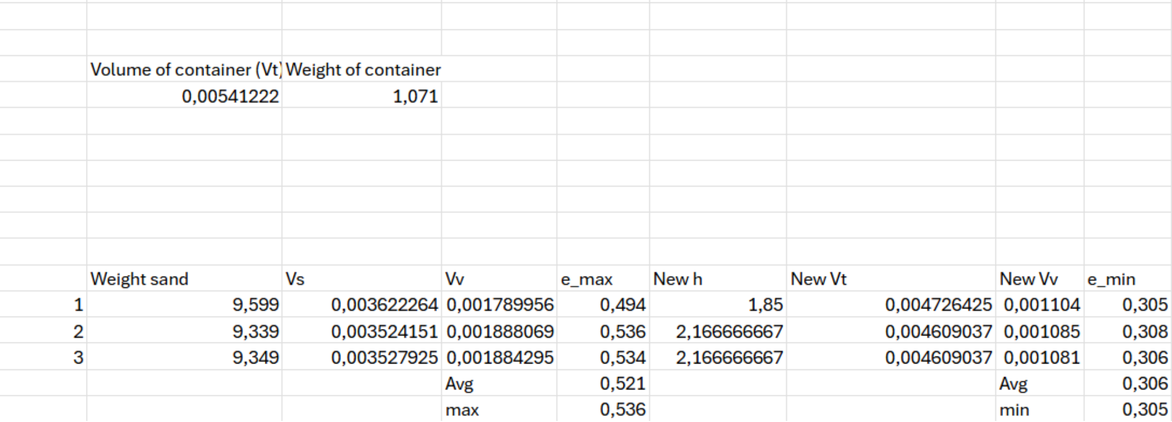
Appendices

A Calculations for void ratio



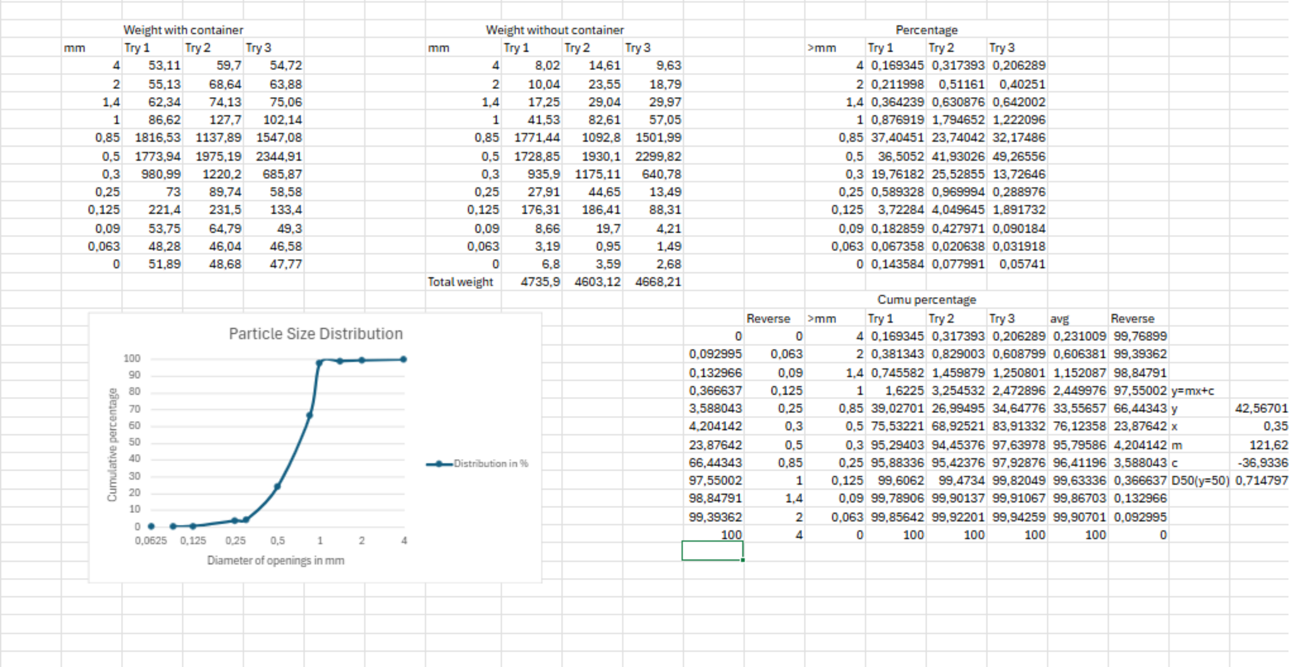
Volume of container (Vt	Weight of container
0,00541222	1,071

	Weight sand	Vs	Vv	e_max	New h	New Vt	New Vv	e_min
1	9,599	0,003622264	0,001789956	0,494	1,85	0,004726425	0,001104	0,305
2	9,339	0,003524151	0,001888069	0,536	2,166666667	0,004609037	0,001085	0,308
3	9,349	0,003527925	0,001884295	0,534	2,166666667	0,004609037	0,001081	0,306
			Avg	0,521			Avg	0,306
			max	0,536			min	0,305

Figure 18: The calculations for void ratio

As discussed throughout the report, the experiment was executed three times, in order to increase the accuracy. The table shows the main values, such as the volume of voids, and solids per each experiment, including the weight of sand. Afterward, the parameter ”new h” describes the height that is lost from the shaking process, which makes it possible to calculate the minimum void ratio. Meanwhile, ”Vs”, and ”Vv” correspond respectively to the Volume of Solids and Volume of Voids, while ”emax” is related to the maximum void ratio. Following that, the ”new Vt”, and ”new Vv” correspond to the Total Volume and Volume of Voids after shaking the sand, while ”emin” shows the minimum void ratio.

B Sieving Experiment



Weight with container

mm	Try 1	Try 2	Try 3
4	53,11	59,7	54,72
2	55,13	68,64	63,88
1,4	62,34	74,13	75,06
1	86,62	127,7	102,14
0,85	1816,53	1137,89	1547,08
0,5	1773,94	1975,19	2344,91
0,3	980,99	1220,2	685,87
0,25	73	89,74	58,58
0,125	221,4	231,5	133,4
0,09	53,75	64,79	49,3
0,063	48,28	46,04	46,58
0	51,89	48,68	47,77

Weight without container

mm	Try 1	Try 2	Try 3
4	8,02	14,61	9,63
2	10,04	23,55	18,79
1,4	17,25	29,04	29,97
1	41,53	82,61	57,05
0,85	1771,44	1092,8	1501,99
0,5	1728,85	1930,1	2299,82
0,3	935,9	1175,11	640,78
0,25	27,91	44,65	13,49
0,125	176,31	186,41	88,31
0,09	8,66	19,7	4,21
0,063	3,19	0,95	1,49
0	6,8	3,59	2,68
Total weight	4735,9	4603,12	4668,21

Percentage

>mm	Try 1	Try 2	Try 3
4	0,169345	0,317393	0,206289
2	0,211998	0,51161	0,40251
1,4	0,364239	0,630876	0,642002
1	0,876919	1,794652	1,222096
0,85	37,40451	23,74042	32,17486
0,5	36,5052	41,93026	49,26556
0,3	19,76182	25,52855	13,72646
0,25	0,589328	0,969994	0,288976
0,125	3,72284	4,049645	1,891732
0,09	0,182859	0,427971	0,090184
0,063	0,067358	0,020638	0,031918
0	0,143584	0,077991	0,05741

Cumu percentage

	Reverse	>mm	Try 1	Try 2	Try 3	avg	Reverse		
0	0	4	0,169345	0,317393	0,206289	0,231009	99,76899		
0,092995	0,063	2	0,381343	0,829003	0,608799	0,606381	99,39362		
0,132966	0,09	1,4	0,745582	1,459879	1,250801	1,152087	98,84791		
0,366637	0,125	1	1,6225	3,254532	2,472896	2,449976	97,55002	y=mx+c	
3,588043	0,25	0,85	39,02701	26,99495	34,64776	33,55657	66,44343	y	42,56701
4,204142	0,3	0,5	75,53221	68,92521	83,91332	76,12358	23,87642	x	0,35
23,87642	0,5	0,3	95,29403	94,45376	97,63978	95,79586	4,204142	m	121,62
66,44343	0,85	0,25	95,88336	95,42376	97,92876	96,41196	3,588043	c	-36,9336
97,55002	1	0,125	99,6062	99,4734	99,82049	99,63336	0,366637	D50(y=50)	0,714797
98,84791	1,4	0,09	99,78906	99,90137	99,91067	99,86703	0,132966		
99,39362	2	0,063	99,85642	99,92201	99,94259	99,90701	0,092995		
100	4	0	100	100	100	100	0		

Figure 19: The calculations for the sieving experiment

Similar to the void ratio experiment, the sieving process is done three times. The first three tables show the weight of each sieve including the diameter of its openings. The columns ”Try 1,2,3” correspond to the trials that were conducted, where one table shows the weight of each sieve with the container and one without it. Then, these values are converted to percentages as shown in the ”Percentage” table. Then, a cumulative percentage is calculated out of them, as shown in the graph, below the ”Reverse” column.

C Direct Shear Test Calculations

Normal Stress Applied(kPa)	Maximum Shear Stress(N)	Maximum Shear Stress(kPa)
22.104	67.72	21.59
28.48	91	29.02
41.23	112	35.71

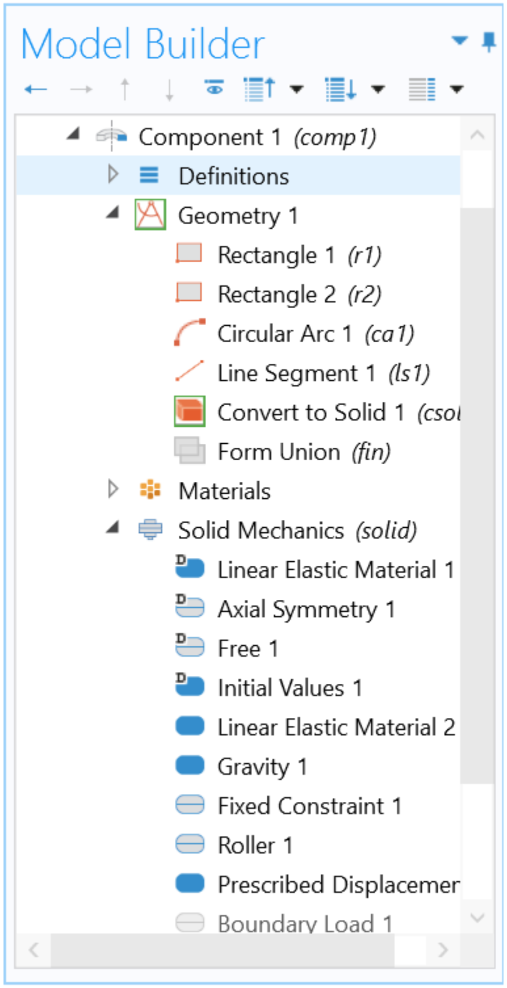
Table 8: The data for the normal and shear stress

The Normal Stress Applied is calculated by adding the weight of the hanger, in this case, 5.03 kg, and the weight added to the equipment. For instance, the first added weight is equal to 20 N, which is converted into kg, by being divided with 9.805. After finding the total weight, the value is divided by the area of the shear box, specifically being 3136 mm^2. Then, the found value is converted to kPa, by multiplying it with the factor of 9806.65.

Afterward, the maximum shear stress is found by the data given on the desktop connected to the equipment, where the unit is in Newton. Then, the third column in Table 8 displays the conversion of the shear stress in kPa, by dividing it with the shear box area and then multiplying it by 1000.

D COMSOL Interface

The main components of the interface are the geometry, which consists of two rectangles, regarding the soil boundary, and a part of the probe that is connected to the tip. Then, the circular arc represents the tip. Afterward, the material is set. In this case, the characteristics of dry sand, including Young's Modulus, bulk density, and poison ratio. Following that, the solid mechanics will connect the geometry to the physical properties. Additionally, Linear Elastic Material 1 is related to the soil properties, while Linear Elastic Material 2 is related to the probe characteristics. Then, gravity is applied to the whole geometry, and prescribed displacement is given to the probe, as the simulations are displacement-based.



Model Builder

- Component 1 *(comp1)*
  - Definitions
  - Geometry 1
    - Rectangle 1 *(r1)*
    - Rectangle 2 *(r2)*
    - Circular Arc 1 *(ca1)*
    - Line Segment 1 *(ls1)*
    - Convert to Solid 1 *(cso*
    - Form Union *(fin)*
  - Materials
  - Solid Mechanics *(solid)*
    - Linear Elastic Material 1
    - Axial Symmetry 1
    - Free 1
    - Initial Values 1
    - Linear Elastic Material 2
    - Gravity 1
    - Fixed Constraint 1
    - Roller 1
    - Prescribed Displacemen
    - Boundary Load 1

Figure 20: The Model Builder for Linear Elastic Model including the components used for deriving the simulations

The same procedure is followed when taking into account the plasticity of the soil. However, in this case, the soil plasticity is implemented to the soil, by applying the Mohr-Coulomb equations. More specifically, the cohesion and friction angle are set.

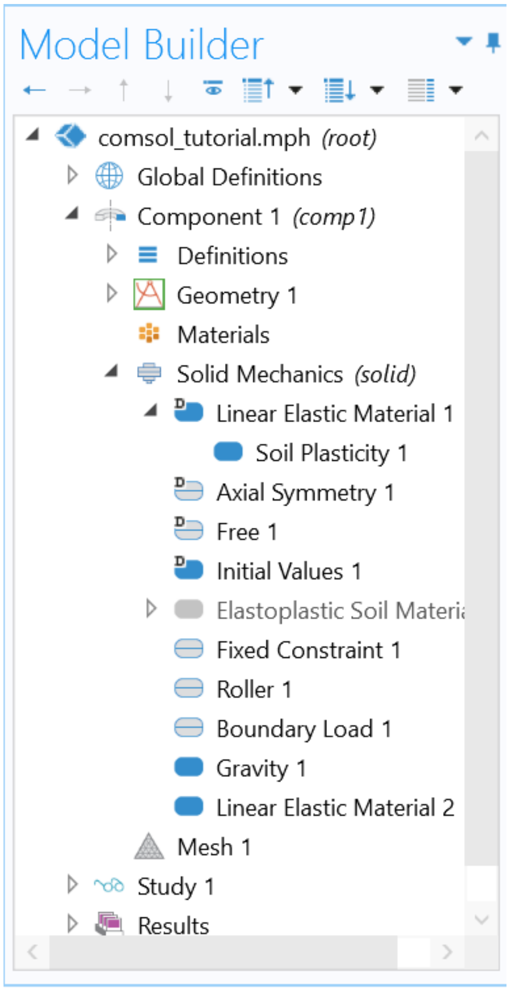


Figure 21: The Model Builder for Elastoplastic Model including the components used for deriving the simulations

E The geometry of probe

The dimensions that are shown in Figure 6 have been measured from the lab, where the soil boundary has a radius of 12 cm and a height of 78 cm, while the probe is approximately 17 cm long.

F Displacement and stress results

Figure 22 and 23 show an overview of how the outputs in COMSOL look like. The stress distribution is taken from the results of probe ratio 2.5 in a density of 1800 $\mathrm{kg\,m^{-3}}$, where the maximum values represent the maximum stress reached, and the colors show the level of magnitude as presented in the legend. The displacement plot is captured from the probe ratio 1, where the displacement is approximately 19.212 cm, while the x-axis shows the amount of pressure exerted in the probe, where 2 equals 200 kPa.

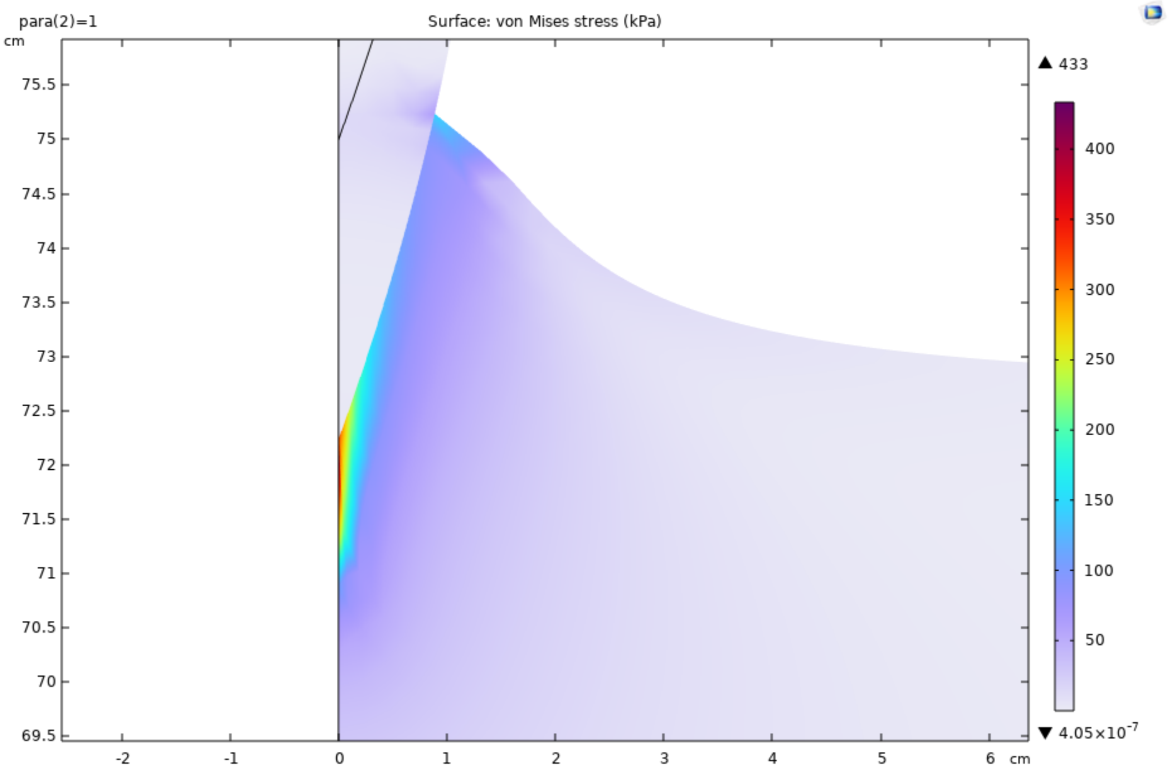


Figure 22: The distribution of stress

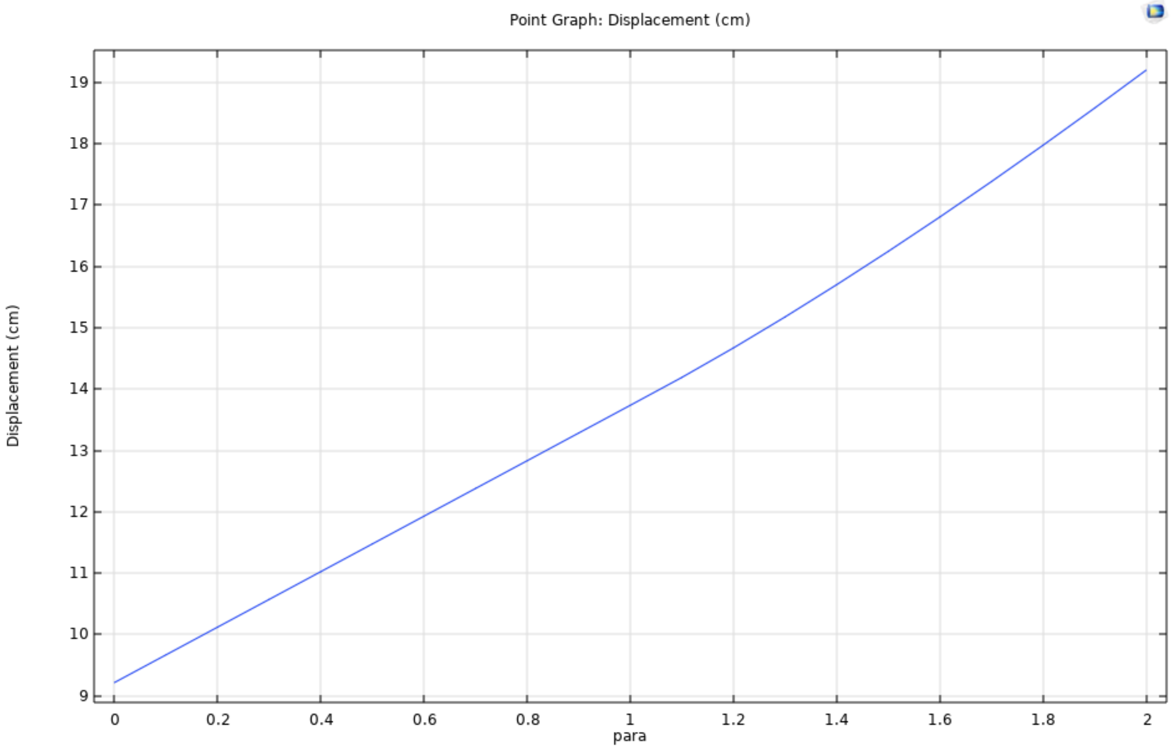


Figure 23: The displacement plot for probe ratio 1, where para represents the load, specifically para 1 equals 100 kPa

G Limitations in Simulations

As it was mentioned in the Sensitivity Analysis section, there is a strange behavior regarding the properties of the soil. For instance, the increase in density would cause an increase in displacement, while in theory, it should be the opposite. However, this is caused due to limitations that are present in COMSOL. For instance, an analysis of pushing a pile into the soil is carried out to observe the nature of changes. A plot is shown below to describe the behavior of the cohesion and friction angle with respect to the stress and displacement.

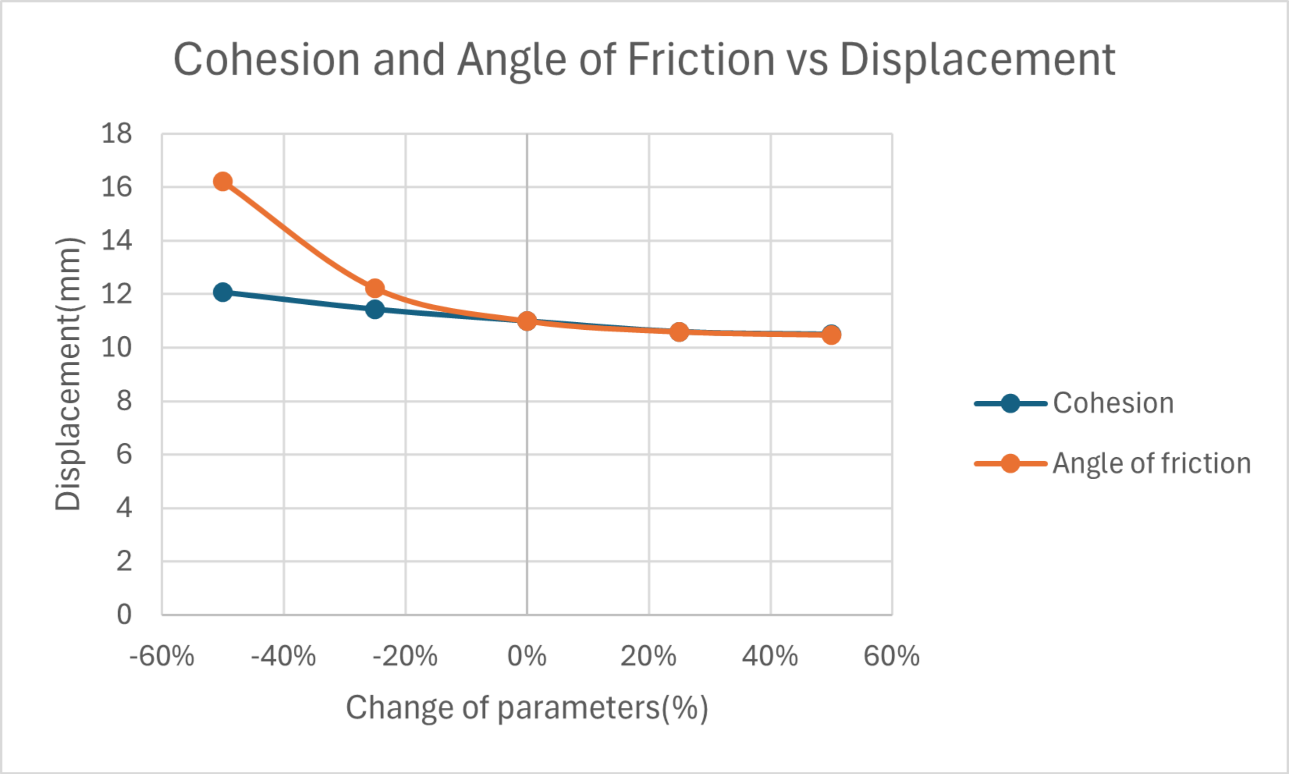


Figure 24: The sensitivity of Cohesion and Friction angle with respect to the displacement

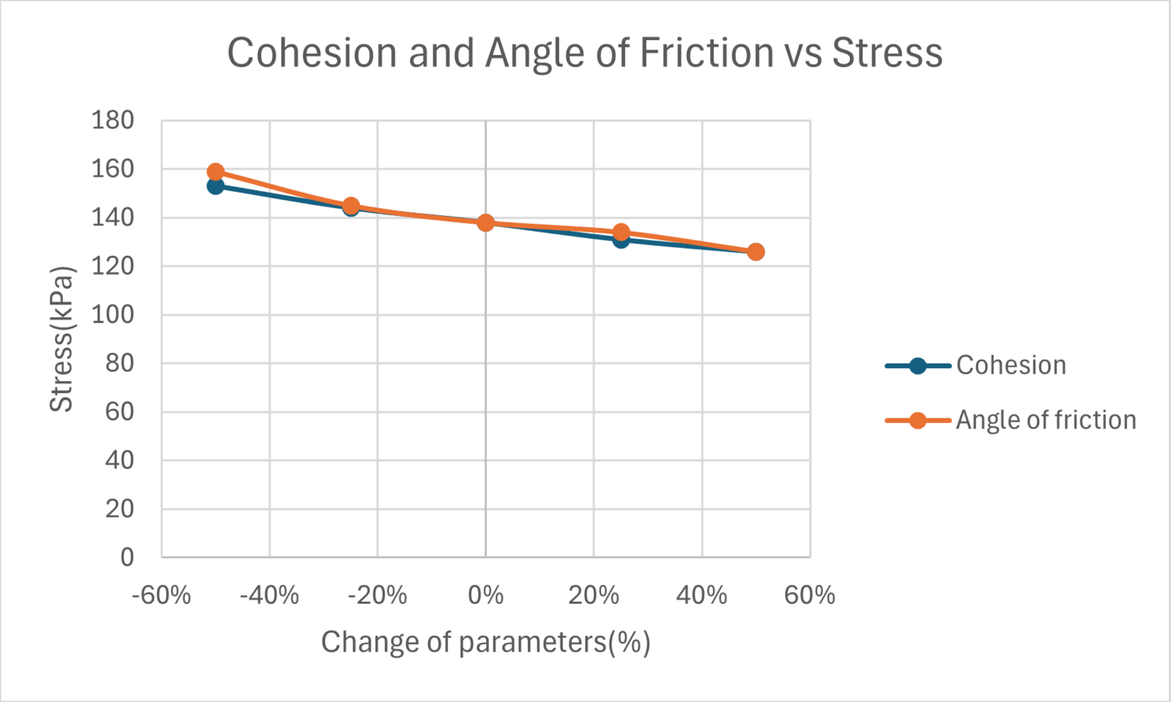


Figure 25: The sensitivity of Cohesion and Friction angle with respect to the stress

The results show that the change in the variables taken into consideration changes both the stress and displacement. Furthermore, it is observed that the decrease in cohesion and friction angle increases both stress and displacement, while in reality, the increase in these physical properties makes the soil more resistant to the probe. COMSOL tries to increase the stress in less cohesive soils, which also logically translates to a higher displacement, as the increase in stress produces a larger force reacting in the pile foundation. In order to have a realistic study, one of the values needs to be constant.

The same issue is faced when dealing with the density. The increase in density shows an increase in the reaction force, which then enlarges the displacement, showing that the increase in density indirectly affects the displacement enlargement. The plots in Figure 26 and 27 show the sensitivity of reaction force and displacement with respect to the bulk density.

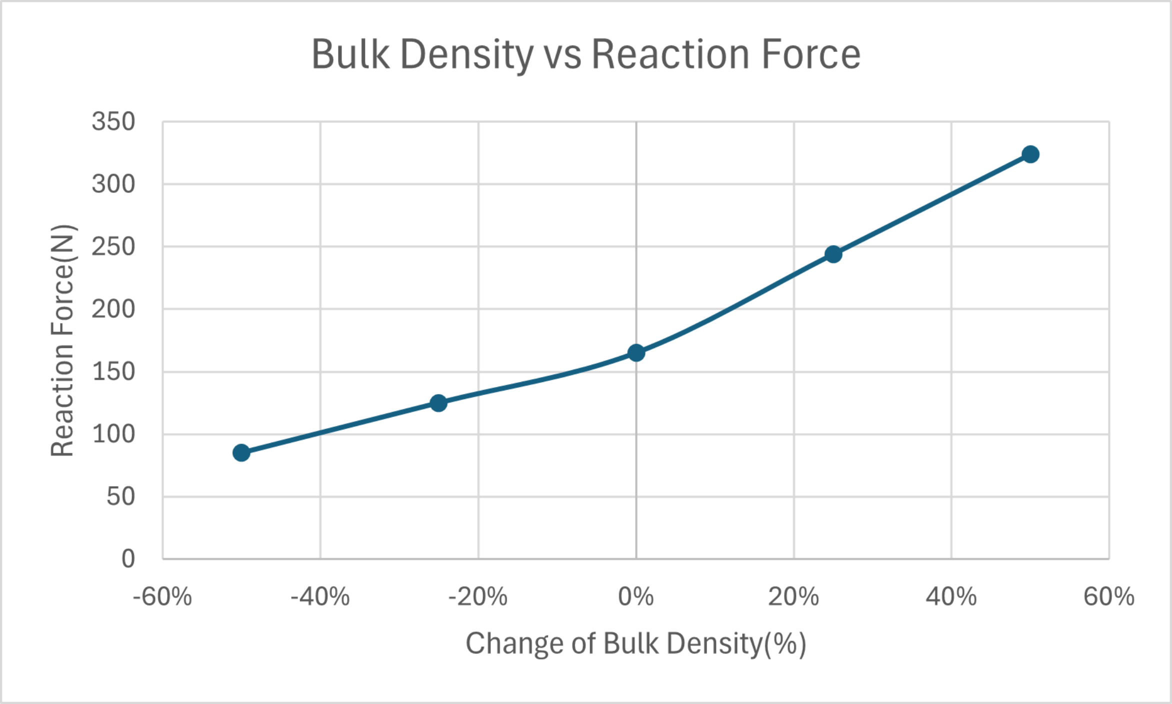


Figure 26: The sensitivity of Reaction Force regarding the bulk density

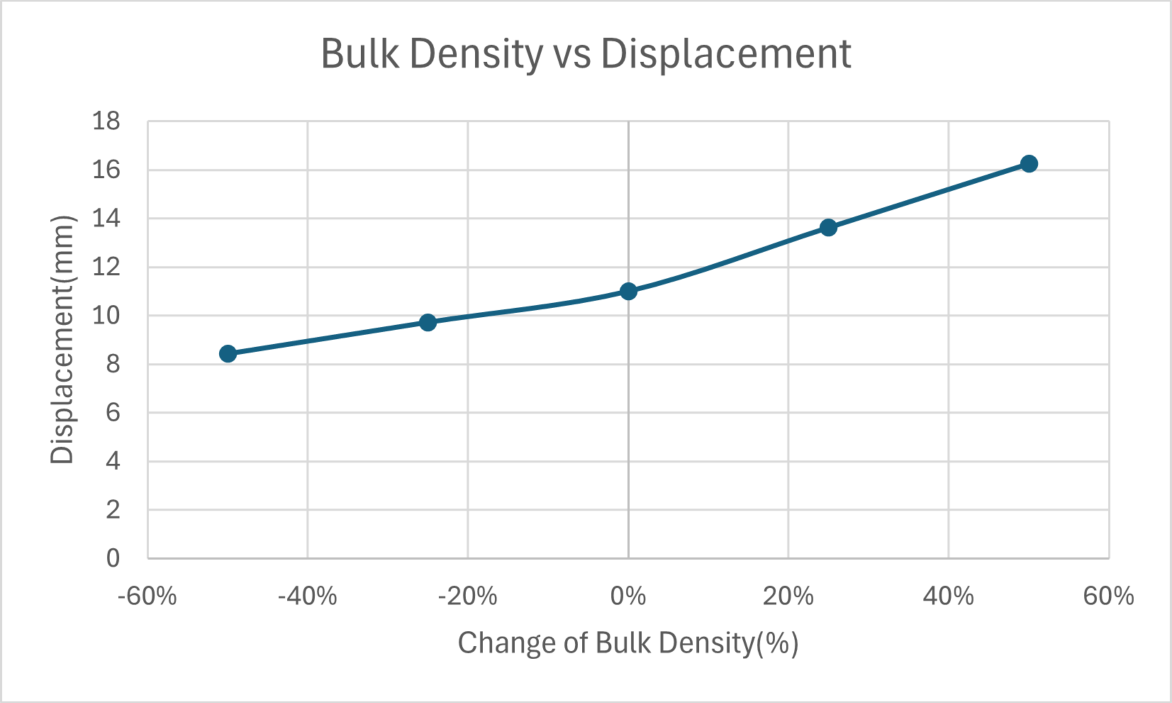


Figure 27: The sensitivity of Displacement regarding the bulk density

As can be noticed the same trend occurs, which doesn't allow giving a proper judgment of the change in density effect to the displacement, as the reaction force needs to stay constant during that change. The change in bulk density was also applied in Linear Elastic Material behavior and it was seen that the reaction force is constant, meaning that this scenario shows a better representation of the density consequences in displacement. Finally, the behaviors of each variable with regard to the input need to be studied before conducting an analysis.

H Data Management Plan

The research was focused on numerical simulations and experimental observations. For this reason, plenty of data was needed to be conducted. In order to achieve a systematic approach, which could also help in coordinating future researches. Similar subjects were studied by two other colleagues that helped in collecting the data related to soil properties or probe tip dimensions. For instance, the experimental observations for the probe tip were captured from Ahmet Tekin(Tekin, 2024), while the experiments to find the soil properties, such as the shear strength and particle size distribution, were done in collaboration with Licheng Guo(Guo, 2024). These informations were all inserted in Microsoft Teams, in order to use them for the specific study. Then, the COMSOL, and Excel files were categorized. Table 9 shows an overview of the files used for conducting and showing the results. The files with extension ".mph" are related to COMSOL, while the files with the extension ".xslx" are derived from Excel.

Category	**F**ile Name
Linear Elastic Behavior	Aspect_Ratio_1_Lin_Ela.mph
Linear Elastic Behavior	Aspect_Ratio_2.5_Lin_Ela.mph
Linear Elastic Behavior	Aspect_Ratio_4_Lin_Ela.mph
Linear Elastic Behavior	Linear_Elastic_Res.xlsx
Elastoplastic Behavior	Aspect_Ratio_1_Elas_Pla.mph
Elastoplastic Behavior	Aspect_Ratio_2.5_Elas_Pla.mph
Elastoplastic Behavior	Aspect_Ratio_4_Elas_Pla.mph
Elastoplastic Behavior	Elasto_Plastic_Res.xlsx
Boundary Conditions	Aspect_Ratio_1_Bou_Con.mph
Boundary Conditions	Aspect_Ratio_2.5_Bou_Con.mph
Boundary Conditions	Aspect_Ratio_4_Bou_Con.mph
Boundary Conditions	Boundary_Conditions_Res.xlsx
Experimental Observations	Direct_Shear_Test.xlsx
Experimental Observations	Particle_Size_Distribution.xlsx
Experimental Observations	Void_Ratio.xlsx
Experimental Observations	Aspect_Ratio_1_2.5_4_Results.xlsx
Sensitivity Analysis	Lin_Ela_Sensitivity.mph
Sensitivity Analysis	Ela_Pla_Sensitivity.mph
Sensitivity Analysis	Sensitivity.xlsx

Table 9: The summary of data management including the category of study and specific files