Reliability-Based Design of Pile Foundations in Layered Soil

Afomiya Alemayehu

A Thesis Submitted to the Department of Civil

Engineering

School of Civil Engineering and Architecture

Presented in Partial Fulfillment of Requirement for the Degree of Master's in

Specialization in Geotechnical Engineering

Office of Postgraduate Studies Adama science & technology universities

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By: Afomiya Alemayehu

Advisor: Argaw Asha(PhD)

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Declaration

I hereby declare that this Master thesis entitled "Reliability-Based Design of Pile Foundations in Layered Soil” 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

Afomiya Alemayehu

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I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled “Reliability-Based Design of pile Foundations in Layered Soil" prepared under my guidance by Afomiya Alemayehu submitted in Partial Fulfillment of requirement for the degree of Master’s science in Geotechnical Engineering.

Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

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Approval Page

I the advisors of the thesis entitled "Reliability-Based Design of pile Foundations in Layered Soil" and developed by Afomiya Alemayehu, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Argaw Asha (Ph.D.)		
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We, the undersigned, members of the Board of Examiners of the thesis by Afomiya Alemayehu have read and evaluated the thesis entitled " Reliability-Based Design of pile Foundations in Layered Soil " 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 Geotechnical Engineering.

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List Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ASD	Allowable Stress Design
ASTM	American Society for Testing & Material
COV	Coefficient of Variation
CPT	Cone Penetration Test
FEM	Finite Element Method
FEA	Finite Element Analysis
FORM	First Order Reliability Method
FS	Factor of Safety
LEM	Limit Equilibrium Method
LRFD	Load and Resistance Factor Design
MCS	Monte-Carlo Simulation
RBD	Reliability-Based Design
RI	Reliability Index
SLS	Serviceability Limit State
SPT	Standard Penetration Test
ULS	Ultimate Limit State

Abstract

The design of pile foundations founded on reliability principles within layered soil constitutes a significant issue in the field of geotechnical engineering. This research thesis seeks to enhance the formulation of a methodology dedicated to the reliability-oriented design of pile foundations in layered soil, whilst addressing the uncertainties pertaining to soil characteristics and applied loads. The methodological approach employed in this research incorporates finite element analysis (FEA) alongside reliability analysis to investigate the performance of pile foundations situated in layered soil. The investigation initiates with a thorough examination of existing literature concerning the reliability-based design of pile foundations in layered soil. This literature review underscores the imperative for a more resilient and precise design framework that integrates the uncertainties linked to soil characteristics and loads. The total displacement recorded for a load of 1000 KN is 2 mm, which increases to 3 mm when subjected to a load of 1500 KN .Upon reaching the maximum tested load. These results imply that settlement is significantly influenced by the consistency of the soil. Thereafter, the research advances towards the development of a finite element analysis model, which emulates the performance of pile foundations in layered soil. This model meticulously accounts for the effects of soil stratification, as well as the parameters of pile length, diameter, spacing, and the magnitude and distribution of loads. To ascertain its validity, the finite element analysis model is subjected to validation through comparison with experimental data derived from prior investigations. Subsequently, a reliability analysis is conducted to assess the likelihood of failure concerning pile foundations situated in layered soil. This reliability analysis incorporates the uncertainties associated with soil properties and loads, thereby providing a measurable assessment of the safety margin inherent in the design of pile foundations. In summary, this research thesis advocates for a holistic methodology for the reliability-based design of pile foundations within layered soil. The proposed methodology acknowledges the uncertainties related to soil characteristics and loads, thereby offering a more precise and resilient approach to design. Geotechnical engineers may utilize this methodology to formulate designs for pile foundations in layered soil that are both secure and dependable.

Keywords: - Finite element analysis, reliability-based design, pile foundations, layered soil

CHAPTER - ONE
INTRODUCTION

1.1. Background of the Study

Pile foundations play a vital role in numerous civil engineering projects, such as buildings, bridges, and various structures. They serve to transmit the structure's weight to the underlying soil, providing stability and support. However, designing pile foundations in layered soil presents several challenges due to the varying soil properties at different depths Shi, et.al. (2014). The conventional approach to pile foundation design relies on deterministic methods that assume fixed soil properties. Unfortunately, this approach fails to consider the uncertainties and variability in soil properties, leading to significant design and construction errors. To tackle this issue, reliability-based design (RBD) has emerged as a promising approach that accounts for uncertainties in soil properties and other design parameters Schmoor,et.al (2018)..

Reliability-based design employs statistical methods to quantify the uncertainties in design parameters and evaluate the probability of failure. It involves creating a mathematical model of the pile foundation system and utilizing probabilistic techniques to assess the system's reliability under different loading conditions Heidarie Golafzani & Jamshidi Chenari, R. (2020).. This approach enhances the safety and efficiency of pile foundation design by providing a more precise evaluation of the risks associated with various design choices. Layered soil introduces additional complexities to pile foundation design due to the substantial variations in soil properties at different depths Kamath, R. P., & Unnikrishnan, N. (2020). These variations can impact the load-carrying capacity of the pile and increase the risk of failure. Consequently, there is a need for research on the RBD of pile foundations in layered soil to develop more accurate and dependable design methodologies that consider the uncertainties and variability in soil properties.

1.2. Statement of the Problem

The existing design techniques for pile foundations in layered soil are predominantly reliant on deterministic methods, which inadequately account for the significant uncertainties and variations inherent in soil properties. These methods often assume homogeneous soil conditions, overlooking the complex spatial variability and unpredictability in soil behavior that can exist across a site. This oversimplification in design assumptions leads to either excessively conservative or overly optimistic outcomes, with conservative designs unnecessarily inflating project costs due to overestimation of required material strength or safety factors. On the other hand, optimistic designs may dangerously underestimate risks, potentially leading to foundation failure, compromising structural integrity, and increasing the likelihood of costly repairs or safety hazards. Zhang, X. L. & Jiao, (2021) emphasize that these traditional deterministic approaches fail to capture the probabilistic characteristics of soil behavior, such as random variations in density, moisture content, and shear strength, all of which significantly influence the performance of pile foundations. By neglecting these factors, deterministic designs do not fully address the range of potential outcomes in real-world construction scenarios, which can lead to unexpected structural settlements or excessive displacement under load. Given the complex and variable nature of soil, there is a growing consensus among researchers and engineers on the necessity for a more inclusive and dependable design approach. Such a methodology would incorporate probabilistic and statistical analyses to better quantify and manage the inherent risks associated with soil variability. This would result in more optimized designs that strike a balance between safety, performance, and cost-efficiency. The development and implementation of probabilistic design methods would allow for a more accurate assessment of the uncertainty in soil properties, improving the reliability and resilience of pile foundations, ultimately contributing to more sustainable and cost-effective infrastructure projects. Therefore, there is a strong imperative to shift towards advanced design techniques that can fully integrate the probabilistic nature of soil behavior and its impact on the long-term performance of pile foundations, ensuring safer and more economical engineering solutions.

1.3. Research Questions

1. How do piles behave in layered soil under different loading conditions and soil compositions?
2. What factors influence the performance of pile foundations in layered soil, and how do they impact load-bearing capacity and settlement?
3. How does the performance of pile foundations vary across soils with different consistencies, such as soft, medium, and dense soils?

1.4. Objectives of the Study

1.4.1. General Objective

The main objective of the study is to investigate the reliability-based design approaches of for pile foundations in layered soil.

1.4.2. Specific Objectives

- To examine the behavior of pile foundations in layered soil under varying soil properties and loading conditions
- To evaluate the performance of pile foundations in layered soil in terms of load-bearing capacity, settlement, and stability
- To compare the performance of pile foundations in soils with different consistences (e.g., soft, medium, dense) to determine the influence of soil variability.

1.5. Significance of the study

Reliability-based design holds utmost importance in ensuring the safety and effectiveness of pile foundations. This design approach takes into consideration the variability of soil conditions and incorporates safety factors to minimize the risk of failure. By accounting for the statistical distribution of soil properties and utilizing techniques like the First Order Reliability Method (FORM), the design can be optimized to meet the required safety standards Zhang, L et al. (2024). Reliability-based design also provides a quantitative assessment of the probability of failure, empowering engineers to make well- informed decisions based on risk evaluation. Hence, reliability-based design plays a significant role in enhancing the safety and dependability of pile foundations Gomes, R.C et al. (2021). In a broader context, the significance of studying the reliability-based design of pile foundations in layered soil lies in its potential to enhance the safety, efficiency, and longevity of geotechnical engineering projects. Moreover, it contributes to the advancement of the field as a whole.

1.6. Limitation of the study

The expected outcomes of this research include:

- A reliability-based design methodology for pile foundations that considers layered soil
- A better understanding of the reliability-based design of pile foundations in layered soil
- Identification of critical design parameters that affect foundation reliability
- Optimization of foundation design to meet desired reliability levels

1.7. Scope of the Study

The scope of this research focused on the reliability-based design of pile foundations in layered soil conditions. The study will investigate the behavior of pile foundations in different soil layers, considering factors such as soil properties, loading condition and design parameters. The research will aim to develop a methodology for assessing the reliability of pile foundation in layered soil, taking into account uncertainties in soil properties and design parameters. This will involve the use of probabilistic methods to quantify the probability of failure and assess the safety and performance of pile foundations in layered soil conditions. Overall, this research aims to contribute to the advancement of knowledge in geotechnical engineering by providing insights into the behavior and performance of pile foundations in layered soil conditions. The findings will be used to develop design guidelines and recommendations for reliable pile foundation design in such complex soil environments.

CHAPTER -TWO

REVIEW OF THE LITERATURE

Extensive research has been conducted regarding the design of pile foundations in layered soil, reflecting a substantial body of knowledge in this field. Numerous studies have specifically focused on the reliability-based design of pile foundations under diverse geological conditions. Chang et al. (2013). conducted a meticulous examination of design methodologies for pile foundation systems in soft soil, recognizing the criticality of considering soil variability and uncertainty throughout the design process. Furthermore, Golafzani et al. (2020). delved into the realm of reliability-based design for piles in sandy soils, underscoring the necessity of incorporating probabilistic approaches to adequately address soil variability and the associated uncertainties. These studies effectively underline the paramount significance of reliability-based design in safeguarding the safety and optimizing the performance of pile foundation systems in layered soil.

2.1. Overview of Pile Foundation Design

Reliability-based design methodologies have garnered considerable recognition in recent times. These methodologies strive to integrate uncertainties and risks inherent in the design process, leading to the creation of more resilient and dependable structures. Among the commonly employed approaches, probability-based design stands out, employing statistical techniques to determine the likelihood of structural failure. Another notable approach is limiting state design, which takes into account both the ultimate limit state and the serviceability limit state as separate considerations Zhang, L et al. (2024). These approaches prove particularly advantageous in the design of pile foundations in layered soil, where uncertainties relating to soil properties can exert a substantial impact on foundation performance Ofongo, A.C.E. (Ed.). (2013).

2.2. Uncertainties in Pile Design

2.2.1. Inherent Uncertainty

Soil intrinsic uncertainty arises from variations in soil properties, both vertically and horizontally, due to geological processes. This uncertainty can be divided into two components:

the trend component and the fluctuation component. The inherent uncertainty model for soil properties is represented by a random field, characterized by the scale of fluctuation, mean, and coefficient of variation (COV) (where COV equals the standard deviation divided by the mean). The scale of fluctuation is a measure of the distance between two samples that are considered to be adequately correlated Ofongo, A.C.E. (Ed.). (2013). A large scale of fluctuation indicates gradual changes in soil properties, while a small scale suggests rapid variations around the mean. Deng et al. & Phoon, K.K. (2017). provide information on the ranges of inherent uncertainty (COV) for various soil parameters, such as undrained shear strength (su), angle of internal friction (/), bulk unit weight (c), SPT-N, and relative density (Dr). For example, the COV of su in clay ranges from 20% to 55%. The COV ranges are 5% to 15% for angle of internal friction (/), 0% to 10% for bulk unit weight (c), 25 to 50 for SPT-N, and 50% to 70% for relative density (Dr). The fluctuation range for su is 50 m in the horizontal direction and 0.8 m to 6.1 m in the vertical direction.

2.2.2. Model Uncertainty

Model uncertainty arises due to the inherent limitations of mathematical models and equations used in engineering analysis. These models are not perfect representations of physical processes but rather approximations based on a set of assumptions. In the context of predicting pile responses, model uncertainty in numerical models (e.g., p-y-based approach) can be quantified using data obtained from field load tests. By establishing a model bias factor, which is the ratio of observed responses to anticipated responses, one can evaluate the predictive capabilities of the numerical model. The mean of the bias factor indicates whether the model tends to overestimate or underestimate the responses, while the coefficient of variation (COV) of the bias factor reflects the level of model uncertainty.

It is important to note that separating model uncertainty from other sources of uncertainty related to field measurements, such as intrinsic soil variability and measurement error, can be challenging. Therefore, estimating model uncertainty solely from field tests has limitations Saride, S., & Avirneni, D. (2019).. However, conducting high-quality tests and considering the averaging effect of soil parameters can help reduce measurement uncertainty and mitigate the impact of intrinsic geographic variability in the soil.

2.2.3. Measurement Uncertainty

Measurement uncertainty arises when estimating soil parameters due to factors such as equipment limitations, procedural and operator influences, and random testing variations. Kumar and samui (2019) indicate that equipment-related uncertainties stem from inaccuracies in measurement devices and limitations in the current standard testing procedures and their implementation by operators. They provide ranges of measurement uncertainty for various tests: SPT (Standard Penetration Test), CPT (Cone Penetration Test), triaxial test, and direct shear test. The ranges of measurement uncertainty reported by Phoon and Kulhawy (1999) are 15% to 45% for SPT, 5% to 15% for CPT, 7% to 56% for triaxial tests, and 3% to 29% for direct shear tests.

2.3. Reliability Analysis in pile Foundation Design

The assessment of reliability plays a crucial role in the design of deep foundations, enabling engineers to evaluate the performance and safety of these structures when faced with unpredictable soil conditions. By taking into account uncertainties associated with soil properties such as strength and stiffness, reliability analysis provides a quantitative evaluation of the likelihood of failure, allowing for the optimization of design parameters. Various techniques, such as the First Order Reliability Method (FORM) and Monte Carlo simulation (MCS), can be utilized to carry out reliability analysis in the design of pile foundations Zhang, & Wang, L. (2023). These methods effectively consider the uncertainties in soil properties and aid in determining a target reliability index that ensures the desired level of safety and performance. Moreover, reliability-based design offers a logical framework for integrating risk and uncertainty into the design process, resulting in pile foundation systems that are more resilient and cost-effective.

2.3.1. First Order Reliability Method (FORM)

In the realm of reliability-based design, there are various methods available, and one commonly employed technique is known as the First Order Reliability Method (FORM). The First Order Reliability Method (FORM) is a method that approximates the limit state using a linear approach Phoon and Kulhawy (2017). It assumes that the limit state function is linear and that the input variables follow a normal distribution. FORM has been extensively applied in geotechnical engineering, particularly in the design of pile foundations in layered soil. By utilizing FORM, engineers can perform a quantitative assessment of the probability of failure and make informed decisions regarding design parameters, ensuring that the desired level of reliability is achieved.

2.3.2. First Order Second Moment (FOSM) Method

The First Order Second Moment (FOSM) methodology constitutes an approximation technique (Baecher and Christian, 2003) predicated upon a Taylor series expansion of a performance function, denoted as g. The methodology encompasses several procedural steps. The initial step involves the determination of mean values, variances, correlation coefficients, and autocorrelation lengths for all stochastic input variables. Subsequent to the calculation of the expected value $[g]$ of the performance function, the partial derivatives of this function with respect to the pertinent variables are derived. This particular step typically utilizes a form of numerical differencing. The contributions of each variable to the systematic and spatial variance, represented as σg, for the performance function are then computed. The final step entails the calculation of the variance within the performance function, from which the reliability index, β, is subsequently derived utilizing the following equation:

$$\beta = \frac{[g]-1}{\sigma g} \quad \text{……………………………………………………………….(2.1)}$$

Where $[g]$ = expected value of the performance function, and

σg = spatial variance for the performance function.

2.3.3. Monte Carlo Simulation

Wang et al.(2011) introduced a more comprehensive reliability-based design method for drilled shafts subjected to axial loading. This method presents the design process as an expanded reliability problem that utilizes Monte Carlo simulation. Compared to Load and Resistance Factor Design (LRFD), this approach offers several advantages:

1. Flexibility in target reliability: Designers can adjust the target reliability index to suit specific requirements for individual projects. This allows for customization and adaptation based on project-specific needs.

2. Transparent process: The design process is transparent, providing designers with valuable insights into how the performance level changes in response to variations in pile diameter or penetration length. This transparency enhances understanding and facilitates decision-making.
3. Accurate estimation of failure probability: By employing a sufficiently large number of samples, the estimate of the probability of failure becomes highly accurate. This ensures reliable and precise assessments of structural performance.

2.3.3. Load and Resistance Factor Design

Since the 1950s, the Load and Resistance Factor Design (LRFD) approach has been developed to ensure a consistent level of reliability across the entire structure during the design process. The core principle of LRFD involves quantifying uncertainties using probabilistic methods to achieve engineered designs with uniform levels of reliability or probability of failure. In the LRFD approach, different types of loads and combinations are multiplied by load factors, while resistances are multiplied by resistance factors. It is crucial to ensure that the factored loads do not exceed the factored resistances.

The LRFD approach offers several advantages over the Allowable Stress Design (ASD) approach when designing deep foundations. One significant advantage is its capability to address uncertainties related to design parameters by utilizing a rational framework based on probability theory. This results in a consistent level of reliability throughout the design process. Consequently, LRFD provides a cohesive design approach for both the superstructure and substructure, leading to improved overall design and construction perspectives.

Furthermore, the LRFD approach reduces the reliance on the designer's experience and engineering judgment compared to the ASD approach. LRFD's key improvements over traditional ASD include the ability to maintain a more consistent level of reliability and the opportunity to account for load and resistance uncertainties separately. This reduction in subjectivity enhances the design process's consistency.

2.4. Ultimate Limit State

In the realm of pile foundation design, two essential criteria must be fulfilled: the ultimate limit state (ULS), also known as ultimate bearing capacity, and the serviceability limit state (SLS). The ULS pertains to the maximum soil strength and, essentially, the soil's ability to endure loading without succumbing to excessive settlement. However, it is important to acknowledge that there exist multiple definitions of what constitutes excessive settlement, thereby establishing the parameters for ultimate capacity. A substantial body of literature has extensively deliberated and examined these definitions of failure. Once the ultimate capacity has been computed, it becomes possible to calculate the ultimate reliability index, thereby evaluating whether the design fulfills the required reliability threshold. An alternative approach involves the utilization of load and resistance factors derived from a design code that has been calibrated to cater to a specific target reliability index. For example, the AASHTO [2017] guidelines for bridge design adopt a load and resistance factor method calibrated to a target reliability factor of 3.5 in the ultimate limit state.

Furthermore, it is noteworthy that the same foundation can be designed using two different design codes, both calibrated to the same reliability index, yet yielding distinct outcomes. This discrepancy arises due to the differing definitions of bearing capacity failure embedded within each design code. Consequently, the variation in failure definitions leads to divergent resistance factors. Zhang et al. [2005] conducted an investigation utilizing a database of static load tests conducted on bored piles, thereby calculating different β values corresponding to various bearing capacity failure definitions. Figure 1 visually presents a comparative analysis of the different failure criteria alongside their corresponding β values.

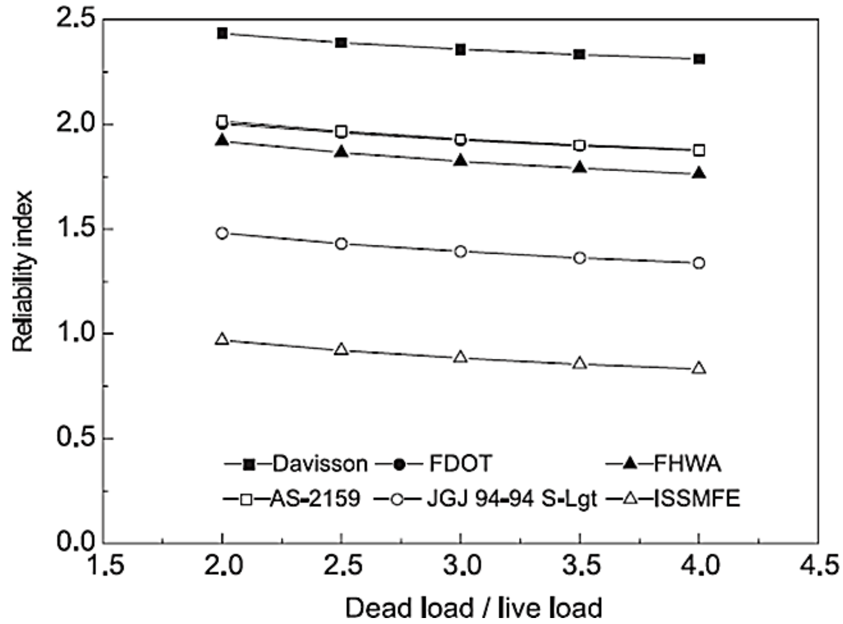

Figure 1: Different failure criteria and corresponding β value (Zhang et al., 2005)

2.5. Serviceability Limit State

The design of pile foundations necessitates the fulfillment of a second criterion, which is the serviceability of the structure. Serviceability can be defined as the permissible movement of the structure while maintaining its intended functionality. Excessive soil displacement can result in cracks and deformations that hinder the operation of the structure. Additionally, serviceability requirements can be expressed through allowable total settlement, differential settlement, or angular distortion. The acceptable levels of settlement or angular distortion are determined either by design code stipulations or by the judgment of the structural engineer.

Furthermore, in reliability analysis, no established formulation exists for calculating the reliability index specifically for serviceability conditions. Design codes offer guidelines regarding permissible settlement depending on the structure type and loading conditions. However, they provide designers with the flexibility to meet these serviceability requirements through either probabilistic or deterministic analyses.

Considering the variability of soil properties within a site, the diversity of foundation types, and the uniqueness of each building's structural design, uncertainties arise regarding the threshold beyond which foundation movement becomes detrimental to the structure. Zhang and Ng (2005 and 2007) conducted analyses on a dataset comprising various cases of foundation settlement and angular distortion. These cases encompassed different soil types, foundation types, and structures. The analysis results revealed that a single limiting value for settlement cannot be universally generalized for a particular soil type or foundation. Table 1 presents the mean and standard deviation of tolerable and intolerable settlement and angular distortion for different structures. The data exhibit significant scatter and high standard deviation, suggesting that a probabilistic approach would be more accurate in capturing the uncertainties associated with serviceability limit design, as opposed to a deterministic approach.

Table 1: Tolerable and intolerable settlement and angular distortion for different structures (Zhang and Ng, 2007)

Statistics		All foundations		Shallow foundations		
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard Deviation
Observed intolerable Settlement (mm)	403	334	399	323	404	384
Limiting tolerable settlement (mm)	123	73	129	72	96	56
Observed intolerable angular distortion	0.0116	0.0143	0.0119	0.0138	0.0107	0.0155
Limiting tolerable angular Distortion	0.0028	0.0024	0.0030	0.0015	0.0025	0.0022

Several researchers have attempted to develop methods for calculating the reliability index, βSL, for the serviceability limit state and establishing its relationship with the ultimate limit state analysis, βULS Phoon and Kulhawy (2008), Zhang and Phoon (2006), Misra and Roberts (2005), Wang and Kulhawy (2008), and Najjar et al. (2014).. The underlying idea behind these methods is similar to calculating βULS, with the distinction that the safety margin, represented by the performance function M, is defined in terms of displacement:

M = yall – y ……..………..…..………………………………(2)

where yall is the allowable settlement and y is the predicted settlement of the foundation. Since yall can be considered a random variable due to the aforementioned reasons, the challenge lies in addressing the uncertainty associated with the calculated settlement.

This uncertainty is influenced by various factors, such as the variability of soil parameters within a site, the variability of loads on the foundation, and the nonlinear relationship between load and settlement. To account for these factors, the aforementioned researchers have developed models that incorporate them into the statistics of y. For instance, Misra and Roberts (2005) developed a mathematical model based on the t-z approach, considering the elasto-plastic behavior of drilled shafts. By using this model and given the statistics of soil parameters, a probabilistic load-displacement curve can be computed. However, a limitation of this model is its assumption of an elasto-plastic load-displacement curve, which may not always reflect the actual behavior.

Phoon and Kulhawy (2008), on the other hand, modeled the load-displacement curve using a curve-fitting equation, as follows: Q/Qm = y/a + by, where Q is the load, Qm is the interpreted capacity, y is the displacement, and a and b are fitting parameters. The statistics of a and b are established based on databases for different foundation types. By utilizing this nonlinear relationship, settlement can be calculated for a given load and directly incorporated into the performance function.

One advantage of this approach is that it establishes a connection between βSL and βULS through the value of Qm, which depends on the definition of the ultimate bearing capacity. However, as previously discussed, there is no consensus on the definition of ultimate bearing capacity within design codes and guidelines. Additionally, it is important to note that the two models discussed do not accommodate advanced design tools, such as finite element method software, which are commonly used in practice to predict settlement.

This brief overview highlights the need for a reliability-based method for the serviceability limit state that is rational, dependable, and relatively practical, taking into account the complexities of settlement prediction and the various definitions of ultimate bearing capacity.

2.6. Reliability Analysis

Reliability analysis is a subset of probabilistic methods that encompass various techniques such as risk analysis, risk-based analysis, and life-data analysis, as defined by the U.S. Army Corps of Engineers (ETL 1110-2-556). Phoon (2009) establishes reliability analysis as the systematic assessment of design risk utilizing probability theory.

The reliability of an engineering system pertains to its capacity to fulfill its intended design purpose within a specific timeframe (ISO 2394, 1998; Harr, 1987; Ayyub and Popescu, (2019). Probability theory serves as the fundamental framework for quantifying this capacity. Within a probabilistic context, the reliability of an engineered system represents the probability of its satisfactory performance under defined service conditions and within the designated timeframe (i.e., the probability of survival). This definition recognizes the inherent uncertainties associated with design variables such as loads and material properties, acknowledging that the success or failure of an engineered system can only be evaluated in probabilistic terms. This perspective highlights the interconnectedness of probability and reliability analysis. The probability of failure, which is the complement of the probability of survival or reliability, sums up to unity. Mathematically, the relationship between the probability of failure (Pf) and reliability (R) can be expressed as follows:

$$R+Pf=1 \quad (2.6a)$$

$$R=1-Pf \quad (2.6b)$$

$$Pf=1-R \quad (2.6c)$$

The reliability of a structure is generally expressed in terms of either the probability of failure or reliability index.

2.6.1.Reliability Index (β) and Probability of Failure (pf)

The probability of failure can be conveniently represented using the "reliability index," β, which serves as a straightforward measure within the realm of reliability analysis. In this context, failure refers to the occurrence of predefined limit states. To ensure an acceptably low probability of reaching any limit state, appropriate load and resistance factors are selected. By knowing the mean and standard deviation of the resistance and load, the probability of failure can be calculated. A quantitative measure of safety is expressed through the probability of survival, ps, given by:

$$ps = P(R > Q) \quad \text{2.6.1}$$

The complement of the probability of survival is the probability of failure, pf, which can be expressed as:

$$pf = 1 - ps = P(R < Q) \quad \text{2.6.2}$$

In order to assess the probability of failure, pf, it is necessary to employ a unified probability density function, g(R,Q), which captures the margin of safety. This limit state function possesses its own distinct statistical properties. The utilization of a combined probability density function, g(R,Q), is examined in the subsequent discussion to demonstrate how the probability of failure can be estimated. Assuming that R and Q follow a normal distribution, the expression for the limit state function, g(R,Q), can be formulated as:

$$g(R,Q) = R - Q \quad (2.6.3)$$

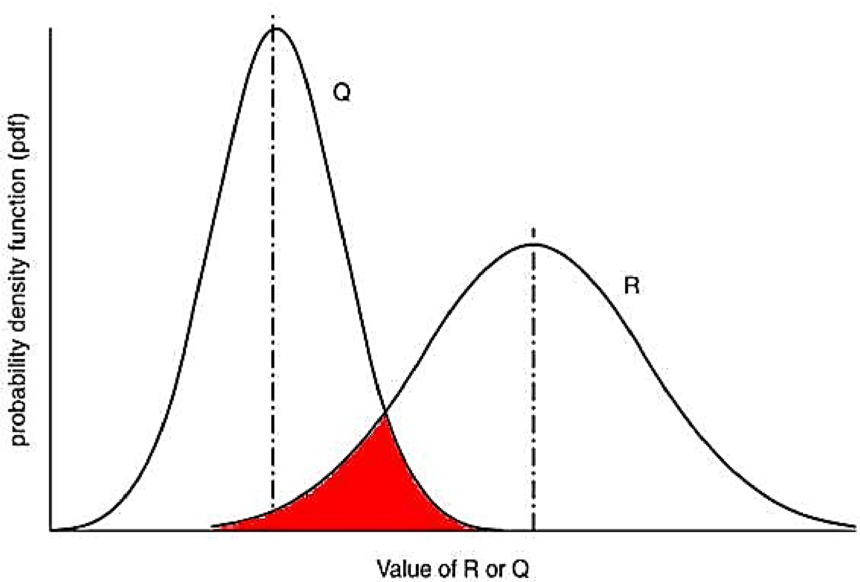

Figure 2:The overlapped area is probability of failure of random variables for Q and R (Subramaniam).

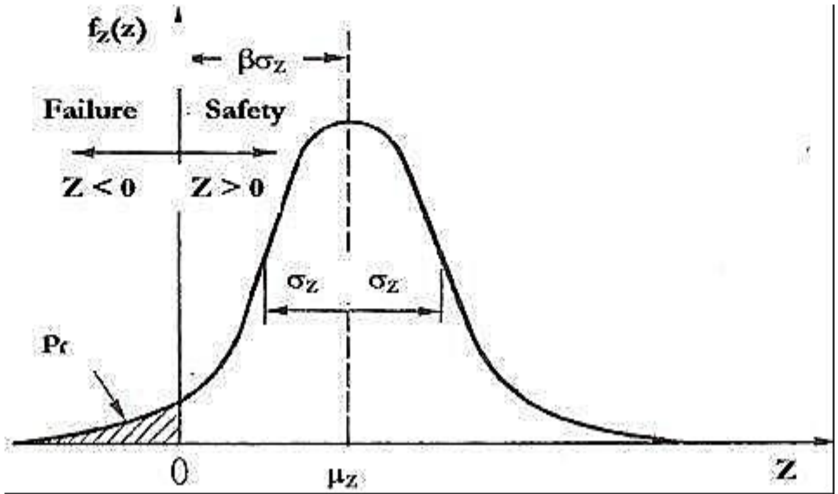

Figure 3: Distribution of safety margin, Z = R-Q (Melchers 2002).

2.7. Choice between probability of failure and reliability index

The decision to utilize either the probability of failure or the reliability index as a metric for assessing design risk is subjective and dependent on individual preference. Based on the preceding discussions, the probability of failure seems to possess greater physical significance. However, in many instances, it involves exceedingly small values that can present challenges in practical applications. Additionally, the term "failure" associated with the probability of failure carries a negative connotation (Phoon, 1995). As a result, the reliability index is gaining prominence, particularly in the calibration of design codes, as it offers a more favorable alternative.

2.8 Summary of Related Studies

Ayyub, B. M., & Wu, Z. (2004): Introduced the concept of reliability-based design in civil engineering, emphasizing the need to incorporate uncertainties in soil properties and loading condition.

Zhang et al. (2016) conducted a study on the influence of soil variability on the reliability of pile foundations in layered soils by employing probabilistic design techniques.

The researchers examined the effects of uncertain soil properties on the reliability of pile foundations and proposed a novel methodology for quantifying the probability of failure. **Baecher, G. B., & Christian, J. T. (2003):** Discussed various reliability analysis techniques such as First Order Reliability Method (FORM) and Second Order Reliability Method (SORM) applicable to geotechnical problems.

Li.X et al. (2018) devised a Bayesian inference framework to integrate prior knowledge and data into the reliability-based design of pile foundations in layered soils. Through an illustrative case study involving the design of a multi-layer foundation system, the authors demonstrated the efficacy of their approach.

Xie.Y et al. (2019) provide a comprehensive overview of recent advancements in utilizing stochastic methods for designing pile foundations in layered soils. The authors present a detailed analysis of various methodologies and discuss the associated challenges in stochastic design, emphasizing the requirement for more advanced models and algorithms.

Cheng,B.M and Chang.Z (2021) employed a reliability-based design approach for designing a single-pile foundation system in a layered soil environment. The authors evaluated the performance of their methodology through both analytical calculations and finite element simulations

2.9. Research Gaps

Upon conducting a thorough examination of the existing literature pertaining to the relevant domain, several research deficiencies have been recognized, which necessitate further inquiry to augment the findings and promote a more profound understanding of the reliability-based design of pile foundations situated in stratified soil environments. The subsequent research deficiencies have been identified:

- Limited research on how layered soils profile affects pile foundation performance, often focusing on homogenous conditions

- Existing models may not fully capture the complex interactions between piles and layered soil under various loading conditions

CHAPTER- THREE

NUMERICAL METHOD

3.1 General

PLAXIS 3D represents an extensive three-dimensional finite element software program that utilizes advanced material modeling methodologies, integrating an array of features that support the simulation of soil behavior and yield outcomes that are more realistic, dependent upon the input parameters and the particular model employed. PLAXIS 3D demonstrates operational differences from PLAXIS 3D and functions as an essential instrument in forecasting soil-foundation interactions (Brinkgreve et al., 2012). This model is especially relevant in circumstances where the depiction provided by PLAXIS 3D is impractical due to geotechnical or financial limitations, such as in projects that involve irregular geometries or volumes, anisotropic soil conditions, or complex geotechnical issues. The numerical analysis performed by PLAXIS 3D is executed through a series of iterations until the requisite equilibrium is achieved, and it possesses the capability to undertake intricate calculations encompassing various types of loads (Brinkgreve et al., 2012). In the realm of PLAXIS 3D, it is essential that all input parameters are meticulously defined; moreover, the configuration of the model and computational framework requires a more significant allocation of time in relation to PLAXIS 3D (Ruigrok, 2010). PLAXIS 3D is utilized to simulate a broad spectrum of soil classifications, encompassing clay, sand, stratified soils, in addition to nonlinear and time-dependent soils, and it possesses the capability to compute horizontal, moment, axial, and cyclic loads (Ruigrok, 2010).

3.1.1. Advantages of PLAXIS 3D

The fundamental benefits of the PLAXIS 3D manual are articulated as follows (Brinkgreve et al., 2012).

• It enhances simulation capabilities and delineates interfaces that are advantageous for modeling soil-structure interaction.

• Users are granted the opportunity to employ sophisticated constitutive soil models.

• It permits the forecasting of realistic states of stress and deformation.

3.2 Material Models

The mechanical behaviour of soils may be modelled at various degrees of accuracy. Hooke's law of linear, isotropic elasticity, for example may be thought of as the simplest available stress-strain relationship. As it involves only two parameters, i.e., Young's modulus E and poisons ratio, it is generally too crude to capture essential features of soil and rock behaviour. For modelling massive structural elements and bedrock layers, however, linear elasticity tends to be appropriate. Out of several models only Mohr-coulomb model and Hardening soil models are used in this work. So the overview of these models is:

3.2.1 Mohr Coulomb model

PLAXIS 3D encompasses a range of constitutive models, such as the Mohr-Coulomb (MC) model and the Hardening Soil (HS) model, among others. Among these, the Mohr-Coulomb model represents the simplest and most readily accessible option within PLAXIS 3D.

This model assumes that the soil exhibits linear elastic behavior alongside perfect plasticity. The underlying principles of an elastic and perfectly plastic model are visualized in Figure 4.

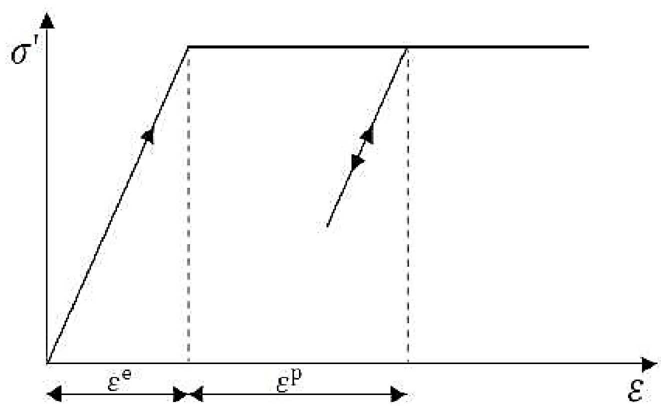

Figure 4: Mohr-Coulomb for an elastic and perfectly plastic model (Brinkgreve et al., 2012).

The Mohr-Coulomb model is used for cohesive soils as well as cohesion- less soil for both drained and undrained soil [Brinkgreve et al., 2012]. The failure criterion determined by Mohr-Coulomb failure envelopes illustrated in Figure 5 (Ruigrok, 2010).

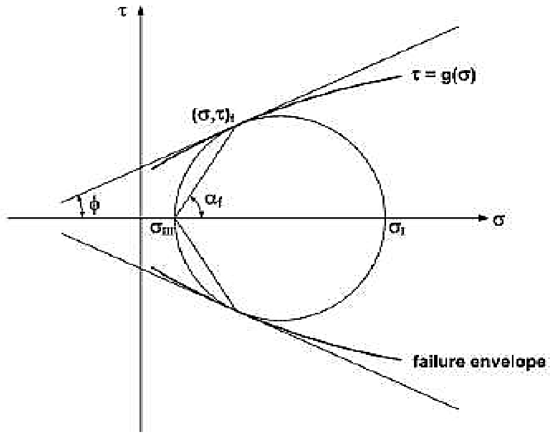

Figure 5: Mohr-Coulomb and failure envelopes [Labuz and Zang, 2012]

The Mohr-Coulomb plasticity model was proposed by Coulomb in 1773 for cohesive frictional materials. The yield criterion is expressed in terms of shear stress and normal stress acting on a plane. The model suggests that the yielding begins as long as the shear stress and normal stress satisfy the following equation;

T=C+sntanφ………………………………………………….... (3.1)

Where, **c** is the cohesion and **φ** is the friction angle. The Mohr-Coulomb model is based on plotting of Mohr's circle for state of stress at failure in the plane of maximum and minimum principal stresses. The failure line is the tangential line to the Mohr's circle as shown in figure Soil-pile interaction

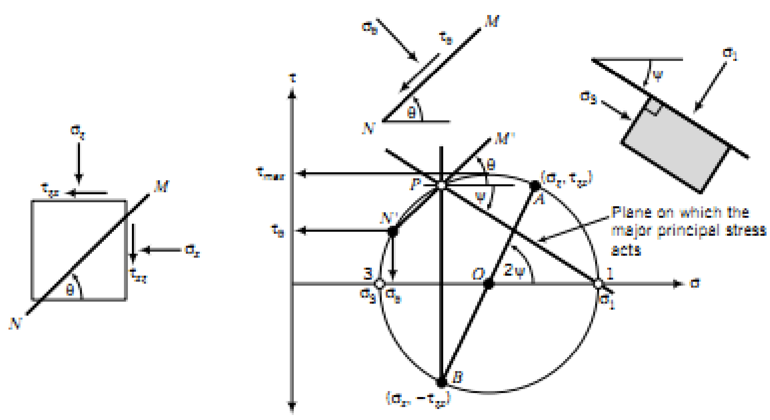

Figure 6 Soil-pile interaction

3.2.2 Hardening Soil model

The Hardening Soil (HS) model, an advanced elasto-plastic constitutive model, is employed to replicate the behavior of both stiff and soft soils. This model establishes a relationship between stiffness parameters and stress levels, capturing the development of plastic strains under compressive loading (Brinkgreve et al., 2012).

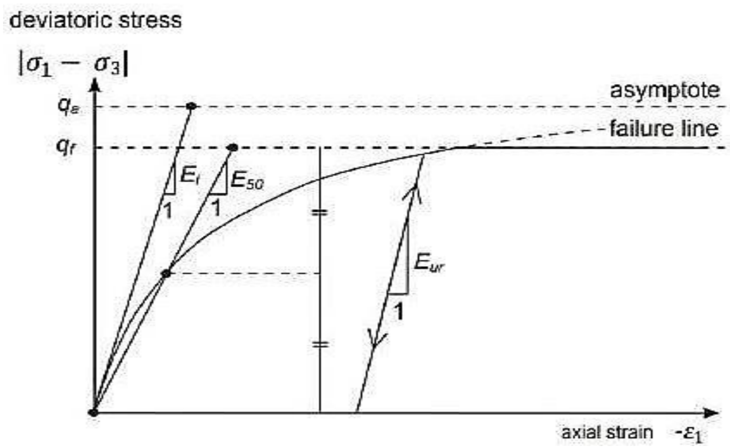

Figure 7:Deviator stress versus axial stress hyperbolic stress-strain curve (Brinkgreve et al., 2012)

The model is represented by a hyperbolic curve, as depicted in Figure 7, which illustrates the stress-strain characteristics employed in the Hardening Soil model.

3.3 Limitations

Although much care has been taken for the development of PLAXIS code and its soil models, the simulation of reality remains an approximation, which implicitly involves some inevitable numerical and modelling errors. Moreover, the accuracy at which reality is approximated depends highly on the expertise of the user regarding the modelling of the problem, the understanding of the soil models and their limitations, the selection of model parameters, and the ability to judge the reliability of the computational results. Some of the limitations of the currently using models are listed below:

3.3.1 Mohr-Coulomb Model

The linear elastic perfectly-plastic Mohr-Coulomb model is a first order model that includes only a limited number of features that soil behaviour shows in reality. Although the increase of stiffness with depth can be taken into account, the Mohr-Coulomb model does neither include stress-dependency nor stress-path dependency nor strain dependency of stiffness or anisotropic stiffness. In general, effective stress states at failure are quite well described using the Mohr-Coulomb failure criterion with effective strength parameters. For undrained materials, the

Mohr-Coulomb model may be used with the friction angle set to zero degrees and the cohesion set to cu, to enable a direct control of undrained shear strength.

3.4 Modelling of Soil Behaviour

Soil and rock tend to behave in a highly non-linear way under load. This non-linear stress-strain behaviour can be modelled at several levels of sophistication. Clearly, the number of model parameters increases with the level of sophistication. The well-known Mohr-Coulomb model can be considered as a first order approximation of real soil behaviour. This elastic perfectly-plastic model requires five basic input parameters, namely Young's modulus, E, Poisson's ratio, μ, cohesion, c, friction angle, ϕ, and dilatancy angle, ψ. As geotechnical engineers tend to be familiar with the above five parameters and rarely have any data on other soil parameters, attention will be focused here on this basic soil model. PLAXIS also supports some advanced soil models.

3.5 Finite Element Method

In contemporary times, the progressive sophistication of engineered structures has surpassed the limitations of conventional analytical calculation methods, which prove excessively time-consuming. As a remedy to this challenge, the finite element method (FEM) has emerged as a computational approach of choice. FEM entails subdividing the structure into discrete elements interconnected by nodes, allowing for the derivation of approximate solutions to differential equations. Numerical analysis, as elucidated by Houghton (1956), encompasses the exploration of numerical approximation techniques to solve mathematical analysis problems.

3.6 Finite Difference Method

This nonlinear analysis technique is employed to address issues associated with the nonlinear interactions between structures and soil (Isenhower et al., 2019). Since the 1960s, numerous scholarly articles by a variety of authors have utilized the finite difference methodology to examine laterally loaded piles (Aasen, 2016). Brom postulates the existence of an ideal elastic material for soil, with the pile functioning as an ideal elastic member throughout the application of lateral loads (Broms, 1964b). Conversely, Poulos and Davis implement a limit equilibrium solution to evaluate the lateral load at the point of failure (Poulos et al., 1980). Several advantages of the finite difference method analysis over the fundamental approaches previously mentioned, such as those proposed by Poulos and Davis and Broms, include (Isenhower et al., 2019): • It postulates a nonlinear interaction between the soil and the pile. • It also incorporates a diagram illustrating bending moments and shear deflection along the length of the pile, grounded in the principles of Winkler analysis theory.

3.7. Data Collection

The data used for this research have been taken from previous studies, experimental investigations and field measurements regarding pile foundation design in layered soils, focusing on key factors such as soil properties, structural characteristics, and loading conditions. Additionally compile information about reliability-based design techniques applied within the context of geotechnical engineering and plaxis 3Ds capabilities

3.8. Software used for Analysis

The contemporary advancements in computer technology have significantly facilitated the widespread application of software programs within the realm of advanced engineering. A variety of geotechnical software applications are employed for the design of pile foundations. Among these, Plaxis 3D stands out as one of the numerous software packages utilized for pile foundation design and is applied in the context of this research.

3.9. Analysis Methods

By using plaxis software packages discussed in brief. These are probabilistic analyses as summarized below.

- Plaxis – Finite Element Analysis
- Finite Element Analysis

3.10. Input parameters

The following parameters are defined for software programs to be used wherever necessary. These data are taken from previous research works on the same location as mentioned the research works in data collection section.

- **Silty CLAY @2m**
  - Unit weight (γ) = 16.00 kN/m3
  - Cohesion (C’) = 7 kpa
  - Internal friction angle (ϕ’) = 23.00º
  - Unit weight (γsat) = 17.00 kN/m3

- Elastic modulus = 25.00 mPa
- Poison's ratio = 0.35

- **Sandy GRAVEL @6m**
    - Unit weight (γ) = 16.00 kN/m3
    - Cohesion (C') = 17 kpa
    - Internal friction angle (ϕ') = 25º
    - sUnit weight (γsat) = 17.00 kN/m3
    - Elastic modulus = 25.00 mPa
    - Poison's ratio = 0.35
- **Clayey SILT @8m**
    - Unit weight (γ) = 16.00 kN/m3
    - Cohesion (C') = 43 kpa
    - Internal friction angle (ϕ') = 30º
    - Unit weight (γsat) = 17.00 kN/m3
    - Elastic modulus = 30.00 mPa
    - Poison's ratio = 0.35
- **Silty SAND @10m**
    - Unit weight (γ) = 16.00 kN/m3
    - Cohesion (C') = 6 kpa
    - Internal friction angle (ϕ') = 23º
    - Unit weight (γsat) = 17.00 kN/m3
    - Elastic modulus = 30.00 mPa
    - Poison's ratio = 0.35
- **Clayey SILT @12m**
    - Unit weight (γ) = 16.00 kN/m3

- Cohesion (C’) = 35 kpa
- Internal friction angle (ϕ’) = 29º
- Unit weight (γsat) = 17.00 kN/m3
- Elastic modulus = 30.00 mPa
- Poison’s ratio = 0.35

- **Clayey SILT @14m**
  - Unit weight (γ) = 16.00 kN/m3
  - Cohesion (C’) = 38kpa
  - Internal friction angle (ϕ’) = 29º
  - Unit weight (γsat) = 17.00 kN/m3
  - Elastic modulus = 30.00 mPa
  - Poison’s ratio = 0.35

- **Clayey SILT @20m**
  - Unit weight (γ) = 16.00 kN/m3
  - Cohesion (C’) = 33kpa
  - Internal friction angle (ϕ’) = 28º
  - Unit weight (γsat) = 17.00 kN/m3
  - Elastic modulus = 30.00 mPa
  - Poison’s ratio = 0.35

CHAPTER- FOUR

RESULT AND DISCUSSION

This chapter delineates the principal findings and engages in a discourse regarding the results succinctly, predicated upon the type of analysis conducted. As articulated in the methodology section, the analyses employed the Finite Element Method (FEM). Nevertheless, the primary emphasis is on probabilistic analysis utilizing the Plaxis 3D software package designed for finite element method applications.

4.1 Examining the Behavior of Piles in Layered Soil:

For the purposes of analysis and modeling of pile foundations, various scenarios of soil layering were contemplated. The initial scenario encompasses seven discrete layers, organized from the uppermost to the lowermost as follows: silty clay, sandy gravel, clayey silt, silty sand, clayey silt, clayey silt, and clayey silt. The thickness of these strata varies, and they exhibit distinct soil types and geotechnical properties, as elucidated in Table 3. The case study pertains to a structure consisting of B+G+7 stories, bearing a point load of 1000 KN per pile, which corresponds to the anticipated load for the foundation of the building.

The subsequent scenario pertains to the modeling of a singular stratum composed of clayey silt. The tertiary scenario incorporates a layer characterized by silty sand. The quaternary scenario utilizes a layer constituted of silty clay, whereas the quintessence, or final scenario, is representative of a layer comprising sandy gravel. The outcomes derived from these scenarios are systematically illustrated in Table 2.

Table 2: Plaxis 3D output result summary

							Layer type			
Sn				**Layers**			**clayey silt**	**silty sand**	**silty clay**	**sandy gravel**
	Parameter	**Symbol**	**Unit**	**Load**			**Load**	**Load**	**Load**	**Load**
				1000 KN	**1200 KN**	**1500 KN**	**1000 KN**	**1000 KN**	**1000 KN**	**1000 KN**
1	**Total displacement**	**Uz**	**Mm**	**2**	**2.33**	**3**	**3.7**	**0.3**	**4.1**	**1.94**
2	**Maximum shear stress**	**Tmax**	**KN/m2**	**80.85**	**81.1**	**81.47**	**87.63**	**49.78**	**52.72**	**63.48**
3	**Bending Moment**	**M2**	**KNm**	**2.056**	**2.43**	**3**	**3.49**	**0.36**	**3.62**	**2.9**
4	**Bending Moment**	**M3**	**KNm**	**1.09**	**1.3**	**1.73**	**3.28**	**0.35**	**2.94**	**1.48**
5	**Incremental**	**ΔU**	**Mm**	**0.24**	**0.3**	**0.38**	**0.01**	**0.15**	**0.01**	**0.97**

	displacement									
6	**Principal Effective Stress**	**σ'1**	**KN/m2**	**141.1**	**145.7**	**142.7**	**145**	**140.8**	**145.1**	**141**
7	**Principal Effective Stress**	**σ'2**	**KN/m2**	**75.26**	**77.85**	**76.72**	**75.09**	**85.8**	**88.49**	**81.47**
8	**Principal Effective Stress**	**σ'3**	**KN/m2**	**75.18**	**77.76**	**76.21**	**75.05**	**85.78**	**88.34**	**81.43**
9	**Principal Total Stress**	**σ1**	**KN/m2**	**337.1**	**345.7**	**338.8**	**342.2**	**336.8**	**341.2**	**337.3**
10	**Principal Total Stress**	**σ2**	**KN/m2**	**271.3**	**277.9**	**272.4**	**272.3**	**282.6**	**284.6**	**278.3**
11	**Principal Total Stress**	**σ3**	**KN/m2**	**271.3**	**277.8**	**272.3**	**272.2**	**282.6**	**284.4**	**278.3**
12	**Total mean stress**	**P**	**KN/m2**	**299.8**	**300.4**	**301.4**	**300.5**	**304.1**	**308.9**	**303.7**

The table shows that presents a summary of the output from a Pile foundation analysis conducted using Plaxis 3D software. The software version used was the latest version available in 2024, chosen for its improved accuracy and reliability. And The table show that outlines the input parameters used for the pile modeling.

Table 3: Material properties

List	Elastic Modulus	Poissons Ratio	(γ)	(γsat)	Cohesion	Friction angle
Clayey Silt @12m	30000	0.4	16	17	35	29
Clayey Silt @14m	30000	0.4	16	17	38	29
Clayey Silt @20m	30000	0.4	16	17	33	28
Sandy gravel @6m	25000	0.4	16	17	17	25
Pile	30000000	0.2	25			
Clayey Silt @8m	30000	0.4	16	17	43	30
Silty sand @10	30000	0.4	16	17	6	23
Silty clay@2m	25000	0.4	16	17	7	23

The output parameters such as settlement (displacement), stress, moments and strain were generated. It is observed from the table that as the applied load increases, the settlement (displacement), moment, maximum shear force, and stress also increase. To visualize the settlement and stress distribution, bar charts and graphs were generated. The graphs illustrate the variations in settlement and stress levels across different soil scenarios, providing a clear comparison of pile behavior under similar loads.

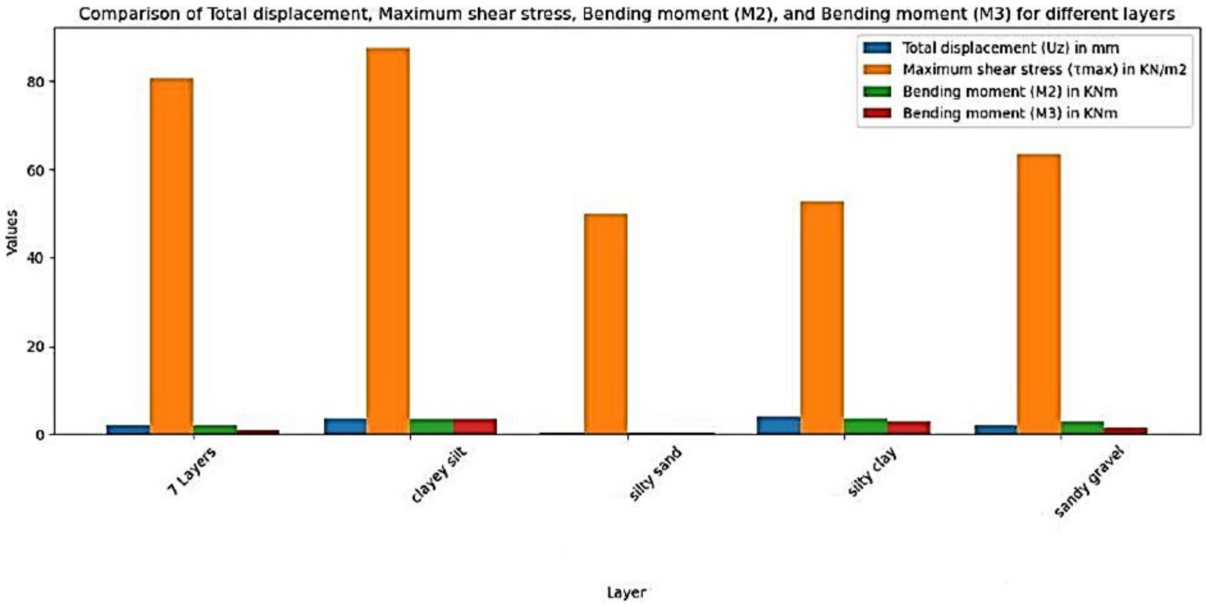

Figure 8: settlement and stress levels across different soil, under similar loads.

4.2 Settlement Analysis

Settlement analysis entails the application of analogous loads to pile foundations across various soil models, followed by an assessment of the resultant displacements. This analytical procedure yields output parameters, including total displacement (Uz), incremental displacement (ΔU), as well as values for stress and strain. The findings derived from the settlement analysis indicate that both total displacement and incremental displacement exhibit considerable variation across different soil types, which can be summarized as follows.

Layer Scenario: The total displacement recorded for a load of 1000 KN is 2 mm, which increases to 3 mm when subjected to a load of 1500 KN.

Clayey Silt Layer: The total displacement amounts to 3.7 mm when subjected to a load of 1000 KN.

Silty Sand Layer: This specific layer demonstrates the least amount of settlement, registering a mere 0.3 mm of displacement under a load of 1000 KN.

Silty Clay Layer: This layer manifests the greatest settlement, recording a displacement of 4.1 mm under the same load.

Sandy Gravel Layer: The total displacement is measured at 1.94 mm under a load of 1000 KN.

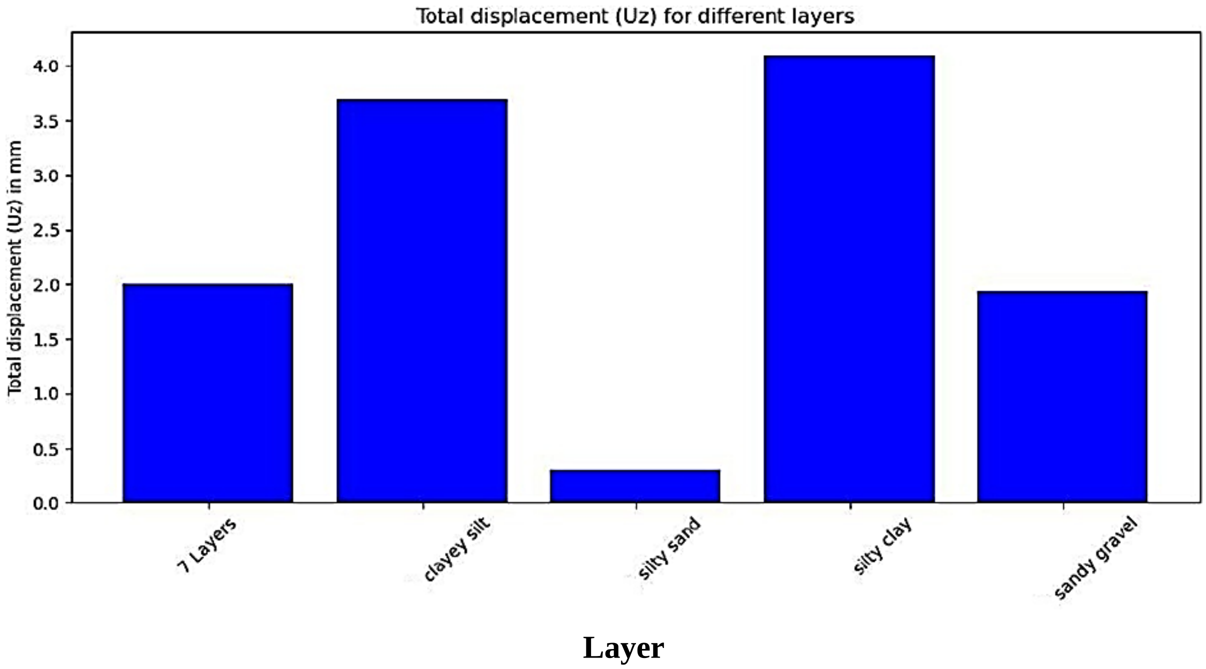

Figure 9: Settlement profiles for different soil layers

The settlement profiles for different soil layers are plotted as shown in the above graph to show the distribution of settlement along the depth of the piles. The profiles indicate higher settlement in softer soils such as silty clay and lower settlement in stiffer soils like silty sand , sandy gravel and the layered soil.

Stress distribution analysis involves examining the distribution of stress within the soil and pile under the applied loads. The analysis generates parameters such as principal effective stress (σ'1, σ'2, σ'3) and principal total stress (σ1, σ2, σ3).

The Different stress types, including Principal Effective Stress (σ'1), Principal Effective Stress (σ'2), Principal Effective Stress (σ'3), Principal Total Stress (σ1), Principal Total Stress (σ2), and Principal Total Stress (σ3), have been analyzed and compared for the different layered soils under a similar applied load of 1000 KN. The comparison results are shown below in the graph. From the output, the silty clay layered soil has higher stress distribution, while the silty sand has a lower Principal Effective Stress (σ'1) and Principal Total Stress (σ1) distribution.

Key observations from the stress distribution analysis include:

- Principal Effective Stress (σ'1): Ranges from 140.8 KN/m² to 145.1 KN/m² across different soil types.

- Principal Effective Stress (σ'2) and (σ'3): Show variations depending on the soil layer, with higher values observed in the silty sand and silty clay layers.
- Principal Total Stress (σ1): Is highest in the silty sand layer at 342.2 KN/m² and lowest in the layer scenario at 337.1 KN/m².
- Principal Total Stress (σ2) and (σ3): Also vary, with the silty clay and sandy gravel layers showing higher stress levels compared to the layer scenario.

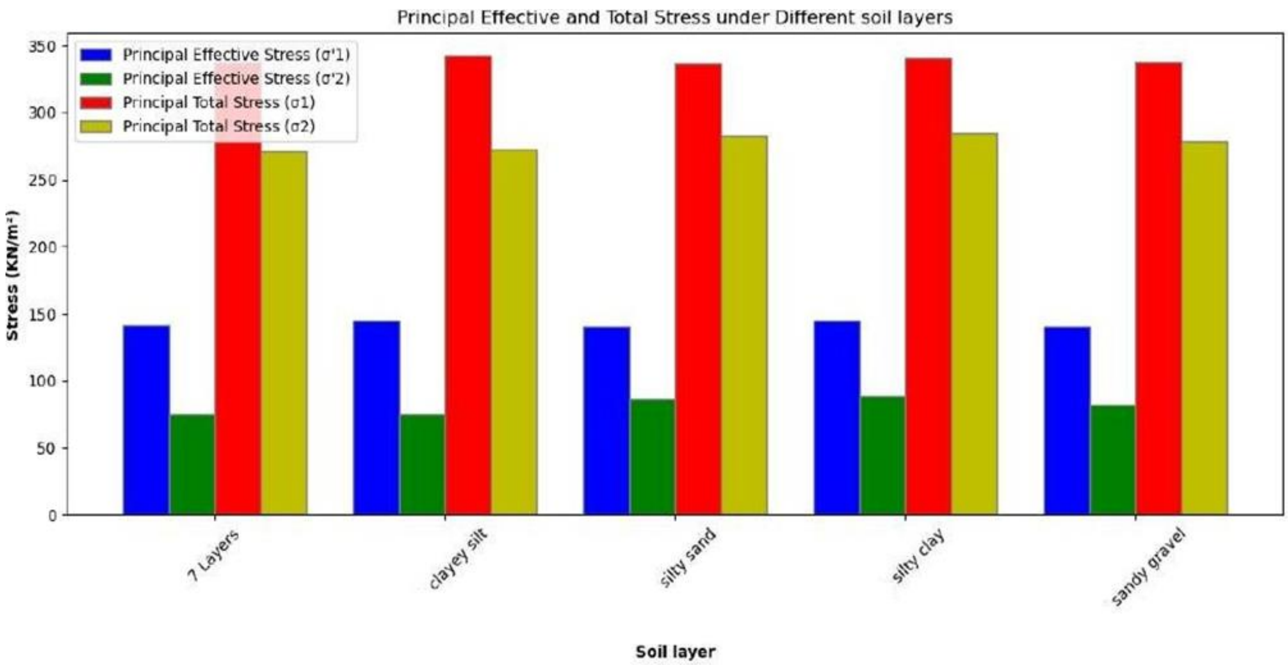

Figure 10: Distribution of stress within the soil and pile under the applied loads

These stress distributions highlight the variability in soil behavior under load, influencing the design and performance of pile foundations.

4.3 Comparison of Soil Layers

As we can see from the graphs and from Tables, though there is no significant difference between the different layers in terms of settlement and stress distribution of silty sand has better performance in terms of settlement, shear force, bending moment, and principal stresses. Silty sand exhibits favorable geotechnical properties, including high shear strength, good compaction characteristics, and lower compressibility compared to other soil types. These properties contribute to its ability to effectively distribute loads and minimize settlement under applied loads. Therefore, it is recommended to apply this layer for the B+ G+7 building.

The analysis of pile foundations in layered soils demonstrates significant variations in settlement and stress distribution depending on soil type and load conditions. Silty clay layers exhibit higher settlement and stress, necessitating careful consideration in foundation design to ensure stability and performance. Conversely, silty sand and sandy gravel layers offer better support with lower settlement and stress levels, making them preferable for pile foundation construction.

4.4. Evaluate the Performance of Pile Foundations in Layered Soil by Applying different loads

To assess the pile performance under varying loads, an analysis was conducted using Plaxis software. The study includes five distinct layers: layered soil, clayey silt at silty sand at, silty clay at, and sandy gravel at. Settlement, maximum shear stress, bending moment, and stresses were analyzed for each layer under load variations of 1000 KN, 1200 KN, 1500 KN, and 1700 KN. The detailed results of the settlement analysis are presented below.

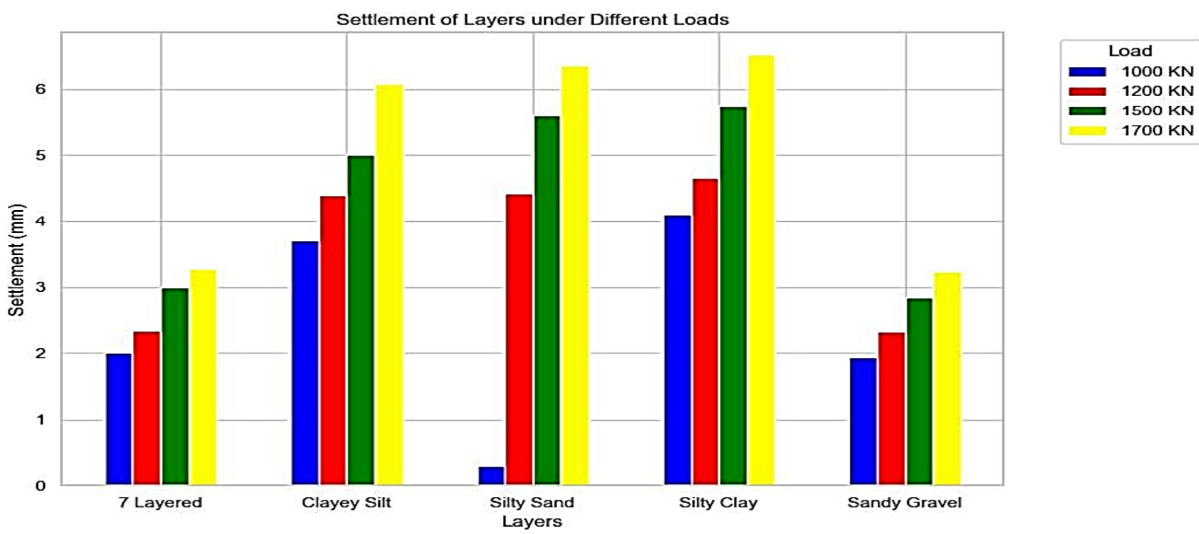

Figure 11:Load-settlement behaviour

As we can see from the graph, the settlement behavior of different soil layers under increasing loads varies. Clayey Silt shows a moderate increase in settlement from 2.33 mm at 1000 KN to 4.65 mm at 1700 KN. Silty Sand, on the other hand, exhibits the lowest settlement at 1000 KN (0.3 mm) but shows a substantial increase to 4.42 mm at 1200 KN, indicating higher sensitivity to load changes within this range. Silty Clay shows a relatively consistent increase in settlement from 3 mm at 1000 KN to 5.75 mm at 1700 KN. Sandy Gravel has the lowest relative increase in settlement, from 1.94 mm at 1000 KN to 3.24 mm at 1700 KN, suggesting greater stability or lower sensitivity to load changes compared to the other layers.Stress Analysis

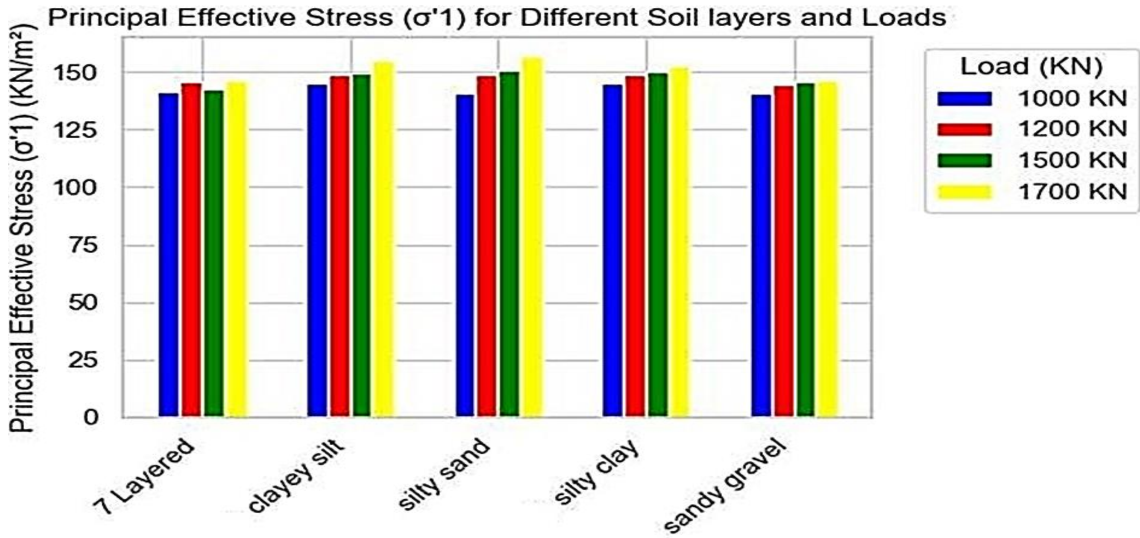

Figure 12: Principal Effective Stress for different soil layers under increasing loads

Based on the Principal Effective Stress (σ'1) graph for different soil layers under increasing loads, we observe varying stress behaviors. The Layered soil shows a slight increase in stress from 141.1 KN/m² at 1000 KN to 146.1 KN/m² at 1700 KN. Clayey Silt exhibits a similar trend, with stress increasing from 145.7 KN/m² at 1000 KN to 155.2 KN/m² at 1700 KN. Silty Sand has a more pronounced increase, starting at 145 KN/m² at 1000 KN and reaching 156.9 KN/m² at 1700 KN. Silty Clay shows a consistent increase from 140.8 KN/m² at 1000 KN to 152.5 KN/m² at 1700 KN. Sandy Gravel demonstrates the least increase in stress, ranging from 141 KN/m² at 1000 KN to 146.2 KN/m² at 1700 KN, indicating its relative stability or lower sensitivity to load changes compared to the other layers.

To compare the behavior of different soil layers under increasing loads based on Principal Total Stress (σ1) in KN/m², a graph was plotted using the provided data as shown. The graph illustrates how each soil type responds to varying loads of 1000 KN, 1200 KN, 1500 KN, and 1700 KN.

Designing using the second dataset will have the same design alternatives and the same piles geometry as the first one. The only difference is the updated soil parameters. Table 4 Shows the alternatives with the mean values of settlement .

Table 4: Settlement prediction summary

	Alternative 1	Alternative 2	Alternative 3
$\mu s1$ (m)	0.02211	0.01654	0.01280
$\mu s2$ (m)	0.02211	0.01654	0.0128 0
$\mu\delta$	0	0	0

One can notice that when the stiffness parameters increased, the mean of *s* significantly decreased. This increase in soil stiffness should be reflected on the magnitude of the variance in the FOSM analysis, and consequently, the probability of failure. Therefore, performing the reliability analysis for the first alternative:

Table 5: FOSM analysis for alternative 1

		xi	COV	Std	altered value of xi	at altered value (m)
Z1	E50Mpa		0.5	78.143		
Z2	E501Mpa	156.286	0.2	31.257		
Z3	E502Mpa		0.2	31.257	155.486	0.02214
Z4	Eoed Mpa		0.5	71		
Z5	Eoed1 Mpa		0.2	28.4		
Z6	Eoed2 Mpa	142	0.2	28.4	141.2	0.02221
Z7	Eur Mpa		0.5	234.286		
Z8	Eur1 Mpa	468.571	0.2	93.714		
Z9	Eur2 Mpa		0.2	93.714	467.771	0.02215
Z10	E pile 1 Mpa	30000	0.1	3000	29000	0.02227
Z11	A1m2	3.142	0.05	0.157	4.87	0.02236
Z12	Loading pile	10	0.15	6.75	11	0.02293
Z13	E pile 2 Mpa	30000	0.1	3000	29000	0.02227
Z14	A2m2	3.142	0.05	0.157	3.11	0.02236
Z15	Loading pile	10	0.15	6.75	11	0.02293

Table 6:Statistics of settlement of alternative 1

E(N)	1	E(S1) (m)	0.011
E(D1)	1	VAR(S1) (m)	2.20E-04
E(D2)	1	STD(S1) (m)	0.013
VAR(N)	1.41E-04	COV(S)	0.649
STD(N)	0.554	E(S2) (m)	0.011
COV(N)	0.554	VAR(S2) (m)	2.20E-04

VAR($D1$)	5.48E-05	STD($S2$) (m)	0.015
STD($D1$)	0.445	COV($S2$)	0.649
COV($D1$)	0.445	E($S1$-$S2$) (m)	0.000
VAR($D2$)	5.48E-05	VAR($S1$-$S2$) (m)	1.10E-04
STD($D2$)	0.445	STD($S1$-$S2$) (m)	0.010
COV($D2$)	0.445	COV($S1$-$S2$)	-

Table 7:Probability of failure analysis of alternative 1

Allowable total settlement (m)	E(S) (m)	std(S) (m)	λs	ζs	P(E(S)>Allowable)
0.076	0.011	0.015	-3.78	0.595	0.88%

Table 8:Probability of failure analysis of alternative 1

$\mu\delta$	0.000
$\sigma\delta$	0.001581
COV	-
$\mu\delta all$	0.003
$\sigma\delta all$	0.0007
COV	0.31
$E(\mu\delta - \mu\delta all)$	-0.002
$STD(\mu\delta - \mu\delta all)$	0.003
P($\delta - \delta all$>0)	10.72%
P($-\delta - (-\delta all)$<0)	10.72%
P(Failure)	23.64%

Table 9 :Analysis of FOSM for alternative 2

		xi	COV	Std	altered value of xi	at altered value (m)
Z1	E50Mpa		0.5	78.143		
Z2	E501Mpa		0.2	31.257		
Z3	E502Mpa	156.286	0.2	31.257	155.486	0.01656
Z4	Eoed Mpa		0.5	71		
Z5	Eoed1 Mpa		0.2	28.4		
Z6	Eoed2 Mpa	142	0.2	28.4	141.2	0.0166
Z7	Eur Mpa		0.5	234.286		
Z8	Eur1 Mpa		0.2	93.714		
Z9	Eur2 Mpa	468.571	0.2	93.714	467.771	0.01655
Z10	E pile 1 Mpa	30000	0.1	3000	29000	0.01666
Z11	A1m2	4.909	0.05	0.245	4.87	0.01664
Z12	Loading pile	10	0.15	6.75	11	0.01717
Z13	E pile 2 Mpa	30000	0.1	3000	29000	0.01666
Z14	A2m2	4.909	0.05	0.245	4.87	0.01664
Z15	Loading pile	10	0.15	6.75	11	0.01717

Table 10:Statistics of settlement of alternative 2

E(N)	1	E($S1$) (m)	0.017
E($D1$)	1	VAR(S_1) (m)	4.20E-05
E($D2$)	1	STD(S_1) (m)	0.006
VAR(N)	2.05E-05	COV($S1$)	0.391
STD(N)	0.275	E($S2$) (m)	0.017
COV(N)	0.275	VAR(S_2) (m)	4.20E-05
VAR($D1$)	2.14E-05	STD(S_2) (m)	0.006
STD($D1$)	0.279	COV($S2$)	0.391
COV($D1$)	0.279	E($S1$-$S2$) (m)	0.000
VAR($D2$)	2.14E-05	VAR(S_1-S_2) (m)	4.27E-05

STD($D2$)	0.279	STD(S_1-S_2) (m)	0.0065
COV($D2$)	0.279	COV($S1$-$S2$)	-

Table 11: Probability of failure analysis of alternative 2

$\mu\delta$	0.000
$\sigma\delta$	0.000980
COV	-
$\mu\delta all$	0.002
$\sigma\delta all$	0.0006
COV	0.3
$E(\mu\delta - \mu\delta all)$	-0.002
$STD(\mu\delta - \mu\delta all)$	0.001
P($\delta - \delta all$>0)	4.08%
P($-\delta - (-\delta all)$<0)	4.08%
P(Failure)	7.17%

Table 12:FOSM analysis for alternative 3

		xi	COV	Std	altered value of xi	at altered value (m)
Z1	E50Mpa		0.5	78.143		
Z2	E501Mpa		0.2	31.257		
Z3	E502Mpa	156.286	0.2	31.257	155.486	0.01281
Z4	Eoed Mpa		0.5	71		
Z5	Eoed1 Mpa		0.2	28.4		
Z6	Eoed2 Mpa	142	0.2	28.4	141.2	0.01276
Z7	Eur Mpa		0.5	234.286		
Z8	Eur1 Mpa		0.2	93.714		
Z9	Eur2 Mpa	468.571	0.2	93.714	467.771	0.0128
Z10	E pile 1 Mpa	30000	0.1	3000	29000	0.01286
Z11	A1m2	7.069	0.05	0.353	4.87	0.01286

Z12	Loading pile	10	0.15	6.75	11	0.01327
Z13	E pile 2 Mpa	30000	0.1	3000	29000	0.01286
Z14	A2m2	7.069	0.05	0.353	4.87	0.01286
Z15	Loading pile	10	0.15	6.75	11	0.01327

Table 13: Statistics of settlement of alternative 3

E(N)	1	E($S1$) (m)	0.013
E($D1$)	1	VAR(S_1) (m)	2.61E-05
E($D2$)	1	STD(S_1) (m)	0.005
VAR(N)	1.36E-05	COV($S1$)	0.399
STD(N)	0.288	E($S2$) (m)	0.013
COV(N)	0.288	VAR($S2$) (m)	2.61E-05
VAR($D1$)	1.25E-05	STD($S2$) (m)	0.005
STD($D1$)	0.276	COV($S2$)	0.399
COV($D1$)	0.276	E($S1$-$S2$) (m)	0.000
VAR($D2$)	1.25E-05	VAR($S1$-$S2$) (m)	2.50E-05
STD($D2$)	0.276	STD($S1$-$S2$) (m)	0.0050
COV($D2$)	0.276	COV($S1$-$S2$)	-

Table 14: Probability of failure analysis of alternative 3

Allowable total settlement (m)	E(S) (m)	std(S) (m)	λs	ζs	P(E(S)>Allowable)
0.075	0.013	0.005	-4.432	0.384	0.00%

Table 15:Probability of failure analysis of alternative 3

$\mu\delta$	0.000
$\sigma\delta$	0.000750
COV	-
$\mu\delta all$	0.002
$\sigma\delta all$	0.0006
COV	0.3

$E(\mu\delta - \mu\delta all)$	-0.002
$STD(\mu\delta - \mu\delta all)$	0.00096
P($\delta - \delta all$>0)	1.86%
P($-\delta - (-\delta all)$<0)	1.86%
P(Failure)	3.73%

The probability of failure has decreased significantly for all of the alternatives due to obtaining more data about the soil stiffness that showed a stiffer soil. Moreover, the variance of the statistics of s has decreased due to the decrease in s. In other words, increasing the soil stiffness would make it less sensitive to the change in the inputs parameters. In addition, one advantage of the FOSM method is that it shows the contribution of each one of the input variables to the variance of the system. This would make it easier to focus on some inputs rather than others to improve.

4.5 Comparative Analysis of Monte Carlo Simulations and Analytical Approximations

Prior to conducting an assessment of the value of information, Monte Carlo simulations will be employed to evaluate the approximations articulated in the first order approximation expression utilized in the variances associated with the settlement parameters.

The objective of this evaluation is to juxtapose the failure probabilities derived from Monte Carlo simulations against the first order and second order approximations of the variance of the settlement

Concerning the second order approximation expression:

$(S1) = [[(D1)*g(x1,x2, ..xn)]2\}*Std(N)2+\{[E(N)*g(x1,x2, ..xn)]2\}*Std(D1)2 +g(x1,x2, ..xn)2*[Std(N)2*Std(D1)2]$

$(S2) = [[(D2)*g(x1,x2, ..xn)]2\}*Std(N)2+\{[E(N)*g(x1,x2, ..xn)]2\}*Std(D2)2 +g(x1,x2, ..xn)2*[Std(N)2*Std(D2)2]$

$(S1-S2) = \{[(N)*g(x1,x2, ..xn)]2\}*Std(D1)2 +\{[E(N)* g(x1,x2, ..xn)]2\}*Std(D2)2 + g(x1,x2, ..xn)2*\{[Std(D1)2+Std(D2)2]*Std(N)2\}$

Subsequently, the Monte Carlo simulation shall be executed as follows:

- For each realization, simulate N utilizing the prior distribution of N.

- Compute the mean of the settlement, denoted as $\mu s1$ and $\mu s2$ for pile1 and pile2, correspondingly. The equation employed is: $\mu si = (Di) * Nsimulated * g(x1, x2, ..xn)$.

- Determine $S1$ and $S2$ utilizing the means of $\mu s1$ and $\mu s2$ and the standard deviations of $D1$ and $D2$, respectively.

- Simulate δ based on the values of $S1$ and $S2$ in each realization.

- Simulate δall according to its assumed distribution.

- Calculate the average probability of ABS(δ) − δall.

An alternative methodology for simulation involves employing the moments of the first order approximations to ascertain the probability of failure, as opposed to directly simulating δ and δall. A screenshot illustrating both simulations is presented subsequently.

Alternative 1	
$s_{predict}$ (m)	0.0221
VAR(S1) m2	2.00E-04
STD(S1) (m)	0.01413
COV(S1)	0.639
E(N)	1
E(D1)	1
E(D2)	1
VAR(N)	0.00014
STD(N)	0.54401
COV(N)	0.54401
VAR(D1)	0.00005
STD(D1)	0.33487
COV(D1)	0.33487
VAR(D2)	0.00005
STD(D2)	0.33487
COV(D2)	0.33487
λN	-0.12962
ζN	0.50916
λD1	-0.05314
ζD1	0.32602
λD2	-0.05314
ζD2	0.32602
Alternative 2	
$s_{predict}$ (m)	0.0166
VAR(S1) m2	4.20E-05
STD(S1) (m)	0.0065
COV(S1)	0.391
E(N)	1.000
E(D1)	1.000
E(D2)	1.000
VAR(N)	0.000
STD(N)	0.275

					0.00003	0.00200	$p_{Failure}$
					0.001804966	0.00060886	20.35%
1.0095	0.0223	0.0225	0.0223	0.0223			
N	μs1 (m)	s1 (m)	μs2 (m)	s2 (m)	δ/L	$(\delta/L)_{all}$	"Failure"
0.65261	0.014	0.01083	0.014	0.009	0.00029	0.002501	0
0.73644	0.016	0.01879	0.016	0.010	0.00136	0.002136	0
0.67557	0.015	0.01025	0.015	0.018	-0.00122	0.003330	0
1.17924	0.026	0.01766	0.026	0.031	-0.00201	0.001029	1
1.53982	0.034	0.04588	0.034	0.027	0.00289	0.002052	1
0.66481	0.015	0.01403	0.015	0.011	0.00051	0.002867	0
0.64292	0.014	0.01479	0.014	0.021	-0.00091	0.002172	0
0.5606	0.012	0.01579	0.012	0.010	0.00085	0.001795	0
3.09076	0.068	0.07353	0.068	0.060	0.00197	0.001490	1
0.79865	0.018	0.01561	0.018	0.014	0.00029	0.001374	0
1.76822	0.039	0.04541	0.039	0.018	0.00409	0.002654	1
0.53554	0.012	0.01128	0.012	0.013	-0.00021	0.001283	0
1.5874	0.035	0.03419	0.035	0.024	0.00149	0.002162	0
0.52515	0.012	0.02145	0.012	0.011	0.00163	0.002556	0
0.56998	0.013	0.00915	0.013	0.014	-0.00069	0.001469	0
1.28345	0.028	0.02581	0.028	0.034	-0.00119	0.002995	0
1.12911	0.025	0.02931	0.025	0.024	0.00076	0.002553	0
0.64736	0.014	0.01793	0.014	0.011	0.00105	0.001151	0
2.60774	0.058	0.05057	0.058	0.047	0.00061	0.001906	0
1.09366	0.024	0.02535	0.024	0.016	0.00139	0.002175	0
1.25779	0.028	0.02658	0.028	0.015	0.00180	0.001774	1
2.07865	0.046	0.05563	0.046	0.024	0.00474	0.001875	1
0.89808	0.020	0.02625	0.020	0.038	-0.00172	0.003263	0
1.71974	0.038	0.03226	0.038	0.041	-0.00128	0.003105	0
0.70901	0.016	0.01971	0.016	0.013	0.00104	0.001857	0
1.1103	0.025	0.01984	0.025	0.034	-0.00207	0.001932	1
1.61657	0.036	0.03711	0.036	0.039	-0.00023	0.001843	0
0.3743	0.008	0.00624	0.008	0.005	0.00016	0.002296	0
1.30661	0.029	0.02594	0.029	0.023	0.00040	0.002365	0
0.87851	0.019	0.02458	0.019	0.028	-0.00045	0.001343	0
0.90924	0.020	0.02496	0.020	0.019	0.00096	0.001930	0
0.65435	0.014	0.01057	0.014	0.008	0.00045	0.001456	0
0.46041	0.010	0.01174	0.010	0.013	-0.00012	0.001772	0

		Alternative 1						
1.0095	0.02251	2.17E-04	0.01451	0.0223	2.17E-04	0.0145	0.0000	1.
N	s1 (m)	VAR(S1) (m2)	STD(S1) (m)	s2 (m)	VAR(S2) (m2)	STD(S2) (m)	E(S1-S2) (m)	VAR(S
0.65261	0.011	1.68E-04	0.013	0.009	1.68E-04	0.013	0.002	4.
0.73644	0.019	1.75E-04	0.013	0.010	1.75E-04	0.013	0.007	5.
0.67557	0.010	1.70E-04	0.013	0.018	1.70E-04	0.013	-0.003	5.
1.17924	0.018	2.21E-04	0.015	0.031	2.21E-04	0.015	-0.005	1.
1.53982	0.046	2.75E-04	0.017	0.027	2.75E-04	0.017	0.007	2.
0.66481	0.014	1.69E-04	0.013	0.011	1.69E-04	0.013	0.004	4.
0.64292	0.015	1.67E-04	0.013	0.021	1.67E-04	0.013	-0.007	4.
0.5606	0.016	1.62E-04	0.013	0.010	1.62E-04	0.013	0.002	3.
3.09076	0.074	6.69E-04	0.026	0.060	6.69E-04	0.026	0.008	1.
0.79865	0.016	1.80E-04	0.013	0.014	1.80E-04	0.013	0.004	7.
1.76822	0.045	3.16E-04	0.018	0.018	3.16E-04	0.018	0.021	3.
0.53554	0.011	1.61E-04	0.013	0.013	1.61E-04	0.013	-0.001	3.
1.5874	0.034	2.83E-04	0.017	0.024	2.83E-04	0.017	0.011	2.
0.52515	0.021	1.60E-04	0.013	0.011	1.60E-04	0.013	0.001	3.
0.56998	0.009	1.63E-04	0.013	0.014	1.63E-04	0.013	-0.001	3.
1.28345	0.026	2.35E-04	0.015	0.034	2.35E-04	0.015	-0.005	1.
1.12911	0.029	2.15E-04	0.015	0.024	2.15E-04	0.015	0.001	1.
0.64736	0.018	1.68E-04	0.013	0.011	1.68E-04	0.013	0.003	4.
2.60774	0.051	5.18E-04	0.023	0.047	5.18E-04	0.023	0.011	7.
1.09366	0.025	2.10E-04	0.015	0.016	2.10E-04	0.015	0.008	1.
1.25779	0.027	2.32E-04	0.015	0.015	2.32E-04	0.015	0.013	1.
2.07865	0.056	3.82E-04	0.020	0.024	3.82E-04	0.020	0.022	4.
0.89808	0.026	1.89E-04	0.014	0.038	1.89E-04	0.014	-0.018	8.
1.71974	0.032	3.07E-04	0.018	0.041	3.07E-04	0.018	-0.003	3.
0.70901	0.020	1.72E-04	0.013	0.013	1.72E-04	0.013	0.003	5.
1.1103	0.020	2.12E-04	0.015	0.034	2.12E-04	0.015	-0.009	1.
1.61657	0.037	2.88E-04	0.017	0.039	2.88E-04	0.017	-0.003	2.
0.3743	0.006	1.52E-04	0.012	0.005	1.52E-04	0.012	0.003	1.
1.30661	0.026	2.38E-04	0.015	0.023	2.38E-04	0.015	0.006	1.
0.87851	0.025	1.87E-04	0.014	0.028	1.87E-04	0.014	-0.008	8.
0.90924	0.025	1.90E-04	0.014	0.019	1.90E-04	0.014	0.002	9.
0.65435	0.011	1.68E-04	0.013	0.008	1.68E-04	0.013	0.007	4.
0.46041	0.012	1.56E-04	0.013	0.013	1.56E-04	0.013	-0.002	2.

Figure 13: Monte Carlo Simulation

The next table presents the comparative results of various methodologies employed in the design process. Then, the other table compares the analytical first-order approximation against the Monte Carlo Simulation (MCS). The objective of this comparison is to elucidate the variability inherent in the application of these methodologies. Furthermore, it is evident that although the analytical solutions are approximations, they nonetheless yield satisfactory outcomes. For the purposes of this analysis, the first-order solution will be designated as a benchmark for comparison with subsequent MCS simulations pertaining to the pile load tests.

Table 16: Probability of failure comparison

Method of analysis	Probability of Failure
First order approximation	20.44%
Second order approximation	23.91%
MCS using first order moments	20.85%
MCS	27.76%

- Careful analysis should be considered to ensure that the input parameters and the meshing size in the finite element model is representative of the real soil behavior and does not affect the final output of the model.
- Different settlement prediction models should be evaluated to increase the accuracy and ensure that the results are reasonable. Moreover, results of these models can be compared against pile response from the field to verify the design assumptions.
- Pile load tests can be used to update the reliability level of the foundation design.
- A reliability model for serviceability of axially-loaded pile foundations has been presented that separates spatial variability and model uncertainties and offers the ability to reduce model uncertainties with results from pile load tests.

CHAPTER -FIVE

CONCLUSIONS AND RECOMMENDATIONS

As articulated in the initial chapter, the principal aim of this research is to elucidate the reliability-based design methodology for pile foundations within stratified soil formations through probabilistic analysis, as it encompasses the inherent uncertainties associated with soil properties. This consideration is imperative, given that soil properties can exhibit considerable variability, and deterministic analyses may fail to adequately represent these fluctuations. An endeavor is undertaken to fulfill the articulated aim, with the primary objective being accomplished by recognizing all constraints pertinent to the study. The paramount focus is placed on probabilistic analysis, yielding favorable outcomes in finite element method (FEM)-based evaluations. Although FEM stands as a well-suited analytical method that mitigates numerous assumptions and operates on the principle of identifying the weakest surface, probabilistic analysis is held in higher regard for its incorporation of soil uncertainties, a notable limitation of FEM.

The examination of settlement and stress responses across various soil strata subjected to differing loads elucidates unique performance attributes. Clayey Silt manifests a moderate increase in settlement, indicative of a moderate sensitivity to variations in load, whereas Silty Sand demonstrates initially low settlement but exhibits heightened sensitivity within the 1000-1200 kN load range. Silty Clay reveals a continuous increase in settlement, suggesting moderate sensitivity. In contrast, Sandy Gravel presents the minimal increase in settlement, implying enhanced stability or reduced sensitivity. Regarding stress responses, both Clayey Silt and Silty Clay exhibit moderate increases, Silty Sand reveals a more significant increase, while Sandy Gravel registers the least increase, thereby signifying its relative stability under escalating loads. Collectively, Sandy Gravel appears to represent the most stable or least sensitive material in response to load variations, as assessed through both settlement and stress analyses.

5.2. Recommendation

Notwithstanding the encouraging findings observed, several considerations merit attention as recommendations for further exploration concerning the same or adjacent topics. Recommendations for prospective research trajectories and potential enhancements to the methodologies applied in the research thesis on Reliability-Based design of pile foundations in stratified soil conditions include:

1- The use of FOSM method can be evaluated by redoing the analysis using first order reliability method FORM. FOSM approximates a linear relationship between the inputs and the output of the performance function, i.e., if soil stiffness decreases the settlement increases, which is a reasonable approximation in this case. However, it would be more accurate to use first order reliability method FORM and calculate the most probable failure point in a non-linear representation of the performance function.

2- The uncertainty in the settlement can be reduced by considering the correlations between the input parameter. For instance, correlation between soil stiffness parameters under the same pile, or correlation between parameters of one pile to the other.

3. Incorporate Advanced Soil Modeling Techniques: Future investigations could gain from the integration of advanced soil modeling methodologies, such as finite element analysis or discrete element modeling, to more effectively capture the intricate behavior of layered soils. This integration would yield more precise projections of pile-soil interactions and enhance the reliability of design outcomes.

4. Consider Dynamic Loading Conditions: The scope of research could be broadened to encompass an inquiry into the reliability of pile foundations under dynamic loading scenarios, such as seismic events or wind forces. Gaining insight into the impact of these dynamic forces on the performance of pile foundations within layered soils would prove invaluable for advancing design practices.

5. Performance of Composite Piles: Investigate the efficacy of composite piles (constructed from diverse materials or incorporating various pile types) in layered soil contexts. Analyzing the performance of these innovative designs under varied conditions could yield more efficient and economically viable foundation solutions.

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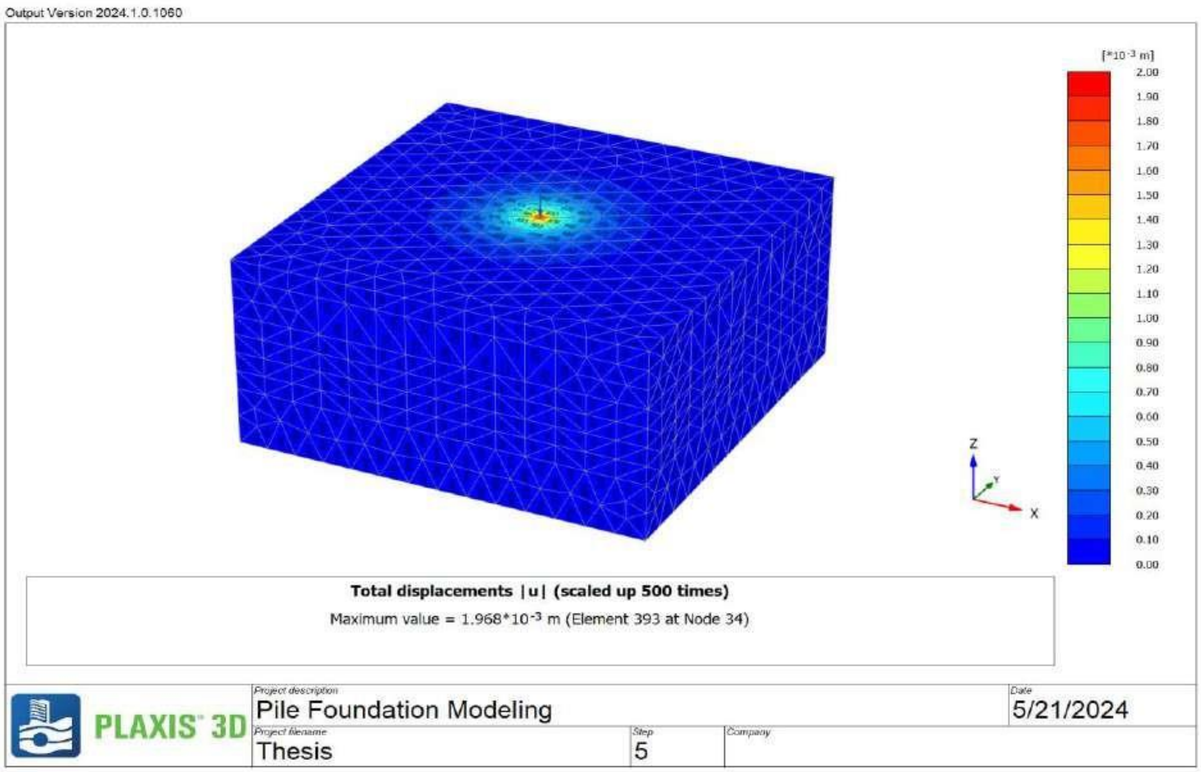
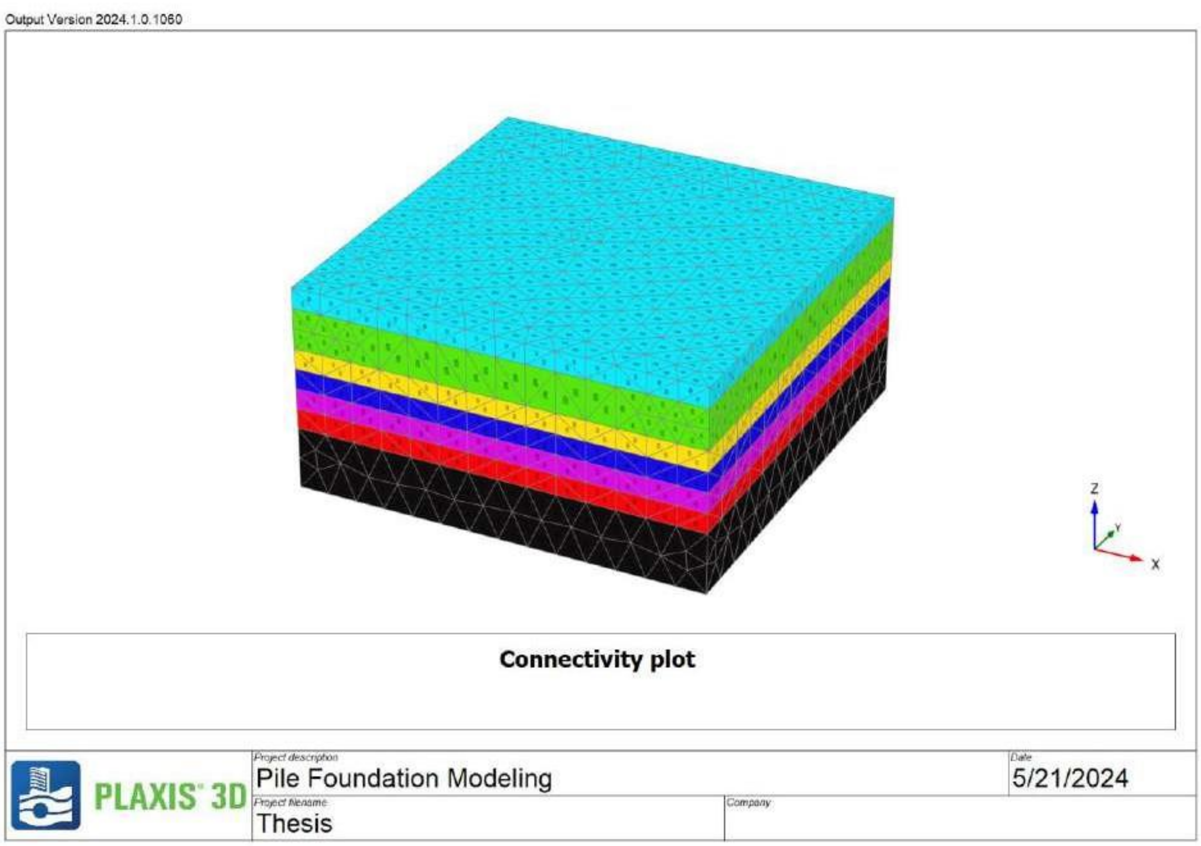
APPENDEX A

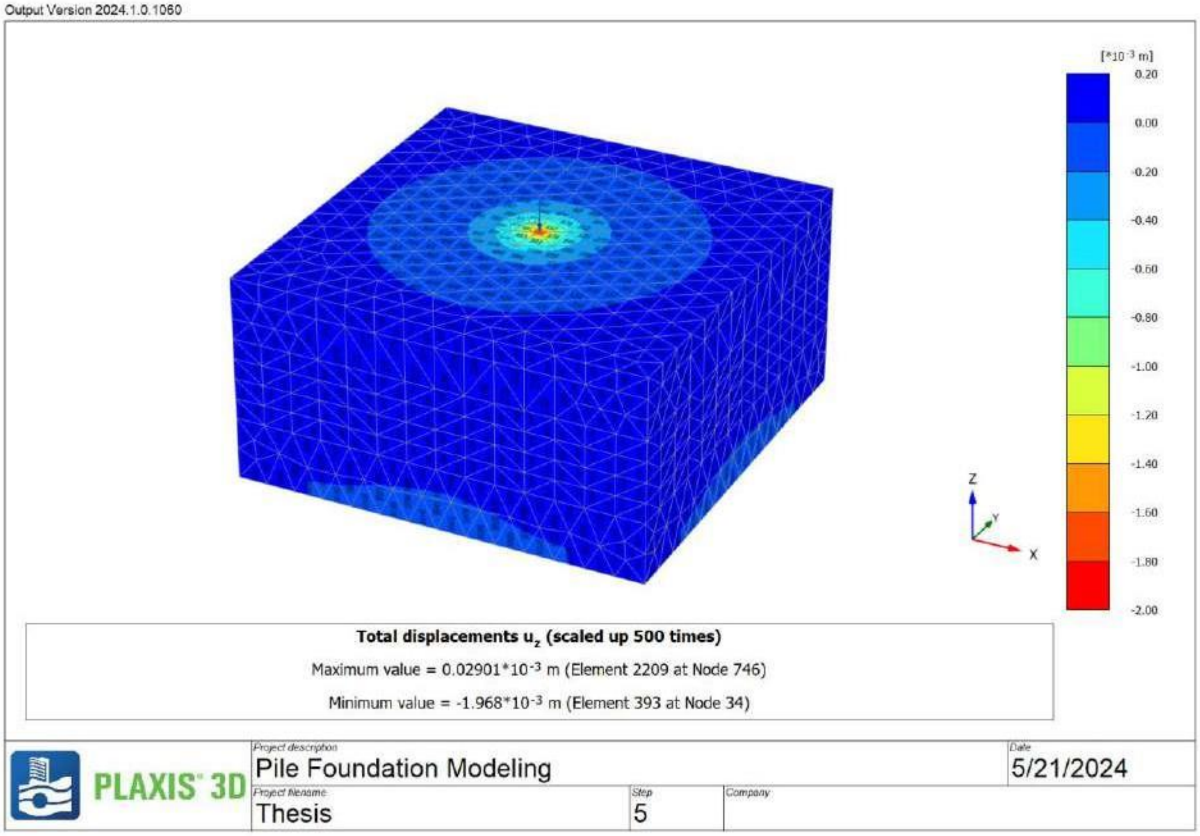


Output Version 2024.1.0.1060
[*10⁻³ m]
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Z
Y
X
Total displacements |u| (scaled up 500 times)
Maximum value = 1.968*10⁻³ m (Element 393 at Node 34)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company

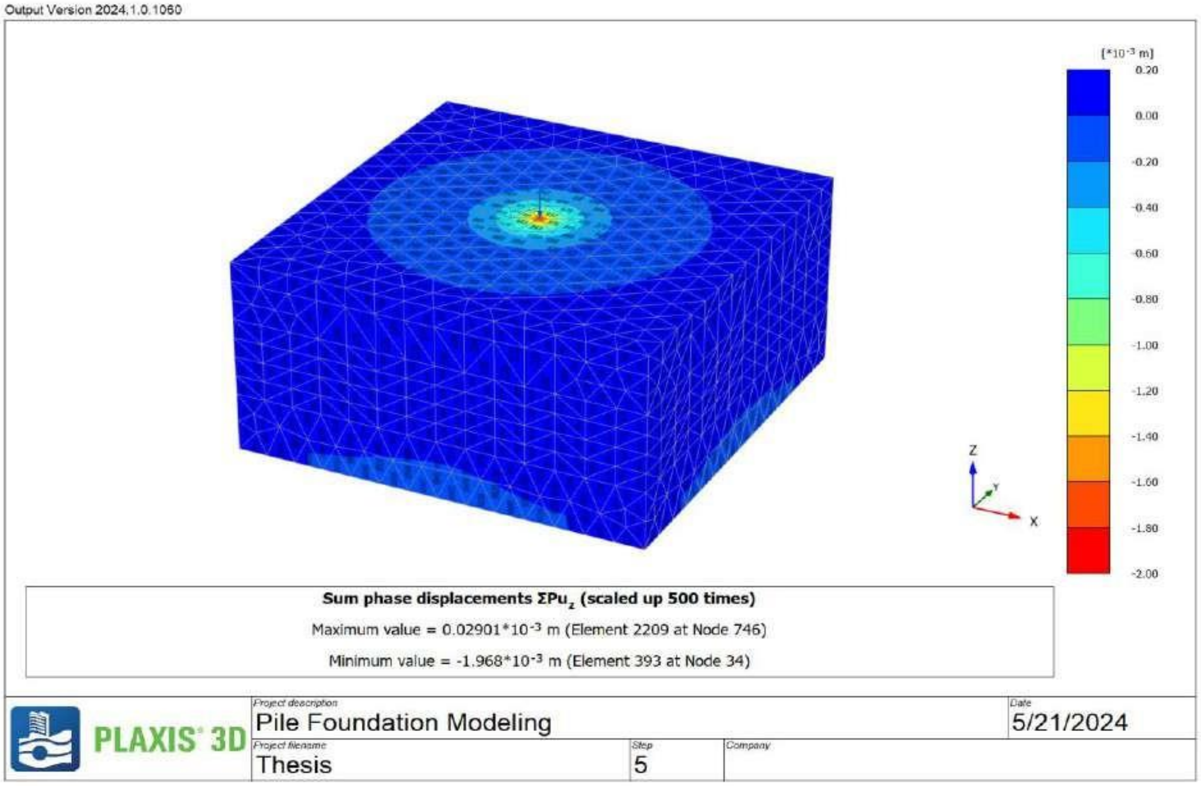


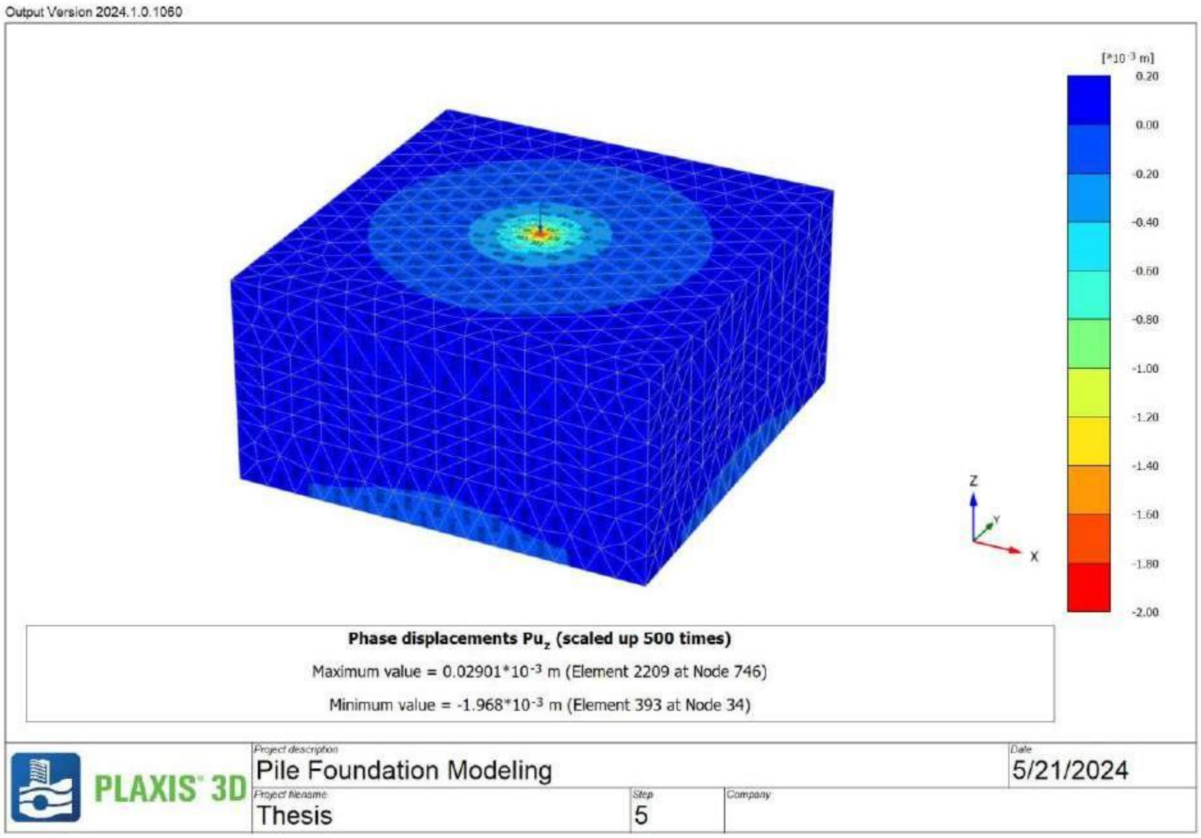
Output Version 2024.1.0.1060
Z
Y
X
Connectivity plot
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Company

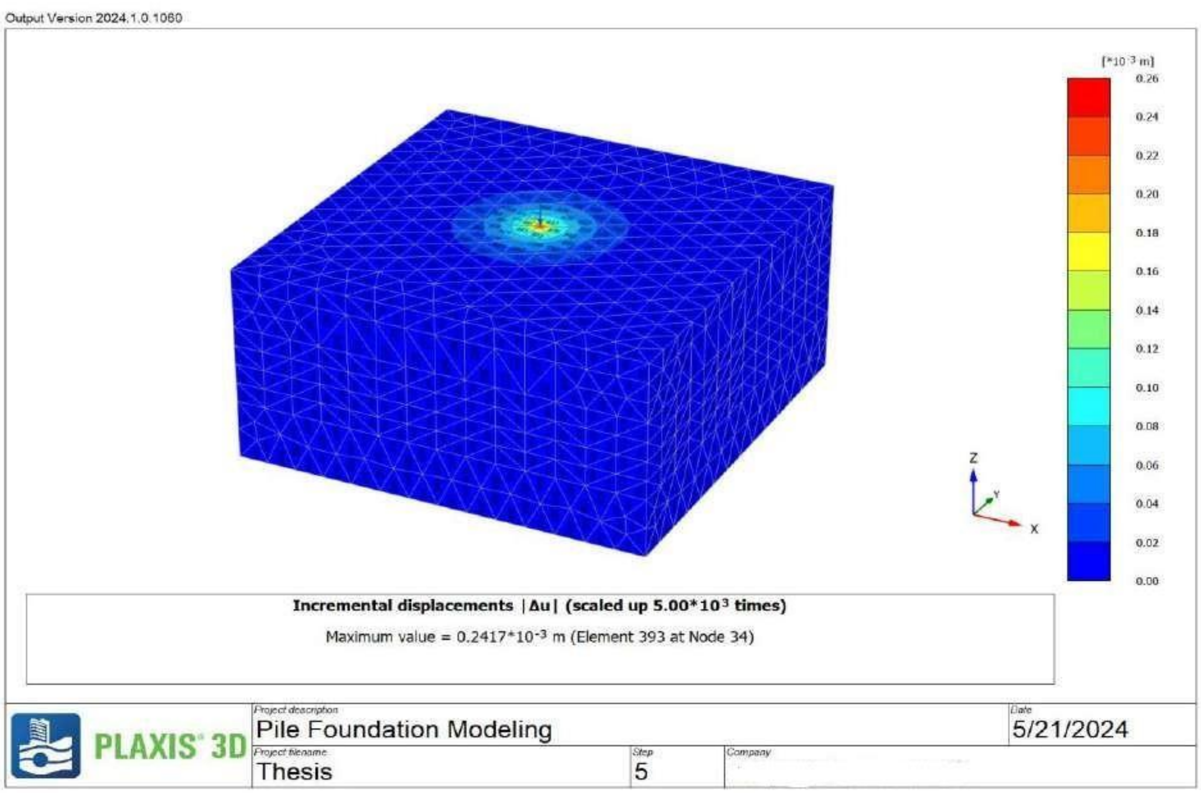
Output Version 2024.1.0.1060

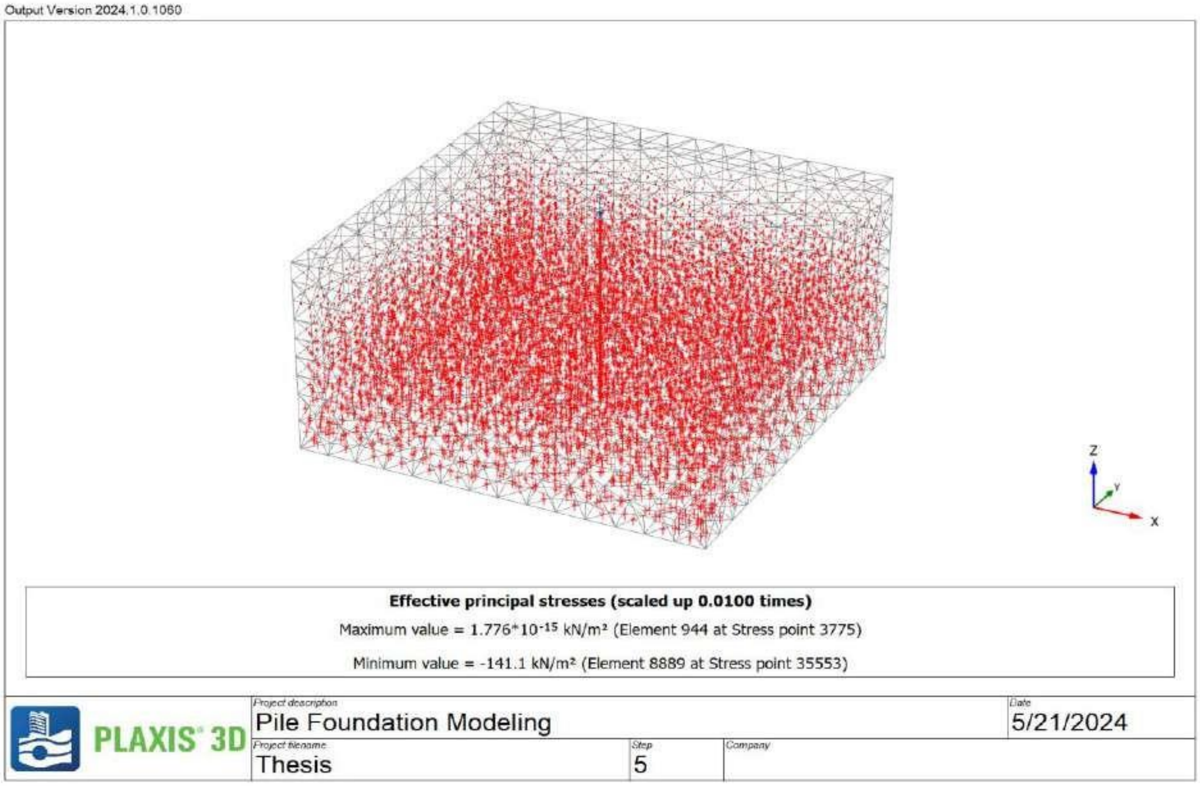


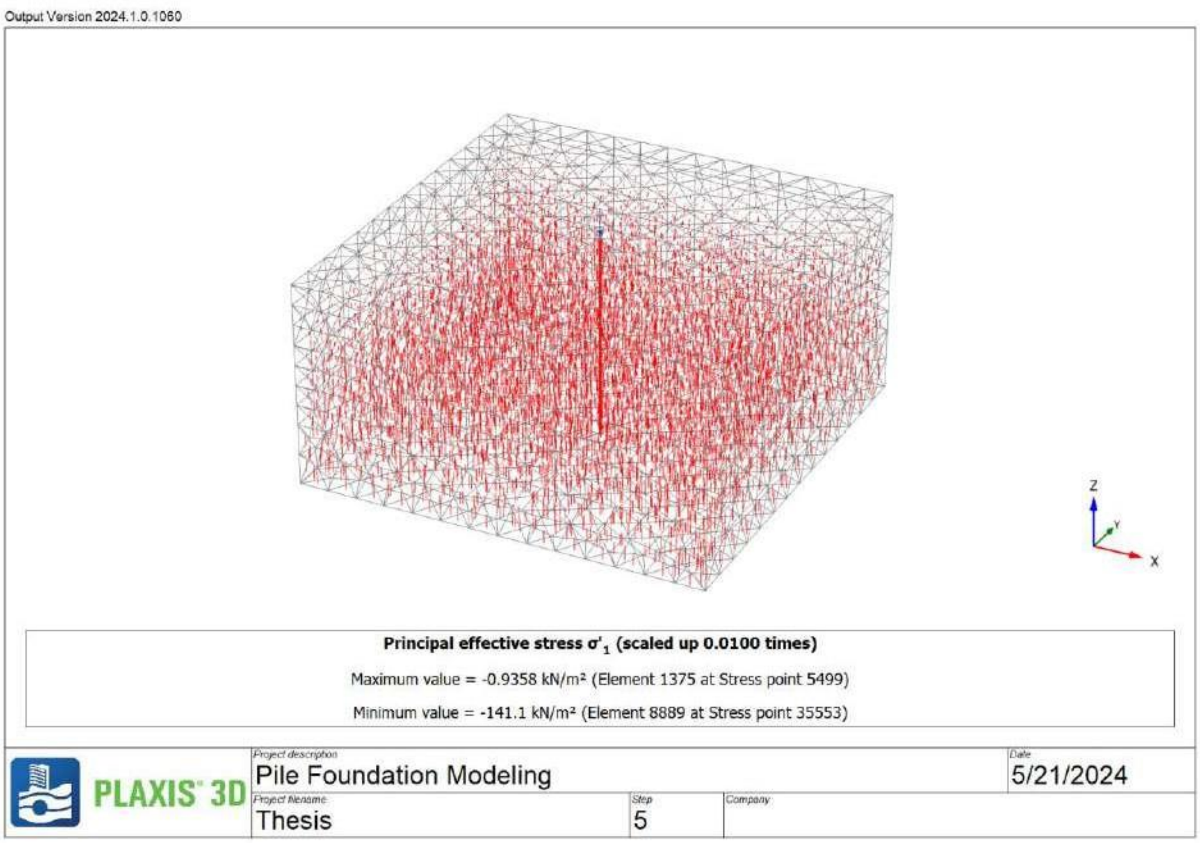
Output Version 2024.1.0.1060



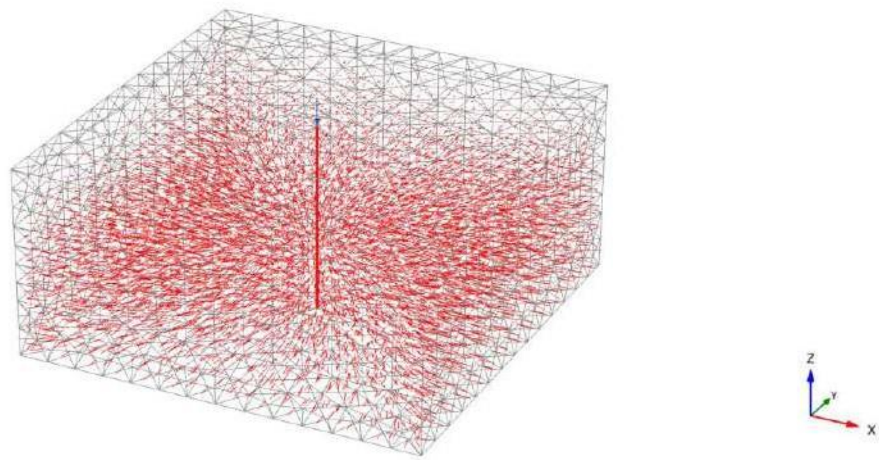

Output Version 2024.1.0.1060
[*10⁻³ m]
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
-1.40
-1.60
-1.80
-2.00
Z
Y
X
Phase displacements Pu_z (scaled up 500 times)
Maximum value = 0.02901*10^{-3} m (Element 2209 at Node 746)
Minimum value = -1.968*10^{-3} m (Element 393 at Node 34)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company


Output Version 2024.1.0.1060
[*10⁻³ m]
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Z
Y
X
Incremental displacements |Δu| (scaled up 5.00*10^3 times)
Maximum value = 0.2417*10^{-3} m (Element 393 at Node 34)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company


Output Version 2024.1.0.1060
Effective principal stresses (scaled up 0.0100 times)
Maximum value = $1.776*10^{-15}$ kN/m² (Element 944 at Stress point 3775)
Minimum value = -141.1 kN/m² (Element 8889 at Stress point 35553)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company
z
y
x


Output Version 2024.1.0.1060
Principal effective stress σ'_1 (scaled up 0.0100 times)
Maximum value = -0.9358 kN/m² (Element 1375 at Stress point 5499)
Minimum value = -141.1 kN/m² (Element 8889 at Stress point 35553)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company
z
y
x

Output Version 2024.1.0.1060



Principal effective stress σ'$_2$ (scaled up 0.0200 times)

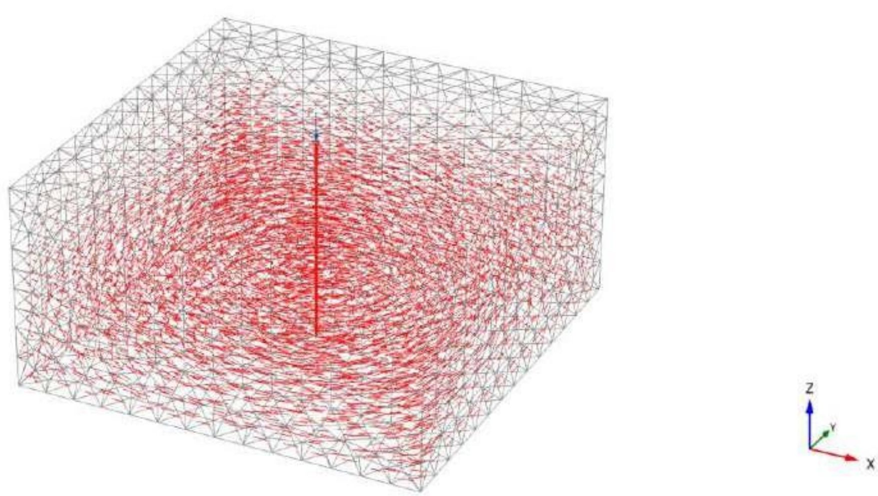
Maximum value = -0.5547 kN/m² (Element 1374 at Stress point 5495)

Minimum value = -75.26 kN/m² (Element 8889 at Stress point 35553)

PLAXIS® 3D

Project description			Date
Pile Foundation Modeling			5/21/2024
Project filename	Step	Company	
Thesis	5		

Output Version 2024.1.0.1060



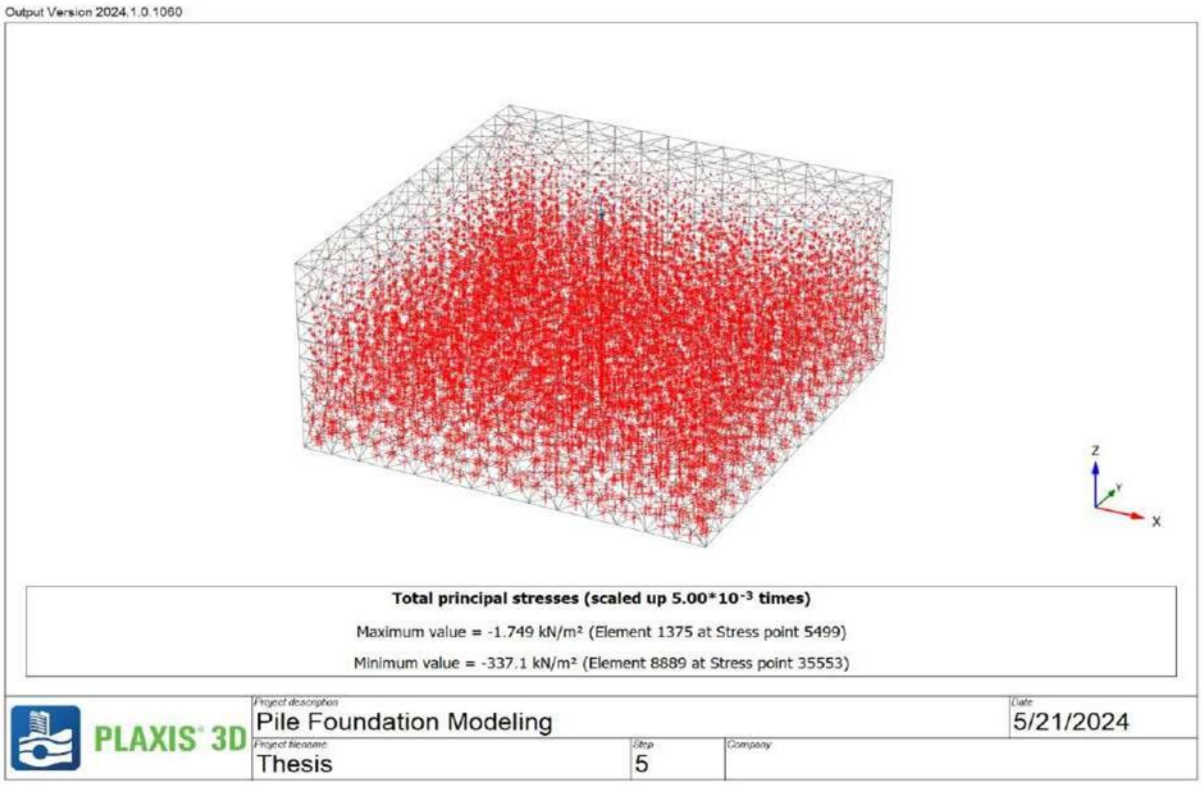
Principal effective stress σ'$_3$ (scaled up 0.0200 times)

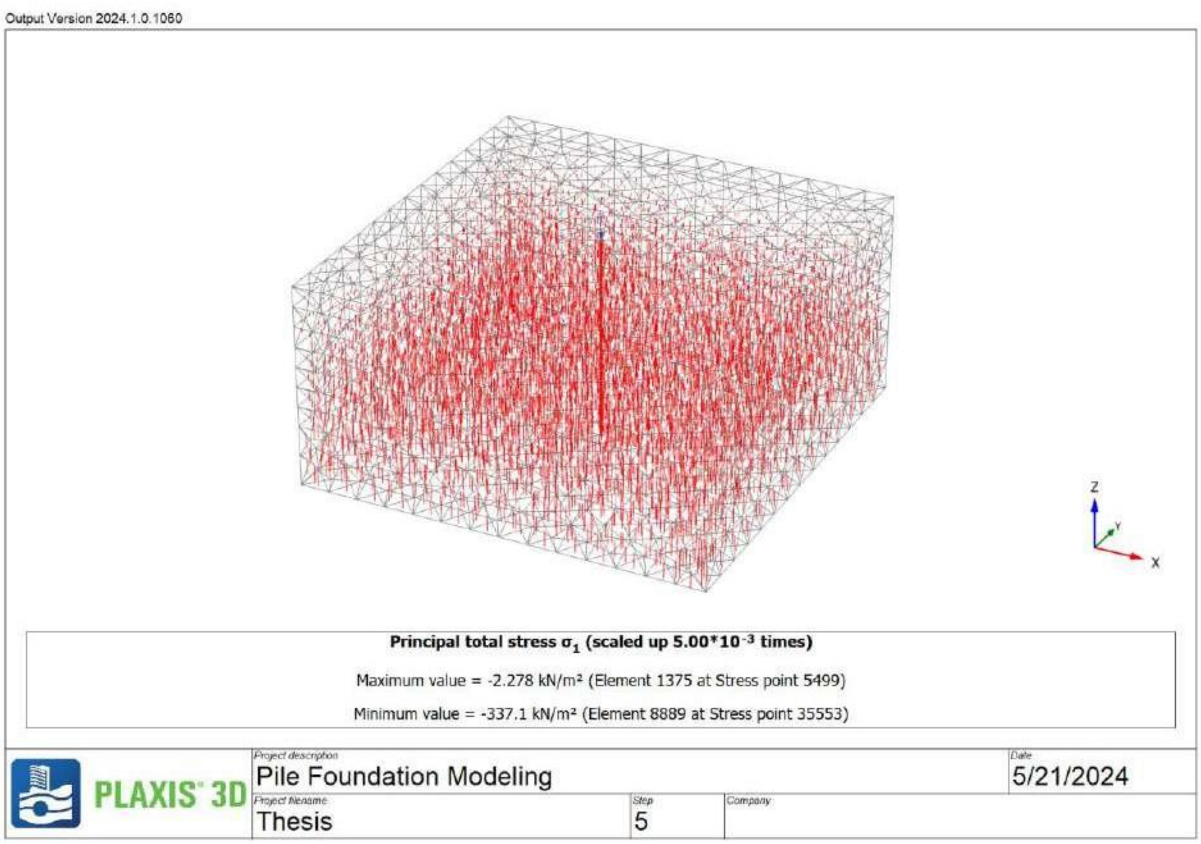
Maximum value = 1.776×10^{-15} kN/m² (Element 944 at Stress point 3775)

Minimum value = -75.18 kN/m² (Element 8889 at Stress point 35553)

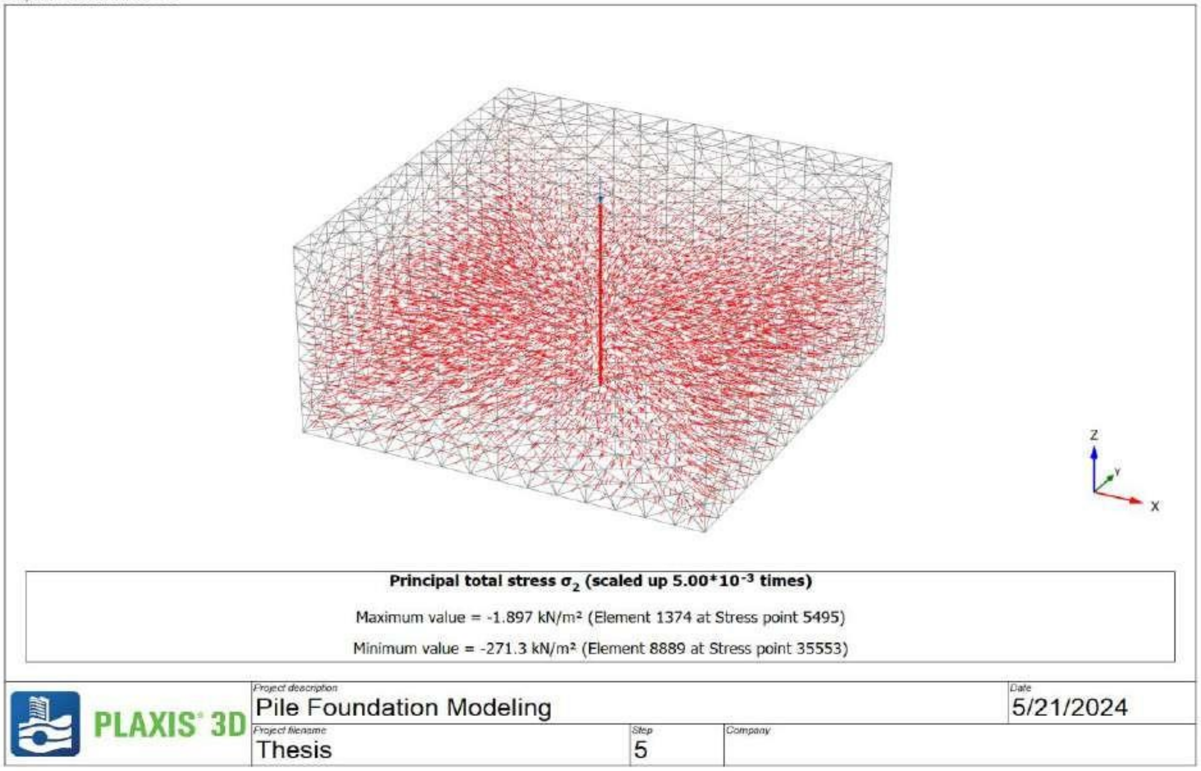
PLAXIS® 3D

Project description			Date
Pile Foundation Modeling			5/21/2024
Project filename	Step	Company	
Thesis	5		

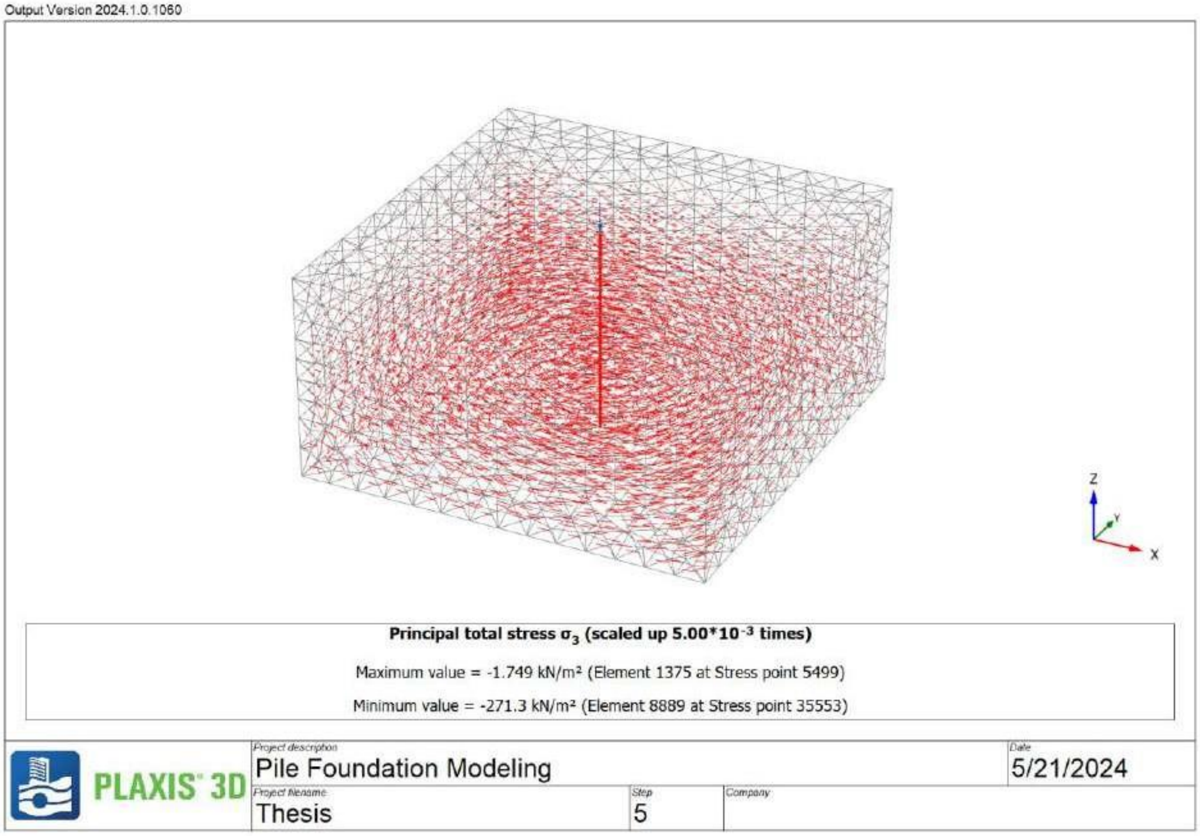

Output Version 2024.1.0.1060
Total principal stresses (scaled up 5.00*10^-3 times)
Maximum value = -1.749 kN/m² (Element 1375 at Stress point 5499)
Minimum value = -337.1 kN/m² (Element 8889 at Stress point 35553)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company


Output Version 2024.1.0.1060
Principal total stress σ1 (scaled up 5.00*10^-3 times)
Maximum value = -2.278 kN/m² (Element 1375 at Stress point 5499)
Minimum value = -337.1 kN/m² (Element 8889 at Stress point 35553)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company

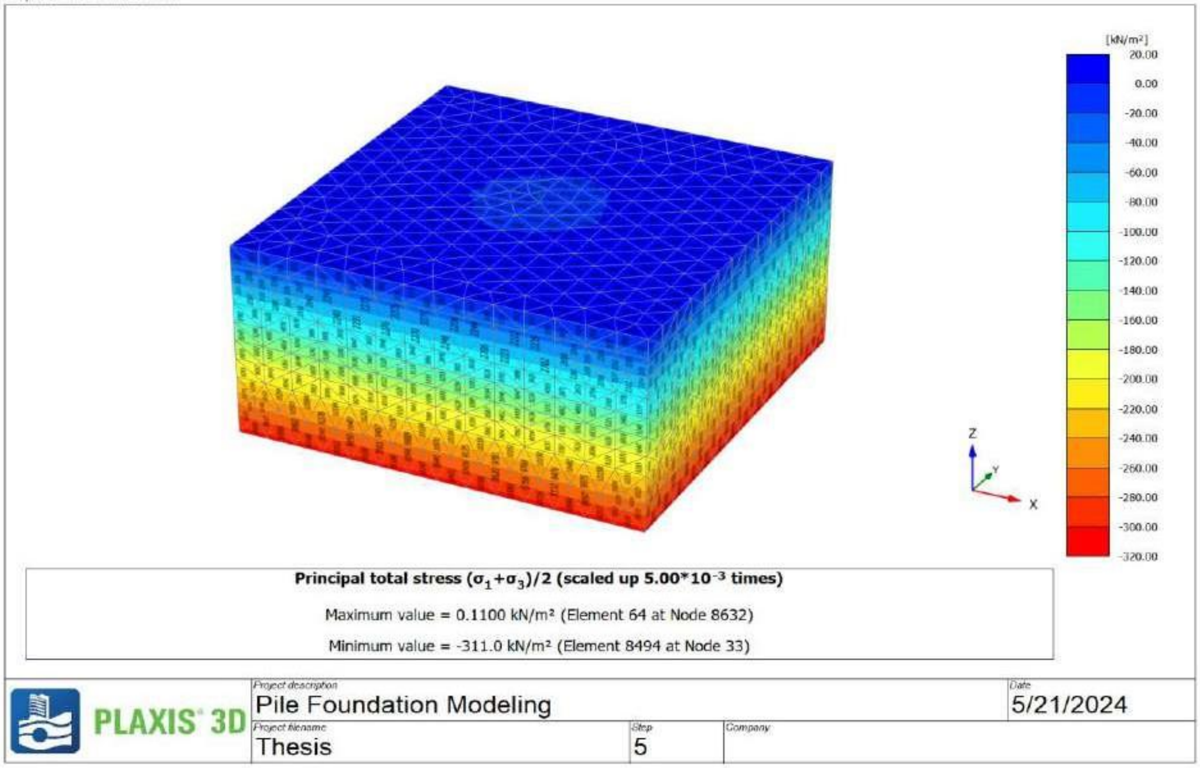
Output Version 2024.1.0.1060



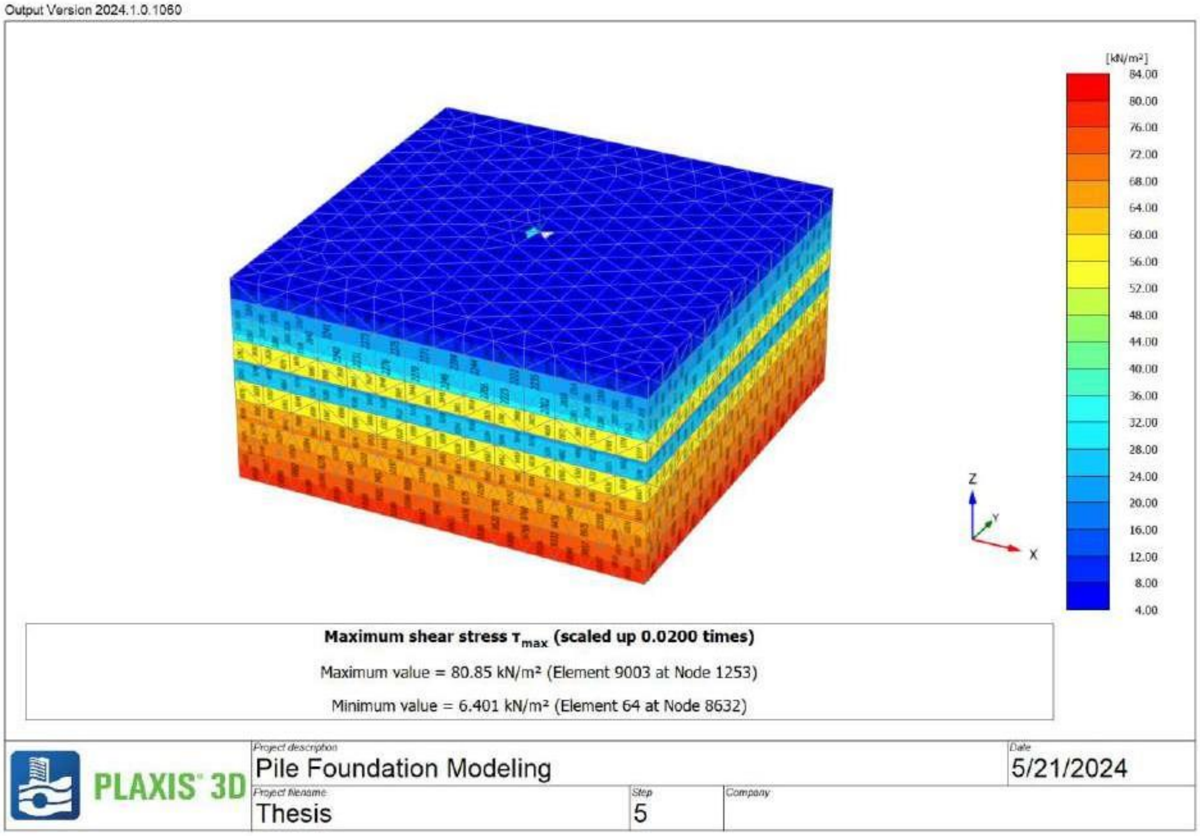
Output Version 2024.1.0.1060

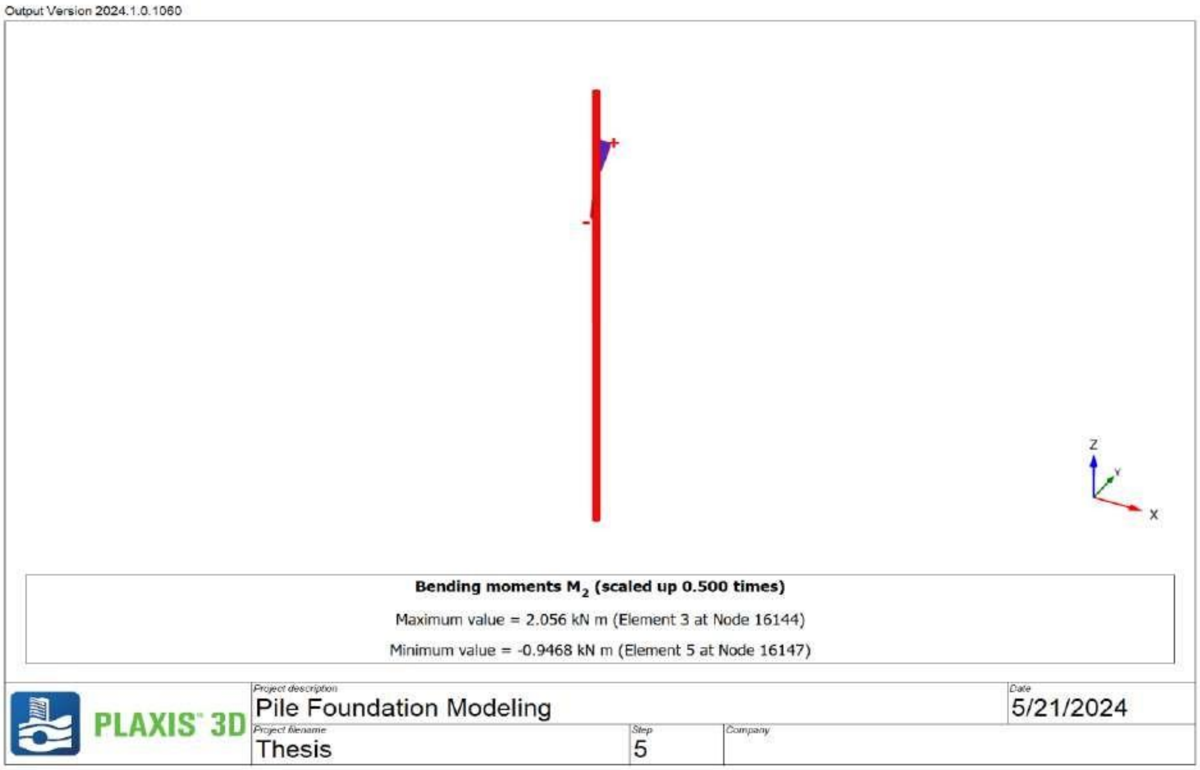


Output Version 2024.1.0.1060

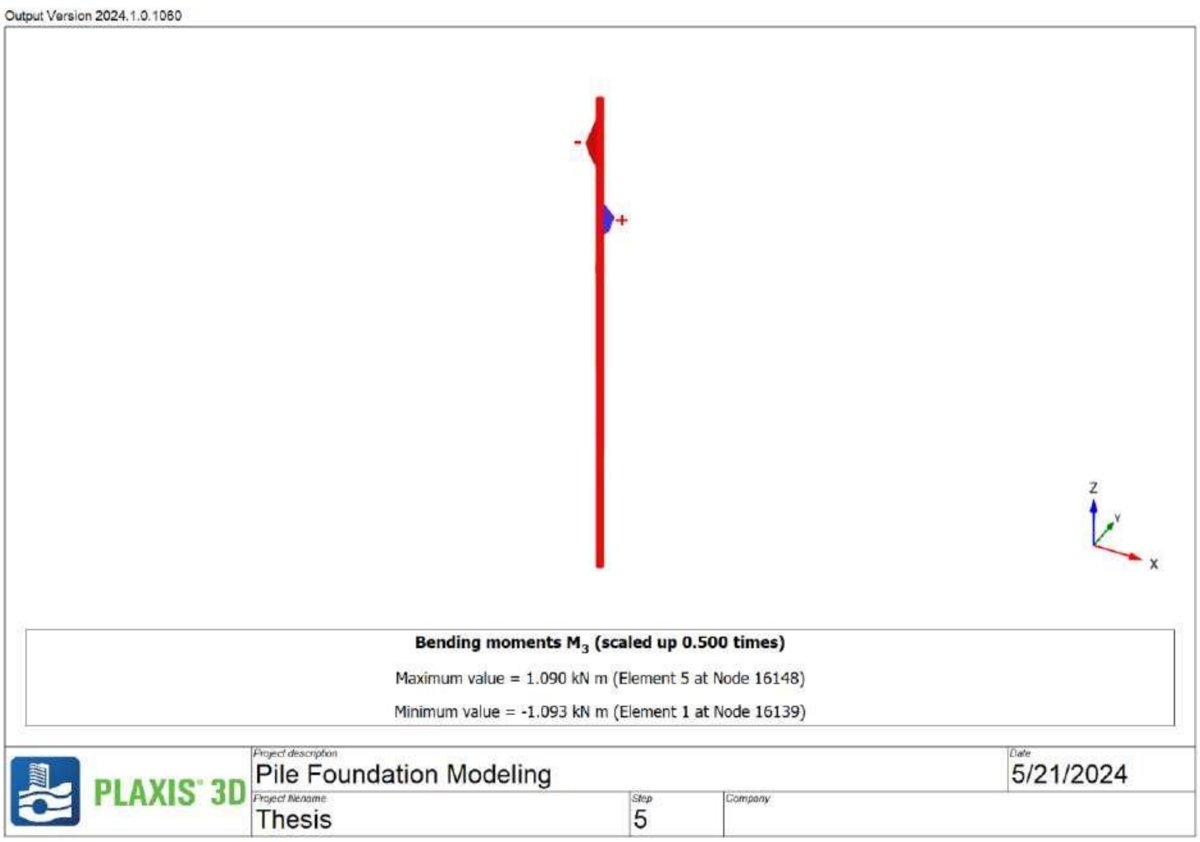


Output Version 2024.1.0.1060

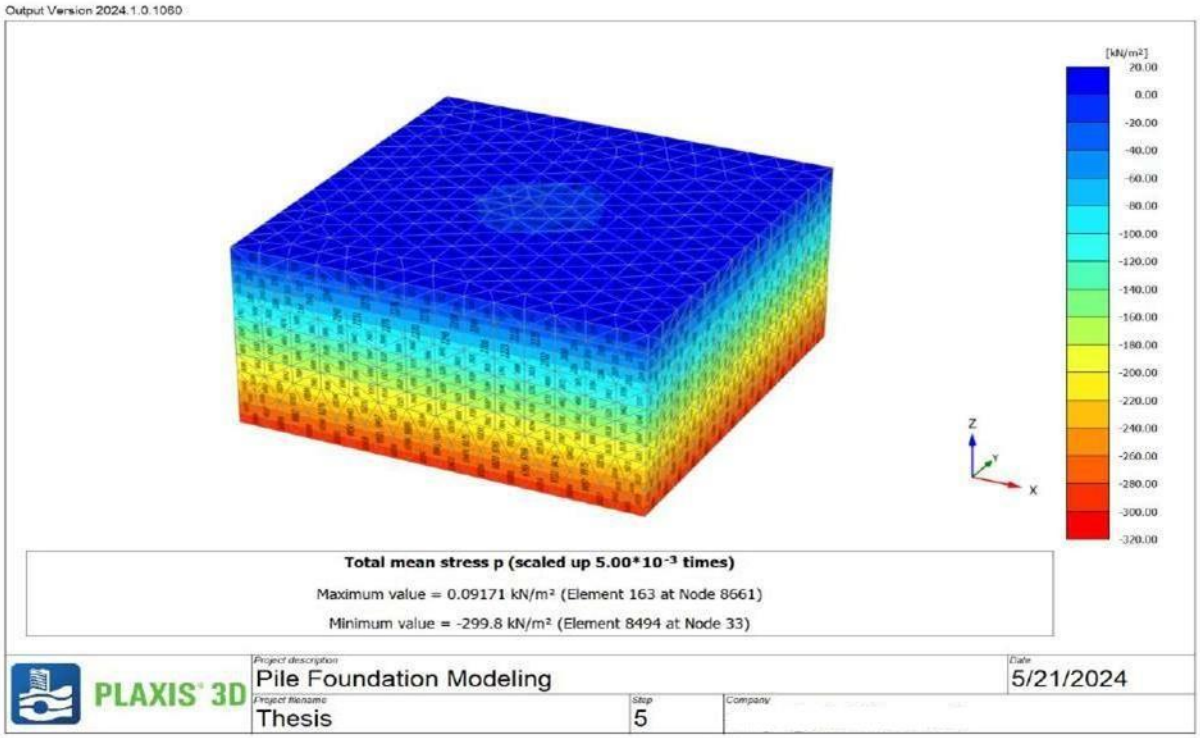




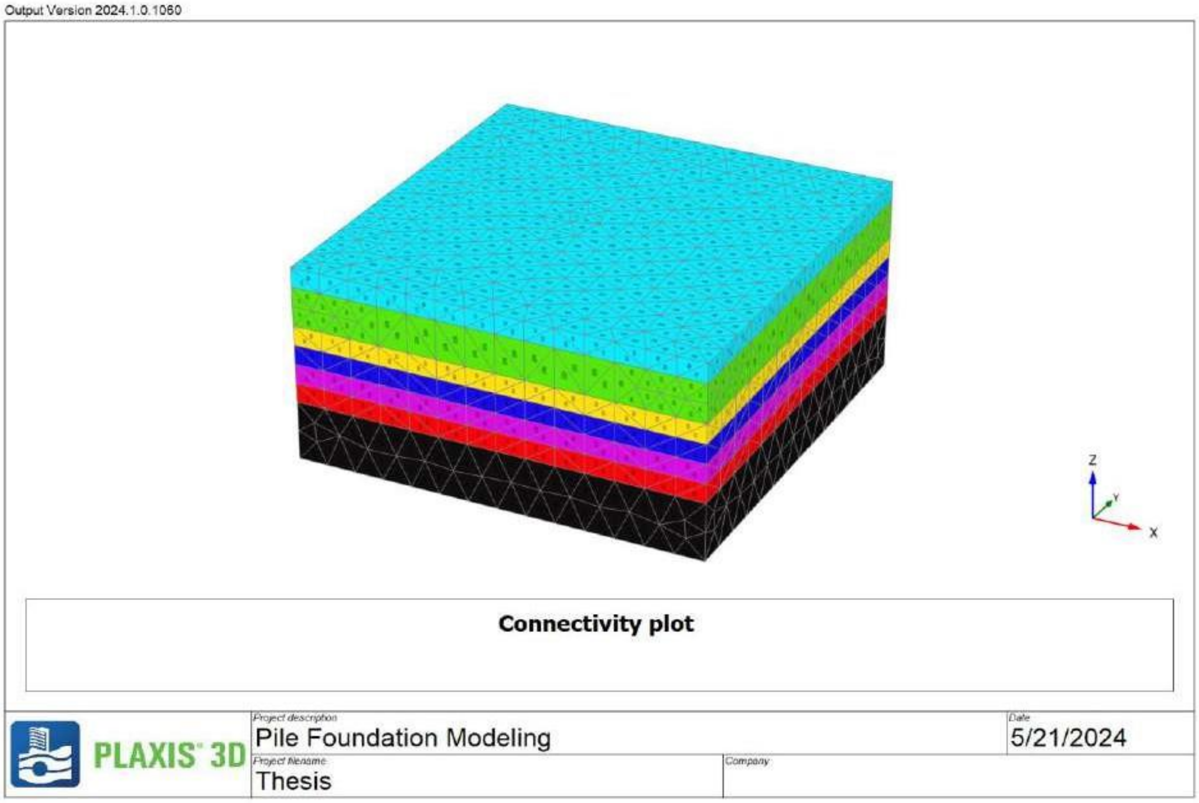
Output Version 2024.1.0.1060
Bending moments M_2 (scaled up 0.500 times)
Maximum value = 2.056 kN m (Element 3 at Node 16144)
Minimum value = -0.9468 kN m (Element 5 at Node 16147)
PLAXIS 3D
Project description
Pile Foundation Modeling
Project filename
Thesis
Step
5
Company
Date
5/21/2024

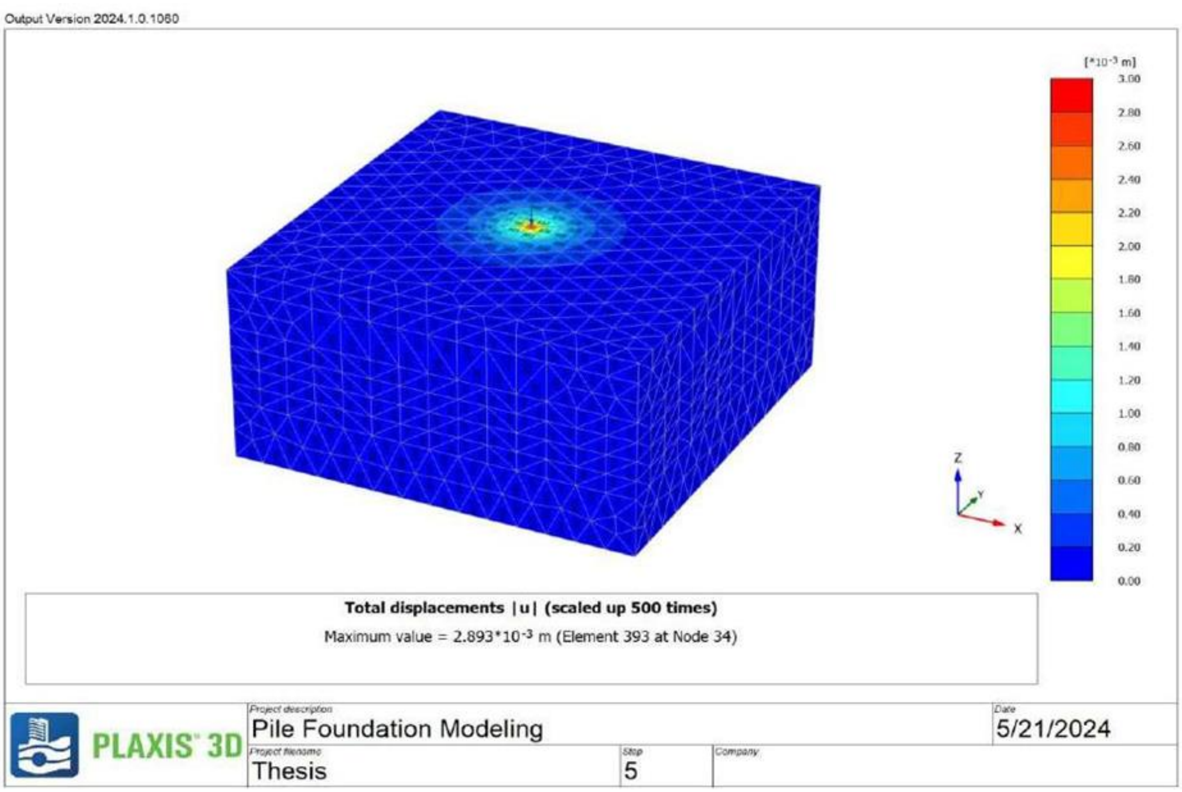


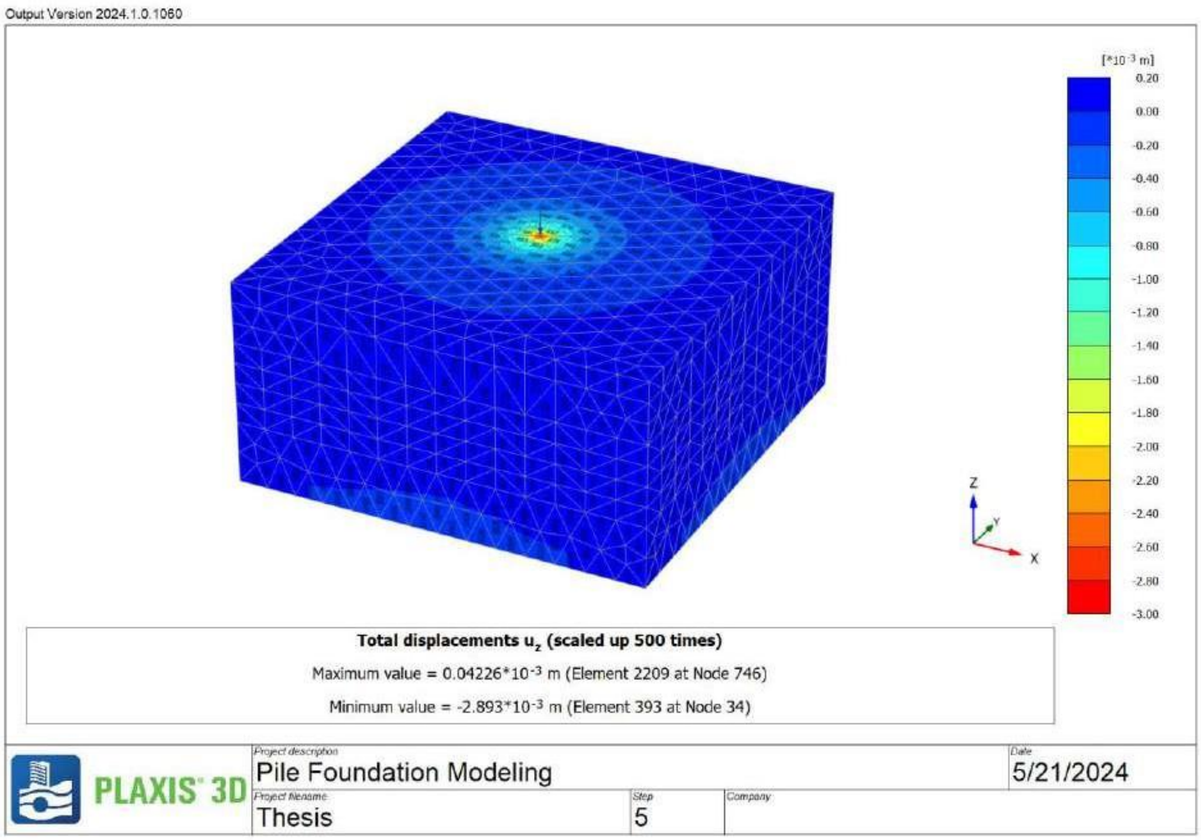
Output Version 2024.1.0.1060
Bending moments M_3 (scaled up 0.500 times)
Maximum value = 1.090 kN m (Element 5 at Node 16148)
Minimum value = -1.093 kN m (Element 1 at Node 16139)
PLAXIS 3D
Project description
Pile Foundation Modeling
Project filename
Thesis
Step
5
Company
Date
5/21/2024

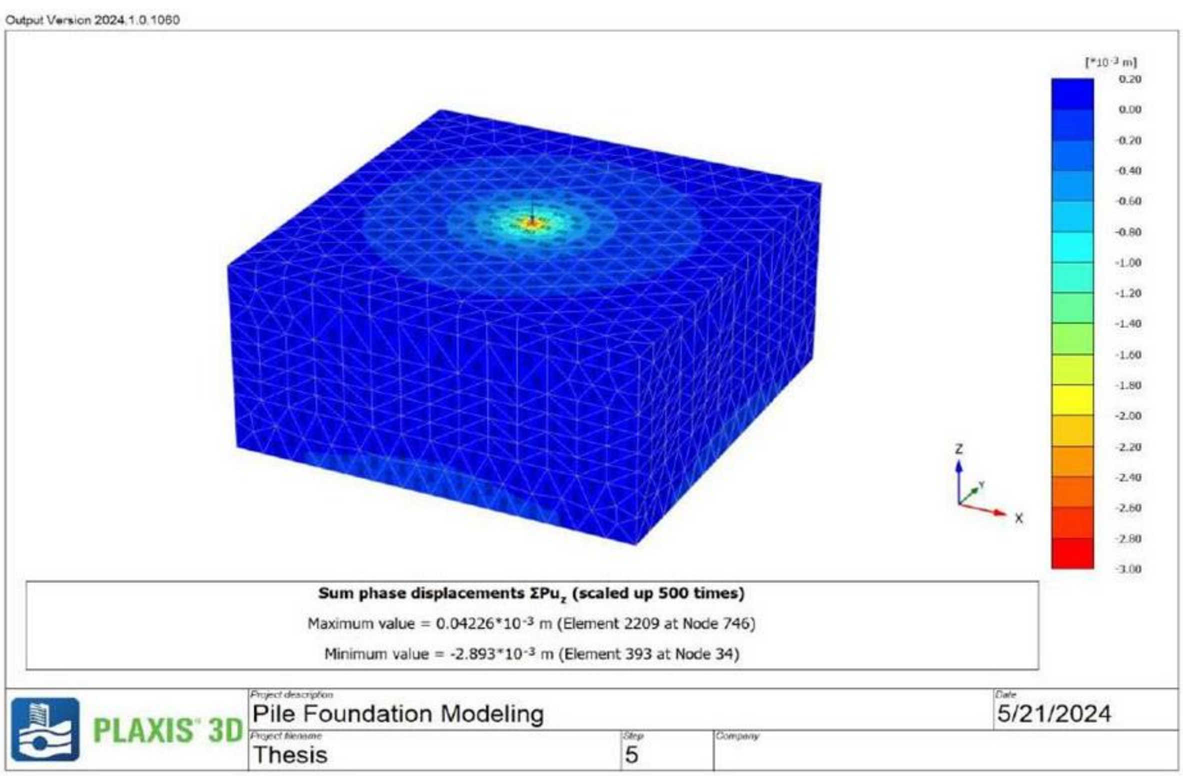

Output Version 2024.1.0.1060
[kN/m²]
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
Total mean stress p (scaled up 5.00*10⁻³ times)
Maximum value = 0.09171 kN/m² (Element 163 at Node 8661)
Minimum value = -299.8 kN/m² (Element 8494 at Node 33)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company

APPENDEX – B

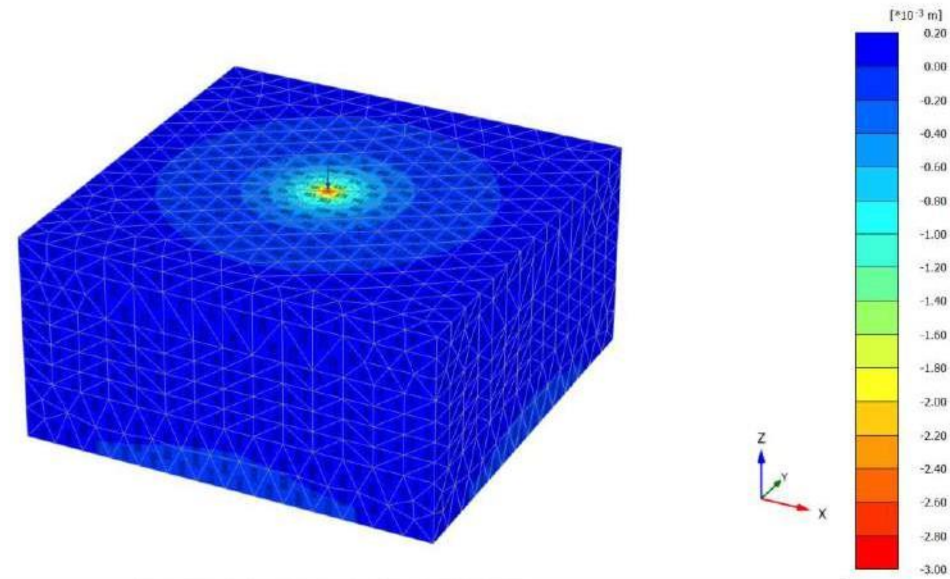

Output Version 2024.1.0.1060
Z
Y
X
Connectivity plot
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Company


Output Version 2024.1.0.1060
[*10^-3 m]
3.00
2.80
2.60
2.40
2.20
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Z
Y
X
Total displacements |u| (scaled up 500 times)
Maximum value = 2.893*10^-3 m (Element 393 at Node 34)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company


Output Version 2024.1.0.1060
[*10^-3 m]
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
-1.40
-1.60
-1.80
-2.00
-2.20
-2.40
-2.60
-2.80
-3.00
Z
Y
X
Total displacements u_z (scaled up 500 times)
Maximum value = 0.04226*10^-3 m (Element 2209 at Node 746)
Minimum value = -2.893*10^-3 m (Element 393 at Node 34)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company


Output Version 2024.1.0.1060
[*10^-3 m]
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
-1.40
-1.60
-1.80
-2.00
-2.20
-2.40
-2.60
-2.80
-3.00
Z
Y
X
Sum phase displacements ΣPu_z (scaled up 500 times)
Maximum value = 0.04226*10^-3 m (Element 2209 at Node 746)
Minimum value = -2.893*10^-3 m (Element 393 at Node 34)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company

Output Version 2024.1.0.1060



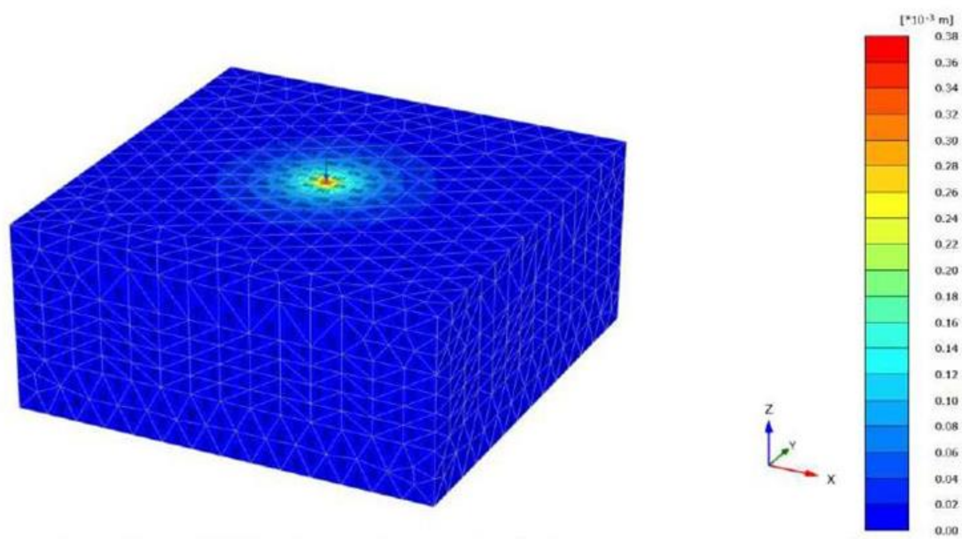
Phase displacements Pu_z (scaled up 500 times)

Maximum value = $0.04226*10^{-3}$ m (Element 2209 at Node 746)

Minimum value = $-2.893*10^{-3}$ m (Element 393 at Node 34)

PLAXIS 3D	Project description: Pile Foundation Modeling		Date: 5/21/2024
	Project filename: Thesis	Step: 5	Company:

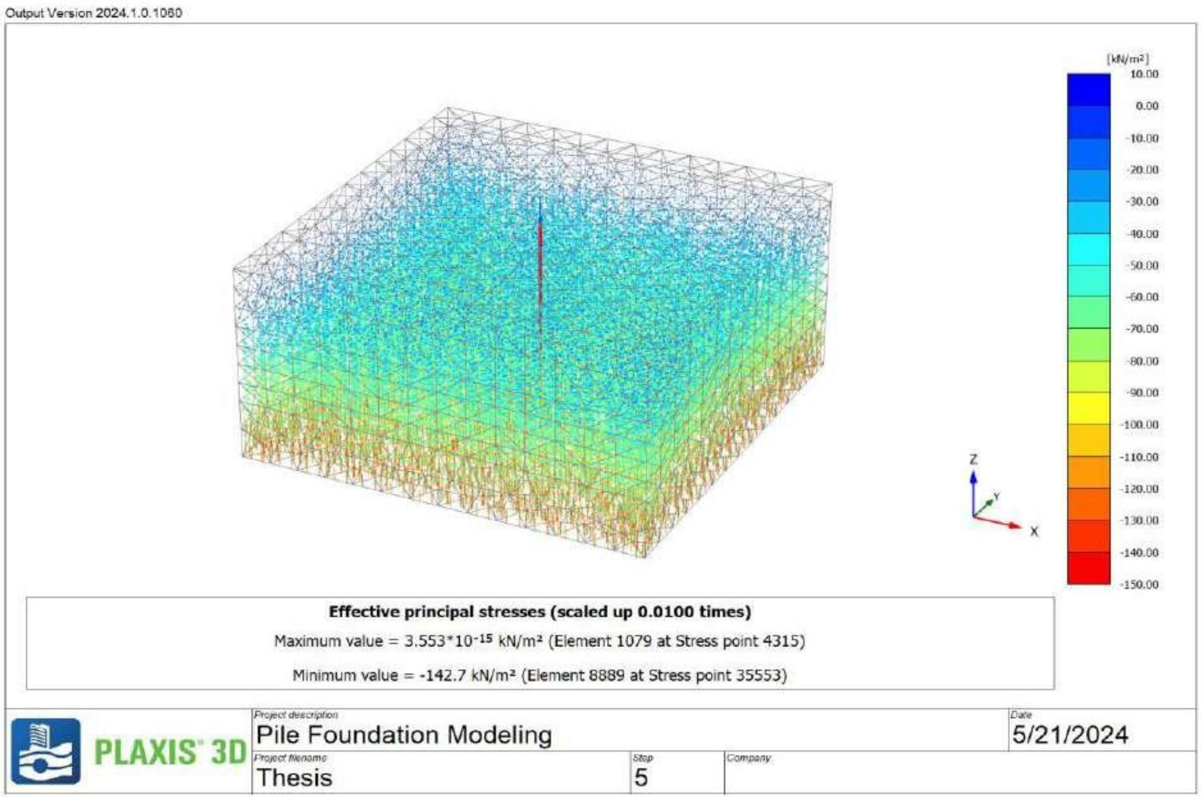
Output Version 2024.1.0.1060

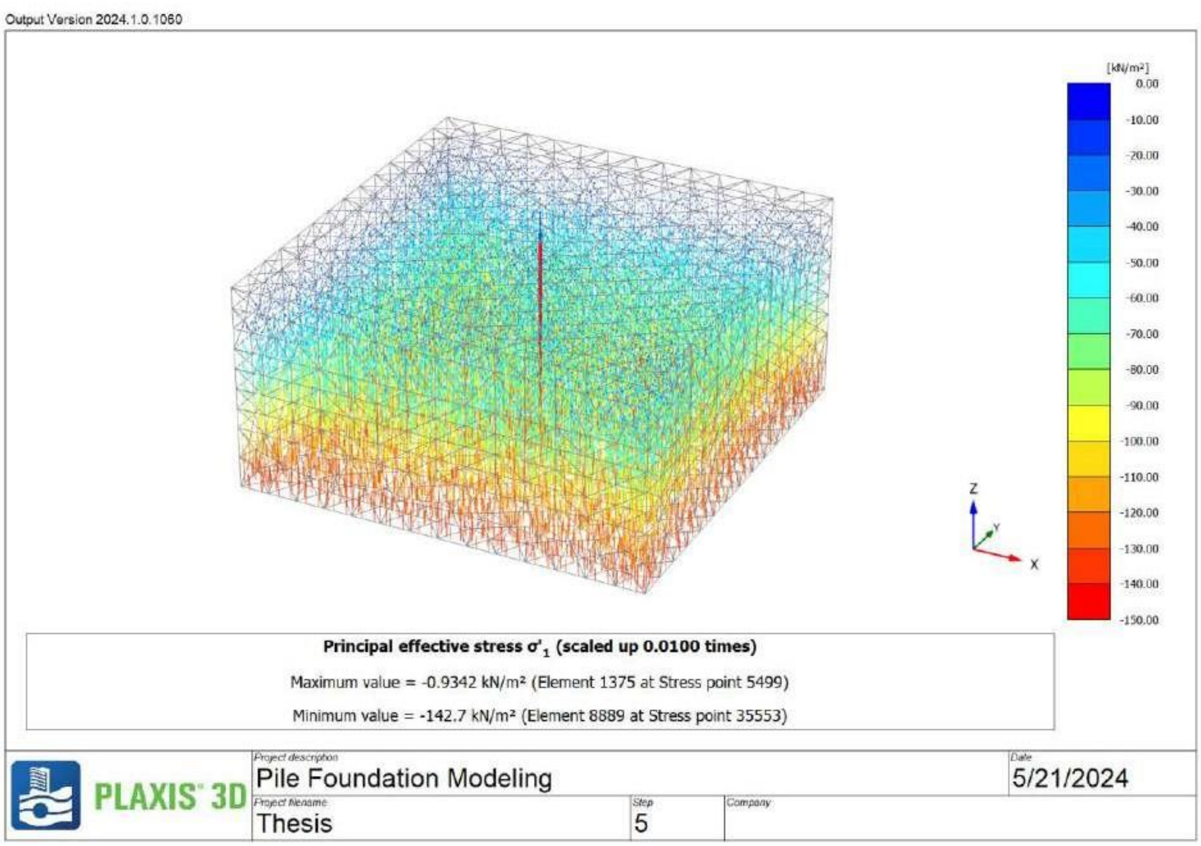


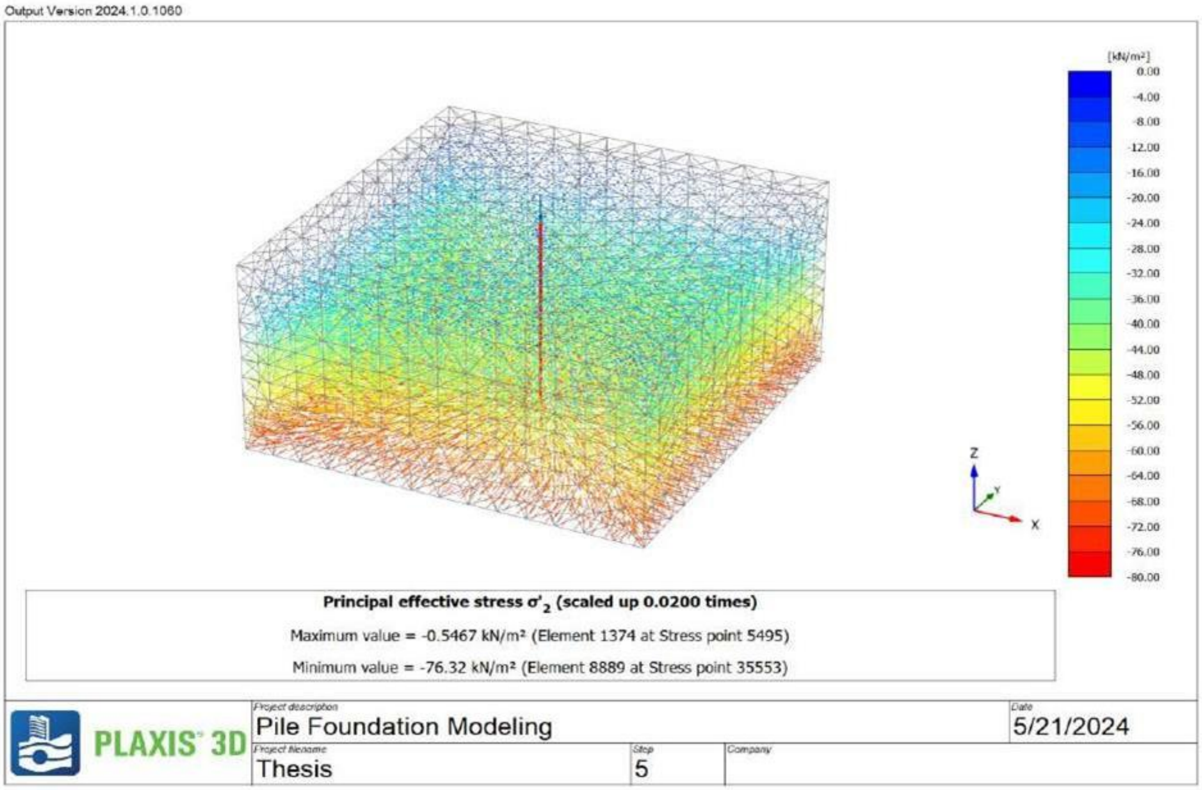
Incremental displacements $|\Delta u|$ (scaled up $5.00*10^3$ times)

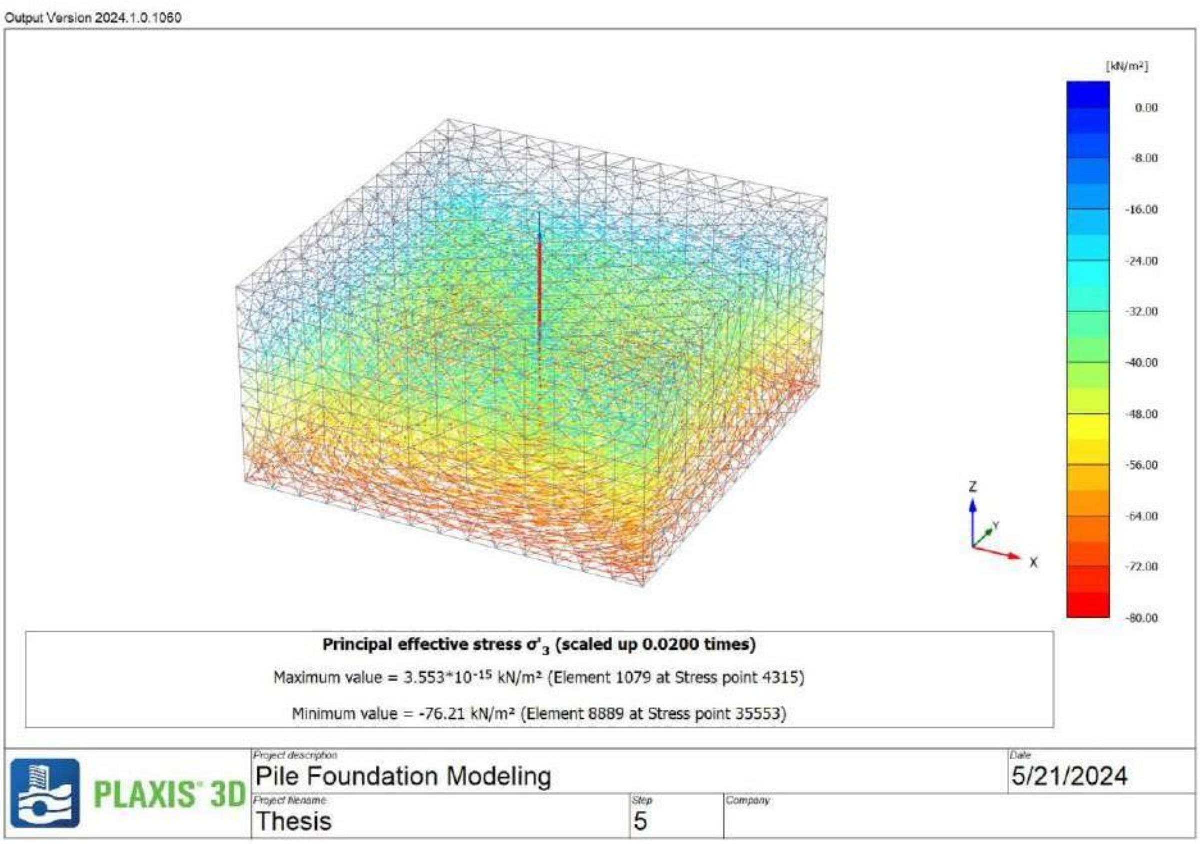
Maximum value = $0.3793*10^{-3}$ m (Element 393 at Node 34)

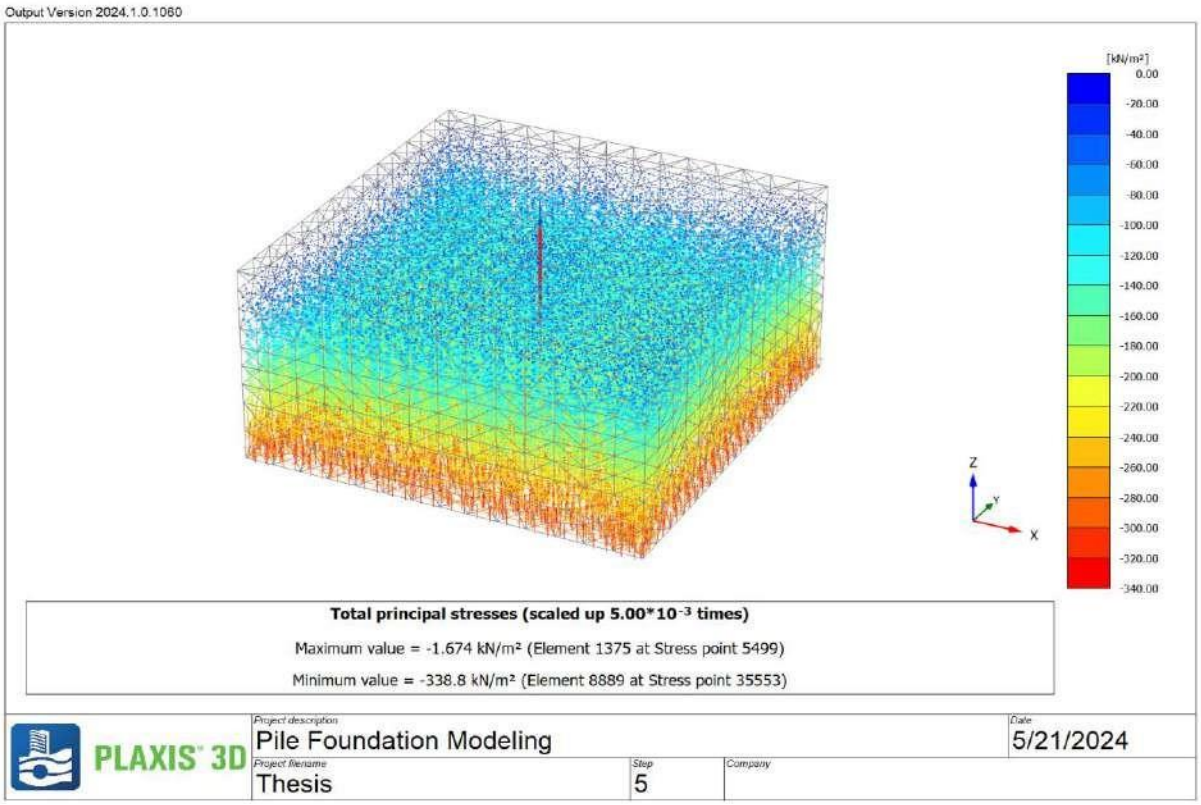
PLAXIS 3D	Project description: Pile Foundation Modeling		Date: 5/21/2024
	Project filename: Thesis	Step: 5	Company:

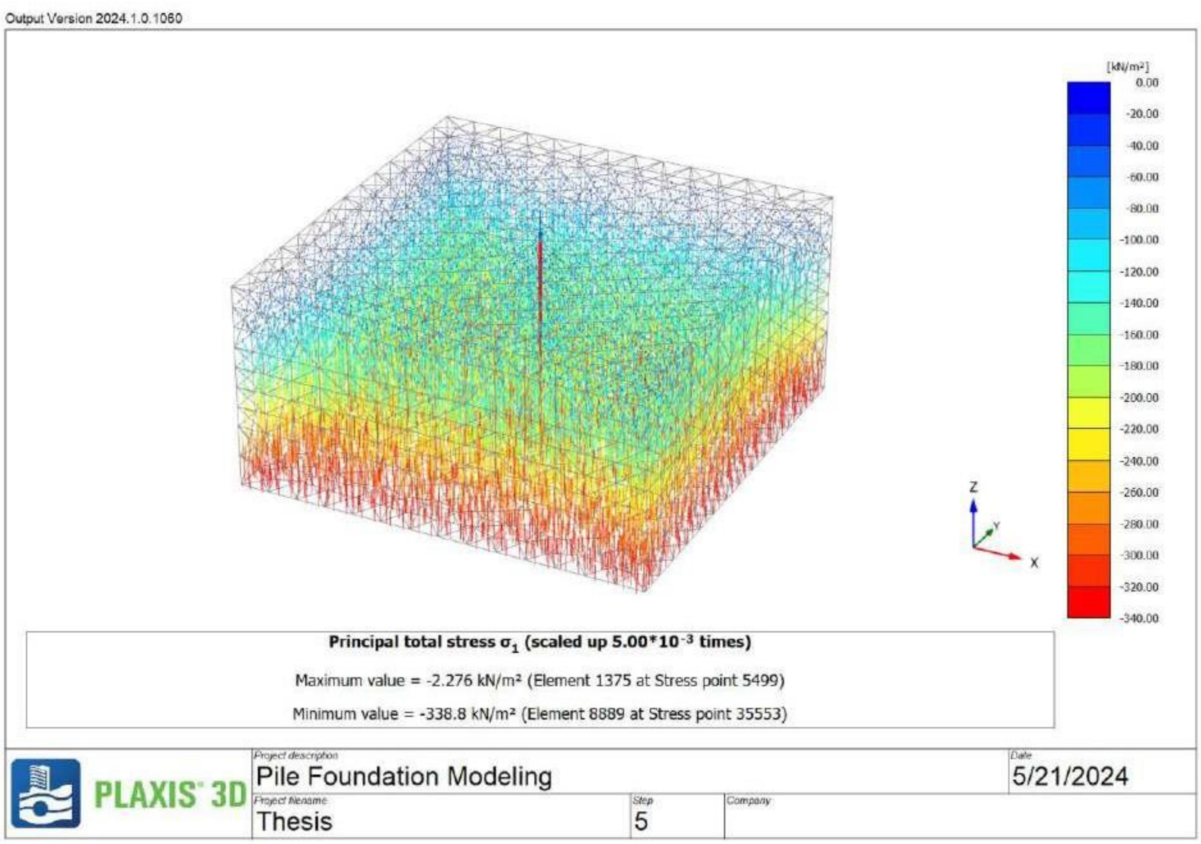

Output Version 2024.1.0.1060
[kN/m²]
10.00
0.00
-10.00
-20.00
-30.00
-40.00
-50.00
-60.00
-70.00
-80.00
-90.00
-100.00
-110.00
-120.00
-130.00
-140.00
-150.00
Z
Y
X
Effective principal stresses (scaled up 0.0100 times)
Maximum value = 3.553*10^-15 kN/m² (Element 1079 at Stress point 4315)
Minimum value = -142.7 kN/m² (Element 8889 at Stress point 35553)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company

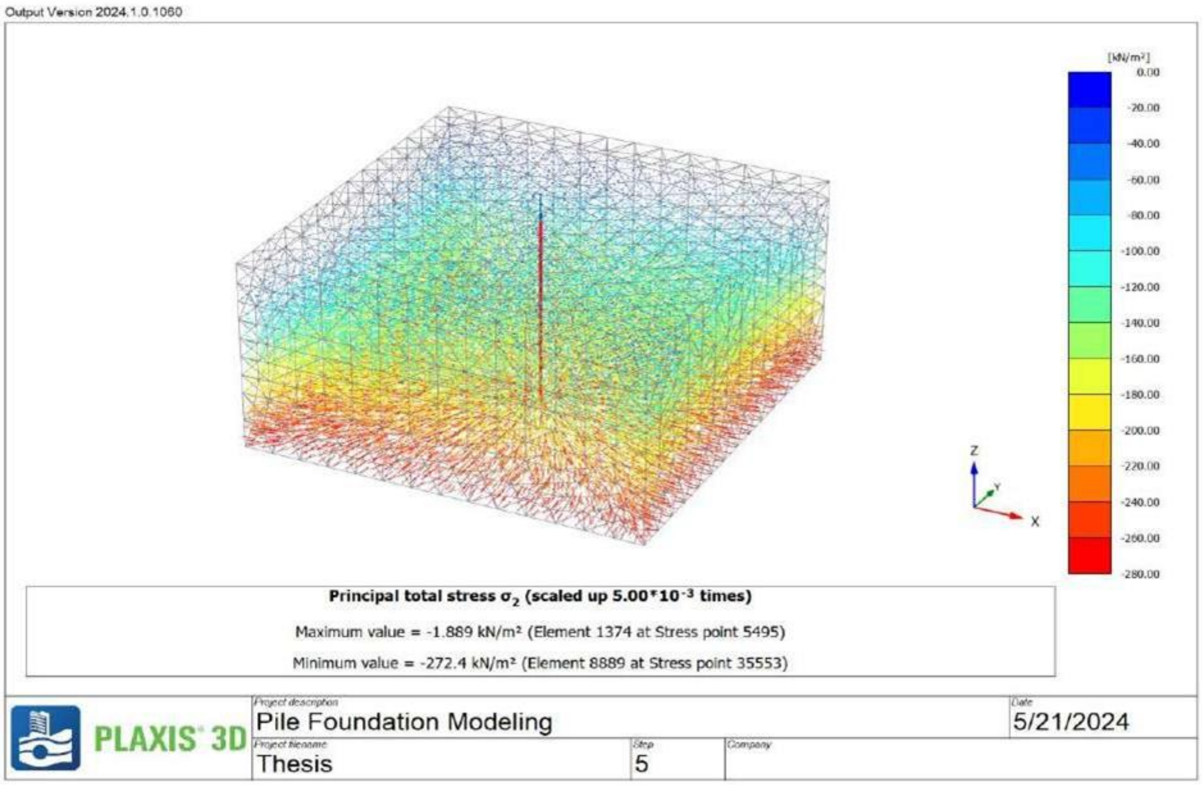

Output Version 2024.1.0.1060
[kN/m²]
0.00
-10.00
-20.00
-30.00
-40.00
-50.00
-60.00
-70.00
-80.00
-90.00
-100.00
-110.00
-120.00
-130.00
-140.00
-150.00
Z
Y
X
Principal effective stress σ'1 (scaled up 0.0100 times)
Maximum value = -0.9342 kN/m² (Element 1375 at Stress point 5499)
Minimum value = -142.7 kN/m² (Element 8889 at Stress point 35553)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company

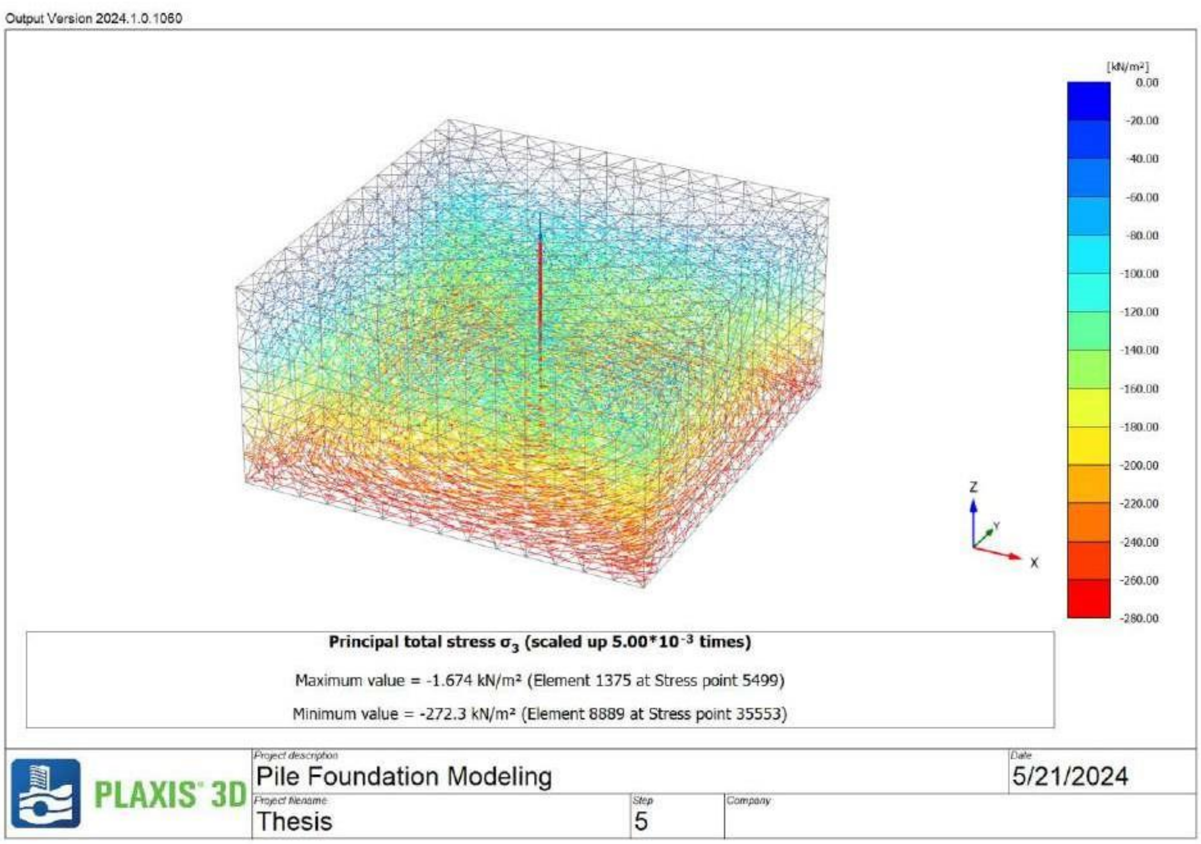

Output Version 2024.1.0.1060
[kN/m²]
0.00
-4.00
-8.00
-12.00
-16.00
-20.00
-24.00
-28.00
-32.00
-36.00
-40.00
-44.00
-48.00
-52.00
-56.00
-60.00
-64.00
-68.00
-72.00
-76.00
-80.00
Z
Y
X
Principal effective stress σ'2 (scaled up 0.0200 times)
Maximum value = -0.5467 kN/m² (Element 1374 at Stress point 5495)
Minimum value = -76.32 kN/m² (Element 8889 at Stress point 35553)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company

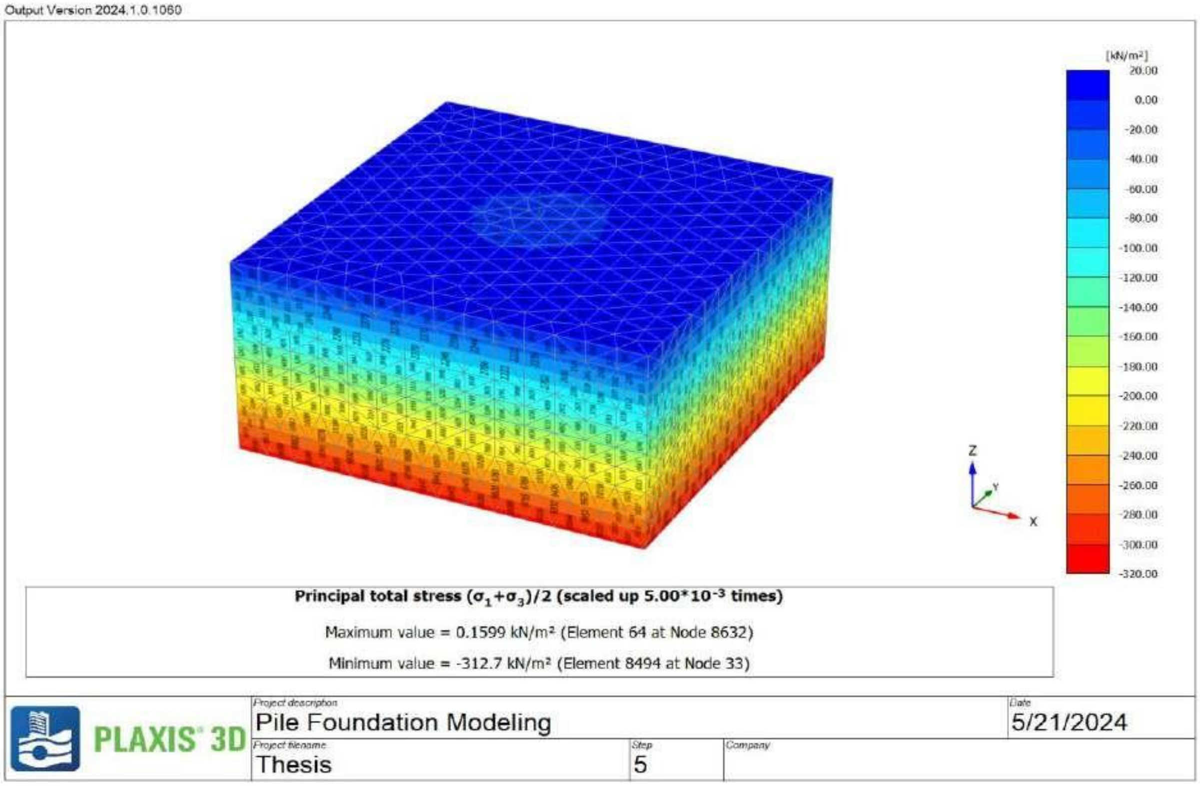

Output Version 2024.1.0.1060
[kN/m²]
0.00
-8.00
-16.00
-24.00
-32.00
-40.00
-48.00
-56.00
-64.00
-72.00
-80.00
Z
Y
X
Principal effective stress σ'3 (scaled up 0.0200 times)
Maximum value = 3.553*10-15 kN/m² (Element 1079 at Stress point 4315)
Minimum value = -76.21 kN/m² (Element 8889 at Stress point 35553)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company

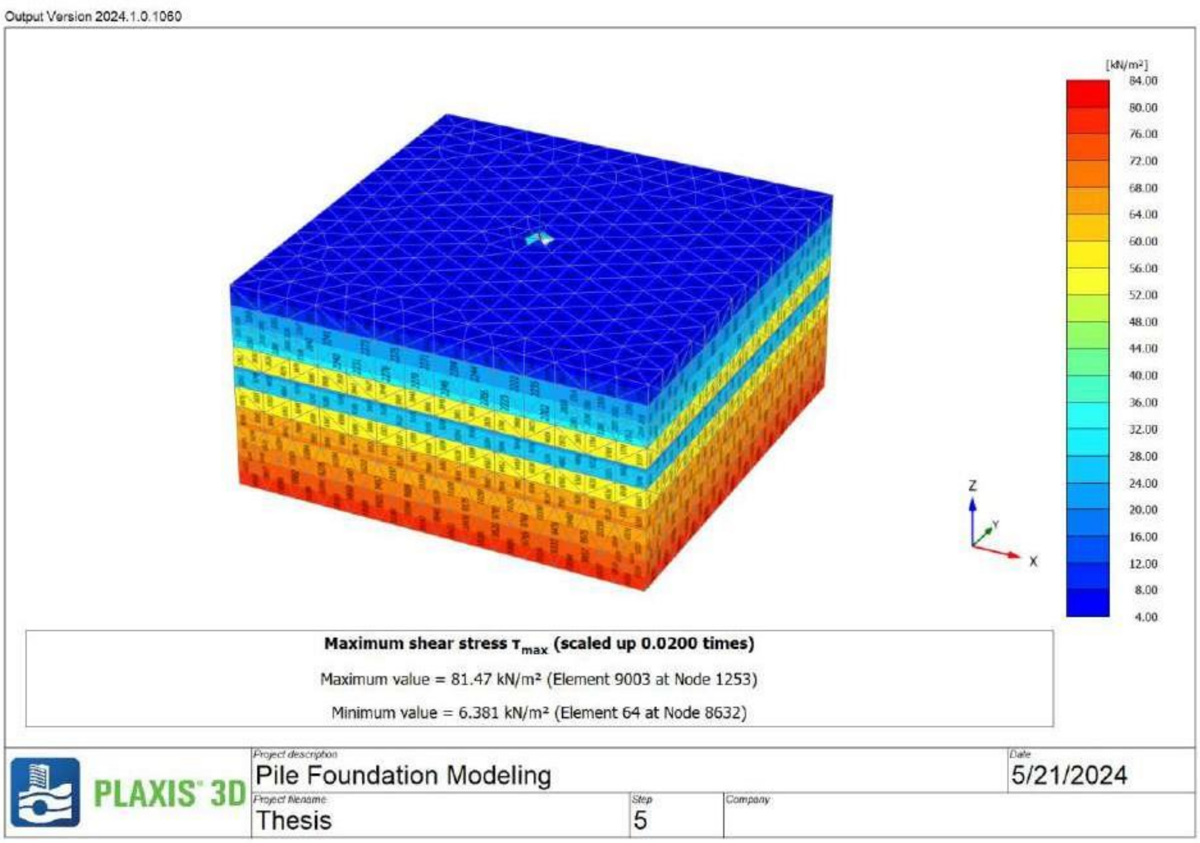

Output Version 2024.1.0.1060
[kN/m²]
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
Z
Y
X
Total principal stresses (scaled up 5.00*10^-3 times)
Maximum value = -1.674 kN/m² (Element 1375 at Stress point 5499)
Minimum value = -338.8 kN/m² (Element 8889 at Stress point 35553)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company

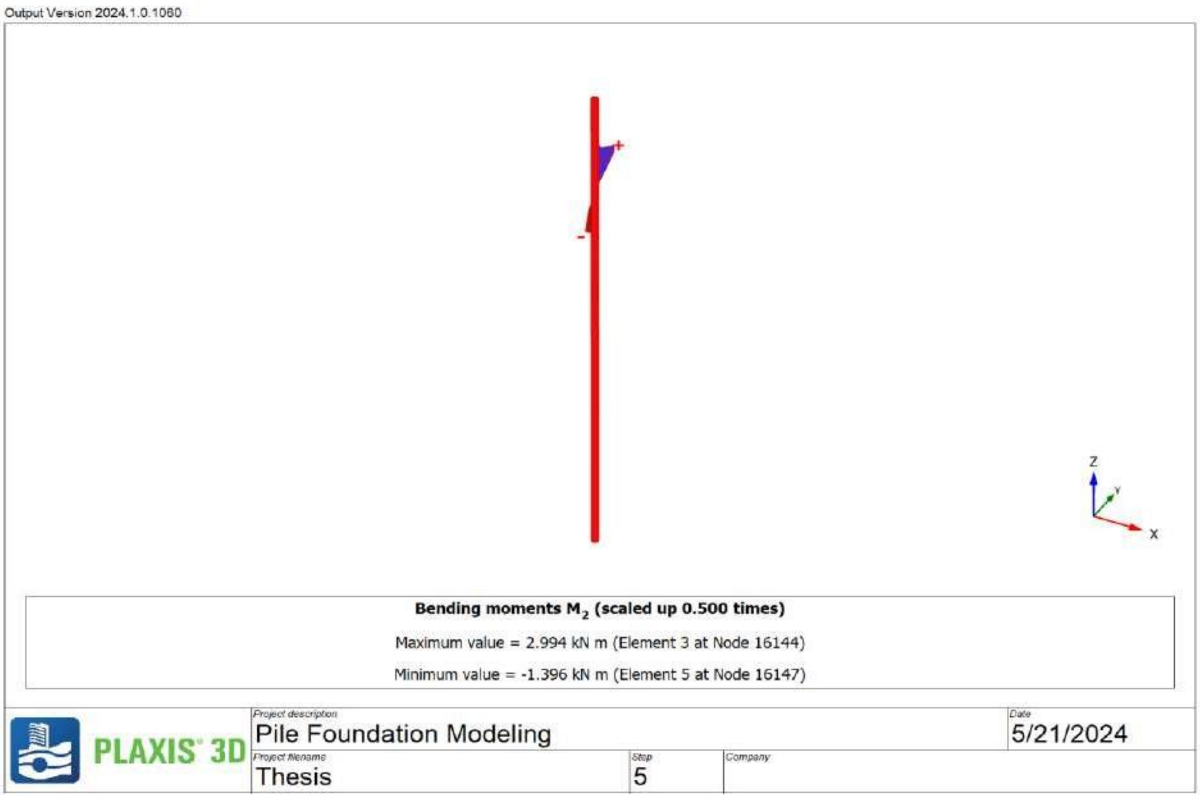

Output Version 2024.1.0.1060
[kN/m²]
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
Z
Y
X
Principal total stress σ1 (scaled up 5.00*10^-3 times)
Maximum value = -2.276 kN/m² (Element 1375 at Stress point 5499)
Minimum value = -338.8 kN/m² (Element 8889 at Stress point 35553)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company

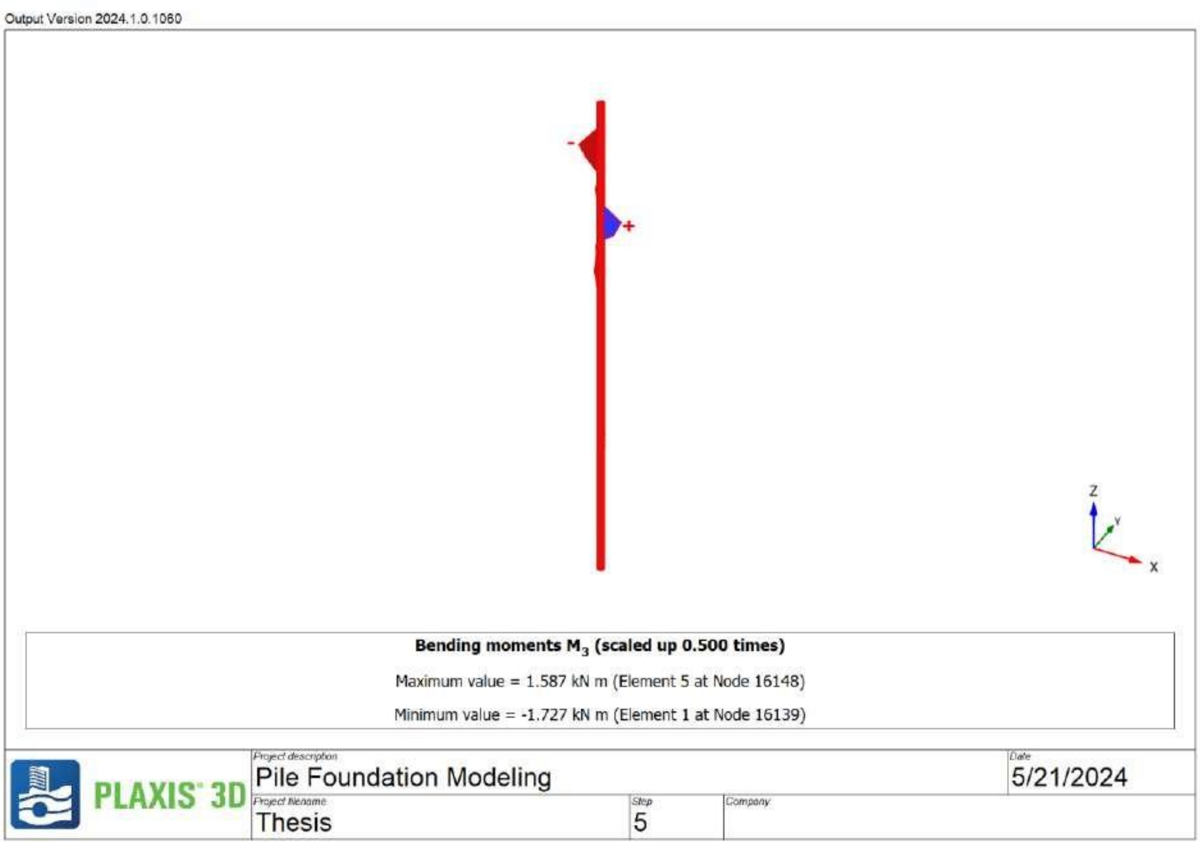

Output Version 2024.1.0.1060
[kN/m²]
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
Z
Y
X
Principal total stress σ_2 (scaled up $5.00*10^{-3}$ times)
Maximum value = -1.889 kN/m² (Element 1374 at Stress point 5495)
Minimum value = -272.4 kN/m² (Element 8889 at Stress point 35553)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company

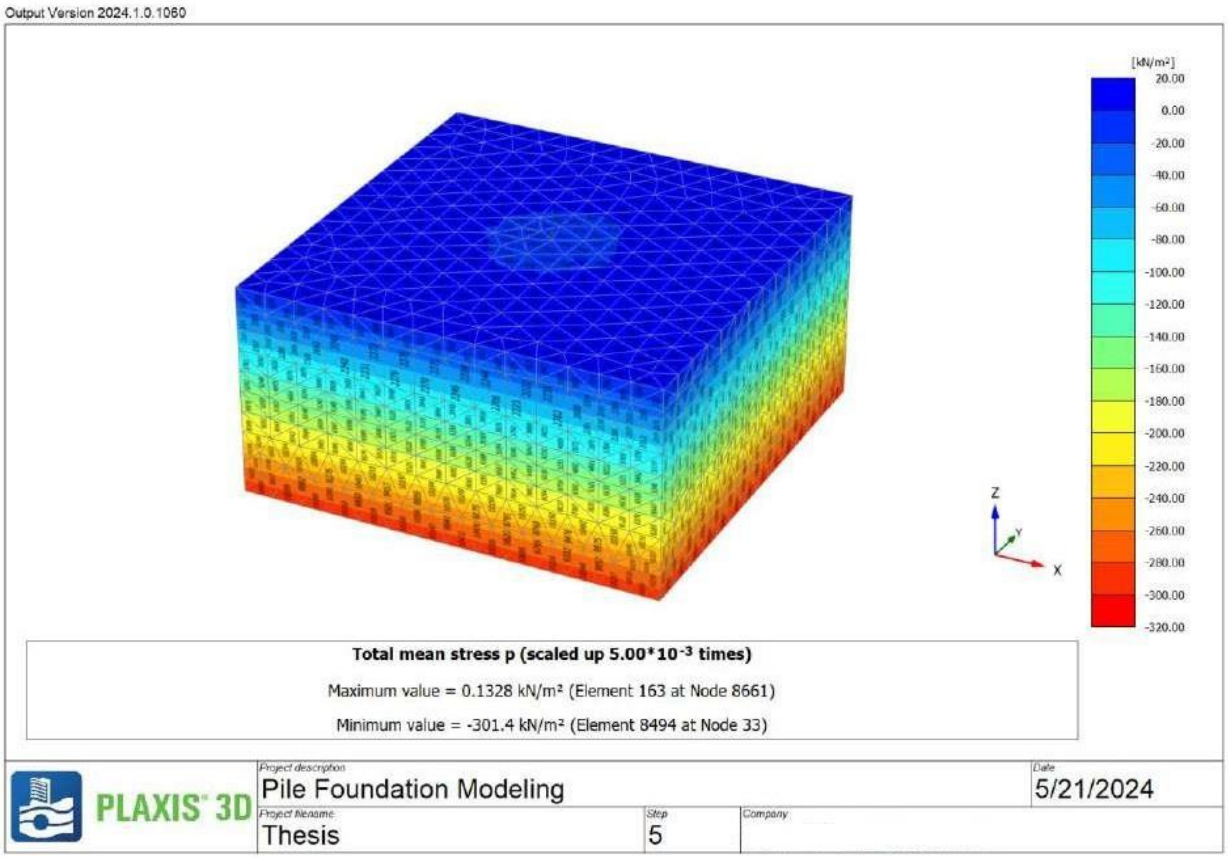

Output Version 2024.1.0.1060
[kN/m²]
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
Z
Y
X
Principal total stress σ_3 (scaled up $5.00*10^{-3}$ times)
Maximum value = -1.674 kN/m² (Element 1375 at Stress point 5499)
Minimum value = -272.3 kN/m² (Element 8889 at Stress point 35553)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company


Output Version 2024.1.0.1060
[kN/m²]
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
Principal total stress (σ1+σ3)/2 (scaled up 5.00*10-3 times)
Maximum value = 0.1599 kN/m² (Element 64 at Node 8632)
Minimum value = -312.7 kN/m² (Element 8494 at Node 33)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company

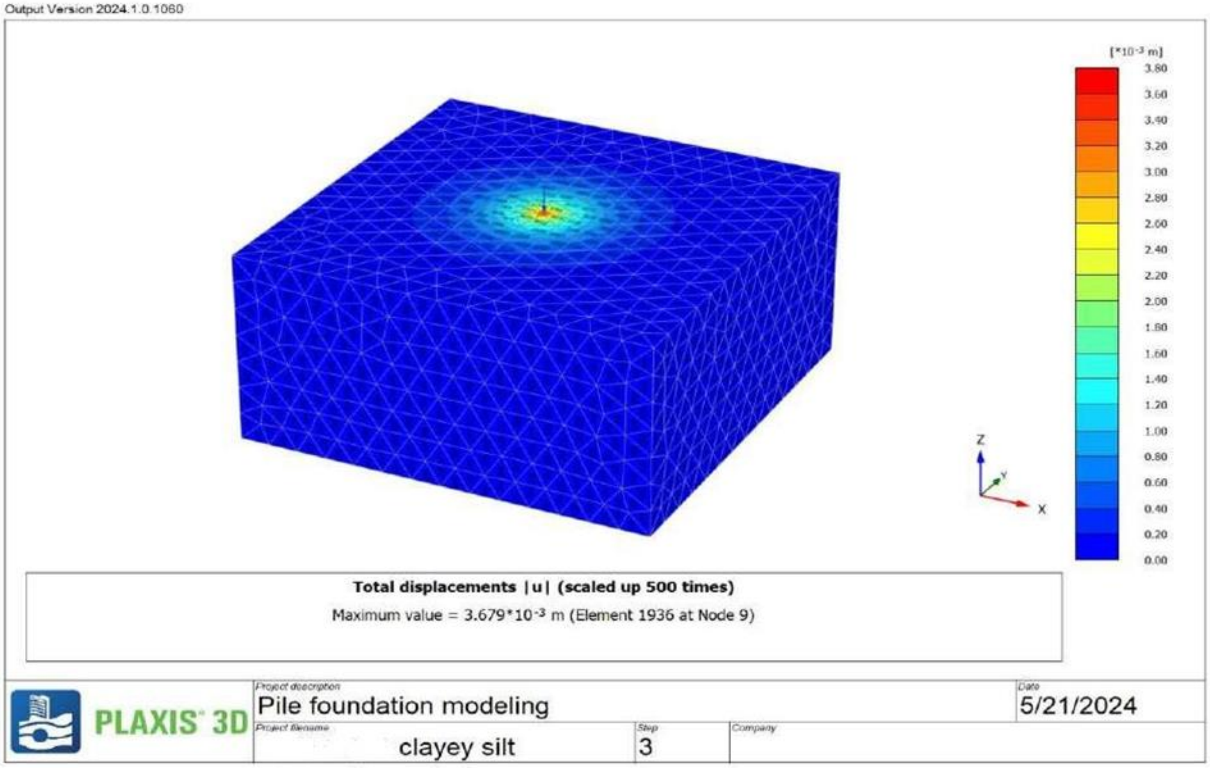

Output Version 2024.1.0.1060
[kN/m²]
84.00
80.00
76.00
72.00
68.00
64.00
60.00
56.00
52.00
48.00
44.00
40.00
36.00
32.00
28.00
24.00
20.00
16.00
12.00
8.00
4.00
Maximum shear stress τmax (scaled up 0.0200 times)
Maximum value = 81.47 kN/m² (Element 9003 at Node 1253)
Minimum value = 6.381 kN/m² (Element 64 at Node 8632)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company

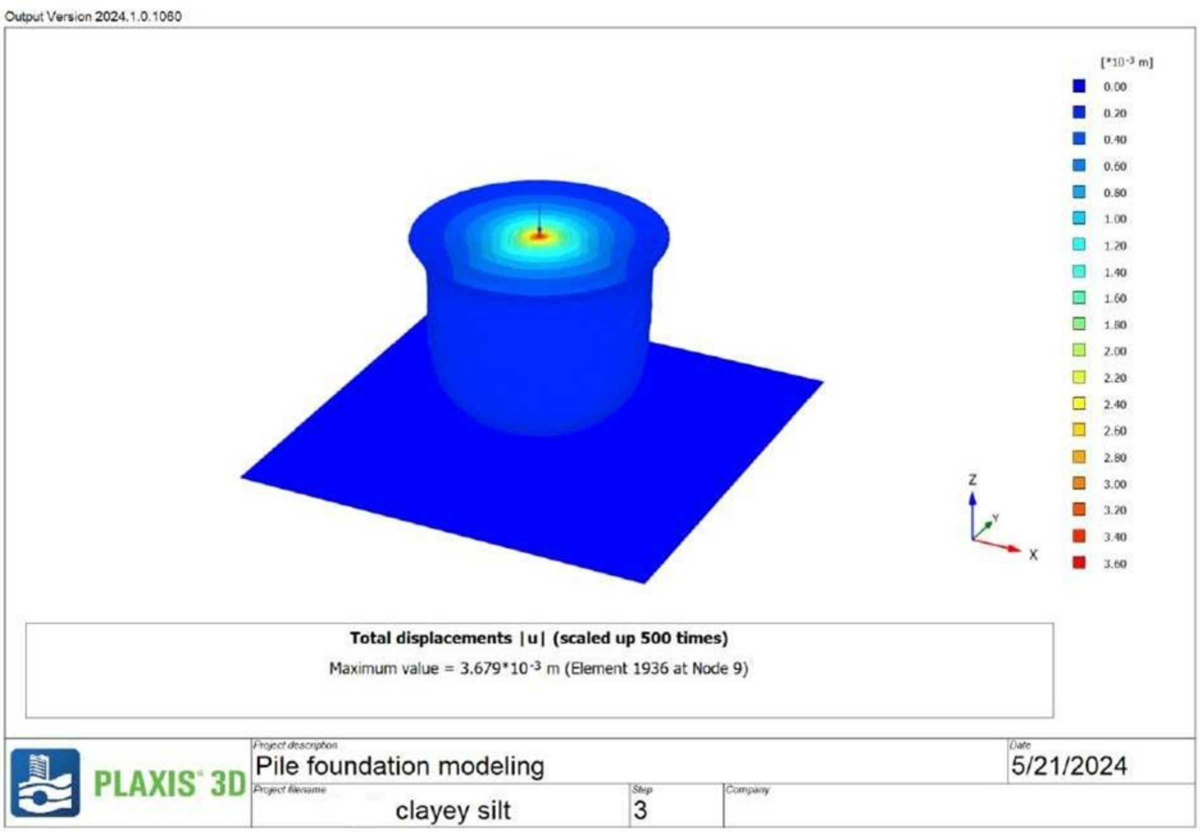

Output Version 2024.1.0.1060
z
y
x
Bending moments M_2 (scaled up 0.500 times)
Maximum value = 2.994 kN m (Element 3 at Node 16144)
Minimum value = -1.396 kN m (Element 5 at Node 16147)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company

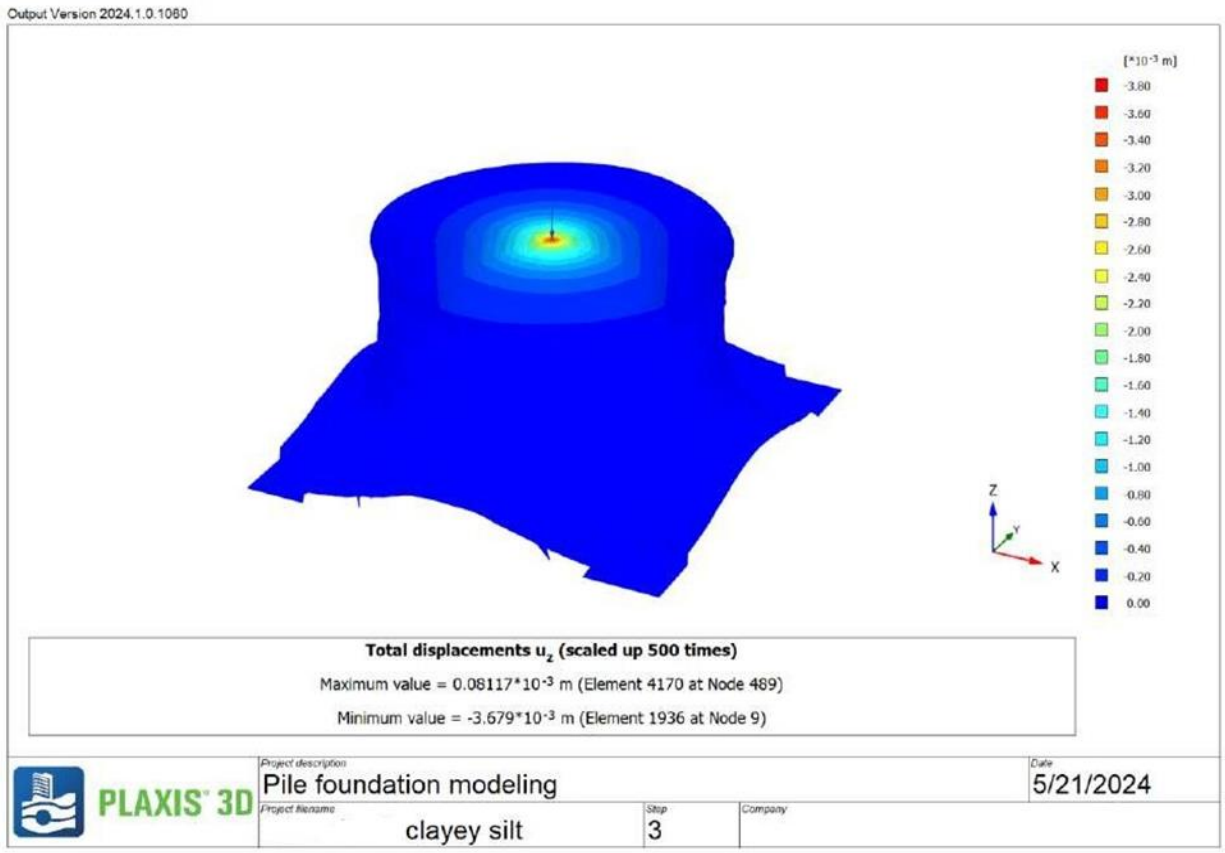

Output Version 2024.1.0.1060
z
y
x
Bending moments M_3 (scaled up 0.500 times)
Maximum value = 1.587 kN m (Element 5 at Node 16148)
Minimum value = -1.727 kN m (Element 1 at Node 16139)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company

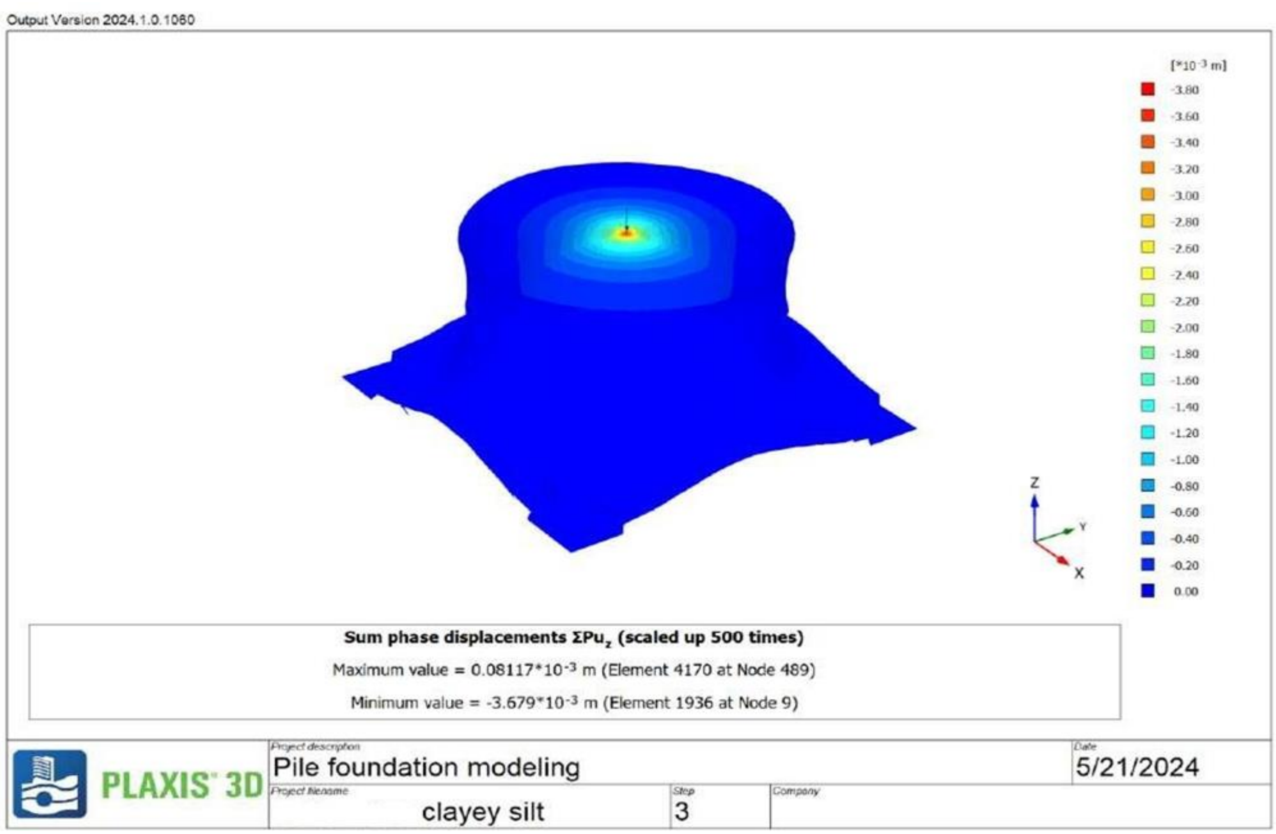

Output Version 2024.1.0.1060
[kN/m²]
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
Z
Y
X
Total mean stress p (scaled up 5.00*10^-3 times)
Maximum value = 0.1328 kN/m² (Element 163 at Node 8661)
Minimum value = -301.4 kN/m² (Element 8494 at Node 33)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
Thesis
Step
5
Company

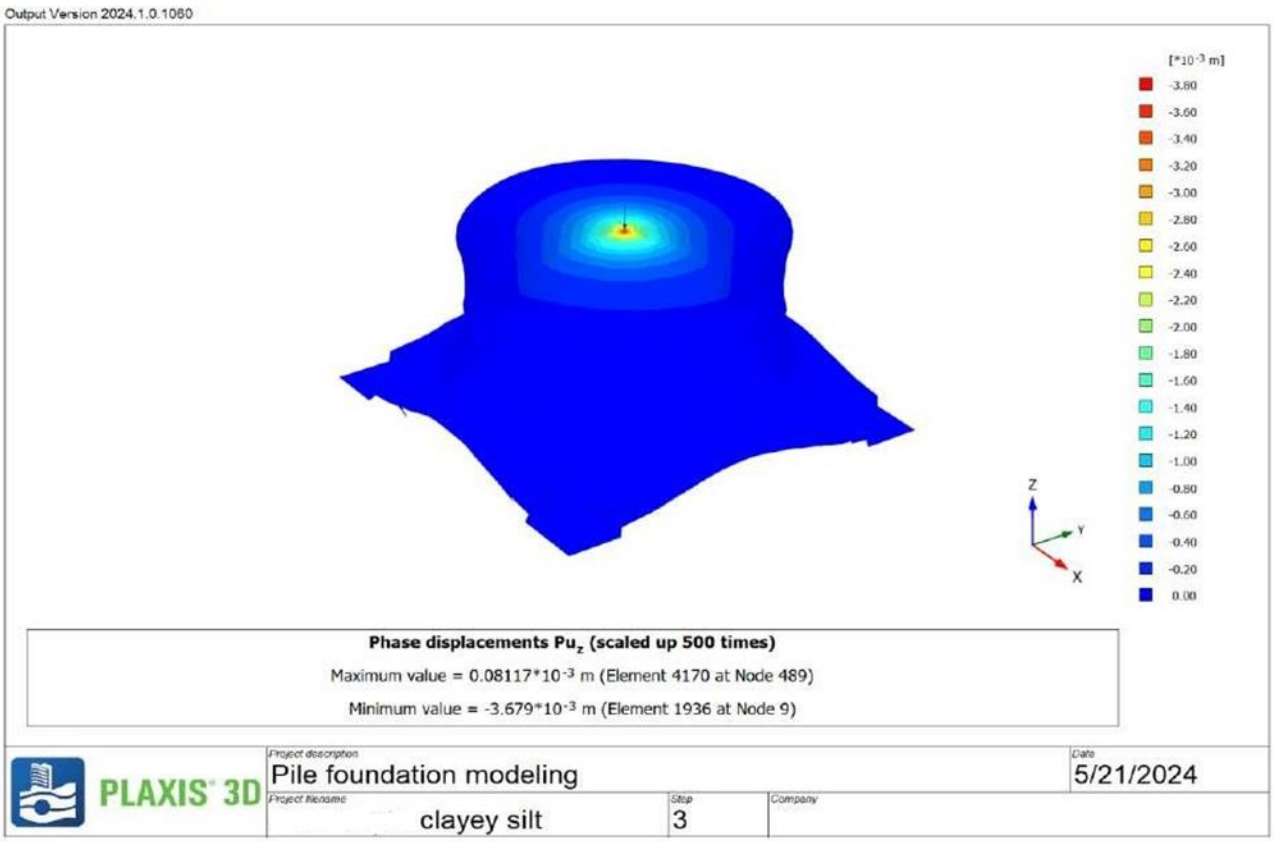
APPENDEX – C

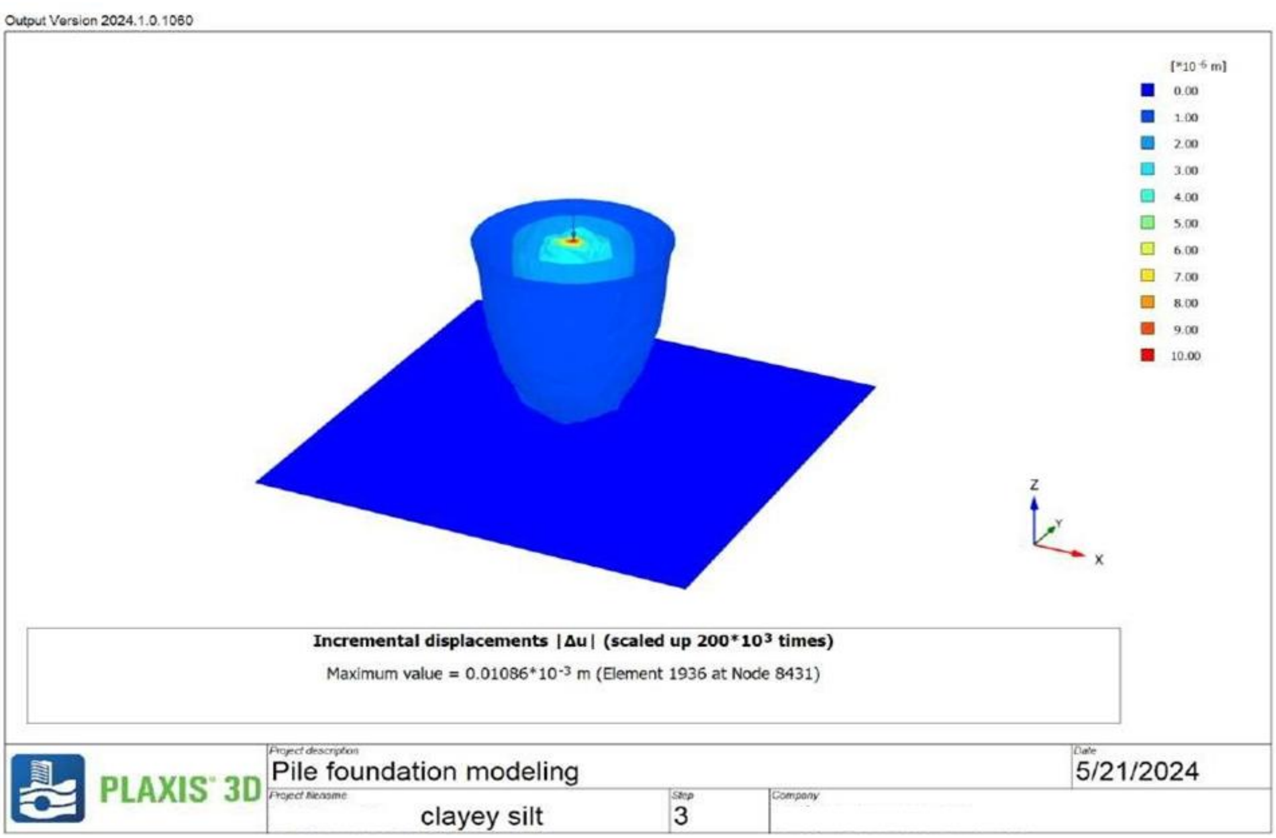

Output Version 2024.1.0.1060
[*10^-3 m]
3.80
3.60
3.40
3.20
3.00
2.80
2.60
2.40
2.20
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Total displacements |u| (scaled up 500 times)
Maximum value = 3.679*10^-3 m (Element 1936 at Node 9)
PLAXIS 3D
Project description
Pile foundation modeling
Date
5/21/2024
Project filename
clayey silt
Step
3
Company

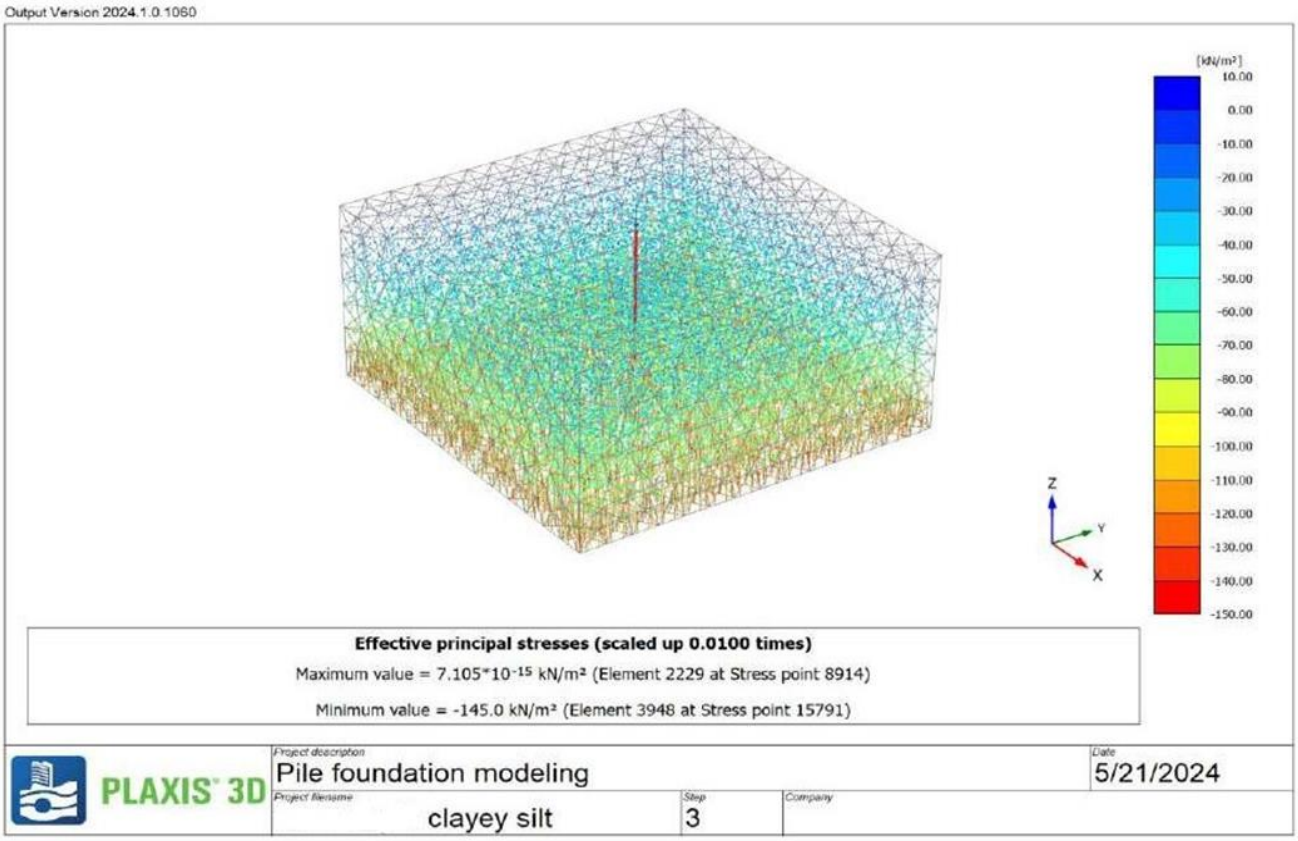

Output Version 2024.1.0.1060
[*10^-3 m]
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
2.20
2.40
2.60
2.80
3.00
3.20
3.40
3.60
Total displacements |u| (scaled up 500 times)
Maximum value = 3.679*10^-3 m (Element 1936 at Node 9)
PLAXIS 3D
Project description
Pile foundation modeling
Date
5/21/2024
Project filename
clayey silt
Step
3
Company

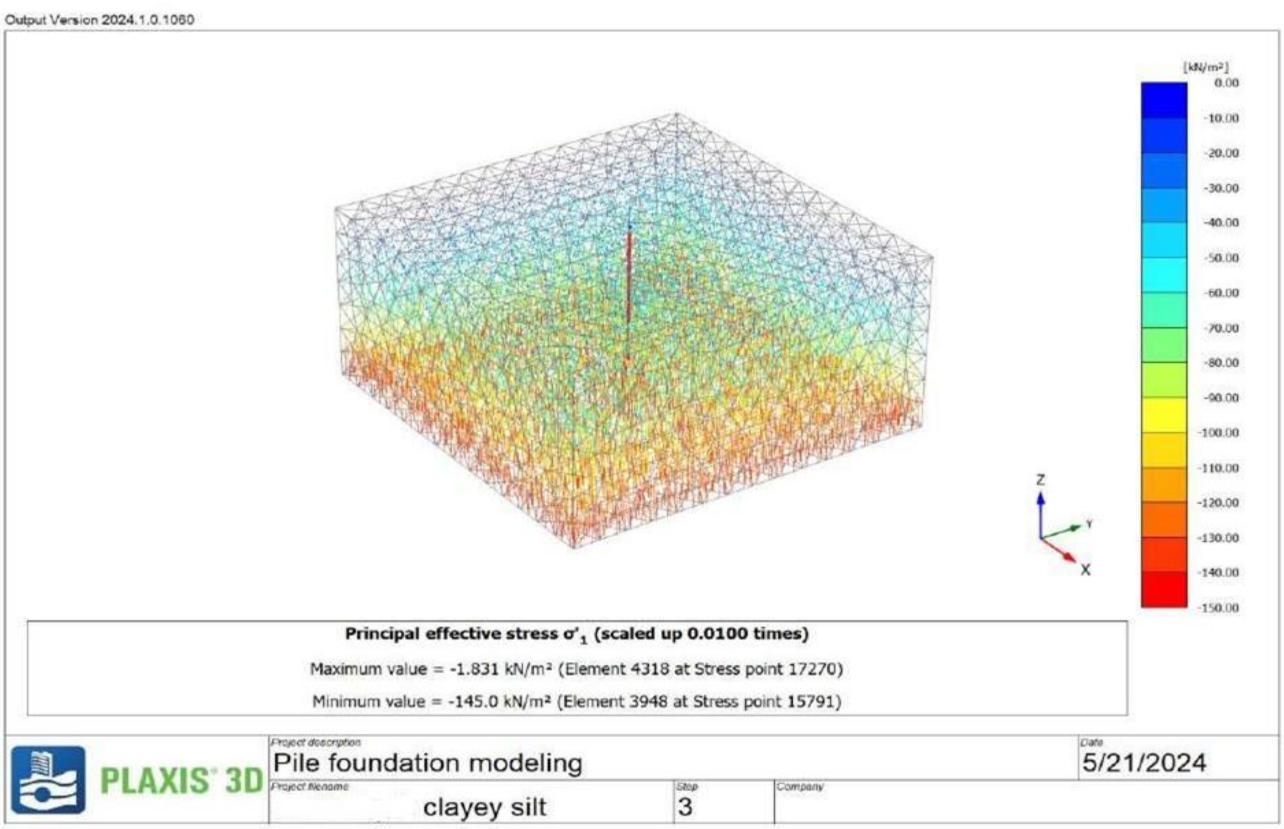

Output Version 2024.1.0.1060
[*10-3 m]
-3.80
-3.60
-3.40
-3.20
-3.00
-2.80
-2.60
-2.40
-2.20
-2.00
-1.80
-1.60
-1.40
-1.20
-1.00
-0.80
-0.60
-0.40
-0.20
0.00
Z
Y
X
Total displacements u_z (scaled up 500 times)
Maximum value = 0.08117*10-3 m (Element 4170 at Node 489)
Minimum value = -3.679*10-3 m (Element 1936 at Node 9)
PLAXIS 3D
Project description
Pile foundation modeling
Date
5/21/2024
Project filename
clayey silt
Step
3
Company

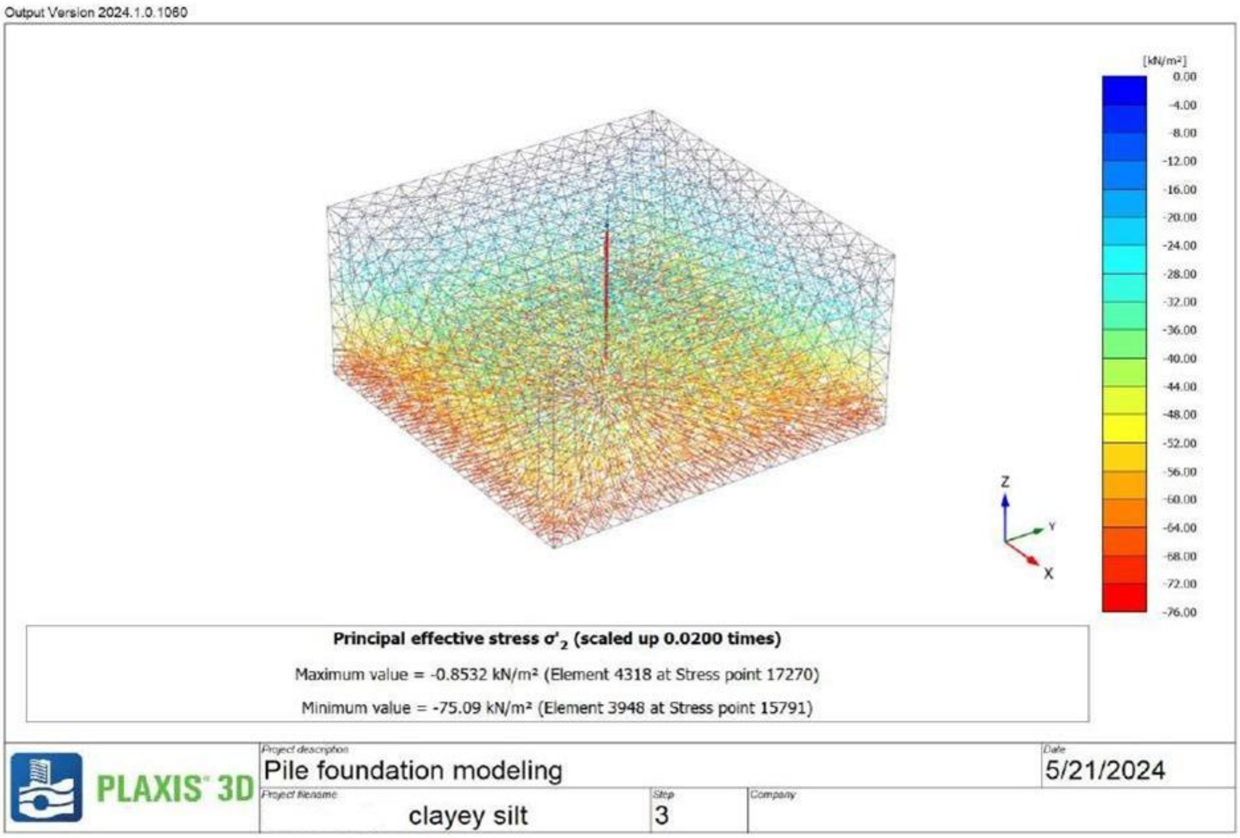

Output Version 2024.1.0.1060
[*10-3 m]
-3.80
-3.60
-3.40
-3.20
-3.00
-2.80
-2.60
-2.40
-2.20
-2.00
-1.80
-1.60
-1.40
-1.20
-1.00
-0.80
-0.60
-0.40
-0.20
0.00
Z
Y
X
Sum phase displacements ΣPu_z (scaled up 500 times)
Maximum value = 0.08117*10-3 m (Element 4170 at Node 489)
Minimum value = -3.679*10-3 m (Element 1936 at Node 9)
PLAXIS 3D
Project description
Pile foundation modeling
Date
5/21/2024
Project filename
clayey silt
Step
3
Company

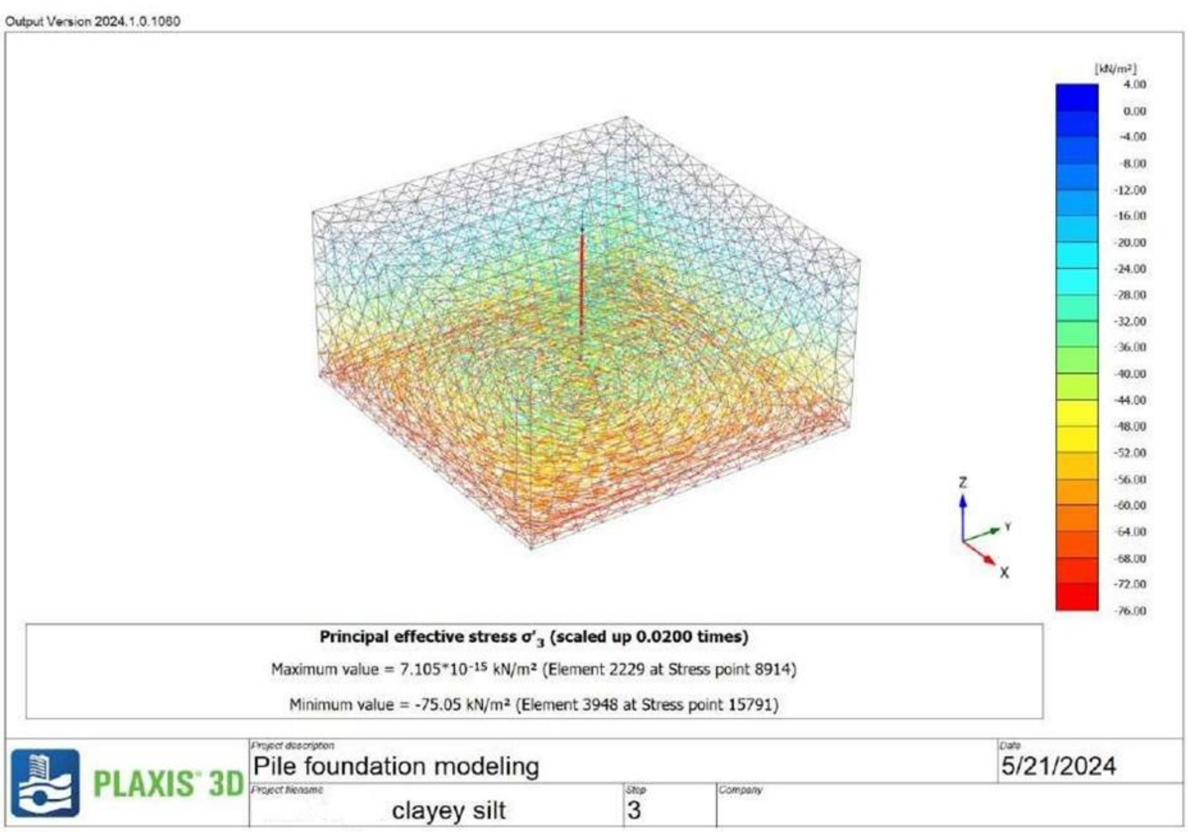

Output Version 2024.1.0.1060
[*10^-3 m]
-3.80
-3.60
-3.40
-3.20
-3.00
-2.80
-2.60
-2.40
-2.20
-2.00
-1.80
-1.60
-1.40
-1.20
-1.00
-0.80
-0.60
-0.40
-0.20
0.00
Z
Y
X
Phase displacements Pu_z (scaled up 500 times)
Maximum value = 0.08117*10^-3 m (Element 4170 at Node 489)
Minimum value = -3.679*10^-3 m (Element 1936 at Node 9)
PLAXIS 3D
Project description
Pile foundation modeling
Date
5/21/2024
Project filename
clayey silt
Step
3
Company

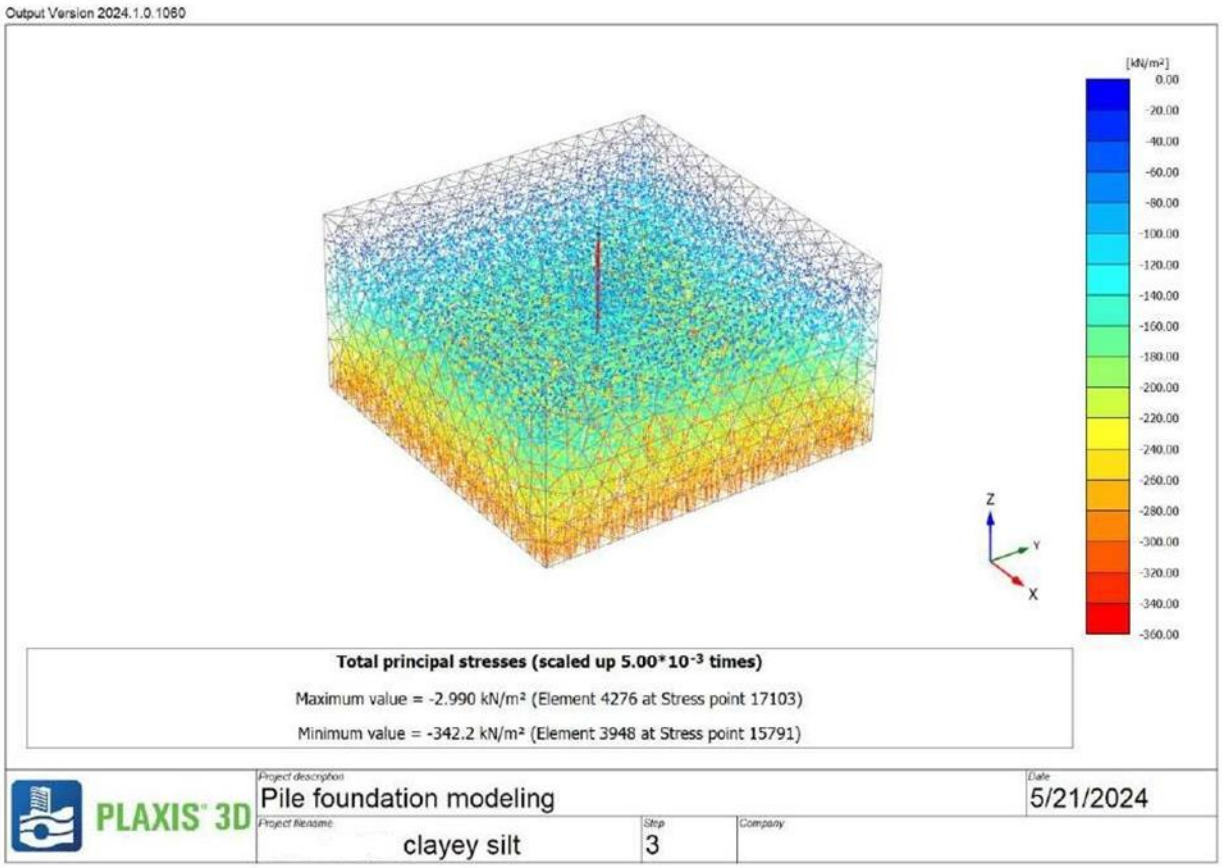

Output Version 2024.1.0.1060
[*10^-6 m]
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
Z
Y
X
Incremental displacements |Δu| (scaled up 200*10^3 times)
Maximum value = 0.01086*10^-3 m (Element 1936 at Node 8431)
PLAXIS 3D
Project description
Pile foundation modeling
Date
5/21/2024
Project filename
clayey silt
Step
3
Company

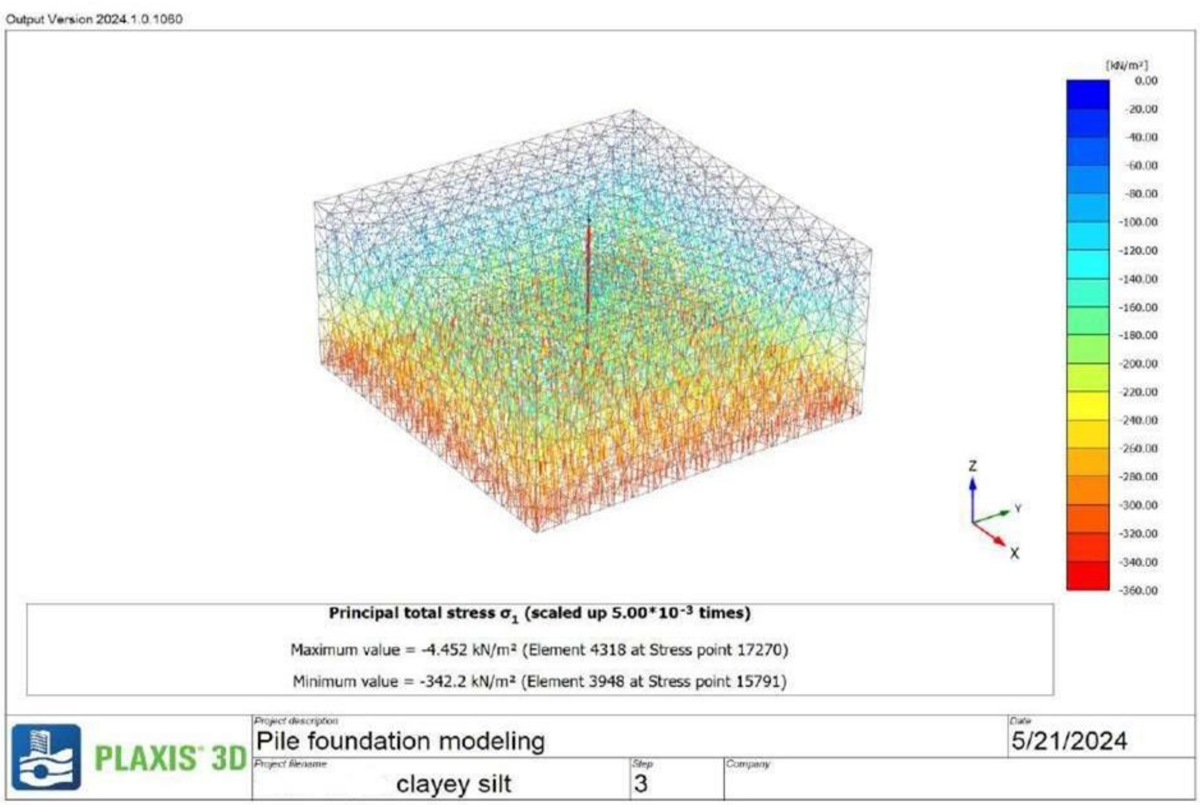

Output Version 2024.1.0.1060
[kN/m²]
10.00
0.00
-10.00
-20.00
-30.00
-40.00
-50.00
-60.00
-70.00
-80.00
-90.00
-100.00
-110.00
-120.00
-130.00
-140.00
-150.00
Z
Y
X
Effective principal stresses (scaled up 0.0100 times)
Maximum value = 7.105*10^-15 kN/m² (Element 2229 at Stress point 8914)
Minimum value = -145.0 kN/m² (Element 3948 at Stress point 15791)
PLAXIS 3D
Project description
Pile foundation modeling
Date
5/21/2024
Project filename
clayey silt
Step
3
Company

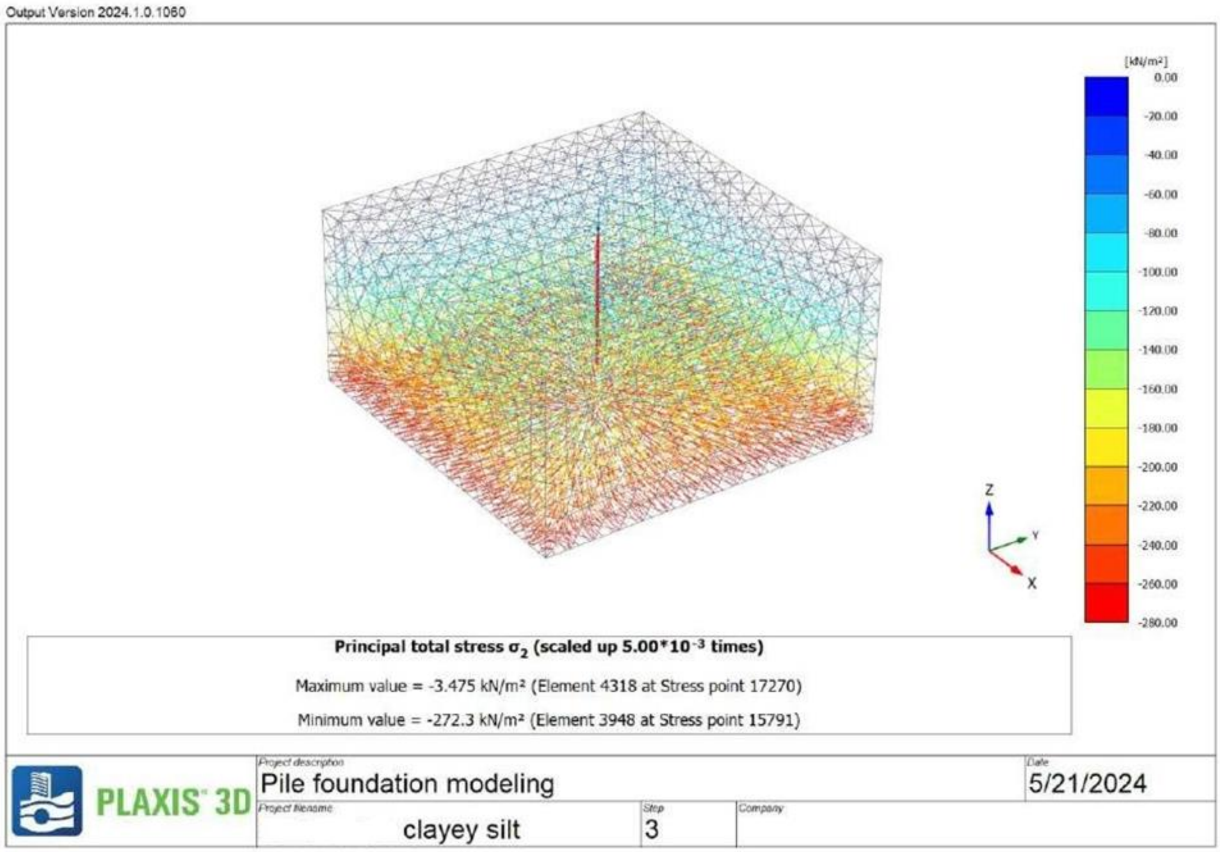

Output Version 2024.1.0.1060
[kN/m²]
0.00
-10.00
-20.00
-30.00
-40.00
-50.00
-60.00
-70.00
-80.00
-90.00
-100.00
-110.00
-120.00
-130.00
-140.00
-150.00
Z
Y
X
Principal effective stress σ'1 (scaled up 0.0100 times)
Maximum value = -1.831 kN/m² (Element 4318 at Stress point 17270)
Minimum value = -145.0 kN/m² (Element 3948 at Stress point 15791)
PLAXIS 3D
Project description
Pile foundation modeling
Date
5/21/2024
Project filename
clayey silt
Step
3
Company

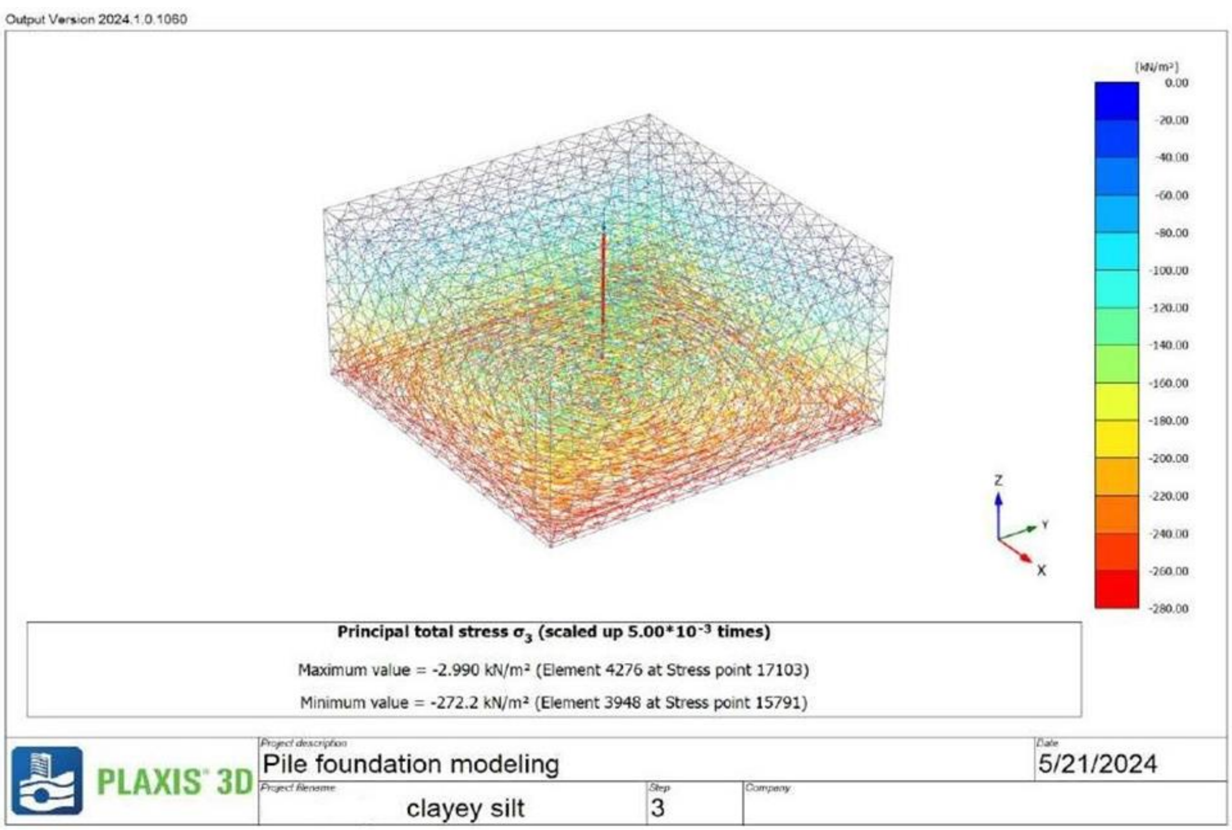

Output Version 2024.1.0.1060
[kN/m²]
0.00
-4.00
-8.00
-12.00
-16.00
-20.00
-24.00
-28.00
-32.00
-36.00
-40.00
-44.00
-48.00
-52.00
-56.00
-60.00
-64.00
-68.00
-72.00
-76.00
Z
Y
X
Principal effective stress σ'₂ (scaled up 0.0200 times)
Maximum value = -0.8532 kN/m² (Element 4318 at Stress point 17270)
Minimum value = -75.09 kN/m² (Element 3948 at Stress point 15791)
PLAXIS 3D
Project description
Pile foundation modeling
Date
5/21/2024
Project filename
clayey silt
Step
3
Company

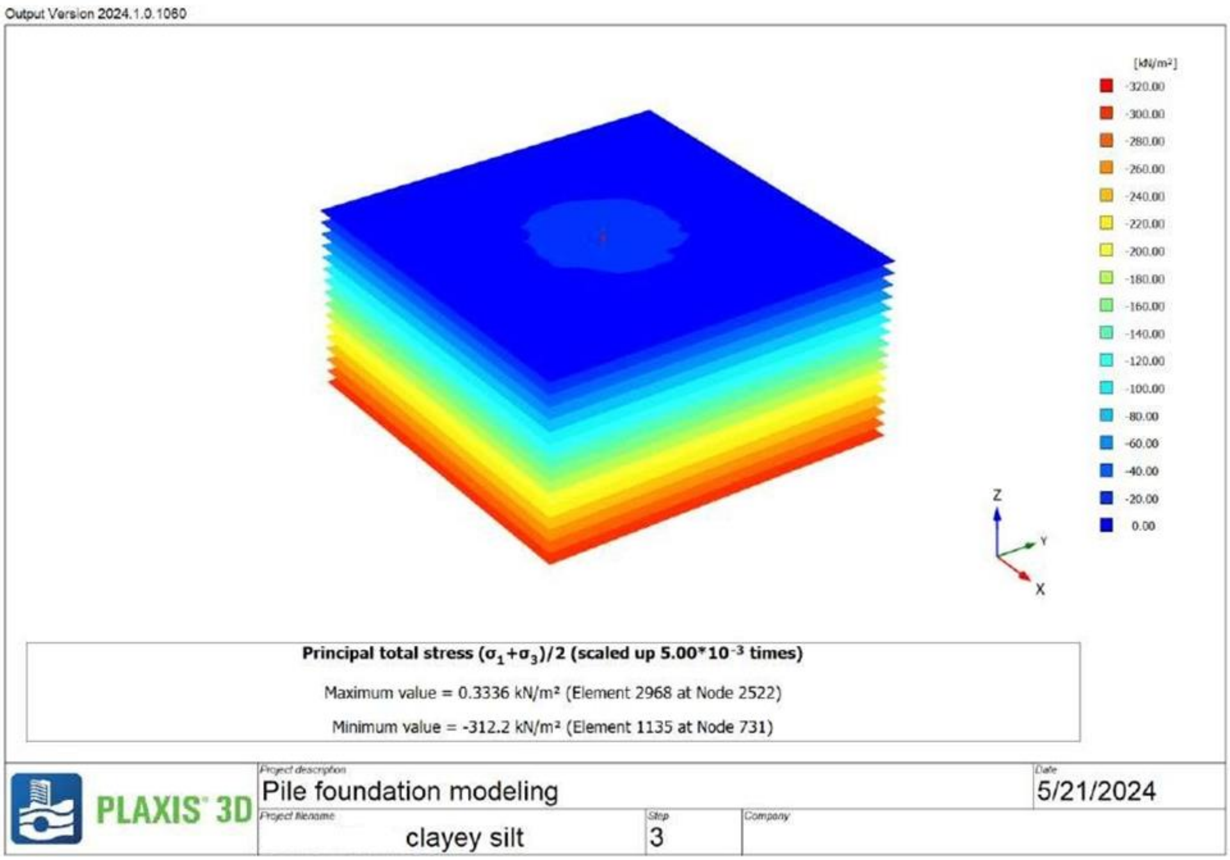

Output Version 2024.1.0.1060
[kN/m²]
4.00
0.00
-4.00
-8.00
-12.00
-16.00
-20.00
-24.00
-28.00
-32.00
-36.00
-40.00
-44.00
-48.00
-52.00
-56.00
-60.00
-64.00
-68.00
-72.00
-76.00
Z
Y
X
Principal effective stress σ'₃ (scaled up 0.0200 times)
Maximum value = 7.105*10^-15 kN/m² (Element 2229 at Stress point 8914)
Minimum value = -75.05 kN/m² (Element 3948 at Stress point 15791)
PLAXIS 3D
Project description
Pile foundation modeling
Date
5/21/2024
Project filename
clayey silt
Step
3
Company

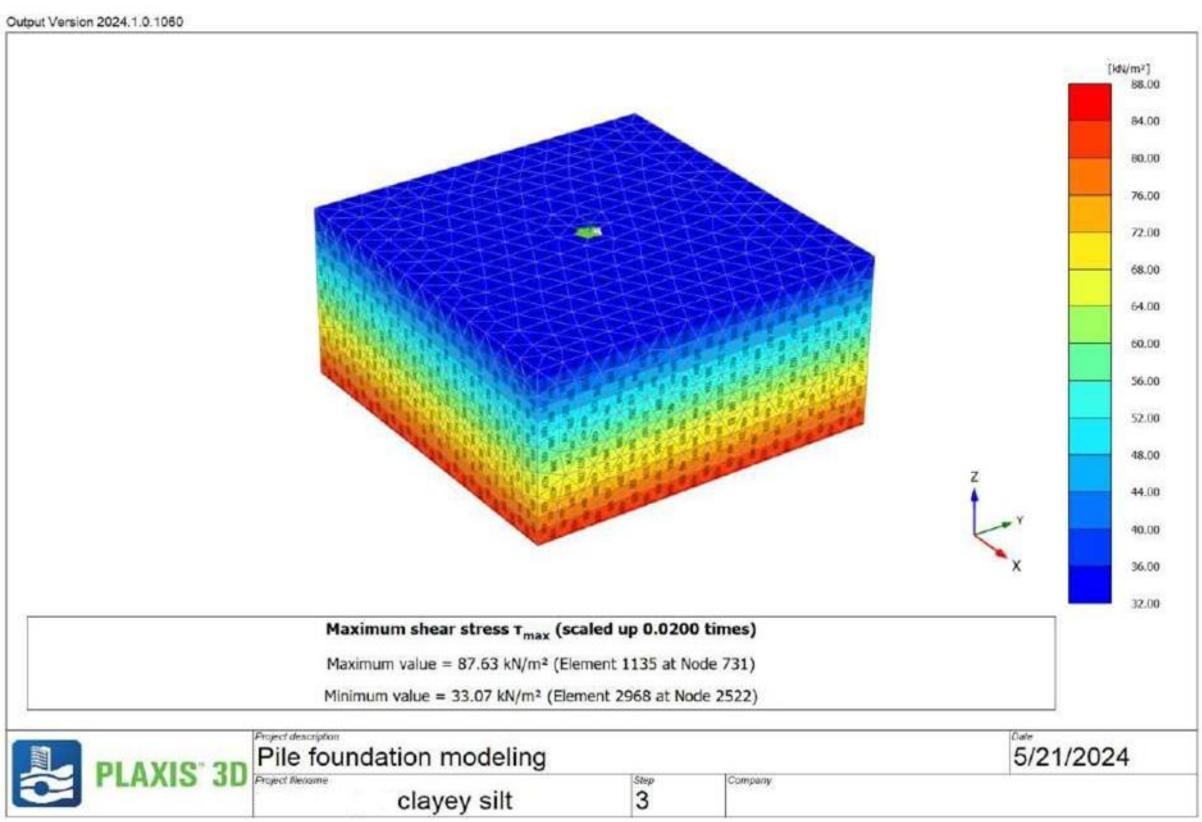

Output Version 2024.1.0.1060
[kN/m²]
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
Z
Y
X
Total principal stresses (scaled up 5.00*10^-3 times)
Maximum value = -2.990 kN/m² (Element 4276 at Stress point 17103)
Minimum value = -342.2 kN/m² (Element 3948 at Stress point 15791)
PLAXIS 3D
Project description
Pile foundation modeling
Date
5/21/2024
Project filename
clayey silt
Step
3
Company


Output Version 2024.1.0.1060
[kN/m²]
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
Z
Y
X
Principal total stress σ1 (scaled up 5.00*10^-3 times)
Maximum value = -4.452 kN/m² (Element 4318 at Stress point 17270)
Minimum value = -342.2 kN/m² (Element 3948 at Stress point 15791)
PLAXIS 3D
Project description
Pile foundation modeling
Date
5/21/2024
Project filename
clayey silt
Step
3
Company

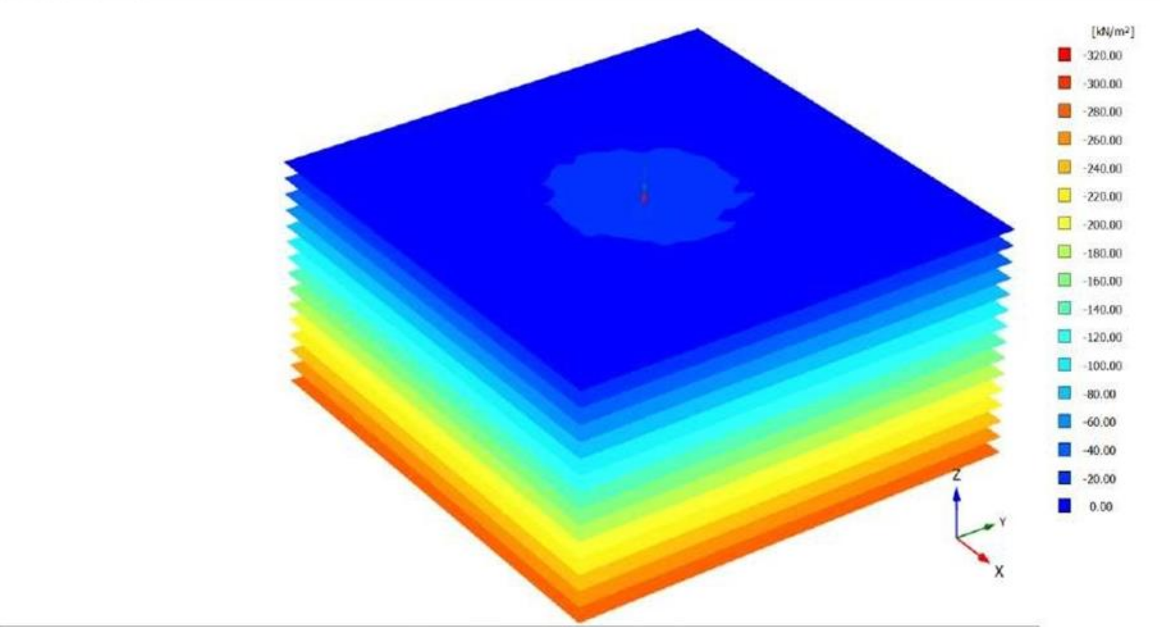

Output Version 2024.1.0.1060
[kN/m²]
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
Z
Y
X
Principal total stress σ2 (scaled up 5.00*10^-3 times)
Maximum value = -3.475 kN/m² (Element 4318 at Stress point 17270)
Minimum value = -272.3 kN/m² (Element 3948 at Stress point 15791)
PLAXIS 3D
Project description
Pile foundation modeling
Date
5/21/2024
Project filename
clayey silt
Step
3
Company


Output Version 2024.1.0.1060
[kN/m²]
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
Z
Y
X
Principal total stress σ3 (scaled up 5.00*10^-3 times)
Maximum value = -2.990 kN/m² (Element 4276 at Stress point 17103)
Minimum value = -272.2 kN/m² (Element 3948 at Stress point 15791)
PLAXIS 3D
Project description
Pile foundation modeling
Date
5/21/2024
Project filename
clayey silt
Step
3
Company


Output Version 2024.1.0.1060
[kN/m²]
-320.00
-300.00
-280.00
-260.00
-240.00
-220.00
-200.00
-180.00
-160.00
-140.00
-120.00
-100.00
-80.00
-60.00
-40.00
-20.00
0.00
Z
Y
X
Principal total stress $(\sigma_1+\sigma_3)/2$ (scaled up $5.00*10^{-3}$ times)
Maximum value = 0.3336 kN/m² (Element 2968 at Node 2522)
Minimum value = -312.2 kN/m² (Element 1135 at Node 731)
PLAXIS 3D
Project description
Pile foundation modeling
Date
5/21/2024
Project filename
clayey silt
Step
3
Company


Output Version 2024.1.0.1060
[kN/m²]
88.00
84.00
80.00
76.00
72.00
68.00
64.00
60.00
56.00
52.00
48.00
44.00
40.00
36.00
32.00
Z
Y
X
Maximum shear stress τ_{max} (scaled up 0.0200 times)
Maximum value = 87.63 kN/m² (Element 1135 at Node 731)
Minimum value = 33.07 kN/m² (Element 2968 at Node 2522)
PLAXIS 3D
Project description
Pile foundation modeling
Date
5/21/2024
Project filename
clayey silt
Step
3
Company

Output Version 2024.1.0.1060



Total mean stress p (scaled up 5.00*10^-3 times)

Maximum value = 0.2597 kN/m² (Element 2925 at Node 2584)

Minimum value = -300.5 kN/m² (Element 1135 at Node 731)

PLAXIS 3D	Project description: Pile foundation modeling		Date: 5/21/2024
	Project filename: clayey silt	Step: 3	Company:

Output Version 2024.1.0.1060

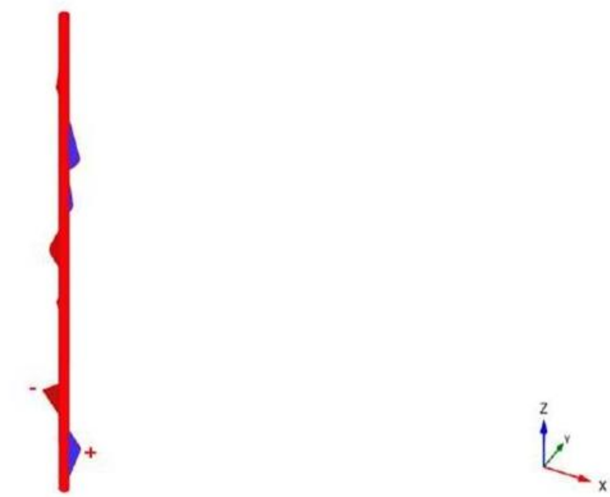
Bending moments M_2 (scaled up 0.500 times)

Maximum value = 3.490 kN m (Element 14 at Node 9927)

Minimum value = -2.050 kN m (Element 17 at Node 9934)

PLAXIS 3D	Project description: Pile foundation modeling		Date: 5/21/2024
	Project filename: clayey silt	Step: 3	Company:

Output Version 2024.1.0.1060



Bending moments M_3 (scaled up 0.200 times)

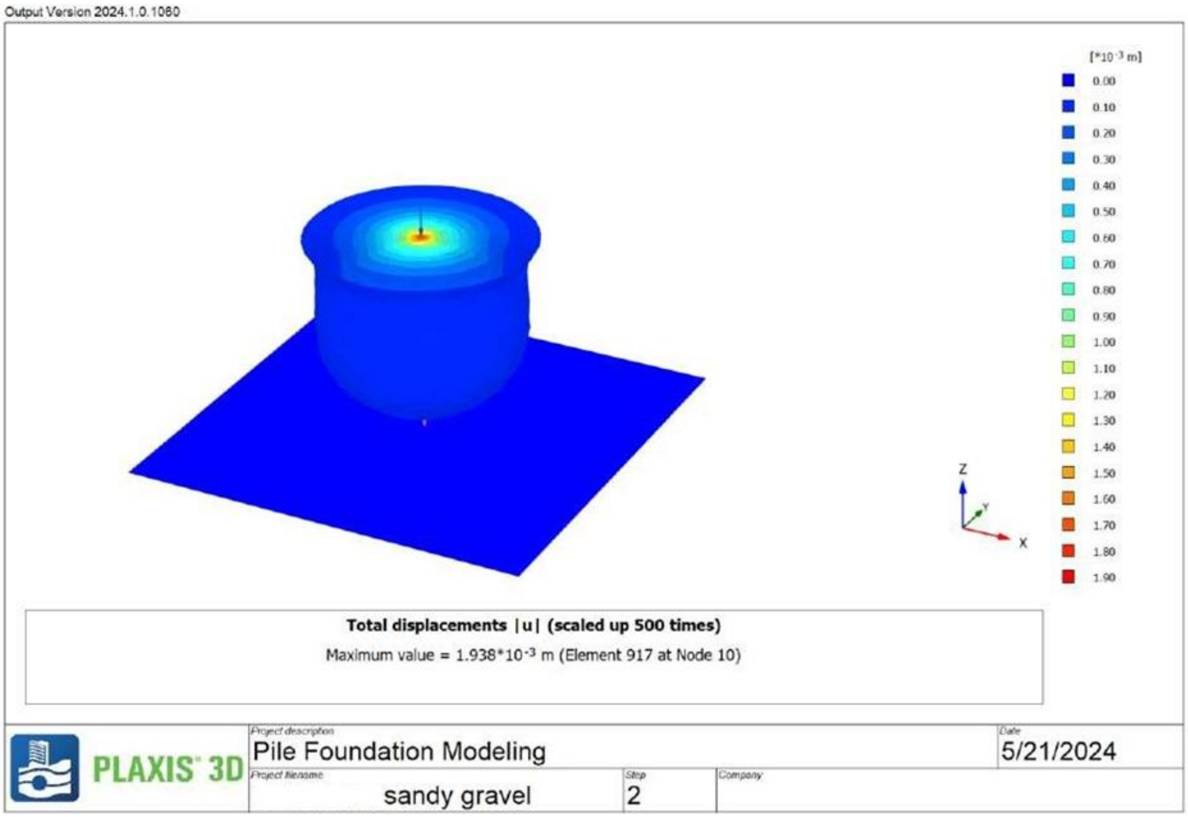
Maximum value = 2.569 kN m (Element 17 at Node 9934)

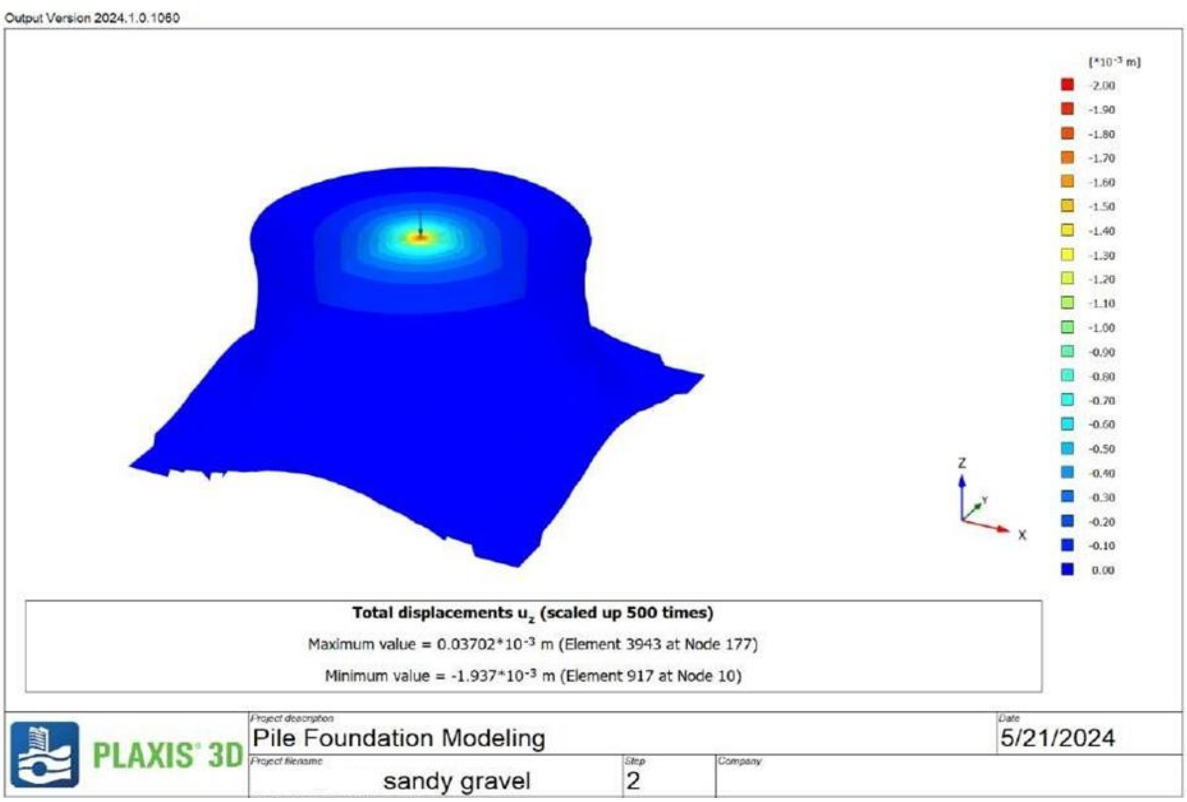
Minimum value = -3.282 kN m (Element 16 at Node 9931)

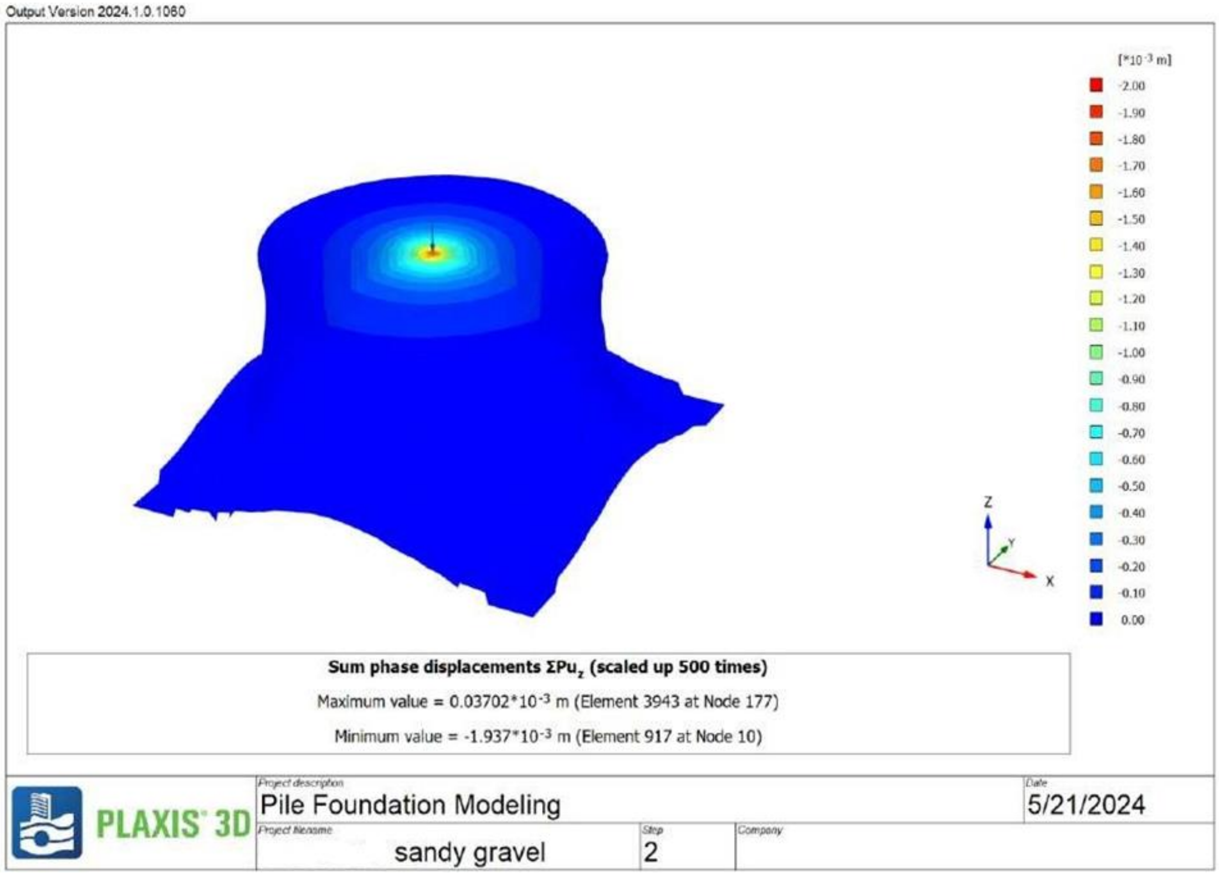
Project description			Date
Pile foundation modeling			5/21/2024
Project filename	Step	Company	
clayey silt	3		

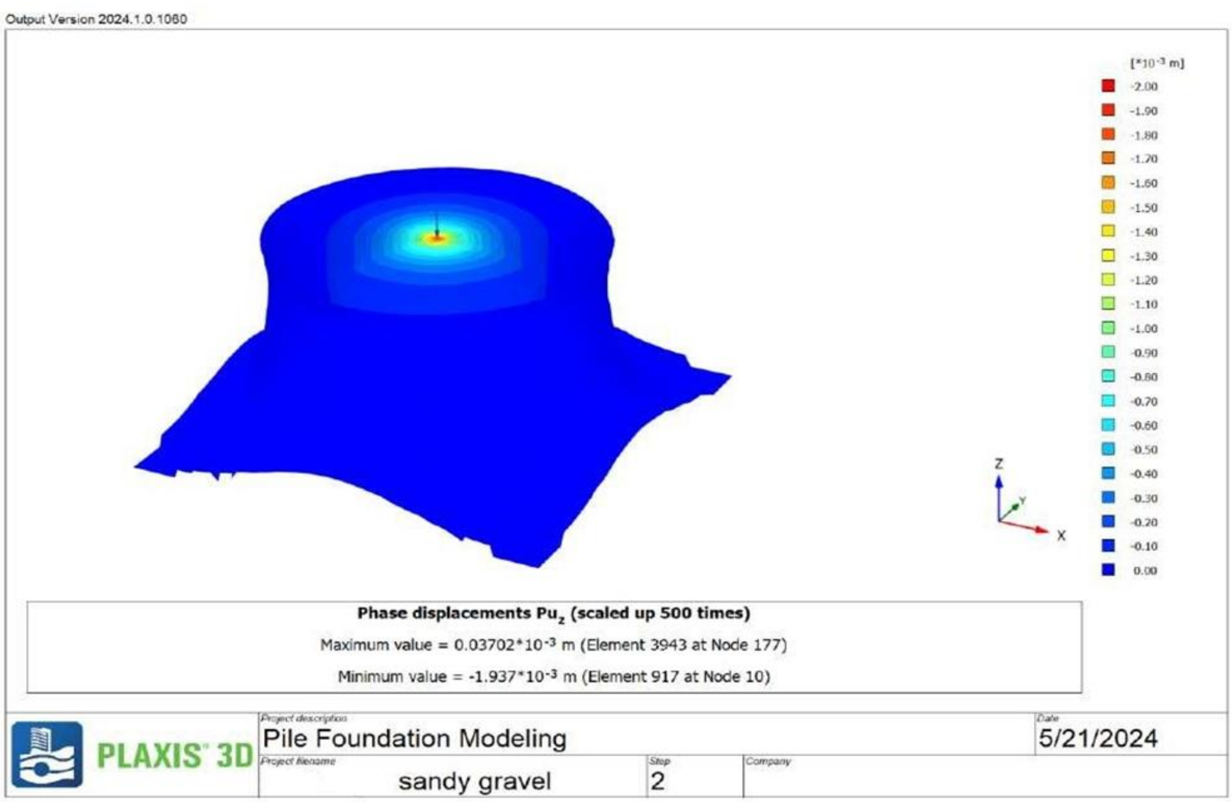
PLAXIS 3D

APPENDEX – D

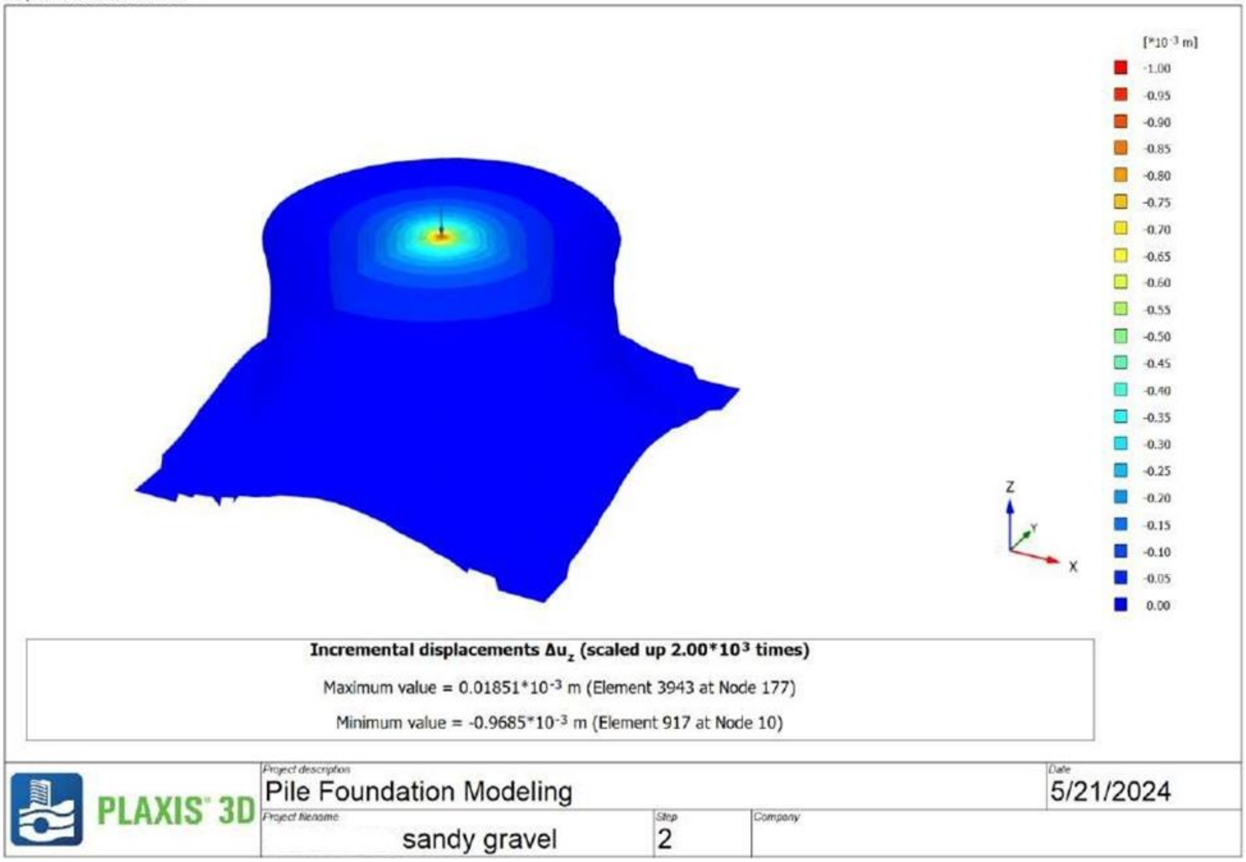

Output Version 2024.1.0.1060
[*10^-3 m]
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
Z
Y
X
Total displacements |u| (scaled up 500 times)
Maximum value = 1.938*10^-3 m (Element 917 at Node 10)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
sandy gravel
Step
2
Company


Output Version 2024.1.0.1060
[*10^-3 m]
-2.00
-1.90
-1.80
-1.70
-1.60
-1.50
-1.40
-1.30
-1.20
-1.10
-1.00
-0.90
-0.80
-0.70
-0.60
-0.50
-0.40
-0.30
-0.20
-0.10
0.00
Z
Y
X
Total displacements u_z (scaled up 500 times)
Maximum value = 0.03702*10^-3 m (Element 3943 at Node 177)
Minimum value = -1.937*10^-3 m (Element 917 at Node 10)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
sandy gravel
Step
2
Company

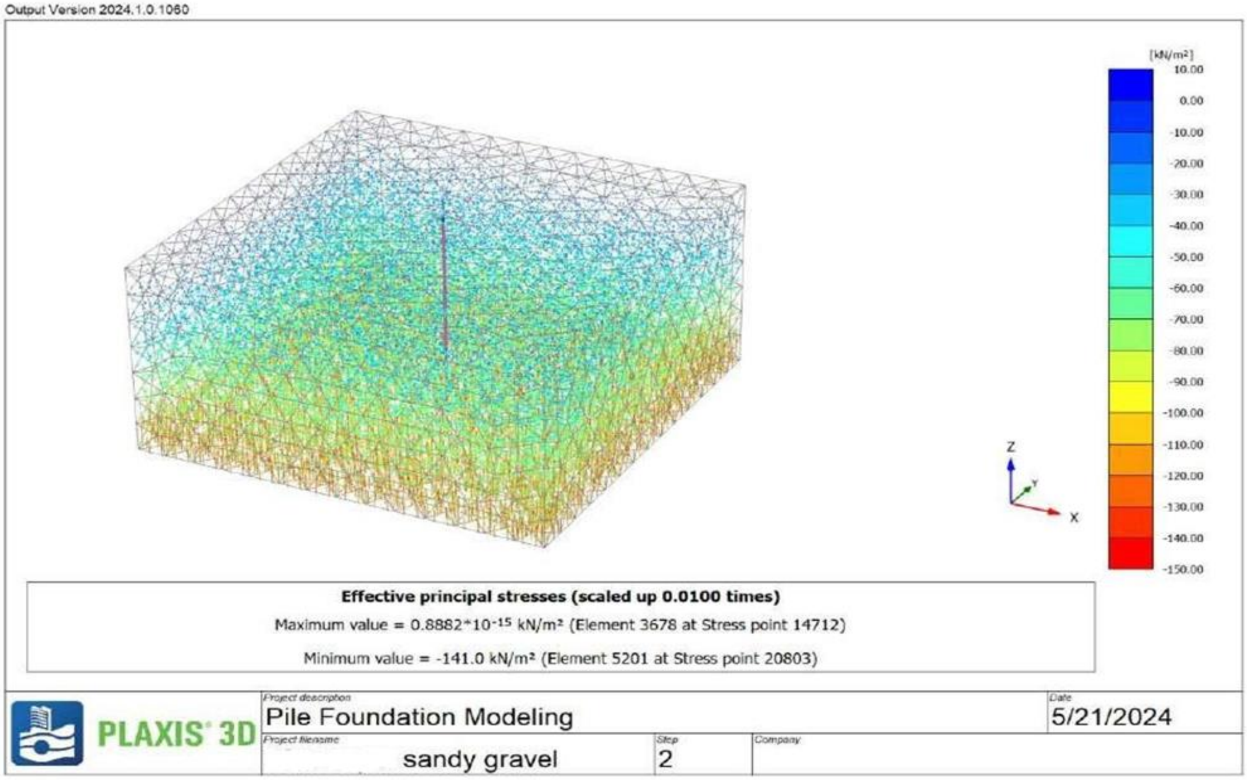

Output Version 2024.1.0.1060
[*10^-3 m]
-2.00
-1.90
-1.80
-1.70
-1.60
-1.50
-1.40
-1.30
-1.20
-1.10
-1.00
-0.90
-0.80
-0.70
-0.60
-0.50
-0.40
-0.30
-0.20
-0.10
0.00
Z
Y
X
Sum phase displacements ΣPu_z (scaled up 500 times)
Maximum value = 0.03702*10^-3 m (Element 3943 at Node 177)
Minimum value = -1.937*10^-3 m (Element 917 at Node 10)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
sandy gravel
Step
2
Company


Output Version 2024.1.0.1060
[*10^-3 m]
-2.00
-1.90
-1.80
-1.70
-1.60
-1.50
-1.40
-1.30
-1.20
-1.10
-1.00
-0.90
-0.80
-0.70
-0.60
-0.50
-0.40
-0.30
-0.20
-0.10
0.00
Z
Y
X
Phase displacements Pu_z (scaled up 500 times)
Maximum value = 0.03702*10^-3 m (Element 3943 at Node 177)
Minimum value = -1.937*10^-3 m (Element 917 at Node 10)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
sandy gravel
Step
2
Company

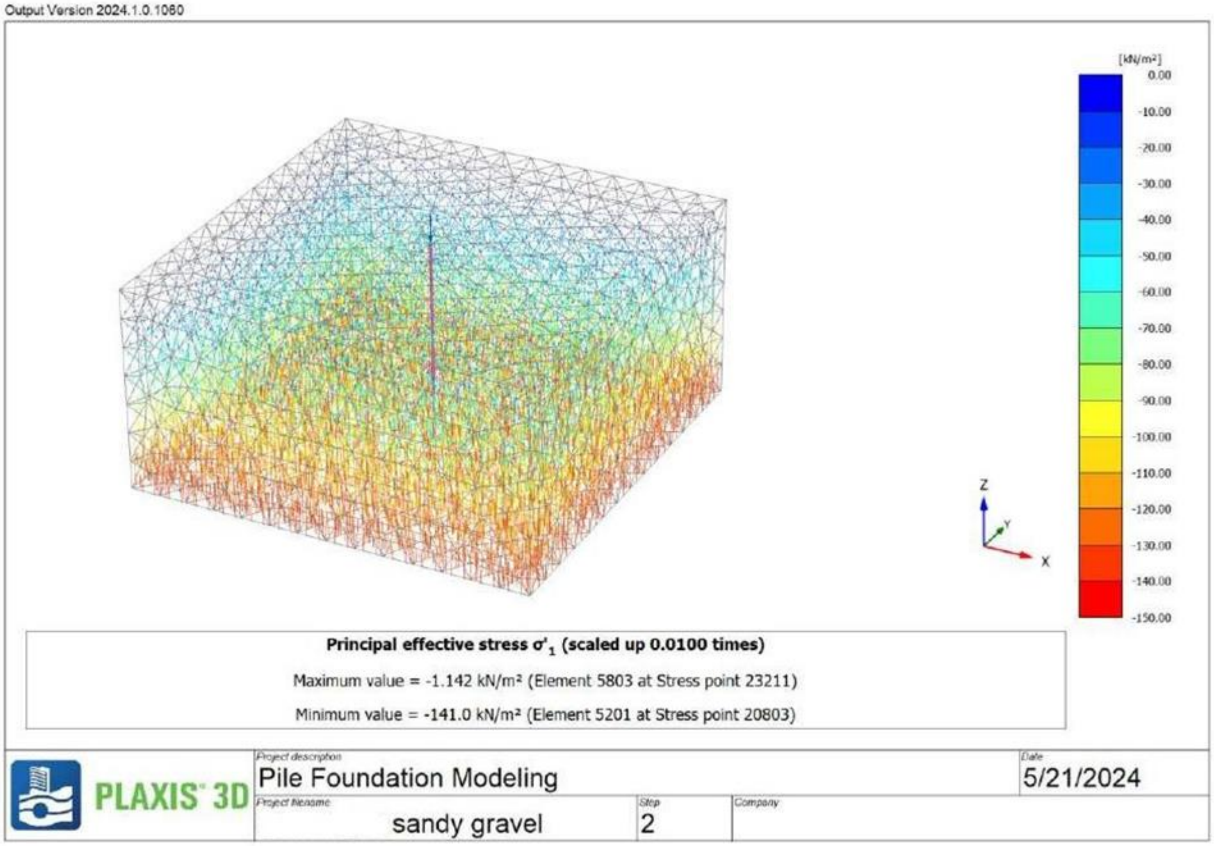
Output Version 2024.1.0.1060



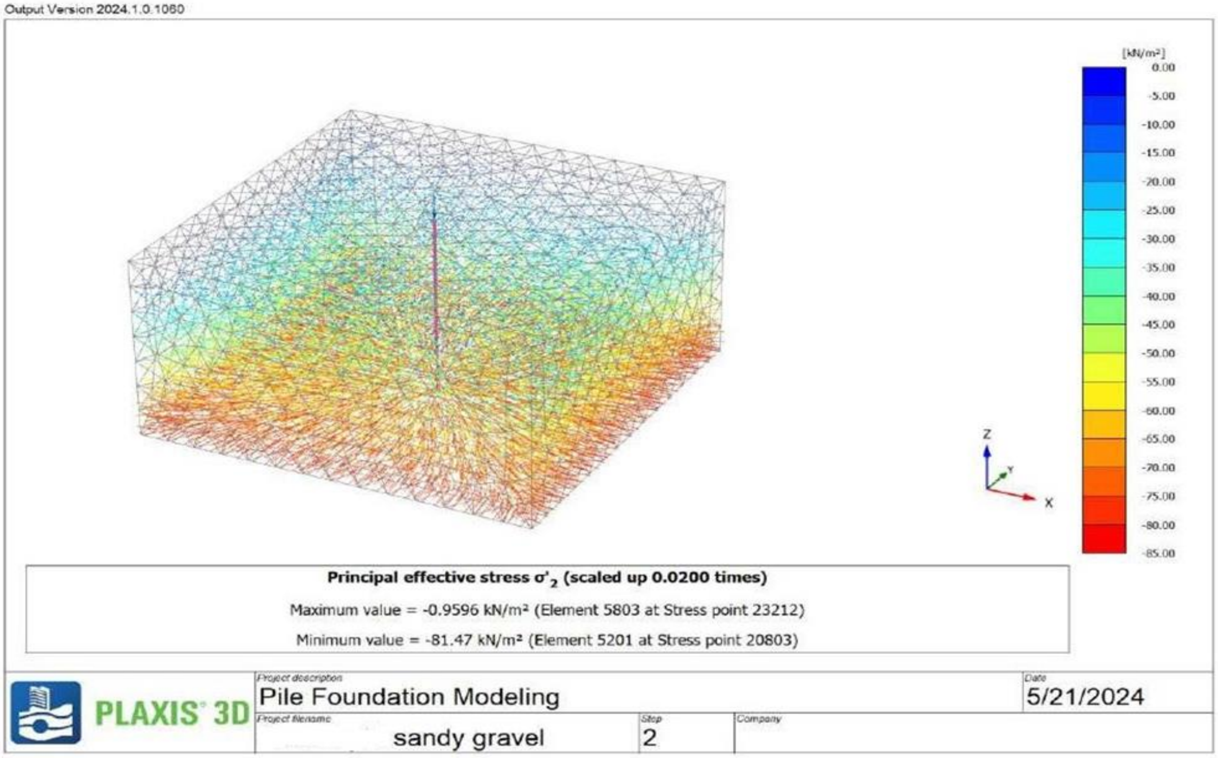
Output Version 2024.1.0.1060



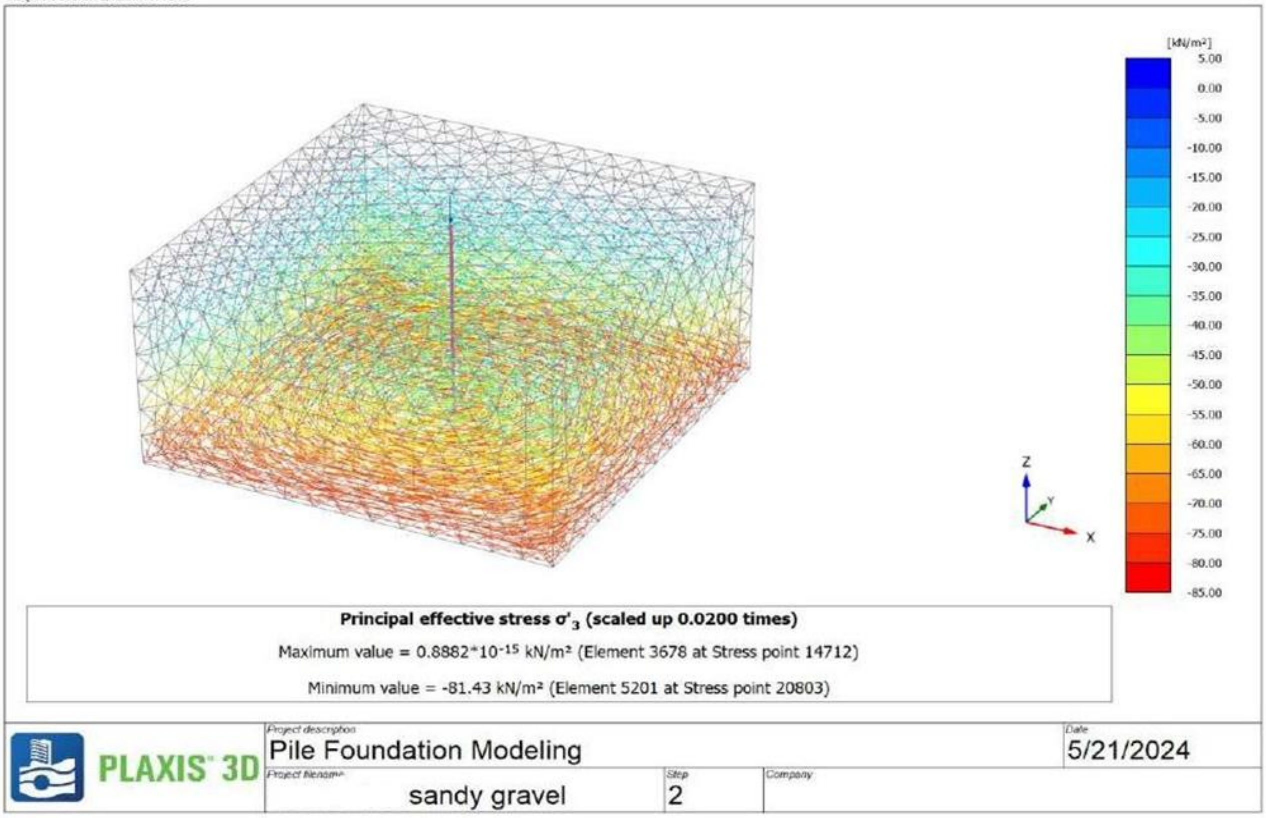
Output Version 2024.1.0.1060



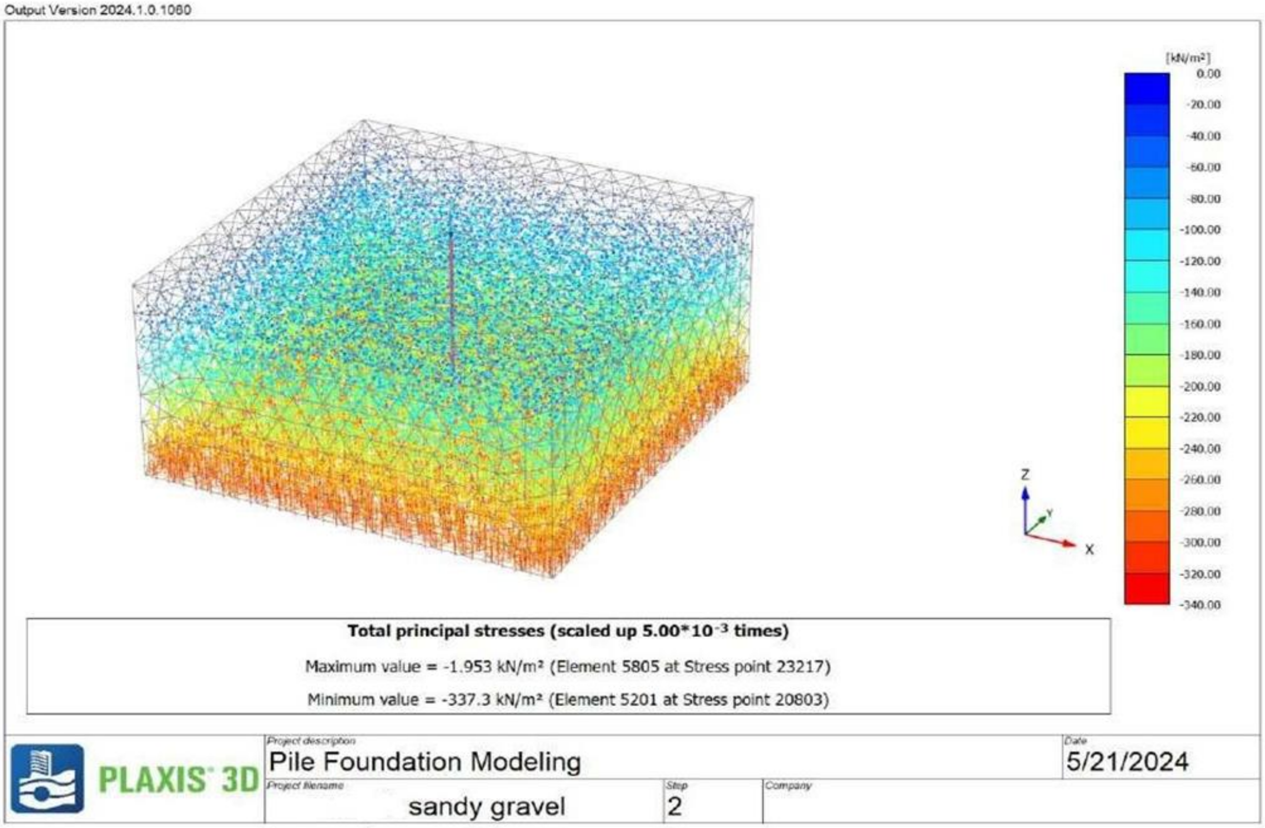
Output Version 2024.1.0.1060

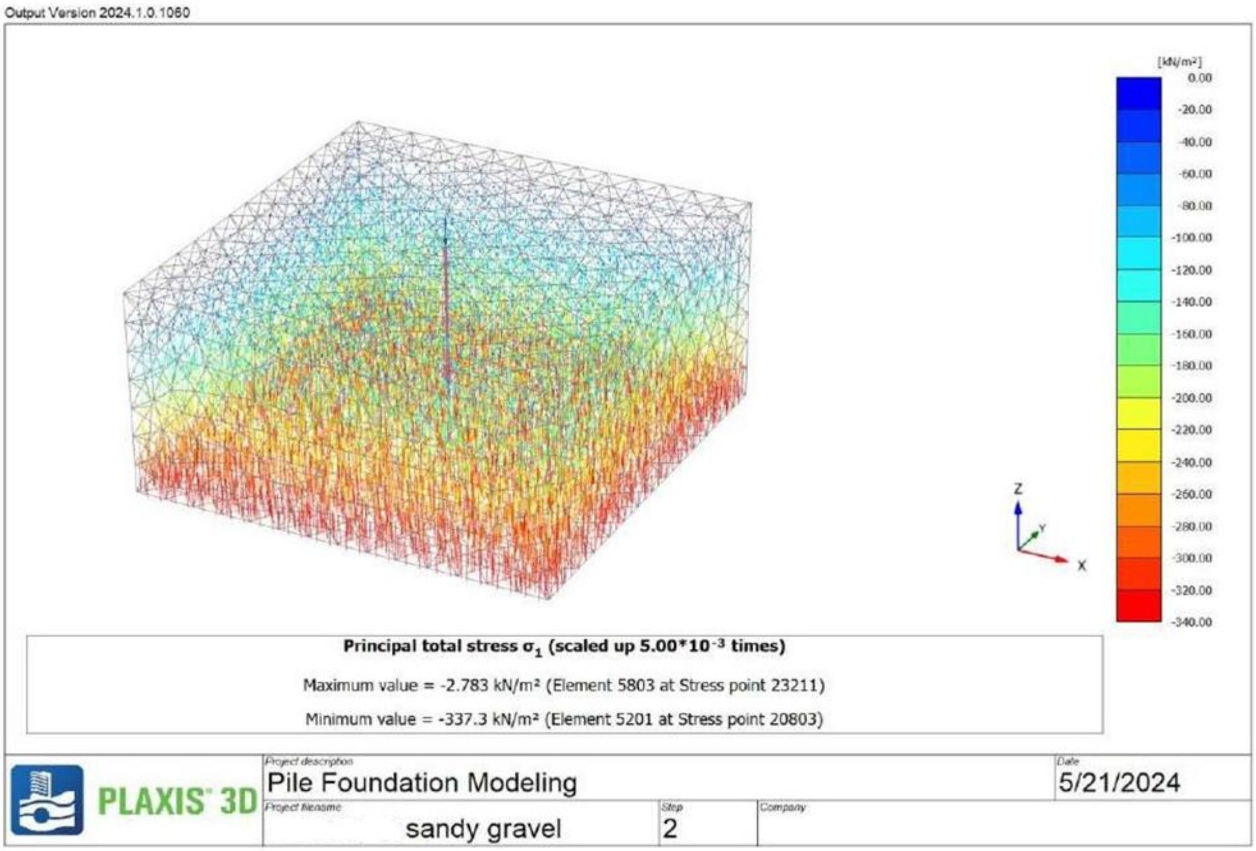


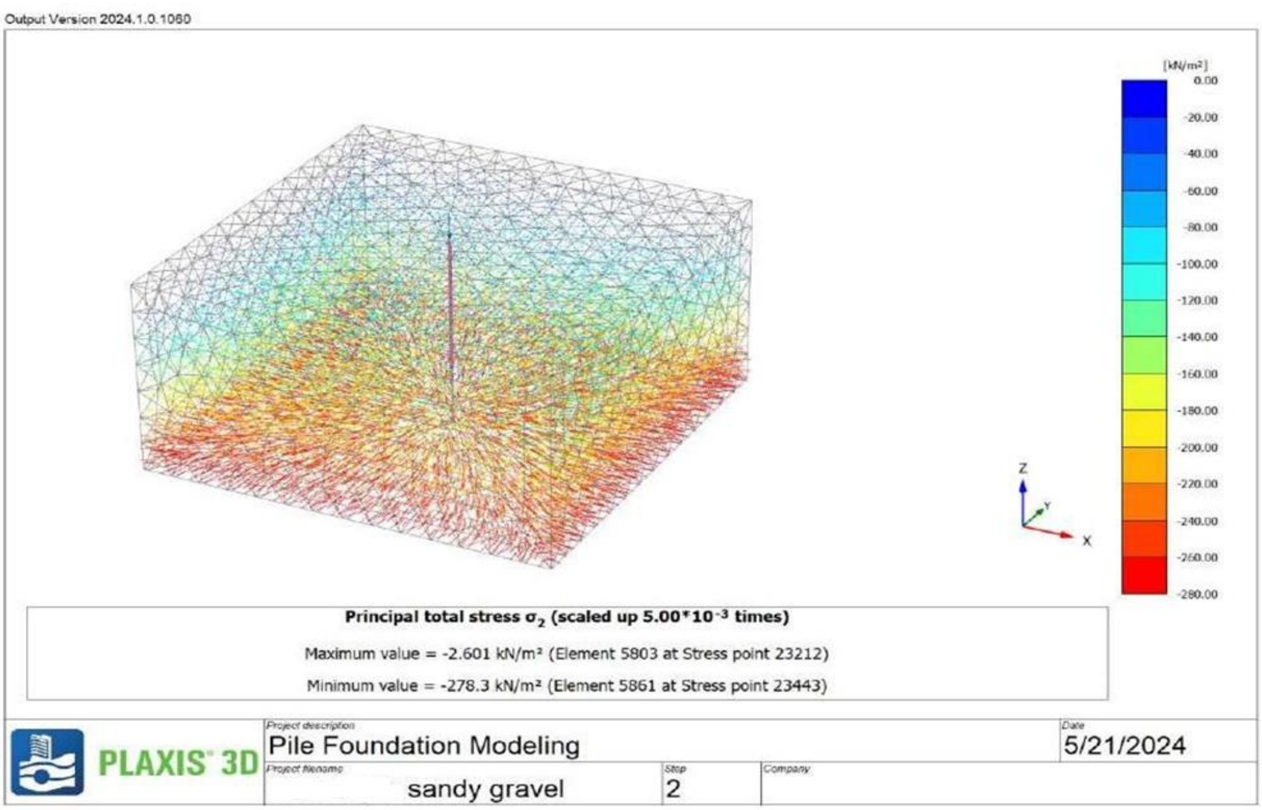
Output Version 2024.1.0.1060



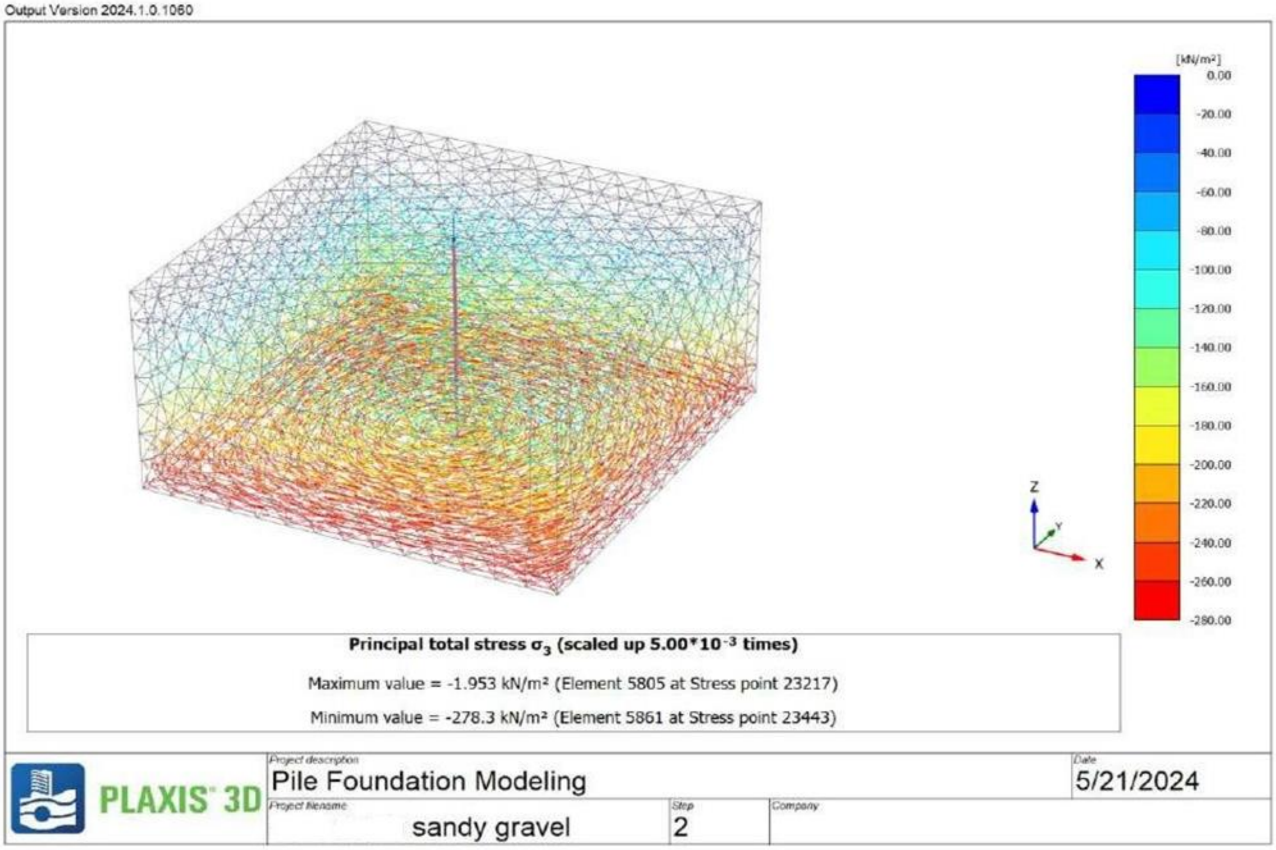
Output Version 2024.1.0.1060



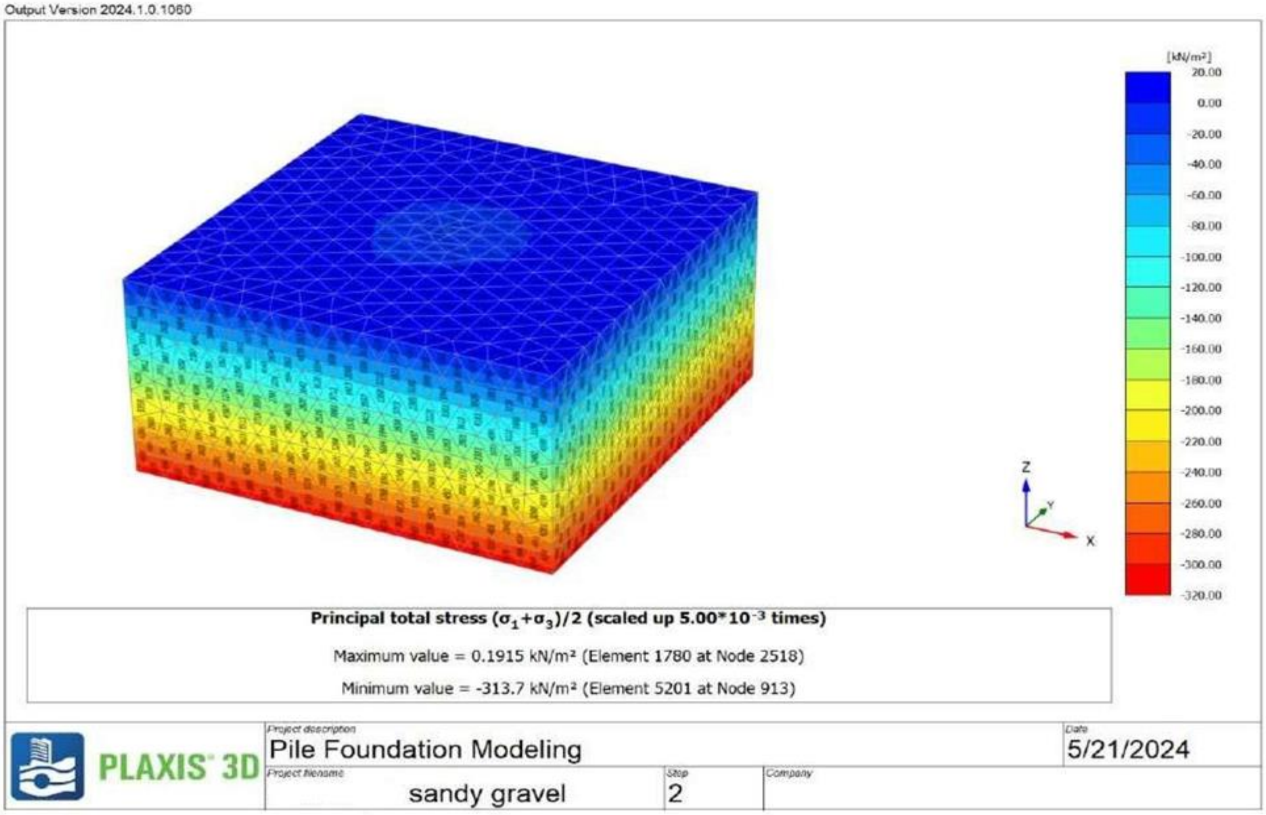

Output Version 2024.1.0.1060
[kN/m²]
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
Z
Y
X
Principal total stress σ1 (scaled up 5.00*10^-3 times)
Maximum value = -2.783 kN/m² (Element 5803 at Stress point 23211)
Minimum value = -337.3 kN/m² (Element 5201 at Stress point 20803)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
sandy gravel
Step
2
Company

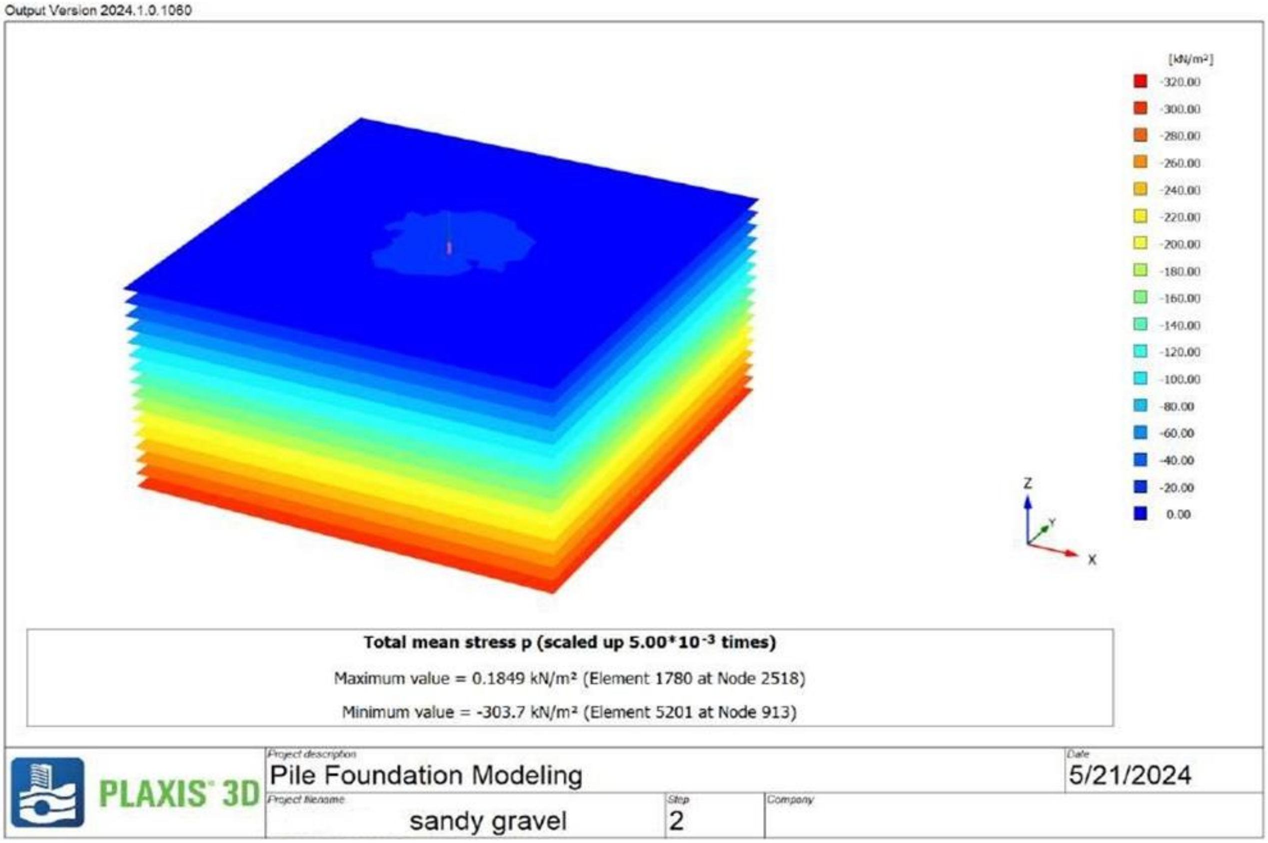

Output Version 2024.1.0.1060
[kN/m²]
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
Z
Y
X
Principal total stress σ2 (scaled up 5.00*10^-3 times)
Maximum value = -2.601 kN/m² (Element 5803 at Stress point 23212)
Minimum value = -278.3 kN/m² (Element 5861 at Stress point 23443)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
sandy gravel
Step
2
Company

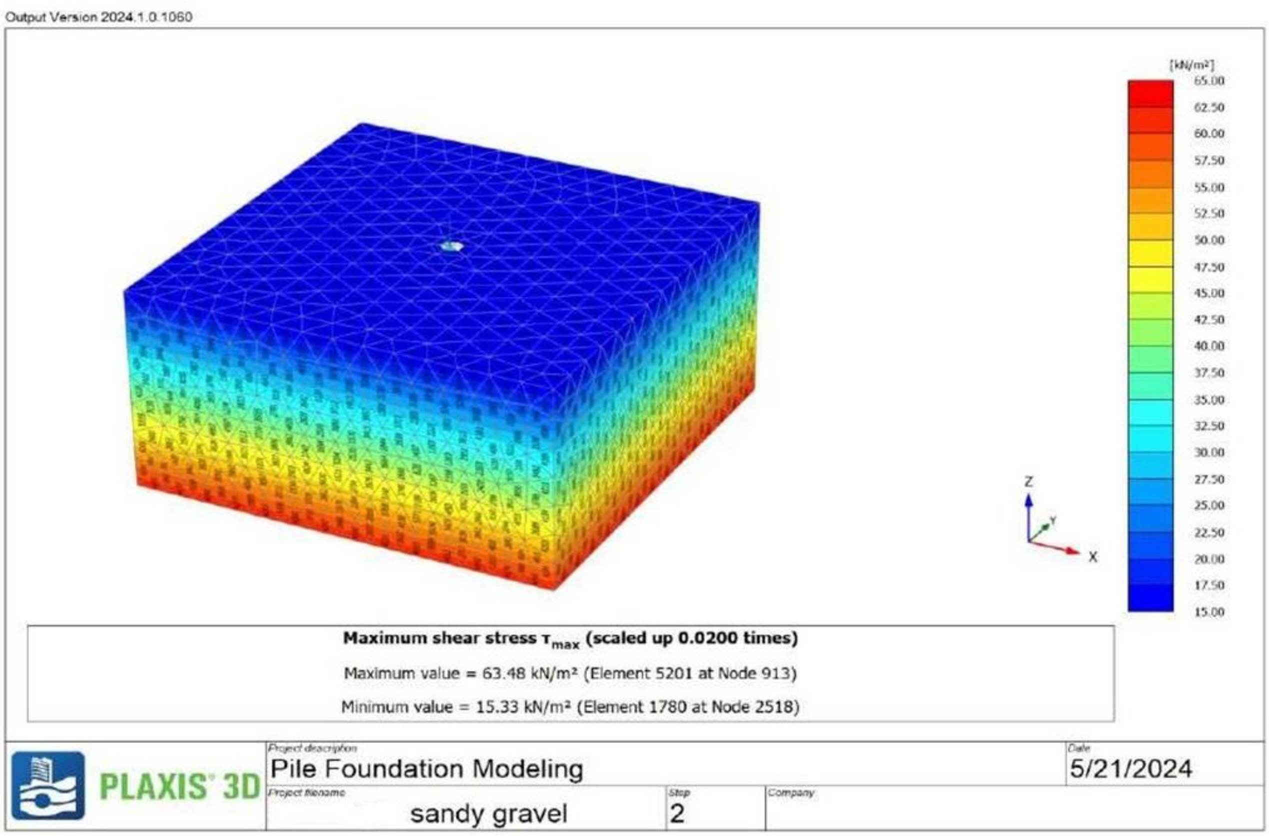
Output Version 2024.1.0.1060



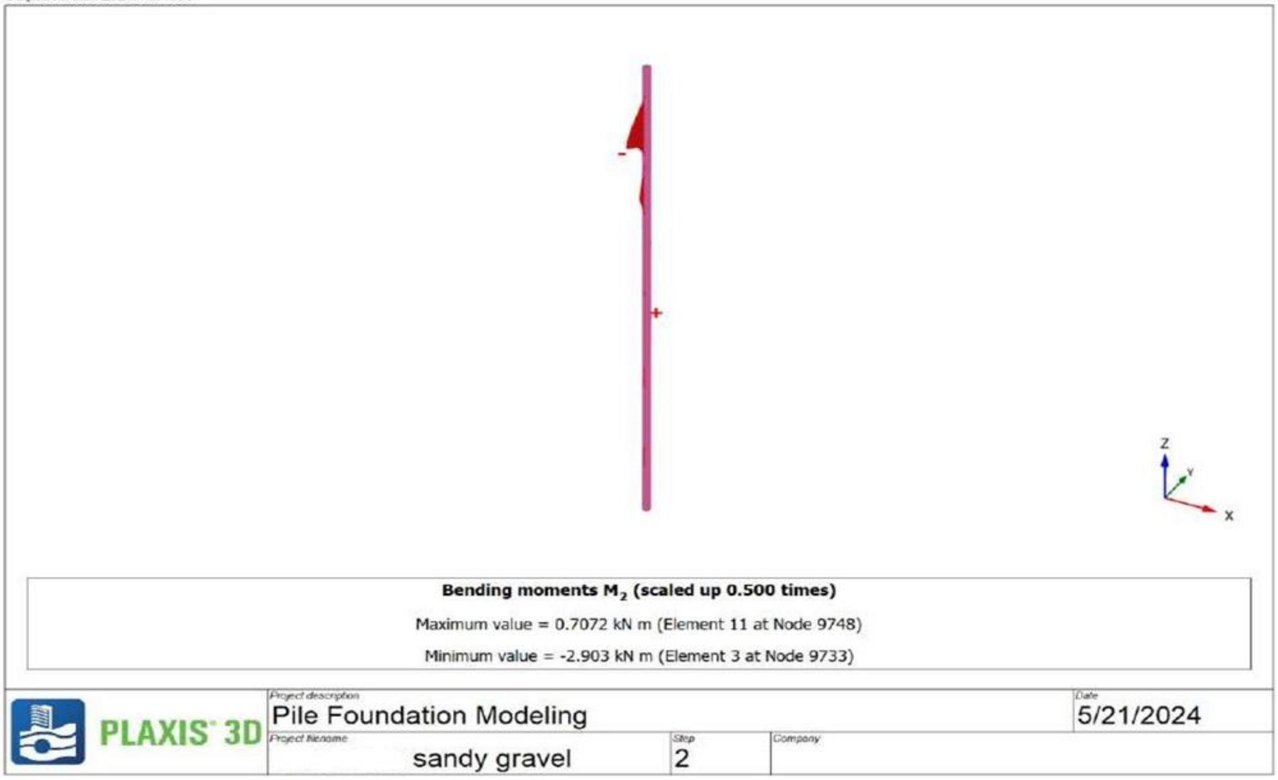
Output Version 2024.1.0.1060



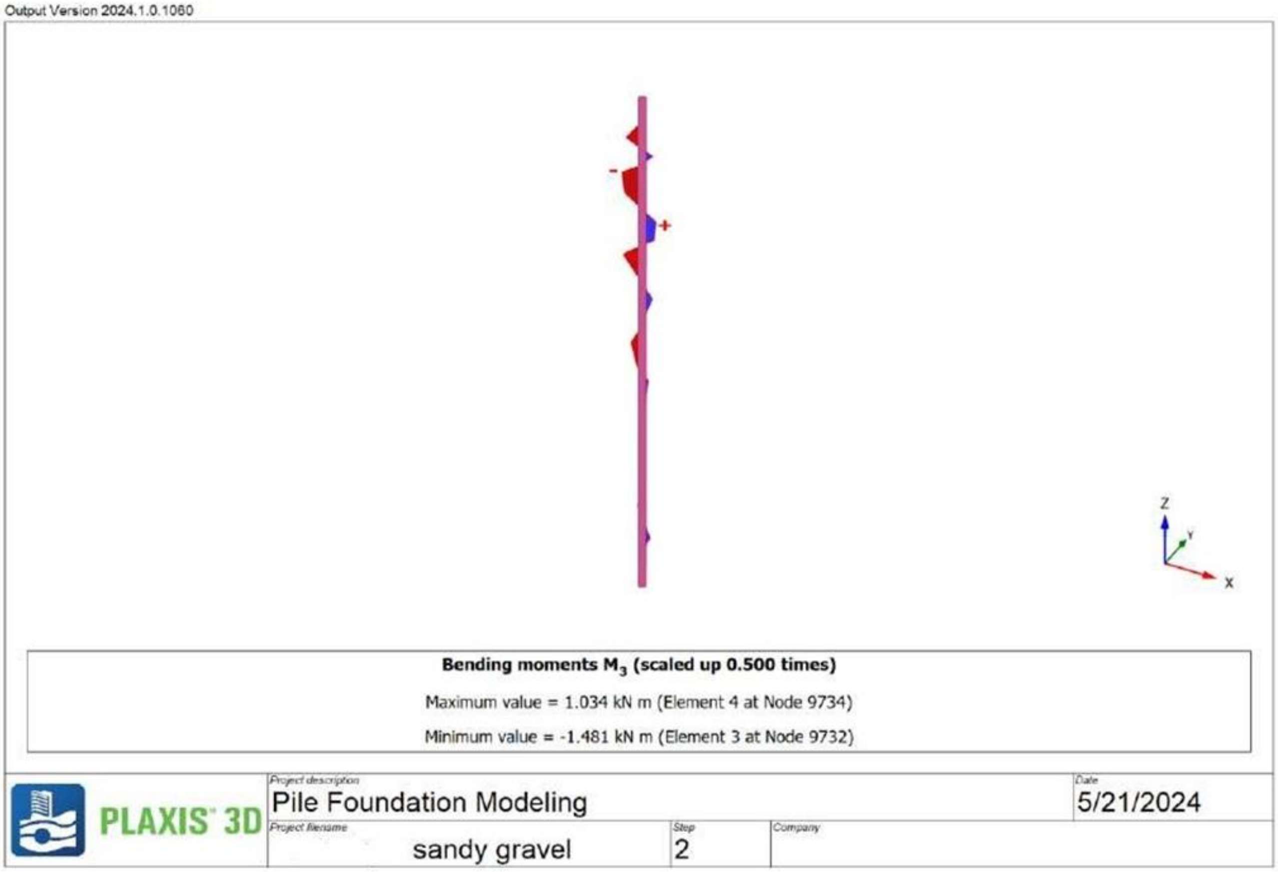

Output Version 2024.1.0.1060
[kN/m²]
-320.00
-300.00
-280.00
-260.00
-240.00
-220.00
-200.00
-180.00
-160.00
-140.00
-120.00
-100.00
-80.00
-60.00
-40.00
-20.00
0.00
Z
Y
X
Total mean stress p (scaled up 5.00*10^-3 times)
Maximum value = 0.1849 kN/m² (Element 1780 at Node 2518)
Minimum value = -303.7 kN/m² (Element 5201 at Node 913)
PLAXIS 3D
Project description
Pile Foundation Modeling
Project filename
sandy gravel
Step
2
Company
Date
5/21/2024


Output Version 2024.1.0.1060
[kN/m²]
65.00
62.50
60.00
57.50
55.00
52.50
50.00
47.50
45.00
42.50
40.00
37.50
35.00
32.50
30.00
27.50
25.00
22.50
20.00
17.50
15.00
Z
Y
X
Maximum shear stress τmax (scaled up 0.0200 times)
Maximum value = 63.48 kN/m² (Element 5201 at Node 913)
Minimum value = 15.33 kN/m² (Element 1780 at Node 2518)
PLAXIS 3D
Project description
Pile Foundation Modeling
Project filename
sandy gravel
Step
2
Company
Date
5/21/2024

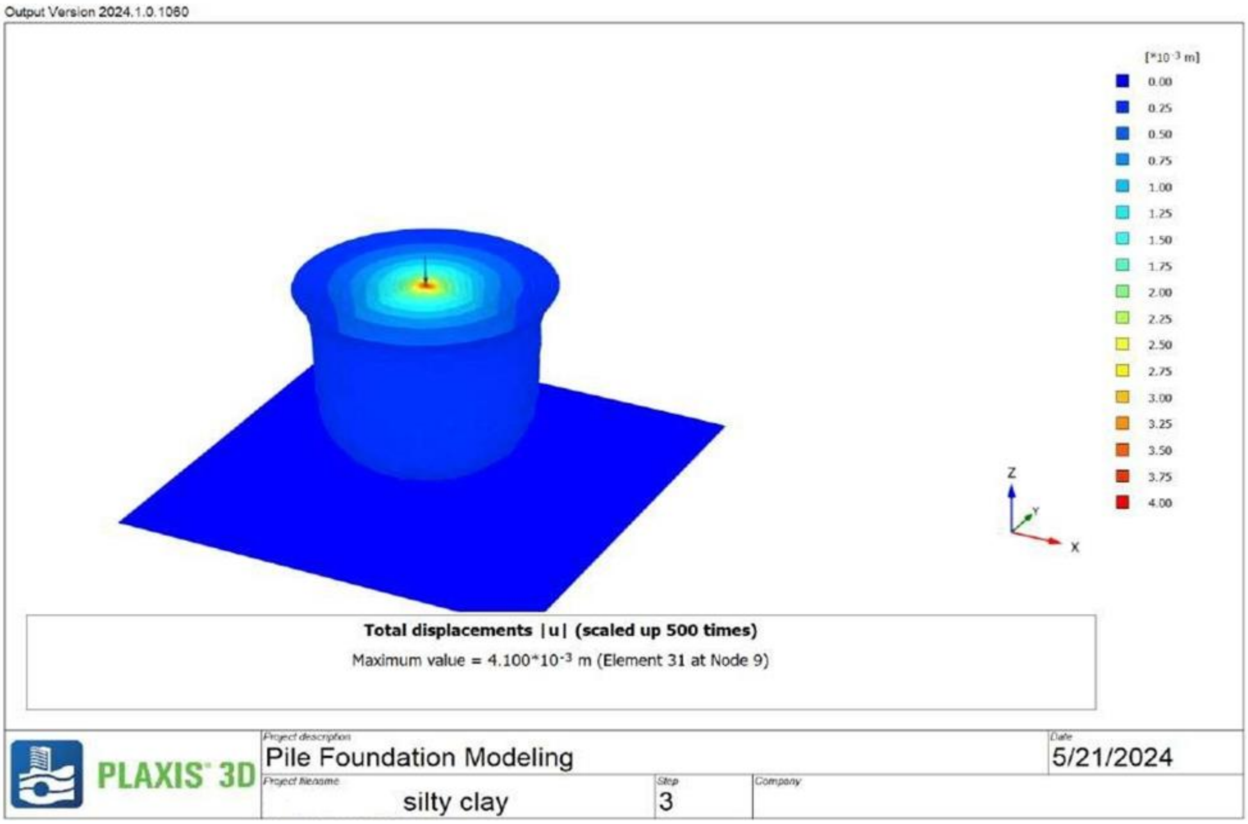
Output Version 2024.1.0.1060

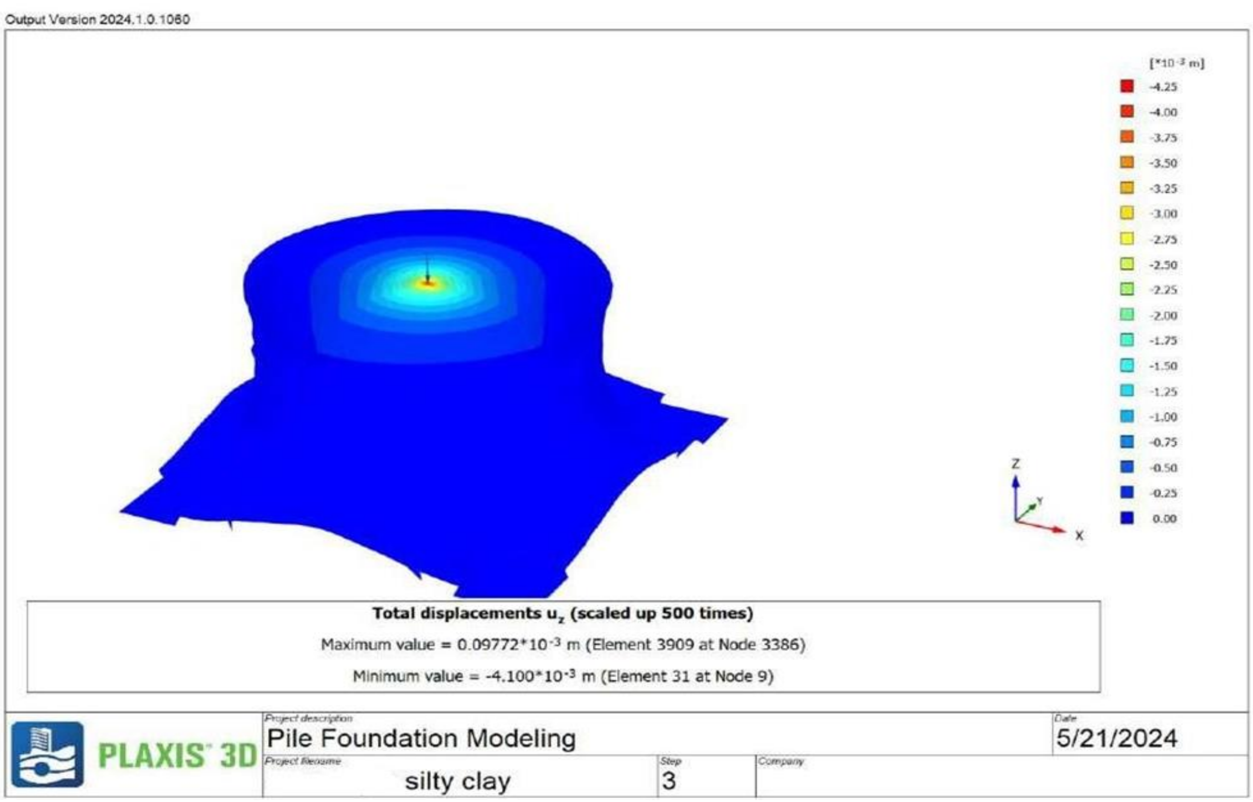


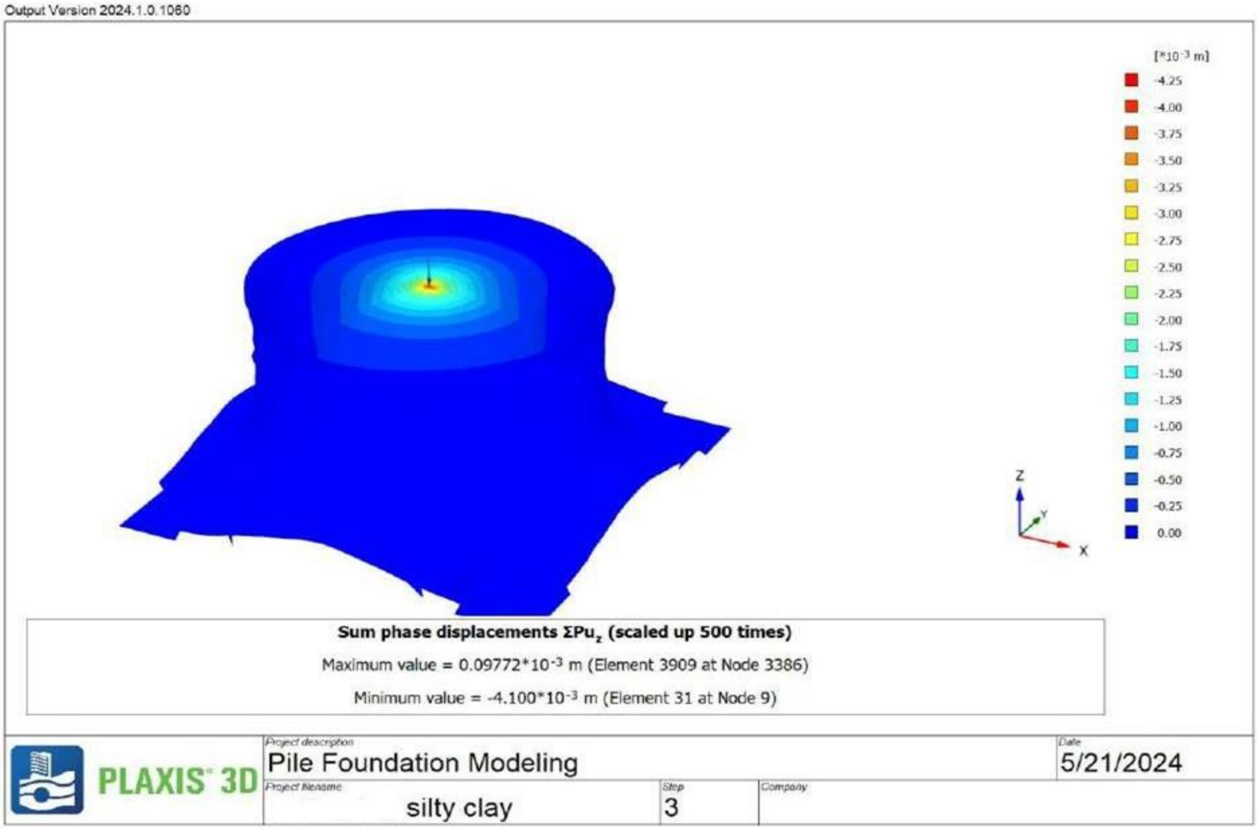
Output Version 2024.1.0.1060

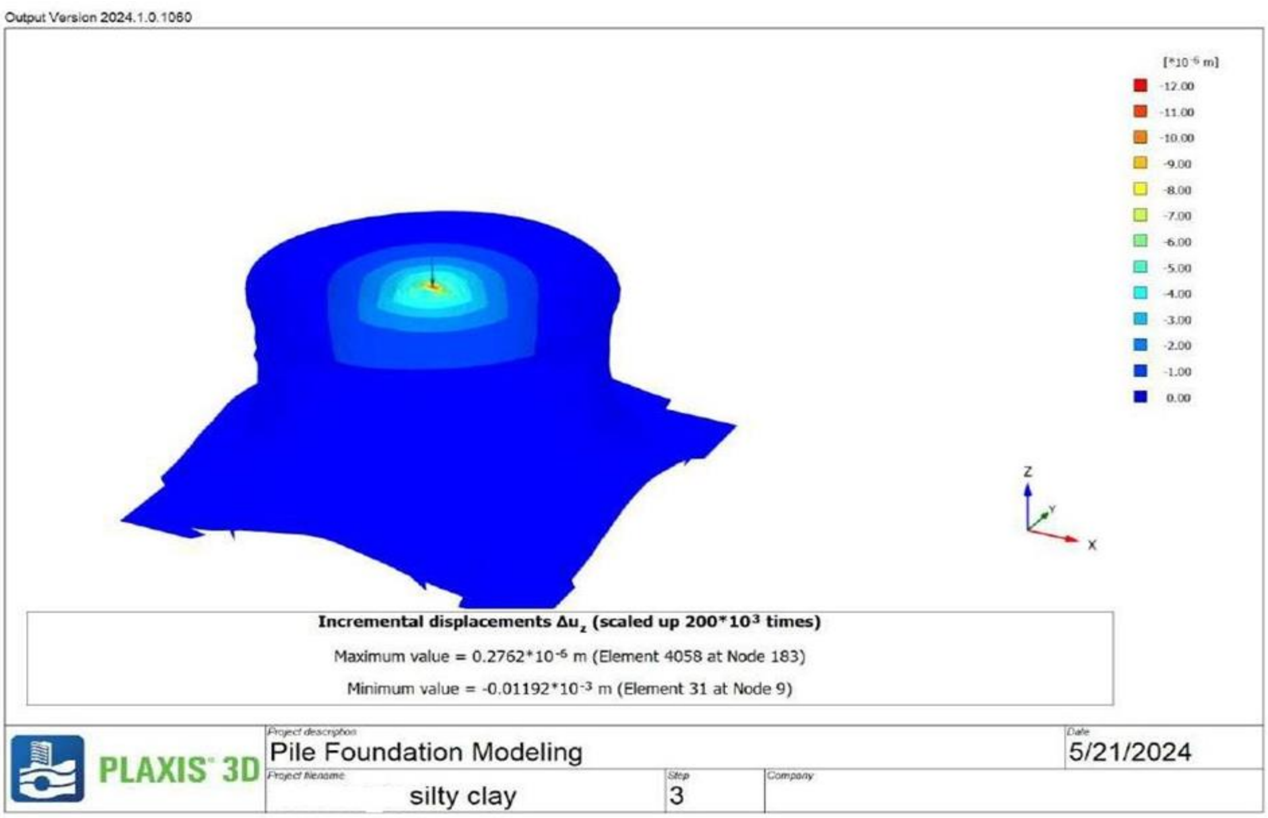


APPENDEX – E

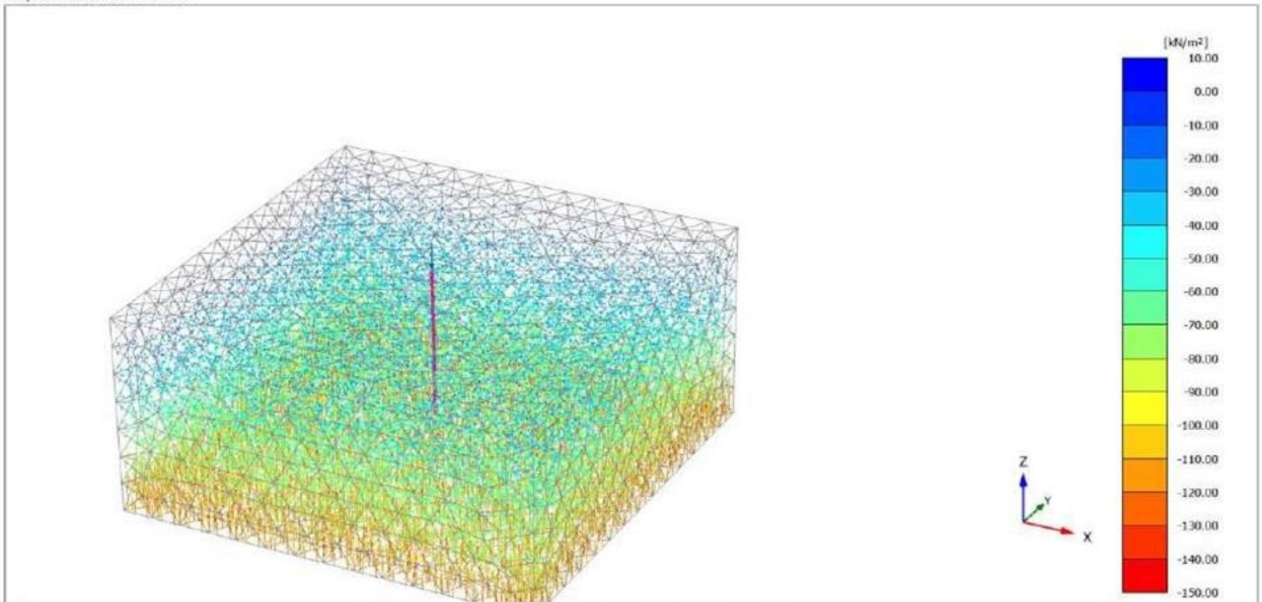

Output Version 2024.1.0.1060
[*10^-3 m]
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50
3.75
4.00
Z
Y
X
Total displacements |u| (scaled up 500 times)
Maximum value = 4.100*10^-3 m (Element 31 at Node 9)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
silty clay
Step
3
Company


Output Version 2024.1.0.1060
[*10^-3 m]
-4.25
-4.00
-3.75
-3.50
-3.25
-3.00
-2.75
-2.50
-2.25
-2.00
-1.75
-1.50
-1.25
-1.00
-0.75
-0.50
-0.25
0.00
Z
Y
X
Total displacements u_z (scaled up 500 times)
Maximum value = 0.09772*10^-3 m (Element 3909 at Node 3386)
Minimum value = -4.100*10^-3 m (Element 31 at Node 9)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
silty clay
Step
3
Company


Output Version 2024.1.0.1060
[*10⁻³ m]
-4.25
-4.00
-3.75
-3.50
-3.25
-3.00
-2.75
-2.50
-2.25
-2.00
-1.75
-1.50
-1.25
-1.00
-0.75
-0.50
-0.25
0.00
Z
Y
X
Sum phase displacements ΣPu_z (scaled up 500 times)
Maximum value = 0.09772*10^-3 m (Element 3909 at Node 3386)
Minimum value = -4.100*10^-3 m (Element 31 at Node 9)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
silty clay
Step
3
Company


Output Version 2024.1.0.1060
[*10⁻⁶ m]
-12.00
-11.00
-10.00
-9.00
-8.00
-7.00
-6.00
-5.00
-4.00
-3.00
-2.00
-1.00
0.00
Z
Y
X
Incremental displacements Δu_z (scaled up 200*10³ times)
Maximum value = 0.2762*10^-6 m (Element 4058 at Node 183)
Minimum value = -0.01192*10^-3 m (Element 31 at Node 9)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
silty clay
Step
3
Company

Output Version 2024.1.0.1060



Effective principal stresses (scaled up 0.0100 times)

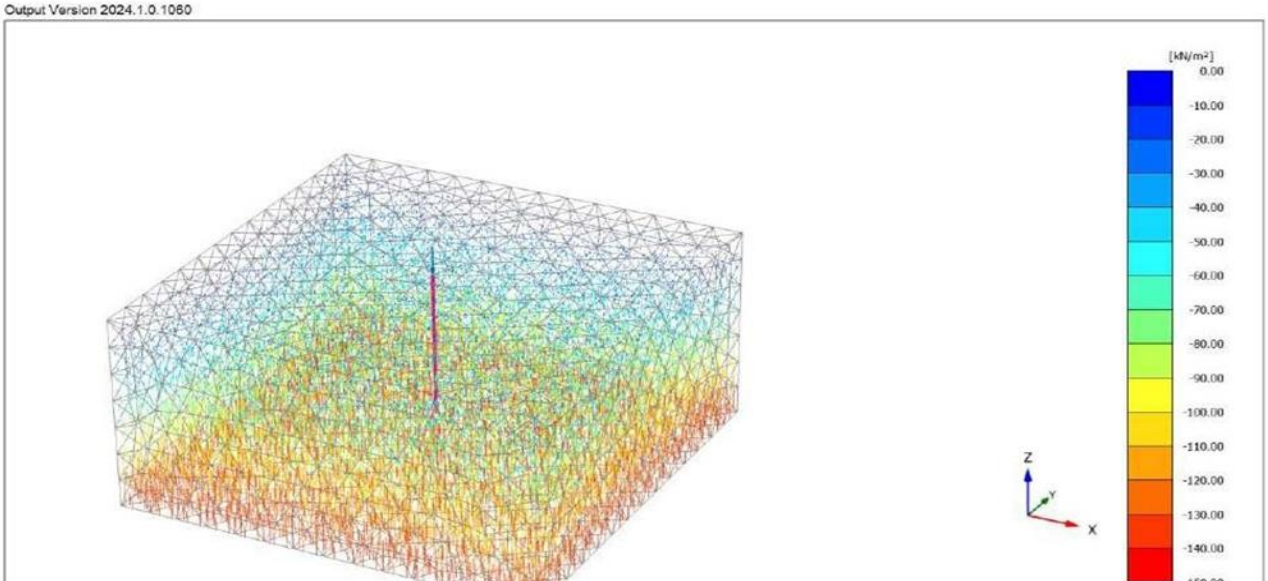
Maximum value = $5.329 \cdot 10^{-15}$ kN/m² (Element 817 at Stress point 3268)

Minimum value = -145.1 kN/m² (Element 3557 at Stress point 14228)

PLAXIS 3D

Project description	Date	
Pile Foundation Modeling	5/21/2024	
Project filename: silty clay	Step: 3	Company

Output Version 2024.1.0.1060



Principal effective stress σ'_1 (scaled up 0.0100 times)

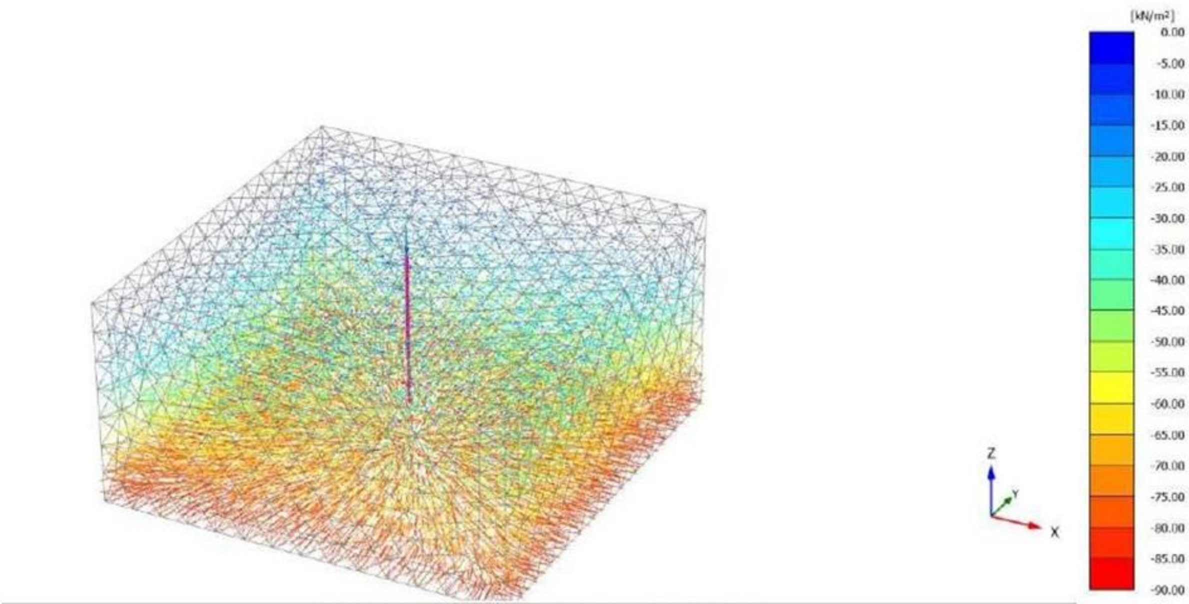
Maximum value = -1.826 kN/m² (Element 4180 at Stress point 16718)

Minimum value = -145.1 kN/m² (Element 3557 at Stress point 14228)

PLAXIS 3D

Project description	Date	
Pile Foundation Modeling	5/21/2024	
Project filename: silty clay	Step: 3	Company

Output Version 2024.1.0.1060



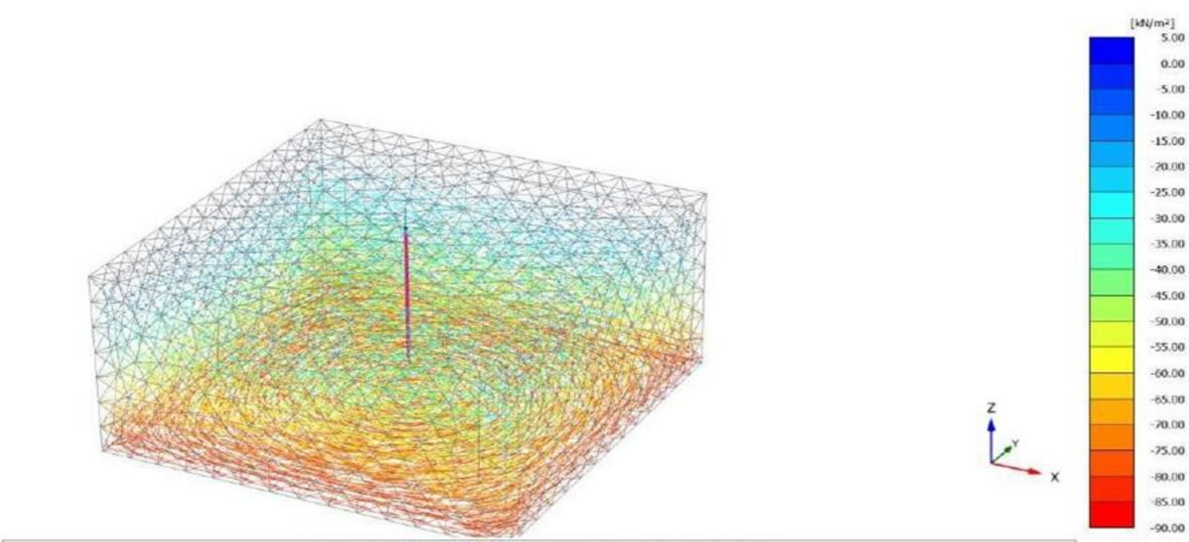
Principal effective stress σ'$_2$ (scaled up 0.0200 times)

Maximum value = -1.016 kN/m² (Element 3534 at Stress point 14133)

Minimum value = -88.49 kN/m² (Element 3557 at Stress point 14228)

PLAXIS 3D	Project description: Pile Foundation Modeling		Date: 5/21/2024
	Project filename: silty clay	Step: 3	Company:

Output Version 2024.1.0.1060

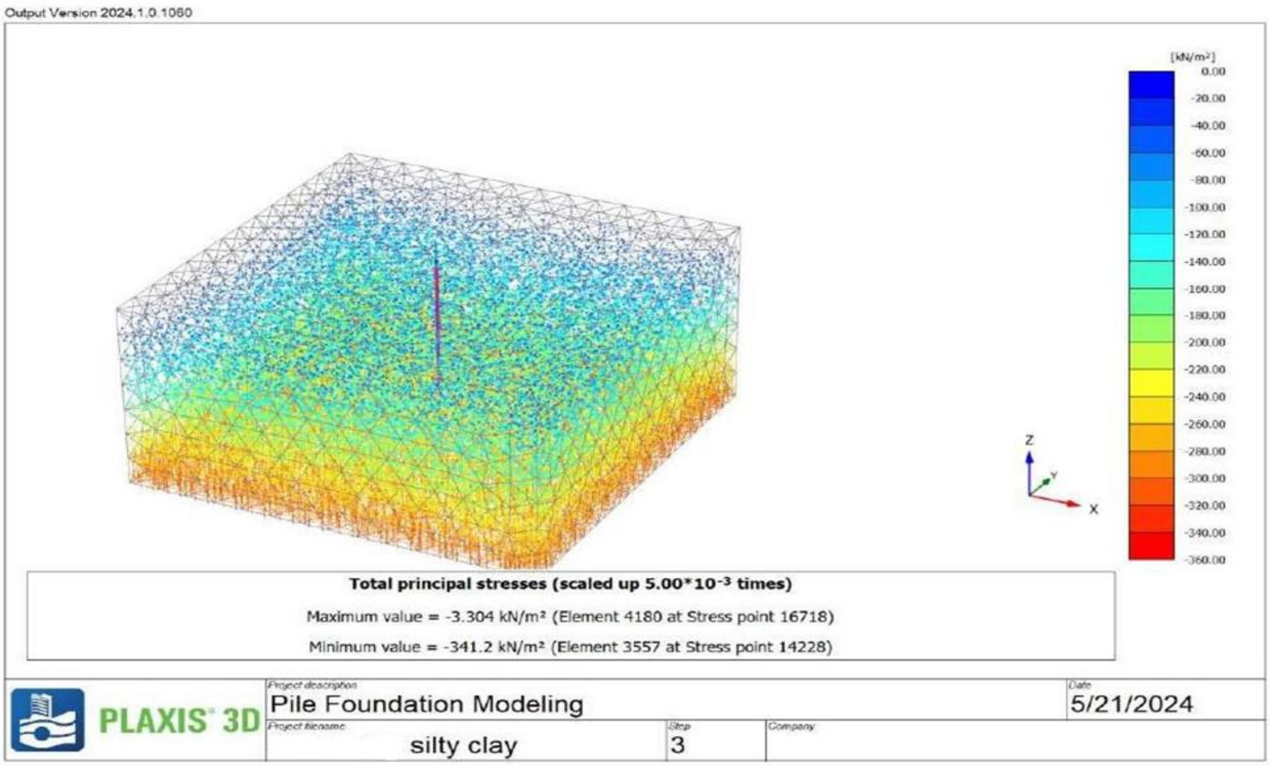


Principal effective stress σ'$_3$ (scaled up 0.0200 times)

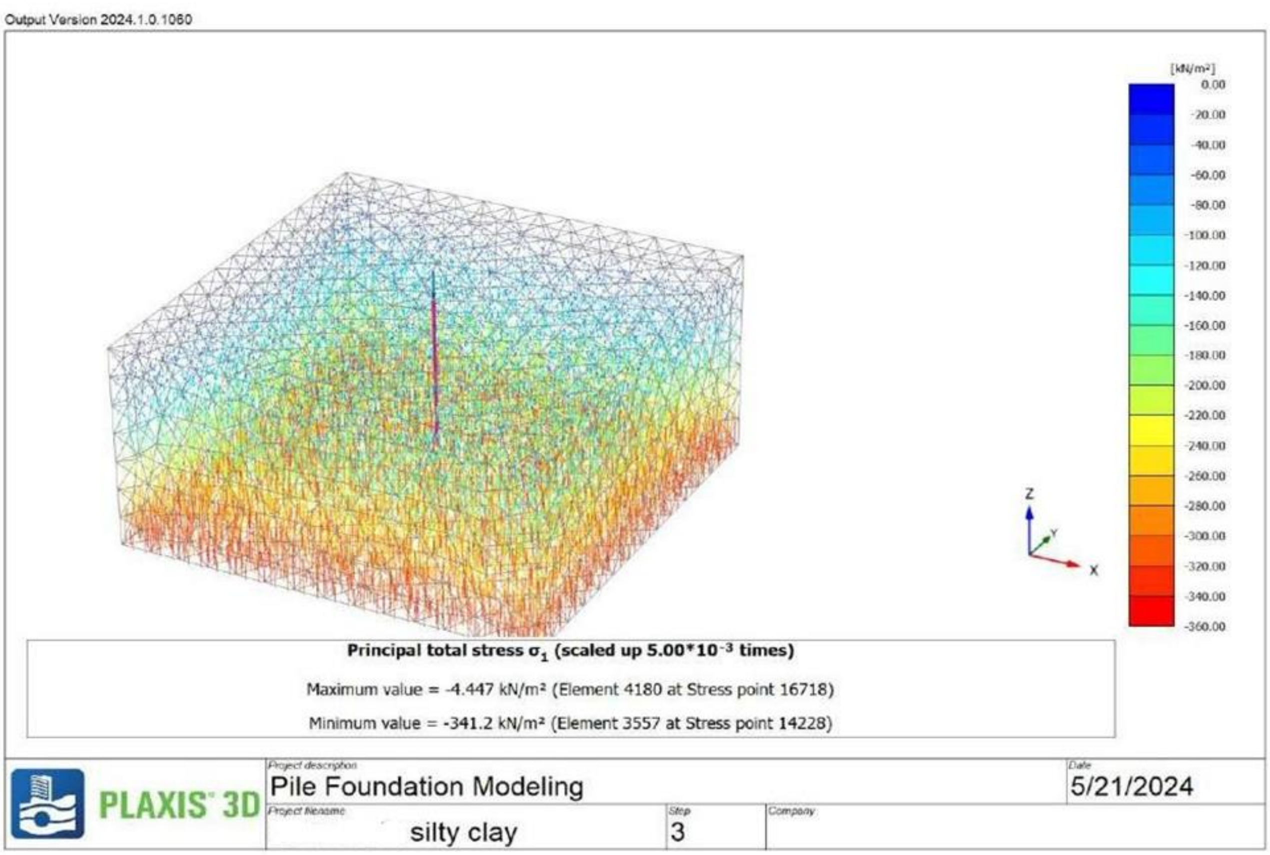
Maximum value = 5.329×10^{-15} kN/m² (Element 817 at Stress point 3268)

Minimum value = -88.34 kN/m² (Element 3557 at Stress point 14228)

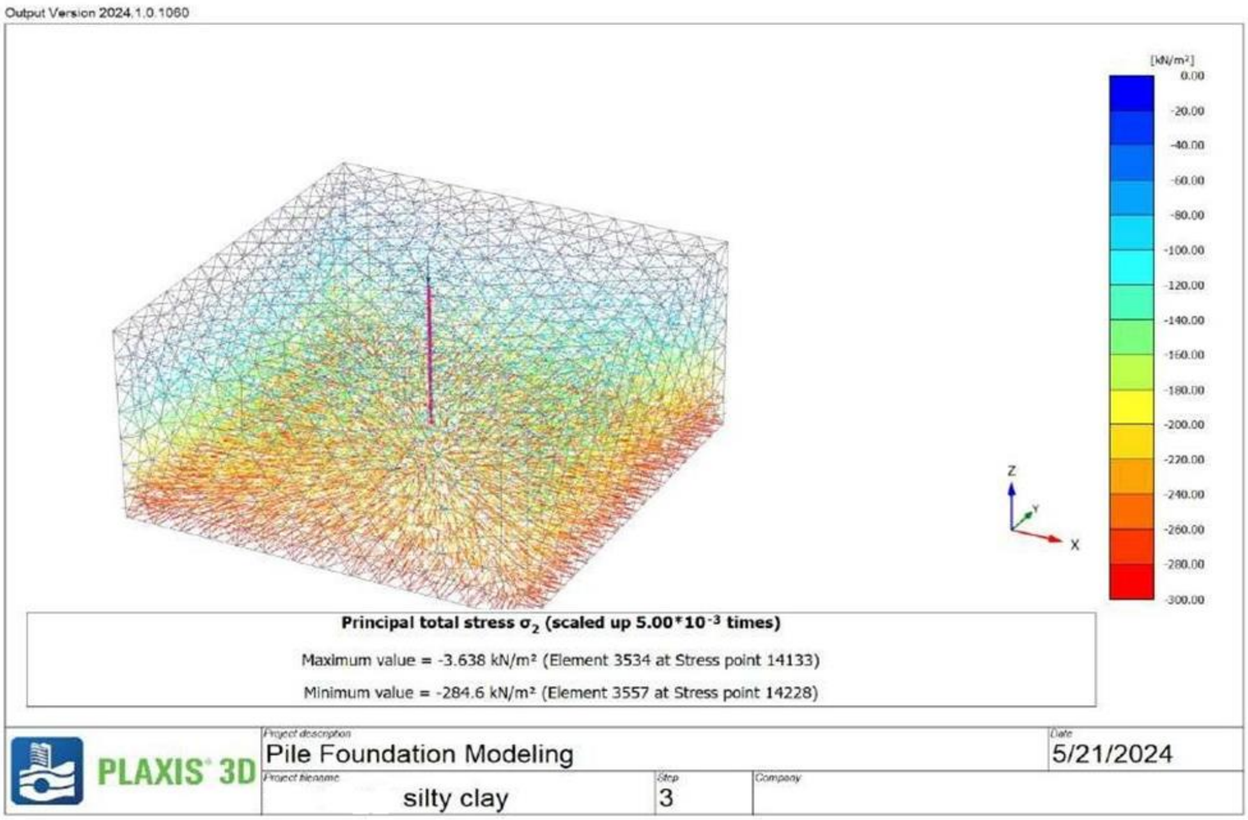
PLAXIS 3D	Project description: Pile Foundation Modeling		Date: 5/21/2024
	Project filename: silty clay	Step: 3	Company:

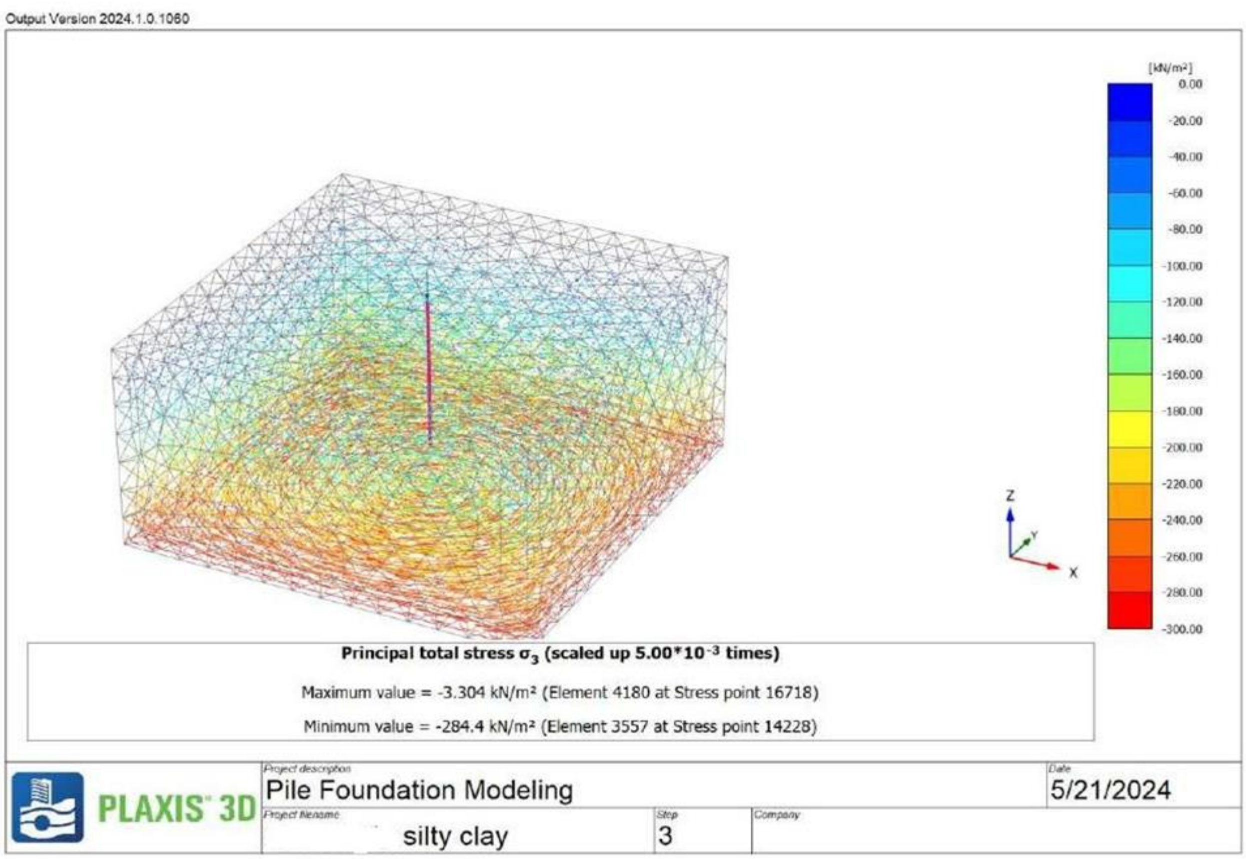


Output Version 2024.1.0.1060
[kN/m²]
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
Z
Y
X
Total principal stresses (scaled up 5.00*10⁻³ times)
Maximum value = -3.304 kN/m² (Element 4180 at Stress point 16718)
Minimum value = -341.2 kN/m² (Element 3557 at Stress point 14228)
PLAXIS 3D
Project description
Pile Foundation Modeling
Project filename
silty clay
Step
3
Company
Date
5/21/2024

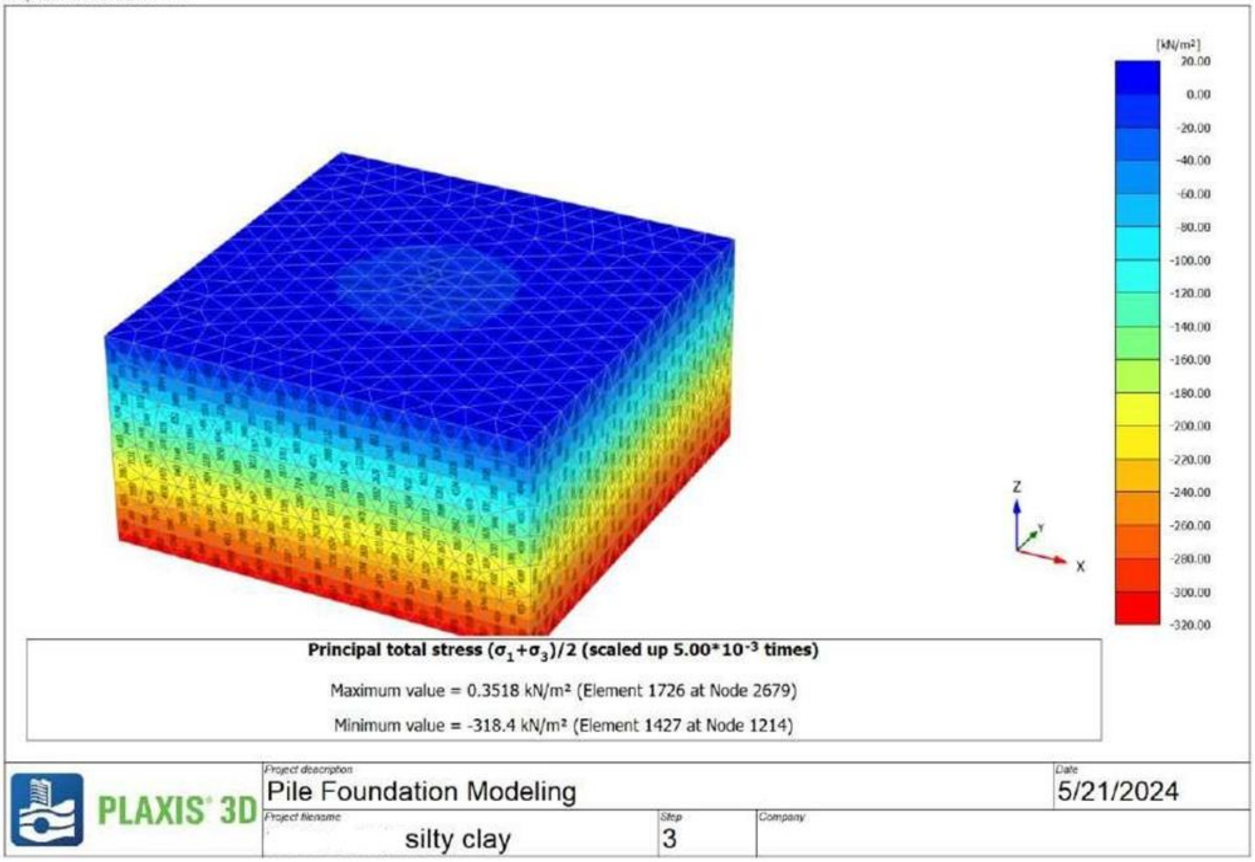


Output Version 2024.1.0.1060
[kN/m²]
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
Z
Y
X
Principal total stress σ1 (scaled up 5.00*10⁻³ times)
Maximum value = -4.447 kN/m² (Element 4180 at Stress point 16718)
Minimum value = -341.2 kN/m² (Element 3557 at Stress point 14228)
PLAXIS 3D
Project description
Pile Foundation Modeling
Project filename
silty clay
Step
3
Company
Date
5/21/2024

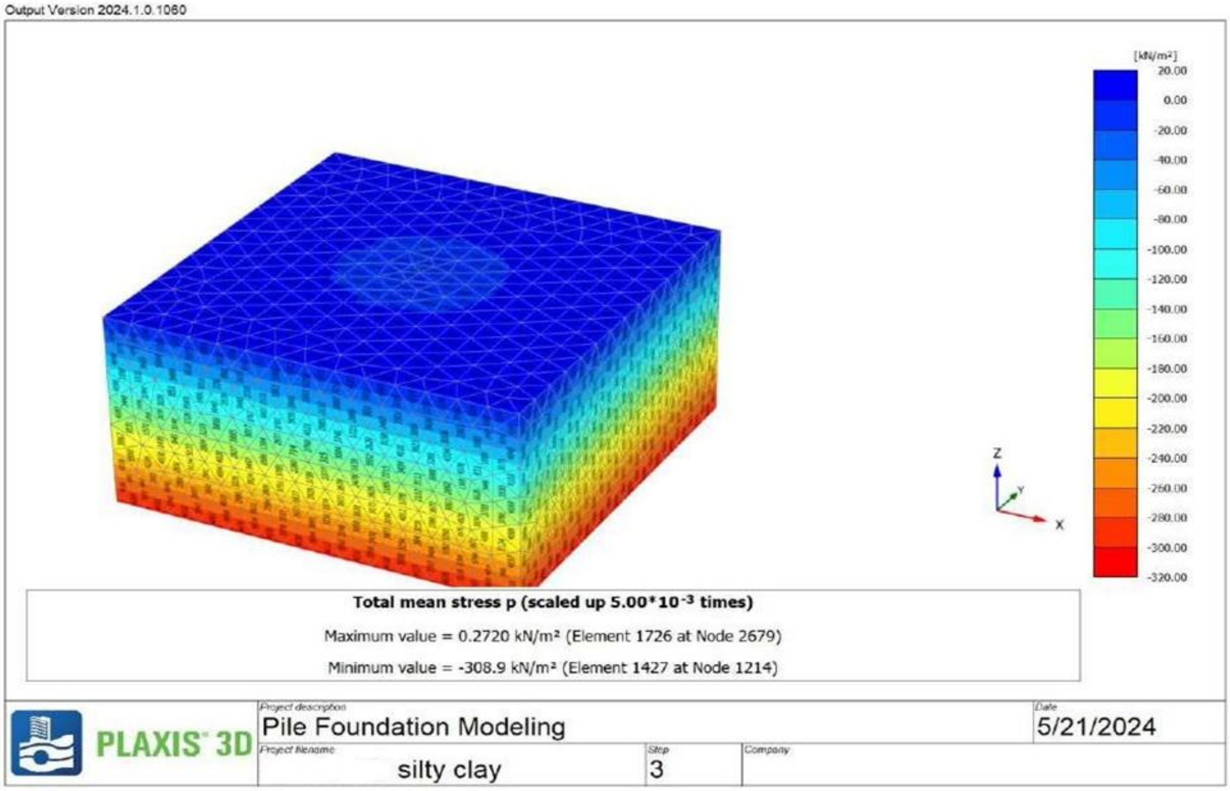

Output Version 2024.1.0.1060
[kN/m²]
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
Z
Y
X
Principal total stress σ2 (scaled up 5.00*10-3 times)
Maximum value = -3.638 kN/m² (Element 3534 at Stress point 14133)
Minimum value = -284.6 kN/m² (Element 3557 at Stress point 14228)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
silty clay
Step
3
Company


Output Version 2024.1.0.1060
[kN/m²]
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
Z
Y
X
Principal total stress σ3 (scaled up 5.00*10-3 times)
Maximum value = -3.304 kN/m² (Element 4180 at Stress point 16718)
Minimum value = -284.4 kN/m² (Element 3557 at Stress point 14228)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
silty clay
Step
3
Company

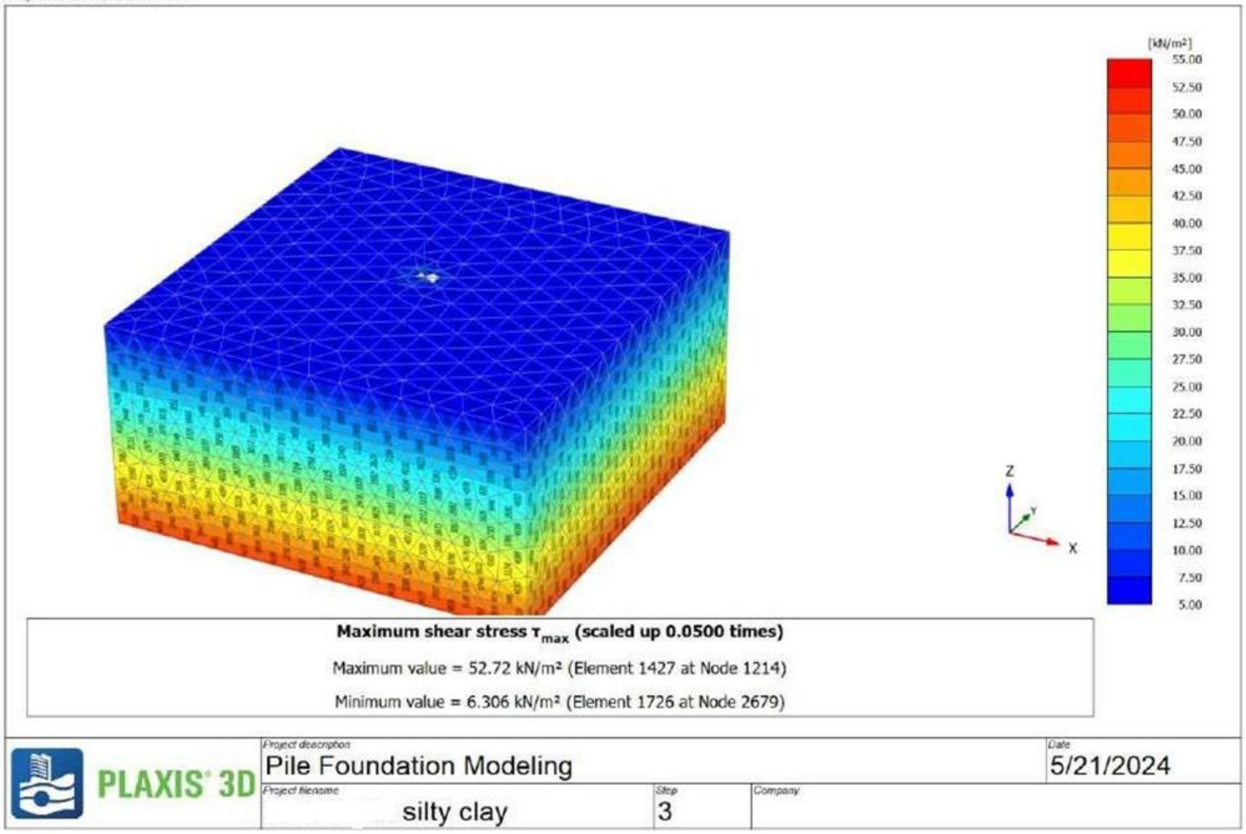
Output Version 2024.1.0.1060



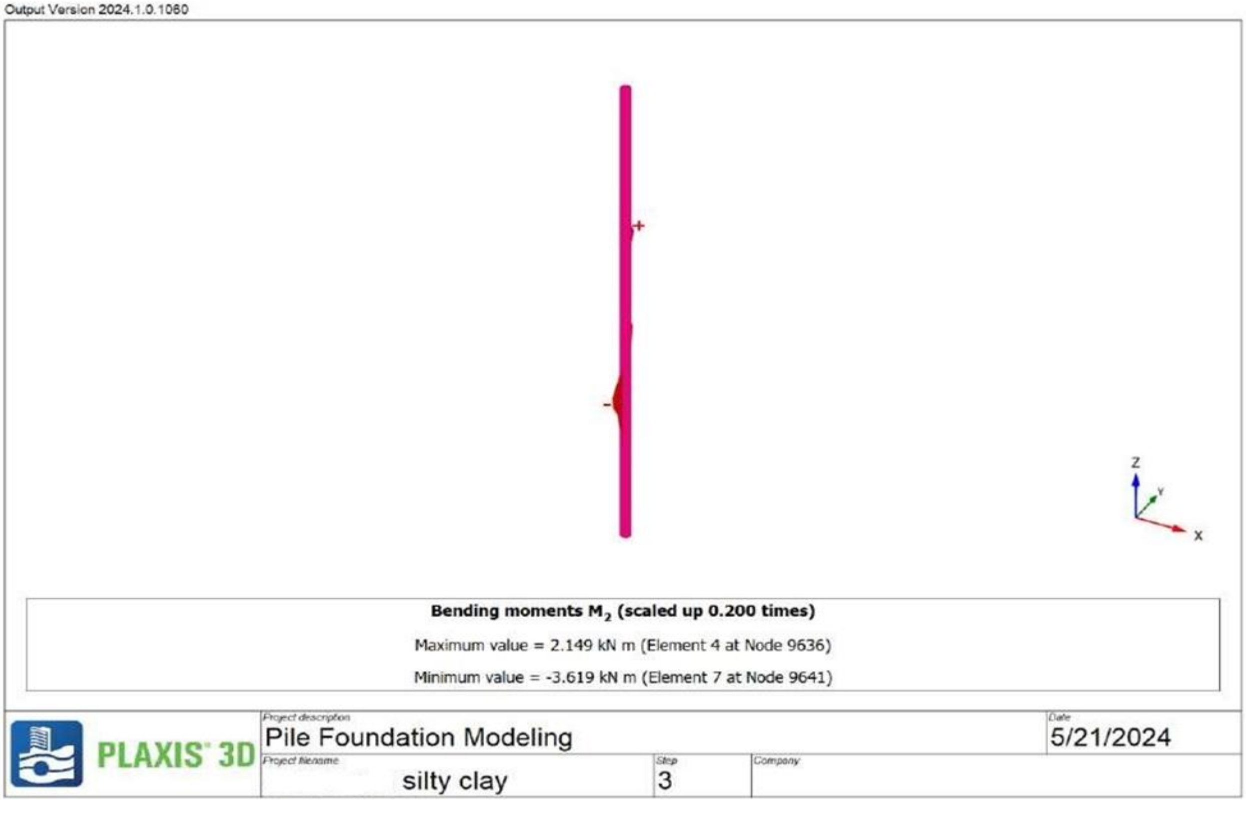
Output Version 2024.1.0.1060

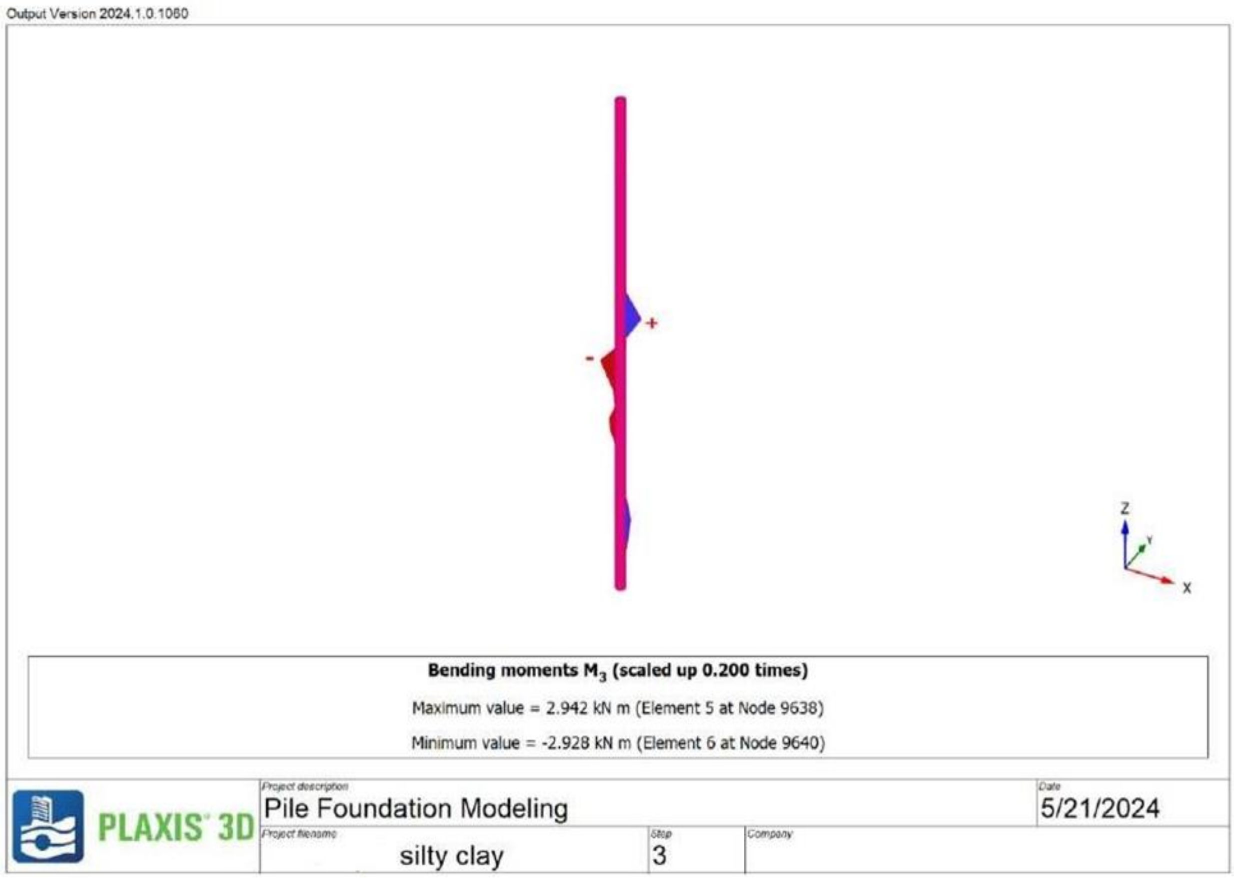


Output Version 2024.1.0.1060



Output Version 2024.1.0.1060

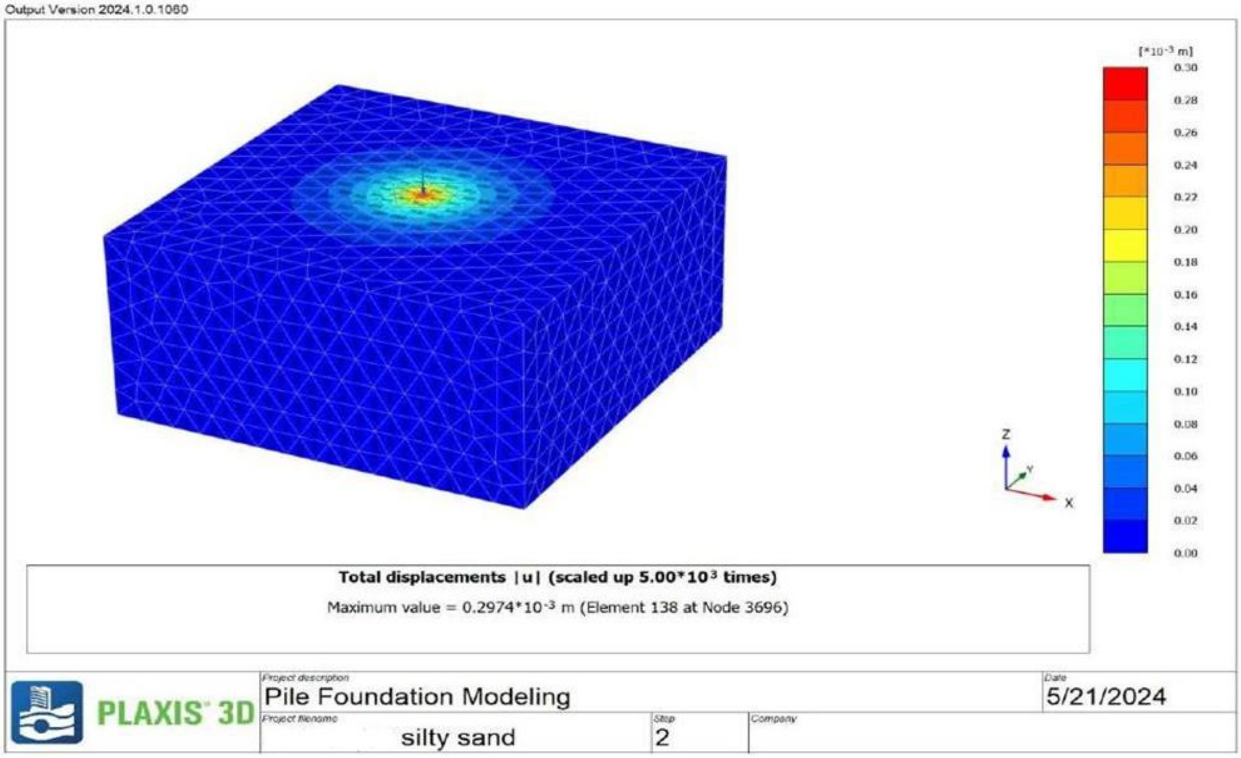




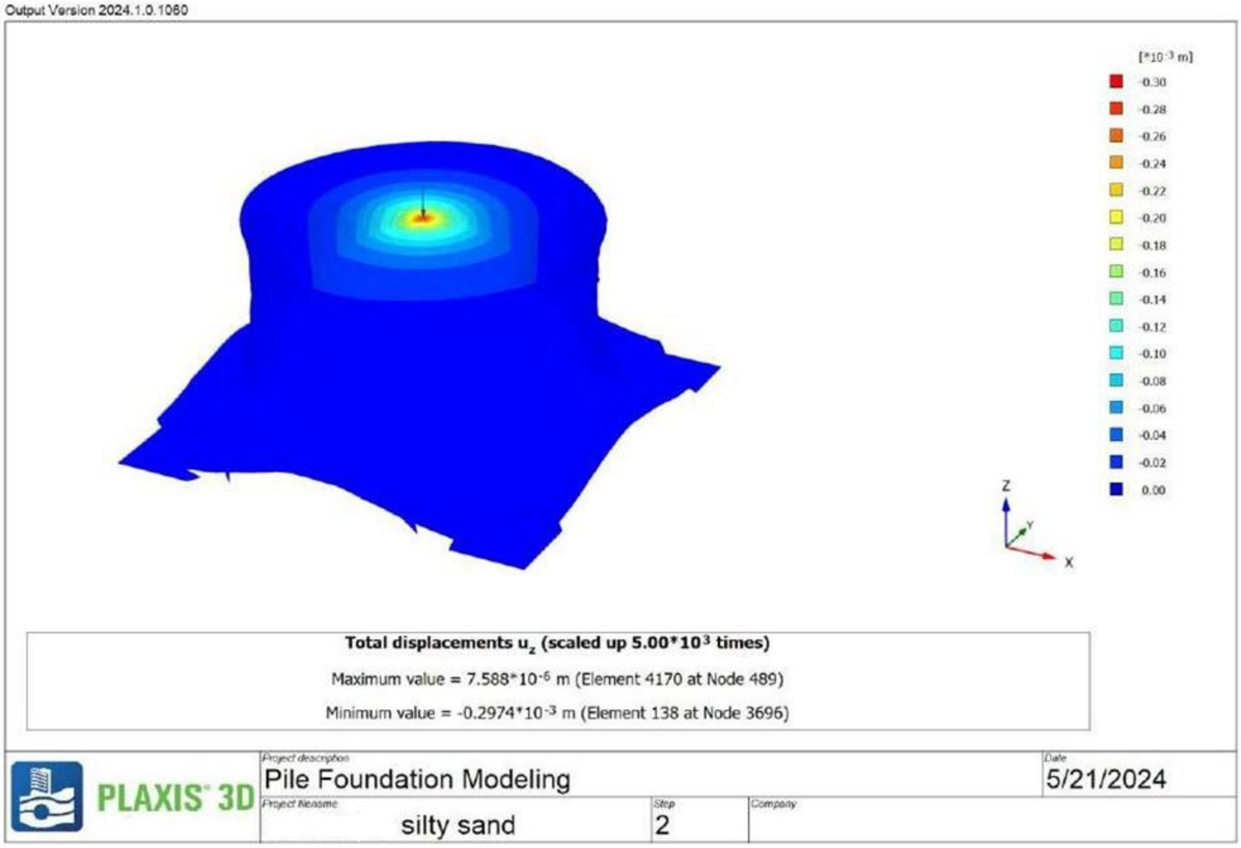
Output Version 2024.1.0.1060
+
-
Z
Y
X
Bending moments M3 (scaled up 0.200 times)
Maximum value = 2.942 kN m (Element 5 at Node 9638)
Minimum value = -2.928 kN m (Element 6 at Node 9640)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
silty clay
Step
3
Company

APPENDEX –F

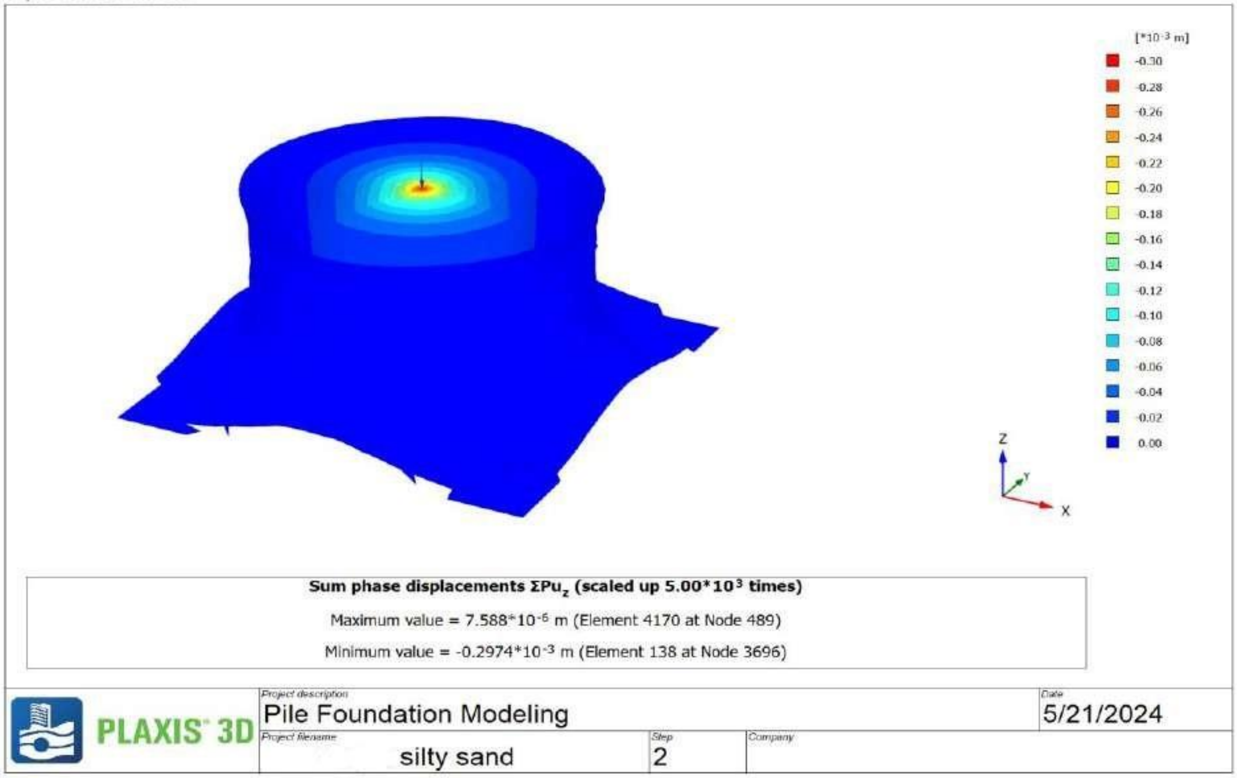
Output Version 2024.1.0.1060



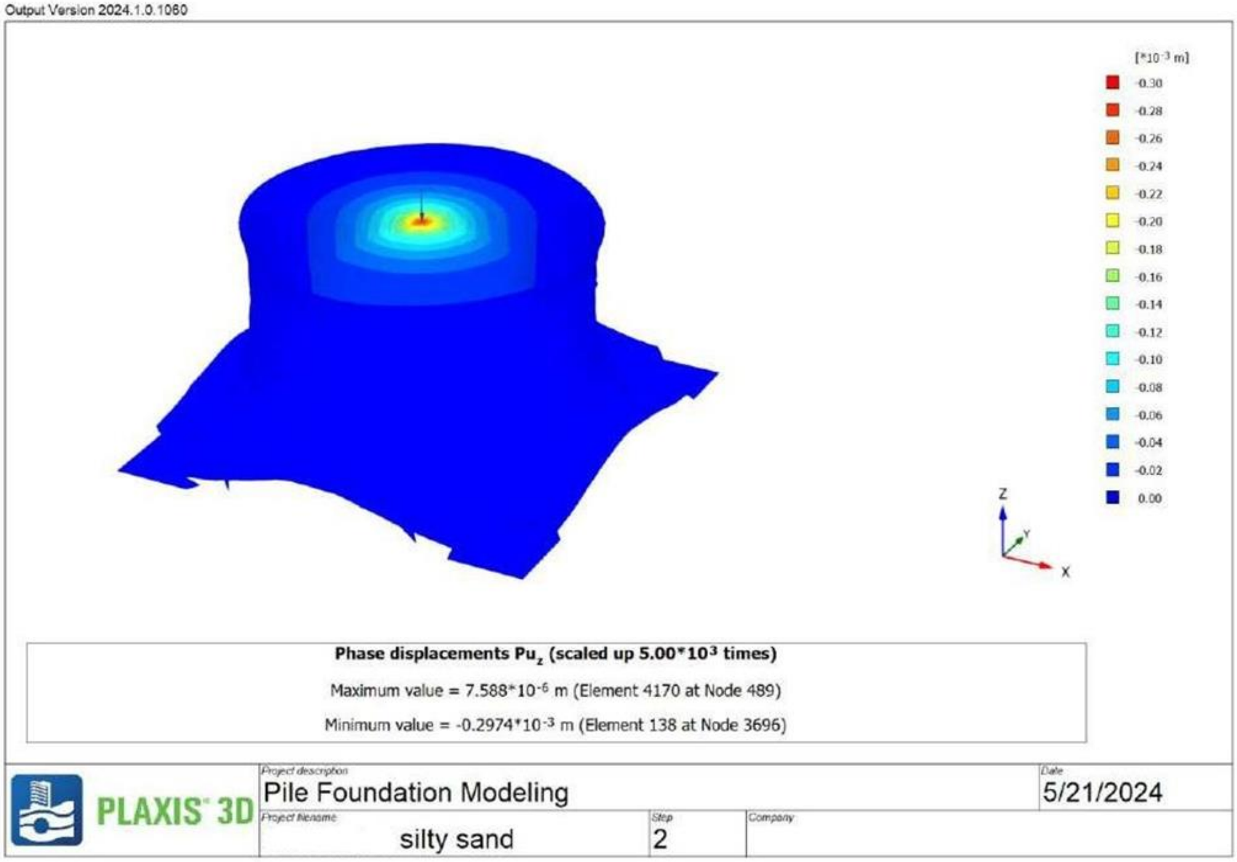
Output Version 2024.1.0.1060



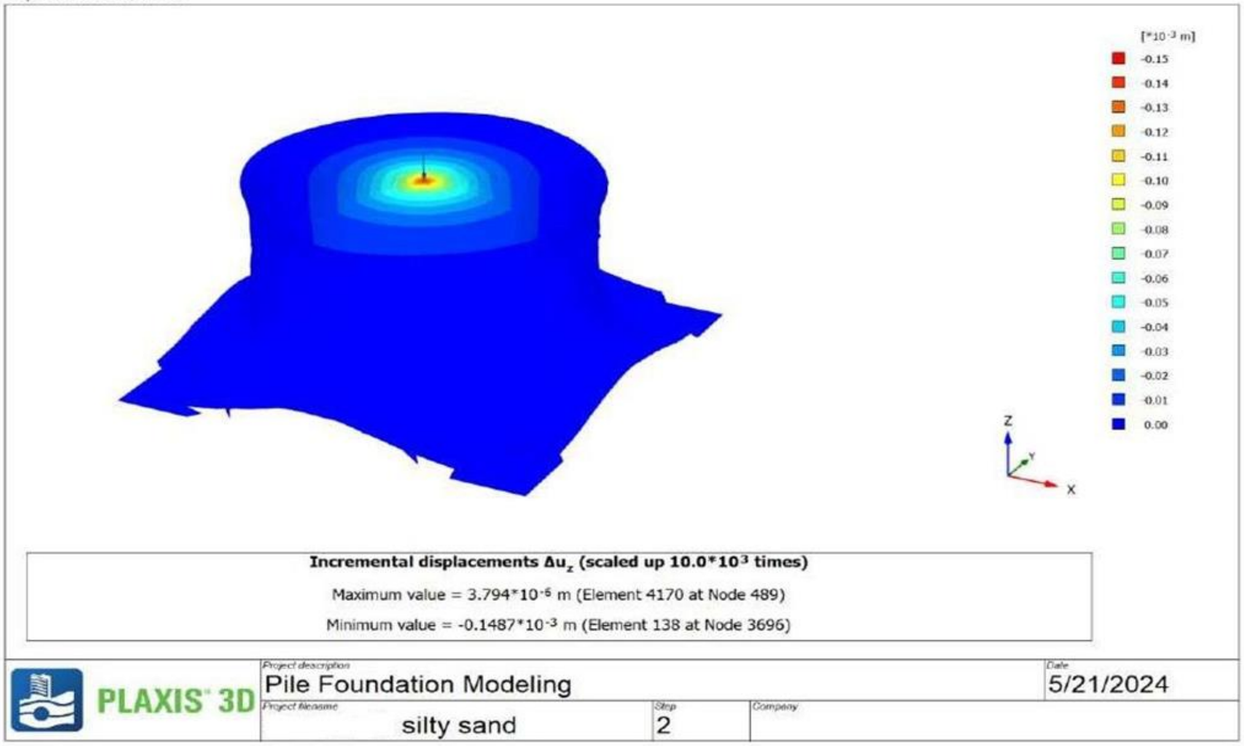
Output Version 2024.1.0.1060



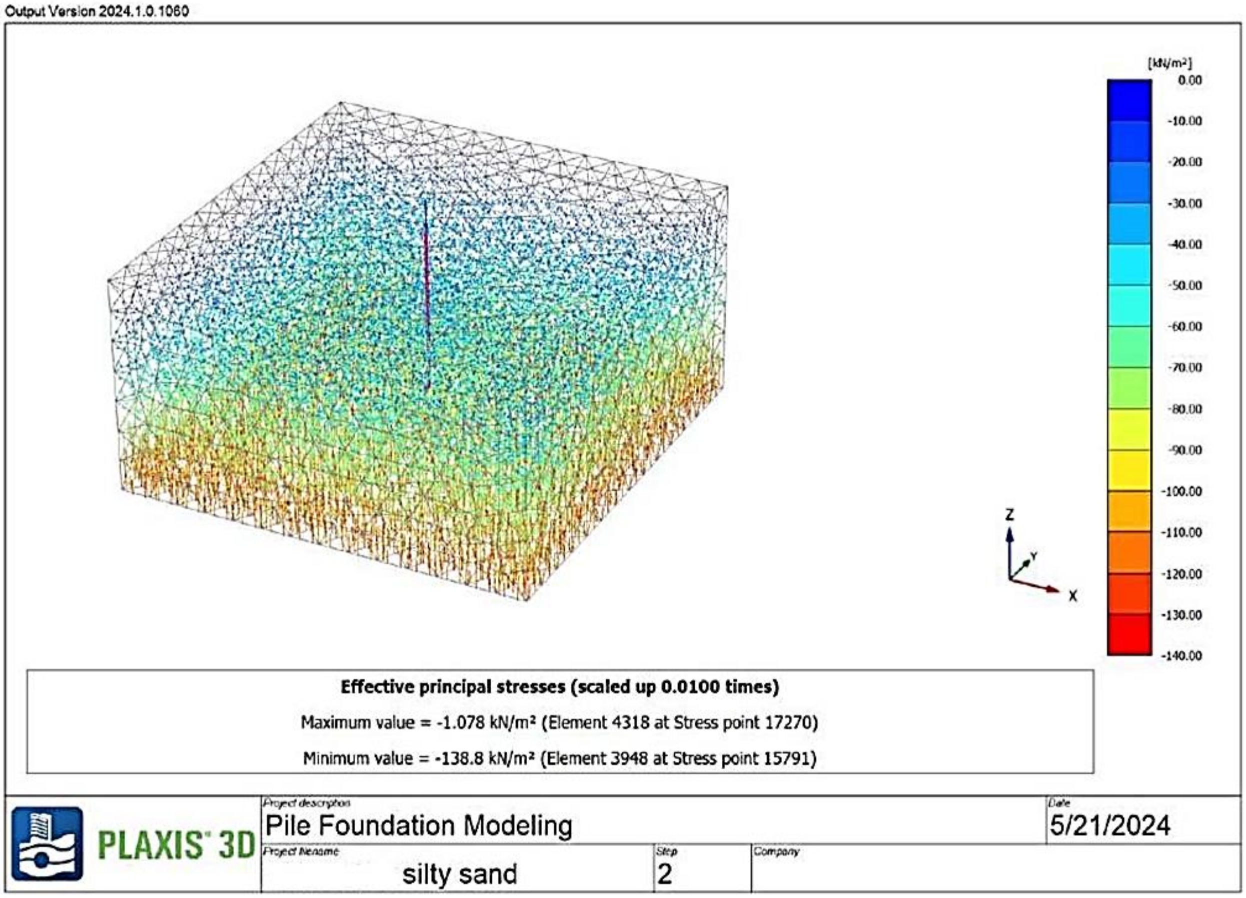
Output Version 2024.1.0.1060

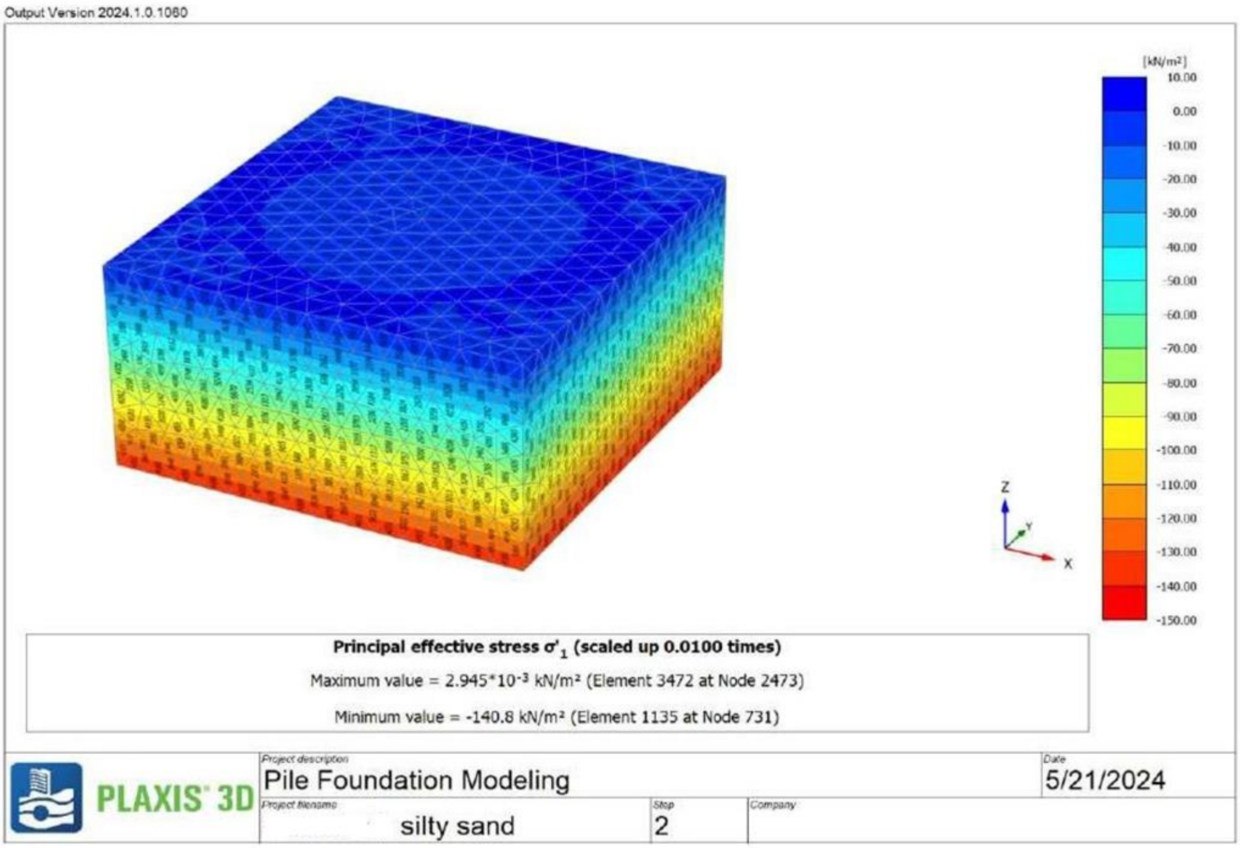


Output Version 2024.1.0.1060

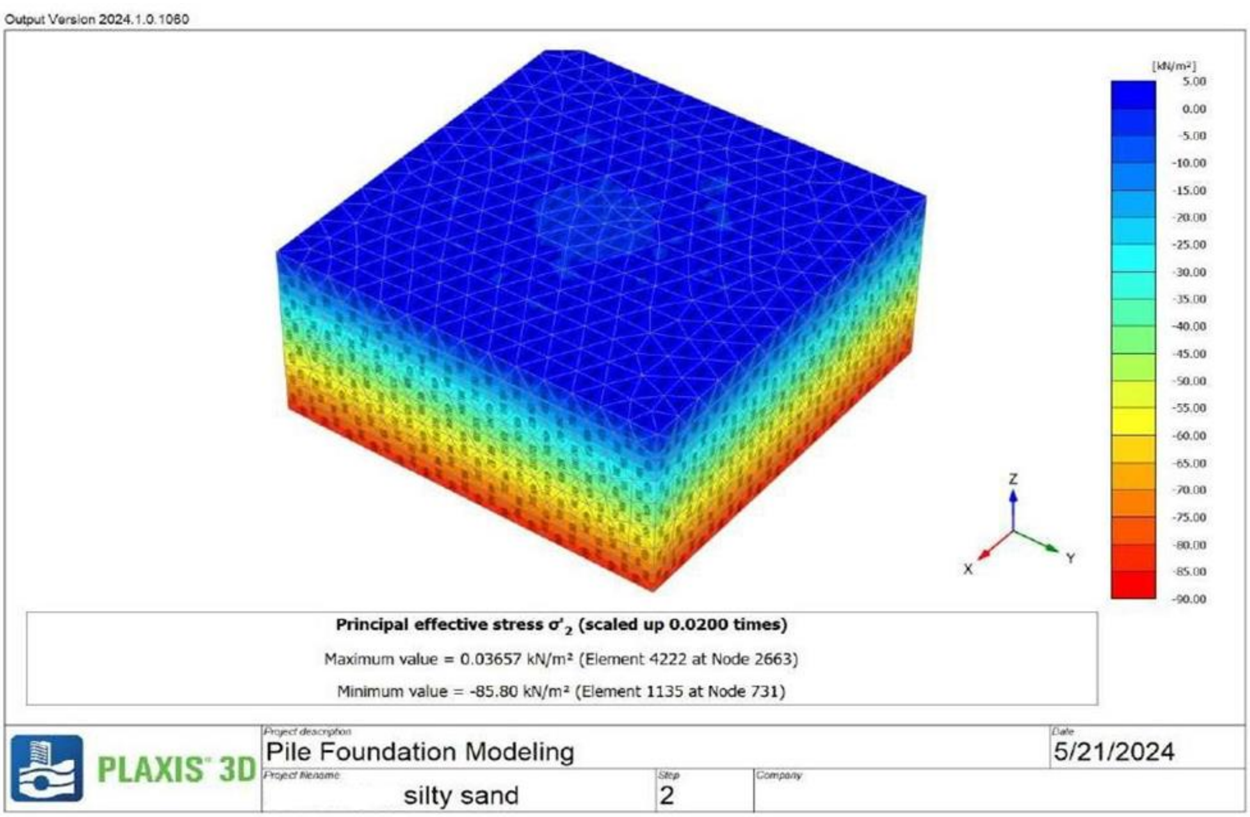


Output Version 2024.1.0.1060

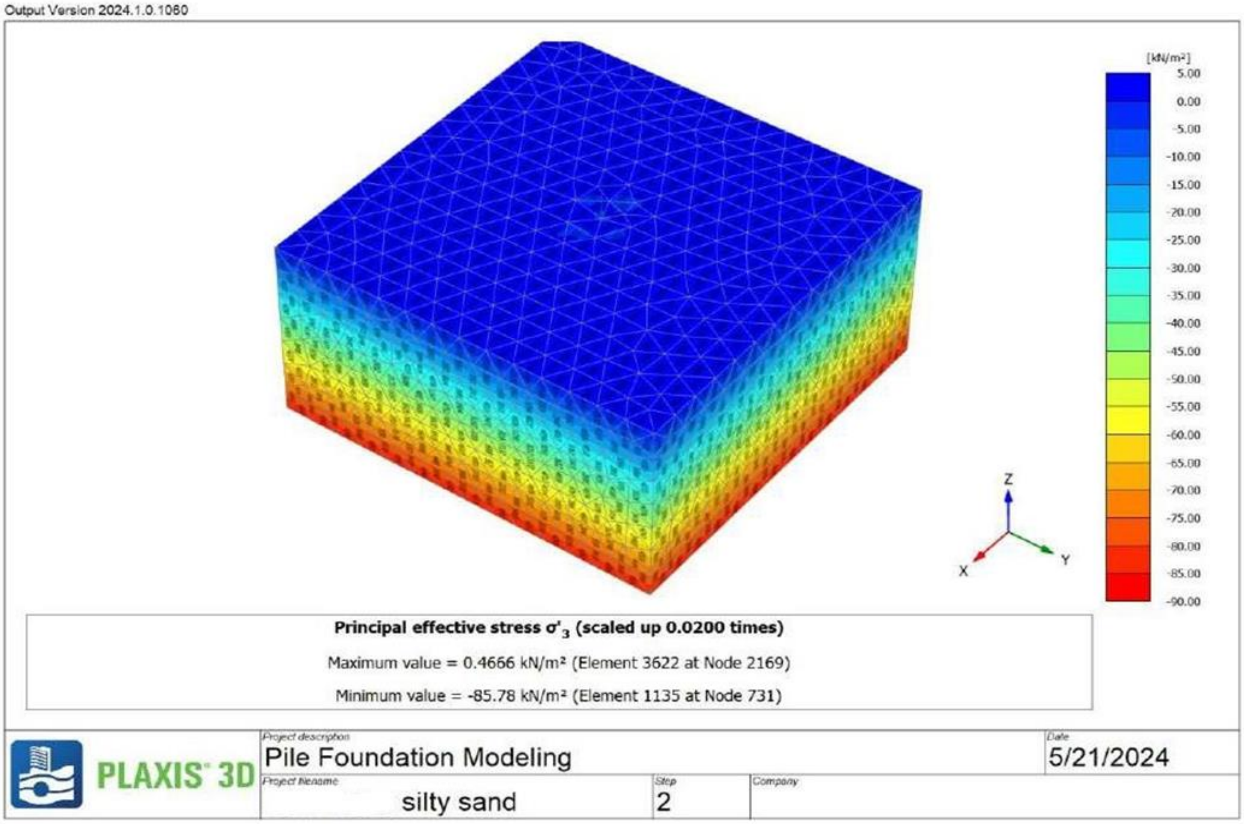


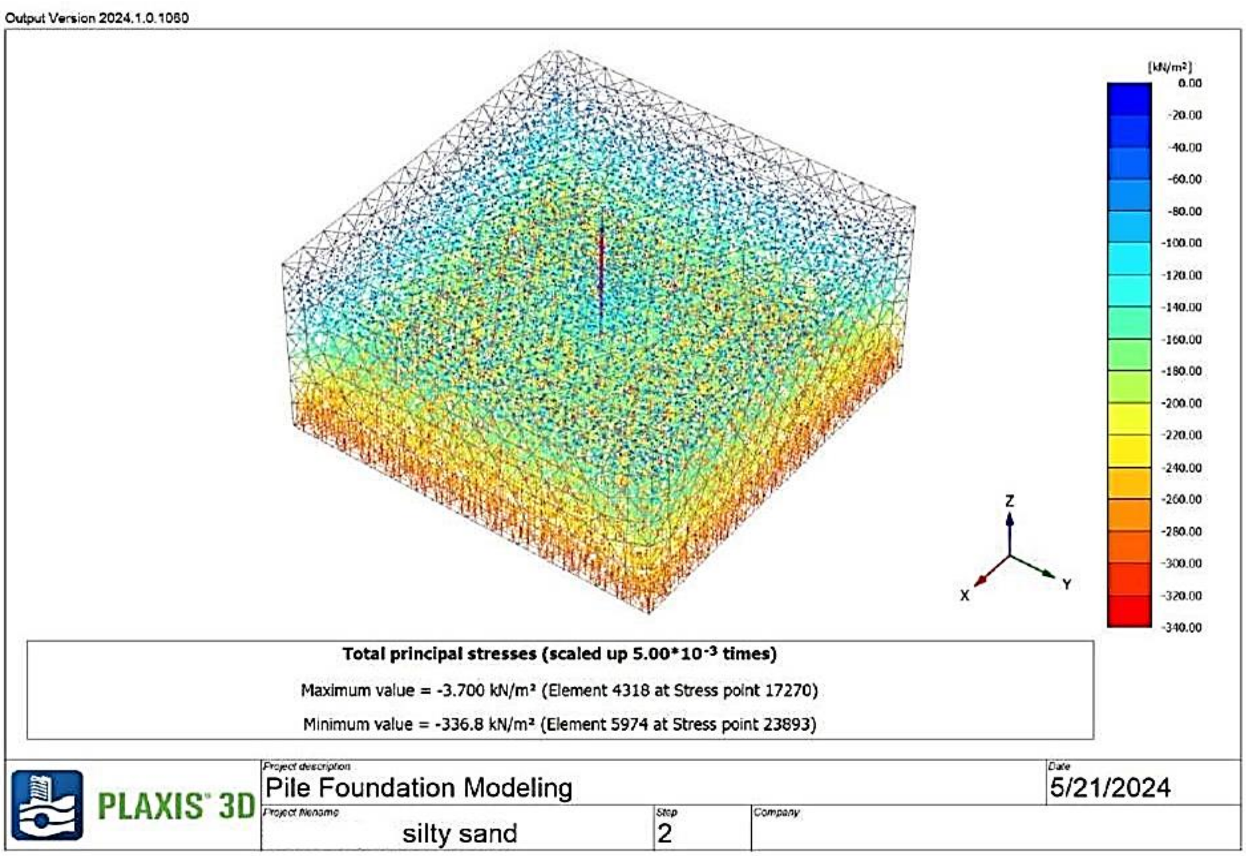


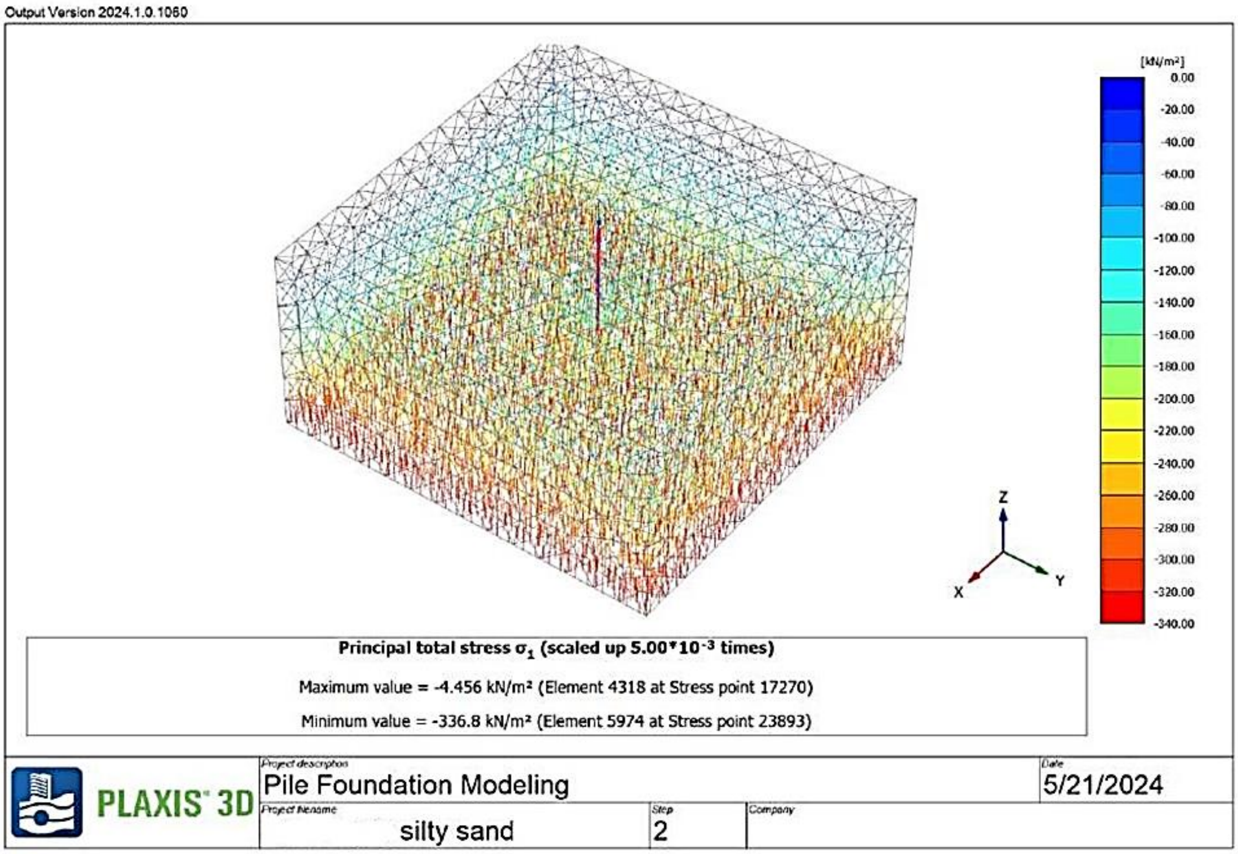
Output Version 2024.1.0.1080
[kN/m²]
10.00
0.00
-10.00
-20.00
-30.00
-40.00
-50.00
-60.00
-70.00
-80.00
-90.00
-100.00
-110.00
-120.00
-130.00
-140.00
-150.00
Z
Y
X
Principal effective stress σ'1 (scaled up 0.0100 times)
Maximum value = 2.945*10-3 kN/m² (Element 3472 at Node 2473)
Minimum value = -140.8 kN/m² (Element 1135 at Node 731)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
silty sand
Step
2
Company

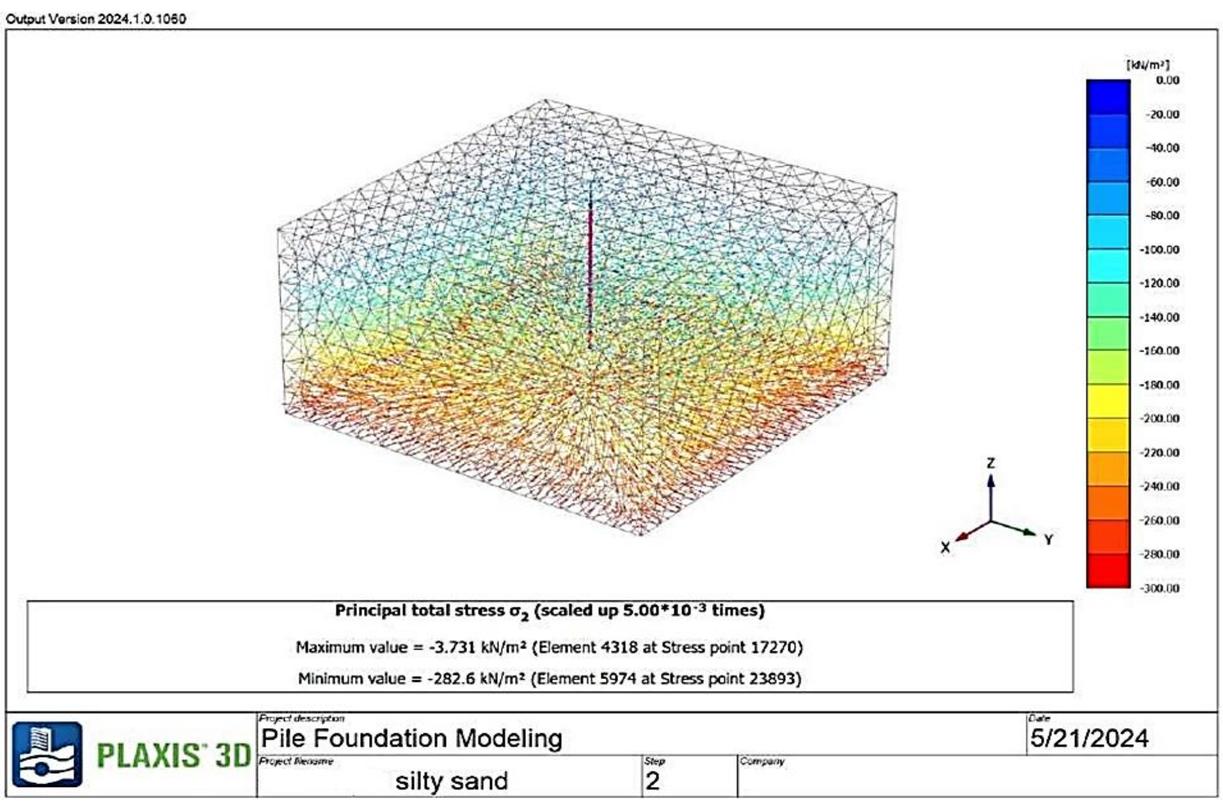


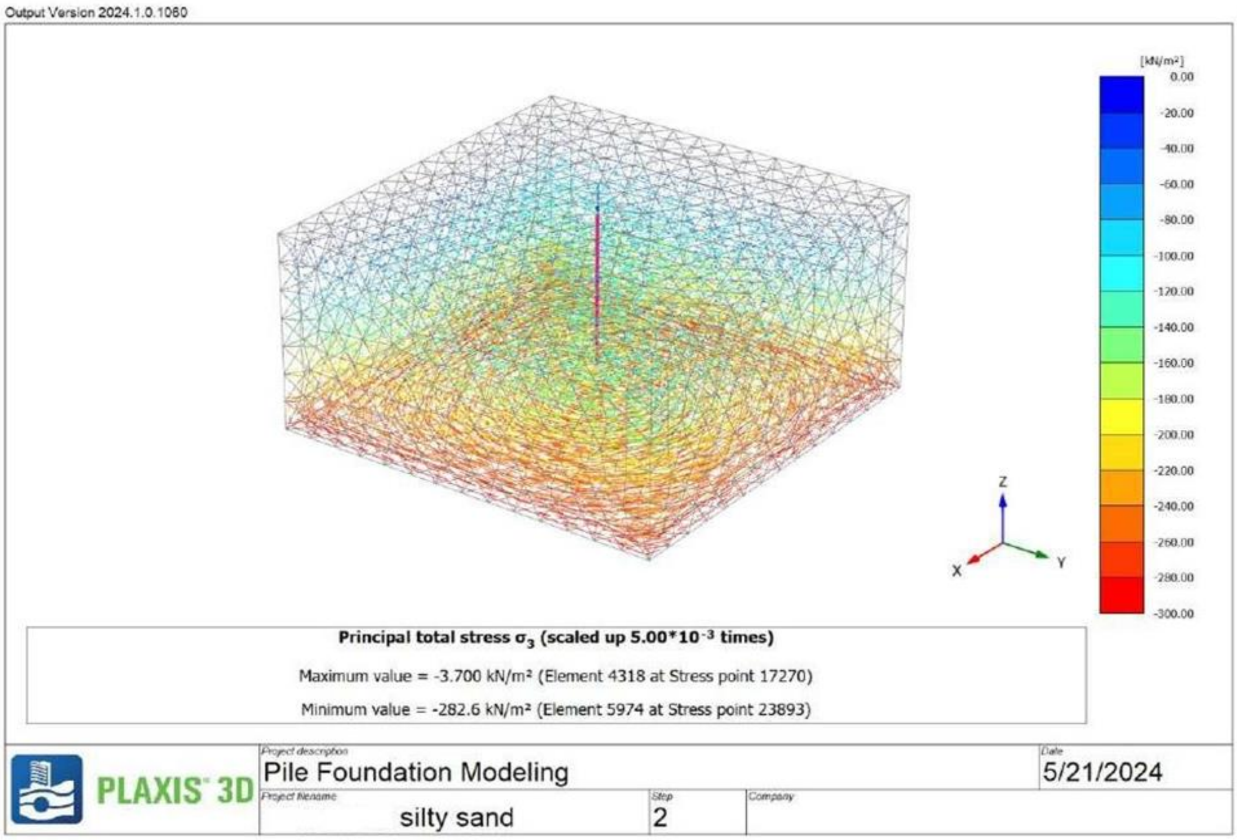
Output Version 2024.1.0.1080
[kN/m²]
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
-30.00
-35.00
-40.00
-45.00
-50.00
-55.00
-60.00
-65.00
-70.00
-75.00
-80.00
-85.00
-90.00
Z
X
Y
Principal effective stress σ'2 (scaled up 0.0200 times)
Maximum value = 0.03657 kN/m² (Element 4222 at Node 2663)
Minimum value = -85.80 kN/m² (Element 1135 at Node 731)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
silty sand
Step
2
Company

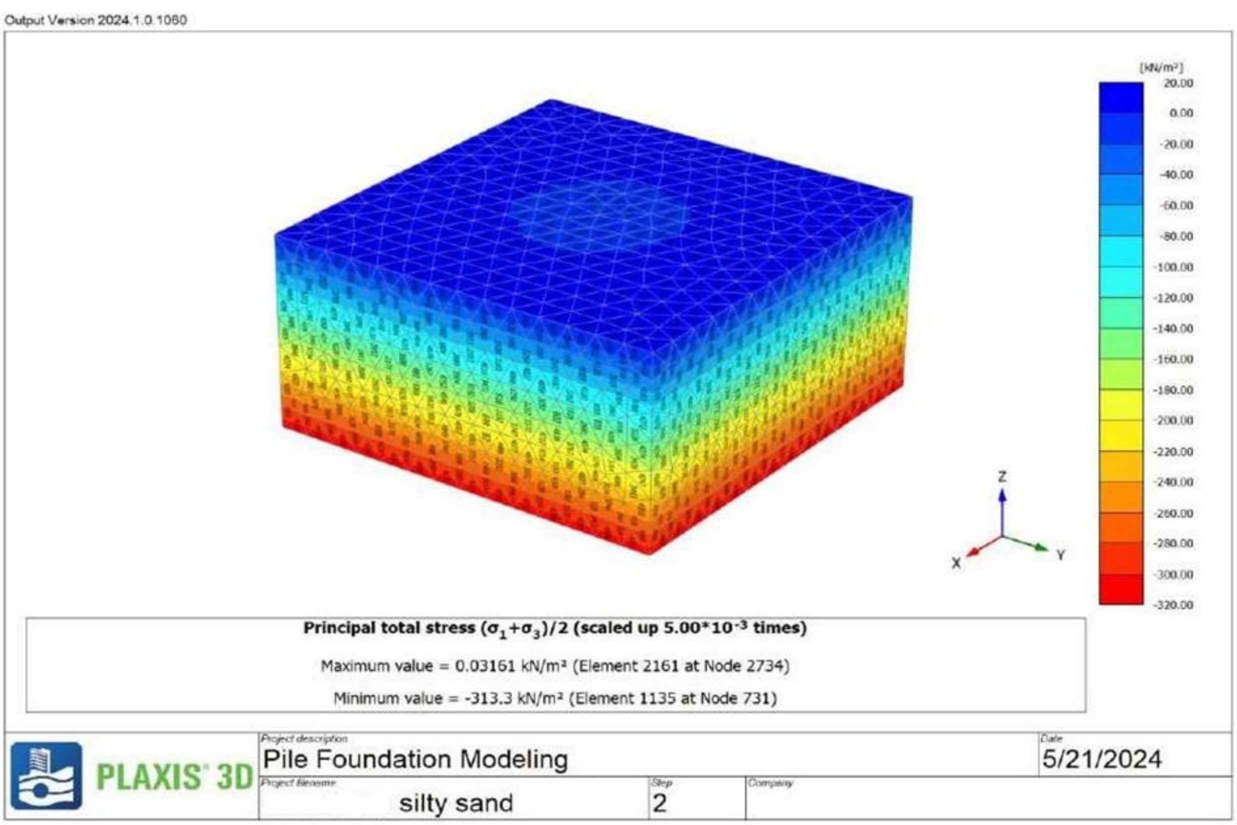

Output Version 2024.1.0.1060
[kN/m²]
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
-30.00
-35.00
-40.00
-45.00
-50.00
-55.00
-60.00
-65.00
-70.00
-75.00
-80.00
-85.00
-90.00
Z
X
Y
Principal effective stress σ'3 (scaled up 0.0200 times)
Maximum value = 0.4666 kN/m² (Element 3622 at Node 2169)
Minimum value = -85.78 kN/m² (Element 1135 at Node 731)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
silty sand
Step
2
Company

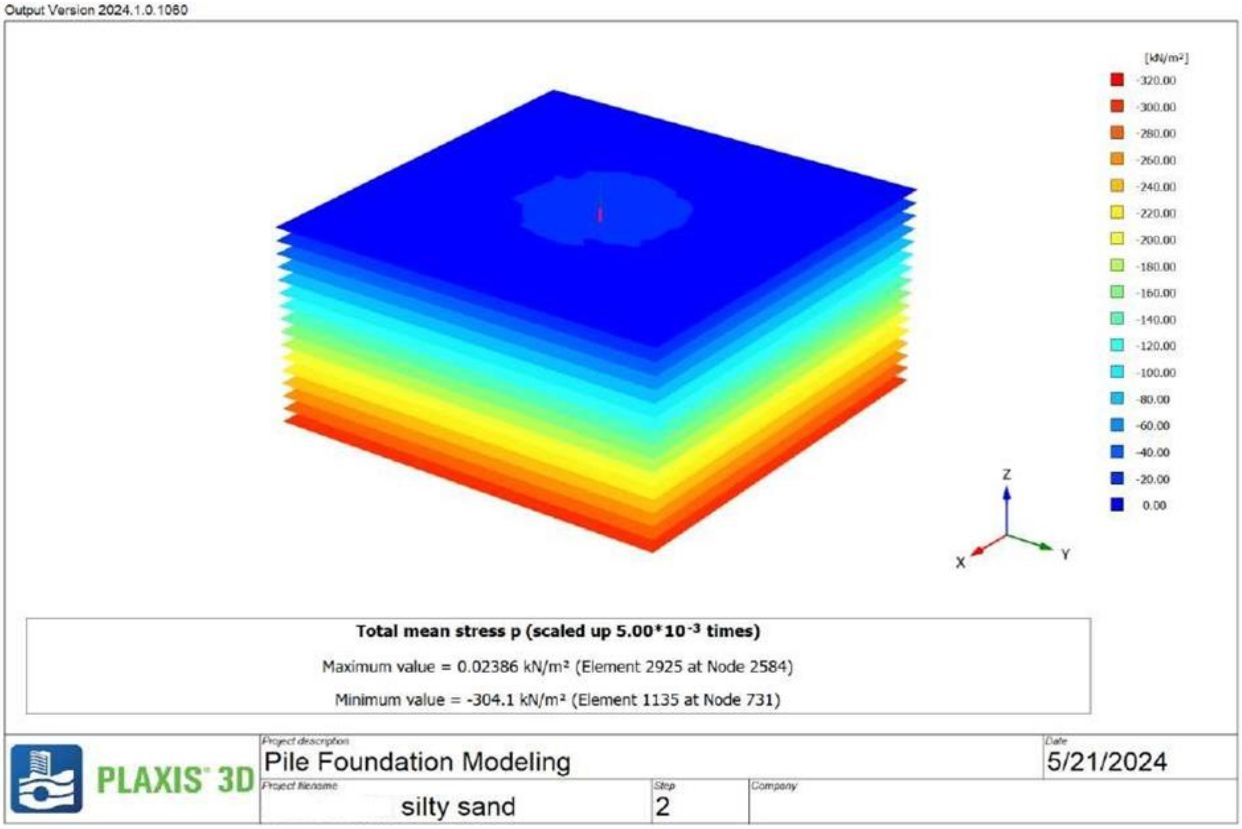

Output Version 2024.1.0.1060
[kN/m²]
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
Z
X
Y
Total principal stresses (scaled up 5.00*10-3 times)
Maximum value = -3.700 kN/m² (Element 4318 at Stress point 17270)
Minimum value = -336.8 kN/m² (Element 5974 at Stress point 23893)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
silty sand
Step
2
Company

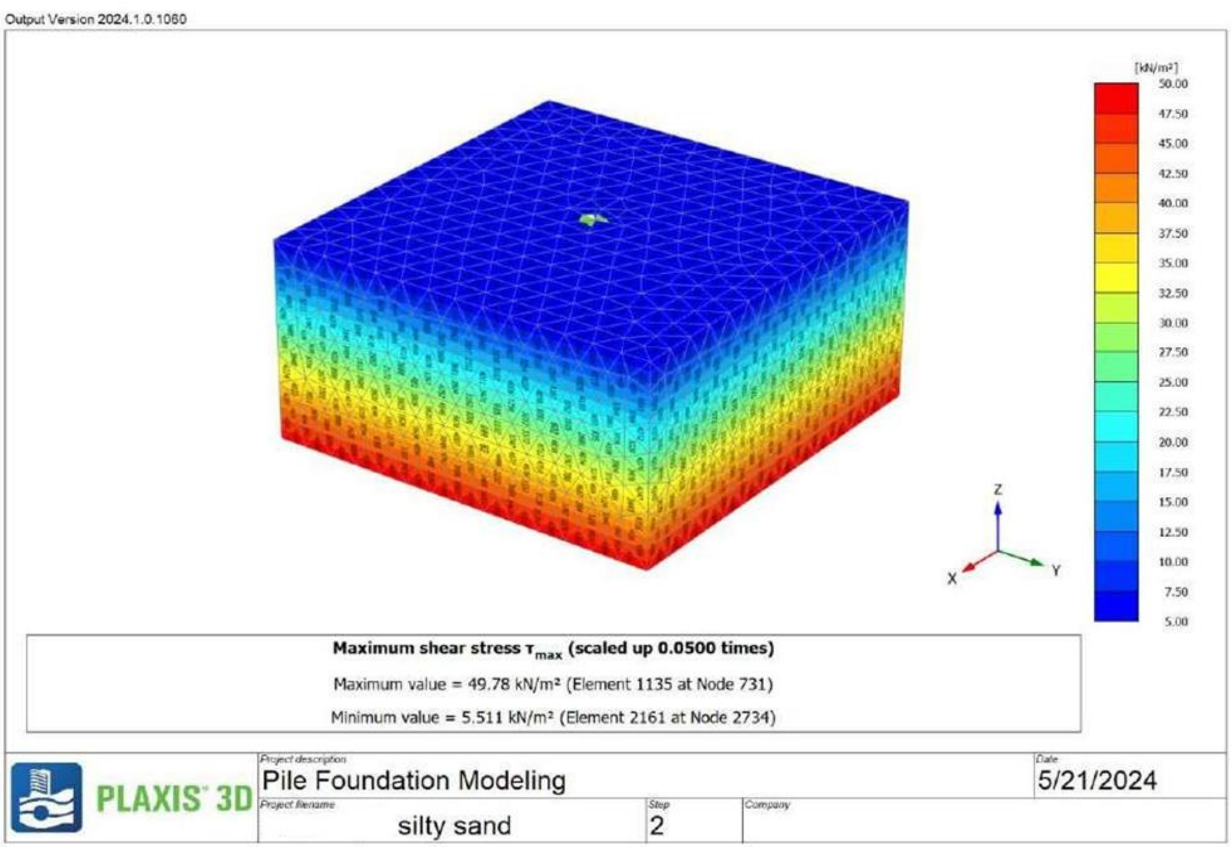

Output Version 2024.1.0.1060
[kN/m²]
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
Z
X
Y
Principal total stress σ1 (scaled up 5.00*10^-3 times)
Maximum value = -4.456 kN/m² (Element 4318 at Stress point 17270)
Minimum value = -336.8 kN/m² (Element 5974 at Stress point 23893)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
silty sand
Step
2
Company


Output Version 2024.1.0.1060
[kN/m²]
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
Z
X
Y
Principal total stress σ2 (scaled up 5.00*10^-3 times)
Maximum value = -3.731 kN/m² (Element 4318 at Stress point 17270)
Minimum value = -282.6 kN/m² (Element 5974 at Stress point 23893)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
silty sand
Step
2
Company

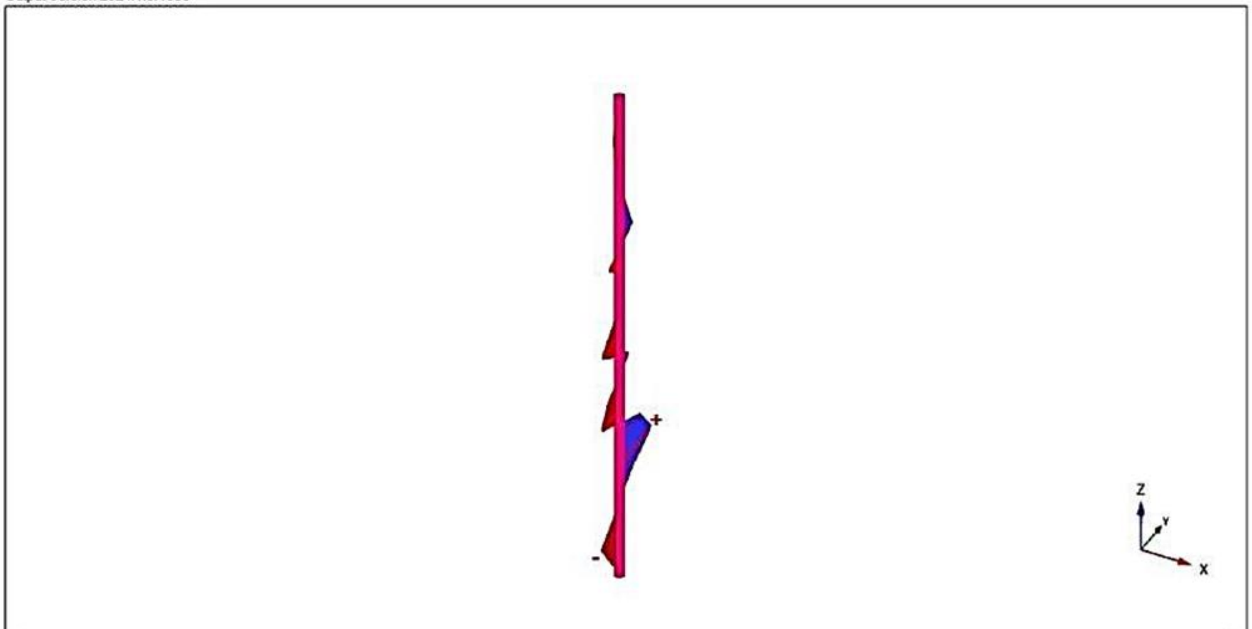

Output Version 2024.1.0.1060
[kN/m²]
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
Z
X
Y
Principal total stress σ3 (scaled up 5.00*10^-3 times)
Maximum value = -3.700 kN/m² (Element 4318 at Stress point 17270)
Minimum value = -282.6 kN/m² (Element 5974 at Stress point 23893)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
silty sand
Step
2
Company


Output Version 2024.1.0.1060
[kN/m²]
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
Z
X
Y
Principal total stress (σ1+σ3)/2 (scaled up 5.00*10^-3 times)
Maximum value = 0.03161 kN/m² (Element 2161 at Node 2734)
Minimum value = -313.3 kN/m² (Element 1135 at Node 731)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
silty sand
Step
2
Company


Output Version 2024.1.0.1060
[kN/m²]
-320.00
-300.00
-280.00
-260.00
-240.00
-220.00
-200.00
-180.00
-160.00
-140.00
-120.00
-100.00
-80.00
-60.00
-40.00
-20.00
0.00
Z
X
Y
Total mean stress p (scaled up 5.00*10^-3 times)
Maximum value = 0.02386 kN/m² (Element 2925 at Node 2584)
Minimum value = -304.1 kN/m² (Element 1135 at Node 731)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
silty sand
Step
2
Company


Output Version 2024.1.0.1060
[kN/m²]
50.00
47.50
45.00
42.50
40.00
37.50
35.00
32.50
30.00
27.50
25.00
22.50
20.00
17.50
15.00
12.50
10.00
7.50
5.00
Z
X
Y
Maximum shear stress τmax (scaled up 0.0500 times)
Maximum value = 49.78 kN/m² (Element 1135 at Node 731)
Minimum value = 5.511 kN/m² (Element 2161 at Node 2734)
PLAXIS 3D
Project description
Pile Foundation Modeling
Date
5/21/2024
Project filename
silty sand
Step
2
Company

Output Version 2024.1.0.1060



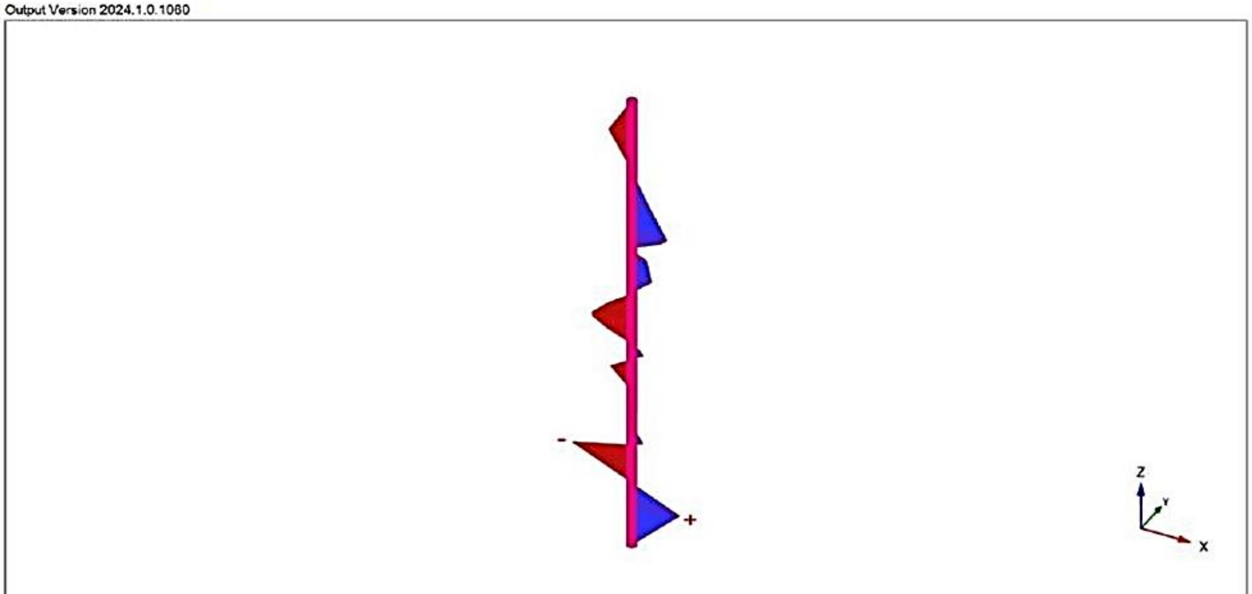
Bending moments M_2 (scaled up 5.00 times)

Maximum value = 0.3624 kN m (Element 14 at Node 9927)

Minimum value = -0.2108 kN m (Element 17 at Node 9934)

PLAXIS 3D	Project description: Pile Foundation Modeling		Date: 5/21/2024
	Project filename: silty sand	Step: 2	Company:

Output Version 2024.1.0.1060



Bending moments M_3 (scaled up 5.00 times)

Maximum value = 0.2796 kN m (Element 17 at Node 9934)

Minimum value = -0.3457 kN m (Element 16 at Node 9931)

PLAXIS 3D	Project description: Pile Foundation Modeling		Date: 5/21/2024
	Project filename: silty sand	Step: 2	Company: