

EFFECT OF RAFT FLEXIBILITY ON ELASTIC SETTLEMENT OF PILED RAFT
FOUNDATION

MSc IN GEOTECHNICAL ENGINEERING

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HAWASSA UNIVERSITY, HAWASSA, ETHIOPIA

JANUARY, 2022

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THESIS SUBMITTED TO THE DEPARTEMENT OF CIVIL ENGINEERING, FACULTY
OF CIVIL ENGINEERING AND BUILT ENVIROMENT, SCHOOL OF GRADUATE
STUDIES, HAWASSA UNIVERISITY

HAWASSA, ETHIOPIA

IN PARTIAL FULFILLMENT OF THE

REQUIREMENT FOR THE

DEGREE OF

MASTER OF SCIENCE IN CIVIL ENGINEERING

(GEOTECHNICAL ENGINEERING)

JANUARY, 2022

HAWASSA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

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ACKNOWLEDGMENT

Above anyone and everything, I praise my almighty God, who enabled me to succeed in my work. Then I would like to express my special thanks to my advisor M U JAGADEESHA and my co-advisor Mr. Zelalem Anberbr for their constructive comments, advice, and encouragement throughout this work. I want to forward my deep appreciation to Hawassa University Institute of Technology and Ethiopian Road Authority (ERA) for giving me a chance to learn, getting knowledge, and finish my research work with financial support.

My deepest thanks also go to my dearest families, friends, and classmates for the invaluable and heartfelt contributions they made for this research work feasible. I am also indebted to Samuel Fikre, Haji Mohammed, Daniel Habtamu, Elias Mohammed, and Sintayehu Asefa for their motivation and help. Furthermore, I thank all those who directly or indirectly contributed to the success of this work.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	Three Dimensional
a	Shear Wall Thickness
ACI	American Concrete Institute
B	Length of Section in the Bending Axis
D	Thickness of Raft or Beam
EI	Flexural Rigidity of the Superstructure
EI _b	Rigidity of Beams
EI _F	Rigidity of Foundation
E _{sav}	Average Soil Young's Modulus along Pile Shaft
E _{sb}	Soil Young's Modulus of Bearing Stratum below Pile Tip
E _{sl}	Soil Young's Modulus at Level of Pile Tip
FEA	Finite Element Analysis
GARP	Geotechnical Analysis of Raft with Piles
GASP	Geotechnical Analysis of Strip with Piles
h	Shear Wall Height
ISSMG	International Society for Soil Mechanics and Geotechnical Engineering
K _p	Stiffness of the Pile Group
K _{pr}	Stiffness of Piled Raft
K _r	Stiffness of the Raft Alone
k _s	Coefficient of Subgrade Reaction
L	Pile Length
P ₀	Design Load
P ₁	Load Carried By the Raft
P _{pile}	Sum of All Pile Loads
P _r	Load Carried by the Raft
P _{su}	Ultimate Shaft Capacity
P _t	Total Applied Load
P _{up}	Ultimate Load Capacity of the Piles in Group
Q _r	Reduced Load
S ₀	Total Settlement

S_a	Design Settlement
S_{pr}	Maximum Settlement of Piled Raft
S_r	Maximum Settlement of Un-Piled Raft
V	Poisson's Ratio
X	Proportion of Load Carried by the Pile
α_{cp}	Raft-Pile Interaction Factor
α_{pr}	Piled Raft Coefficient
$\xi_{\Delta s}$	Coefficient of Maximum Settlement

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ABSTRACT

Rapid growth of population and the advance way of technology in the recent years, the need for high-rise buildings and high-loaded superstructures has been increased rapidly. When considering foundations for high-rise buildings, a major task is the reduction of settlements and differential settlements to ensure safety and serviceability. Piled-raft foundation for high rise buildings have been proved to be an appropriate alternative instead of conventional pile or mat foundation.

This thesis work concern the effects of raft stiffness on the load sharing and settlement analysis of piled raft foundations. For this analysis, the thickness of the raft varies between 0.5-3m with 0.5m interval. The relative soil/foundation stiffness index (K_r) values differentiate the raft as flexible and rigid. Two raft cases were considered; one case considered rigid raft behavior with K_r value of 3.75 and raft thickness of 2m and two cases considered flexible raft behavior with K_r values of 0.054 and with raft thickness of 0.5m.

The built-in material models of the Finite Element (FE) program PLAXIS were used to capture the settlement and load carrying capacity of pile and raft at different spacing(3d-6d) and length(10m-40m) of the pile for the two raft cases. Static analysis carried out using Mohr-Columb soil material model and for pile and raft linear-elastic model were used.

The FE analysis results indicated that, increase in raft thickness in the piled raft foundation, the load shared by the raft decrease. Due to the decrease in contact with the subsoil. The load sharing percent achieved its 50-50 percent, nearly at 1.8m raft after that more loads are taken by piles.

Due to contact pressure between raft and soil, the load carried by the raft was about 58.3% and 49.99% at the spacing of 4d at $t= 0.5$ & 2 m. On this study, larger pile spacing is observed to be more efficient in reducing the average settlement and enhancing the load-sharing coefficient. For this particular study, the optimum spacing of piled raft to minimize differential settlement is 4.5d. The length of pile is observed to be efficient in reducing both differential and total settlement.

Keywords: settlement, rigid piled raft, flexible piled raft, and PLAXIS 3D, axial load distribution

1. INTRODUCTION

1.1 Background

A foundation system consists of the combination of the soil supporting a structure and a footing that spreads the imposed load of the structure over a volume of soil large enough to form a stable system. Aspects typically considered during the design of a foundation system are ultimate limit state capacity and serviceability limit state (Aiban & Znidarcic 1995). It is widely accepted that a shallow foundation system can be used to support relatively small structures. Larger structures such as high-rise buildings, on the other hand, generally require a deep foundation system due to the large pressures they generate.

Piled raft is a geotechnical foundation consisting of three elements raft, piles, and soil domain. It provides some advantages such as reducing settlement and increasing the bearing capacity of the foundations. Such advantages are recognized to the contribution of the raft to the load-carrying capacity and to the efficient use of the piles to reduce the settlement. (Burland et al., 1977). El-Mossallamy et al (2009) stated that the main criterion, which governs the design of piled-raft foundations, concerns the load sharing between the raft and piles and the effect of additional pile support on the foundation settlement.

The stiffness of the pile cap influences the load transfer mechanism of the foundation system. The role of the pile cap becomes significant if the pile cap is in direct contact with the foundation soil. However, the concept of the piled raft foundation requires a comprehensive evaluation of a number of factors that affect the performance of the foundation system (Wiesner and Brown, 1980). Settlement profile and soil contact pressure for raft foundation are dependent on the relative stiffness of raft and supporting soil. The rigid pile cap shows less deformation, resulting in higher computed loads and moments than for a flexible pile cap (Won et al., 2006).

In this study, the load transfer mechanism and settlement of a piled raft foundation were investigated by analyzing the effects of the three parameters which were thickness of the raft, spacing and length of the pile. Since the study of the settlement and load distribution of piled raft system was focused on sand, this study considered drained conditions. This load transfer

mechanism study was conducted by investigating the portions of the load carried by the raft and the piles.

For this study, a 3D numerical model of a piled raft and the surrounding soils have been analyzed in the PLAXIS 3D (Brinkgreve and Swolfs (2013)). 2011. Twenty four numbers of tests have been conducted to study the behaviors of a piled raft under vertical loading. Out of these, two tests are chosen for validation. The validation of the 3D finite element model is examined by comparing the results with those from the experiments conducted on clay and sand soil reported by Sommer/ Katzenbach (1990) and Eslami et al.

The relative soil/foundation stiffness index (K_r) values differentiate the raft as flexible and rigid. The analysis test is performed on a 25,36,49,64,81 number of piles located under a 26 m x 26 m raft with 0.5 m & 2m in thickness. Each pile is 30 m in length and 1 m in diameter. Other analysis is performed on a same-size raft with 10, 20, 30 and 40 pile length. The subsoil comprises loss sand whose behavior is represented by elastic-perfectly plastic Mohr-Coulomb model. The 10-node tetrahedral element elements are utilized to model the subsoil.

1.2 Statement of the Problem

In piled raft foundations, the raft and piles both contribute to load transferring and settlement of the foundation. The raft can carry the load through contact with soil piles through skin friction. Raft design was a compromise between the desire to keep the differential settlement of the raft & super structure to a minimum by avoiding excessive stiffness in the raft. Flexibility in the raft gives minimum bending moment, minimum stiffness and influences the distribution of loads in piles. The role of the pile cap becomes significant if it's in direct contact with the foundation soil. Control the maximum differential settlement thicker rafts were the best solution. On this assumption, raft flexibility is not taking into account. The raft thickness has a significant effect on its flexibility. This paper investigates the importance of taking the flexibility of the pile cap into account in making a settlement analyses of piled raft foundations. Such analyses are valuable in leading to a better understanding of the details of piled raft behavior.

1.3 Objectives

1.3.1 General Objective

The main objective of this thesis was to investigate the effect of raft flexibility on the settlement of piled raft foundations by using finite element-based numerical analysis.

1.3.2 Specific Objectives

- ❖ To investigate the effect of raft thickness on the settlement and load distribution.
- ❖ To study the effect of spacing of piles on the settlement of piled raft foundation.
- ❖ To examine the effect of length of piles on settlement of piled raft foundation.
- ❖ To carry out and compare load proportion of pile and raft in piled raft system.

1.4 Significance and of the Study

The finding of this study had a significant impact on piled raft analysis in a flexible raft approach rather than a conventional raft gives information about the proportion of loads carried by pile and raft to produce a more suitable design for the piled raft system. Evaluating the parameters that affect raft flexibility gives a noticeable understanding of piled raft foundations performance subjected to vertical loading. In addition, the study was used as a reference by those researchers who want to conduct studies on the future details of piled raft foundations and related issues. Thus, the results presented in this paper can serve as a guideline to produce a safe and economical design for piled raft foundations.

1.5 Research Question

In this study, the following questions have been answered:

How the thickness of raft govern the settlement and load distribution in piled raft foundation?

By taking varied length of the piles how the settlement is affected and also at what value further increasing in the length of piles gives not significant effect on the settlement reduction?

By applying static load on the raft how the variation in the spacing of piles decrease the total settlement of piled raft system under the raft for that specific loading condition?

Based on the flexible and rigid raft assumption how the total, differential settlement and load distribution are varied?

1.6 Scope of the Study

This thesis addresses the described objects and the study desired to address considering the flexibility of raft on the settlement analysis and load distribution of piled raft foundation under the application of uniformly distributed vertical load by using the PLAXIS 3D model.

1.7 Organization of Thesis

This thesis is divided into five Chapters, reference, appendices and detail coverage of specific topics. The first Chapter deals with general background of the thesis, problem statement, objective, significance of the study, scope of the thesis, and organization of the study. Chapter two is review of different analysis methods for piled raft foundation and also of previous studies on the flexible piled raft foundation. Chapter three covers material and methods with verification of PLAXIS 3D. In Chapter four result and discussion are presented. Chapter five focused on conclusion and recommendation. Finally in Appendices relevant PLAXIS outputs, tables, calculations and theoretical formulation of PLAXIS 3D is presented.

2. LITERATURE REVIEW

2.1 Introduction

Foundation of any structure transmits the total structural load to the soil. To serve this purpose satisfactorily, it should be designed properly to satisfy the strength, serviceability, constructability and economic requirements. Increasing urbanization in recent years all over the world led to a rapid increase in the number and height of buildings even in problematic subsoil conditions. The foundation's system that designers are most likely to consider for massive structures is reinforced concrete rafts or pile foundations. In the design of foundation for a large building a deep deposit of clay, Harry.G.Poulos and Edward.H.Davis, 1980 found that a raft foundation would have an adequate factor of safety against ultimate bearing capacity failure, but that the settlements would be excessive. The traditional practice would then be to pile the foundation and to choose the number of piles to give an adequate factor of safety against individual pile failure, assuming the pile takes the entire load. However, it is unreasonable to design the pile on an ultimate-load basis when they have only been introduced to reduce the settlement of an otherwise satisfactory raft. A Piled-raft foundation is a combination of shallow and deep foundations, which transfers the load of the superstructure to the soil via a complex soil-structure interaction mechanism. Many works of literatures can show that piled rafts have been used as a foundation system for high-rise buildings in different soil conditions, e.g., in soft to stiff clay as well as in medium-to-dense sand.

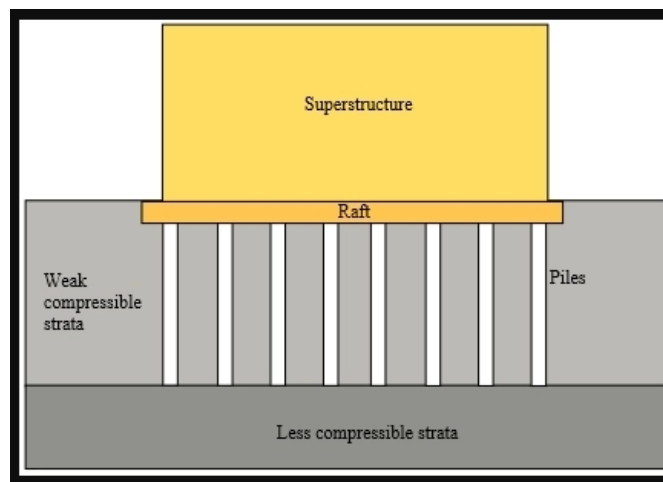


Figure 2-1 piled raft foundation sectional view

The concept of settlement reducer piles was presented by Burland et al. (1977) in which the piles are used to limit the average and differential settlements. A piled raft foundation has some advantages over the pile group in terms of design and from serviceability and economic point of view. They include the following.

- ❖ For a piled raft, the piles will provide sufficient stiffness to control the settlement and differential settlement at serviceable load (Burland et al. 1978)
- ❖ A raft in the piled raft foundation can carry 30–50% of the applied load (Clancy and Randolph, 1993). Hence, a piled raft foundation will require fewer piles in comparison to a pile group to satisfy the same design requirements.
- ❖ In case any piles in the piled raft become defective, the raft allows re-distribution of loads from the damaged piles to the other piles (Poulos et al., 2011).
- ❖ the pressure applied from the raft to the subsoil may increase the lateral stress between underlying piles and the soil (confining pressure), which can increase the pile load carrying capacity accordingly compared to the piles in a pile group.(Katzenbach et al., 1998).

Different researchers have conducted analysis, design, and performance evaluation of piled raft foundations. It ranges from simple analysis methods, by making several assumptions to sophisticated analysis tools like finite element, finite difference, boundary elements, and case studies with site measurements. Technical Committee TC18 of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) has focused on the effort of piled raft foundation since 1994. They also gathered important information about piled rafts. This information was focused mainly on the analysis and design method of a piled raft. Finally, they prepare an updated report and reviews on the general philosophy of piled raft design and the analysis issues which need to be addressed in the design.

2.2 Design Philosophy

Many works have been done and are still in progress to develop a fixed design method for piled raft foundation. Researchers use their design philosophy to formulate the design approach for piled raft foundation. Randolph (1994) categorized the various design philosophy into three different design approaches.

a) The conventional approach,

In this approach, the foundation is designed as a pile group with fixed spacing over the whole foundation area, to carry the major portion of the load (60 – 75% of the total structural load) and allowance is made for the raft to transmit some load directly to the ground. This approach have some limitations that, any design by this philosophy will remain certainly in elastic system, where the piles are loaded below their shaft capacity and piles are evenly distributed over the whole foundation area. Determination of the shaft capacity of the group pile is “extremely difficult and has not resolved yet” (Braja, M. Das, 2008). Moreover, the allowance for the raft to transmit the load is not defined in this approach, which they let it for engineering judgment.

b) Creep piling approach

These approach were proposed by Hansbo, S. and Jendeby, L. (1983), in which, piles are designed to operate at a working load, at which significant creep starts to occur, typically at about 70 – 80% of its ultimate load bearing capacity. Sufficient piles are included to reduce the net contact pressure between the raft and the soil to below the pre-consolidation pressure of the soil. The creep piling approach again sets the limitation of operating the pile below the creep load, which is, as mentioned above, as 70% to 80% of ultimate load-bearing capacity. However, the ultimate capacity is based on conventional group theory, is under investigation. Moreover, the reduction of net contact pressure between raft and soil by means of pile addition will remain the raft from transmitting the load to its full capacity directly to the soil. In creep piling where the piles operate at a lower factor of safety, but because there are fewer piles, the raft carries more load than conventional approach.

c) Differential settlement control approach

On this approach, pile supports are designed strategically in order to minimize differential settlement rather than reducing average settlement significantly. The differential settlement control approach could be the economic one, as piles are located strategically to reduce the differential settlement. It will require less number of piles, in comparison to the other two approaches. This will make the settling area of the raft more stiff which ultimately reduce the differential settlement.

Poulos (2001), concludes that the above three approaches are most beneficial to economical foundation design, and will be given special attention. He briefly describes and illustrates, conceptually, the load-settlement behavior of piled rafts by curves designed according to the first two strategies. Curve 0 shows the behavior of the raft alone, which in this case settles excessively at the design load. Curve 1 represents the conventional design philosophy, for which the behavior of the pile-raft system is governed by the pile group behavior, and which may be largely linear at the design load. In this case, the piles take the majority of the loads. Curve 2 represents the case of creep piling, where the piles operate at a lower factor of safety because there are fewer piles, the raft carries more load than for curve 1. Curve 3 illustrates the strategy of using the piles as settlement reducers, and utilizing the full capacity of the piles at the design load. Therefore, the design depicted by Curve 3 is acceptable and is likely to be significantly more economical than the designs described by Curves 1 and 2.

Curve 0: Raft only (settlement excessive)

Curve 1: Raft with pile designed for conventional safety factor

Curve 2: Raft with piles designed for lower safety factor

Curve 3: Raft with piles designed for full utilization of capacity

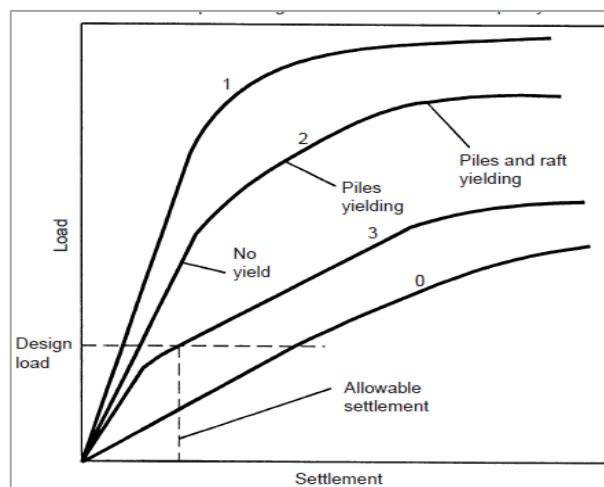


Figure 2-2 Load-settlement curves for piled rafts according to various design philosophies

The key questions that arise in the design of piled rafts concern are the relative proportion of load carried by raft and piles, and the effect of the additional pile support on absolute and differential settlements (Randolph, 1994). Therefore three coefficients are introduced to quantify the performance of piled rafts:

- a. the piled raft coefficient, α_{pr} , describes the ratio of the sum of all pile loads, P_{pile} , to the total load on the foundation, P_{tot}

$$\alpha_{pr} = \frac{\sum P_{piles}}{P_{tot}} \quad 2.1$$

A piled raft coefficient of unity represents the case of a fully piled raft without contact pressure beneath the raft, whereas a piled raft coefficient of zero describes an un-piled raft (the case of shallow foundation).

- b. The coefficient of maximum settlement, $\xi_{\Delta s}$, is defined as the ratio of the maximum settlement of the piled raft, S_{pr} , to the maximum settlement of the corresponding un-piled raft, S_r :
- c. The coefficient of differential settlement, $\xi_{\Delta s}$, is defined correspondingly. Unless otherwise stated, this is the differential settlement between the center and the middle of the shorter side of the raft.

2.3 Method of Analysis

Analytical, numerical and physical modeling approaches were employed to evaluate the performance of piled raft foundations. From the literature survey it has been found that the analyses of piled raft can be ranged from simplified hand Calculation to some innovative approaches. These can be classified into three broad categories.

- ❖ Simplified calculation methods
- ❖ Approximate computer-based methods
- ❖ More rigorous computer-based methods

2.3.1 Simplified Calculation Methods

Simplified methods involve the hand calculation using the theoretical solution for a raft and for a pile in elastic continuum. This includes those of Poulos and Davis (1980), Randolph (1983, 1994), Burland (1995), Hemsley (2000) and Poulos (2001). All methods involve a number of simplifications while considering the soil domain and applying load on the raft. A brief discussion is made below.

A. Poulos – Davis - Randolph (PDR) Method

PDR method is the combination of both Poulos-Devis and Randolph methods. This method is used for assessing the overall bearing capacity and load settlement behavior of piled raft in the preliminary design stage. The method involves two main steps:

1. Estimation of the ultimate load capacity of the foundation.
2. Estimation of the load – settlement behavior via a simple tri – linear relationship.

For assessing vertical bearing capacity of a piled raft foundation using simple approaches, the ultimate load capacity can generally be taken as the lesser of the following two values (H.G Poulos, 2002)

- ❖ The sum of the ultimate capacities of the raft plus all the piles.
- ❖ The ultimate capacity of a block containing the piles and the raft, plus that of the portion of the raft outside the periphery of the piles.

For estimating the load-settlement behavior, an approach similar to that described by Poulos and Davis (1980) can be adopted. However, a useful extension to this method can be made by using the simple method of estimating the load sharing between the raft and the piles, as outlined by Randolph. (Randolph, 1983; 1994) has developed very approximate equations for the stiffness of piled raft system and load-sharing between the piles and the raft. This method is restricted to linear behavior of the piled raft system which indicates that the foundation is designed essentially as a pile group with allowance for the load carried by the raft. The stiffness of the piled raft foundation can be estimated as follows:

$$\frac{K_p + K_r(1 - \alpha_{cp})}{(1 - \alpha_{cp}) \frac{2K_r}{K_p}} \quad 2.2$$

Where K_{pr} = stiffness of piled raft

K_p = stiffness of the pile group

K_r = stiffness of the raft alone

α_{cp} = raft-pile interaction factor

The definition of the pile problem considered by Randolph is shown in Figure 2-3

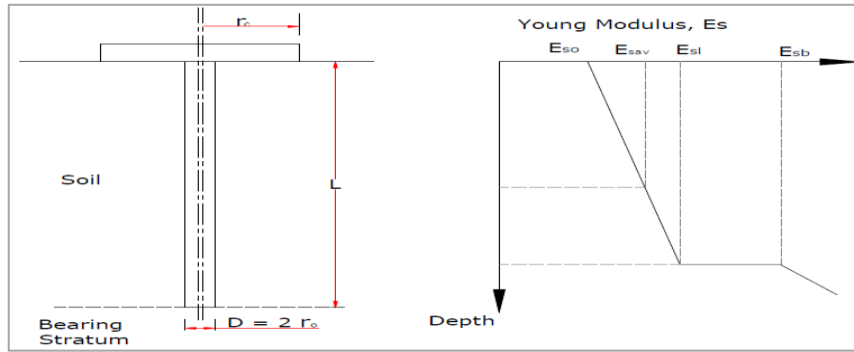


Figure 2-3 piled raft unit Simplified representation (Randolph, 1994)

The raft stiffness K_r can be estimated via elastic theory and also the single pile stiffness is computed from elastic theory, and then multiplied by a group stiffness efficiency factor which is estimated approximately from elastic solutions.

The proportion of the total applied load carried by the raft is:

$$\frac{P_r}{P_t} = X = \frac{K_r(1 - \alpha_{cp})}{(K_p + K_r(1 - \alpha_{cp}))} \quad 2.3$$

Where P_r = load carried by the raft

P_t = total applied load

The raft-pile interaction α_{cp} can be estimated as follows

$$\alpha_{cp} = 1 - \ln \frac{r_c}{r_0} \zeta \quad 2.4$$

Where r_c = average radius of pile cap, (corresponding to an area equal to the raft area divided by number of pile.) and r_0 = radius of pile

$$\zeta = \ln \left(\frac{r_m}{r_0} \right) \quad 2.5$$

$$r_m = \{0.25 + \zeta[2.5\rho(1 - \nu) - 0.25]\} * L \quad 2.6$$

$$\xi = E_{sl}/E_{sb}$$

$$E_{sav}/E_s$$

ν = poisson's ratio

L = pile length

E_{sb} = soil young's modulus of bearing stratum below pile tip.

E_{sav} = average soil young's modulus along pile shaft.

E_{si} = soil young's modulus at level of pile tip.

The above equations can be used to develop a tri-linear load-settlement curve as shown in Figure 2.4. First, the stiffness of the piled raft is computed from equation (2.2) the stiffness of the piled raft foundation is computed for number of piles being considered. This stiffness will remain operative until the pile capacity is fully mobilized. The total load on the foundation at which the pile yields is given by

$$P_1 = \frac{P_{up}}{(1 - X)} \quad 2.7$$

Where

P_{up} = ultimate load capacity of the piles in group

X = proportion of load carried by the pile

When the pile capacity is reached fully mobilized point, beyond that point (Point A in Figure 2-4), the stiffness of the foundation system is that of the raft alone and this holds until the ultimate load capacity of the piled raft foundation system is reached (Point B in Figure 2-4). At this stage, the load-settlement relationship becomes horizontal.

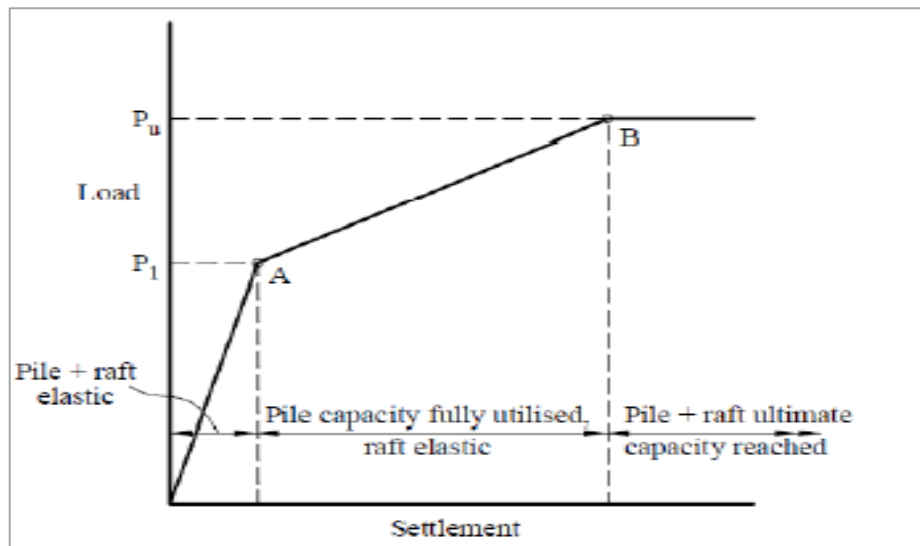


Figure 2-4 Load-settlement curve for preliminary analysis simplified approach (Poulos, 2001).

According to a Report Prepared on Behalf of Technical Committee TC18 on Piled Foundations they mention that on the simplified analysis method, the load – settlement curves for a raft with various numbers of piles can be computed with the aid of a computer spreadsheet or a mathematical program such as MATHCAD. While those spreadsheets, such

as the one developed by (Lee et al., 2005) at Virginia Polytechnic and State University, do not consider three dimensional effects, varying subsurface conditions and asymmetric loading, they provide insight on the approximate percentage settlement reduction obtained for similar conditions for an individual raft and can thus be very helpful. The Lee et al. (2001) spreadsheet was used in the 167 Johnson case-histories. In this way, it is simple to compute the relationship between the number of piles and the average settlement of the foundation. Such calculations provide a rapid means of assessing whether the design philosophies for creep piling or full pile capacity utilization are likely to be feasible.

B. Burland's Approach

Burland, 1995 has developed some simplified process of design when piles are designed to act as settlement reducer and to develop their full capacity at the design load. He has developed the following simplified process of design:

- ❖ Estimate the total long-term load-settlement relationship for the raft without piles which is shown (Figure 2.5). The design load P_0 gives a total settlement S_0 .
- ❖ Assess an acceptable design settlement S_a , which should include a margin of safety.
- ❖ P_1 is the load carried by the raft corresponding to S_a .

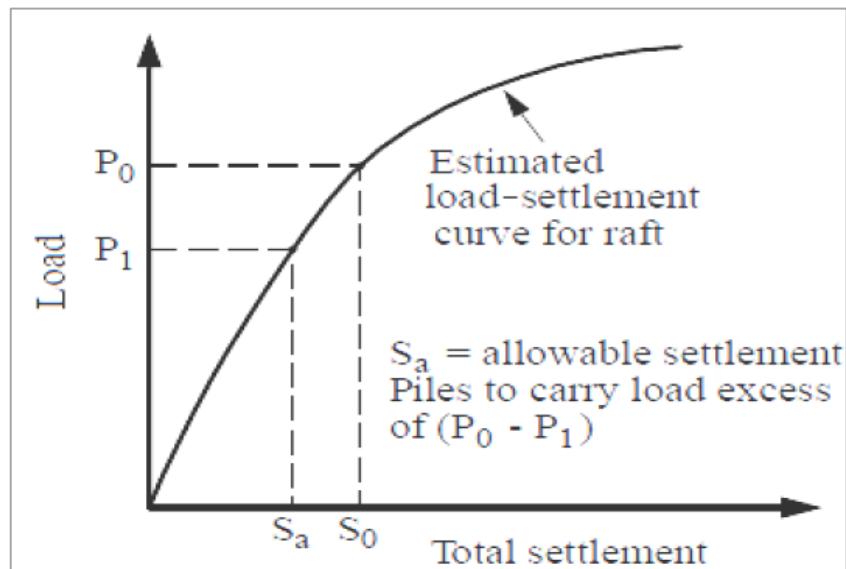


Figure 2-5 Load-settlement curve for raft (Burland, 1995)

- ❖ The load excess $P_0 - P_1$ is assumed to be carried by settlement-reducing piles. The shaft resistance of these piles will be fully mobilized and therefore no factor of safety

is applied. However, Burland suggests that a “mobilization factor” of about 0.9 be applied to the ‘conservative best estimate’ of ultimate shaft capacity, P_{su} .

- ❖ If the piles are located below columns which carry load in excess of P_{su} , the piled raft may be analyzed as a raft (Figure 2.6) on which reduced column loads act. At such columns, the reduced load Q_r is:

$$Q_r = Q - 0.9P_{su} \quad 2.8$$

- ❖ The bending moment in the raft can be obtained by analyzing the piled raft as a raft subjected to the reduced loads Q_r .
- ❖ The process for estimating the settlement of the piled raft is not explicitly set out by Burland, but it would appear reasonable to adopt the approximate approach of (Randolph, 1994) in which:

$$S_{pr} = \frac{S_r * K_r}{K_{pr}} \quad 2.9$$

Where S_{pr} = settlement of piled raft;

S_r = settlement of raft without piles subjected to the total applied load;

K_r = stiffness of raft;

K_{pr} = stiffness of piled raft;

$$K_{pr} = \frac{K_p + K_r(1 - \alpha_{cp})}{(1 + \alpha_{cp} \frac{2K_r}{K_p})} \quad 2.10$$

Where: - K_{pr} = stiffness of piled raft;

K_p = stiffness of the pile group;

K_r = stiffness of the raft alone;

α_{cp} = raft – pile interaction factor.

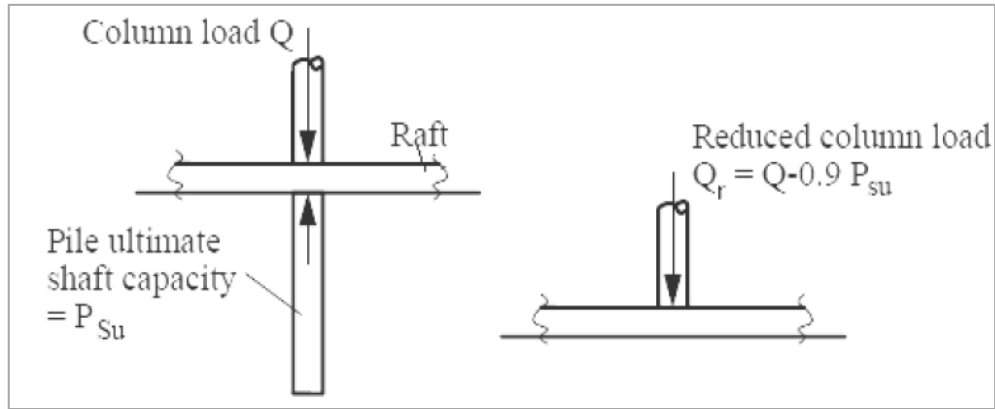


Figure 2-6 Simplified representation of pile-raft unit (Burland, 1995)

C. Hamsley's Approach

Another simplified method for analysis of piled-raft foundation that presented by Hamsley (2000). According to its stiffness, the raft distributes the total load transferred from structure (S_{tot}) as contact pressure below raft represented by R_{raft} , as well as load over each of the 'n' piles represented by $\sum R_{pile,i}$.

Therefore, the total resistance of the piled raft (R_{tot}) is given by;

$$R_{tot} = R_{raft} + \sum_{i=1}^n R_{pile,i} \geq S_{tot} \quad 2.11$$

In piled raft foundations, the contribution of the raft and piles is taken into consideration to verify the ultimate bearing capacity and the serviceability of the overall system. Moreover, the interaction between the raft and the piles makes it possible to use the pile up to a load level which can be significantly higher than the permissible design value of a comparable single isolated pile. Thus, the behavior of a piled raft foundation can be characterized with an interaction coefficient β_{pr} defined as

$$\beta_{pr} = \frac{\sum_{i=1}^n R_{pile,i}}{R_{tot}} \quad 2.12$$

A coefficient of $\beta_{pr} = 0$ represents the case of a shallow foundation, and a coefficient of $\beta_{pr} = 1$ represents the case of a fully piled foundation without contact pressure beneath the raft.

The influence of the piles to diminish the settlements of raft depends on the piled raft interaction coefficient, which in turn depends on the subsoil surrounding and the geometric

proportions of the piled raft. For the same subsoil conditions and the same area of the raft, the coefficient is a function of the number and length of the piles, as shown in Figure 2.7.

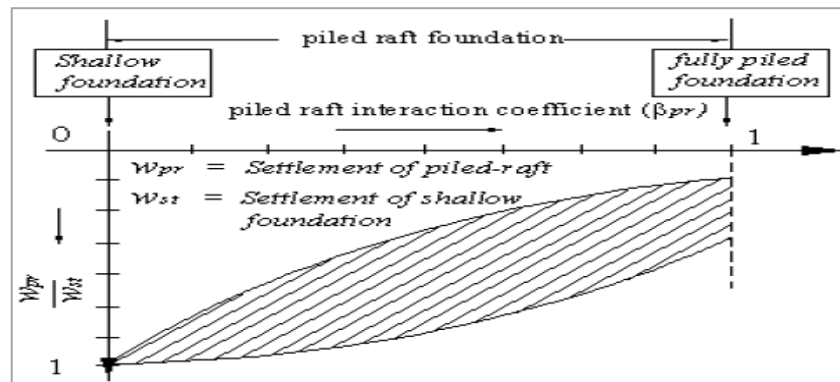


Figure 2-7 Foundation settlement as a function of piled raft coefficient (Hemsley, 2000)

D. Other Methods

Other methods under this category are those of (van Impe & Clerq, 1995) and Equivalent Raft and Equivalent Pier Methods. The Equivalent Raft and Equivalent Pier methods are discussed in detail by (Randolph & Wroth, 1979).

2.3.2 Approximate Computer-Based Analysis

The approximate computer-based methods are based on elastic theory and mainly have two approaches (H. Poulos 2001). Strip on Springs Approach (GASP) and Plate on Springs Approach (GARP).

i. Strip on Springs Approach

In this method, a section of the raft is represented by a strip and the supporting piles by springs. (Brown and Wiesner, 1975) describe the strip-superposition method, in which solutions for pile-strip footings are superimposed to obtain the settlement of the raft. This method does not require the use of computer but is limited to giving settlement only.

Another example in this category is that presented by (Poulos, 1991) and illustrated in Figure 2.7. He modeled piled raft foundation as a strip supported on springs in which the strip represents the raft in one direction and the springs represent the piles. Approximate allowance is made for all four components of interaction (raft-raft elements, pile-pile, raft-pile, pile-raft), and the effects of the parts of the raft outside the strip section being analyzed are taken into account by computing the free-field soil settlements due to these parts. These settlements are

then incorporated into the analysis, and the strip section is analyzed to obtain the settlements and moments due to the applied loading on that strip section and the soil settlements due to the sections outside the raft.

The method has been implemented via a computer program GASP (Geotechnical Analysis of Strip with Piles) and has been shown to give settlement which is in reasonable agreement with more complete methods of analysis. However, it does have some significant limitations, especially as it cannot consider torsional moments within the raft, and also because it may not give consistent settlements at a point if strips in two directions through that point are analyzed.

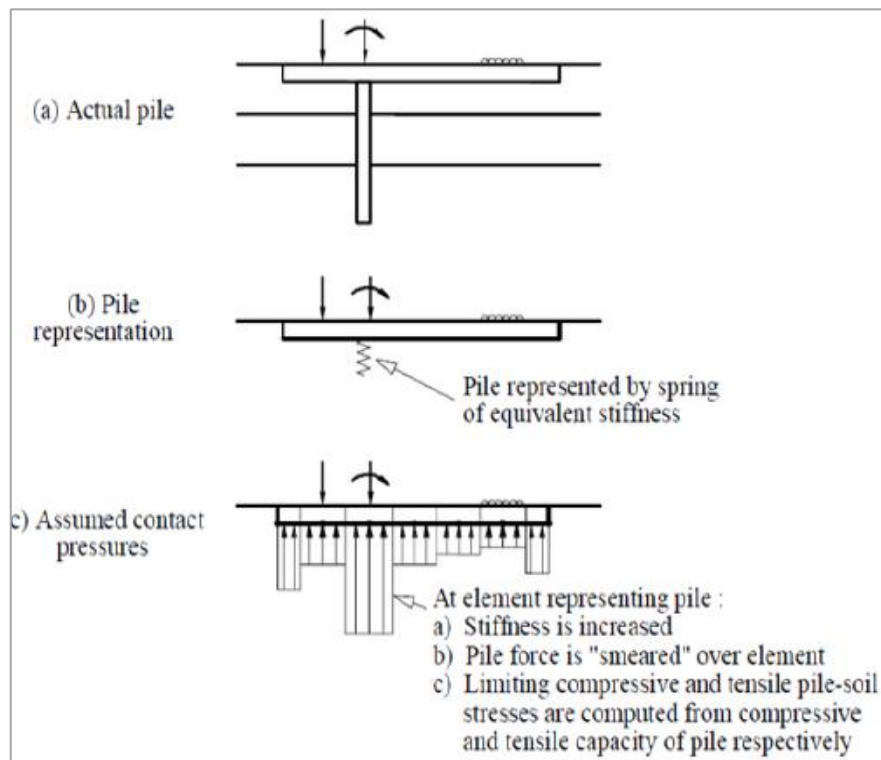


Figure 2-8 Representation of piled strip problem via GASP analysis (Poulos, 1991)

Soil non-linearity can be taken into account in an approximate manner by limiting the pile load to not exceed the compressive and uplift capacities of the piles. In carrying out a non-linear analysis, it has been found desirable to only consider nonlinearity in longer direction and to consider the pile and raft behavior in the shorter direction to be linear. Such a procedure avoids unrealistic yielding of the soil beneath the strip and hence unrealistic settlement predictions.

ii. Plate on Spring Approach

In this type of analysis the raft is represented by an elastic plate, the soil is an elastic continuum and the pile as an interacting spring. There are some early approaches in this category which neglect some of the components of interaction and give piled-raft stiffness which were too large (e.g. Hongladaromp et al., 1973).

(Poulos, 1994) presented a method of analysis of piled-raft foundations in which the raft is modeled as a thin plate and the piles as interacting springs of appropriate stiffness. The analysis is based on elastic theory, but allows for the important non-linear features of the system: the development of limiting pressures below the raft and of the ultimate load capacity of the piles. It allows consideration of the foundation response to applied loads and moments and also to free-field vertical soil movements. This analysis is implemented via the computer program GARP (Geotechnical Analysis of Raft with Piles) which employed a finite difference method for the raft with the consideration of various interactions via approximate elastic solution. Allowance has been made for layering of the soil profile, the effects of piles reaching their ultimate capacity, the development of bearing capacity failure below the raft, and the presence of free-field soil settlements acting on the foundation system.

(Russo , 1998) and Russo and Viggiani (1997) have defined a similar approach to the above methods, in which the various interactions are obtained from elastic theory, and non-linear behavior of the piles is considered via the assumption of a hyperbolic load settlement curve for single piles. Pile-pile interaction is applied only to the elastic component of pile settlement, while the non-linear component of settlement of a pile is assumed to arise only from loading on that particular pile.

In most of the analysis of piled rafts, the raft is being treated as thin plate. It should be the interest to see the effect using raft as thick plate. Poulos (2001) has examined the effect by taking raft thickness of 0.5m. He found no significant difference in the computed deflections for the raft, for both a stiff raft and a flexible raft.

It was concluded that the use of thin shell elements to represent the raft will lead to reasonable estimates of deflections, and therefore moments, as long as the raft is not extremely thick. Stresses in the soil will be higher for the thin shell analysis, and this effect may become important if yield of the soil due to concentrated loads is of concern.

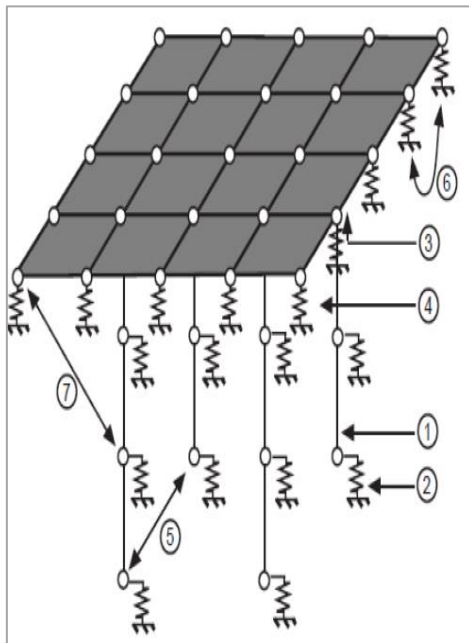
2.3.3 More Rigorous Methods of Analysis

Bearing capacity and average settlement of rafts are considered on the preliminary design. This helps to decide the number of piles required and where these piles should be located, but other issues such as differential settlement, raft shear force and bending moment, distribution of load among the piles etc. are not considered. So it is necessary to carry out a more detailed design in order to assess the detailed distribution of settlement and decide upon the optimum locations and arrangement of the piles.

I. Hybrid Approach

Hybrid Method, as the name implies, combines two or more methods to simulate the complex piled raft foundation behavior. The purpose of combining two or more numerical geotechnical method is to reduce the mathematical interpretation and thereby to reduce the computer memory and time consumption requirements.

(Clancy and Randolph, 1993) employed a hybrid method which combined finite elements and analytical solutions. The Method described here is a 'hybrid' numerical method, which has been developed specifically to minimize the amount of computation. It combines finite elements to model the structural elements of the foundation (the raft and pile) and simplified closed form analytical expressions for the diagonal terms of the soil response stiffness matrices. The three kinds of interactions, namely, pile- soil-pile, pile-soil-raft and raft-soil-raft are accounted for using the elastic theory of Mindlin. The major features of this hybrid finite element-elastic continuum-load transfer approach are presented in Figure 2.9.



- 1) One-dimensional pile element
- 2) Lumped soil response at each pile-node-load transfer spring.
- 3) Two-dimensional plate-bending finite element raft mesh.
- 4) Ground resistance at each raft node represented by an equivalent spring
- 5) pile-soil-pile interaction effects calculated between pairs of nodes-Mindlin's equation.
- 6) raft-soil-raft interaction.
- 7) pile-soil-pile interaction.

Figure 2-9 Numerical representation of piled raft foundation

This method provides a relatively rigorous and considerably more efficient method of analysis for pile rafts. Fewer equations need to be solved than for the finite element method and the time-consuming numerical integrations of boundary element method are not necessary. The hybrid method allows for variable geometry, pile stiffness, soil stiffness and raft stiffness. Although only vertical applied loading and linear elastic soil conditions are considered here, it is relatively straightforward to allow for non-linear response at the pile-soil interface, or to extend the analysis to include horizontal or inclined loading. However, the method is limited to homogeneous soil.

I. Boundary Element Methods

On this approach, discretization is only necessary on the boundary of the system under consideration. This method requires the transformation of the governing partial differential equation into an integral equation. As only the boundaries have to be discretized, the number of sets of equations to be solved is generally smaller than the finite element or finite difference methods. Solutions such as stresses and displacements can be obtained directly by solving the system of equations. Since only the boundaries are discretized, interpolation errors are confined to the boundaries. (Simeneh Abate, 2009)

II. Two – Dimensional Numerical Analysis

This method usually involve the presentation of the pile group or piled raft as either a plane strain problem, e.g. (Desai, 1974), or as an axi-symmetric problem, (Hooper, 1973). There is significant approximations need to be made. In each case, finite elements are used to discretize both the raft and the soil, and it is therefore a relatively simple matter to take account for nonlinear soil and raft behavior. The main problem in such a 2D approach is that only regular loading patterns maybe analyzed, also as with the plate on springs approach, this analysis cannot give torsional moments in the raft.

III. Three – Dimensional Numerical Analysis

Although there are many geotechnical problems that can be approximated to either plane strain or axi-symmetric conditions, some remain which are very three dimensional. Such problems will therefore require full three dimensional numerical analysis. In terms of ability to model a real problem, three-dimensional finite element analysis are usually considered to be the “ultimate weapon”, at least as far as the analysis is concerned (the problem of assigning appropriate parameters still remains, of course).

A complete three-dimensional analysis of a piled raft foundation system can be carried out by finite element analysis (e.g. Katzenbach et al., 1998). In principle, the use of such a program removes the need for the approximate assumptions inherent in the other’s analyses. (Zhuang, Lee, & Zhao, 1991) and (Lee, 1993) have used a linear three-dimensional analysis to derive parametric solutions for the settlement and load distribution with in piled rafts. Among the varied parameters, the relative raft stiffness, the relative pile length, and the number of piles were presented.

IV. Variational Approach

An alternative approach was investigated by the researchers to overcome the limitations of existing numerical method (e.g. discretization, time and computer resources requirements of numerical method) by employing the work energy principles.

This approach makes use of the principle of minimum potential energy to simulate the response of the foundation system. Discretization are only required at the interface between the raft and soil. (Shen, Chow, & Yong, 1999) developed a vibrational approach for analysis of pile groups with rigid pile cap not in contact with the ground. An extension of the method was developed by the same authors for the analysis of the cap in contact with the group (Shen,

Chow, & Yong, 2000). Interaction between the cap, piles and soil was simulated by the use of Mindlin's solution and finite series were used to represent the deformation and shear stresses along the piles. The soil was modeled as an isotropic elastic half space and the piles were assumed to be linearly elastic.

The analysis involved the isolation of the pile group-soil system from the pile-cap foundation and the interface between the pile cap and soil was discretized into a number of elements. The pile group-pile cap system was analyzed by the minimum potential energy principle.

Generally some of the available methods for analysis of piled raft behavior presented by different researcher are reviewed. All involved were different from one to another because of the number of simplifications in relation to modeling of the soil profile and the loading conditions. The simple methods can be implemented with minimal computer requirements with some limitations. Three-dimensional analysis using numerical method based software which can give more realistic solution. Analysis of foundations embedded in non-homogeneous soil can be done by using finite element based commercial software package. However, solutions those were given by Poulos (2001), Randolph (1994) are mostly used in the design analysis of piled raft foundations.

2.4 Design Issue

The performance of piled raft foundation depends on different factors since it is composed of piles, raft and soil, its behavior is mainly depends on these factors. A sound prediction of piled raft foundation behavior implies a full interaction between piles, raft and soil. Hence, the following factors must be considered which are the raft characteristics, piles characteristics, and soil characteristic.

(H. Poulos 2001) suggested that in order to provide an optimum piled raft foundation design, the following aspects shall be considered and checked:-

1. Ultimate geotechnical capacity under vertical, lateral and moment loadings,
2. Maximum and total settlements,
3. Differential settlement and angular rotation,
4. Lateral movement and stiffness,
5. Load sharing between the piles and raft,
6. Raft moment and shear for the structural design of raft and its stiffness,

7. Pile loads and moments for the structural design of the piles and its stiffness.

2.5 Interactions in Piled Raft Foundation

Complex soil-structure interaction plays an important role in the design of a piled raft foundation as the loads are shared between the piles and raft. The raft and piles load the soil and cause it to deform. Many analysts of piled raft foundations employ structural analysis programs in which the raft is represented by a plate and the piles as springs. It is common for the spring stiffness of the piles to be computed for a single isolated pile, ignoring the effects of pile-soil-pile interaction. It is also common for such analyses to ignore the effects of raft-pile and pile-raft interaction. Such analyses will therefore tend to give a foundation stiffness which is too large, and settlements which are too low. So, it appears that the use of structural programs for piled raft analyses, without due consideration of the interactions involved in the piled raft system, may lead to serious underestimates of settlement. As a by-product, they may also lead to inaccurate estimates of raft bending moments and pile loads.

The load bearing behavior of piled raft foundation is characterized by complex soil – structure interaction between the element of foundation and sub soil. The load bearing behavior of piles as part of piled raft differs with free standing pile. The ultimate bearing capacity of pile beneath piled raft is greater than as compared with single isolated pile whereas its stiffness smaller than the stiffness of a single isolated pile. This is due to the effect of pile - pile and pile - raft interactions (Giretti 2009).

Pile-soil-raft interactions are important factors that control the piled-raft foundation behavior. Unlike the traditionally designed pile group wherein the interaction is only between piles and the soil, in the case of piled raft there are four different types of interaction that need to be computed in the analysis (fig 2.11)

- 1) Pile-Pile Interaction – deflection of an unloaded pile caused by loading of an adjacent pile
- (2) Pile-Soil Interaction – deflection of an unloaded soil surface caused by loading of the pile
- (3) Soil-Pile Interaction – deflection of an unloaded pile caused by loading the soil surface
- (4) Soil-Soil Interaction – deflection of the soil surface caused by another loaded soil area

Pile-soil-raft interaction could have favorable and unfavorable effects on bearing capacity and the settlement of piled rafts, respectively. The pressure between the raft and the soil favorably increases the horizontal stress on the pile shaft and consequently increases the shaft resistance. Whereas, this pressure may induce a negative skin friction on the piles which increases the settlement. The pile-soil-raft interaction mainly controls the load sharing mechanism of piled raft foundations when pile spacing (S) is more than $3.5d$ (d = pile diameter (Vakili 2015)).

Further in the case of piled raft the pile group alone is not intended to ensure the safety of the system but it is the combined system of raft, pile and the soil ensures the safety of the structure. To model for full analysis and design of piled raft foundations has to predict these interactions accurately (Poulos, 2000).

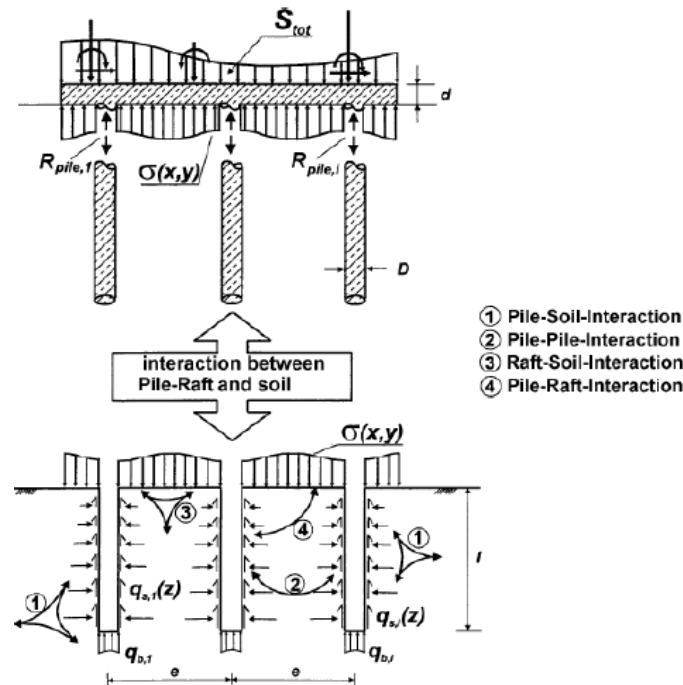


Figure 2-10 Interactions of piled raft elements

On the basis of the dimensions of the raft and piles, the piled raft can be classified as a small piled raft ($B_r < L_p$) and large piled raft ($B_r > L_p$) (Viggiani 2001). In a small piled raft, the primary reason to add the piles is to achieve a sufficient factor of safety against the bearing failure. The width of the raft B_r , belonging to this category, is generally small in comparison to the length L of the piles ($B_r / L < 1$) and amounts to a few meters. The flexural stiffness of the raft is usually high and the differential settlement does not signify a problem. However, in a

large piled raft, piles are added essentially to reduce the settlement. Bearing behavior of the piled raft foundation is described by pile-raft coefficient α_{pr} which is defined by ratio between the sums of the characteristic pile resistance to the characteristic value of the total resistance.

$$\alpha_{pr} = \frac{\sum_{j=1}^n R_{pile,k,j}}{R_{tot,k}} \quad 2.13$$

A piled raft coefficient of $\alpha_{pr} = 0$ represents the case of shallow foundation, and a coefficient of unity ($= 1$) represents the case of a fully piled foundation without contact pressure beneath the raft. Piled raft foundation cover the range $0 < \alpha_{pr} < 1$ (Fisseha Kiros, 2019).

2.6 Raft Analysis Approach

Basically two approaches have been suggested for analyzing the behavior of raft foundation:

a. Rigid foundation approach

The conventional rigid method is an approximate method where the mat is assumed to be infinitely rigid. The mat is divided into several strips in x and y directions loaded by a line of columns and resisted by soil pressure. The soil pressure is linearly distributed and the center of the soil pressure coincides with the line of action of the resultant column loads. These strips are then analyzed and designed as combined footings. This method can be used when the mat is very rigid, the column spacing pattern is fairly uniform in both directions, and column loads do not vary much over 20% (ACI Committee 336 Report). This method is not recommended at present because of the substantial amount of approximations and the wide availability of computer programs using the finite element method. In rigid rafts, differential settlements are comparatively low but bending moment and shear forces to which raft is subjected are considerably high.

b. Flexible foundation approach

The approximate flexible method assumes the soil to be equivalent to an infinite number of elastic springs (Winkler foundation), with elastic constant as the coefficient of subgrade reaction (k_s). With this approach the raft is considered to distribute load in the area immediately surrounding the column depending upon the soil characteristics, the moments, the shear, and deflection can be computed using the various equations. In this approach

differential settlements are comparatively larger but bending moments and shear forces to which the raft is subjected are comparatively low.

Also there are an available computer based methods to analyze raft foundations like finite element and finite differences methods. Finite differences method is based on the approach of uniformly distributed elastic springs and can consider one value of sub-grade modulus for the entire area. Finite element method transforms the problem of plates on elastic foundation into a computer oriented method of matrix structural analysis. In this method, plate is idealized as a mesh of finite elements inter-connected only at the nodes (corners), and the soil may be modeled as a set of isolated springs or as an elastic isotropic half space. The matrix structural analysis can be extended to include the influence of the super-structure as well. Thus, the interaction between the super-structure, the foundation and the soil can be accounted for. It is possible to consider different values of sub-grade modulus in different areas of the raft foundation. (Sharat Chandra, 1997)

2.7 Relative Stiffness Factor of Raft Foundations

According to ACI 336 (1988) whether a raft as a whole behaves as a rigid or a flexible structure depends on the relative stiffness of the structure and the foundation soil. This relation can be expressed by the stiffness factor K_r given below.

$$\text{For the whole structure, } K_r = \frac{EI}{E_s B^3 A} \quad 2.14$$

$$\text{For rectangular structure, } K_r = \frac{E}{12E_s} \left(\frac{D}{B} \right)^3 \quad 2.15$$

$$\text{For circular rafts, } K_r = \frac{E}{E_s} \left(\frac{D}{2R} \right)^3 \quad 2.16$$

Where

EI = flexural rigidity of the superstructure and foundation per unit length at right angle to B
 kg/cm^2

E_s = modulus of compressibility (or elasticity) of foundation soil in kg/cm^2

B = length of section in the bending axis in cm

A= length perpendicular to B

D= thickness of raft or beam in cm

R= radius of raft in cm

Also for raft with beam and shear wall

$$EI = E(I_F + \sum I_b + \sum ah^3 / 12) \quad 2.17$$

Where

EI_F = rigidity of foundation

EI_b = rigidity of beams

a= shear wall thickness

h= shear wall height.

Where $K_r > 0.5$, the raft can be considered as rigid with the ratio of differential settlement to total settlement being equal to 0. For $K_r = 0.5$, the ratio of differential settlement to total settlement is 0.1 and, if $K_r = 0$, then this ratio is equal to 0.35 for square mats and 0.5 for long foundations. (Braja Das, 2011)

Raft foundations are commonly used where settlements may be a problem, for example, where a site contains erratic deposits or lenses of compressible materials, suspended boulders, etc. A problem of more considerable concern is differential settlement. Again the mat tends to reduce this value.

Raft is only a large footing and, like a footing, it must satisfy the requirements that the factor of safety with respect to a base failure should be adequate and that the settlement should not exceed an amount acceptable to the designer of the superstructure. The factor of safety of raft foundations depends on the nature of the subsoil. If the soil consists of very loose sand in a saturated state, it should be compacted before the raft is constructed. If the sand is medium or dense, the factor of safety of a raft is considerably greater than that of footing, and its adequacy can be taken for granted without any computation. The factor of safety of raft

foundation on clay is practically independent of the size of the loaded area. It is commonly very low, and several failures have occurred.

2.8 Verification Example

Computer-oriented finite element methods become tools for engineering problems in numerical modeling of the structural response. The software used for developing the model must be validated before its result is accepted and applied to simulate. Studies make verification before any analysis. Validation is the only way to justify the predictions of a numerical model (Sinha 2013). Performance and accuracy of PLAXIS 3D carefully tested by known theoretical solution. PLAXIS 3D has also been used to carry out predictions and back-analysis calculations of the performance of the full-scale structure as additional checks on performance and accuracy. In this part, we will see whether the results of PLAXIS 3D software are reliable or not. Thus, to support the results obtained by the computer program, PLAXIS 3D Foundation, two cases are taken for literature to verify the results.

2.8.1 Messeturm Piled Raft

The piled raft was extensively used in Germany to optimize the foundation of high-rise buildings as well as bridges in different subsoil conditions. Some case studies will be given to demonstrate the application of the piled raft as an economic foundation system. Messeturm was the tallest high-rise building in Europe until 1997. Figure 3-2 shows a layout of Messeturm with the piled raft according to Chow/ Small (2005). The building lies in Frankfurt city in Germany. It is 256 m high and standing on a piled raft foundation. The building has a basement with two underground floors and 60 stories with a total estimated load of 1880 MN.

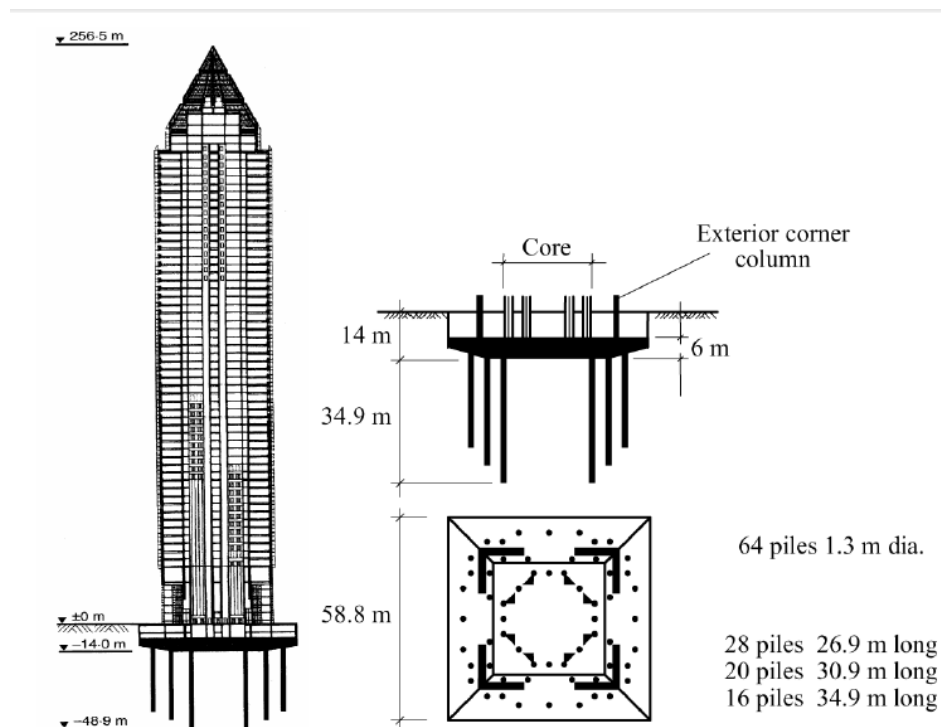


Figure 2-11 Layout of Messeturm with piled raft after Chow/ Small (2005)

A square piled raft with a cross sectional area of 58.8 m×58.8m at a depth 14m under the ground surface. Thickness varies from 6 m at the middle to 3 m at the edge (for verification average value is used). A total of 64 bored piles with equal diameters of 1.3 m are arranged under the raft in 3 rings. Pile lengths vary from 26.9 m for the 28 piles in the outer ring to 30.9 m for the 20 piles in the middle ring and to 34.9 m for the 16 piles in the inner ring (for verification average value is used). The pile spacing varies from 3.5*D up to 6*D. The subsoil at the location of the building consists of gravels and sands up to 8 m below the ground surface underlay by layers of Frankfurt clay extending to great depth of more than 100 m below the ground surface. The groundwater level lies at 4.75 m under the ground surface. The construction of Messeturm started in 1988 and finished in 1991. According to Katzenbach et al. (2000), the recorded settlement at the center of the raft in March 1990 was 8.5 cm, while the last recorded settlement in December 1998 was 14.4 cm according to Reul/ Randolph (2003). If Messeturm stands on a raft only, the expected settlement would have been between 35 cm and 40 cm based on geotechnical studies according to Sommer (1989). Therefore, to reduce the settlement, a piled raft was considered where the expected final settlement in this case would be between 15 cm-20 cm according to Sommer/ Katzenbach (1990). To examine

NPRD for the Messeturm piled raft, results are compared with those using Randolph's analysis, which was carried out by EL-Mossallamy (1996). The book called analysis of piled rafts by the program ELPLA published in 2017 Summarizes the results of the immediate and total settlements for Randolph's analysis (1994) and NPRD we used that result as a comparison purpose on this thesis shown in the figure below.

A similar modeling has been done by using PLAXIS 3D as a verification example by using the available data and taking standard assumptions. The settlement predictions using the developed PLAXIS 3D model is in good agreement with the predictions of Randolph's analysis and NPRD (Nonlinear Analysis of Piled Rafts, Russo 1998) Comparison between the results of the developed models is summarized in figure 2-12.

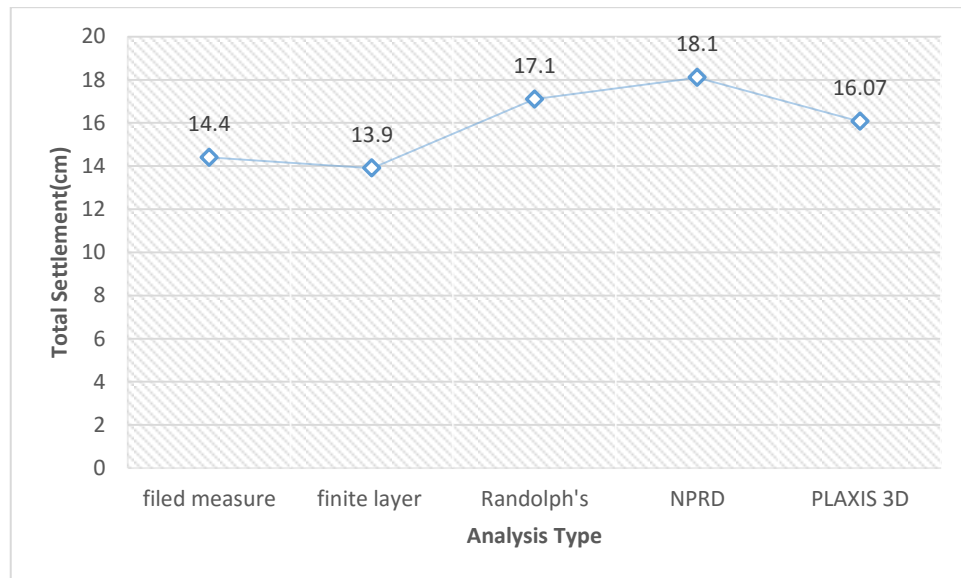


Figure 2-12 comparison of different analysis results

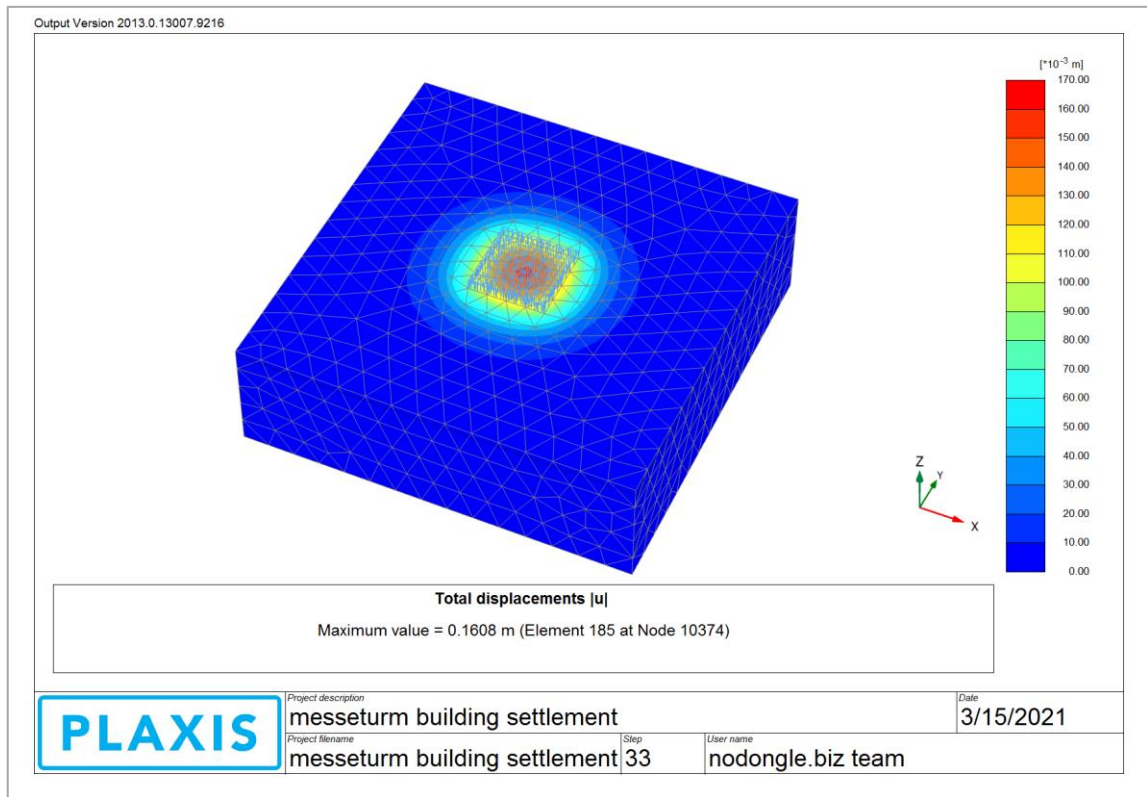


Figure 2-13 Messeturm Building total displacement by PLAXIS 3D

2.8.2 Afsoon Coastal Building

Afsoon, a 12-storey coastal building is located in Babolsar, near shoreline of the Caspian Sea in northern Iran. The dimensions of the mat foundation in plan are 25m×25m. A total vertical dead load of 53.28MN is expected to be carried by the combined foundation. Subsoil layers consist of coastal sand, blown sand and some silty sands in the deep layers. SPT blow counts, in the depth, with an average of 18, show a loose to medium subsoil condition down to 22.0m below ground level. Dense to very dense layers (SPT blow counts greater than 45) is located below 22.0m depth. Elasticity coefficient, poisson's ratio and soil internal friction angle are 35MPa, 0.3 and 30° respectively for subsoil layers. A composition of driven piles and a mat foundation is employed to resist the liquefaction and control further settlements. 23 driven piles with a circular section and an average length of 8.5m and 19 vibrio-driving H-piles with average length equal to 10.0m were penetrated into the ground to improve subsoil properties (circular bored piles are used for simplification). The mat thickness is 0.8m and embedded in -1.5m elevation below the ground level. A site monitoring and surveying program was performed to measure the average settlement of the foundation system. The maximum

settlement of about 26.0mm is obtained. Also two and three-dimensional finite element modeling of this project is done. The results demonstrate that a 19.0mm average settlement can be considered for the foundation which shows a good agreement with measured data. This value has been obtained by the simplified equivalent elastic analysis instead of a highly complicated nonlinear FE analysis. The maximum settlements from two and three dimensional analyses were obtained to be 26.8mm and 23.3mm consequently. (Eslami et al., 2011)

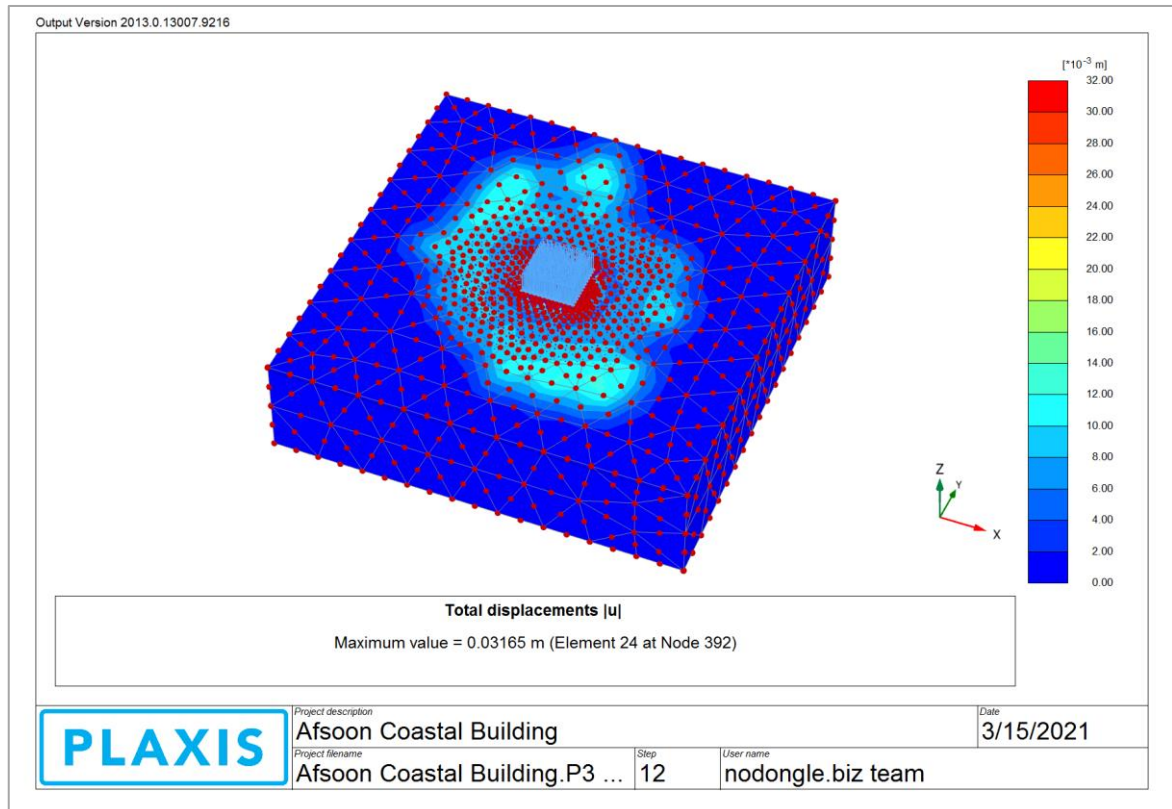


Figure 2-14 Afsoon coastal building total displacement by PLAXIS 3D

By taking the same data from literature the analysis of Afsoon Coastal building by PLAXIS 3D were done and the results demonstrate that a 31.65 mm total settlement can be considered for the foundation which shows a good agreement with measured data.

After review, the results obtained from the developed numerical model agreed with the experimental data and other numerical models. Therefore, PLAXIS 3D results are reliable adopted for my analysis.

2.9 Related Studies

Settlement analysis of piled raft foundation by numerical method is not new. The piled raft has proved to be an economical foundation type compared to conventional pile foundations. Since 1970 many researchers had studied about the different properties of piled raft foundation and its influence on reducing the maximum and differential settlement. In many cases using raft foundation only induces excessive settlements which are not acceptable due to serviceability requirements. Earlier settlement analysis of piled raft foundation for different type of soil have been developed. Some of the carried-out researches, which are found in the literature, are as listed below.

Brown and Weisner (1975). Has given the graphical results for load taken by piles, maximum displacement and differential displacement, and maximum positive and negative moments, due to uniformly distributed loading applied to a smooth strip footing which is supported by piles in deep homogeneous isotropic elastic foundation.

The flexible foundations were analyzed by, but they analyzed the pile with the classical beam theory, which limits the scope of application of the method.

Mendoca and Paiva (2003). A static analysis of vertically loaded raft and piled raft foundations in smooth and continuous contact with the supporting soil is presented. They developed a hybrid method to study the behavior of rigid and flexible piled raft foundation. In this approach the finite element method (FEM) and the boundary element method (BEM) are coupled. The boundary element method was adopted to simulate the elastic behavior of homogeneous half-space soil, which is difficult to be extended for non-homogeneous layered soils and nonlinear soil behaviors. While the bending plate is assumed to have linear elastic properties and is modelled by FEM. The pile is represented by a single element and the shear force along the shaft is interpolated by a quadratic function. The plate-soil interface is divided into triangular boundary elements (soil) also called cells and finite elements (plate) and the subgrade reaction is linearly interpolated across each cell. The subgrade tractions are eliminated from the FEM and BEM algebraic systems of equations, resulting in the governing system of equations for plate-pile-soil interaction problems. Numerical results are presented and they are close to those resulting from much more elaborate analyses. However the boundary element method to simulate the elastic behavior of homogenous half spaced soil,

which is difficult to be extended for non-homogeneous layered soil and nonlinear soil behaviors.

Metshafa Mekbib (2004). On his thesis he presents the investigation of the performance of the concept of piled raft foundation compared to the conventional pile and raft foundation for Addis Ababa soils. To support the results of the investigation, soil profile from Wabe Shebele river bridge site were considered. On his work, different design philosophies and method of analysis were revised. The analysis was conducted by hybrid method of analysis. The case studies indicate that piled raft foundation concept has significant advantages in comparison to conventional foundation for some Addis Ababa soils.

Won et al., (2006). They developed a numerical method that takes into account the coupling between the rigidities of the piles, the cap, and the column has been developed for analyzing the response of pile group supported columns. Special attention is given to consideration of pile cap flexibility. The numerical method developed has been verified by comparing the results with other numerical methods for pile groups. Through comparative studies, it has been found that the maximum load on the individual piles in a group is highly influenced by pile cap flexibility. Considering the axial load in the pile, the piles near the outer parts of the foundation tend to carry higher loads than those in the interior parts of the foundation, especially for large foundations, which may lead to difficulties in the structural design of the piles. The flexibility of the pile cap or raft is governed by several factors including the raft thickness and spacing between piles. In general they conclude that, the flexibility of the pile cap or raft influences the distribution of pile loads, bending moments and shear forces in individual piles.

Simeneh Abate (2009)

Presented the three dimensional nonlinear finite element analysis of piled raft foundation which is under the application of uniformly distributed load (UDL). The material nonlinearity of the soil medium has been idealized by Mohor-Columb model. He tried to analyze piled raft foundation on deep deposit of clay. Also parametric study of piled raft foundation were conducted. According to their effect on the response of piled raft system, a number of parameters were selected from the elements of the piled raft system. He varied raft thickness, the spacing of piles, number and length of piles for his study. The study is performed using finite element based software, PLAXIS.

Raft thickness were one parameters among the other's the analysis was conducted by considering the raft as rigid and evaluating the parameters that affect piled raft performance from serviceability perspective. On examining the effectiveness of Simeneh's parametric study, it is observed that was considered the effect rigid (thick) raft however the parametric study was done only either for thick raft. The thickness of the raft, number of piles, spacing and length are the major variables for his analysis.

Aluniam et al., (2015). A detailed 3D analysis on piled raft foundation have been conducted by to examine the effect of raft flexibility. The width of raft and diameter of piles on load sharing behavior of piles and raft by using finite element method were investigated. In their paper, a 3D finite element model was verified using published geotechnical centrifuge test data. The study was performed on cohesion less soil with linearly increasing stiffness with depth. An extended parametric study in which the effect of different parameters, such as pile spacing, piled diameter, raft width, and raft thickness on the overall behavior of a piled raft was conducted. A finite element analysis (FEA) was carried out using the Plaxis 3D bv.2011 software package. The result showed that the percentage of load shared by the piles increase as pile diameter increase and decreases as raft width increase. But raft flexibility has significantly affected the load shared by piles and raft. Flexibility of raft is depending on raft thickness and pile spacing. From there result one may notice that piles spacing have a great influence on load sharing behavior of piled raft foundation.

H.S.W.Chow and H.G.Poulos (2015) had also study the importance of taking the flexibility of the pile cap into account in making assessments of the load and moment distribution in the pile raft analysis. On their analysis the case of a hypothetical soil profile were considered first and then the case of a super tall building that are found in Korea were considered. A simple example is considered three cases by varying the number of piles. For each case, both a rigid raft and a flexible raft are taken into account. Analyses have been carried out for the pile groups subjected to a uniform axial load and a uniform horizontal load. A case study of the Incheon 151 twin tower with a height of 601m located in Songdo, Korea was selected.

According to them, considering a rigid raft for the foundation, the total and differential settlement was predicted to be smaller, with higher pile head loads for corner and center edge piles, thus resulting in higher vertical pile stiffness values, especially on the outer piles when compared with those for a flexible raft. On their finding, for a flexible raft for the foundation,

the pile load distribution is fairly uniform, with slightly higher pile loads being predicted at the center of the foundation where the heavily loaded core is located. The loads on piles for a rigid raft case are approximately two times the loads for a flexible raft, except for the center piles.

Based on the assessment, they conclude that it is important to model the flexibility of the raft to avoid having to design for unrealistically large loads in the outer piles within the group.

Mehader Mamo (2018). Perform his research to assess piled raft foundation for high rise building found in Addis Abeba for the case of Zemen, Nib and United Bank Head quarter buildings. Both factored and un-factored load were used to investigate the settlement, angular distortion and load distribution of piled raft foundation. For this study the only varied parameter was the spacing of pile. The study conclude that, settlement response of piled raft foundation for pile spacing 3D and 6D were the same and the settlement of raft alone was insignificant too. According to his findings doubling pile spacing doesn't have significant importance on settlement reduction and but play a role in load sharing under vertical load.

Fissaha Kiros (2019). The main objective of his study was to investigate the contribution of the raft to bearing behavior of piled raft foundation and to the assess load sharing mechanisms between the raft and piles. He used ABAQUS model has been developed to study the behavior of piled raft foundation in case of pile tips resting on a stiff stratum. The researcher used commercial bank Ethiopia head quarter building as a case study. On his paper, it has illustrated the process of design of a piled raft foundation using two stage procedures, in the first stage an initial assessment of piled raft foundation was carried out using simplified method , and in the second stage a detailed design of the foundation and assessing its behavior was carried out using finite element method.

The results of the analyses show that the raft alone can carry the superstructure load with allowable settlements. But when the raft is analyzed with 46 piles, the raft contribution became insignificant. The load sharing between the raft and the piles depends not only on the ratio of the stiffness of the piles to that of the raft but also depends on the settlement of the foundations. The load carried by the raft increases significantly when the settlement of the raft increases.

Table 2-1 Summary of related studies

Year	Author	Findings	Remark
1975	Brown and Weisner	Graphical results for load taken by piles, moment distribution and settlement under strip footing	Flexible foundation analyzed by classical beam theory
2003	Mendoca and Paiva	They developed a hybrid method to study the behavior of rigid and flexible piled raft foundation	Difficult to be extended for non-homogeneous layered soil and nonlinear soil behaviors.
2004	Metshafa Mekbib	The studies indicate that piled raft foundation concept has significant advantages in comparison to conventional foundation	Case studies for addis abeba soil
2006	Won et al	It has been found that the maximum load on the individual piles in a group is highly influenced by pile cap flexibility. Special attention is given to consideration of pile cap flexibility.	Spacing and thickness of the raft were the only governed parameters
2009	Simeneh Abate	The thickness of the raft, number of piles, spacing and length are the major variables for his analysis.	He tried to analyze piled raft foundation on deep deposit of clay.
2015	Aluniam et al	a 3D finite element model was verified using published geotechnical centrifuge test	Layered soil

		data	
2015	H.S.W.Chow&H.G.Poulos	Analyses have been carried out for the pile groups subjected to a uniform axial load and a uniform horizontal load.	
2018	Mehader Mamo	Both factored and unfactored load were used to investigate the settlement, angular distortion and load distribution of piled raft foundation	Case study Only spacing were the varied parameter
2019	Fissaha Kiros	he has illustrated the process of design of a piled raft foundation using two stage procedures,	Case study

3. MATERIAL AND METHODS

3.1 Introduction

The literature review presented in Chapter two shows several studies related to piled-raft foundations & different analysis methods. Numerical analyses using finite element techniques are popular in recent years in the field of foundation engineering. Finite element computer programs were developed with several facilities and to suit different needs. The behavior of soil with appropriate stress-strain laws incorporates as applied to discrete elements. (Reul, O. and Randolph, M. F., 2003). Because of the complexity of piled-raft foundations, each method of analysis had its advantages and disadvantages. The developed numerical model was then used to study the influences of various foundation parameters on its bearing behavior.

In order to construct the model, some of the available commercial programs were examined to identify the most appropriate program for achieving the objectives of the intended numerical model. Programs such as ABAQUS, FLAC and PLAXIS were considered for comparison. It was found that ABAQUS software, which is based on the finite element method, has applications for many engineering field but it is not specially developed for analyzing geotechnical problems. It is a general-purpose program. FLAC program is software which is developed mainly to be used for solving and modeling geotechnical problems. However, FLAC is based on the finite difference method. It was reported by some researchers that the finite difference method cannot model the interaction between piles in pile group foundations as accurate as the finite element method (Zkaria Mohamed Omeman, 2012).

It was also reported by some researchers that the most powerful tool for analyzing piled raft foundations is the finite element method because it accounts for the interactions between the piles. Therefore, the finite element method was selected in this study to develop a numerical model to predict the load-settlement relationship and load sharing between the piles and the raft of the piled-raft foundations. The developed model offers a considerable saving in computational effort and time while improving the accuracy of three-dimensional modeling of piled-raft systems. PLAXIS is geotechnical software based on the finite element method and it is intended especially for analyzing geotechnical problems. It can be considered as a special-purpose program. It can be used as a tool for practical analysis for most areas of geotechnical engineering.

3.2 Modeling of Piled Raft Foundations Using PLAXIS 3D

3.2.1 Introduction

A 3D numerical model was developed to simulate the case of a piled raft foundation. The model consisted of the soil continuum, the geometry of the foundation elements, the contact zone, and the applied loads. This section explains how to model piled raft foundations using PLAXIS, which is one of the powerful finite element program software. 3D numerical modeling involves considerably more elements and therefore more nodes and interaction points than 2D modeling. The modeling process is started by defining the element materials for soil and concrete.

3.2.2 Element type

Different element types are available in PLAXIS software (i.e., beam, plate, and embedded pile) which are implemented based on the nature of projects. The basic soil element of the 3D finite element mesh are the 10-node tetrahedral element (fig 3.3). In addition to the soil elements, special types of element are used to model structural behavior. For beam element, 3-node line element are used, which are compatible with the 3-node edges of a soil element. In addition, 6-node plate and geogrid element are used to simulate the behavior of plate and geogrids respectively. Moreover 12-node interface elements are used to simulate soil-structure interaction behavior.

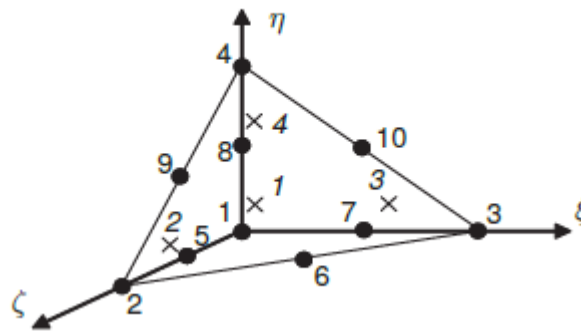


Figure 3-1 3D soil elements (10-node tetrahedrons)

The first step in FEM analysis is to define the problem domain, which usually includes all the materials enclosed by a set of restraints or boundary conditions. The problem domain can be broken (discretized) into a series of continuum elements to form a mesh. The elements in the

problem domain are connected together by nodes that transfer forces and displacements between elements. The force applied on the element is represented by a load vector act of the forces that at the nodes. The elements consist of a number of nodes and each node has two degrees of freedom (DOF). According to the deformation theory, the degrees of freedom correspond to the displacement components has horizontal and vertical directions.

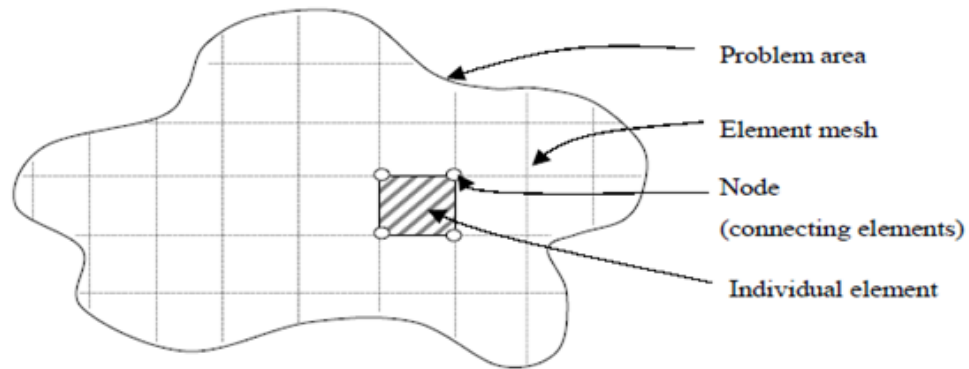


Figure 3-2 typical mesh problem domain for FEM (Kate 2005)

3.2.3 Geometry

As the first step of the modeling process, the geometry of the piled raft and the soil block were defined. The geometry model was the composition of boreholes and horizontal work planes. The work planes define geometry lines & structures contour lines along with the elevation level & the borehole defined the soil properties, ground surface level, and the location of the water table. Taking advantage of symmetry across the x and y-axis quarter of the piled raft system was modeled to reduce the computational effort and time. Model boundary placed at sufficient distances from the foundation to minimized deformation influence set at a distance equal to $2B$ (where B is raft width) measured from the edge of the raft & the depth of the model was approximately two times the pile length.

Table 3-1 Geometric configuration of pile-raft model for parametric analysis

Parameters	Unit	Value
Raft width	M	26
Raft length	M	26
Raft thickness	M	1,1.5, 2, 2.5, 3, 3.5, 4,6
Number of piles	M	16,25,49,36,81
Pile spacing	M	3d,4d,4.5d,6d,8d
Pile length	M	10,20,30,40
Pile diameter	M	1

3.2.4 Modeling of Concrete Piles

The pile element in PLAXIS are modeled as embedded pile. The embedded pile elements consider the piles as slender beam elements, which are connected to the surrounding soil by embedded skin interfaces and embedded foot interfaces which can penetrate the soil volume elements at any arbitrary location and orientation. Although the diameter d , the unit weight, γ and the modulus, E are assigned to the embedded beam element, it remains a line element in the finite element model. The diameter, d , in the material data set determines an elastic zone in the soil around the beam (pile) in order to avoid failure in a soil element which should physically be a pile element (Engin (2006)).

The behavior of the piles was assumed linear. Therefore, the linear-elastic model was utilized to simulate the materials behavior of the piles. For the linear-elastic model two main parameters are used, which are the modulus of elasticity, E , and Poisson's ratio, μ . This model is based on the Hooke's law of isotropic linear elasticity (Brinkgreve, 2002).

The piles are assumed to be made of concrete with a circular cross-section of 1m in diameter. Piles can be either driven or cast in place. Pile driving is achieved by: impact dynamic forces from hydraulic and diesel hammers; vibration or jacking. Concrete and steel piles are most common. Driven piles which tend to displace a large amount of soil due to the driving process are called full-displacement piles. Cast-in-place (or bored) piles do not cause any soil displacement, therefore, they are non-displacement piles. The pile installation process is rather

complicated and not modelled here. The stress change in the soil during the pile installation is therefore not included (wished in place) to model the bored piles. So for this analysis, the piles were assumed as non-displacement concrete piles.

3.2.5 Modeling of Concrete Raft

The raft is also made of concrete and numerically modelled by plate elements. The raft is modelled as an isotropic elastic material with material parameters given by modulus of elasticity, $E = 3.2 \times 10^7$ kPa and Poisson's ratio, $\gamma = 0.25$. The pile heads are assumed to be connected to the raft rigidly

3.2.6 Modeling of Soil

The soil was assumed to be homogenous sand soil. To predict the behavior of piled raft foundations at large settlements a non-linear analysis is required. Therefore, the behavior of the soil was considered as non-linear. Sandy soils laid up to a depth of 80m were considered for this analysis which stiffens vary with depth and the groundwater table located at foundation level. The increased stiffness calculate in Appendix. There are many constitutive models used to simulate the soil behavior such as the Linear Elastic Model, Mohr-Coulomb model, Cam Clay Model, Drucker-Prager and Hardening Soil Model. The elastic perfectly-plastic Mohr-Coulomb model was used to simulate the non-linear stress-strain behavior of the sand soil. The Mohr-Coulomb model is a non-linear model which is based on soil parameters that are well-known in engineering practice. For this model, the modulus of elasticity of soil, E_s , and Poisson's ratio, μ_s , are used for the soil elasticity while the friction angle, ϕ , and the cohesion, c , are used for the soil plasticity and the dilatancy angle is needed to model the increase of volume. The properties of the subsoil as reported by eleventh east asia-pacifi conference on structural engineering and construction were used for the analysis.

3.2.7 Mesh Generation

Generating a mesh is the process of dividing the domain into many subdomains (Finite elements). In FE the accuracy of the domain depends on the nature of the mesh. The finer mesh is the more accurate the result will be, but it consumes large computational time.

Piled-raft foundation is a three dimensional problem, which requires three dimensional modeling. However, in three-dimensional models the computational time and effort are

excessive due to the large number of elements in the mesh. The time required for the computations depends on the number of elements used in the model. Katzenbach et al. (2005) reported that three-dimensional finite element simulations of piled-raft foundations with an average number of elements in the range of 10,000 to 25,000 elements need about 18 hours of computational time on a Sun-Ultra 2 workstation. They also expected that increasing the number of elements and considering other issues in the simulations such as consolidation would lead to an enormous increase of computational time. Therefore, reducing the number of elements could save much time in the calculation process. However, reducing the number of elements in the mesh can affect the accuracy of the model.

A collection of elements which are connected to each other by shared nodes form a mesh in a finite element model. A trade-off exists between the level of accuracy and the computational complexity—higher density mesh produces more accurate result at the cost of additional complexity. In the area where large stress concentrations or large deformation gradients are expected, it is desirable to have a more accurate (finer) finite element mesh, whereas other parts of the geometry might not require a fine mesh. Local refinement is based on a local fineness factor that can be specified for each geometry entity. This factor gives an indication of the relative element size with respect to the target element size as determined by the element distribution parameter. By default, the fineness factor value is set to 1.0 for most geometry entities whereas this value is 0.5 for structural objects and loads. A fineness factor value of 0.5 reduces the element size to half the target element size. The fineness factor can be changed by selecting the geometry entity and clicking on the fineness factor in the selection explorer. Values in the range from 0.0625 to 8.0 are acceptable. Using a value larger than 1.0 coarsens the mesh locally.

3.2.8 Soil Mass Boundaries

The boundaries of the soil in the model must be constrained in the vertical and lateral directions where the displacement of the soil due to the foundation load is negligible. In order to minimize the boundary effects in the model many authors suggested different locations of these boundaries. The boundaries of the model were placed at sufficient distances from the foundation so that the influence of the boundaries on the deformations of the foundation is minimized. For this analysis a quarter of the piled raft was modeled taking advantage of the

similarity across the x and y-axes. The boundaries of the model were set at a distance equal to $1.5b \sim 2b$ measured from the edge of the raft, and the depth of the model was approximately two times the pile length.

3.2.9 Application of Loading

The analysis was performed in three phases: the first phase was initial phase in which the in situ stress were calculated and the structural components are not activated; the second phase activated the structural components without applying the load; the third phase applied uniformly distributed load and calculate the results. In all the parametric study, only one parameter was varied at a time and standard values were selected for all other parameters. Parameter, which was used for the analysis of piled raft in finite element method were presented on table 3-4. PLAXIS 3D Foundation Software requires additional parameters to be filled as ultimate value for skin friction and base resistance. The calculation is illustrated in Appendix 2.

3.3 Physical Model of Piled Raft System

Piled raft 3D models consisting of Raft, Piles, and Soil. Each part of the structural system is separately modeled and then discretized into several finite elements. The plate element considers as a raft with a linear elastic model. Plate elements are the 6-node triangles with six degrees of freedom per node (three translational and three rotational). Embedded piles consider as piles. Embedded piles are structural elements developed by PLAXIS 3D modeled like beam elements. The benefit of the embedded piles was interaction to the continuum as the skin resistance and the base resistance. The embedded piles can be placed in any direction within the subsoil without any alteration of the mesh by crossing through a 10-node tetrahedral element while creating virtual nodes.

A 52m by 52m square raft was the cross-sectional area of the raft. By being symmetrical about both axes, a quarter of rafts were analyzed (26m by 26m) with 70m by 70m boundaries of the finite element model. The thickness of raft, pile spacing, and length of piles, taken as variables of the study. After the generation of the finite element model for all cases, simulated under a uniform vertical surface load of 200kN/m^2 imposed on the whole of the raft and uniformly distributed pile arrangements were considered. A typical 3D finite element model of the foundation system shows in Figures.

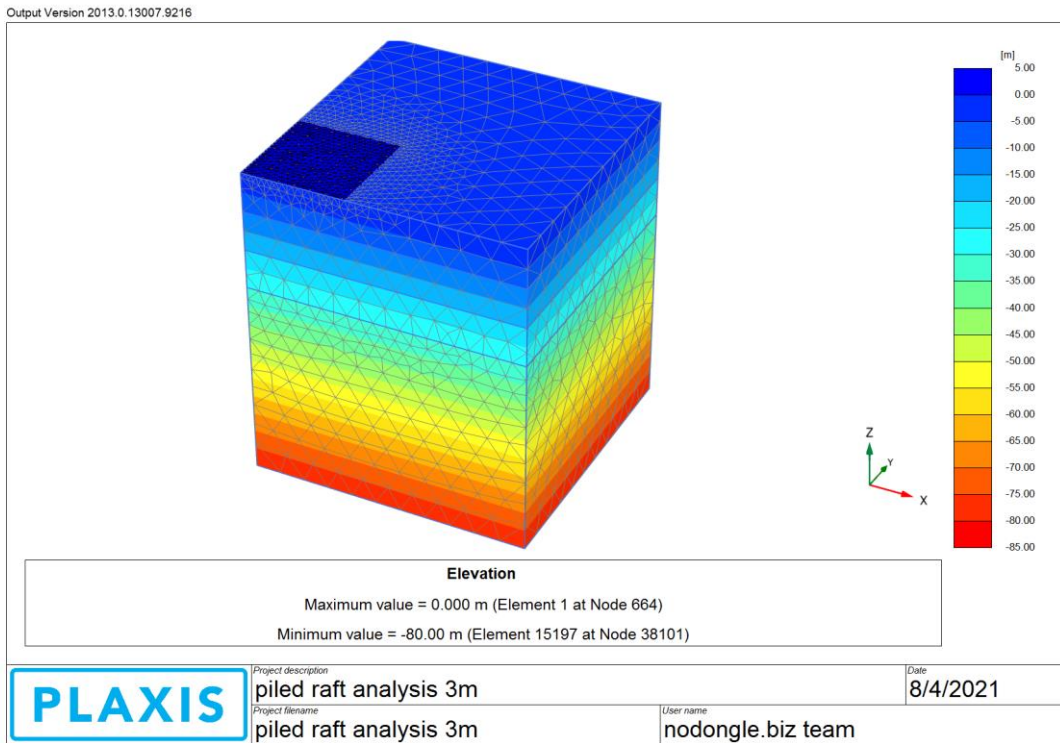


Figure 3-3 PLAXIS output of a typical 3D finite element mesh of soil and piled raft

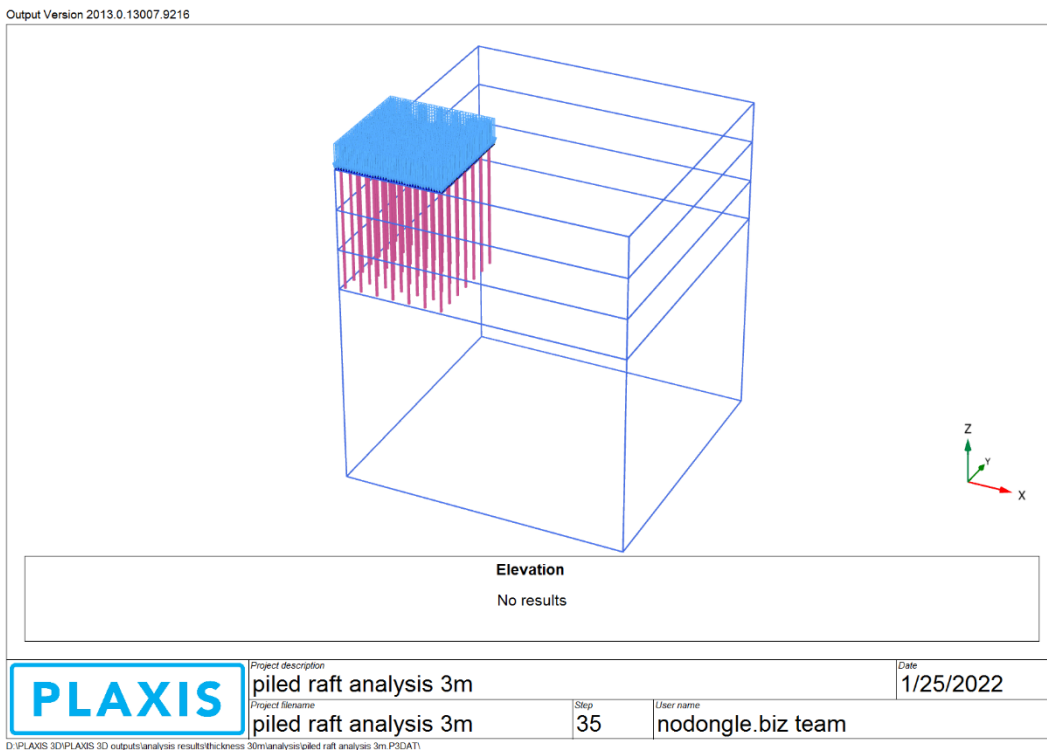


Figure 3-4 PLAXIS typical three-dimensional model of the piled raft

A short description of soils and concrete material models is present in Appendix A. The input soil properties, pile, and raft considered in this numerical analysis are present in Table 3.2.

Table 3-2 Summary of basic soil and concrete parameters used for PLAXIS 3D

Parameters	loose to medium sand	Raft(from EBCS for C-25)	Pile(from EBCS for C-25)
Thickness(m)	80m		
Unit weight, γ (kN/m ³)	$\gamma_{\text{unsat}}= 15$ $\gamma_{\text{sat}} =18$	$\gamma=25$	$\gamma=25$
Young's modulus, E_0 (kN/m ²)	10000	$3.2*10^7$	$3.2*10^7$
Poisson's ratio, V_s	0.3	0.2	0.2
Cohesion, C_u (kN/m ²)	0	-	-
Friction angle, ϕ	30	-	-
Dilatancy angle, ψ	0	-	-
R_{int}	0.67	-	-

3.4 Parameter Identification

Piled-raft foundations are a combination between a raft and piles. The load sharing and the load-settlement relationship are the most important aspects in designing piled-raft foundations. El-Mossallamy et al (2009) stated that the main criterion, which governs the design of piled-raft foundations, concerns the load sharing between the raft and piles and the effect of additional pile support on the foundation settlement. A parametric study was performed to link and establish the influence of various key parameters of the piled-raft foundation system on its load carrying capacity. The foundation system was modeled using the PLAXIS 3D foundation finite element based software. Identifying the important parameters which significantly affect the performance of piled-raft foundations can assist in optimizing the design of such foundations. This study focused on the effect of some parameters on the load-settlement relationship and the load sharing between the raft and piles of piled-raft foundations. The effect of the selected parameters on the load-settlement relationship will be investigated. The effect of the selected parameters on the settlement will be investigated. The tests in this study were carried out using the developed PLAXIS 3D model. Square piled-rafts supported by 16,

25, 36, 49 and 81 piles, as shown in the table, were studied. The parameters considered in this study can be summarized as follows:

Table 3-3 parameters considered in FEM

Raft thickness(m)	Pile diameter(m)	Number of piles	Spacing of piles(m)	Length of piles(m)
1,1.5,2,2.5,3,3,4&5	1	49	4D	30
1&3	1	81,49,36,25&16	3D, 4D, 4.5D, 6D, 8D	30
1&3	1	49	4D	10,20,30,40

3.5 Raft bearing capacity calculation

Prior to the detailed numerical modeling the load to be applied in raft were calculated first. This is to investigate the adequacy of the raft alone, in regard to ultimate bearing capacity. The favorable application of piled raft occurs when the raft has adequate loading capacities, but the settlement or differential settlement exceed allowable values. For the purposes of this analysis, square plates 26m by 26m raft in plan were used.

The ultimate capacity of the raft alone can be determined by using Bowles J.E (2002) in case of drained condition (long term).

$$q_{ult} = CN_c S_c + q' N_q S_q + 0.5 \gamma' N_\gamma S_\gamma r_\gamma$$

$$\text{Where } N_q = e^{\pi \tan \phi} \tan^2 (45 + \phi / 2)$$

$$N_c = (N_q - 1) \cot \phi$$

$$N_\gamma = (N_q - 1) \tan \phi$$

$$S_c = 1 + 0.2(B' / L')$$

$$S_q = 1 + (B' / L') \sin \phi$$

$$S_\gamma = 1 - 0.3(B' / L')$$

$$r_\gamma = 0.7B'$$

3.1

Taking the soil parameter from Table 3-2 and substituting in to (Eq. 3.1), the ultimate bearing capacity of the raft (q_{ult}) becomes 1.747MPa. Taking a factor of safety of 3 the allowable

bearing capacity (q_a) 0.6 MPa. Therefore, the raft capacity is estimated by using EBCS-7 and it can carry a maximum pressure of 0.6MPa.

3.6 Sensitivity Analysis/Mesh Refinement

The discretization of the soil, raft and pile into finite element influence directly the simulated output of the modeled piled raft behavior. Generally, the finer the element the more accurate would be the result. Where large stress concentration or deformation expect, it is desirable to have a finer finite element mesh, whereas other parts of the geometry might not require a fine mesh. Several finite element analyses used to investigate the influence of the number of elements and their sizes on the settlement behavior of the pile raft foundation. By varying their number and sizes by keeping material properties and other parameters kept constant analysis perform.

Table 3-4 Sensitivity analysis (Influence of mesh size on maximum Total settlement)

Model	Mesh Type	Numbers of Element	Deformation(mm) 3m raft thickness
Model 1	Very Coarse	2555	198.2
Model 2	Coarse	5895	200.5
Model 3	Medium	17997	204.9
Model 4	Fine	51962	205.4
Model 5	Very Fine	127456	206.0

Before finalizing the element geometry of each model, the size of the mesh was investigating as a sensitivity parameter. Table 3-1 shows, at certain mesh types further refinement, is not required. Maximum settlement increased with an increased number of elements reaches 17997. Further increased the element numbers has no significant effect on the central settlement results. Conversely, the increased number of finite element contributes to the increased number of nodes, which in turn, increase the computational process of the program. For this study, to minimize the computational time, medium-mesh was selected to the entire soil domain & fine mesh at the vicinity of the structural elements with a fineness factor of 0.2.

4. RESULT AND DISCUSSION

The vertical load applied to a piled raft foundation is transmitted to the ground by the raft and piles. As the load is transferred from the piled raft to the soil, the underlying soil deforms accordingly, which affects the magnitude and distribution of the contact pressure. The load sharing between the raft and piles for a typical piled raft foundation is affected by several parameters. The raft flexibility, which is governed by its thickness, the spacing between the piles, and the length of the pile has a strong influence on load sharing and settlement. This section examined the influence of varying raft thickness, pile length and its spacing in the three aspects of piled raft foundation. These three aspects are total settlement, differential and load proportion carried by the piles and raft.

4.1 Influence of Raft Thickness

The behavior of piled raft is dependent on the flexibility or stiffness of the raft. The raft flexibility, which is governed by its thickness, has a strong influence on the load sharing and settlement behavior of piled raft system. Whether or not a foundation behaves flexible or rigid fashion, it can be assessed using a dimensionless parameter K_f that incorporates a representative Young's modulus for the soil, combined with terms representing the stiffness of the footing to determine equivalent system stiffness. Horikoshi and Randolph (1997) proposed Eq. 4.1 to evaluate the K_f value. The increased K_f indicates that the raft behavior alters from flexible to rigid.

$$K_f = 5.57 \frac{E_r(1-V_s)}{E_s(1-V_r)} \left(\frac{B}{L}\right)^\alpha \left(\frac{t_r}{L}\right)^3 \quad 4.1$$

Where E_r = Young's modulus for the raft; v_s = soil Poisson's ratio; E_s = average soil elastic modulus at depth v_r = raft Poisson's ratio; B = width of the raft; L = length of the raft; t_r = raft thickness; and α = optimal value = 0.5

According to the formula above, K_f values for a raft thickness of 0.5, 1, 1.5, 2, 2.5 and 3m are 0.054, 0.83, 1.65, 3.75, 7.33, and 12.7 respectively. From this raft with 0.5 m is comparatively more flexible than other. In this section, thickness of the raft was varied by keeping the spacing, number, and diameter of piles as a constant parameters.

26x26m raft with different thicknesses were investigated. The modeling technique, boundary condition, and analysis steps were mentioned in the previous sections. The influence of raft thickness on pile-raft foundation behavior with a pile spacing of 4D and 30m length subjected to a UDL of 0.2MPa were studied.

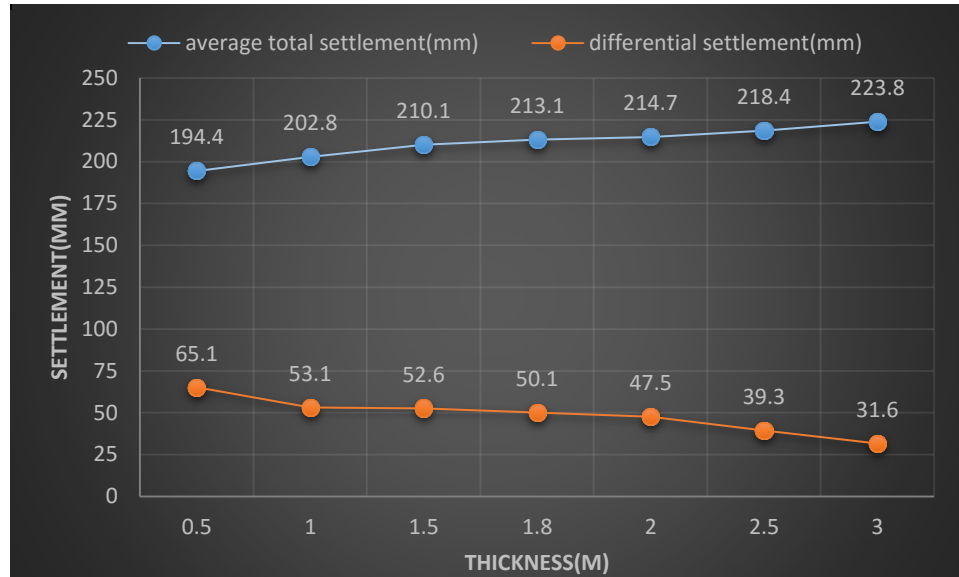


Figure 4-1 the graph of total and differential settlement against thickness of the raft

Maximum differential settlement and the percentage of load shared by the piles are very sensitive to raft thickness. The deflection of a raft is more or less dependent on the thickness. Raft stiffness is a function of soil and concrete stiffness. But in this study, we use the stiffness of the raft which represented by its thickness. The effect of raft thickness on total settlement and maximum differential settlement for uniformly distributed load has presented in Figure 4-1. It is interesting to note that, increase in the thickness, the total settlements also increase which is due to the increase in self-weight of the raft. The number to be increase with an increase in the raft thickness is as follow 8.4, 7.3, 4.6, 3.7 and 5.4 for the raft thickness of 0.5, 1, 1.5, 2, 2.5 and 3m respectively. This show as an increase the thickness of raft, the increasing in the settlement is small rate. For flexible raft which is 0.5m on this study the total settlement is much smaller than the other thickness this is due to smaller self-weight of concrete raft. The plot implies that the settlement rate is smaller when the raft thickness reaches 2m. Therefore the effect of increasing raft thickness on the total settlement condition is not significant.

Table 4-1 Raft maximum differential settlement for various thickness

Raft thickness	Settlement		
	Center	Corner	Differential
0.5	194.4	129.3	65.1
1	202.8	149.7	53.1
1.5	210.1	157.5	52.6
2	214.7	167.2	47.5
2.5	218.4	179.1	39.3
3	223.8	192.2	31.6

Another set of investigations, in this context, was performed to observe the influence of raft thickness on the maximum differential settlement magnitudes. Theoretically, the settlement should be computed for various points in a structure, such as center, corner, and heaviest column locations, to compute differential settlement. But for this study, differential settlement about center and edge of raft was also observed and it is found that raft thickness plays an important role in reducing differential settlement. The differential settlement, rather than the total settlement, is important in the design of foundations as the consequences of showing a detrimental effect. Points on Plaxis which is used to calculate the differential settlement were (0, 26) and (70, 26) for this case. The differential settlement of various raft thicknesses is shown in figure 4-1 and tabulated in table 4-1. Which indicate that an increase in raft thickness, the maximum differential settlement decreasing due to increase raft stiffness.

Initially increase in raft thickness reduces differential settlement more rapidly and beyond a limit it r to reduce total settlement reduces the settlement but with decrease in reduction rate of differential settlement that may be because beyond that limit of raft thickness combined piled raft system begins to behave as rigid foundation. Fig. 4-1 indicate that optimum thickness of piled raft in view to reduce differential settlement it is about 1.8 m for that particular case.

From the output of the above analysis, one can deduce that a reduction in differential settlement can be observed however with an increase of the bending moment. As the raft stiffness increase, differential settlement decrease significantly. This will incur more load to be taken by the raft which ultimately yields higher bending moments. The rate of decrease in settlement and increase in moment seem to disappear at some specific raft thickness (around 1.8m). From this point on, an increase in thickness of raft will not bring any significant change on both the settlement and moment of the raft. Thus, in order to decrease the total or differential settlement of a raft, one has to consider the associated increase in moment. The tabular form of this discussion followed by statistical analysis is presented in Table 4.2.

It is usually the differential settlement rather than total settlement which can cause damage to the structures. Distortion, caused by differential settlement, may cause serious structural problems, especially in tall buildings. It induces bending in structural elements and is the cause of most cracking in structures.

Table 4-2 Results of positive moments when raft thickness increase.

Thickness	M ₁₁ (kNm)	M ₂₂	M ₁₂
0.5	1079	1199	525.7
1	1666	1788	991.8
1.5	1817	1836	1174
1.8	1919	1866	1068
2	1947	1875	1151
2.5	1969	1903	972.5
3	1998	1904	778.4

The maximum bending moment in the raft is considerably affected by the raft thickness. The values of bending moments in a raft may vary several times depending upon the raft thickness. Result of maximum moments in the raft, with various thicknesses, are shown in table 4.1. It shows that the moment increases with the increase of raft thickness. The analysis indicates that thick rafts induce higher bending moments than thin rafts. A raft of 2m thickness has a higher bending moment than 0.5m for a raft dimension of 26 m × 26 m supported with 49 piles.

The maximum bending moment for the rigid raft was greater than that of the flexible. The smallest value of increasing bending moment occurred when the raft reaches 1.8m, further an

increase in thickness of raft were small effect on the bending moment so, a raft thickness of 1.8m is considered a limited thickness. Increasing the thickness of the raft affected the maximum bending moment (see table 4-2).

Generally, a raft of lower thickness is susceptible to larger maximum differential settlement and substantial bending due to its flexibility comparatively thicker raft may be uneconomical because of the requirement of a large amount of concrete and reinforcement requirements. The structural design is high when the flexibility of the raft isn't taking into consideration. Therefore, the thickness of the raft should select by differential settlement should within a tolerable limit, and bending moment in the raft should be minimum so economical and efficient design of piled raft can be achieved.

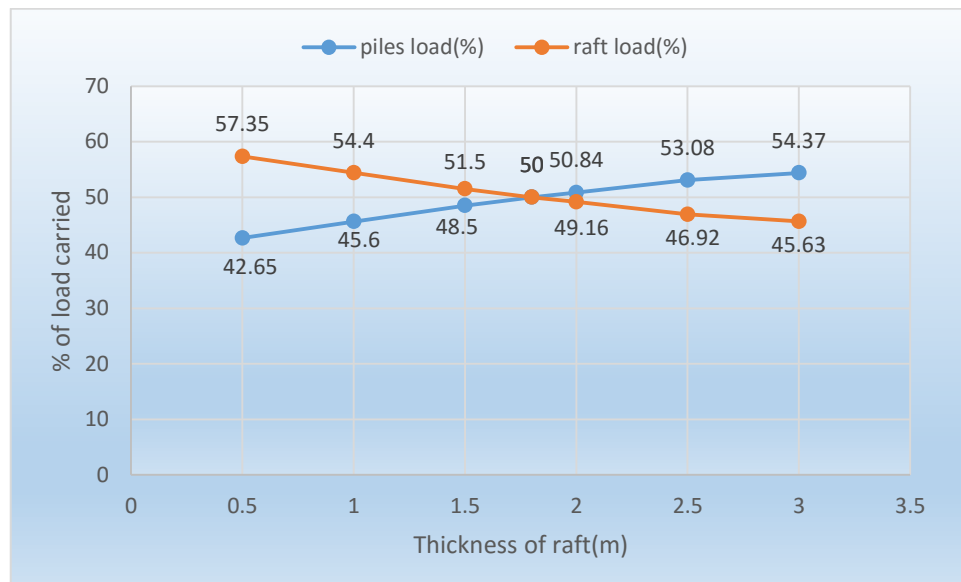


Figure 4-2 percentage of load carried by piles and raft against raft thickness

The load carried by raft and piles determine by load sharing coefficient α_{pr} . Determination of load sharing ratio between pile and raft, the summation of all pile loads divided by total structural load, is an important parameter.

Flexible rafts tend to deform more than stiff rafts. Due to excessive deformation, a flexible raft establishes larger deformation in the subsoil, which leads to more load being transferred by the raft and this will induce higher reaction force. The load sharing ratio is estimated for rigid and flexible rafts and summarized in figure 4-2. Increase in raft thickness in the piled raft foundation, the load shared by the raft decrease. The load sharing percent achieved its 50-50

percent, nearly at 1.8m raft thickness as shown in figure 4-2. The contribution of a raft on the load sharing behavior of piled raft foundation decreased if there is any additional thickness, more loads carried by the piles. Due to excessive deformation in flexible rafts, high stress established in the subsoil leads to more loads transferred into the raft, induced a higher reaction force. For example, at 0.5 m thickness, the ratio of load carried by raft and piles was 57.37% to 42.63%, a thickness of 2m, the ratio was 50.8% to 49.2%, which implies that load sharing in the raft was decreased by 6.57%. The raft behaves like flexible when its stiffness is low, and the soils underneath the raft will immediately experience the loading over the area not supported by the pile's this results the load shared by the raft is high due to interaction between the raft and the sub-soil. Therefore, the load sharing between the raft and piles as a function of the total applied load reported in Figure 4-2 shows a significant reduction in the total load carried by the raft with an increase in thickness as compared to the piles.

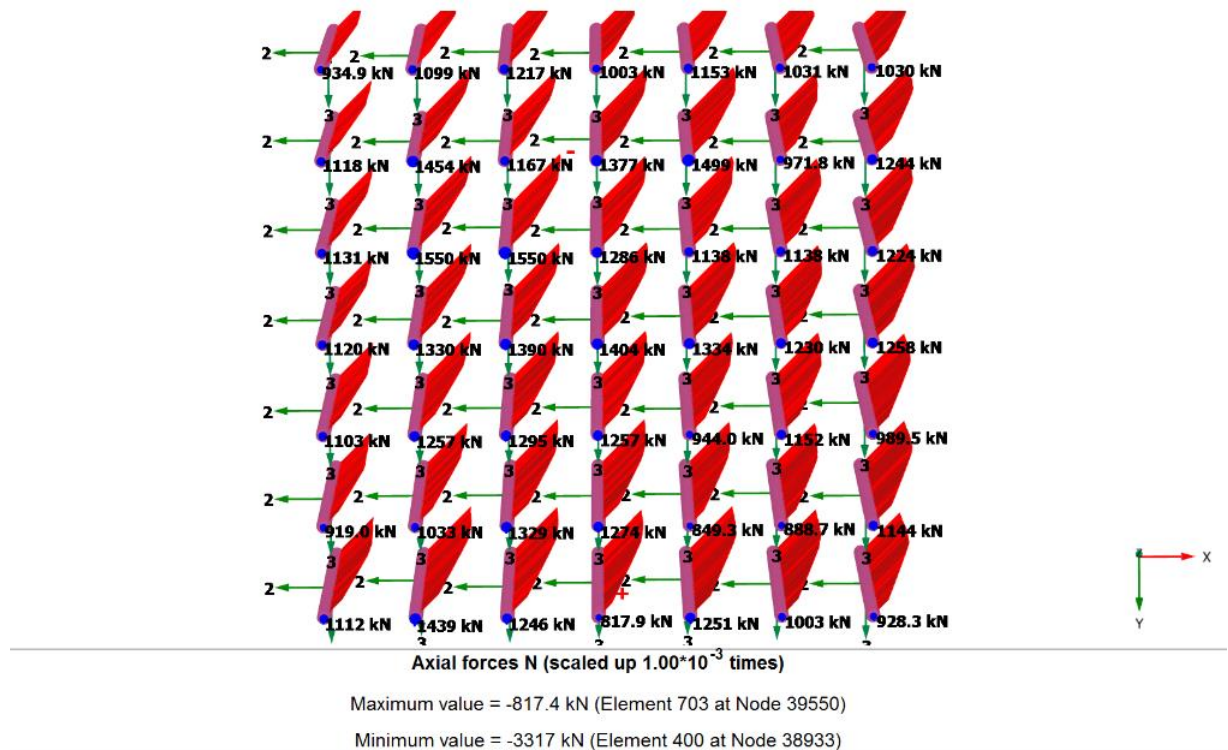


Figure 4-3 axial load distribution within a piles for 0.5m raft thickness

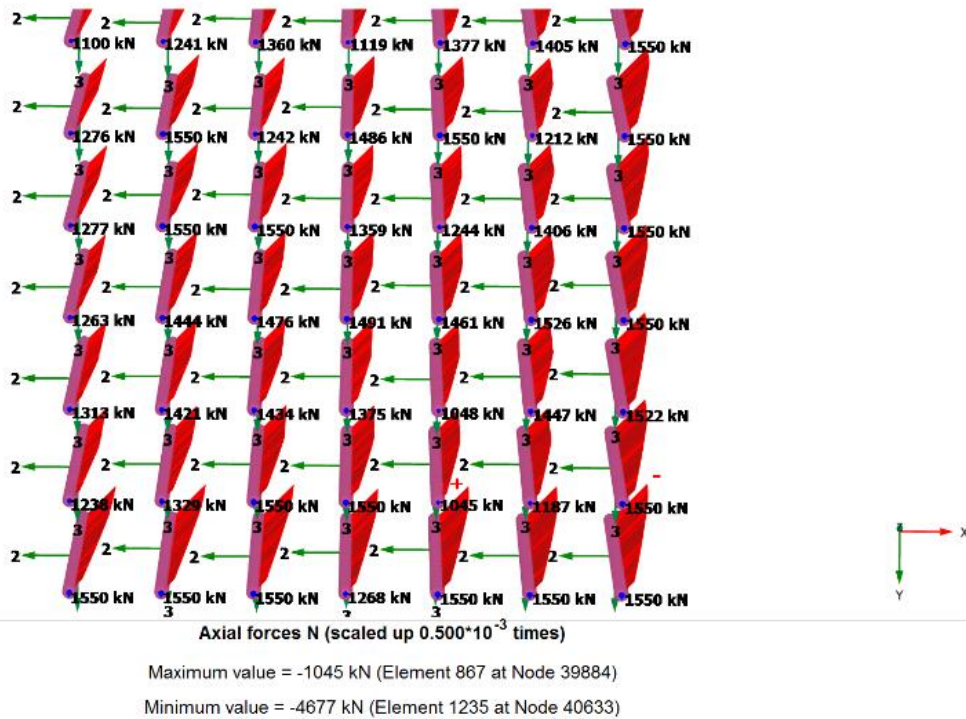


Figure 4-4 axial load distribution within a piles for 2m raft thickness

In addition, the load carried by piles increases with an increasing the thickness of the raft. Central piles carry higher loads to corner piles with flexible rafts whereas, in rigid rafts, all have approximately the same load sharing within the pies shown in Figures 4-3 and 4-4. The detailed load distributions of a piled raft with varying thicknesses are presented in Appendix C.

4.2 Influence of Pile Spacing

The pile spacing dictates the pile numbers, significant influence on the behavior of piled raft foundation. Piles spacing on piled raft analysis also has a substantial effect on its load-carrying capacity, which can affect the performance of the piled raft. In this section, the influence of pile spacing in load-sharing and settlement was studying through a uniform piled raft configuration at 30m pile length. To examine the effect of pile spacing on its load share in a piled raft with the spacing of 3d, 4d, 4.5d and 6d were considered for both flexible and rigid raft conditions with other parameters kept constant. The raft was subjected to a uniform distributed load of 0.2 MPa,

The piled raft coefficient α_{pr} was defined previously, evaluate the percentage of load taken by piles. It is the ratio of the sum of all pile loads to the total load of the foundation.

$$\alpha_{pr} = \frac{\sum R_{Pile}}{R_{Tot}} \quad 4.2$$

At initial spacing, in both flexible and rigid conditions, the loads carried by the raft are small compared to the pile which is 53 % and 45.1% at 3D pile spacing due to piles contact with the subsoil and the total area of the raft are more cover by piles compared to the other spacing. As an increase in the spacing creates more contact b/n raft and subsoil resulted in a portion of the loads transferred through the contact between the raft-soil interfaces. Loads carried by rafts in rigid and flexible conditions increased 5.3% and 4.89% respectively, when the pile of spacing increased from 3d to 4d.

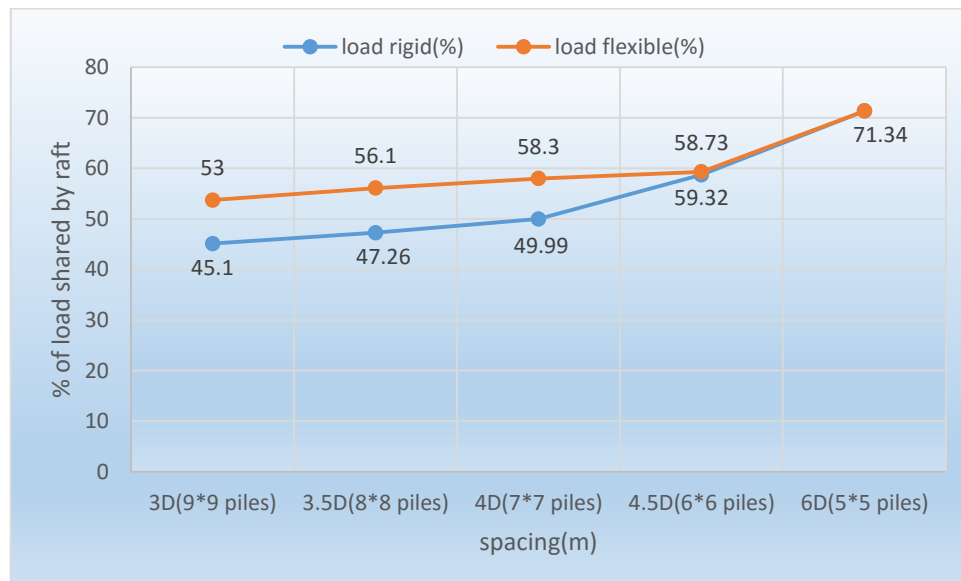


Figure 4-5 variation of load sharing of raft with spacing

As shown in Figures 4-5 the load carried by the raft for a flexible and rigid condition for five different pile spacing are presented as load-spacing graph. The variation in load carried by the raft was very noticeable at the spacing increase. The load carried by the raft was about 58.3% and 49.99% at the spacing of 4d at t= 0.5 & 2 m, this show us due to contact pressure between raft and soil in the flexible raft, loads carried by the raft were high compared to the rigid raft. Figure 4-6 also demonstrates that the percent of load carried by the raft for flexible and rigid

rafts at pile spacing changes. Load transferred by the raft increased from 53 % to 58.73% & 45.1% to 59.32% spacing of piles increased from 3D to 4.5D.

The raft load ratio increased considerably with increasing pile spacing under a given load. As the center-to-center pile spacing increase the raft contact area also increase which decrease the stiffness in the pile. With larger pile spacing the thick raft behaving more like flexible this is due to area of the raft are in direct contact with the soils underneath the raft that why figure 4-6 shown that the percentage of load shared by the raft are the same for flexible and rigid raft at 6d spacing.

This increase in the percentage occurred because the raft started to interact with the soil across a larger surface area more load was carried by the raft. It has a significant effect when the raft is rigid. However, the pile spacing on the raft load share is the same, as the spacing reaches the higher end of the range considered 4.5D. For small pile groups, loads on piles are relatively uniform distribution (5*5). Detail load distributions within piles are presented in Appendix C. The increased pile spacing reduces the load carried by the pile and increases the load carried by the raft.

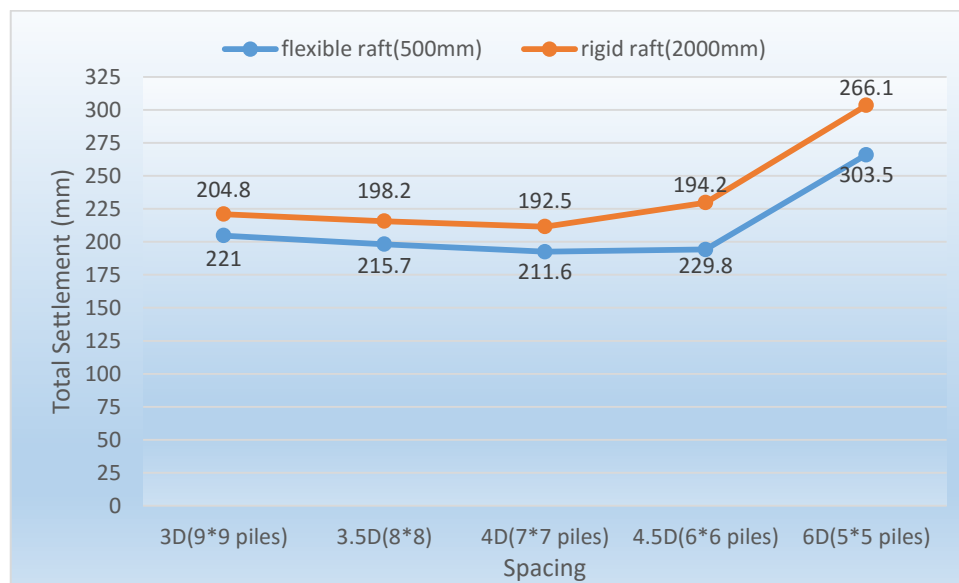


Figure 4-6 average central settlement against the spacing piles

Besides the load sharing behavior, the influences of spacing of piles in the central and differential settlements were investigated in this study. A piled raft with small pile spacing for both cases, was experiencing a larger central settlement of raft to the piled raft with large pile spacing. For closely spaced piles, the stresses over-lap area was larger create to higher central

settlement due to a possibility of pressure isobars over-lap in adjacent piles and soil was stressed highly. Therefore, increasing the spacing of piles decreases the total number results in a reduction in the total cost of the piled raft foundation. Figure 4-6 shows the raft average central settlement for various pile spacing imply that the settlement decrease with increase in pile spacing. However, after a spacing of 4.5d it changes and show an increment. This phenomenon dictates that the pile spacing for pile raft should not be greater than 4.5D for this particular study.

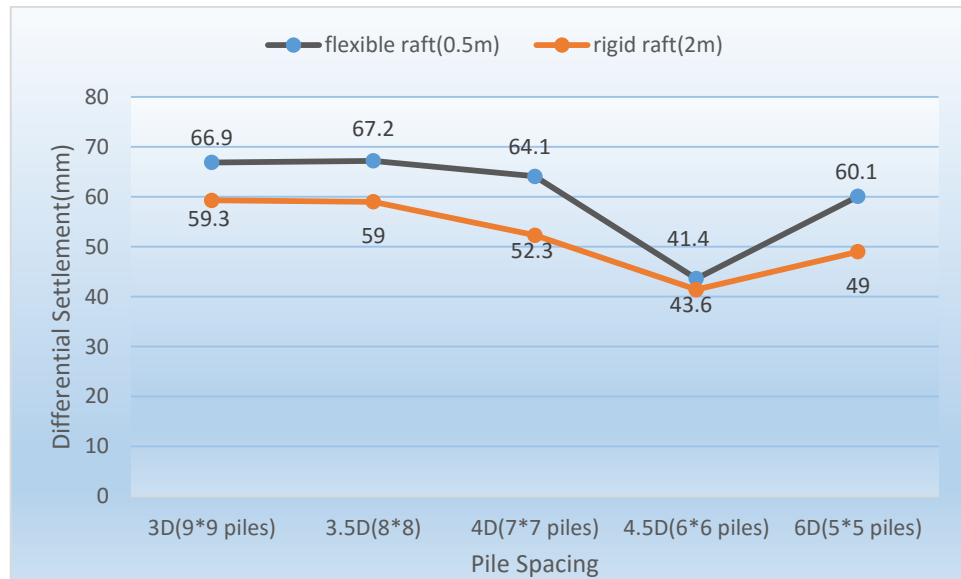


Figure 4-7 maximum differential settlement against the spacing of piles

Figure 4-7 indicates that, differential settlements at the center and edge points were observed for flexible and rigid rafts & found that spacing of piles plays a role in the differential settlement reduction. Initially, an increase in the spacing of piles reduces differential settlement more rapidly. At a spacing of 4.5d further, an increase in spacing results in increases in a differential settlement. At 4.5d spacing, the rigid rafts system begins to behave as a flexible raft & the differential settlement was decreased. For this particular study, the optimum spacing of piled raft to minimize differential settlement is 4.5d.

4.3 Influence of Pile Length

To capture the influence of pile length on the load settlement behavior of piled rafts. The analyses were conducted with varying pile lengths of 10m, 20m, 30, and 40m. These four types of pile length have been simulated numerically for 4D pile spacing. The simulated

output of the numerical analyses through PLAXIS 3D FE software, in the form of raft settlement, is illustrated in Figures 4-8.

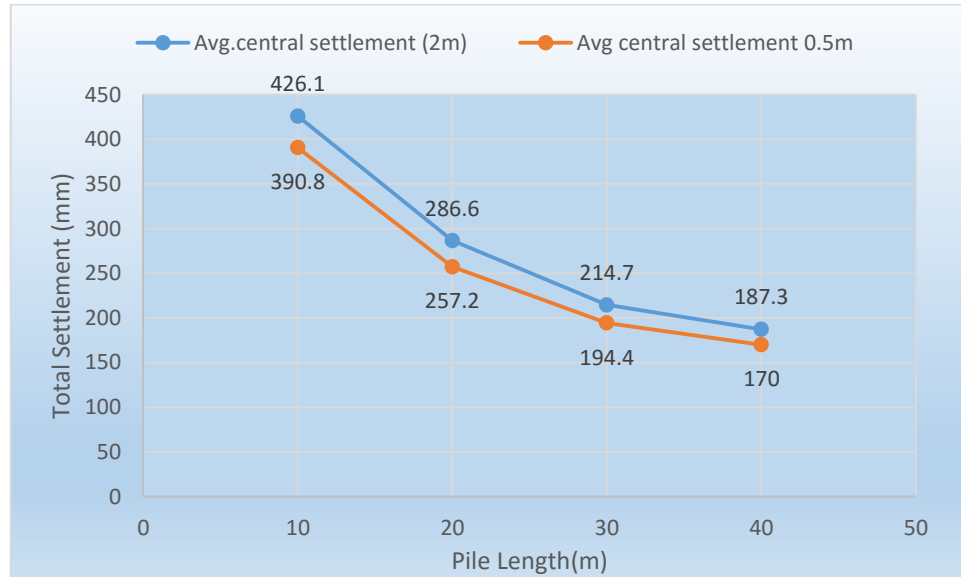


Figure 4-8 average central settlement against length of the pile

From figure 4-8, the increase of pile length for flexible and rigid rafts decreases in the central settlement it increases the stiffness of the pile group, which causes the contact pressure between the soil and the raft to reduce. For each case, the central settlement decreased with the increase in pile length. The reduction had a similar pattern but a different reduction rate. Increase lengths from 10m to 20m, 20m to 30m, and 30m to 40m the percentages of reduction in the average settlement were 32.74% and 25.09%, 12.76%, and 34.19%, 24.42%, 12.55% for flexible and rigid raft respectively & the reduced rate were the almost same at piles reach at the length of 30m-40m. Therefore, an increase in the length of piles effectively decreases central settlement.

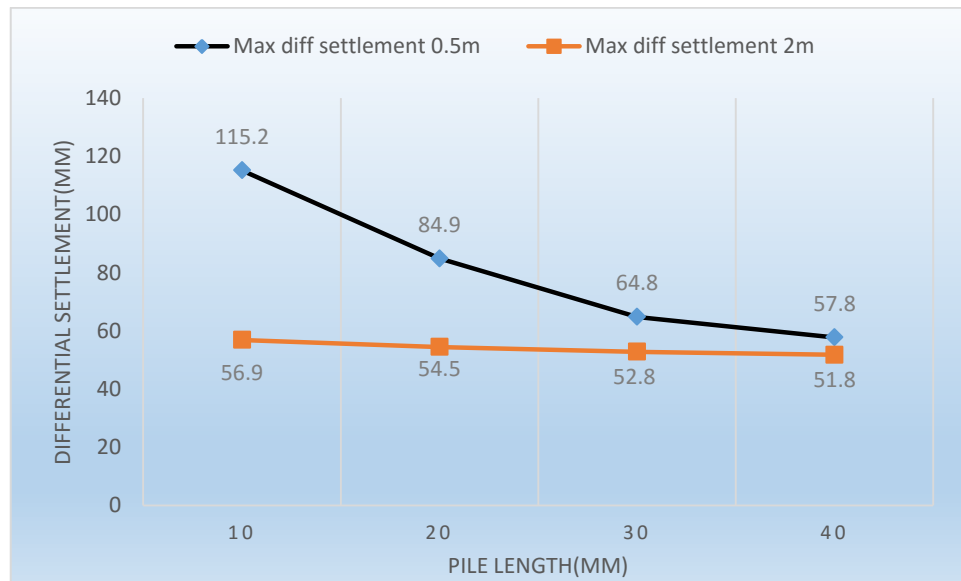


Figure 4-9 maximum differential settlement against length of the pile

The differential settlement does not vary significantly with the pile length variation in the case of the rigid raft. Yet large magnitudes in the differential settlements are observed for the flexible raft at the increase in lengths of piles have no influence in the differential settlement reduction in a rigid raft that means the rate of differential settlement does not vary significantly with the changes in pile length. Figure 4-9 illustrates the maximum differential settlement variation with varying pile lengths for the pile spacing of 4D. Increasing lengths in the piles increase the bearing capacity of piled raft foundation by reducing overall settlement at the limiting value of pile stiffness. The analyses showed, differential settlement decrease with increasing pile length. This pile length effect was due to the enhancement in the shaft resistance of the piles when the pile length increases.

4.4 Comparison of Analysis Result with Literatures

In section 2.8, several numerical and analytical approaches were from the other author presented in related studies. Their assumptions made, results obtained and conclusions reached are briefly discussed. This section tries to compare the work done on this thesis with some of the literature. Discuss the differences and similarities.

Poulos (2001) summarized his study for the influence of raft thickness variation on maximum settlement, differential settlement, raft moment, and load sharing on loads of 12 MN. The study showed that maximum settlement wasn't affected by raft thickness except for thin rafts, whereas the differential settlement decreases significantly with increasing raft thickness. On the other hand, the maximum moment in the raft and the percentage of the total load carried by the piles increase with increasing raft thickness. He concluded that increasing the thickness of the raft is effective in reducing the differential settlement & very effective in resisting the punching shear from both piles and column loadings.

H.S.W.Chow and H.G.Poulos, 2015, studied the importance of taking the flexibility of the pile cap into account in making assessments of the load and moment distribution in the pile raft analysis. They clearly stated that the flexibility of the raft decreases as the raft thickness increases. In small pile groups, the computed axial loads on piles with a rigid raft were similar to those with a flexible raft. For large pile groups, the axial loads in the flexible raft are relatively uniform & with rigid rafts, corner piles carry significantly higher than the center piles. Therefore, flexible raft assumptions for large pile groups will be more appropriate in the axial pile load assessment.

Alnuaim et al. 2017 reported the loads are transferred from piled raft to the subsoil, the underlying soil deforms affect the magnitude & distribution of the contact pressure. A flexible raft-induced deformation in subsoil leads to increased contact pressure. Flexible rafts tend to deform more than stiff rafts. As the settlement level increases, the load carried by the pile decreases due to the contribution of the raft.

Shivanand Mali, Baleshwar Singh (2020) has reported the maximum bending moment & maximum shear force in a raft are considerably affected by the raft thickness. Lower thickness rafts were susceptible to larger differential settlement and substantial bending because of their flexibility, comparatively thicker rafts may be uneconomical because of the requirement of a large amount of concrete.

Effect of pile length studies in different literature like (Reul & Randolph, 2004) and (Rabiei, 2009). The results show that an increase in the length of piles significantly reduces the total and differential settlements.

Katzenbach et al. (2012) presented a 3D finite element model to simulate piled rafts in layered soil. He states that the load carried by the raft increased by increasing the pile spacing. For various spacing imply that the total settlement in piled raft increases with an increase in spacing. The same observation was made by Horikoshi and Randolph (1996 & 1998) in their so-called centrifuge model. It concluded that the maximum pile spacing for pile raft foundation should not be greater than six times the pile diameter.

5. CONCLUSION AND RECCOMENDATION

5.1 Conclusion

Piled raft foundation can minimize the settlement on sand soil. Spacing, length and thickness of the raft influences the settlement. Thicker rafts is an effective solution in reducing differential settlement. Due to the minimal interaction between the raft and the subsoil, the load carried by the raft is lower for rigid raft (2m) compared to the flexible raft (0.5m). The percentage of load carried by piles increased as the raft thickness increased. However, the rate of increase was higher for small raft thickness. A flexible raft is expected to experience larger deflection, and hence induce more deformation in the subsoil which leads to increased contact pressure between the subsoil and the raft. On the other hand, the moment in the raft and the percentage of the total load carried by the piles increase with increasing raft thickness.

In this study, it can estimate that a ratio of stiffness of the pile group to the raft governs the load sharing between the piles and the raft. As spacing between the piles decreases from 3d to 4.5d, the settlement also decreases. Spacing between the piles directly affects the load distribution within the piles. Percentage of load carried by piles for flexible and rigid raft, till diameter and length remaining constant, increases by 11.42 % & 5% respectively as pile spacing increases from 3 to 4D. The study also reveals that total settlement increases with an increase in pile spacing, the load carried by piles sharply increases for pile spacing smaller than 4.5D. The results presented suggest that the optimum spacing to control both differential and total settlement are 4.5D

The variation in load carried by the piles was the same at the spacing reached 6d for both cases. This is because at large spacing, even the thick raft behaved more flexibly, which resulted in stronger raft-soil interaction, compared to the same raft with smaller pile spacing. Using the spacing instead of length yields more accuracies in representing the flexibility of the piled raft. More detailed work has to be conducted to evaluate the performance of a flexible piled raft under different circumstances such as the number of piles, different soil layers and loading scheme.

Respect to the average settlement, the piled raft foundation optimum performance can be achieved by the increased length of piles it produced a Smaller average settlement.

5.2 Recommendation

Though this research is limited in its scope, it can be a good starting point for researchers in the area. For a further improvement in designing and construction of piled rafts, it is essential to:

Raft flexibility governed by its stiffness and its size, study raft size effect in the load sharing and settlement of piled raft foundation. Increasing the raft thickness is effective in reducing the maximum differential settlement but the limiting raft thickness has had an advantage for the optimistic design of piled raft foundation.

Increasing in the Spacing of the piles, significantly reduced both total and differential settlement until it reached $4.5d$ then after it does not appear that increasing the spacing beyond this value is beneficial so the recommendation is therefore that the spacing of pile is not more than $4.5d$.

Length has not significant effect in controlling the differential settlement in rigid raft case. So it is recommended that the use of length variation to control the total settlement in piled raft foundation is effective other than total settlement.

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APPENDIX

APPENDIX A

Deformation Theory

The basic equations for the static deformation of soil body are formulated within the framework of continuum mechanics. A restriction is made in the sense that deformations are considered to be small. This enables a formulation with reference to the original un-deformed geometry. The continuum description is discretized according to the finite element method.

Material Model

PLAXIS 3D foundation program has a number of material models that can be used in analysis of Geotechnical problems. They range from the simple models like linear elastic model to complex ones. The more complex model is selected more material data is required. For detailed information regarding to PLAXIS 3D foundation material manual and also a reader interested in the detail formulation and modeling of PLAXIS software is referred to the full scientific manuals that are found enclosed with the software. The soil in my analysis is modeled as linear elastic perfectly plastic model (Mohr-Coulomb Model).

Linear Elastic Perfectly Plastic Model

The linear elastic perfectly-plastic Mohr-Columb model is a first order model that includes only a limited number of features that soil behavior show in reality. The effective stress states at failure are quite well described. On this model plasticity is associated with the development of irreversible strains. In order to evaluate whether or not plasticity occurs in a calculation, a yield function, f , is introduced as a function of stress and strain. Plastic yielding is related with the condition $f = 0$. This condition can often be presented as a surface in principal stress space. A perfectly- plastic model is a constitutive model with a fixed yield surface, i.e. a yield surface that fully define by model parameters and not affected by (plastic) straining. For stress state represented by points within the yield surface, the behavior is purely elastic and all strains are reversible. The basic principle of Elasto-Plastic is that strains and strain rates are decomposed into an elastic part and plastic part:

$$\varepsilon = \varepsilon_e + \varepsilon_p$$

Hooke's law is used to relate the stress rates to the elastic strain rates. According to the classical theory of plasticity, plastic strain rates are proportional to the derivative of the yield function with respect to the stresses. This means that the plastic strain rates can be represented as vectors perpendicular to the yield surface. This classical form of the theory is referred to as associated plasticity. However, for Mohr-Coulomb type yield functions, the theory of associated plasticity overestimates dilatancy.

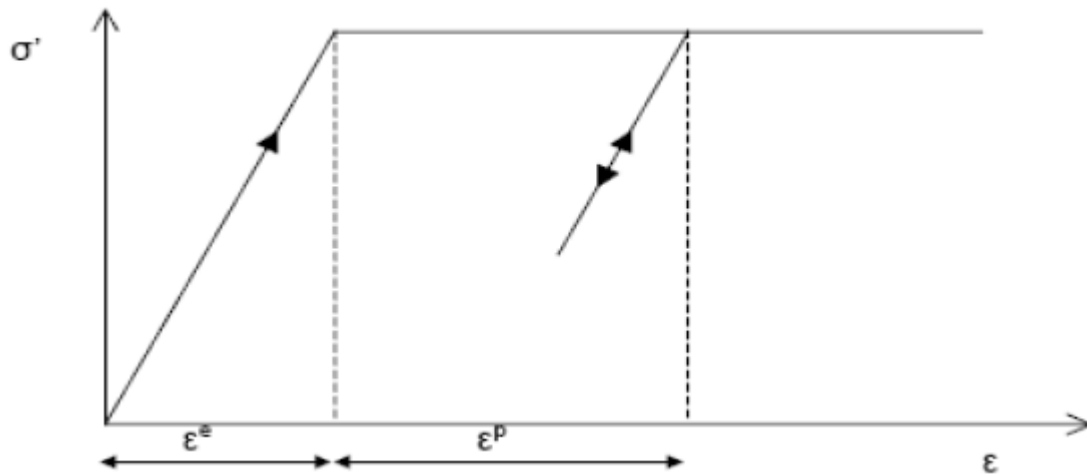


Figure A- 1 Basic idea of an elastic perfectly plastic model

The Mohr-Coulomb yield condition is an extension of Coulomb's friction law to general states of stress. In fact, this condition ensures that Coulomb's friction law is obeyed in any plane within a material element. The full Mohr-Coulomb yield condition consists of six yield functions when formulated in terms of principal stresses and six plastic potential functions. The two plastic model parameters appearing in the yield functions are the well-known friction angle ϕ and the cohesion c . The condition $f_i=0$ for all yield functions together (where f_i is used to denote each individual yield function) represent a hexagonal cone principal stress space as shown in the Figure A-2.

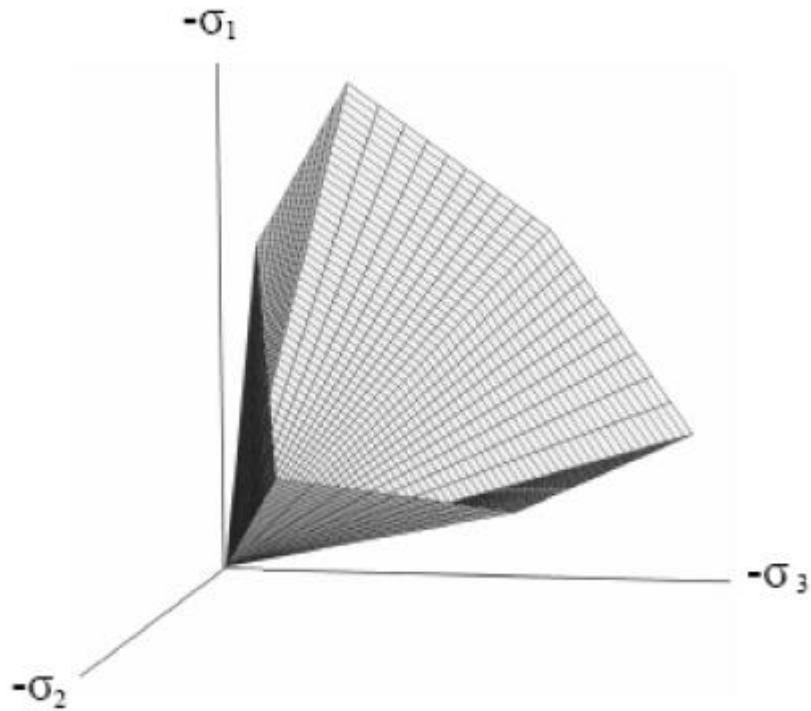


Figure A- 2 the Mohr-Coulomb yield surface in principal stress space ($c = 0$)

The plastic potential functions contain a third plasticity parameter, the dilatancy angle ψ . This parameter is required to model positive plastic volumetric strain increments (dilatancy) as actually observed for dense soils. For stress states within the yield surface, the behavior is elastic and obeys Hooke's law isotropic linear elasticity, as discussed above. Hence, besides the plasticity parameters c , ϕ , and ψ input is required on the elastic Young's modulus E and Poisson's ratio ν .

Basic parameters of the Mohr-coulomb model

The Mohr-Coulomb model requires a total of five parameters, which are generally familiar to most geotechnical engineers and which can be obtained from basic tests on soil samples.

These parameters with their standard units are listed below:

E : Young's modulus [kN/m^2]

ν : Poisson's ratio [-]

ϕ : Friction angle [$^\circ$]

c : Cohesion [kN/m^2]

ψ : Dilatancy angle [$^\circ$]

Formulation of the Mohr-Coulomb Model

The Mohr-Coulomb yield condition is an extension of Coulomb's friction law to general states of stress. In fact, this condition ensures that Coulomb's friction law is obeyed in any plane within a material element. The full Mohr-Coulomb yield condition consists of six yield functions when formulated in terms of principal stresses: The full Mohr-Coulomb yield condition consists of six yield functions when formulated in terms of principal stresses

$$f_{1a} = \frac{1}{2}(\sigma'_2 - \sigma'_3) + \frac{1}{2}(\sigma'_2 + \sigma'_3) \sin \varphi - c \cos \varphi \leq 0$$

$$f_{1b} = \frac{1}{2}(\sigma'_3 - \sigma'_2) + \frac{1}{2}(\sigma'_3 + \sigma'_2) \sin \varphi - c \cos \varphi \leq 0$$

$$f_{2a} = \frac{1}{2}(\sigma'_3 - \sigma'_1) + \frac{1}{2}(\sigma'_3 + \sigma'_1) \sin \varphi - c \cos \varphi \leq 0$$

Elastic material model

The available theory for elasticity was developed and established on the basis of homogenous and isotropic behavior of construction material (e.g Steel, iron). Elastic constitutive models can be linear or nonlinear Figure A-3.

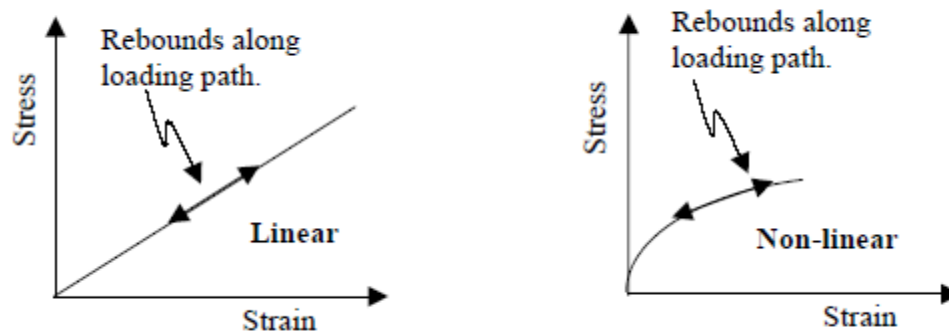


Figure A- 3 Linear and non- linear relation of stress and strain curve (Kate 2005)

Linear elastic constitutive model is probably the most common model used to approximate the stress – strain relationship of materials. Linear elastic models involve two elastic stiffness parameters namely Young's modulus (E) and Poisson's ratio (ν). These two parameters are used to relate stresses as function of strain in this manner:

$$\sigma_x = \left\{ \frac{E}{(1+\nu)(1-2\nu)} \right\} (\varepsilon_x(1-\nu) + \nu(\varepsilon_y + \varepsilon_z))$$

$$\sigma_y = \left\{ \frac{E}{(1+\nu)(1-2\nu)} \right\} (\varepsilon_y(1-\nu) + \nu(\varepsilon_x + \varepsilon_z))$$

$$\sigma_z = \left\{ \frac{E}{(1+\nu)(1-2\nu)} \right\} (\varepsilon_z(1-\nu) + \nu(\varepsilon_y + \varepsilon_x))$$

where: $\sigma_x, \sigma_y, \sigma_z$ = normal stresses in x,y and z directions respectively and

$\varepsilon_x, \varepsilon_y, \varepsilon_z$ = normal strains in x,y and z directions respectively

The behavior of soil mass, which is a combination of a number of discrete particles, cannot be modeled by the pure elastic theory, in reality; the stress-strain behavior of soil becomes non-linear, particularly as failure conditions are approached (Sinha 2013). Hence, the researcher's represent the soil stress-strain constitutive behavior by means of elasto-plastic, models, which are the combination of the elastic and plastic theories.

APPENDIX B

In PLAXIS 3D software the maximum or ultimate values of skin friction with its distribution pattern and base resistance are required as an input. Thus, here calculation is done according to Bowles (1997). The value calculated here are simple approximations because all piles with the same length will have the same value in the parametric study.

The skin friction increase with depth more or less linearly to a depth L' and remain constant thereafter. The magnitude of the critical depth L' is 15 to 20 pile diameter. Thus, the maximum skin friction values at the top and bottom are needed for PLAXIS 3D as an input parameter.

The skin friction according to Tomlinson (1971) is given by

$$Q_f = (K \sigma_z \tan \delta)(\Pi dL)$$

$$K = 1 - \sin \phi$$

$$\sigma_z = \gamma z + \text{uniformly distributed load}$$

Stress Distribution

Load applied to the surface of a body distributes over a successively wider area. The simplest way to calculate the stress distribution is by means of the 2:1 method. This method assumes that the load is distributed over an area that increases in width in proportion to the depth below the loaded area, as is illustrated in Fig. B-1. Since the same vertical load, Q , acts over the increasingly larger area, the stress (load per surface area) diminishes with depth. The mathematical relation is as follows.

$$q_z = q_0 \times \frac{B * L}{(B + Z)(L + Z)}$$

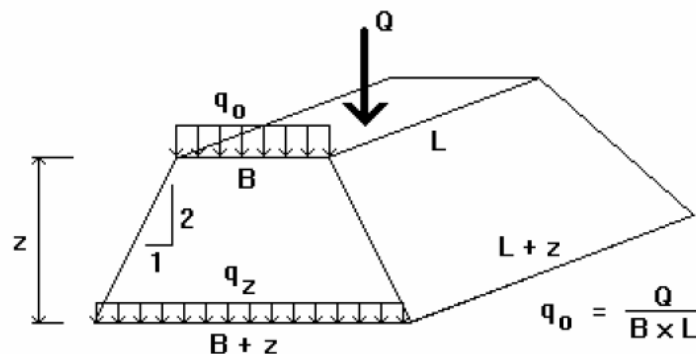


Figure B- 1 The 2:1 method

Note: The 2:1 distribution is only valid inside (below) the footprint of the loaded area and must never be used to calculate the stress outside the footprint.

Maximum Skin Friction at the Top ($T_{top,max}$)

$$Q_f = (K\sigma_z \tan \delta)(\Pi d)$$

At the top $\sigma_z =$ uniformly distributed load= 200KN/m²

For $\tan\delta$, value of δ is usually taken as 0.75 ϕ for concrete pile

$$Q_f = (0.5*200*0.41)3.14*1 = 128.74\text{KN/m}^2$$

Tomlinson, 1995 recommends that friction in sands should not exceed 110 kN/m² (11t/m²) in straight piles. Therefore, Maximum Skin Friction at the bottom ($T_{top,max}$) is considered to be 110 KN/m².

Maximum Skin Friction at the Bottom ($T_{bottom,max}$)

$$Q_f = (K\sigma_z \tan\delta) (\pi d)$$

σ_z is calculated from over burden pressure and from the distributed load which vary with depth of piles.

Table B- 1 Calculation for maximum skin friction at bottom of piles

Depth(m)	10	20	30	40
γz (KN/m ²)	80	160	160	160
q_0	104.32	63.89	63.89	63.89
σ_z (KN/m ²)	184.32	223.9	223.9	223.9
$T_{bot,max}$ (KN/m)	118.65	144.12	144.12	144.12

For design purposes the pile-tip bearing capacity can be assumed to increase linearly to a critical depth (D_c) and then remains constant. The same critical depth relationship used for skin friction can be used for end bearing. (U.S. Army Corps of Engineers Washington, 1991).

Base Resistance (F_{max}) is calculated from Bowles (1997) by Hansen's Equation.

$$F_{max} = A_p (cN'_c d_c S_c + \eta q N'_q d_q S_q + \frac{1}{2} \gamma' B_p N'_\gamma S_\gamma)$$

N_γ term is often neglected when the pile width is not large. So the equation become

$$F_{max} = A_p (\eta q N'_q d_q S_q)$$

$$N_q' = (\tan \phi' + \sqrt{((1 + \tan^2 \phi') \exp(2\psi \tan \phi'))}) = 7.93$$

The value of ψ for the Janbu equation may vary from 60° in soft compressible to 105° in dense soils.

$$\eta = S_q = 1.0$$

$$dq = 1 + 2 \tan \phi' (1 - \sin \phi')^2 \tan^{-1}(L/B)$$

Table B- 2 Calculation for maximum base resistance at bottom of piles

Depth(m)	10	20	30	40
σ_z (KN/m ²)	184.32	223.9	223.9	223.9
d_q	1.05	1.11	1.11	1.11
F_{max}	1205	1547.1	1547.1	1547.1

Stiffness calculation

The soil stiffness is assumed to increase with depth according to the Janbu (1963) relation

$$E_s(z) = \frac{E_0(\sigma_{(z)})}{P_{ref}}$$

Where, E_s denotes Young's modulus of soil and σ_z is the mean stress due to the soil self-weight which is determined as:

$$\sigma_{(z)} = \frac{(1 + 2K_0)\gamma z}{3} \quad z \geq z_0$$

$$\sigma_{(z)} = \sigma(z_0) \quad z \geq z_0$$

Where, z denotes depth, γ is soil unit weight, P_{ref} is a reference pressure (100 kPa), E_0 denotes Young's modulus when $\sigma=P_{ref}$ and z_0 is the thickness of the surface soil layer, which is assumed to have a constant stiffness. K_0 is the coefficient of lateral earth pressure at rest.

Table B- 3 Calculation for variation of soil stiffness within depth

Depth	$\sigma(z)$	E_0	$E(z)$
0	0	10000	10000
10	120	10000	12000
20	240	10000	24000
30-80	360	10000	36000

APPENDIX C

PLAXIS 3D Analysis outputs

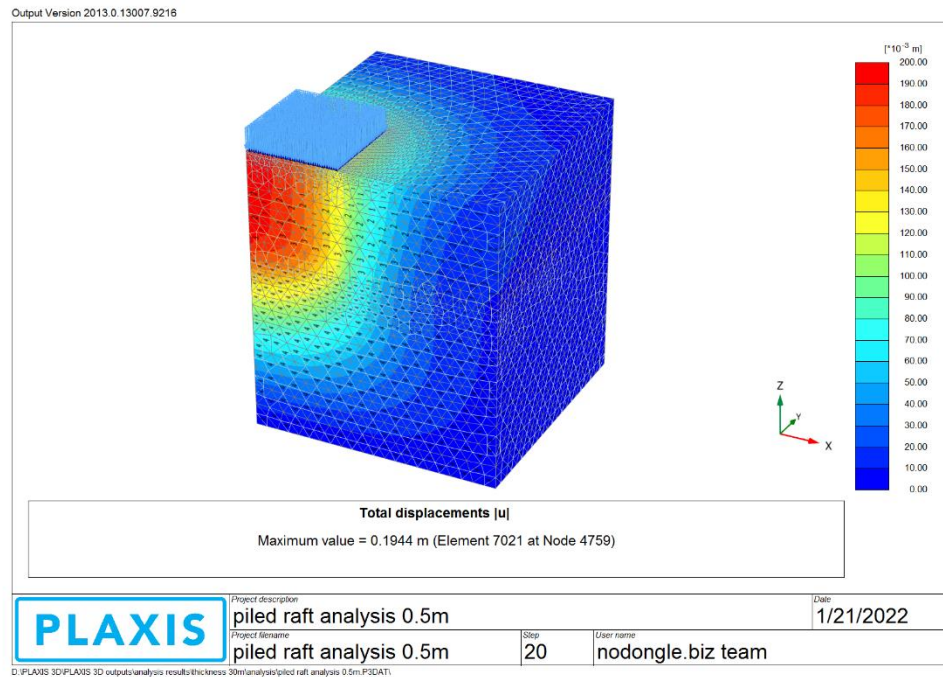


Figure C- 1 Central Settlement at 0.5m raft thickness

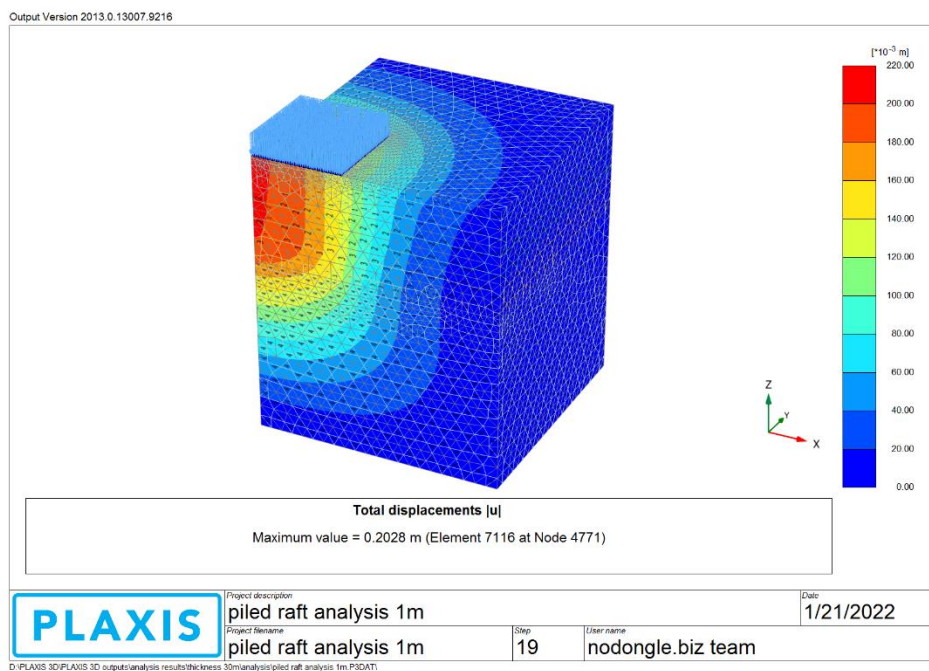


Figure C- 2 Central Settlement at 1m raft thickness

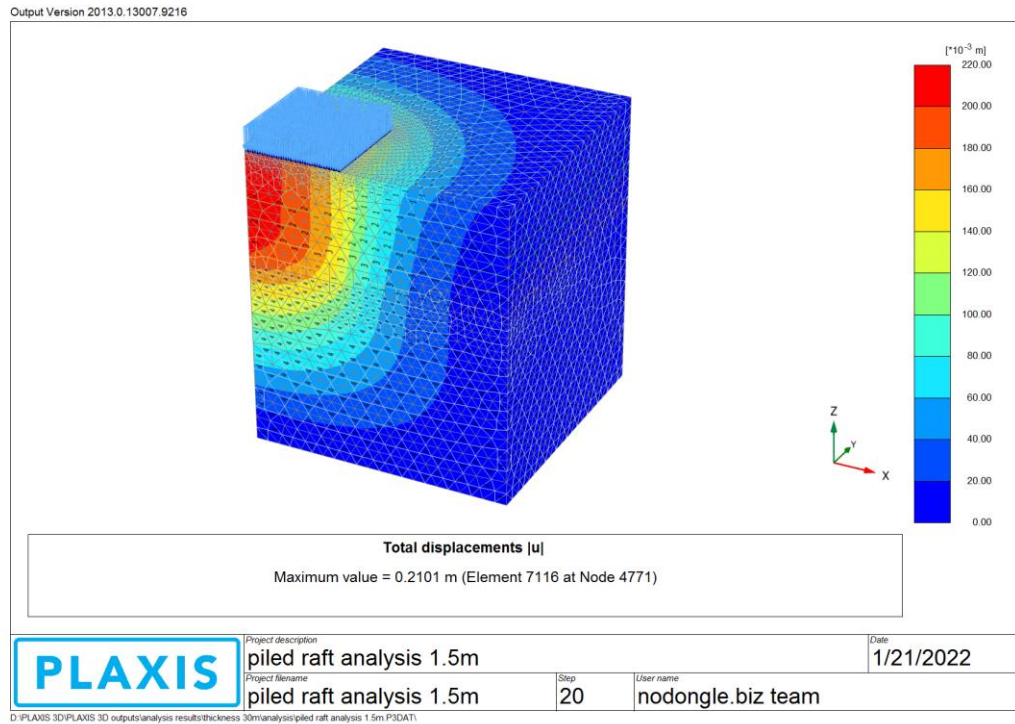


Figure C- 3 Central Settlement at 1.5m raft thickness

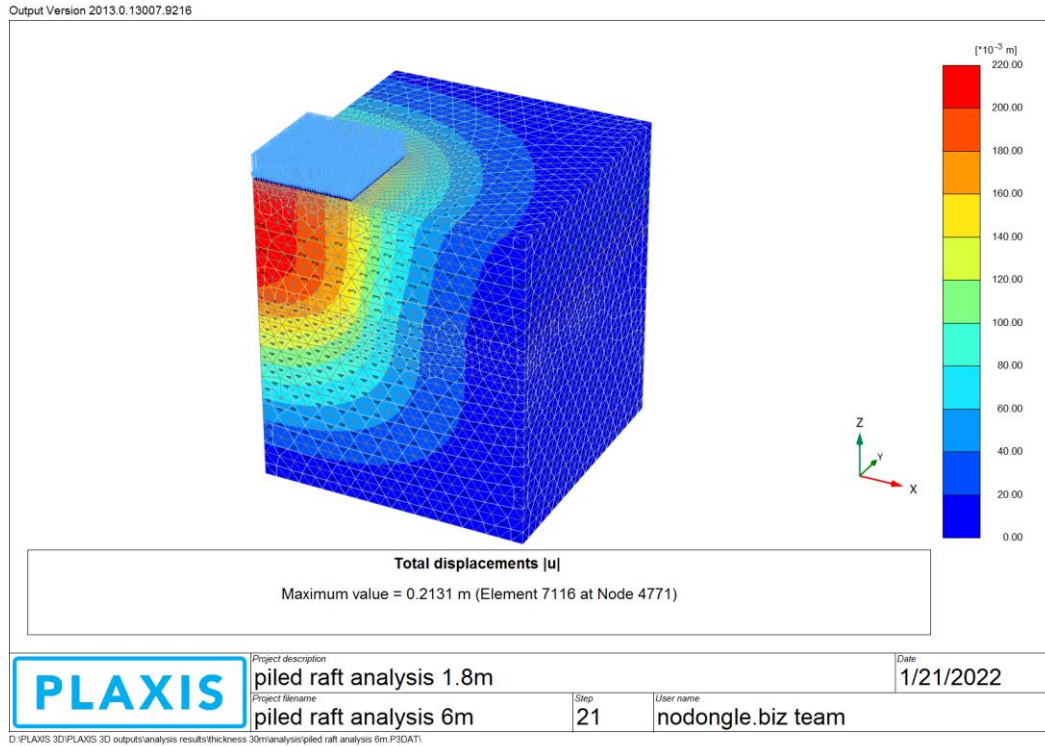


Figure C- 4 Central Settlement at 1.8m raft thickness

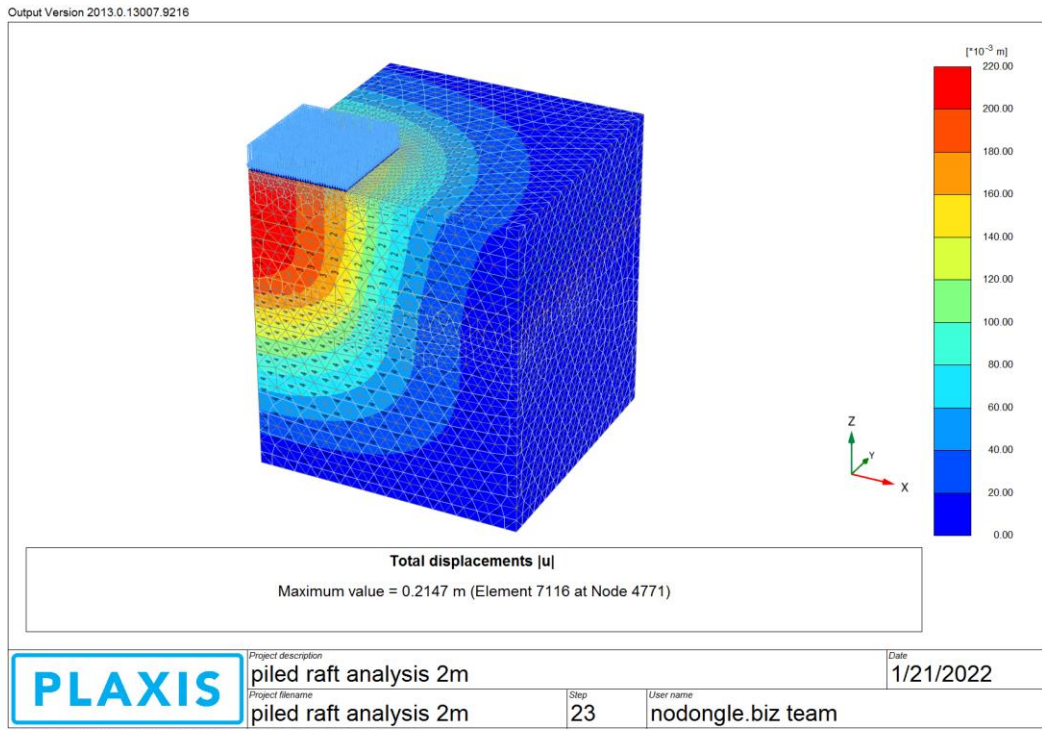


Figure C- 5 Central Settlement at 2m raft thickness

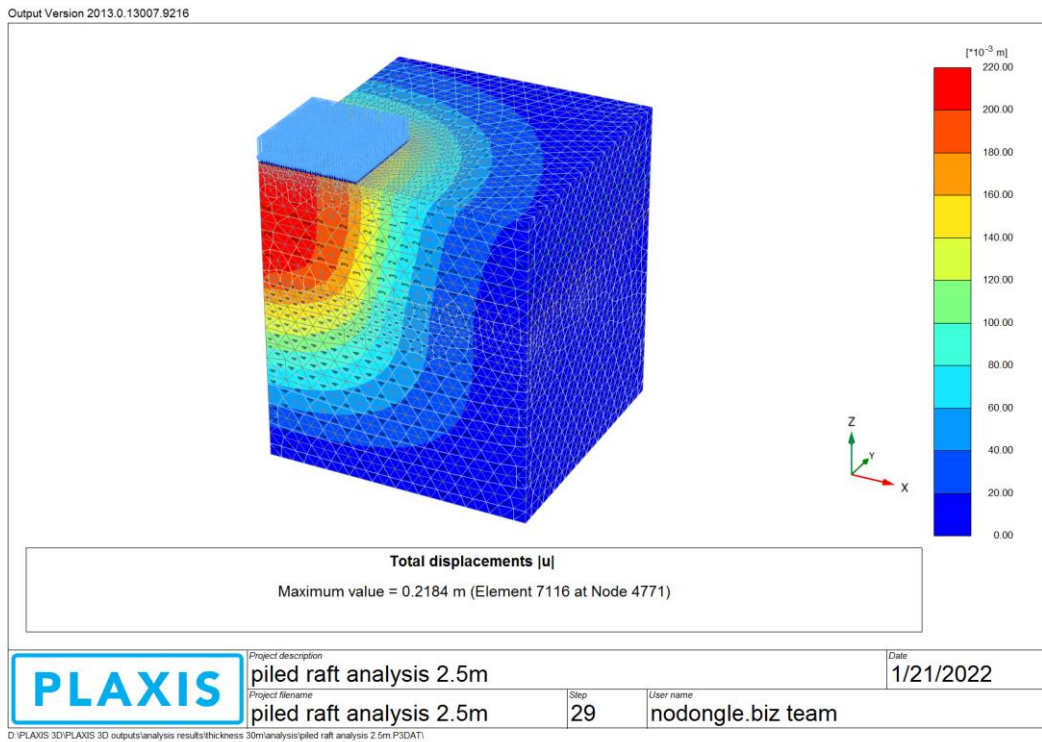


Figure C- 6 Central Settlement at 2.5m raft thickness

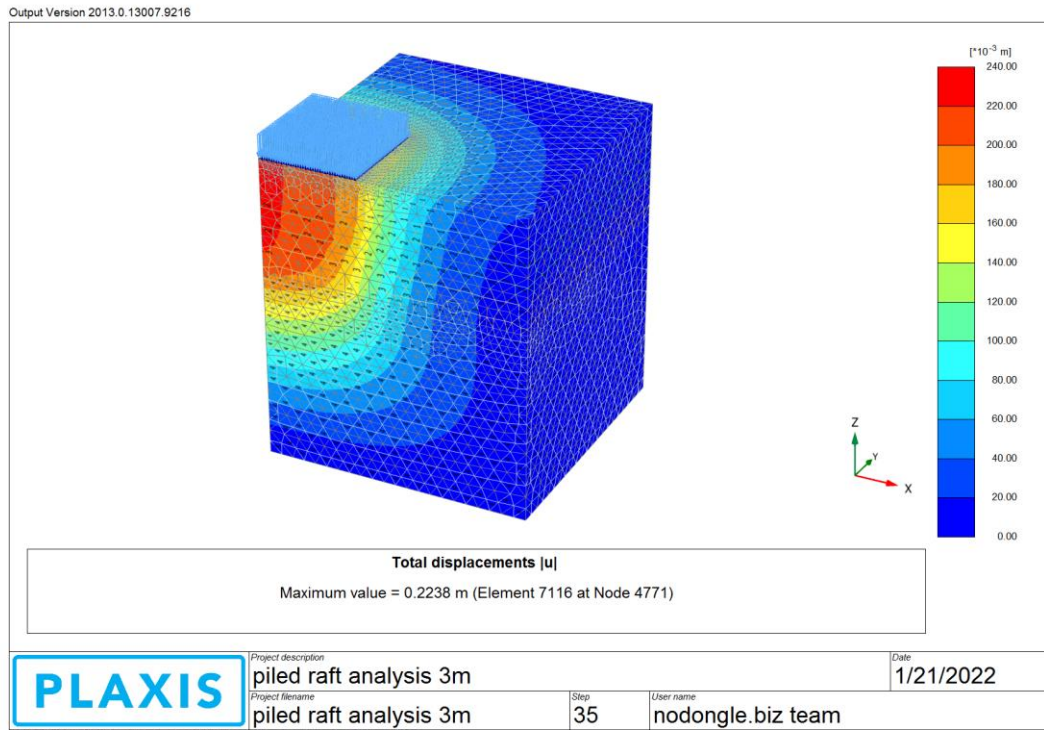


Figure C- 7 Central Settlement at 3m raft thickness

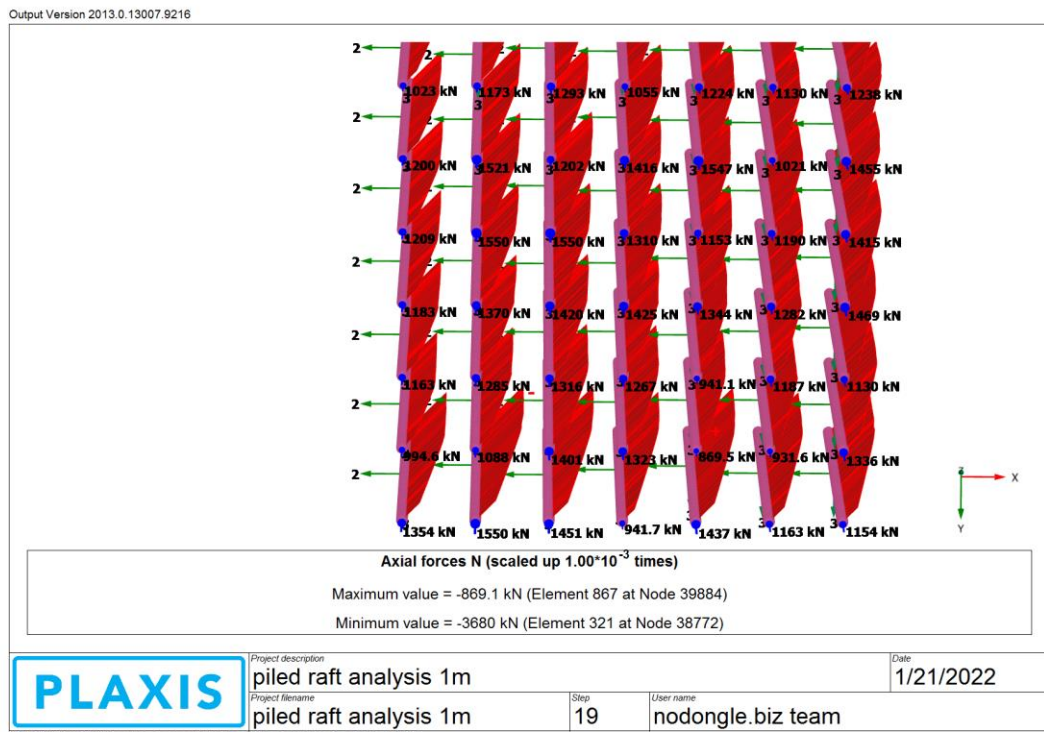


Figure C- 8 Axial Load Distribution within a piles for 1m raft thickness

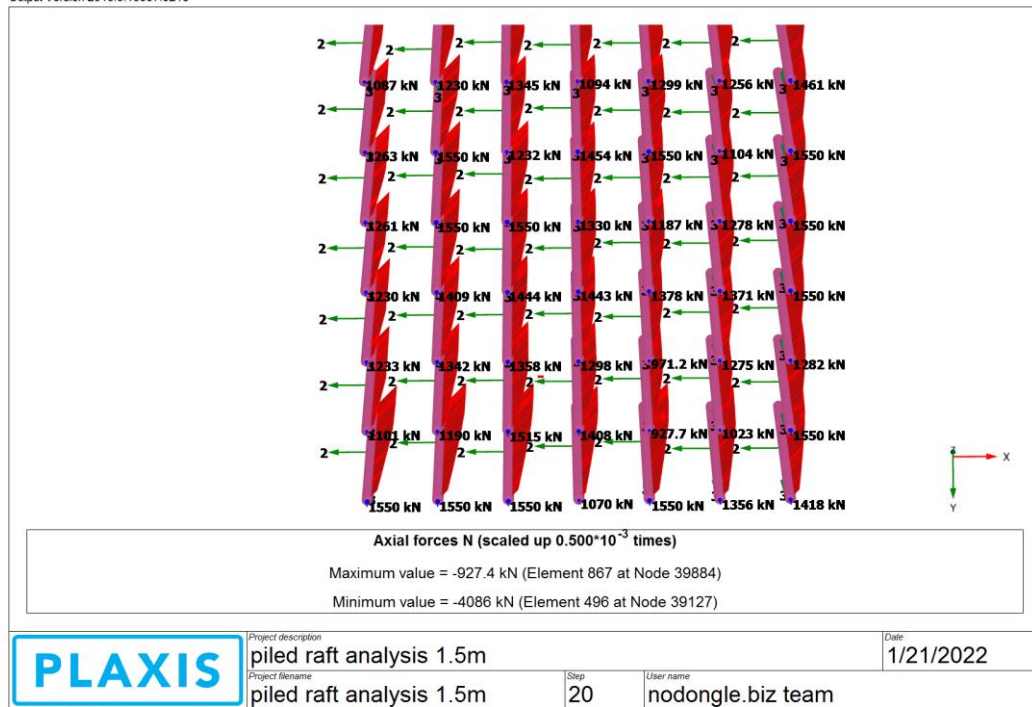


Figure C- 9 Axial Load Distribution within a piles for 1.5m raft thickness

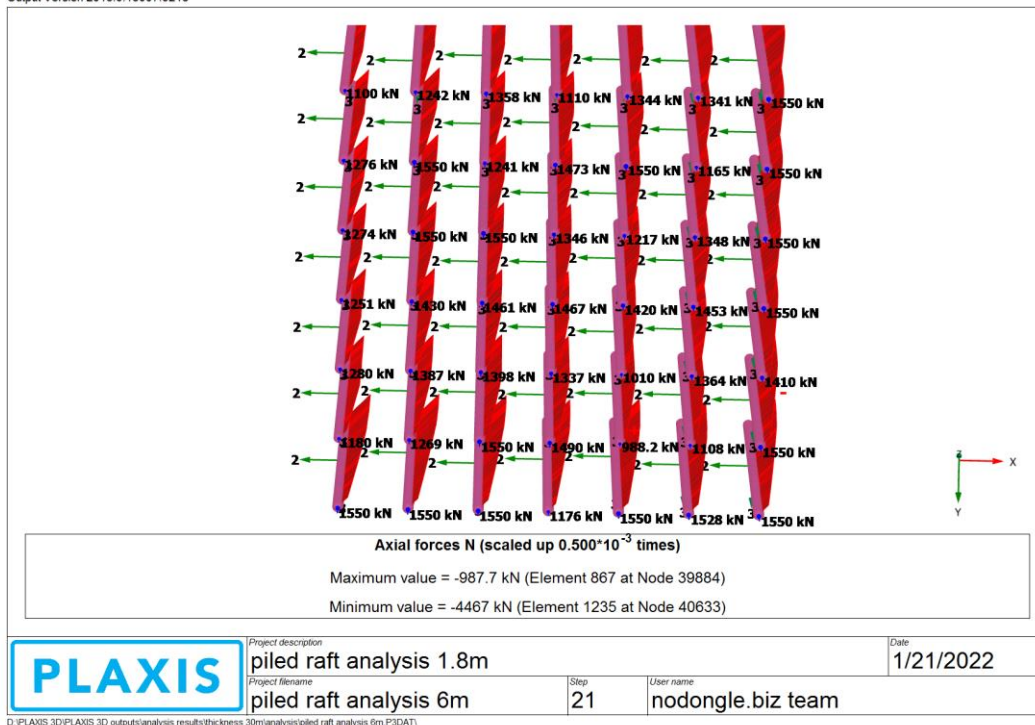


Figure C- 10 Axial Load Distribution within a piles for 1.8m raft thickness

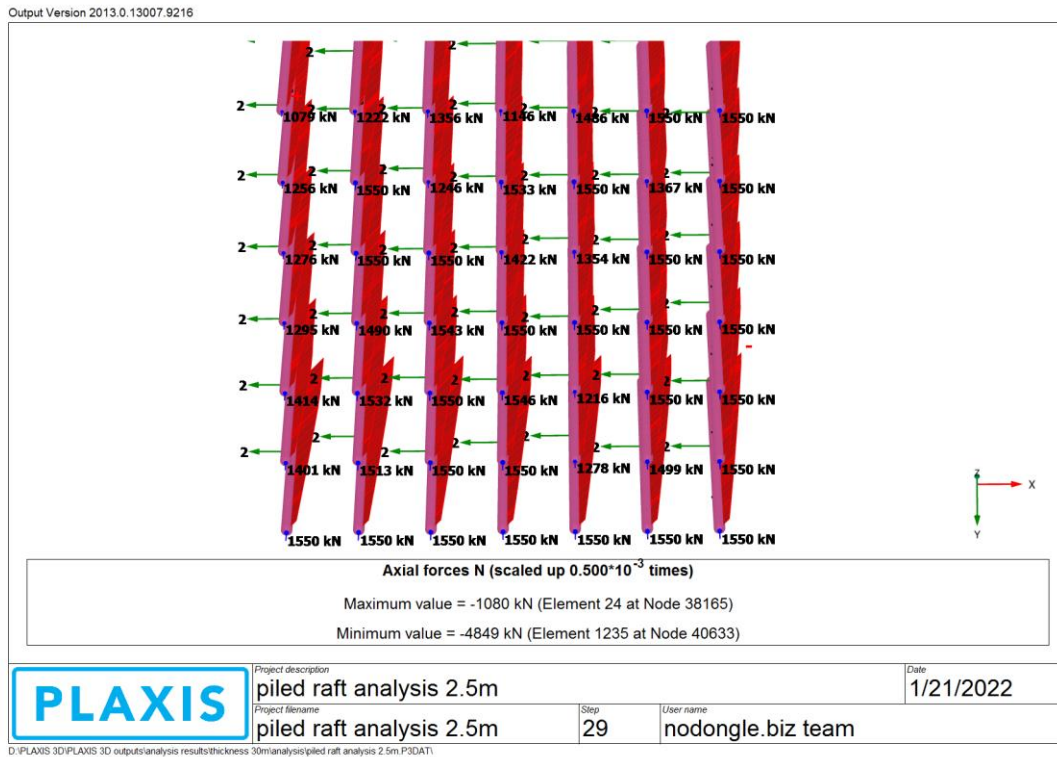


Figure C- 11 axial load distribution within a piles at 2.5m raft thickness

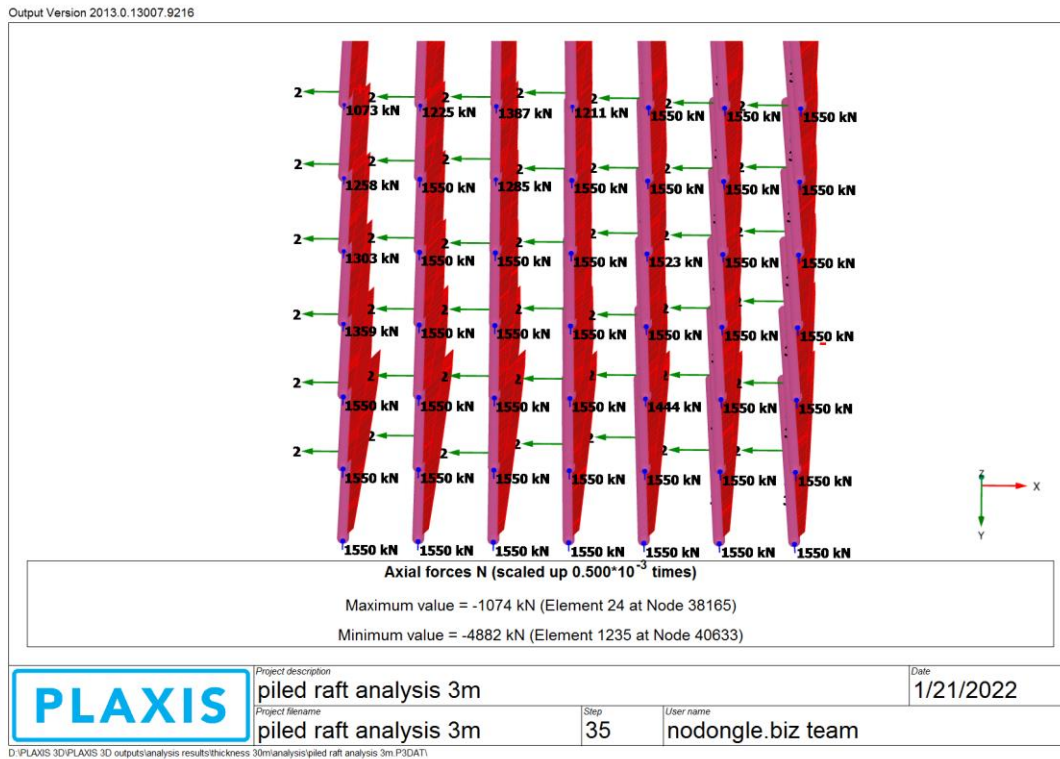


Figure C- 12 axial load distribution within a piles at 3m raft thickness

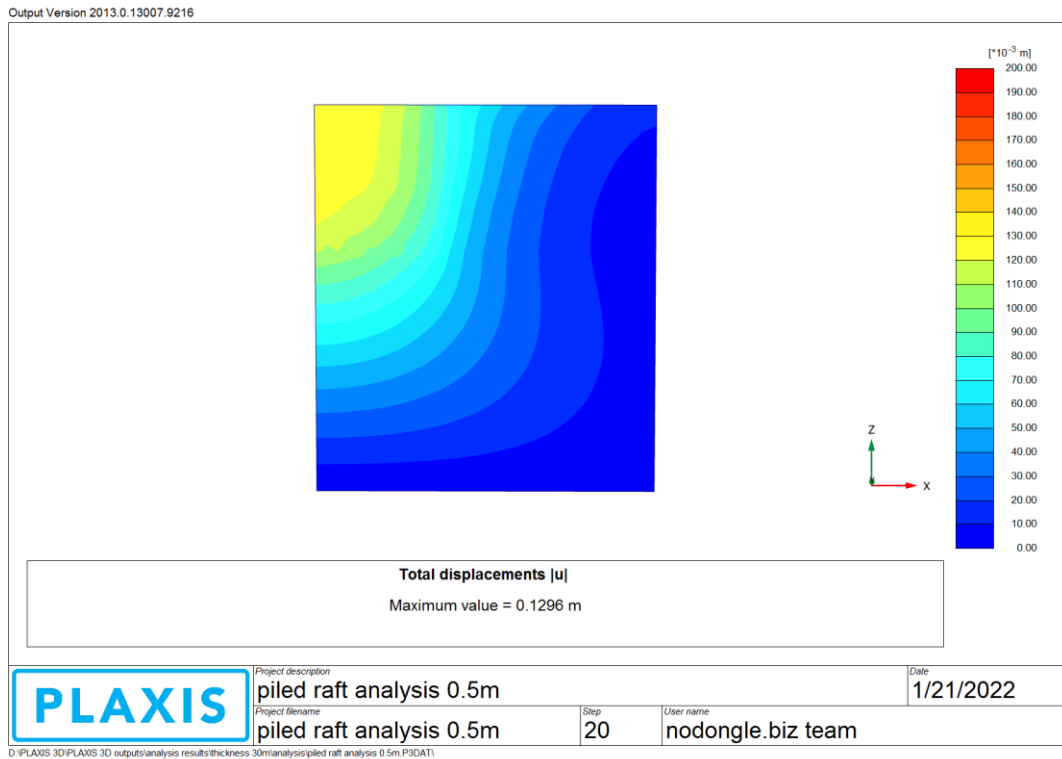


Figure C- 13 Corner Settlement at 0.5m raft thickness

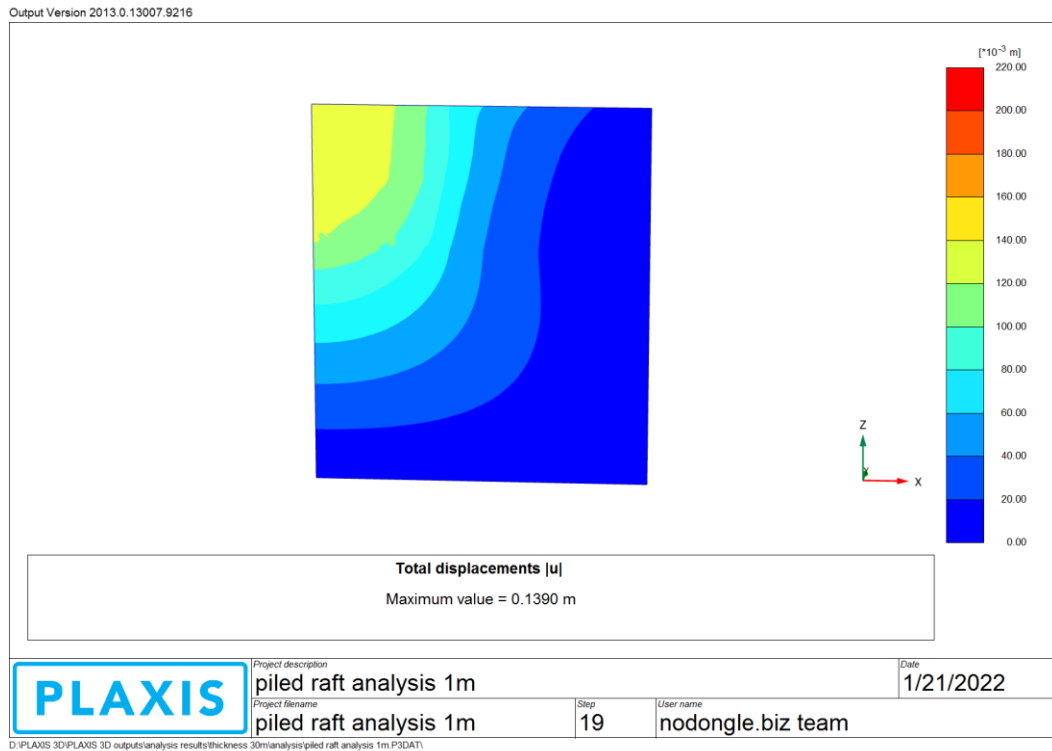


Figure C- 14 Corner Settlement at 1m raft thickness

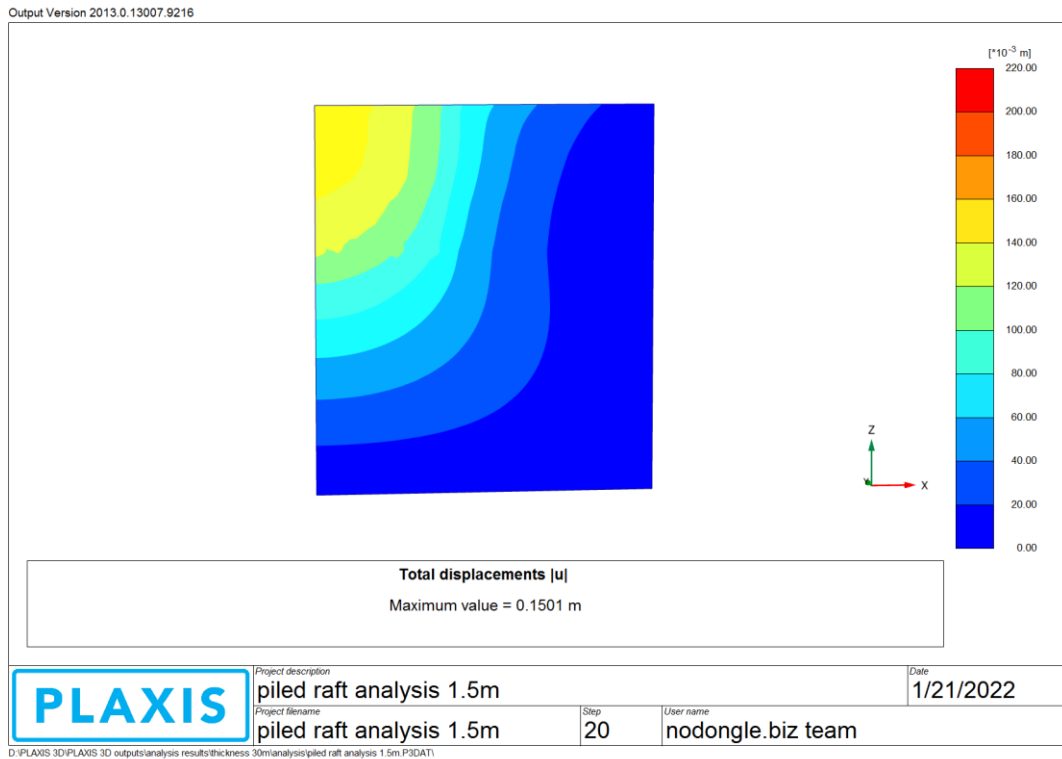


Figure C- 15 Corner Settlement at 1.5m raft thickness

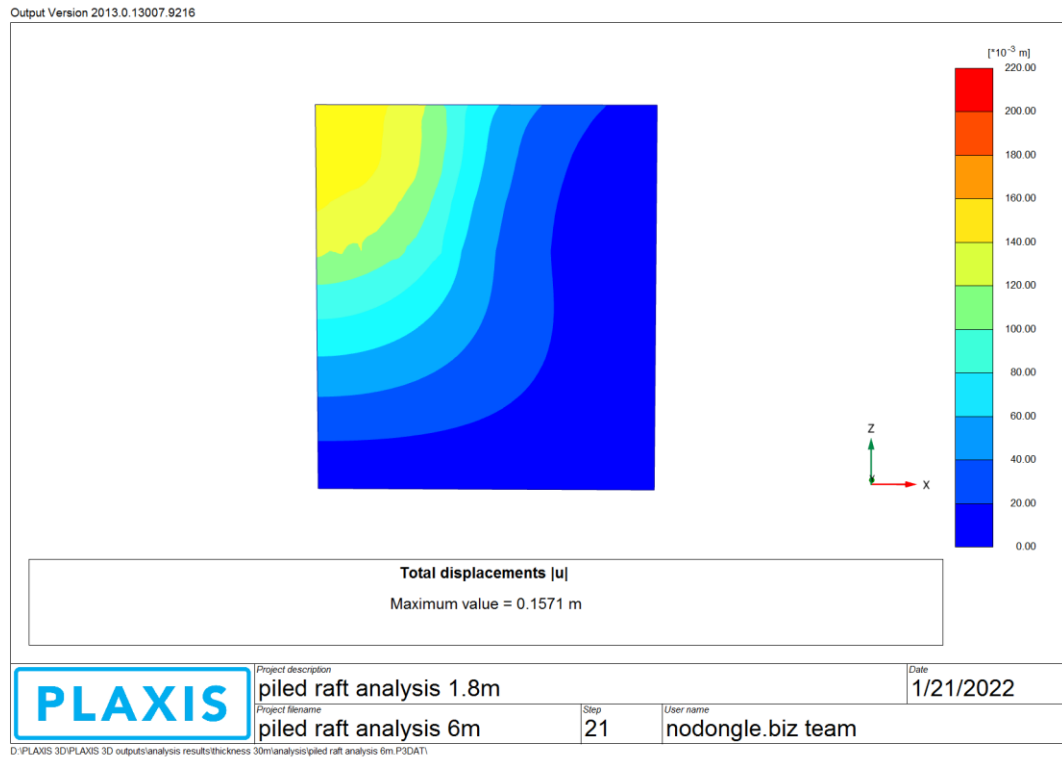


Figure C- 16 Corner Settlement at 1.8m raft thickness

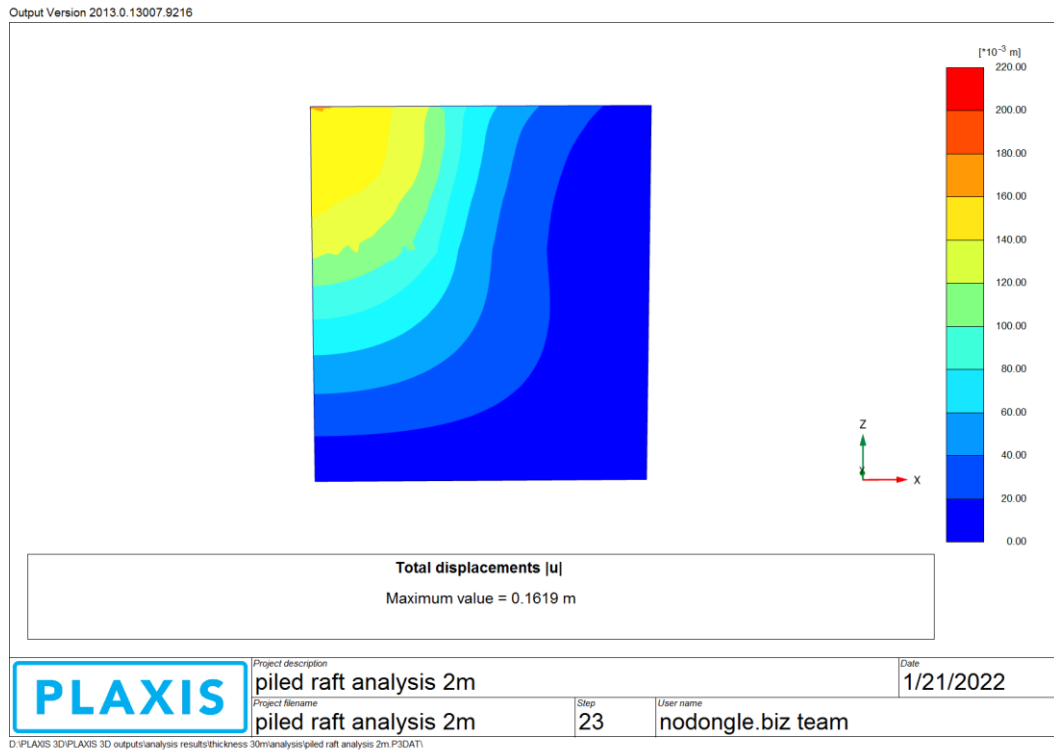


Figure C- 17 Corner Settlement at 2m raft thickness

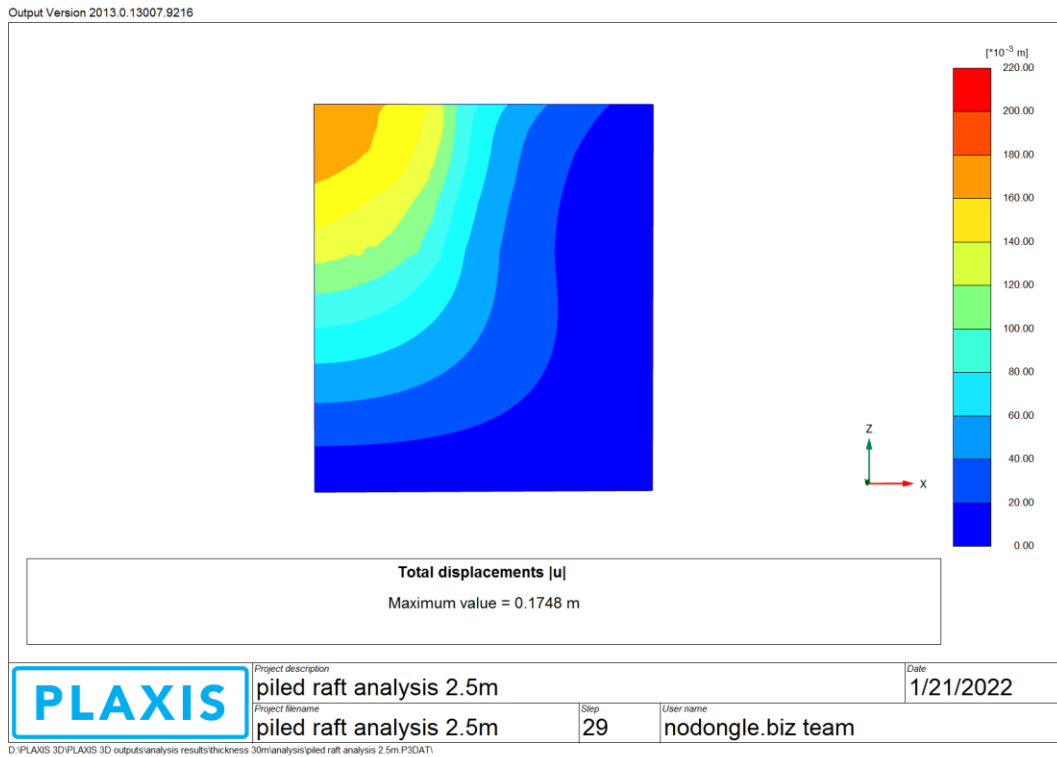


Figure C- 18 Corner Settlement at 2.5m raft thickness

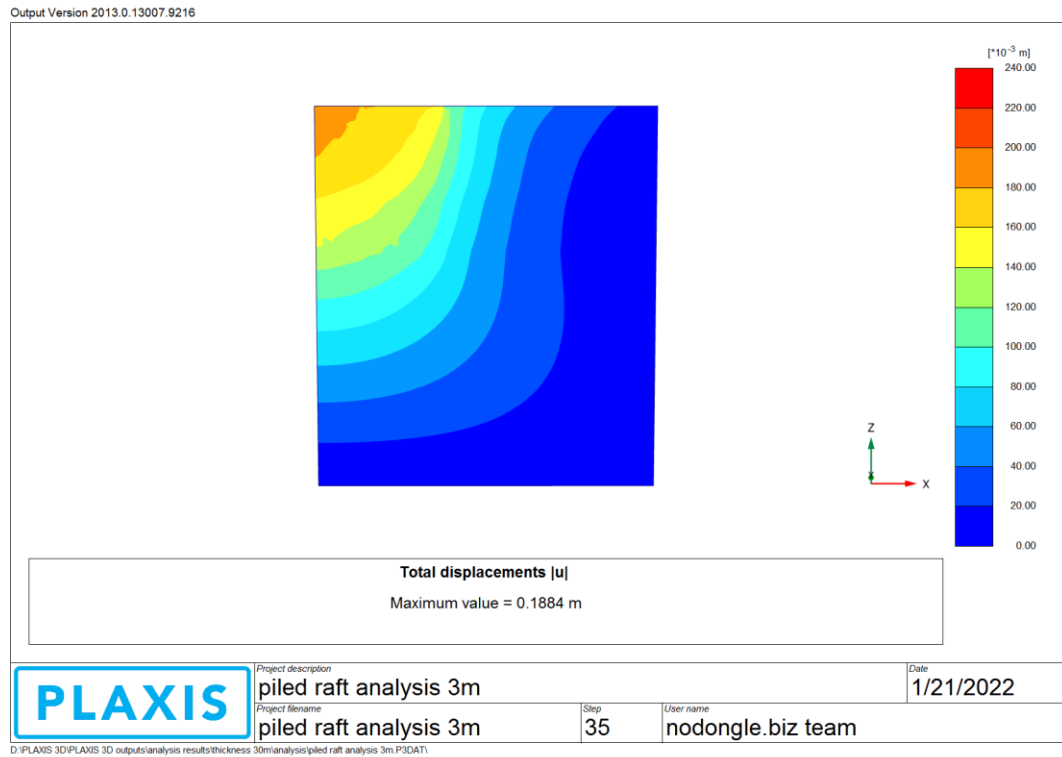


Figure C- 19 Corner Settlement at 3m raft thickness

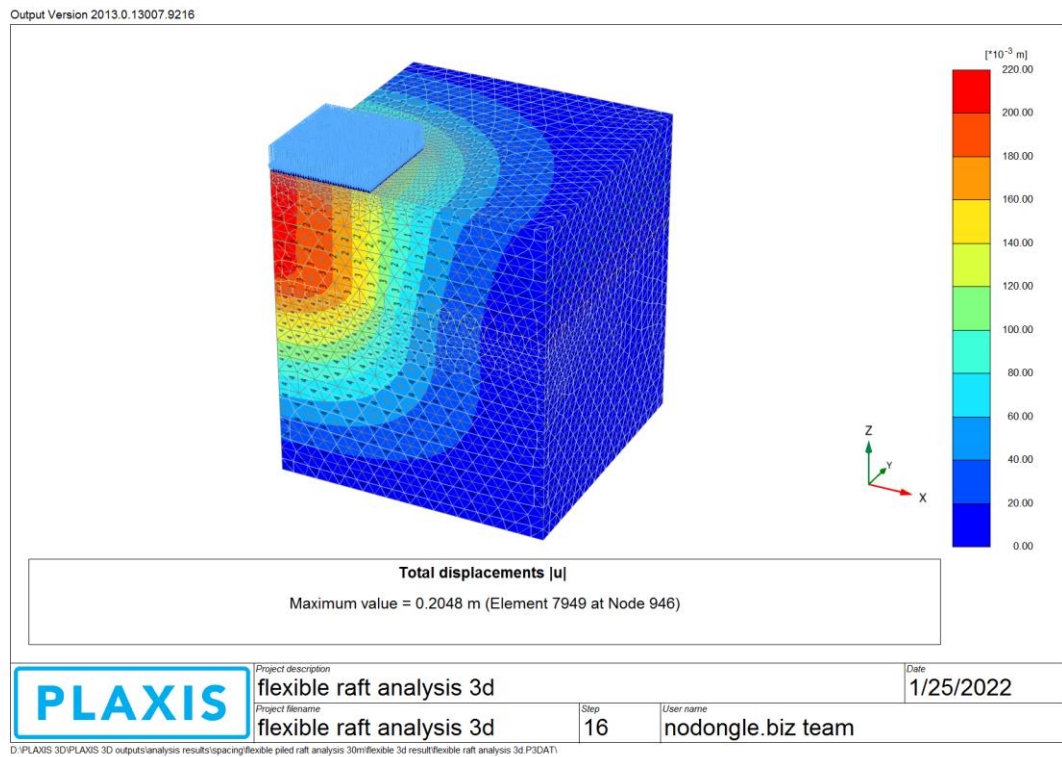


Figure C- 20 central settlement of flexible raft at 3d pile spacing

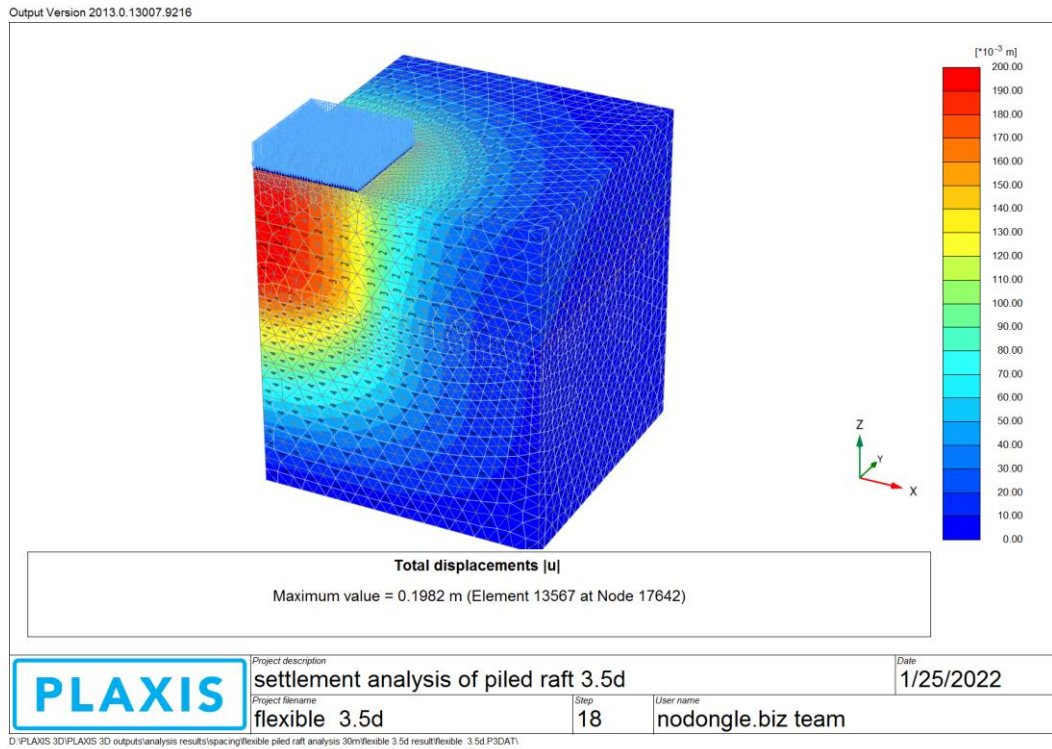


Figure C- 21 central settlement of flexible raft at 3.5d pile spacing

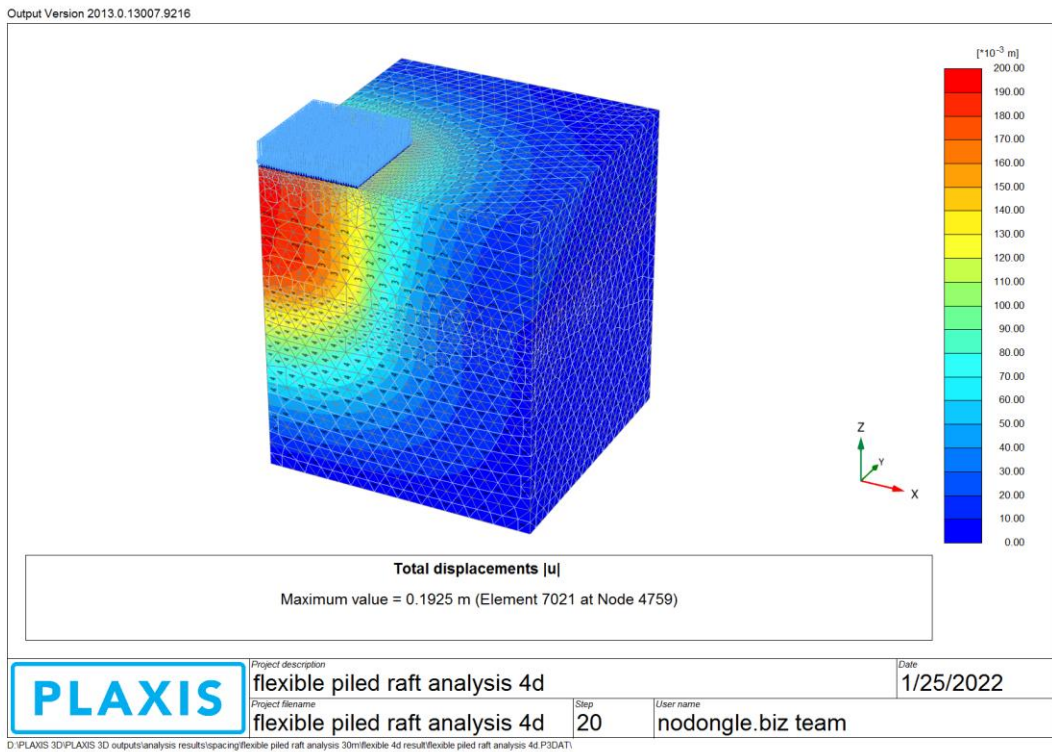


Figure C- 22 central settlement of flexible raft at 4d pile spacing

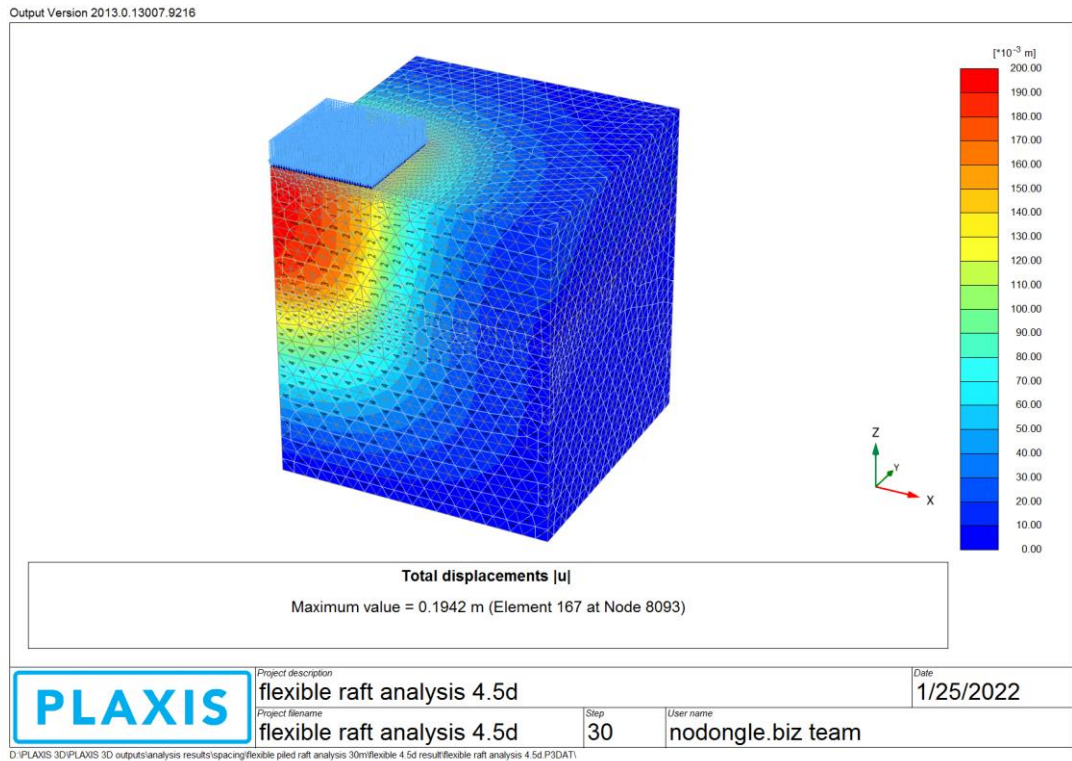


Figure C- 23 central settlement of flexible raft at 4.5d pile spacing

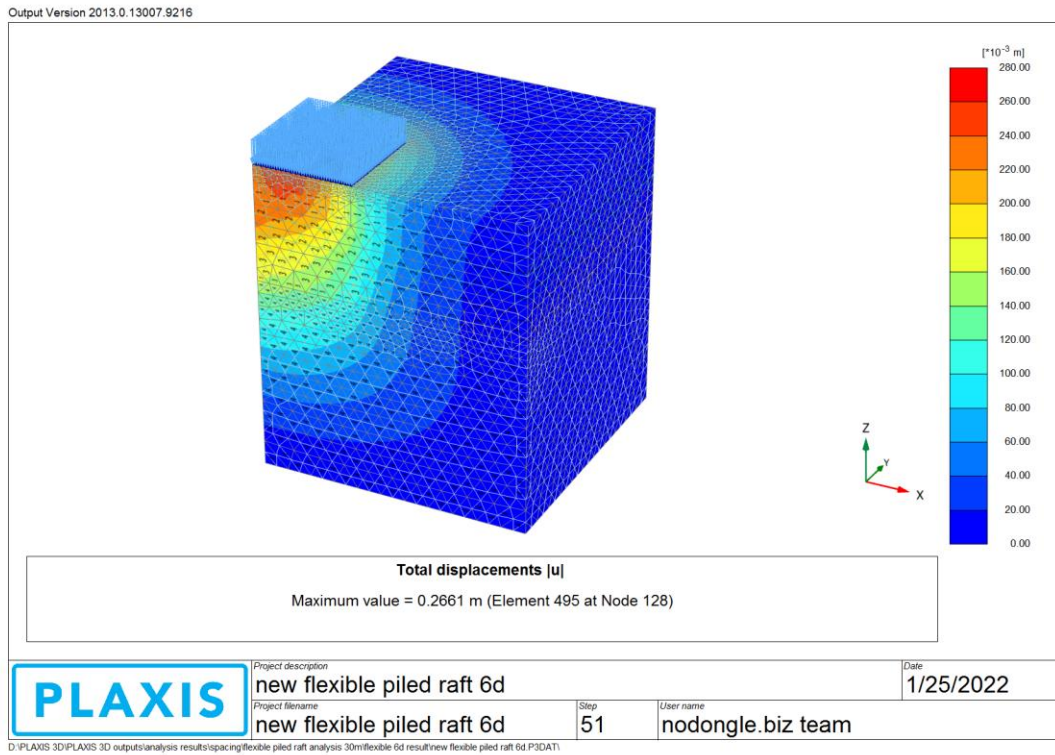


Figure C- 24 central settlement of flexible raft at 6d pile spacing

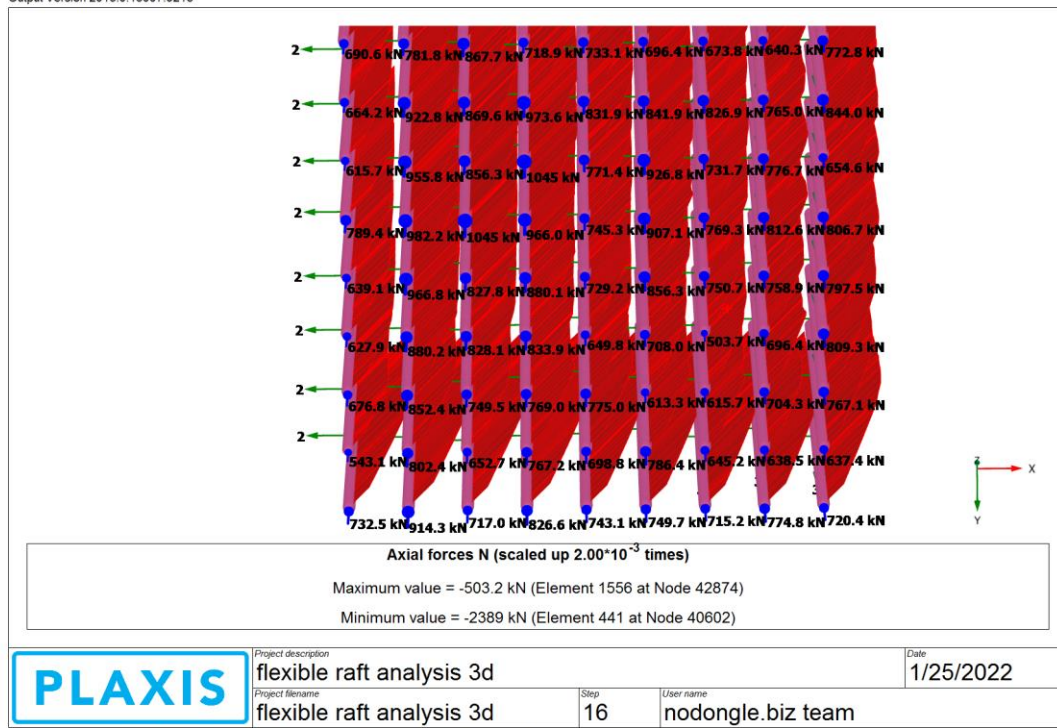


Figure C- 25 Flexible raft axial load distribution within a piles for 3d pile spacing

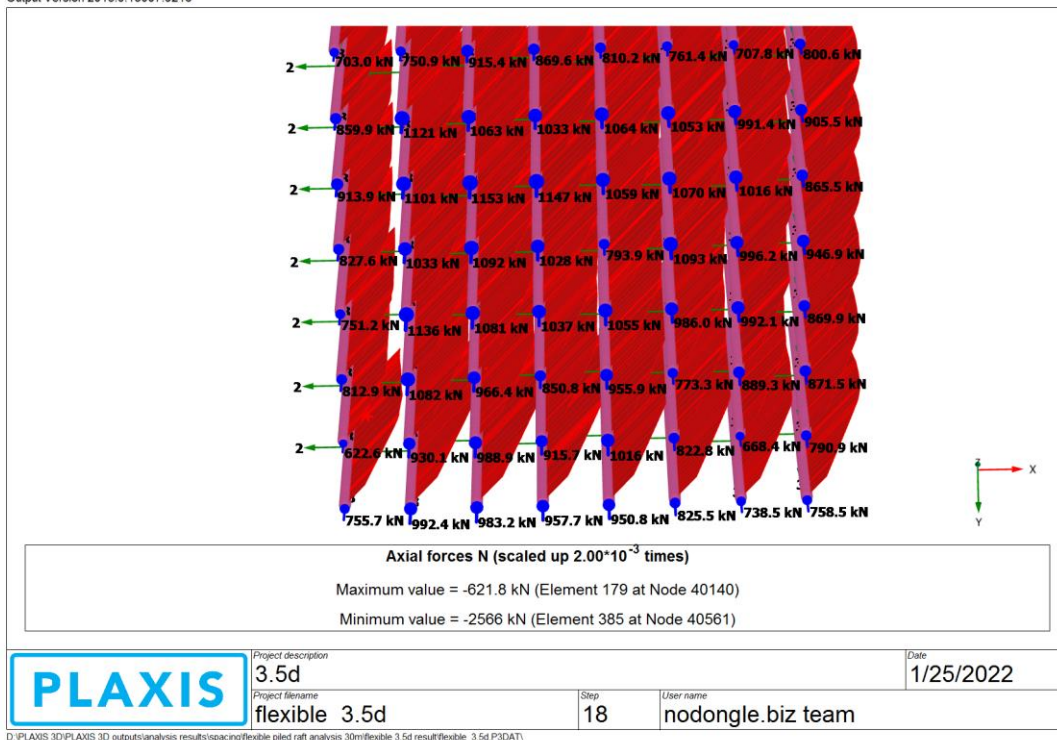


Figure C- 26 Flexible raft axial load distribution within a piles for 3.5d pile spacing

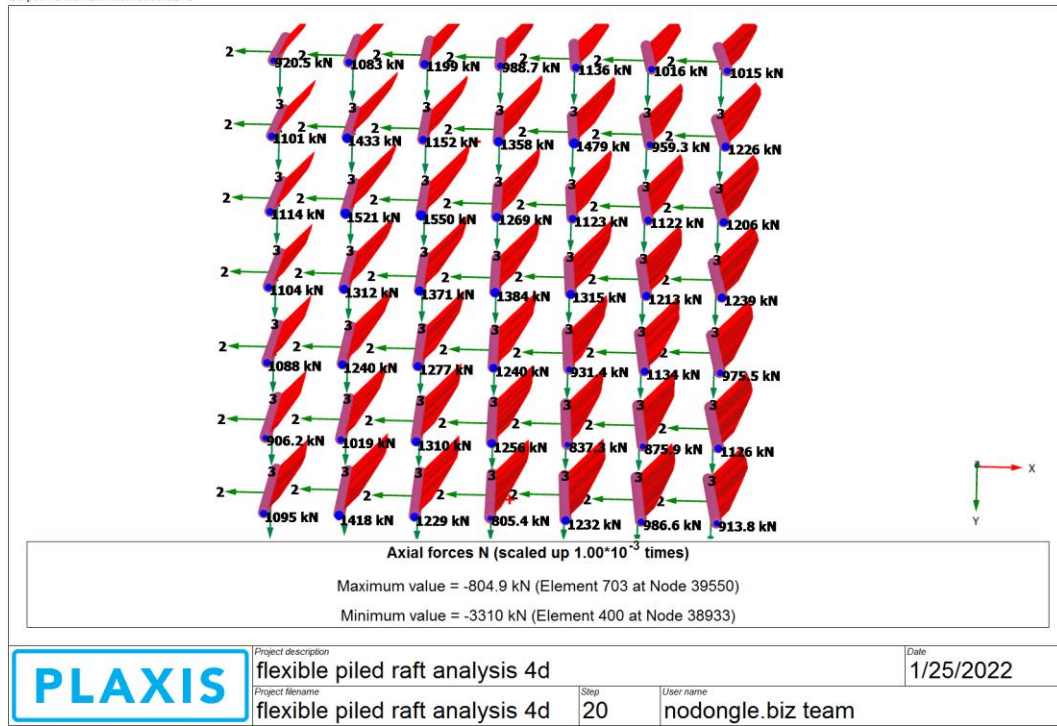


Figure C- 27 Flexible raft axial load distribution within a piles for 4d pile spacing

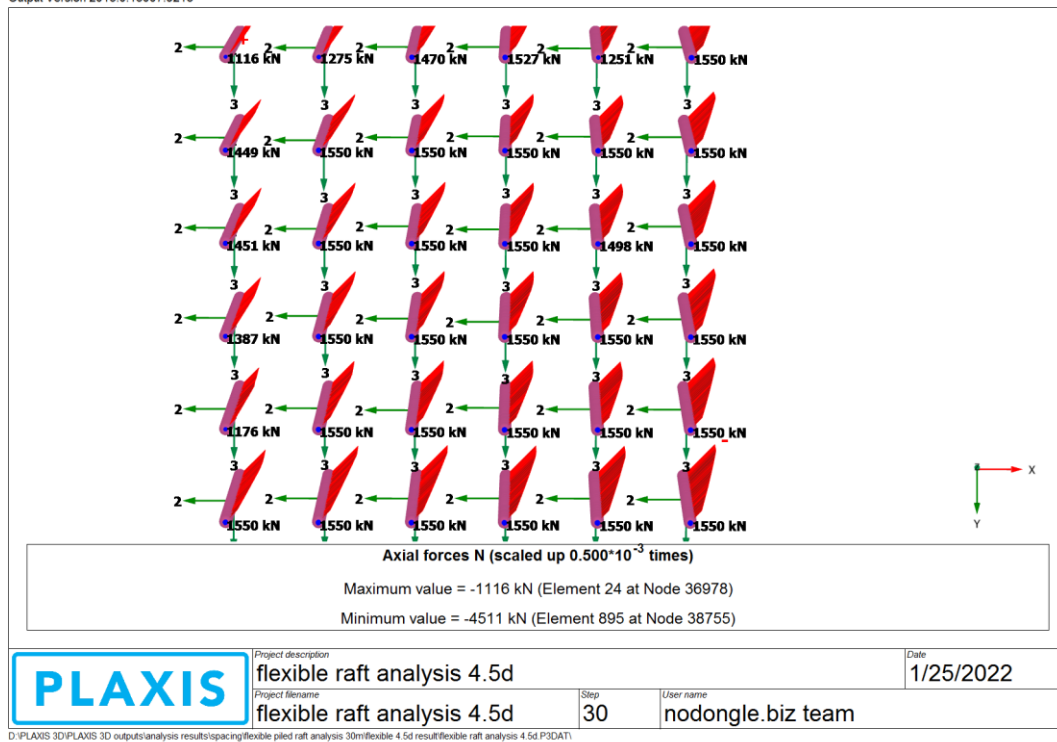


Figure C- 28 Flexible raft axial load distribution within a piles for 4.5d pile spacing

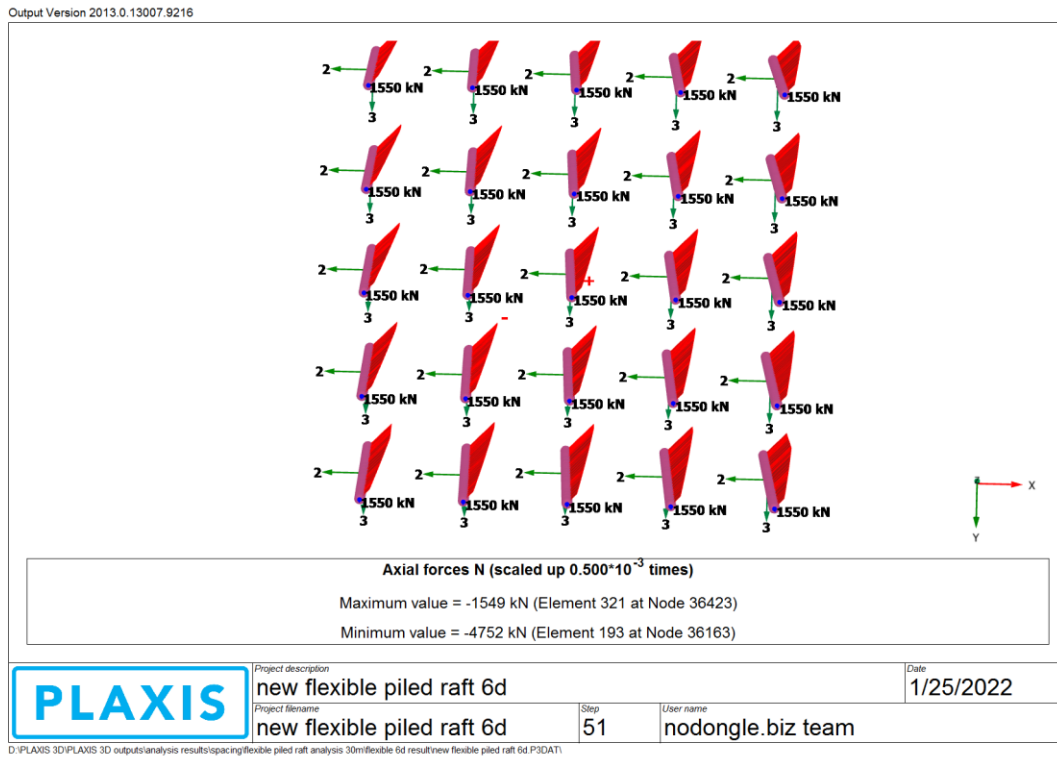


Figure C- 29 Flexible raft axial load distribution within a piles for 6d pile spacing

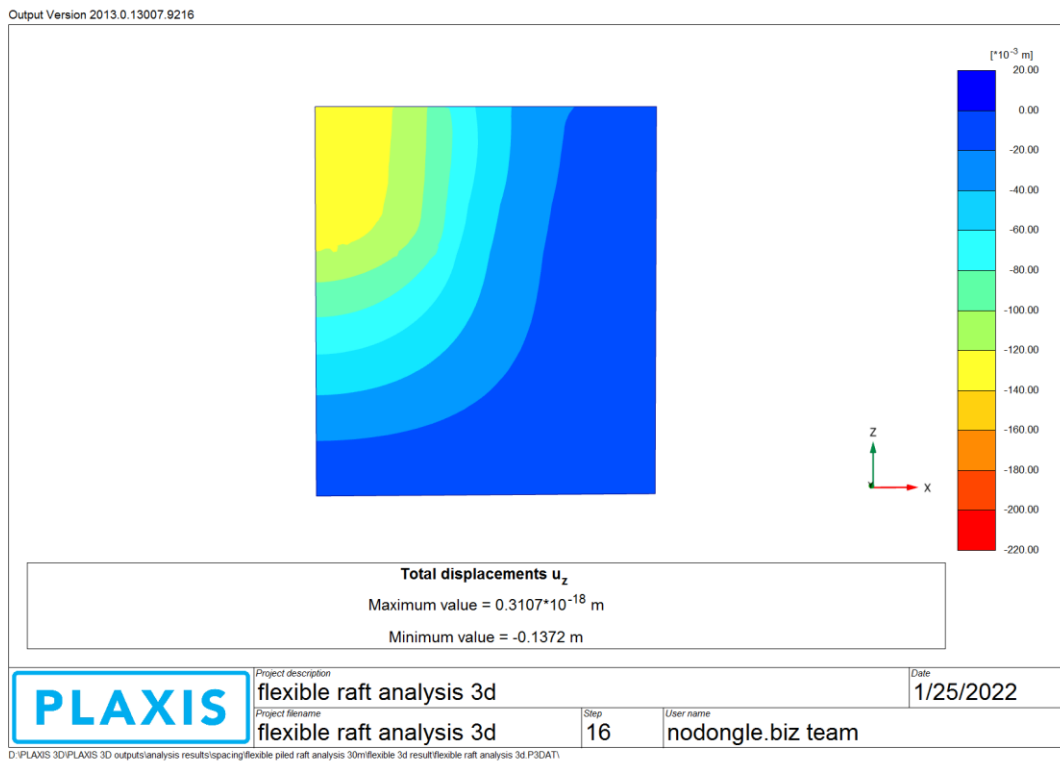


Figure C- 30 Corner Settlement for flexible raft at 3d pile spacing

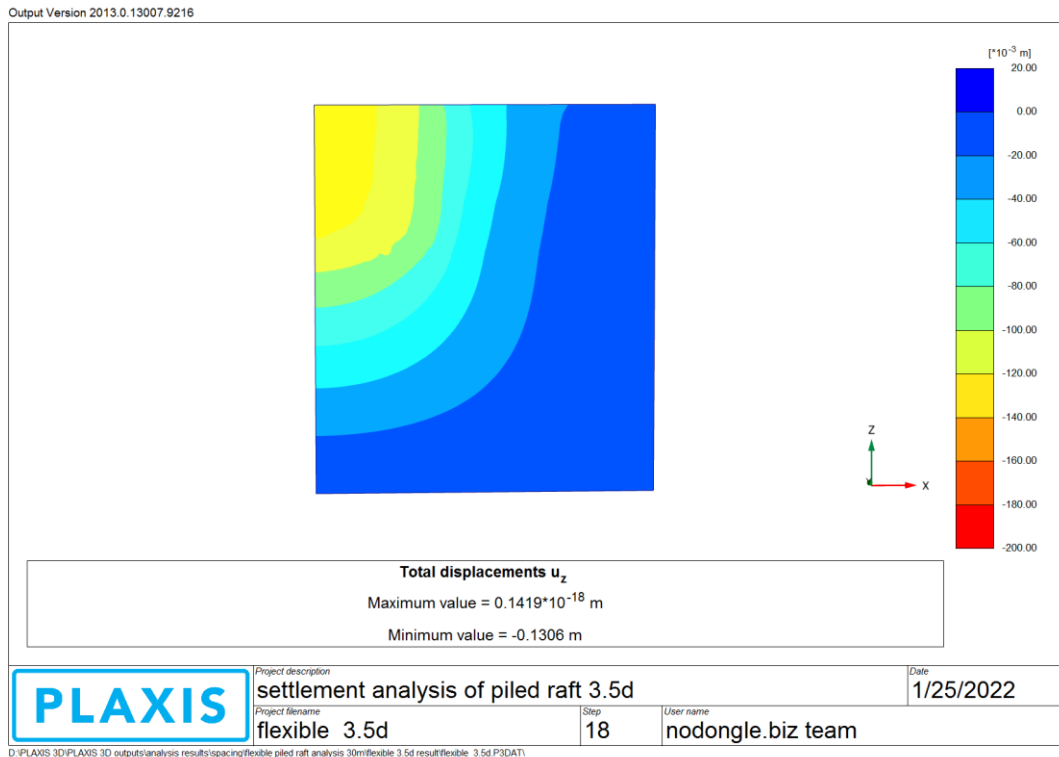


Figure C- 31 Corner Settlement for flexible raft at 3.5d pile spacing

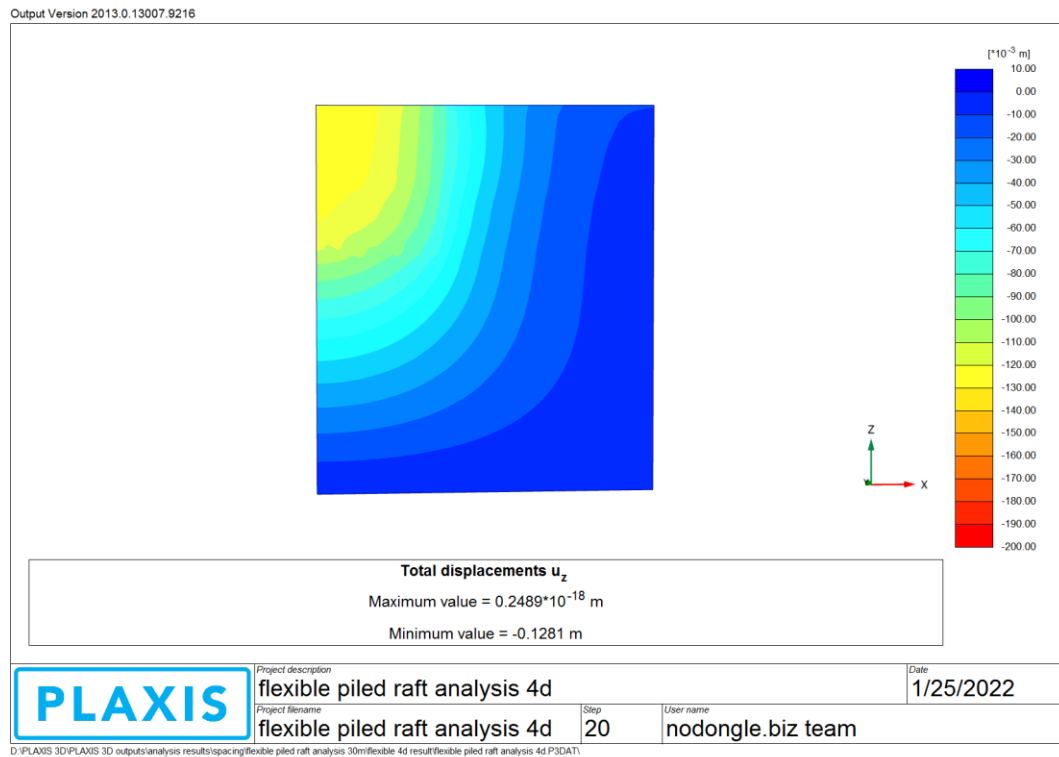


Figure C- 32 Corner Settlement for flexible raft at 4d pile spacing

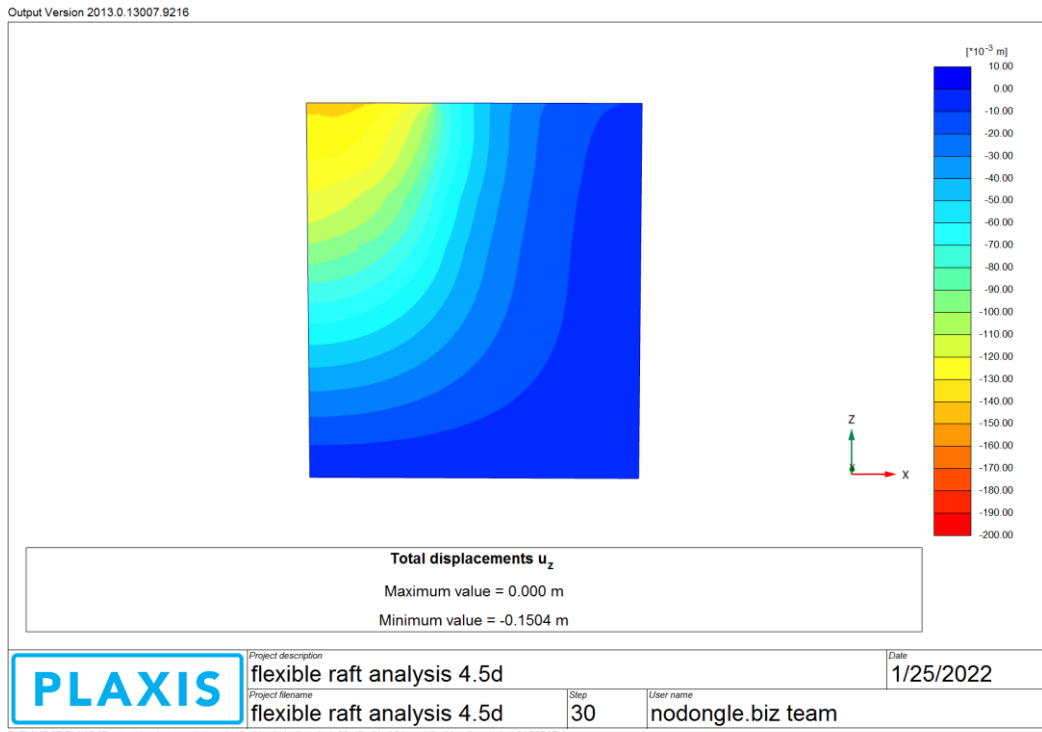


Figure C- 33 Corner Settlement for flexible raft at 4.5d pile spacing

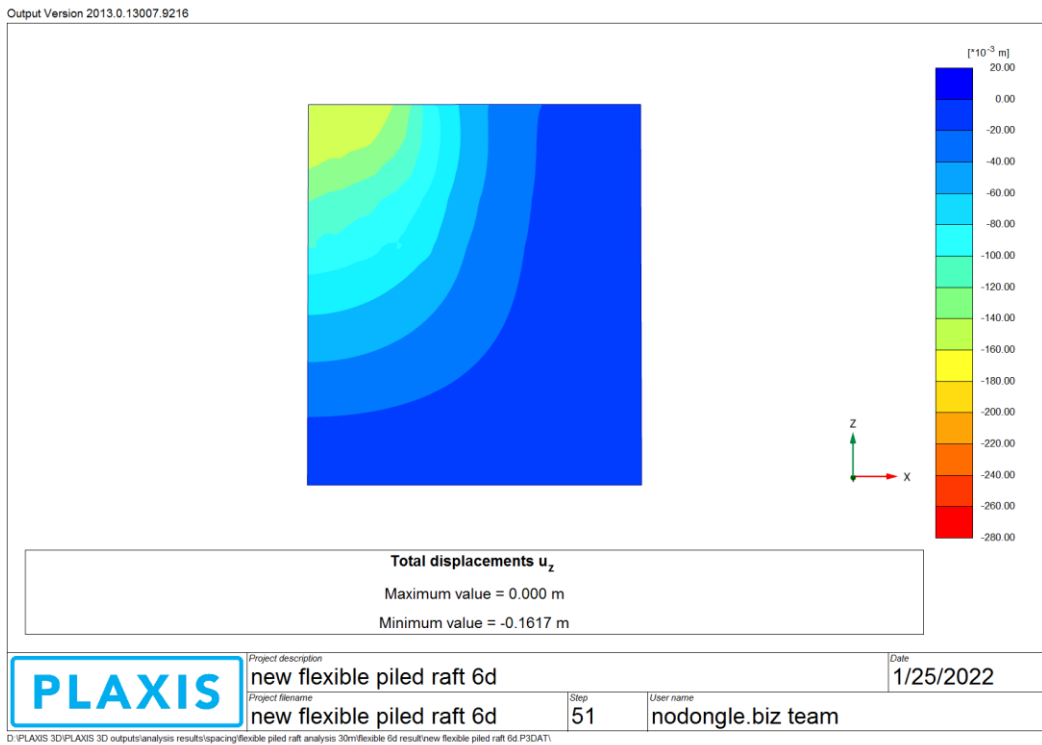


Figure C- 34 Corner Settlement for flexible raft at 6d pile spacing

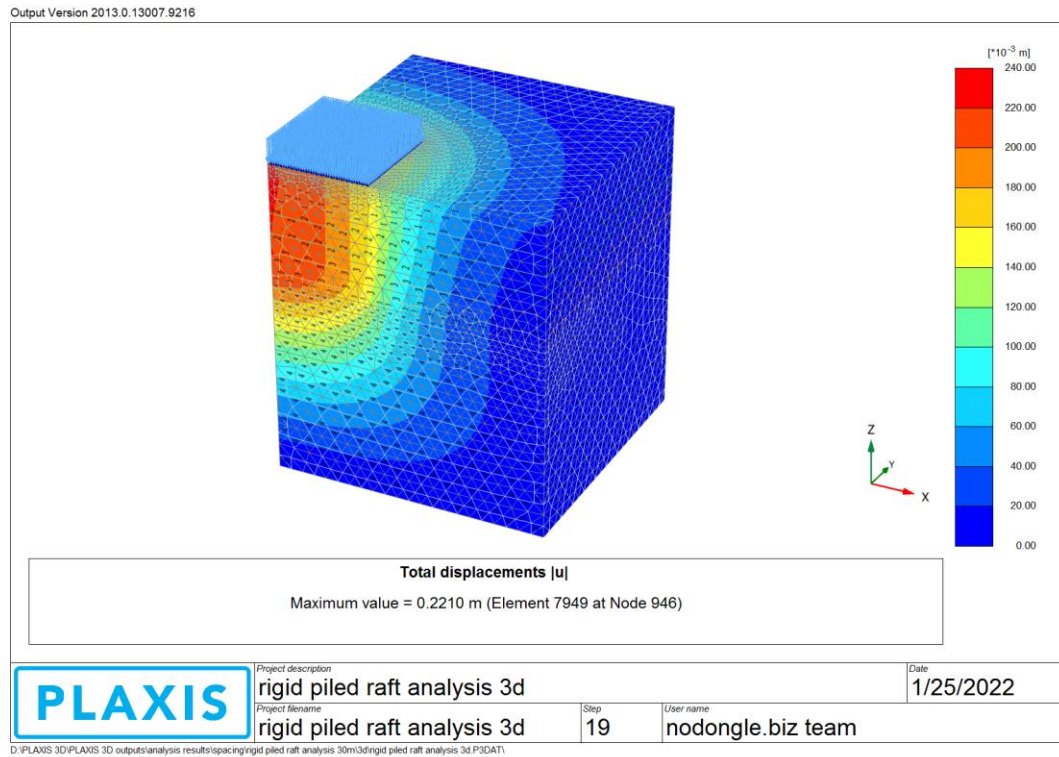


Figure C- 35 central settlement of flexible raft at 3d pile spacing

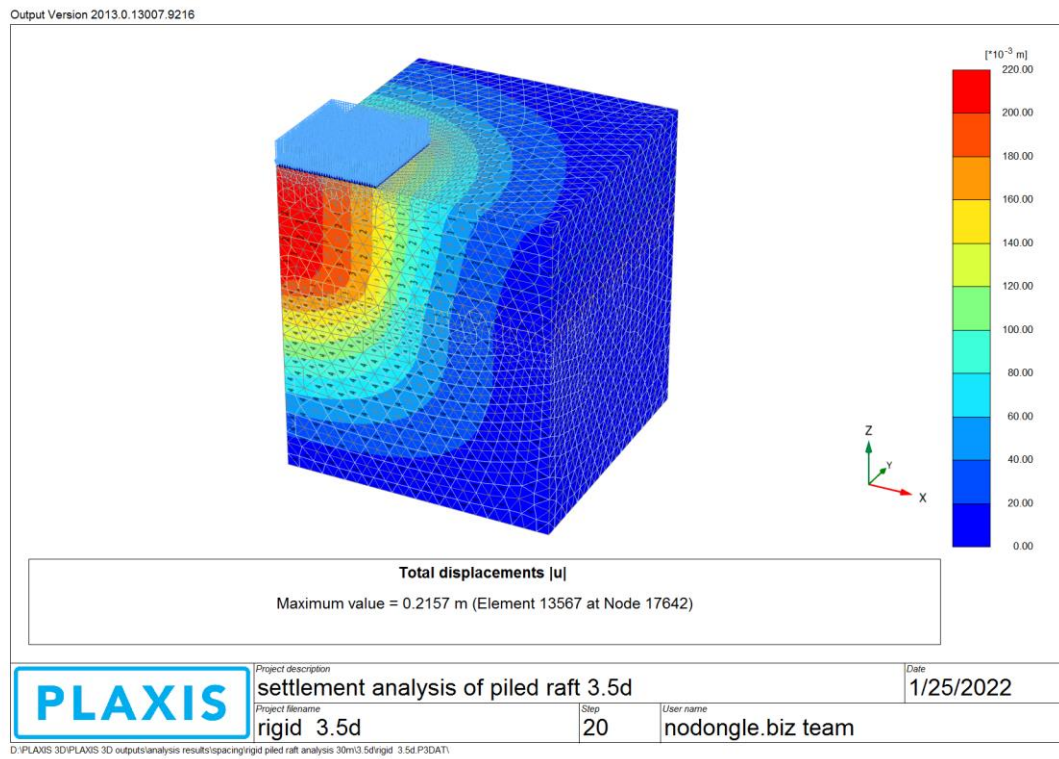


Figure C- 36 central settlement of flexible raft at 3.5d pile spacing

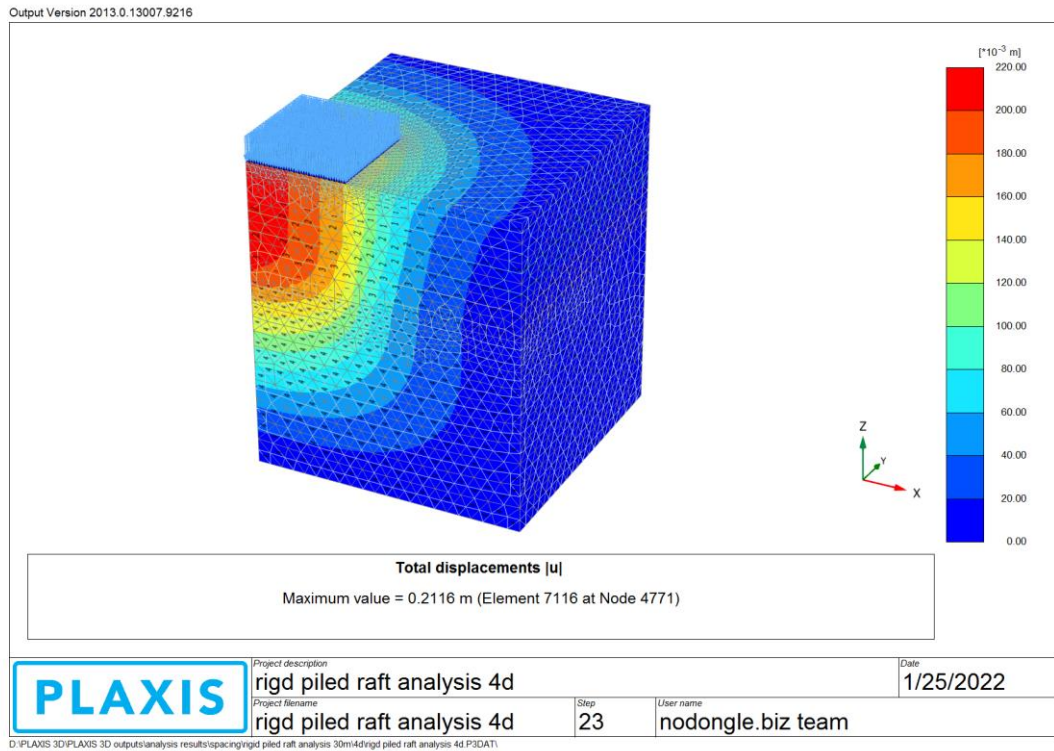


Figure C- 37 central settlement of flexible raft at 4d pile spacing

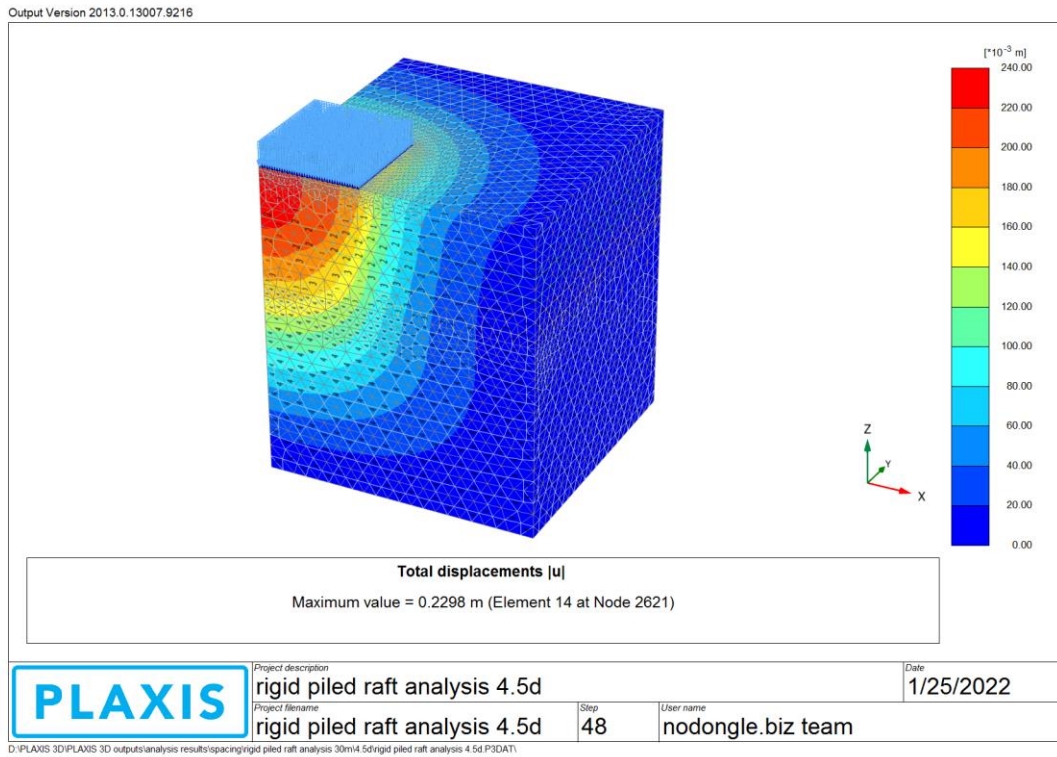


Figure C- 38 central settlement of flexible raft at 4.5d pile spacing

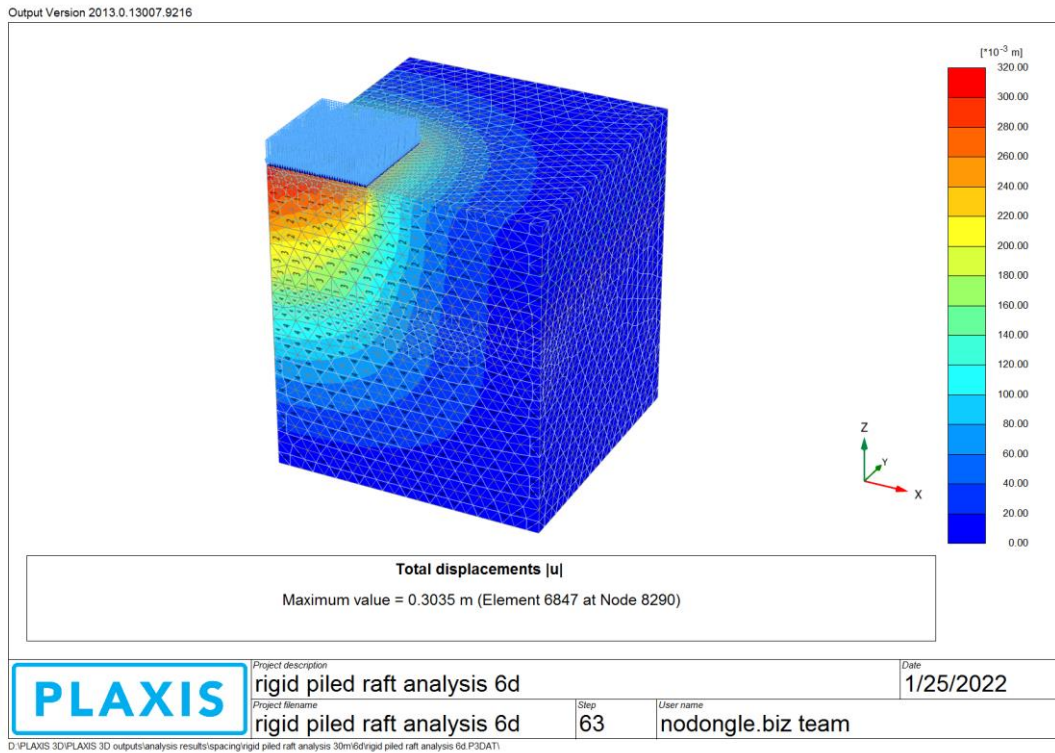


Figure C- 39 central settlement of flexible raft at 6d pile spacing

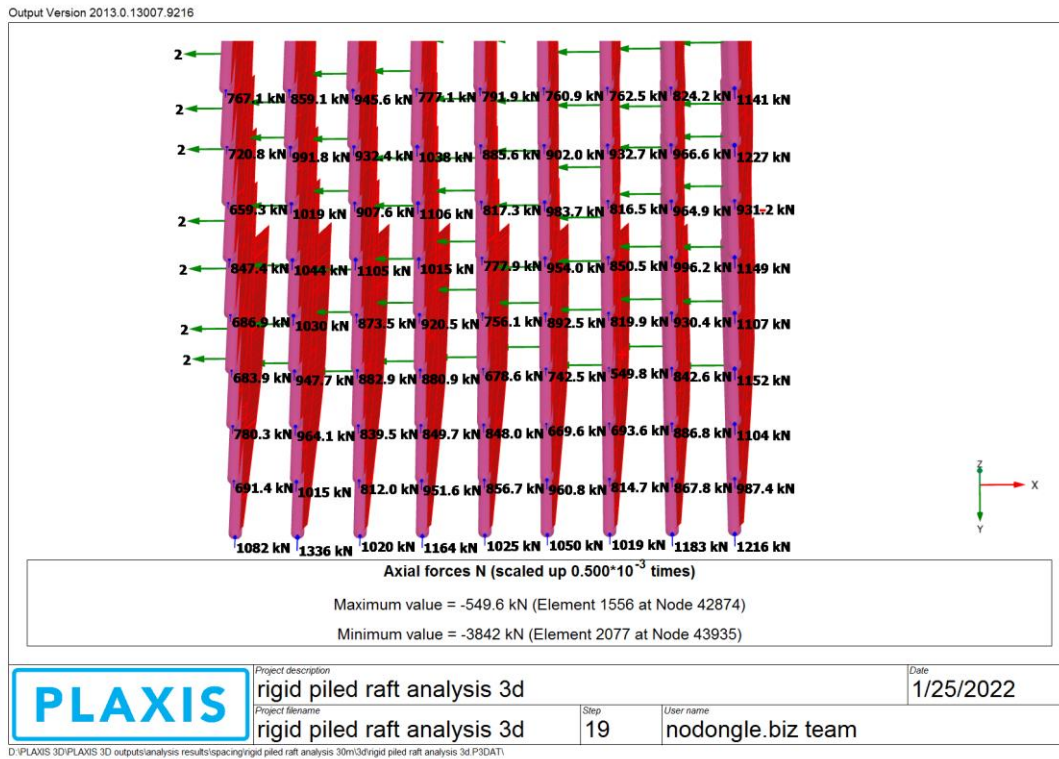


Figure C- 40 rigid raft axial load distribution within a piles for 3d pile spacing

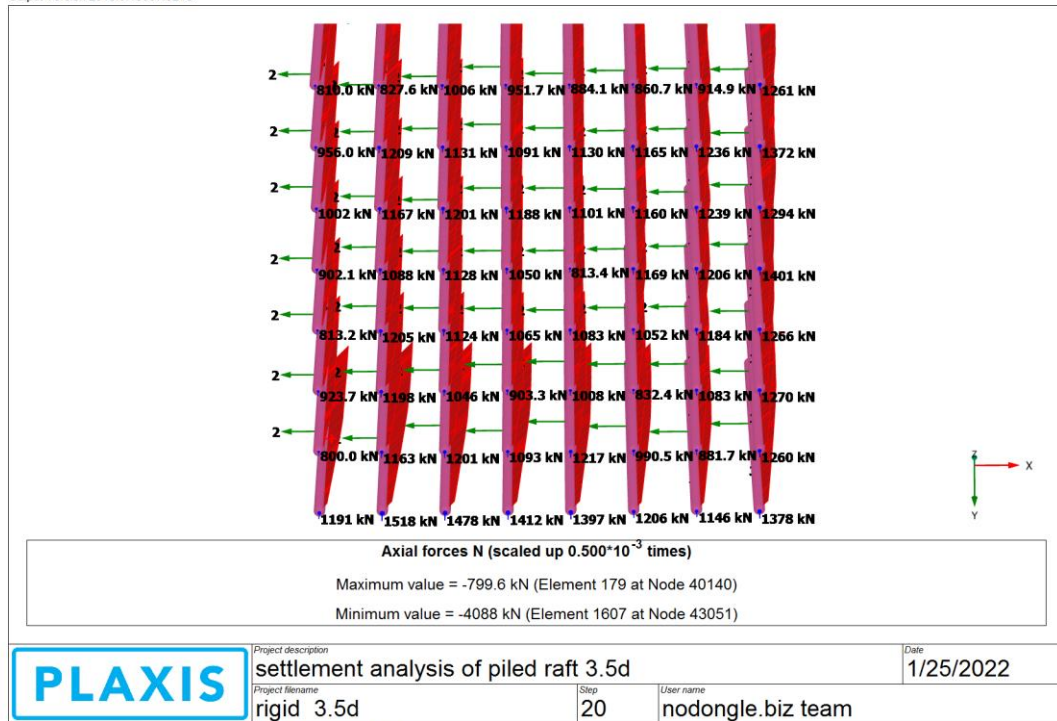


Figure C- 41 rigid raft axial load distribution within a piles for 3.5d pile spacing

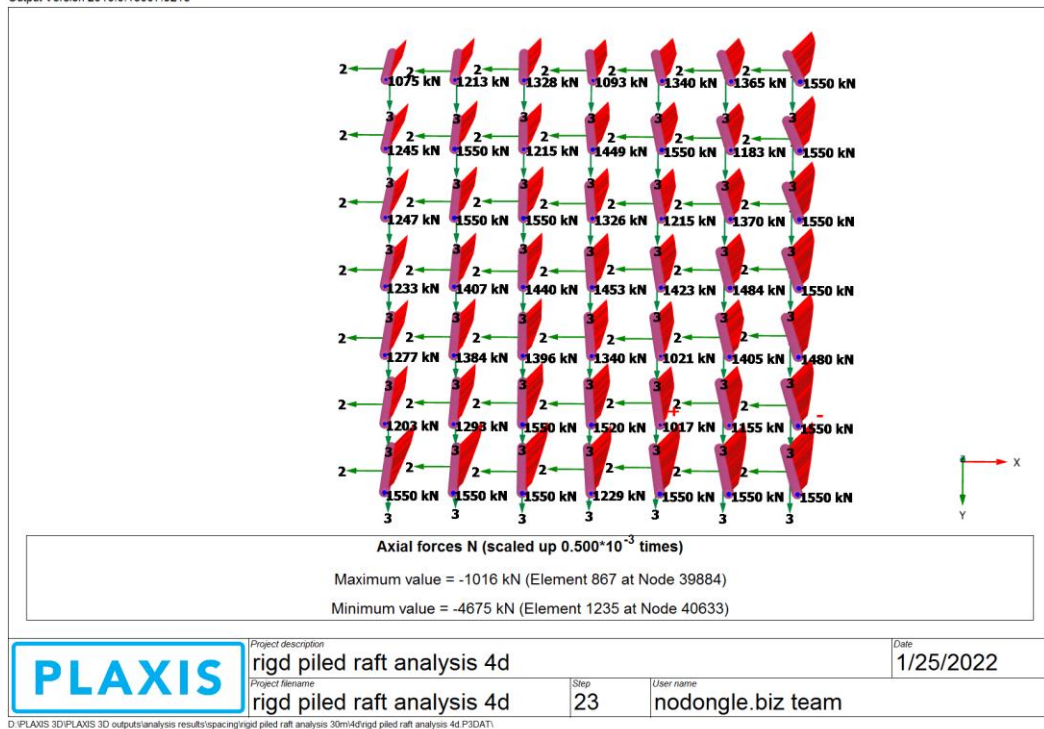


Figure C- 42 rigid raft axial load distribution within a piles for 4d pile spacing

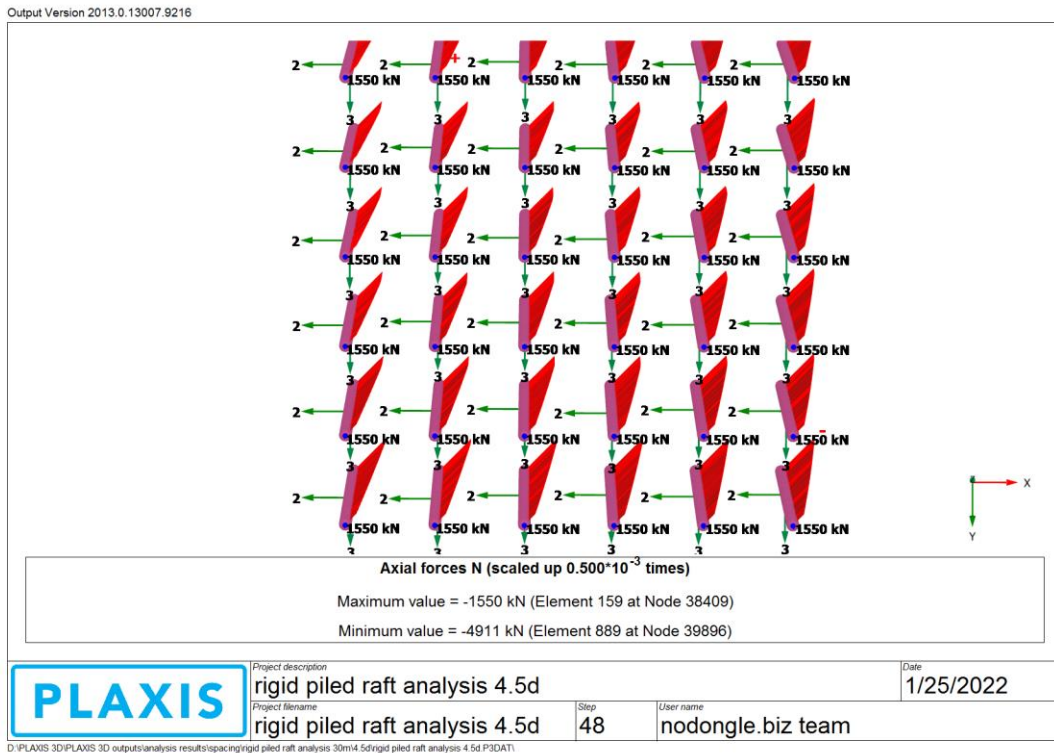


Figure C- 43 rigid raft axial load distribution within a piles for 4.5d pile spacing

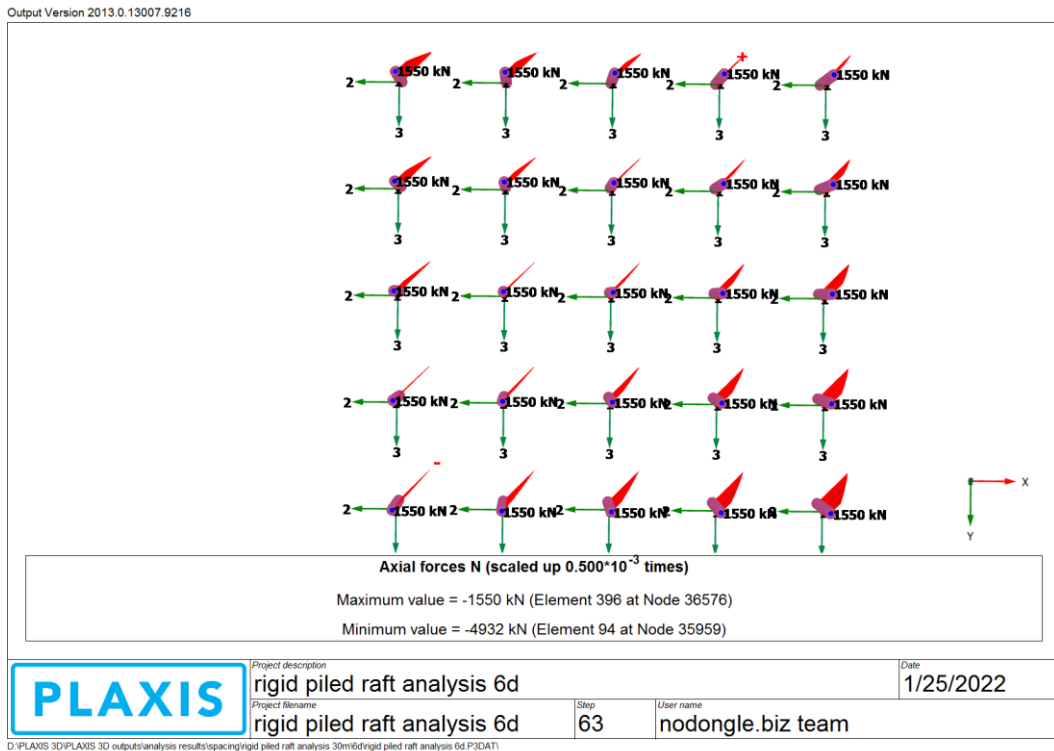


Figure C- 44 rigid raft axial load distribution within a piles for 6d pile spacing

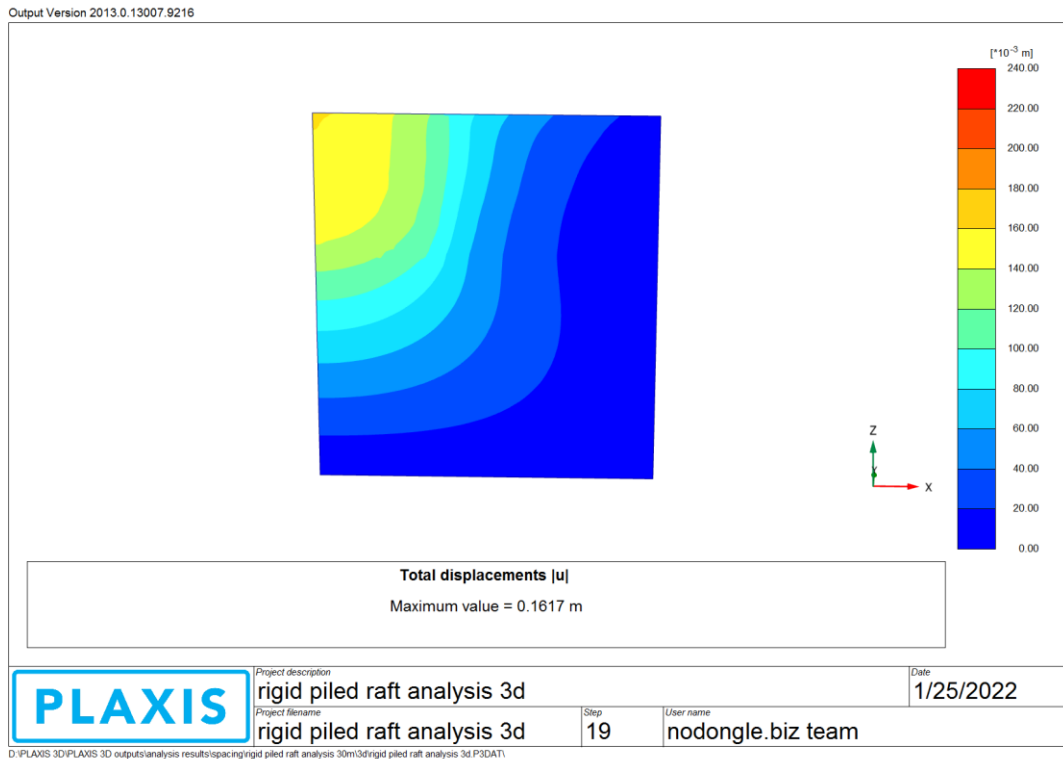


Figure C- 45 corner settlement for rigid raft at 3d pile spacing

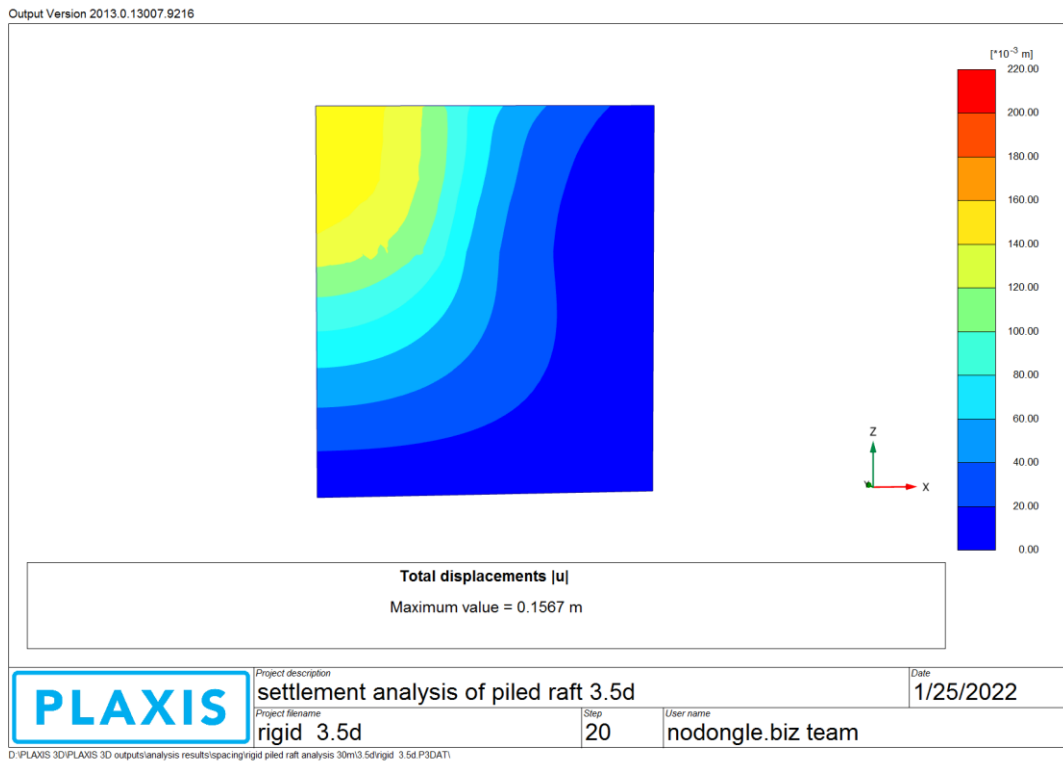


Figure C- 46 corner settlement for rigid raft at 3.5d pile spacing

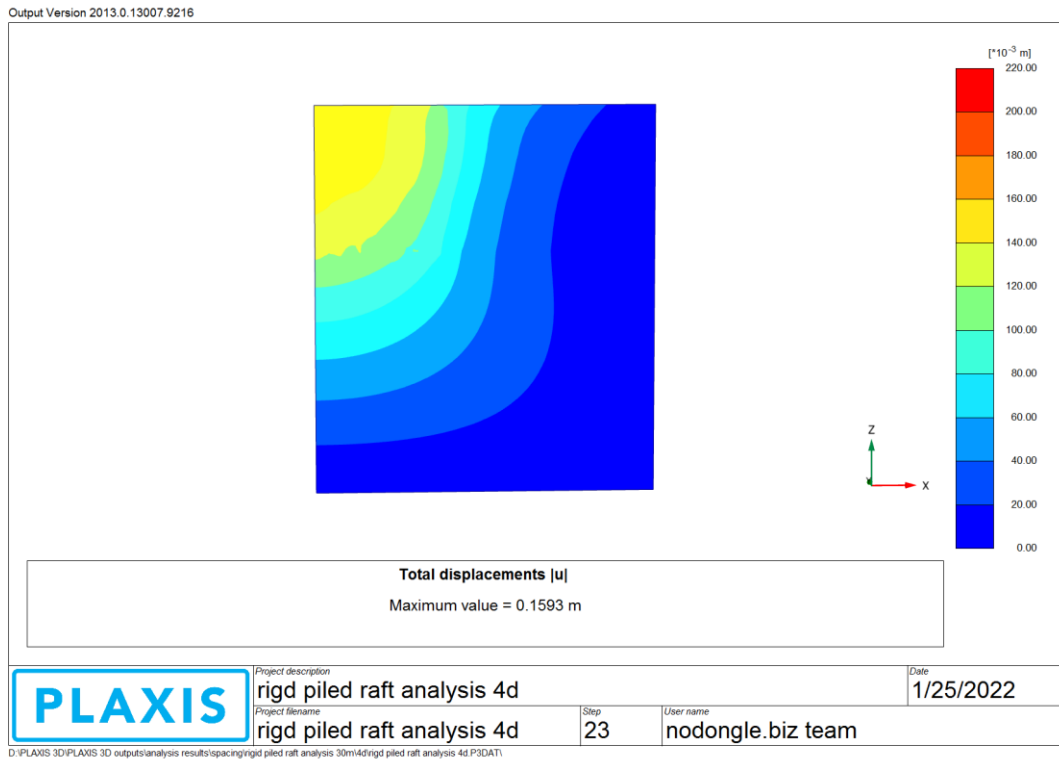


Figure C- 47 corner settlement for rigid raft at 4d pile spacing

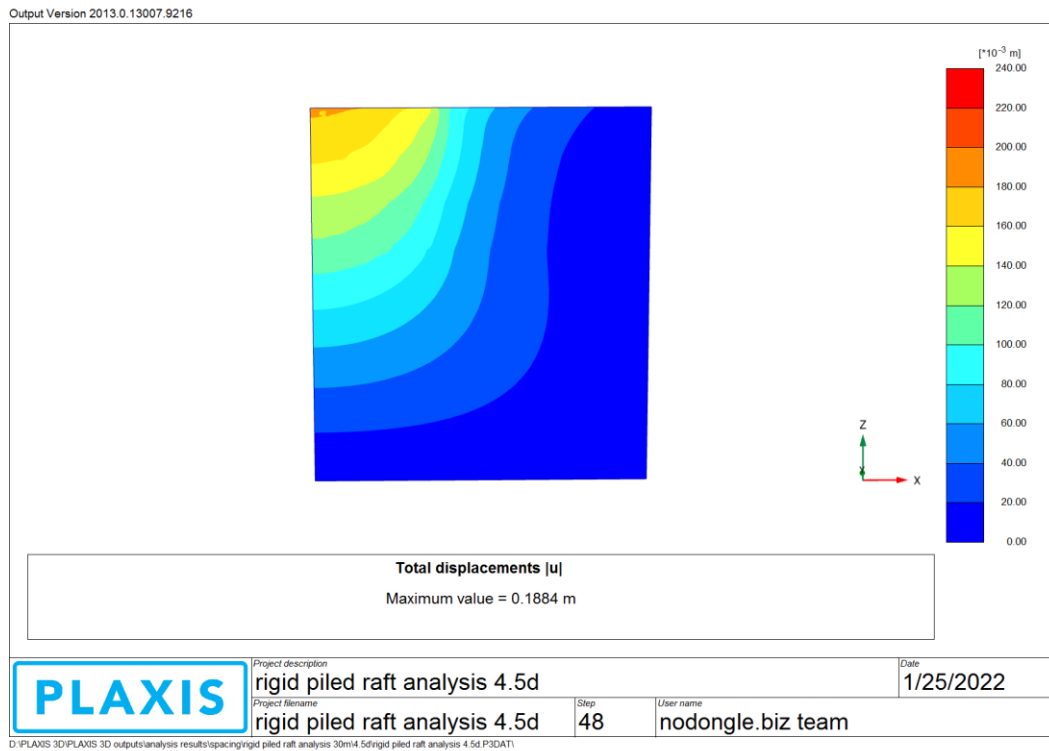


Figure C- 48 corner settlement for rigid raft at 4.5d pile spacing

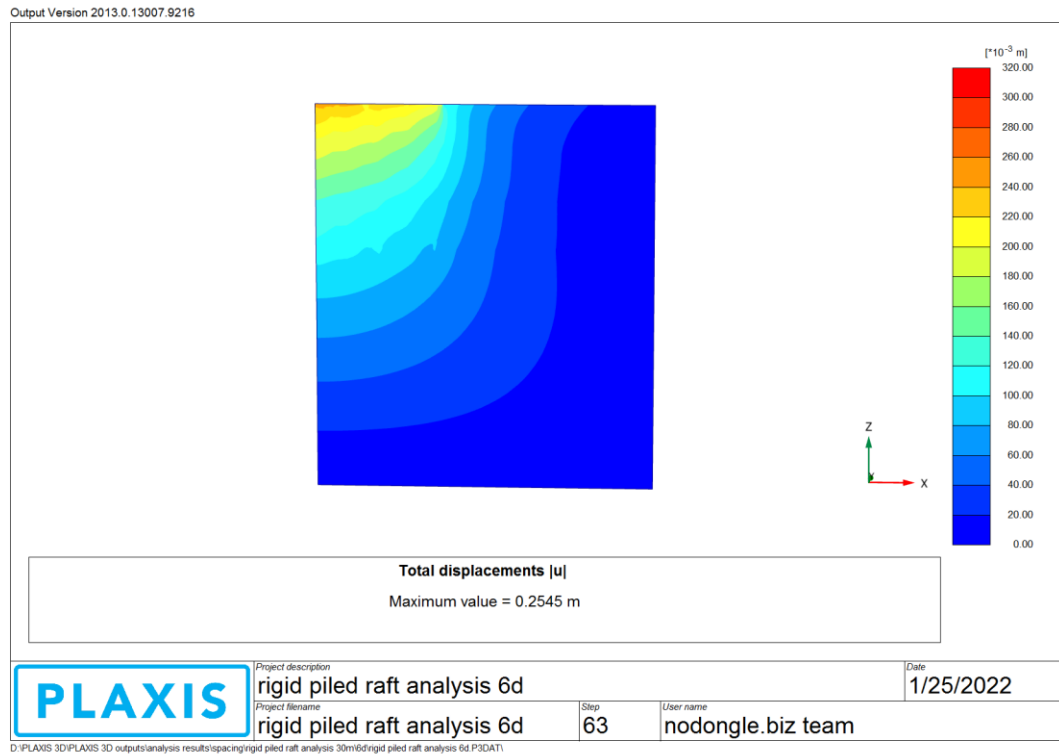


Figure C- 49 corner settlement for rigid raft at 6d pile spacing

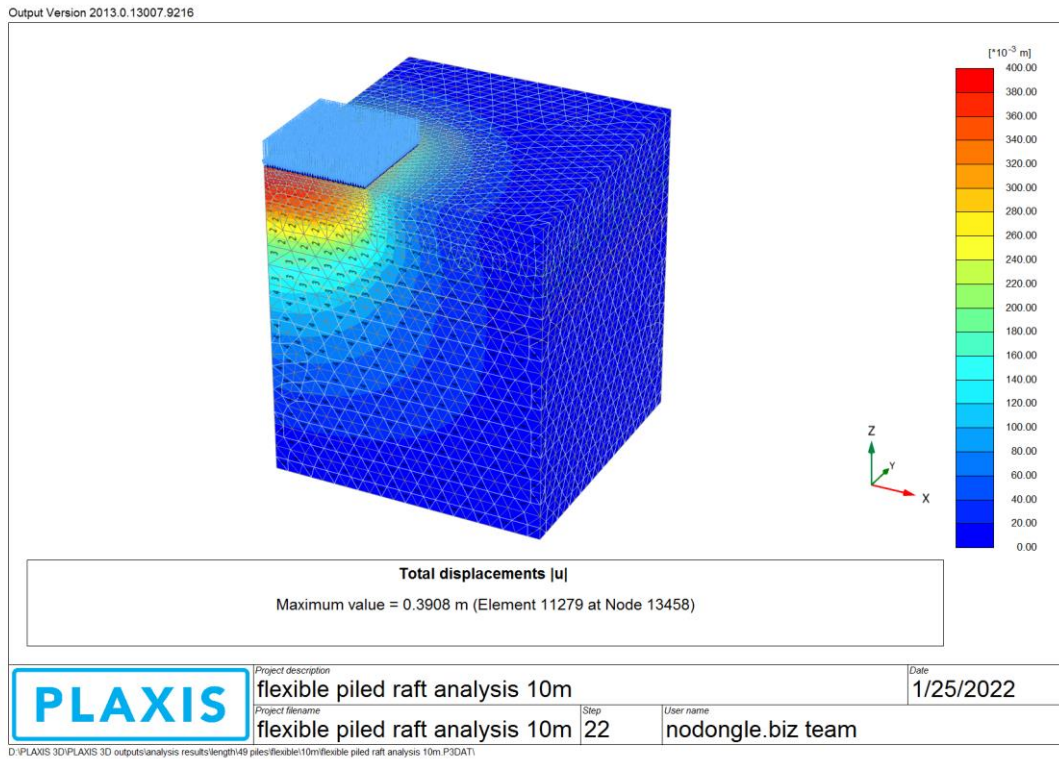


Figure C- 50 central settlement of flexible raft at 10m pile length

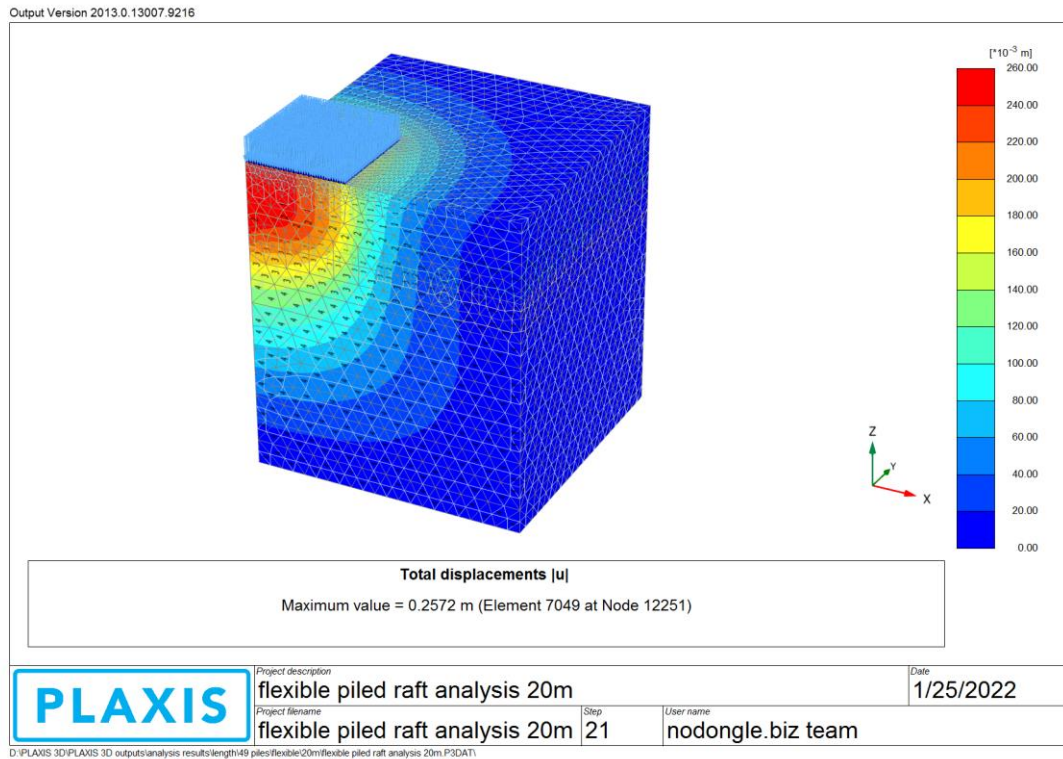


Figure C- 51 central settlement of flexible raft at 20m pile length

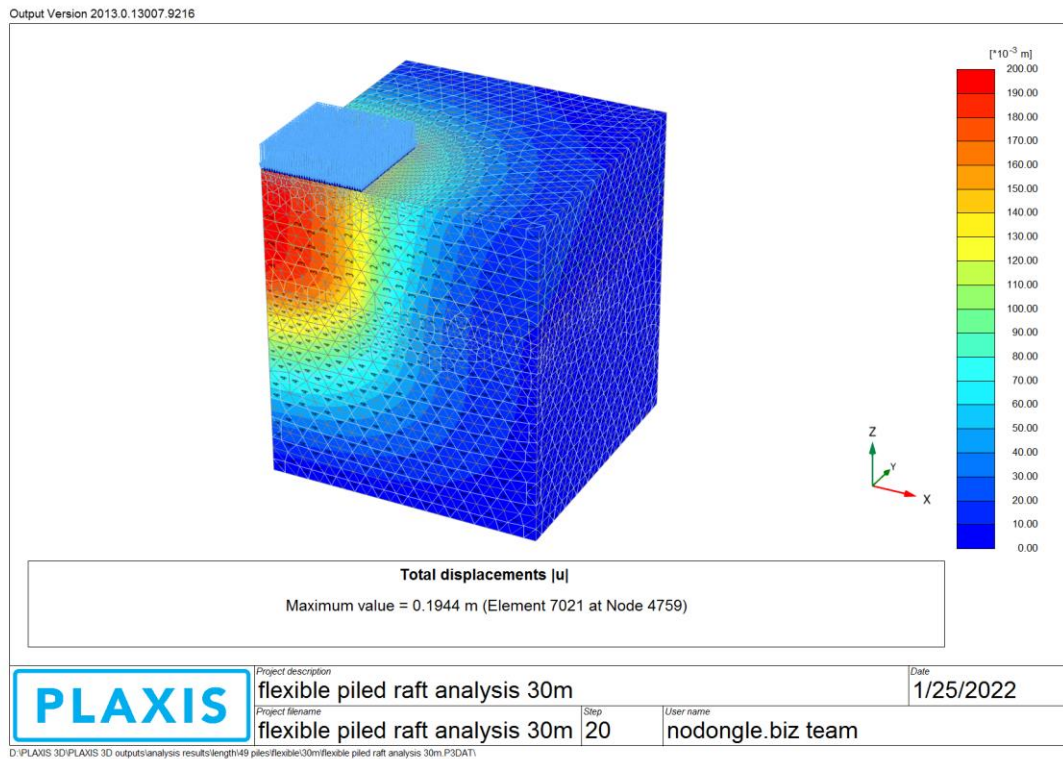


Figure C- 52 central settlement of flexible raft at 30m pile length

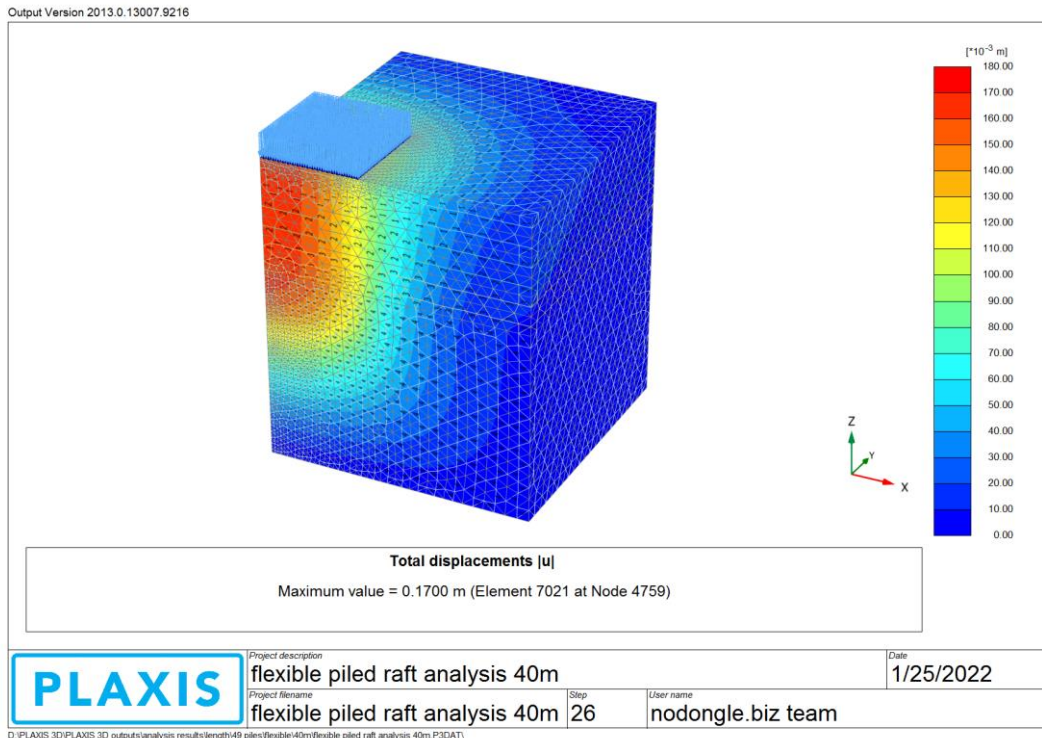


Figure C- 53 central settlement of flexible raft at 40m pile length

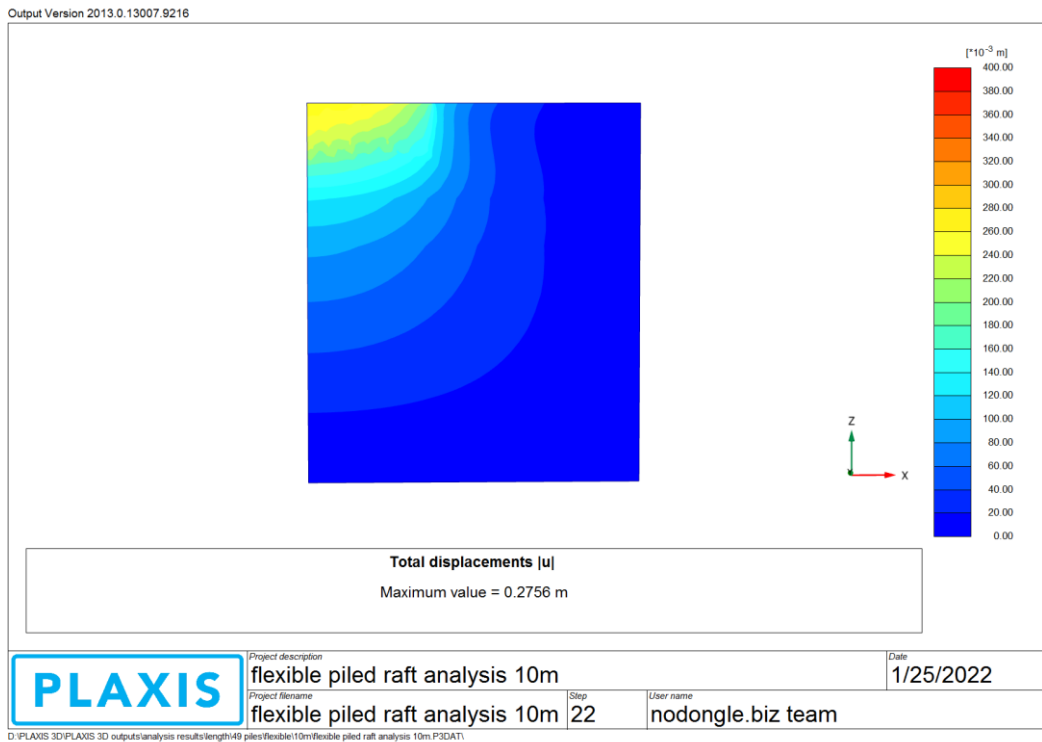


Figure C- 54 corner settlement for flexible raft at 10m pile length

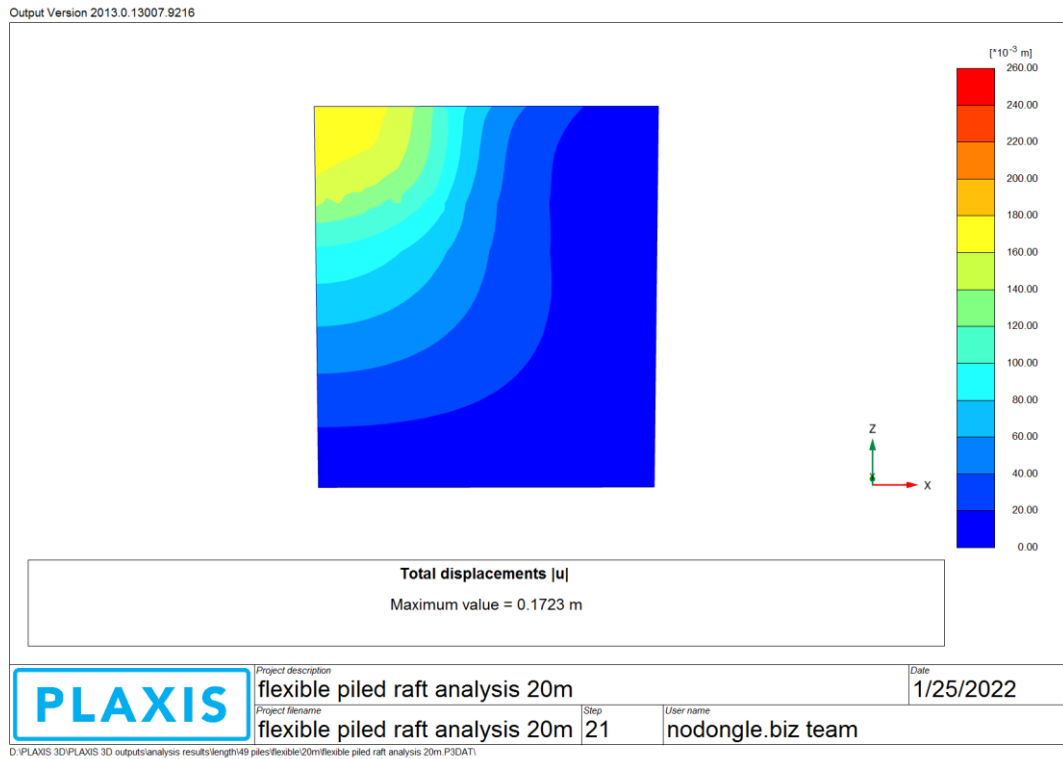


Figure C- 55 corner settlement for flexible raft at 20m pile length

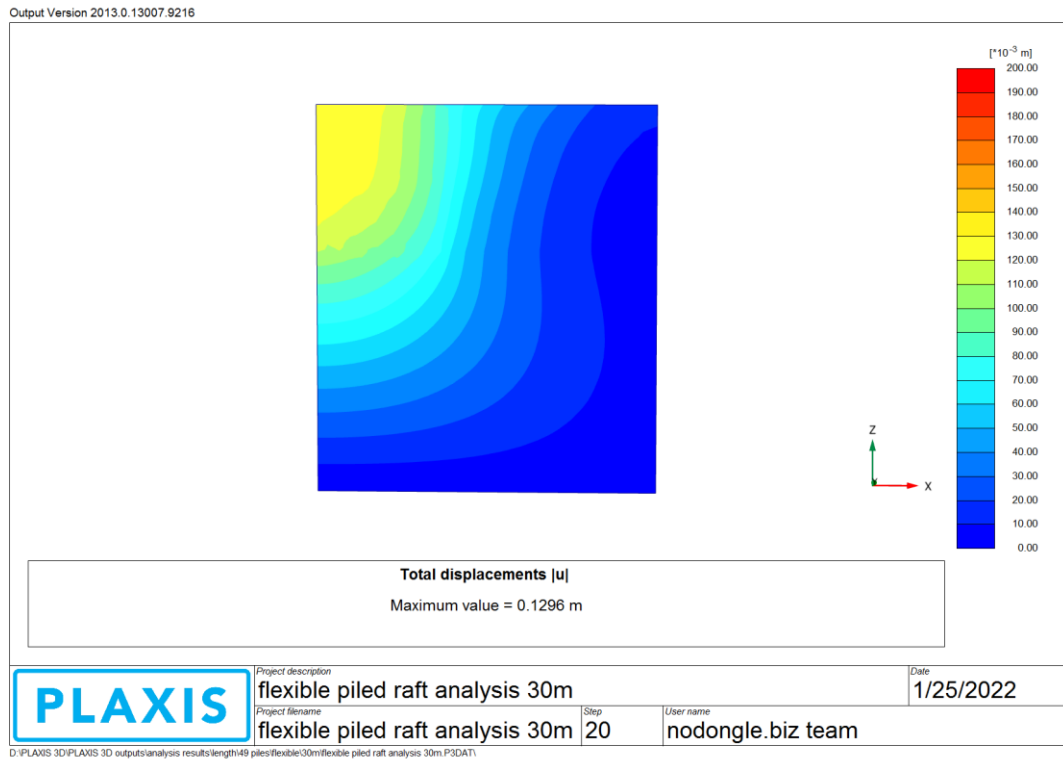


Figure C- 56 corner settlement for flexible raft at 30m pile length

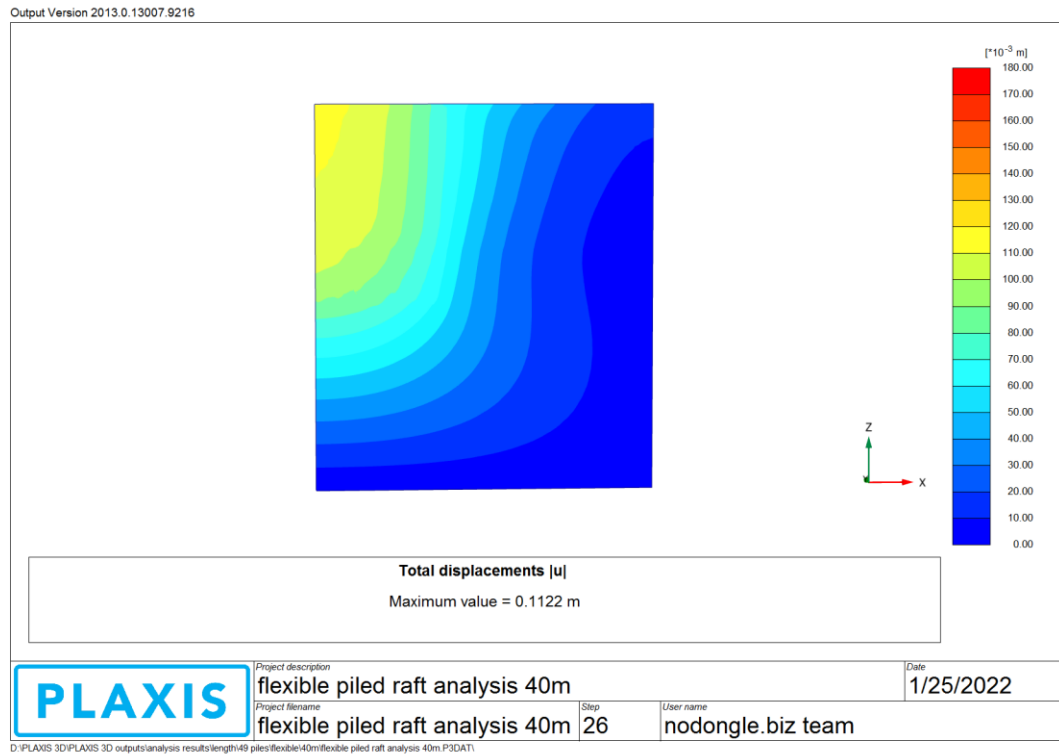


Figure C- 57 corner settlement for flexible raft at 40m pile length

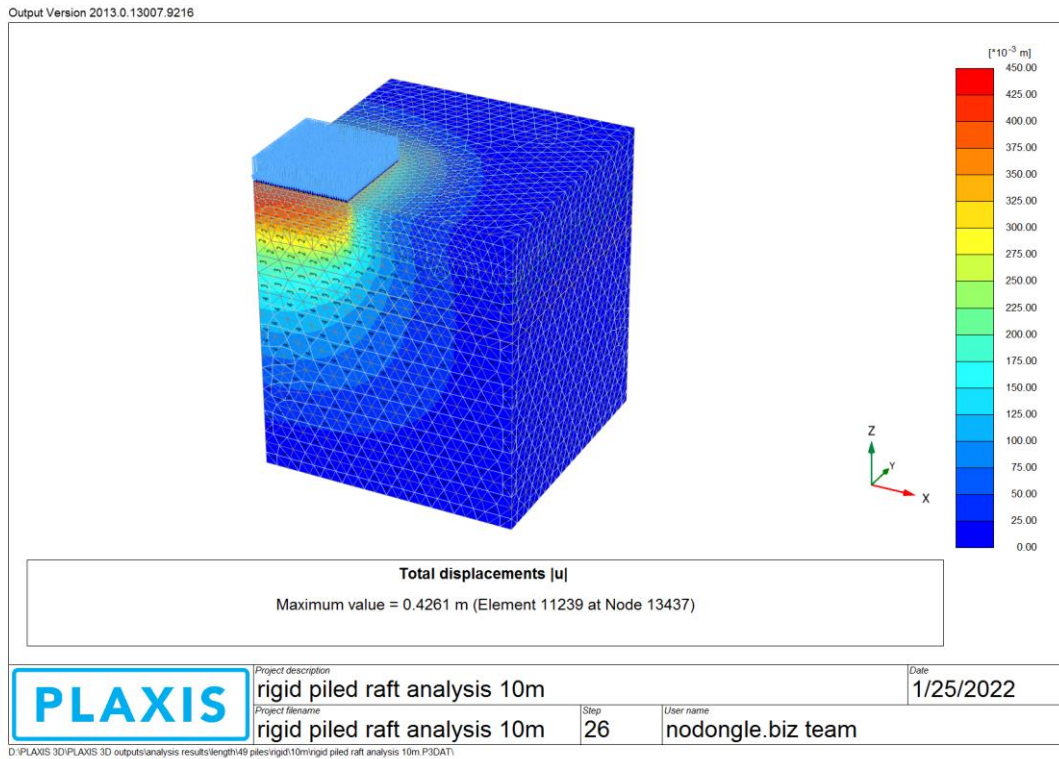


Figure C- 58 central settlement of rigid raft at 10m pile length

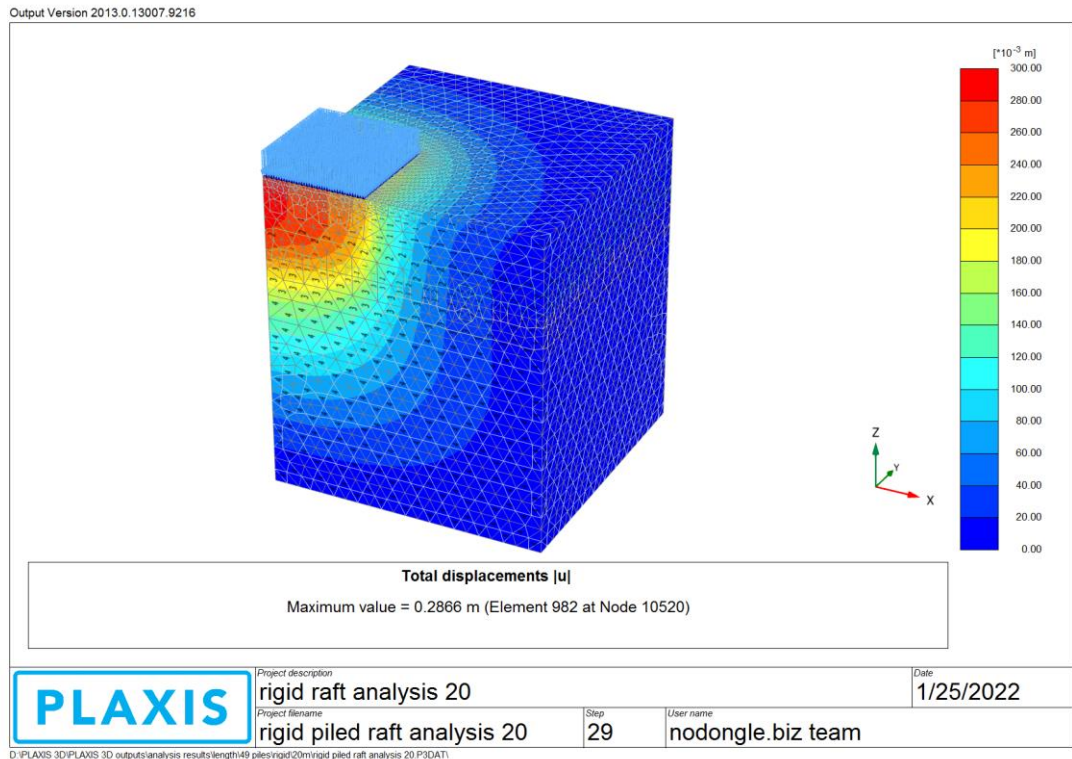


Figure C- 59 central settlement of rigid raft at 20m pile length

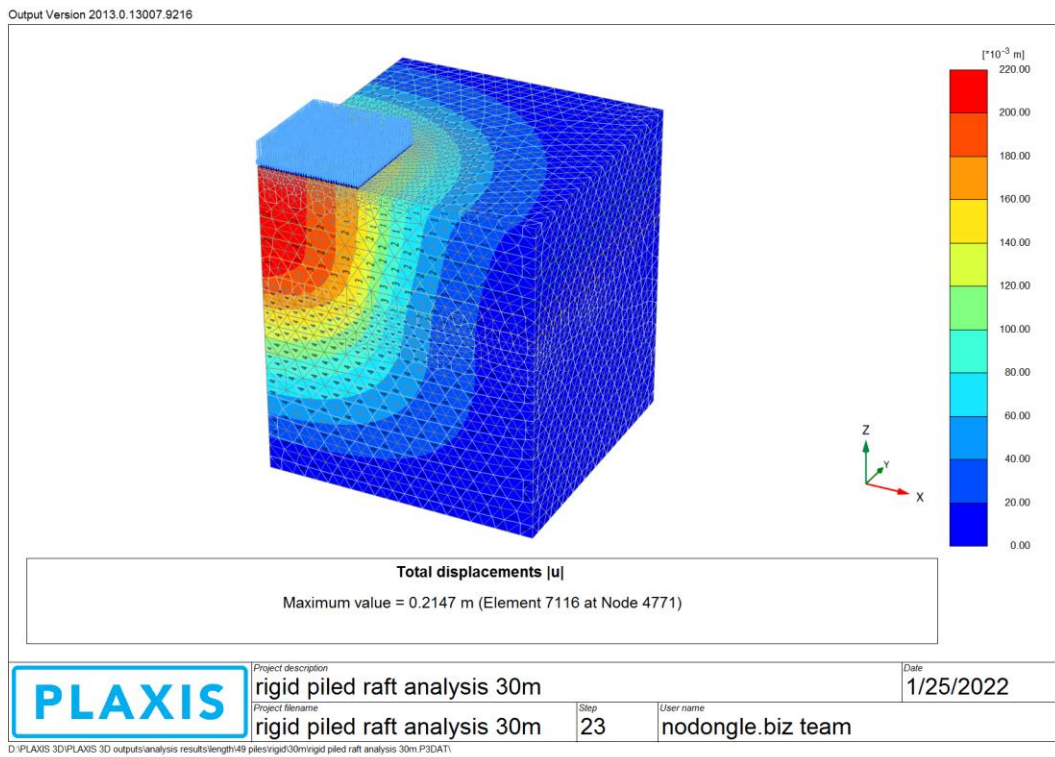


Figure C- 60 central settlement of rigid raft at 30m pile length

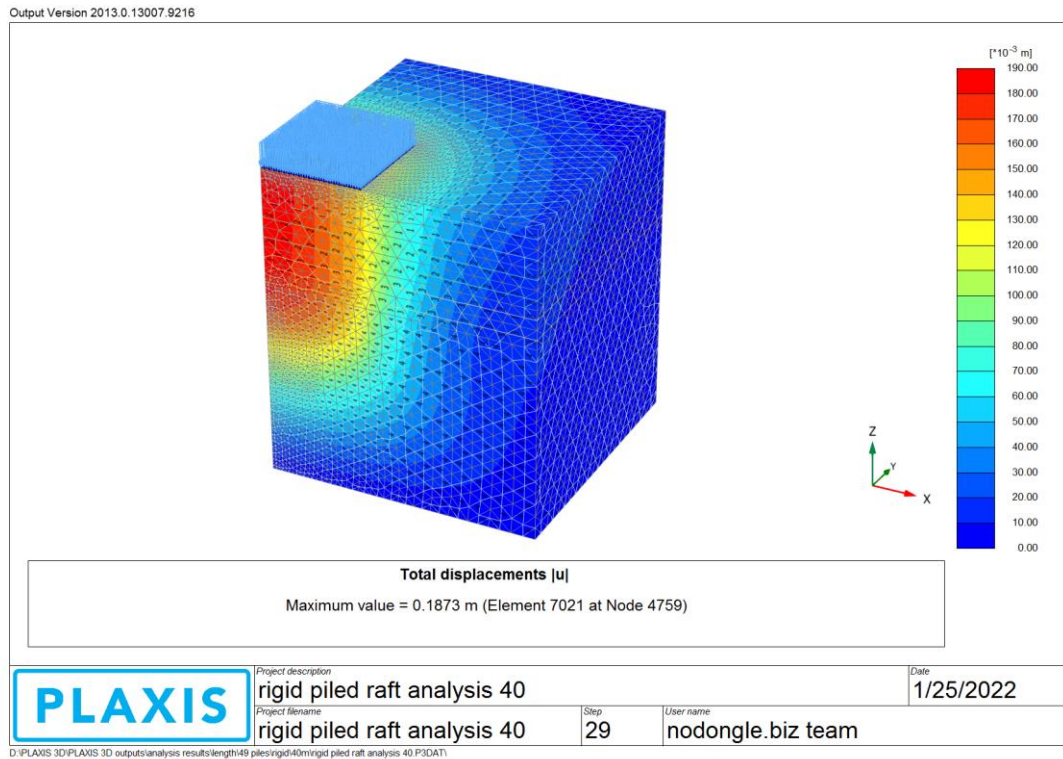


Figure C- 61 central settlement of rigid raft at 40m pile length

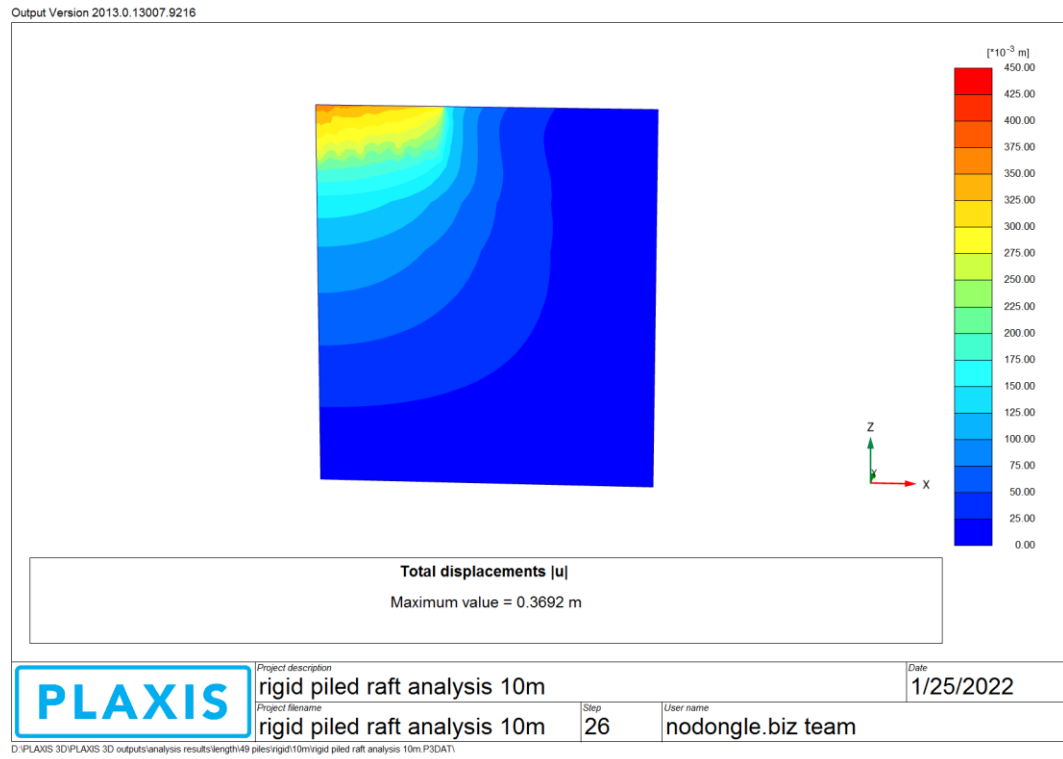


Figure C- 62 corner settlement for flexible raft at 10m pile length

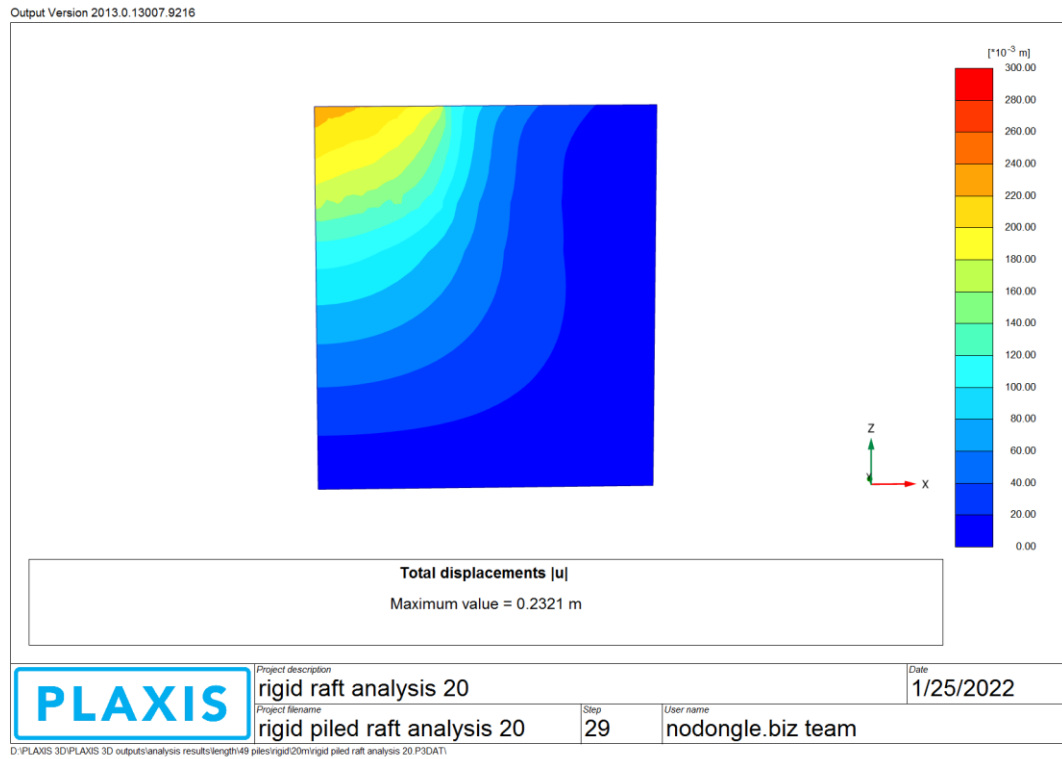


Figure C- 63 corner settlement for flexible raft at 20m pile length

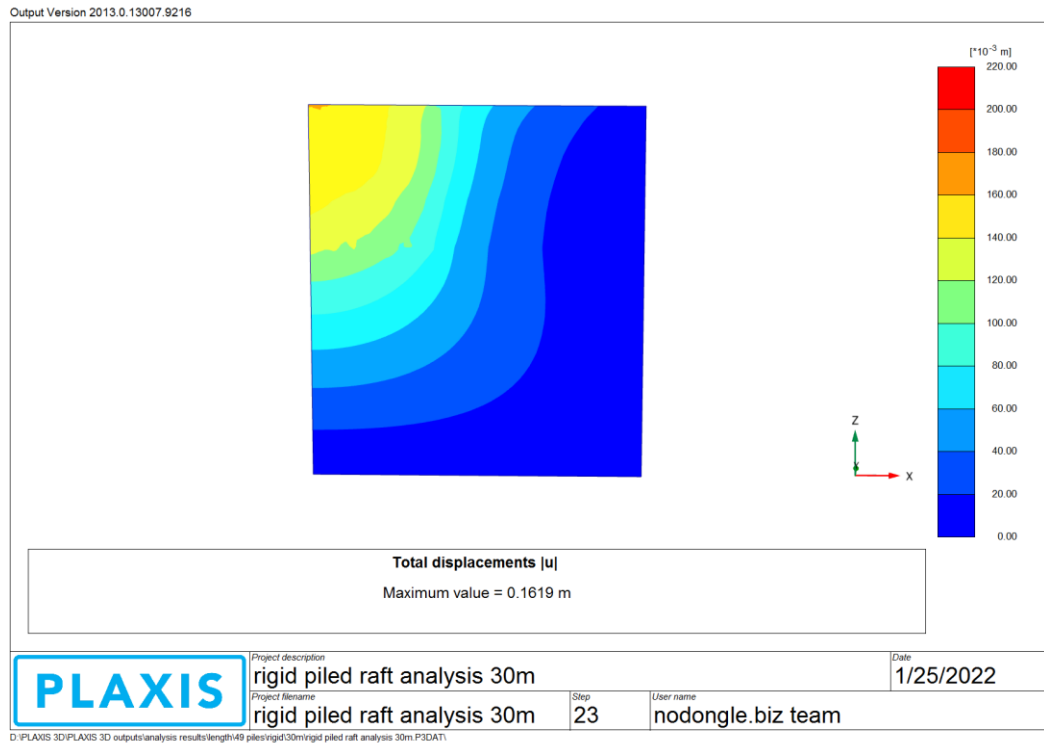


Figure C- 64 corner settlement for flexible raft at 30m pile length

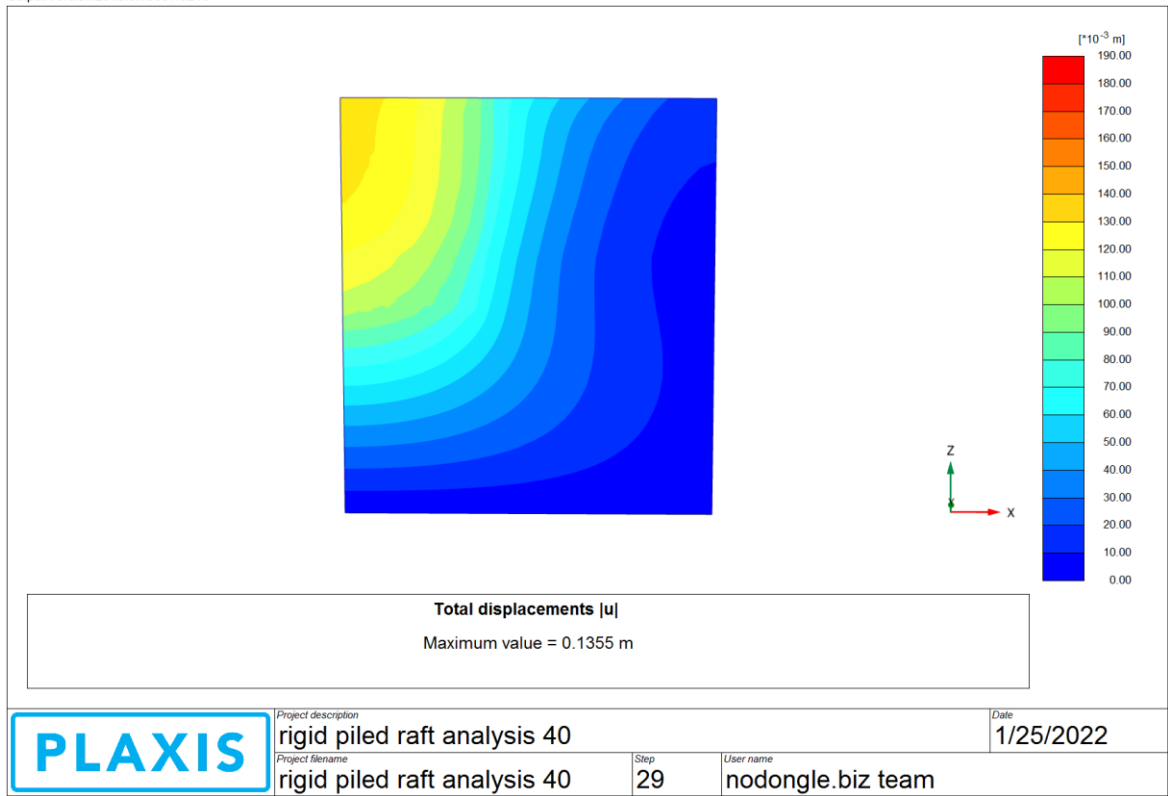


Figure C- 65 corner settlement for flexible raft at 40m pile length