The Impact of Using Specialist Geotechnical Software in Modeling of Pile Raft Foundation (PRF)

دراسة تأثير استخدام البرامج الجيوتقنية في نمذجة الأساسات المركبة من الخوازيق العميقة واللبشة المسلحة (PRF)

by

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Abstract

Due to rapid urbanization, the construction of tall towers has become common in all the metro cities. The column loads from the towers will be very high depending on the height of the tower and they require very efficient foundation system to carry them. It is very common these days that most of the towers are founded on Piled raft foundation systems.

Reinforced concrete slabs of uniform thickness acting as shallow foundations, covering complete plinth area of building are called as Raft foundations. Raft foundations help in distributing the loads from the wall or columns to the lower soil layers effectively. Piled Raft foundation (PRF) is formed by addition of piles to a Raft Foundation and it increases the load bearing capacity. Horizontal loads can be resisted to a maximum extent due to the addition of piles to a raft foundation. Reduction of settlements, both maximum and differential and enhancing the ultimate load capacity will improve the performance of the foundation to a greater extent.

Various software's are available to analyze the piled raft foundations under various loading conditions, for providing the optimum design. Piled raft foundations are analyzed using CSI SAFE by most of the structural engineers. Since the Raft Foundations will be supported directly on soil, structural software like CSI SAFE do not simulate the exact site conditions, since they model the soil only as springs. Hence a sophisticated geotechnical software PLAXIS 3D is used to analyze the results of Piled raft foundation for a case study and the results are compared with the results from the other software. Plaxis 3D have got various constitutive models to simulate the exact ground conditions and simulates the soil structure interaction between the raft, piles and soil more effectively.

A case study of one of the towers in Abu Dhabi is considered to check the comparison between two software initially. Later, a typical piled raft foundation is considered based on the typical details of first case study. This dissertation includes the detailed procedure regarding modelling the piled raft for the second case study using both the software, comparison of results and discusses the advantages and disadvantages of both the software in case of geotechnical applications.

الملخص

نظرا للتطور العمراني المتزايد، تزايدت الحاجة إلى المباني الشاهقة في المدن المكتظة بالسكان، وباتت المباني الشاهقة تعتمد اعتمادا رئيسا على الخوازيق العميقة واللبشات المسلحة كنظام انشائي أساسي في تحميل وتفريغ الأحمال الضخمة إلى باطن الأرض.

تتنوع البرامج الإنشائية المستخدمة في نمذجة الأساسات العميقة،ومن أشهرها برنامج SAFE ، الذي يعد البرنامج الأوسع شهرة والأكثر انتشارا في بلديات أبوظبي ودبي والعين، وهو برنامج تصميم انشائي ، ويتعدى استخدامه إلى نمذجة الأساسات.

في هذه الرسالة، يتم تسليط الضوء على دراسة الفروقات في نمذجة الأساسات العميقة المركبة باستخدام برنامج SAFE وهو برنامج انشائي مشهور، وبين استخدام أحد البرامج المتخصصة في نمذجة الأساسات والتربة المحيطة ودراسة تأثير طبقات الأرض المختلفة وتماسكها على الأساسات العميقة المركبة(الخوازيق العميقة واللبشة المسلحة) .

تسخدم الدراسة دراسة مبنى انشائي قائم في مدينة أبوظبي ونمذجته مرة باستخدام برنامجSAFE ومرة باستخدام برنامج Plaxis 3D.ثم الدراسة الثانيه للبشه مسلحة مرتبطة بالخوازيق العميقة باستخدام برنامجSAFE ومرة باستخدام برنامج Plaxis 3D ثم يتم تسليط الضوء على الاختلافات الجوهرية في التصميم والنتائج مع تحليل علمي لاسباب اختلاف النتائج وتباينها.

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List of Abbreviations

W_P = Pile weight

Ab = Cross sectional area

C = Cohesion of the soil

γ = Soil unit weight

D = Pile Diameter

μ = Poisson's ratio

q'_t = Unit toe bearing resistance

$(q'_t)_m$ = Mobilized net unit bearing resistance at toe

f_s = Unit skin friction resistance

q = Bearing pressure at point

E_s = Young's modulus

$N\gamma$ = Soil bearing capacity factors

$\sigma' v$ = Effective vertical stress along pile shaft

$\sigma' vb$ = Effective vertical stress at the pile base level

$F\omega$ = Correction factor for tapered pile (=1.0 for uniform diameter pile)

σ'_{v0} = Effective soil overburden pressure at the pile base level

N_q = Pile bearing capacity factor

A_b = Area of the pile base "cross sectional area"

K_s = Coefficient of the soil horizontal stress

δ = Friction angle between the pile & soil

A_s = Area of the pile shaft

S=Pile tip settlement

N= Axial pressure at the pile trip

L=Pile Length

E=Modulus of elsticity of pile

A=Pile Area

C0=Vertical reaction of pile toe when single axial limit compression.

α = Reduction factor related to quc

β = Correction factor related to the discontinuity spacing in the rock mass

δ = Elastic deformation of the pile

P = Applied load

Q_u = Ultimate pile capacity

δ_u = Pile displacement at failure

Q_u = Ultimate pile capacity

Δ = Pile displacement

Aims and Objectives

The aims and objectives of the present research are mentioned below:

1. Carry out a detailed review of literature for the piled raft foundations of various projects executed all over the world.
2. Model the piled raft foundation of one of the completed towers in Abu Dhabi using the software Plaxis 3D and CSI SAFE.
3. Model and analyze one typical case study utilizing the similar soil parameters and loading details as the completed project in Abu Dhabi, using the two sophisticated software CSI SAFE and PLAXIS 3D.
4. Calculate the straining actions (Bending moment and Shear force) in the raft foundations from the two software on the case of study.
5. Compare the results from both the software and proposal of better software to use from geotechnical perspective.
6. Further research to check any other completed project, analyzing the same using the two software and compare the results from the two software with the actual results to assert the suitability of software for general purposes.

Chapter 1 Introduction

A pile is a slender column which is a type of deep foundation that is normally driven or bored deep into the ground on the project sites, as shown in Fig. 1.1.

Figure 1-1: Piles

Piles are often used in deep foundations ("a category of foundations that tend to transfer column loads of a building to a stronger stratum below the earth's surface than shallow foundations do to a substance layer of depth";Mandolini, 2014). It is noteworthy that geotechnical engineers prefer deep foundations over shallow ones; especially for momentous design loads on poor soils, which portend shallow depths and site impediments like the presence of property lines (Mandolini, 2014). Although engineers adopt different naming conventions, deep foundations are normally fabricated from prestressed concrete, timber, reinforced concrete, or steel. . A pile foundation denotes a system of foundation that tends to transfer loads to a competent and deeper soil layer (Mandolini, 2014). They are utilized in case of insufficient bearing capacity of shallow foundations; where there is a need for preventing uplift forces and minimizing excessive settlement. In building constructions, piles represent the post-like foundation member that civil engineers employ in buttressing structures. Specifically, geotechnical engineers may drive piles of woods, concrete, or steel into the ground in a bid to support a structure that they are constructing

(Mandolini2014). In addition, they may exploit groups of large-diameter piles to support bridge piers. On soils that show unstable characteristics, civil engineers may use piles as building supports. Even on soils that possess stable qualities, the subject engineers may make use of piles when remarkably enormous structural loads are concerned. The machines responsible for driving piles into the ground are called pile drivers. In essence, pile drivers, shown in Fig. 1.2, are machines that comprise a high frame which contains appliances for dropping and raising a pile hammer or even for reinforcing and directing an air hammer or stream (Mandolini et al., 2014).

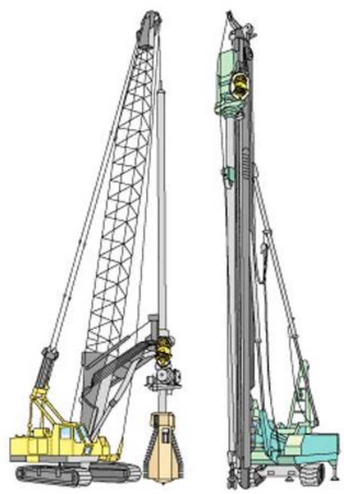


Figure 1-2: Pile Drivers

1.1 Pile History

Pile foundations (or piling) comprise piles that engineers drive into the soil until they reach a layer with stable soil. In this way, piles tend to transfer building loads to the bearing ground that possesses superior bearing capacity. Historically, people have been using piles or pile foundations for many years in a bid to transfer and carry loads to soils that they consider to possess a weak structure due to its conditions (Mandolini et al., 2005). A monograph is used to explore various literature on pile settlements (PS). To fulfill this goal, this paper shall evaluate the existing body of knowledge regarding the history of piles, types of piles, selection of the pile type, piled raft foundation (PRF), settlement calculation for sand and rocks, and comparing the maximum stress and deformation of piles using PLAXIS 3D and SAFE software.

Foundations consisting of piles are often valuable in areas with unstable upper soil is prone to erosion or to reinforce momentous building constructions. In the initial development stages, towns and villages were situated proximate to rivers and lakes because of water availability and for protection purposes. Obviously, the soils in the vicinity of rivers and lakes are unstable due to surrounding water conditions, hence, the need to reinforce buildings. To do this, aboriginal communities used to reinforce the weak-bearing ground with timber piles that were either manually driven into the ground or fastened in hollows that were then jam-packed with sand and stones. Builders modified these primitive methods of installing files during the industrial revolution by the introduction of diesel or steam driven machines. As a result of the advancement in soil mechanics technologies, individuals have progressively devised superior piles in addition to pile installation systems (A.E. Yates Group, 2018). Despite the more recent accounts of the history of writing, A.E Yates Ltd asserts that piling as a technique is traceable to the fourth century BC and Herodotus. This traveling Greek writer records the ways in which the Paeonians subsisted in dwellings that they formed by erection of lofty piles, driven into lake bed (A.E. Yates Groups 2018). In addition, the piling technique can be traced back to the Swiss lake inhabitants who, approximately six-thousand years ago, erected structures on pile foundations to hoist dwellings (houses) in a bid to protect their occupants against any potential attacks (A.E Yates Group 2018). Moreover, the Roman and Greek engineers are thought to have employed piles in their shore works in multiple locations along the coast of the Mediterranean Sea. In Great Britain, a bridge built by the Romans spanned the Tyne at Corbridge, roughly twenty meters West of Newcastle on Tyne, utilizing piles to reinforce the structure (A.E. Yates Group 2018). In addition, the Romans had also constructed a bridge across the Thames around AD60 using timbre piles. Ancient records are replete with evidence that testifies to the unmatched skills of the Romans to inventing difficult foundation solutions. In particular, the cities of Venice and Ravenna evince how the Romans had mastered the utilization of piles in supporting structures.

Antique records show that individuals used timber branches to form piles. In fact, they trimmed timber branches down with a minute diameter at the bottom and drove them into the ground until further penetration was impossible. They called the impossibility of further penetration "refusal". Notably, refusal denoted "a combined function of the limitations of driving tools and the soil strata" (A.E Yates Group 2018). This concept is demonstrated in more detail in Maharaj (2004). The early builder drove timber-branch piles using "hand mauls, water wheel drivers, hand-operated machine mauls, gang-operated rams and treadmill drivers" (A.E. Yates Group 2018). Although the equipment became obsolete, contemporary civil engineers still use the concept "refusal" in the piling industry. Since this early time, engineers have continually improved the piling techniques to enable soil stabilization of poor soil profiles and thus allow for construction. Today, civil engineers utilize piles, for example, steel screw piles, in residential construction of joist and bearer construction and slab on ground construction. In such constructions, the steel screw pile acts as posts forbearer in subfloor structures. Although engineers often use concrete or steel to fabricate piles and most of the equipment they utilize are modern instead of those utilized by the Romans, they continue to exploit piles today as deep foundations for reinforcing numerous kinds of structures and ground conditions. In fact, appreciating the historical evolution of piles allows an individual to fully understand their current use by civil engineers, and perhaps, how they advance in the future.

1.2 Types of Piles

There are two basic ways of categorizing piles: either by considering their basic design~~,~~ (such as friction, end-bearing or a combination of friction and end bearing) or using their construction technique, (such as replacement (bored) or displacement (driven)) (Tomlinson & Woodward 2014). It is noteworthy that the **piles in end bearing** get most of the resistance related to them below their pile's toe, standing on a firm layer (Tomlinson & Woodward 2014). They transfer the load straight to the firm strata and then take up horizontal restriction from the subsoil. Piles that get most of their skin friction capacity from shear stresses developed along their perimeter are called floating or friction piles. For that reason, they are appropriate in foundations with deep hard layers. In reality, Pressure bulb will be diminished by transmission of load to the adjacent soil using friction resistance between the piles and the soil.

1.2.1 Displacement or driven piles

Piles tend to be driven, jacked, screwed, or even vibrated deep in the ground, therefore relocating the soil surrounding the pile shaft downwards and outwards instead of eradicating them. They are suitable for onshore applications because there are firm in soft-squeezing soils, and they have the ability to densify wobbly soils. Driven piles are either *driven in-situ* using enduring steel or concrete casing or using impermanent casing (Tomlinson & Woodward 2014). The performed category of driven piles is often prefabricated offside from concrete, timbre, or steel (Tomlinson & Woodward 2014).

1.2.2 Bored/Replacement Piles

These piles are casted directly by removing the soil from the shaft and placing the steel and concrete within short span of drilling the shaft. Replacement piles are commonly used in cohesive subsoil to form friction piles or pile foundations proximate to extant buildings. Specifically, they are often used in urban areas where there are minimal vibrations, headroom is constricted, there are no heave risks, and the length variation is necessary (Tomlinson & Woodward 2014). Markedly, where pouring and boring occur concurrently, the piles are referred to as *continuous flight auger* (CFA) (Tomlinson & Woodward 2014).

1.2.3 Screw Piles

These piles retain a spiral adjacent to their toes; hence, engineers can drive them to ground through screwing (Tomlinson & Woodward 2014). In essence, the concept and process are conterminous to driving a screw into a piece of wood.

1.2.4 Micro piles/Mini Piles

The Mine piles are utilized in cases of restricted access, for instance, underpinning structures that have been affected by the settlement. They are appropriate for shallow bedrock, cavities and boulders, and immediate firm strata (Tomlinson & Woodward 2014).

1.2.5 Pile Walls

This type of piles can be employed in creating momentary or stable retentive walls (Tomlinson & Woodward 2014). In reality, engineers craft them by arranging piles adjacently~~,~~ and "they may exist as contiguous pile walls which are spaced closely or as secant pile walls formed by interlocking" (Tomlinson & Woodward 2014). They can either be soft-hard, firm-hard or hard-hard secant walls based on the constitution of the auxiliary intermediary piles (Tomlinson & Woodward 2014).

1.2.6 Geothermal Piles

The geothermal piles tend to "integrate closed-loop ground source heat pump systems with pile foundations" (Tomlinson & Woodward 2014). This process offers reinforcement to structures and serves as heat sinks and sources. In these pile types, pipe loops are vertically laid within the pile to offer the necessary support (Tomlinson & Woodward 2014).

1.3 Selection of Pile Type

Civil and geotechnical engineers make several considerations before selecting the type of pile to utilize in a particular foundation. As seen above, there are many types of piles that are applicable to different conditions. For instance, recent years have witnessed numerous constructions' projects fabricated on soft soil. Because the soft soil portends unique characteristics, structures erected on it are subject to differential settlement (Wulandari and Tjandra 2015). This means that civil engineers must make several considerations prior to selecting a pile type. For example, if an engineer wants to build on the soft soil whose structures are subject to differential settlement, then he or she should utilize the PRF to diminish the consequent differential settlement (Wulandari and Tjandra 2015). The reason is that although the raft foundation (RF) has sufficient bearing capacity, it has the potential of causing excessive settlement. For that reason, engineers utilize pile together with the raft foundation (or PRF) in a bid to stem the settlements to a standard quantity. Other factors that civil engineers consider when selecting the pile type in a particular foundation are the character of the load to be reinforced or supported, ground/soil conditions (hard or soft), level of ground water, material durability employed, availability of the pile type, cost of the pile type, sensitivity of the pile type to vibration or shakeups, and the proximity to other building structures.

1.4 Pile Raft Foundation (PRF)

The PRF tends to transmit the load straight to the subsoil (Singh &Ningombam 2011). In specific, the PRF comprises three primary components: subsoil, raft, and piles. In the PRF, "to verify the serviceability and ultimate bearing capacity of the whole system, the contribution of raft is taken into consideration" (Singh &Ningombam 2011). The principle of the PRF integrates the subsoil, the raft, and the piles like the load- conveying components to form a compound configuration. A complex coordination in between the raft, subsoil and piles determines the behavior of the PRF and hence appreciating it is vital for a reliable design (Small &Poulos 2011). In the PRF, "the Piled raft settlement determines the load sharing ratio between piles and, and there is no linear correlation between them" (Singh &Ningombam 2011). Specifically, the piles realize their definitive capability faster compared to the raft; thus, "increasing the pile number do not enhance the optimum foundation capacity, and there exists an upper expedient limit" (Singh &Ningombam 2011). In addition, the thickness of the raft tends to affect the differential settlement, yet it has minimal effect on the optimum load sharing or settlement of the PRF. For control differential settlement, it is possible to attain optimum performance using a few piles located in the middle segment, afore utilizing many piles evenly distributed over the raft area (Singh & Singh 2011). According to Poulos , Small, and Chow (2011), "Most of the tall buildings are using effective and economical foundation systems such as piled raft foundations". The reason is that integrated PRF contain a raft which can provide a reasonable measure of load resistance and stiffness. Moreover, PRFs employ piled reinforcement for controlling settlements with piles that afford significant stiffness at loads under serviceability conditions and components of raft that offer additional capacity in case of ultimate loading conditions (Poulos, Small & Chow 2011). For that reason, an engineer can minimize the number of piles needed because the raft affords additional support. What is more, the raft is capable of providing the piles with redundancy in case some piles are weaker or defective or if some of them experience karstic conditions in the subsoil. The piled raft foundation system performs such the raft permits an appreciable measure of load redistribution from the affected piles to the unaffected ones, and stemming the probable impact of pile weakness.

Additionally, the lateral stress between the soil and underlying pile component is increased by the pressure directed by the raft to the subsoil, and consequently raise the ultimate pile load capacity (PLC) contrasted against free-standing piles (Poulos, Small & Chow 2011). A geotechnical evaluation of the PRF design should consider the pile elements capacity, the raft elements capacity, and the combined capacity of the raft and pile components as well as their interaction under serviceability loading (Poulos, Small & Chow 2011). Pile rafts reached the most effective application when the raft is capable of affording adequate load capacity (LC), yet the differential settlements (DS) and/or settlement of the raft only surpass the permissible estimates (Poulos, Small & Chow 2011). For instance, PRFs are suitable for soil profiles with stiff or relatively stiff clays and dense sands (Poulos, Small & Chow 2011).

Moreover, soft soils contain properties that cause structures erected on them to portend differential settlement. For that reason, geotechnical engineers utilize the RF in moderating differential settlement. Although this foundation possesses enough bearing capacity, it may engenders excessive settlement and thus necessitate the use of piles with it as a PRF. In reality, geotechnical add piles to minimize the settlements to an acceptable quantity (Wulandari & Tjandra 2015). The fabrication of the PRFs for tall buildings poses numerous design issues, which geotechnical engineer must strive to address~~.~~ The issues can be summarizes as the overall foundational capacity in terms of lateral, vertical, and combinations of moment loading, the cyclic character wave impact, earthquakes, and winds loads on the movement of foundation and capacity, settlements both overall and differential, the foundation system's structural design, etc., the effects of earthquakes, such as structural foundation system's response to excitation by the earthquake and the potential for surrounding soil's liquefaction, and structural foundation system's dynamic response to forces induced by the winds.(Poulos, Small & Chow 2011). In addition to these issues, Poulos, Small & Chow (2011) suggested that engineers should also consider the limit states under serviceability and ultimate conditions, as well as cyclic loading conditions when fabrication the limit state design (LSD) for the PRF.

Further, Maharaj (2018) posits that "the concept of sharing of total load from the superstructure partly by the raft through the contact with soil and the transfer of remaining load by skin friction using piles is called as Piled raft foundation".The PRF is more cost-effective than pile foundation (PF) since piles in the former structure must not enter the maximum profundity of the layer of clay, and it is possible to terminate it at higher elevations (Maharaj 2018). In fact, the PRF "undergoes less settlement than the raft foundation and more settlement than the pile foundation" (Maharaj 2018, p. 1). Also, engineers can fully appreciate the effect of the pile as well as raft stiffness on the PRF performance using the load-settlement curve (LSC). In fact, "the load carrying capacity of raft (LCC) is increased and settlement is decreased due to increase in stiffness of raft" (Maharaj 2018). Moreover, the increase inpile's stiffness effectively augments the LCC and substantially minimizes settlement of the PRF with either a flexible or stiff raft. Nonetheless, beyond a specific restrictive value of pile stiffness, additional escalation of stiffness is insubstantial because it does not aid in settlement diminution and LCC increase. In fact, the PFR has been successfully employed in different countries, a fact that demonstrates their reliability. Accordingly, geotechnical engineers should take into account the restraining combination of pile and raft stiffness when designing and fabrication a PRF.

1.5 Settlement Calculation

1.5.1 in Single Pile: Sand

According to Sitharam (2013), the procedure for estimating PS includes:

1. Calculate the *average axial force in a pile* (APAF) in every section of the length, L., the *average cross-section*, $A_{av,}$ as well as *elasticity's shaft modulus*, E_p from the pile toe to point using the formula below.

$$\Delta Hs,s=\frac{P_{av}\times \Delta L}{A_{av}\times E_p}\text{……..(1.1)}$$

Add these estimates to get the *axial total compression* (ATC).

$$\Delta H_a=\sum \Delta Hs,s\text{……..(1.2)}$$

2.Calculate the settlement point employing the formula below.

$$\Delta H_{pt}=\Delta qD\left(\frac{1-\mu^2}{Es}\right)mI_s\, I_f\, F_1\text{……..(1.3)}$$

Where,

- $mI_s=1$
- I_f = Fox embedment factor, with the following values:

$$I_f=\begin{cases}0.55, if\ \frac{L}{D}\leq 5\\ 0.50, if\ \frac{L}{D}>5\end{cases}$$

D = Pile Diameter

μ = Poisson's ratio

q = Bearing pressure at point = $\frac{Input\ load}{A_p}$

E_s= Young's modulus

SPT: E_s = 500(N+15)

CPT: 3-6 q_c

- F_1=is th reductionfactor as defiened below:

$$F_1=\begin{cases}0.25, if\ the\ axial\ skin\ resistance\ reduces\ the\ point\ load\ P_p\leq 0\\ 0.5, if\ the\ point\ load\ P_p>0\\ 0.75, if\ the\ point\ bearing\end{cases}$$

1.5.2 In Groups of Piles: Sand

Sitharam (2013) notes that piles are mostly utilized in groups that contain one pile cap. As a result of this group action (GA), consolidation as well as immediate values of the group of piles, tend to be greater than those of single pile in the sandy ground (Mandolini&Viggiani 1997). Sitharam (2013) asserts that "the total foundation load is assumed to be carried by toe of piles of an imaginary foundation of same size as plan of the pile group in case of end bearing piles." as Fig. 1.3 below illustrates.

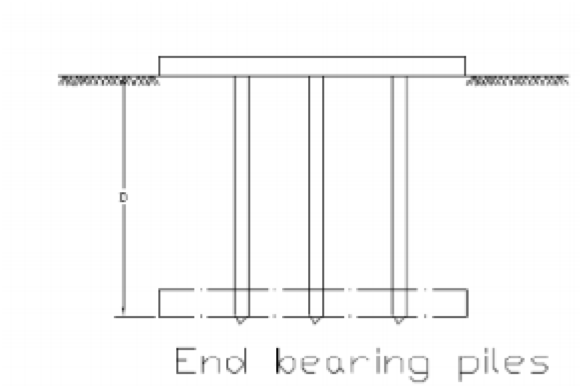


Figure 1-3: End-bearing group piles

The settlement of groups of piles on sand may be computed using the following formula:

1. As per Skempton:

$$\frac{S_g}{S_i} = (\frac{4B+2.7}{B+3.6})^2 \;\le 16 \ldots\ldots.(1.4)$$

2. As per Meyerhof, for a square pile group:

$$\frac{S_g}{S_i} = \frac{S[5-\left(\frac{S}{3}\right)]}{[1+\frac{1}{r}]^2} \ldots\ldots.(1.5)$$

In this case, S denotes the ratio of spacing between piles to the diameter of the pile, and r represents row number in a group of piles.

1.5.3 In single Pile: Rock

On the rock (bedrock), Chen (2011) points that the end-bearing PS tends to be "the sum of the compressive deformation of the bedrock at piles toes and elastic compressive deformation of the pile body", is computed as follows:

$$S=\frac{NL}{EA}+\frac{N}{C_0 A}\ldots\ldots..(1.6)$$

Where: S- Pile tip settlement;

N- the axial pressure at the pile trip;

L- Pile Length;

E- Modulus of elsticity of pile;

A-Pile Area;

C_0- The vertical reaction of pile toe when single axial limit compression.

1.5.4 In Groups of Pile: Rock

If groups of piles are to be driven through a rock, they should only be forced to their refusal in a bid to derive their maximum LCC (Sitharam 2013). However, "if the rock at the surface is strong, the penetration of pile will be negligible and will be difficlut to drive the pile. In these cases, the pile shaft length governs the LCC of the piles" (Sitharam 2013). Moreover, where the groups of piles are driven to weak rocks, it is not possible to compute working loading using the available stress on the pile shaft material. In such case~~s~~, it is obligatory to compute the frictional resistance which is developed over the rock penetration as well as the end-bearing resistance. The proposed formula for computing settlement of groups of piles resting on a rocky ground using their end-bearing is as follows.

Chapter 2 Literature Review

2.1 Pile Foundation Design:

As per Donald Coduto, most of deep foundations are designed to have total settlement of 12 mm. However, there are certain conditions that produce excessive settlement which engineers must recognize and evaluate them such as:

- The structure is especially very sensitive to settlement.
- Large diameter of pile.
- Majority of allowable capacity is due to toe bearing.
- Present of strata especially below the toe.
- Developing of the down drag loads during the life of the structure.

Adapted from Fellenius (1999), the load settlement response of deep foundation is approximately described by the following relationships, which may be used to develop approximate load settlement curves:

$$\frac{(q_t')_m}{q_t'} = (\frac{\delta}{\delta_u})^g \text{ .... (2.1)}$$

$$\frac{(f_s)_m}{f_s} = (\frac{\delta}{\delta_u})^h \leq 1 \text{ .... (2.2)}$$

Where:

- q_t' = unit toe bearing resistance
- $(q_t')_m$= mobilized net unit bearing resistance at toe
- f_s= unit skin friction resistance
- δ = settlement

$$\delta = \begin{cases} \dfrac{B}{10}, for\ toe\ bearing \\ 10\ mm, for\ side\ friction \end{cases}$$

- g= $\begin{cases} 0.5\ clay \\ 0.1\ sand \end{cases}$
- h= 0.02-0.5

O'Neill and Reese (1999) developed the charts in Fig. 2.1 and Fig. 2.2 to estimate the settlement of drilled shafts under service load. These charts showing the settlement in terms of the ratio of mobilized resistance to actual resistance. The charts were developed from full-scale load test, which is more accurate than Fellenius equations (1999).

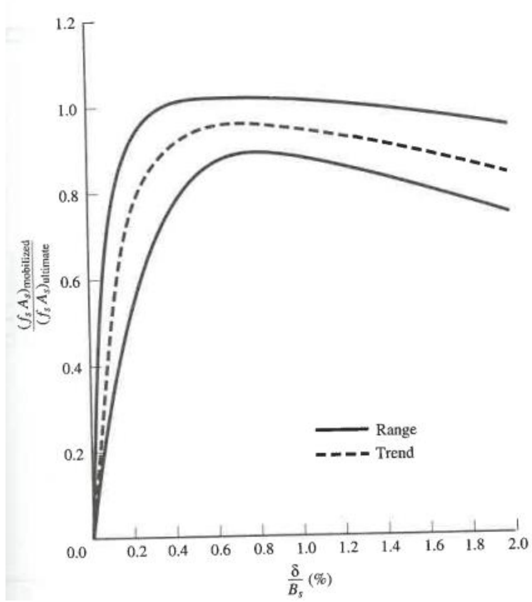


Figure 2-1: Normalized curves showing load transfer in side friction Vs settlement for drilled in clays.

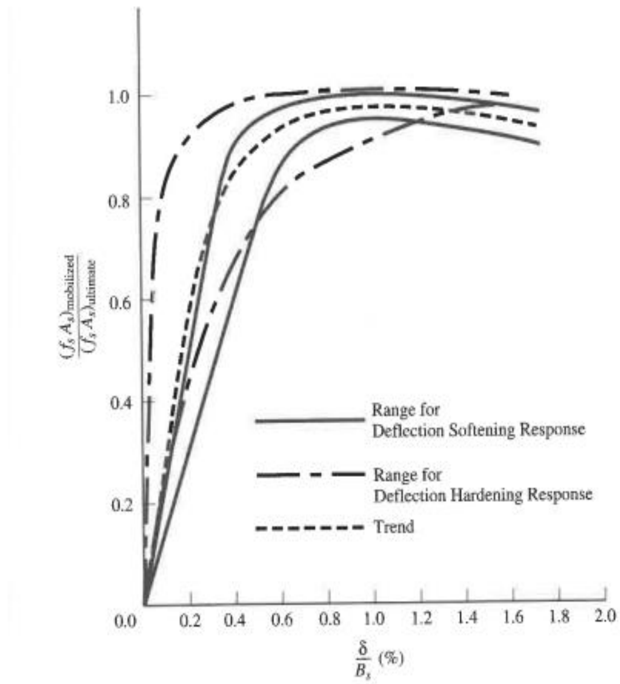


Figure 2-2: Normalized curves showing load transfer in side friction Vs settlement for drilled in sand.

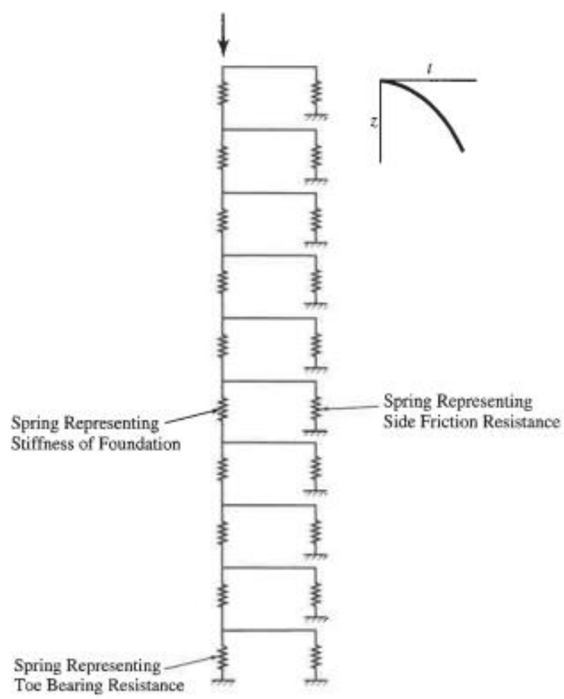


Figure 2-3: Numerical model for t-z method

The t-z method uses the numerical model shown in Fig. 2.3 to compute the settlement of deep foundation. The model divides the foundation into a series of element; each element has a certain modulus of elasticity. The spring in model represents the side-friction resistance acting on each element and toe bearing resistance. The load-displacement characteristics of these springs are defined using t-z curve (Kraft, Ray and Kagawa, 1981) where z is the settlement of pile segment and t is the load. A load is then applied to the top of the model and the foundation moves downward until it reaches static equilibrium. The corresponding settlement is then recorded.

To make the total settlements of a single pile or group of piles to be within tolerable limits, the working load on the pile is calculated ultimate resistance is divided by a safety factor. Using load - settlement curves, which have been obtained from various static tests in different types of soil, shows that for small to medium diameter of piles (up to 600 mm), the allowable settlement will not be exceeded by 10 mm under working load if safety factor is more than 2.5. This 10 mm settlement is satisfying the most building and civil structures.

However, for larger diameter piles (more than 600 mm), under working load, the individual pile settlements becomes complicated with the increase in diameter length and required deep evaluation of the base load and skin friction. For large-diameter bored piles in stiff clays, Fig. 2.4 shows the load –settlement relationships. It shows that at a settlement of 10mm, the maximum shaft resistance is mobilized, while 150mm settlement is required for the base resistance. At 150 mm settlement, the pile has reached the failure load of 4.2MN. For more economic design, the piles should be designed to approach the settlement limit at the working loads, which is acceptable by the structural designer by mobilizing the full shaft resistance.

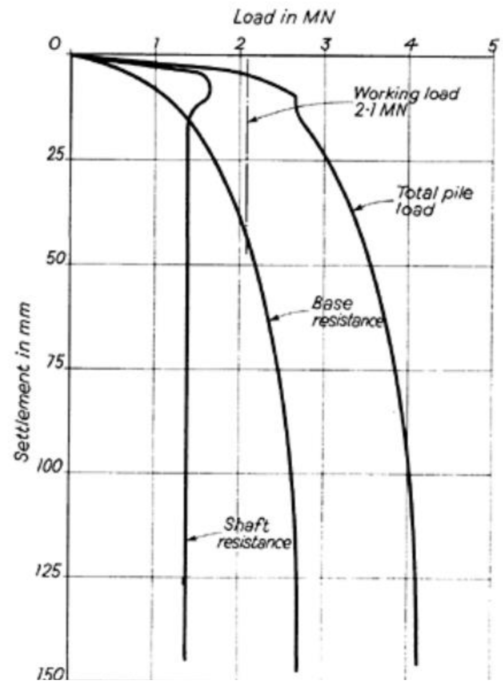


Figure 2-4: Load-settlement relationships for large-diameter bores piles in stiff clay

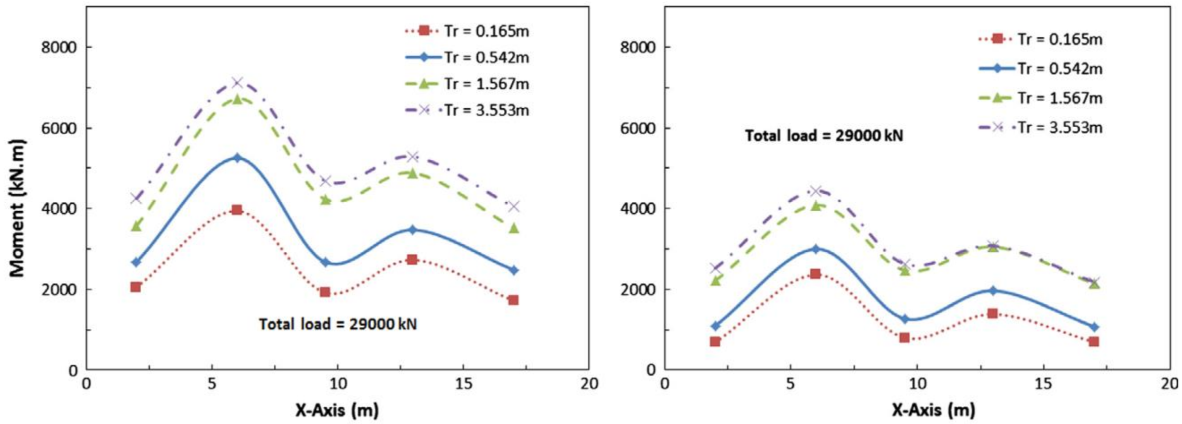
2.2 PRF design concept

Oliver Reul and Mark Randolph (2004) discussed the optimization of piled raft design under non-uniform loading in vertical. Their study contains 259 different pile raft configurations with four different load configurations analyzed by three-dimensional elastoplastic finite element analyses. Oliver and Mark found that due to the nonlinear pile resistance-settlement behavior, with increasing load level the normalized overall stiffness decreases. The absolute value of the normalized differential settlement increases with decreasing raft-soil stiffness ratio.

Moreover, installation piles only under the central area of the raft, with the actual length required, reduces the normalized differential settlement and it can be reduced even to zero. (Horikoshi and Randolph 1998) supported this design concept based on the piled raft analyses with uniform loading. Oliver Reul and Mark Randolph (2004) reported that using a smaller number of longer piles instead of a greater number of shorter piles will result in significant reduction of average settlement. In addition, Stiffness ratio of raft-soil and the configuration of load affect the differential settlements to a greater extent than the average settlement.

2.3 PRF optimal Design

Dong-Soo and Seong (2013) studied the design optimization of large piled raft foundations on sand layers. They highlighted the needs of optimal design as the uniformly placing piles increasing the settlement and bending moment. In this study, they considered an economical design methodology where piles were placed beneath column positions. They simulate the data using PLAXIS 3D software package. Their study showed that the concentrated pile arrangement method can sufficiently effectively help reducing the total settlement and differential settlement as well as reducing bending moment of the raft. Fig. 2.5 shows the comparison of bending moment between different cases of raft thicknesses.



(a) Uniform pile arrangement

(b) Optimal pile arrangement

Figure 2-5: Comparison of induced bending moment between different raft thickness cases

Moreover, different parameters such as pile number, pile length, load types on the piled raft foundation and raft thickness were checked to help choosing piled raft parameter in combination with the method of arrangement of piles so that an economic design is produced.

2.4 optimal numbers of piles and thickness of raft in PRF system

H.G.Poulos (2001), discussed regarding the design and applications of Piled raft foundations. He discussed regarding various issues that will be considered for the design of piled raft foundations. The main issues to be considered in the design are ultimate load capacities, maximum and differential settlements and shear and bending moments for both raft and piles. He also discussed regarding the most favorable and unfavorable circumstances for piled rafts. After examining various soil profiles, he concluded that soil profiles consisting of relatively dense sands and stiff clays and are more suitable for the piled raft foundations. Piled raft foundations are not preferable for profiles of soils with soft clay and loose sand layers near the surface. Both the favorable and unfavorable cases are dependent on the bearing capacity and stiffness of the raft.

He suggested that the design of a piled raft foundation contains three stages. Initial stage is to check the practicality of using the piled raft, second stage is assessment of piles and third stage is obtaining the location and optimum number of piles.

He concluded based on a hypothetical example that both the load carrying percentage of piles and the maximum settlement are not affected to a greater extent by the raft thickness. Raft behavior based on the raft thickness is shown in Figure 2.6 below. Increasing raft thickness will help in reducing the settlement but would result in more bending moment and hence more steel.

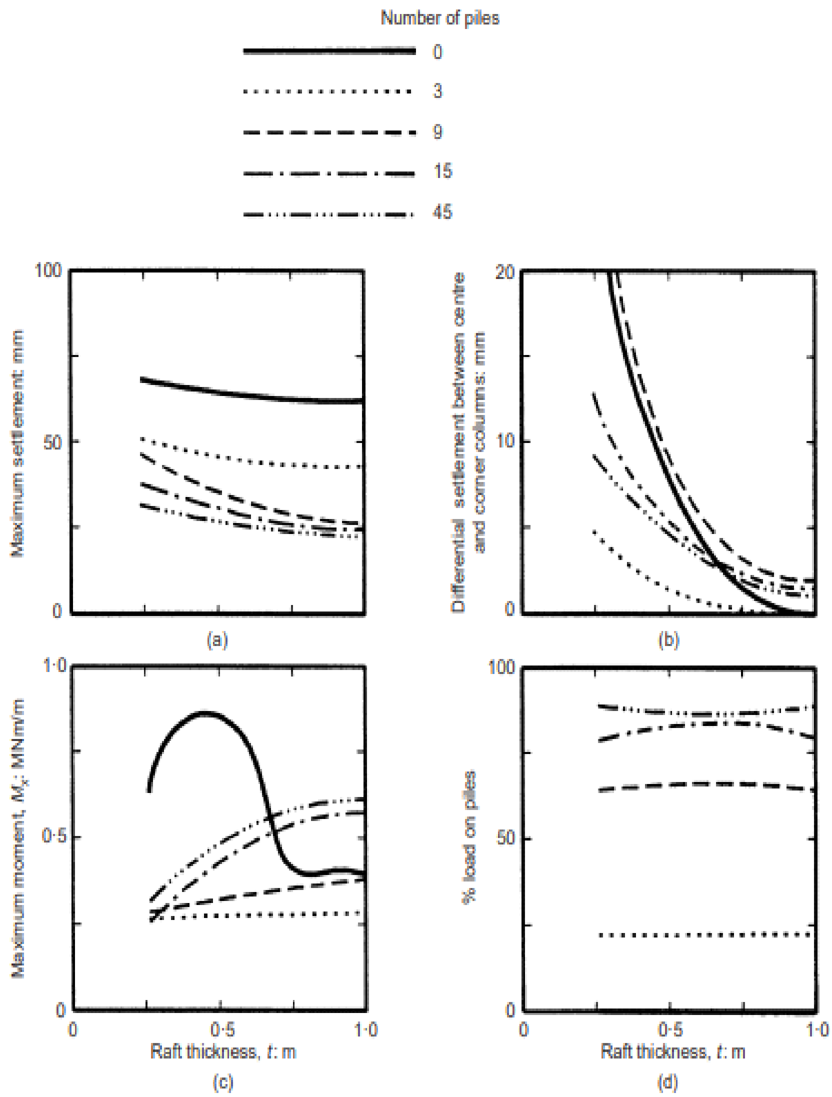


Figure 2-6 the effect of raft thickness on raft behavior

Based on different case histories he concluded the following:

- Increasing the quantity of piles beyond a limit will have very little benefit. Hence suggested to check the optimum number of piles required.
- Referring to Figure 2.6, the load carrying capacity percentage and the maximum settlement of piles is less related to the thickness of raft.

- Strategic distribution of piles below the raft decreases the differential settlement and increases the performance of piled raft, rather than using greater number of piles or by increasing the thickness of raft.
- Bending moment and the Differential settlements are dependent on the nature of load applied. However, the maximum settlement does not depend on it.

2.5 Effect of settlement characteristics in PRF system

Nirmala John and Hashifa Hassan (2014) discussed the study of combined pile raft foundation settlement characteristics founded on sand using Plaxis 3D software with different arrangements of piles. In their study, they considered a piled raft foundation for a 10-storey building. They considered 22 cases of different arrangement of piles below the raft. The arrangement included different diameters of piles provided beneath the raft at different zones under the raft. Based on their study, they concluded that inclusion of piles beneath the raft decreases both maximum settlement and differential settlement in a cohesion less soil. Piles with different diameter were better suitable for reducing the settlement than using piles of equal diameter. Provision of larger diameter piles in the center / interior region of raft reduces both maximum settlement and differential settlement.

2.6 Pile-soil interaction modeling using Plaxis 3D

Mohammad Jalali1and others (2012) published a paper on study of interaction between the pile and soil its effect on the shear stresses and pile settlements. The soil-structure interaction behavior in case of Finite element method is modelled using two kinds of constitutive equations. As per Desai, 1981; Ghaboussi et al., 1973, the first equation considers interface between the soil-structre as a thin continuum, and the thickness of the interface elements shall be specified. As per Boulon and Jarzebowski, 1991; Gens et al., 1989), a two-dimensional continuum replaces the interface zone, exhibiting tangential as well as normal displacement jumps and is subjected to kinematic discontinuities in case of the second approach.

They carried out the numerical modeling by using Finite Element method which helps in modeling

- Complicated nonlinear soil behavior
- Interface conditions
- Different geometries
- Soil properties

Some of the advantages of using Plaxis software as listed by them are, better modeling of soil-pile interaction behavior, ability to check the excess pore-pressure and various in-built constitutive models of soil available readily in the software to model the soil characteristics effectively.

They modelled the piles in soil using two different soil constitutive models such as Mohr-Coulomb and the Hardening soil model. Mohr-coulomb model is generally used for rough estimate of soil/rock behavior. It is a perfectly elasto-plastic model with a fixed yield surface. It gives the results much faster compared to other constitutive models and require less soil parameters to be input. Hardening soil (HS) model is comparatively an advanced model with basic difference from Mohr-coulomb model in calculation of stiffness. HS model represents the soil more accurately.

They modelled the piles using both the constitutive models in the Plaxis 2D and suggested the following as per their results.

- Using Mohr-Coulomb model with the interface coefficients (0.7 to 1.0) gives more accurate results compared to the hardening soil model, comparing with Vesic and Meyerhof’s reference graphs at the end of loading.

- Taking appropriate interface coefficient into account, the shear stresses measured at the pile-soil interface are more accurate in case of Mohr-coluomb model compared to Hardening soil model, Vesic and Meyerhof's reference graphs.

They even carried out a three-dimension dynamic analysis using ANSYS software and concluded that the degree of freedom in the Z direction and dynamic parameters of velocity are not influenced much by varying different interface coefficients.

Chapter 3 Research Methodology

The main purpose of the research is to highlight the importance of using special geotechnical software while modeling Piled Raft foundation system. The research methodology can be summarized below:

1. Two different cases of study are selected and the required data are collected to determine the Piled raft moments such as:
    a. Municipality approved piling drawings with information regarding the raft, such as raft thickness, extent, etc., and pile schedule showing the pile capacities, cut-off and toe levels and the pile diameters.
    b. Interpretative soil investigation reports specific to the site.
2. The first step is using Plaxis 3D software for the creation of a finite element model to get the results of the Piled raft foundation. Soil parameters that are used in the analysis are extracted directly from the soil report.
3. Similarly, the model is created using a structural software CSI SAFE to get the results for the piled raft. Spring elements are used to model the piles and the plate elements are used to model the raft.
4. Finally, a comparison between the results of the above two software programs is made and conclusions and recommendations are discussed.

3.1 Cases of Study

This research consists of two cases of study, one corresponding to a completed project in Abu Dhabi, UAE and other corresponding to a typical piled raft foundation system that is modelled based on the parameters from the first case of study. Details of each case of study is discussed in detail in the following sections 3.1.1 and 3.1.2.

3.1.1 Case Study 1- Mixed Use Tower, Corniche, Abu Dhabi

Mixed Used Tower project consists of 38 floors tower with a mezzanine floor. The project is to have four basements for parking. The tower consists of five floors for offices, one floor for amenities, two floors for service and 30 floors for tenants.

The site is located at Plot No. C22, Sector: W5, Corniche, Abu Dhabi, UAE.

Figure 3-1: Mixed Use Development Tower, Corniche, Abu Dhabi

Figure 3-2: Mixed Use Development Tower Location

Table 3-1 below shows the pile schedule for the mixed-use development tower.

Table 3-1: Pile Schedule showing Pile Lengths

PILE SCHEDULE							
PILE	PILE TYPE	PILE DIA. (mm)	LEVELS C.O.L (NADD)	LEVELS TOE LVL (NADD)	PILE LENGTH (m)	TOTAL NOS.	Fcu (N/mm2) (OPC)
	P1A	900	-17.125	-28.00	10.875	106	50
	P1B	900	-16.025	-28.00	11.975	21	50
	P2A	900	-16.825	-30.00	13.175	17	50
	P2B	900	-17.125	-30.00	12.875	5	50
	P3A	1500	-18.125	-39.750	21.625	48	50
	P3B	1500	-20.225	-39.750	19.525	12	50
	P4A	1500	-18.125	-46.250	28.125	27	70
	P4B	1500	-20.225	-46.250	26.025	7	70
				TOTAL		243	

Table 3-2: Pile Schedule showing Pile Loads

TABLE 2 **PILE SCHEDULE**

	SERIAL	PILE LEGEND		P1 ø900mm PILE	P2 ø900mm PILE	P3 ø1500mm PILE	P4 ø1500mm PILE
NUMBER	01	NUMBER OF PILES		127	22	60	34
	02	NUMBER OF PILES (PRELIMINARY TEST PILE)		1	1	1	1
CAPACITY	03	ALLOWABLE CAPACITY OF WORKING PILES	COMPRESSION	4000 KN	5500 KN	22000 KN	29000 KN
			TENSION	3000 KN	3300 KN	5000 KN	3000 KN
			horizontal	150 KN	150 KN	550 KN	550 KN

The pile layout approved by the ADM is shown in Fig. 3.3.

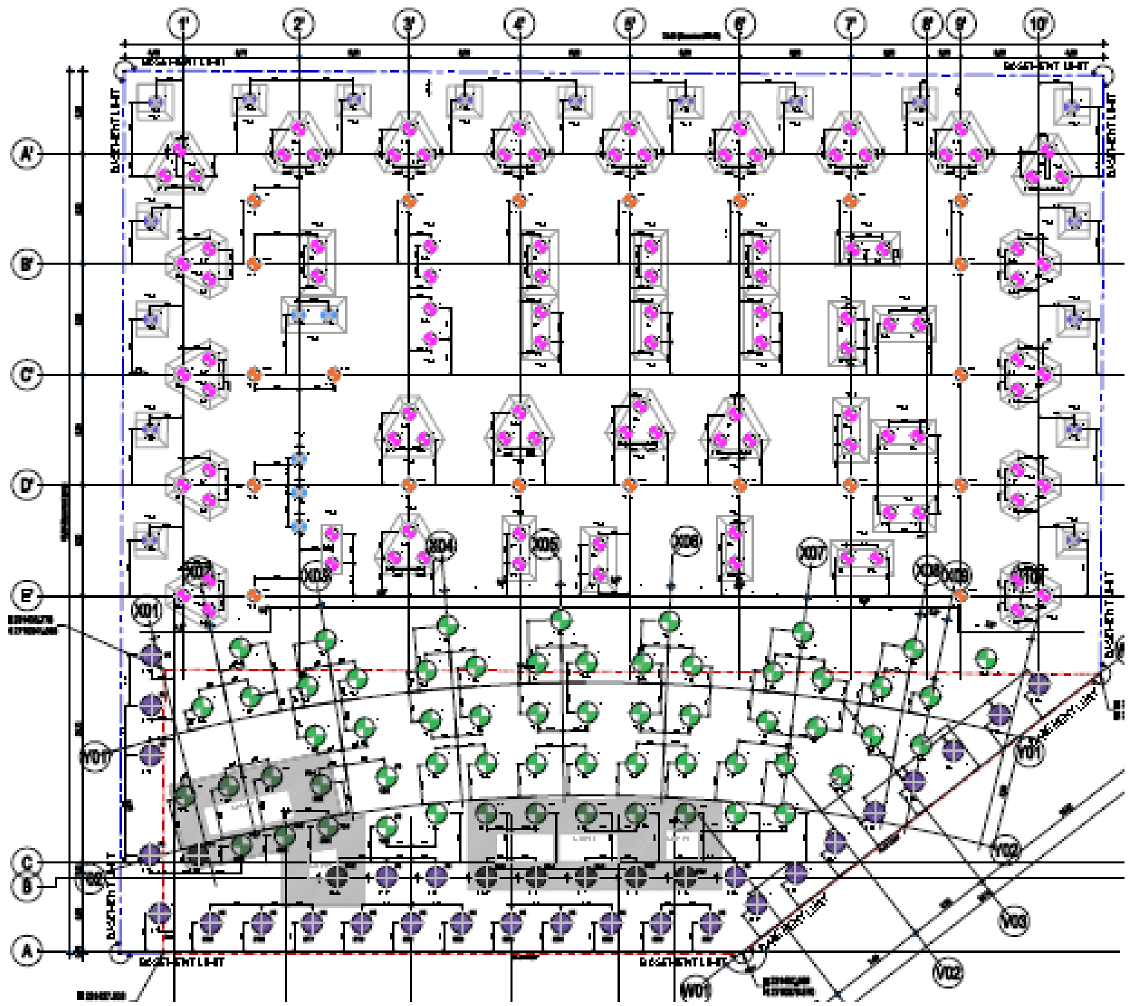


Figure 3-3: ADM Approved pile layout for the Mixed-Use Development Tower

3.1.1 Ground Model

Referring to interpretative soil investigation report from M/S Gulf Laboratory REF: GL/S15-040 REV 0, the soil layers' classifications is as explained below.

The idealized ground model at the site, adopted as part of the analyses carried out, comprises the following sequence:

- Superficial deposits, generally including silty to dense sand, extending to a depth of approximately 8.5m below ground level.

- Alternate Layers of Calcarenite and Sandstone, often interbedded with layers of Gypsum.
- Mudstone.

Table 3-3 below shows the recommended soil parameters as per the soil report.

Table 3-3: Recommended Soil Properties as per Soil Investigation Report

S.No	Soil Layer	Layer Depth (m)	Soil Parameters
1	Medium Dense Sand	6.5	E = 8250 kPa γ_{sat} = 18.4 kN/m^3 γ_{unsat} = 17.4 kN/m^3 ϕ' = 33^0 ϑ = 0.3
2	Dense Sand	1.0	E = 11750 kPa γ_{sat} = 20.2 kN/m^3 γ_{unsat} = 20.2 kN/m^3 ϕ' = 39^0 ϑ = 0.3
3	Medium to Dense Sand	0.5	E = 11000 kPa γ_{sat} = 18.8 kN/m^3 γ_{unsat} = 18.8 kN/m^3 ϕ' = 37^0 ϑ = 0.3
4	Calcarenite and Sandstone	14.2	E = 150000 kPa γ_{sat} = 22.0 kN/m^3 γ_{unsat} = 22.0 kN/m^3

			$\phi' = 34^0$ c' = 50 kPa $\vartheta = 0.25$
5	Mudstone with interbedded layers of Gypsum	40	E = 120000 kPa $\gamma_{sat} = 20.0$ kN/m^3 $\gamma_{unsat} = 20.0$ kN/m^3 $\phi' = 30^0$ c' = 90 kPa $\vartheta = 0.25$

All the above strata have been modelled as drained, with the Plaxis Mohr-Coulomb model.

Piled raft foundation is modelled by using Plaxis 3D software and is shown in the Fig 3.4.

Two rafts of different thicknesses 0.7m and 2.8 m are used to model the raft foundations. The piles are provided using embedded piles option to the required level as per the approved drawings.

Fig. 3.4 below shows the plan view of the 1st case of study modelled in Plaxis 3D.

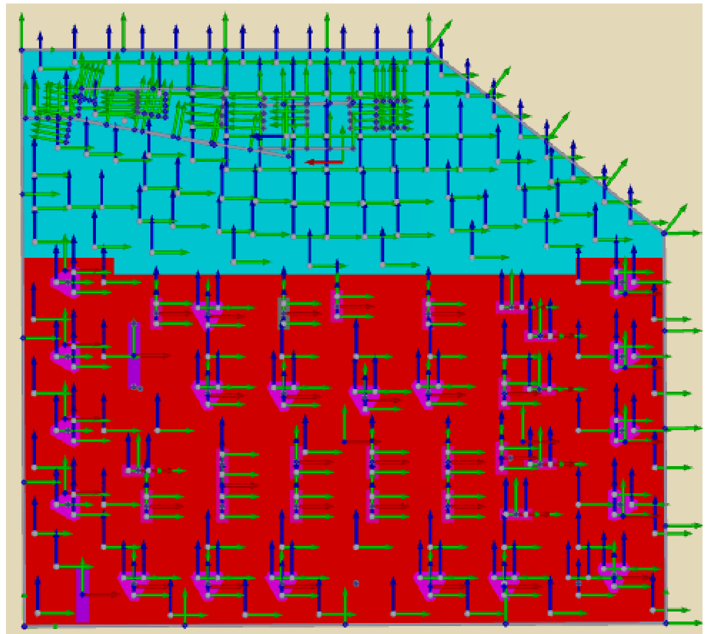


Figure 3-4: Top view of the Plaxis 3D model for the Piled Raft of Mixed Use Development Tower

Fig. 3.5 below shows the perspective view of the 1st case of study modelled in Plaxis 3D.

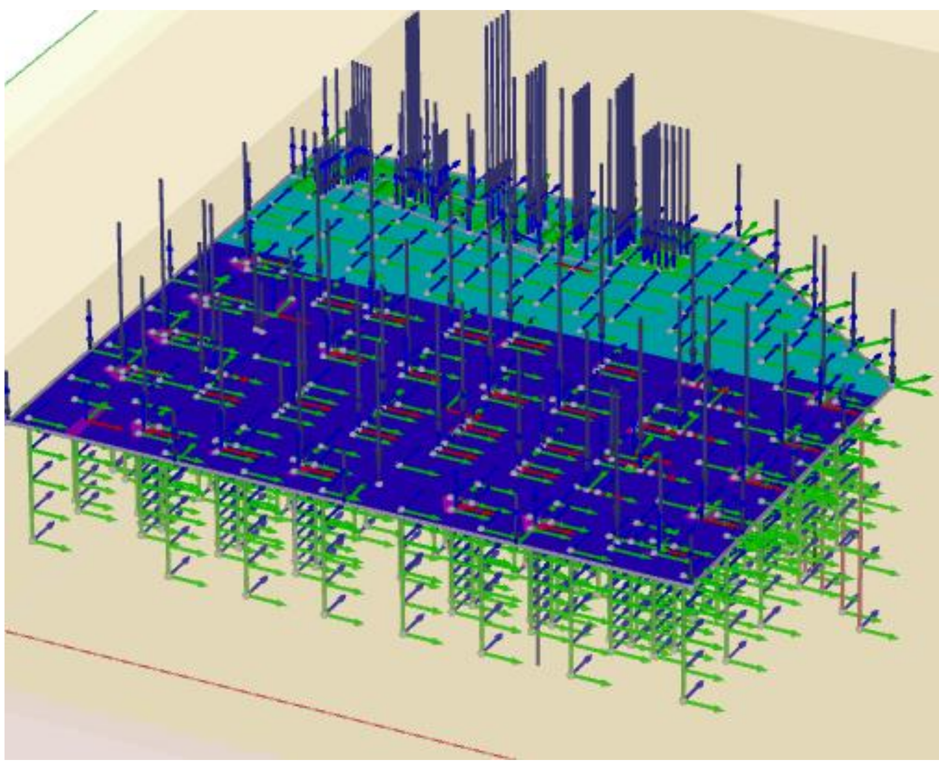


Figure 3-5: Perspective view of the Plaxis 3D model for the Piled Raft of Mixed Use Development Tower

Fig. 3.6 below shows the screenshot of the Plaxis 3D model.

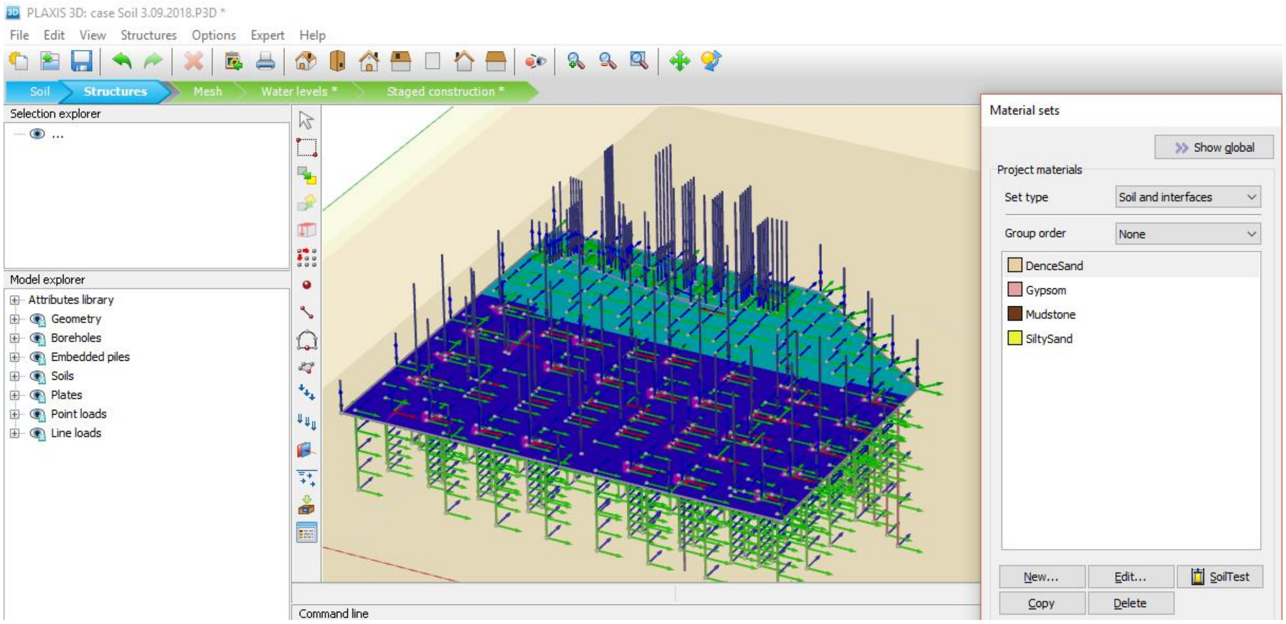


Figure 3-6: Screenshot of the Plaxis 3D model for the Piled Raft of Mixed Use Development Tower

Unfortunately, the analysis results shown erroneous results, after all the analysis are carried out.

So, another case study with assumed parameters is considered to check the comparison of results between the Plaxis 3D and SAFE software.

3.1.2 Case Study 2

A typical piled raft foundation of 1.5m thick founded on piles is used to simulate case study 2. Piles considered in this case are of 1000mm diameter and are assumed to carry axial loads of 4000 kN, 8000 kN and 16000 kN respectively as shown in the Fig 3.7. Additionally, a surcharge load of 10 kPa is used to simulate the floor loading on raft.

However, the soil parameters considered are based on the same soil report referenced above, since they represent the common soil parameters in Abu Dhabi.

Fig. 3.7 below shows the details of the piled raft model used in the analysis.

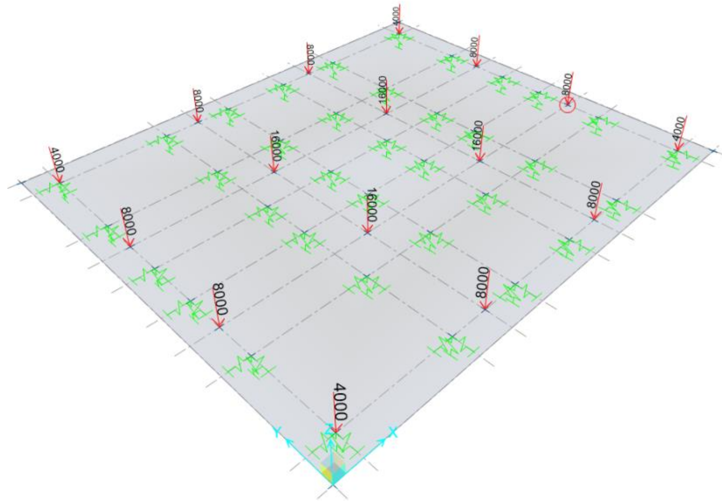


Figure 3-7: Plan view of Piled raft model for Case study 2

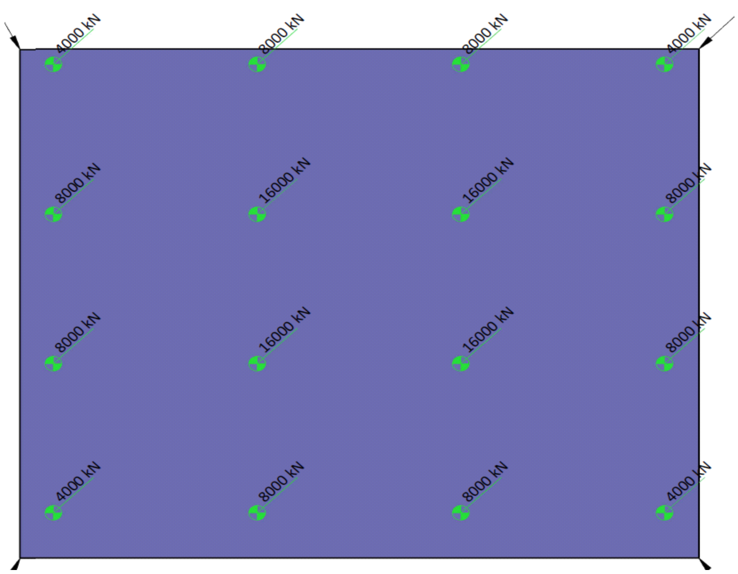


Figure 3-8:Plan view of Piled raft model for Case study 2

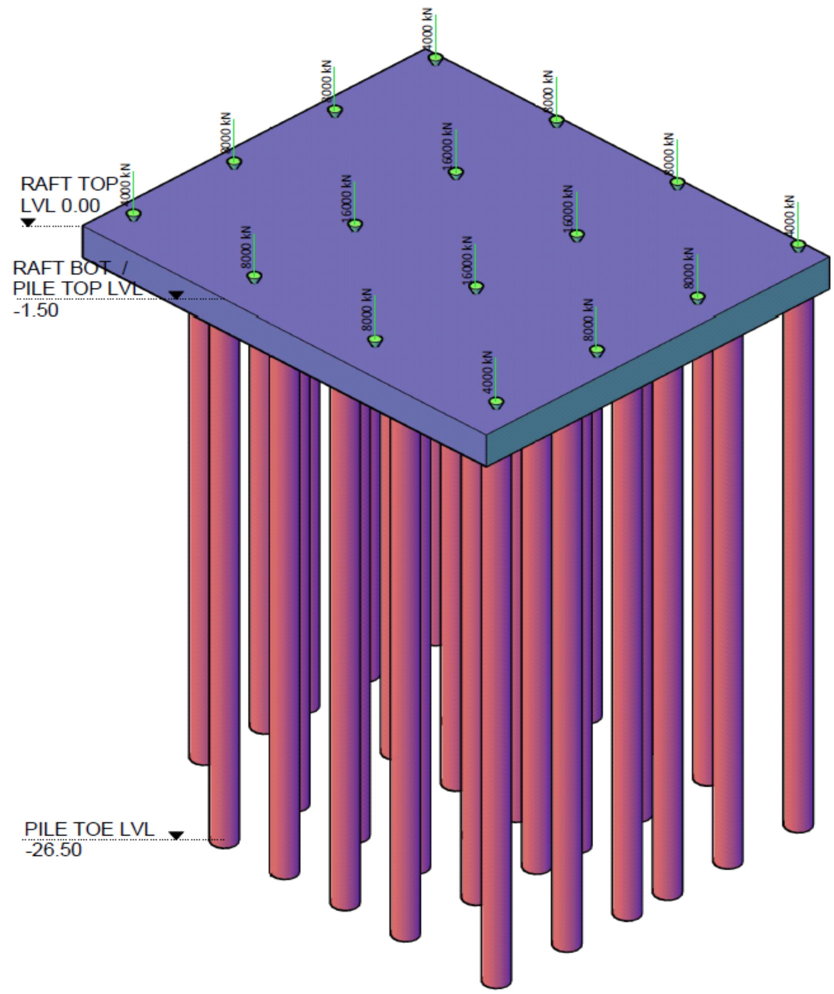


Figure 3-9: Perspective view of Piled raft model for Case study 2

Chapter 4 Research Modelling

This chapter covers the analysis of case studies using two different software Plaxis 3D and SAFE. Plaxis is a finite element program, developed for the analysis of stability, ground water and deformation in geotechnical engineering. Advanced constitutive models are necessary in Geotechnical applications for the simulation of time dependent, non-linear, and anisotropic behaviour of subsoil materials. Many sophisticated feature to deal with various complex geotechnical structures are equipped in case of Plaxis 3D software.

CSI SAFE is a very good software for designing foundation systems and concrete floors. Many aspects of the engineering design process like framing the layout to production of detail drawing, an easy and intuitive environment is integrated by CSI SAFE.

The main differences between Plaxis 3D and CSI SAFE that, Plaxis is a geotechnical specialist software, where the user can model the soil layers with different soil properties in proper way. For example, the piles elements can be modelled as structural element driven through different soil layers, the software can develop and calculate the structure – soil interaction.

On the other hand, CSI SAFE is a structural software using approximation methods to represent the soil layers and structure – soil interaction. For example, in case of pile – raft foundation, the piles represented by point springs, this approximation modelling to consider the effect of the piles on the raft foundation. Nevertheless, CSI SAFE has no option to model the different soil layers with different soil properties, and it has no option to study the soil – structure interaction as well.

Practically, most of engineers are using SAFE to study the Piled– Raft foundations, this is because of the ease of using the software. But unfortunately, the using of approximation method to represent the structure will lead to more errors in the results compared to actual results

Both the software is used to analyse the case studies discussed in Chapter 3 and the obtained values from Plaxis 3D analysis for each case of study are stated and compared with the results from SAFE software. Later on, in the following chapter the results are discussed in details.

4.1 Plaxis 3D Analysis

PLAXIS 3Dfinite element software is used to model the selected piled raft foundation for each case of study. The piled raft model is modeled by using plate and embedded piles option available in the software. The parameters of soil layers are modeled by using Mohr-Coulomb option. Surface loads from the floors and the corresponding vertical loads on the piles are applied using the options available in the software.

The major aspects in the modeling are the assertion of boundaries, classifying the soil layers and using proper constitutive model. All the governing factors are discussed in the next two sections.

4.1.1 Graphical Boundaries

Fig. 4.1 shows the boundaries of the graphical model, which should be followed in the modelling process.

The boundaries are as follows;

- B is the maximum raft dimension.
- L is the pile depth.
- Width and depth of the model are considered as 1.5 L.

• Model edge is considered as fixed boundary, with no horizontal and vertical displacements.

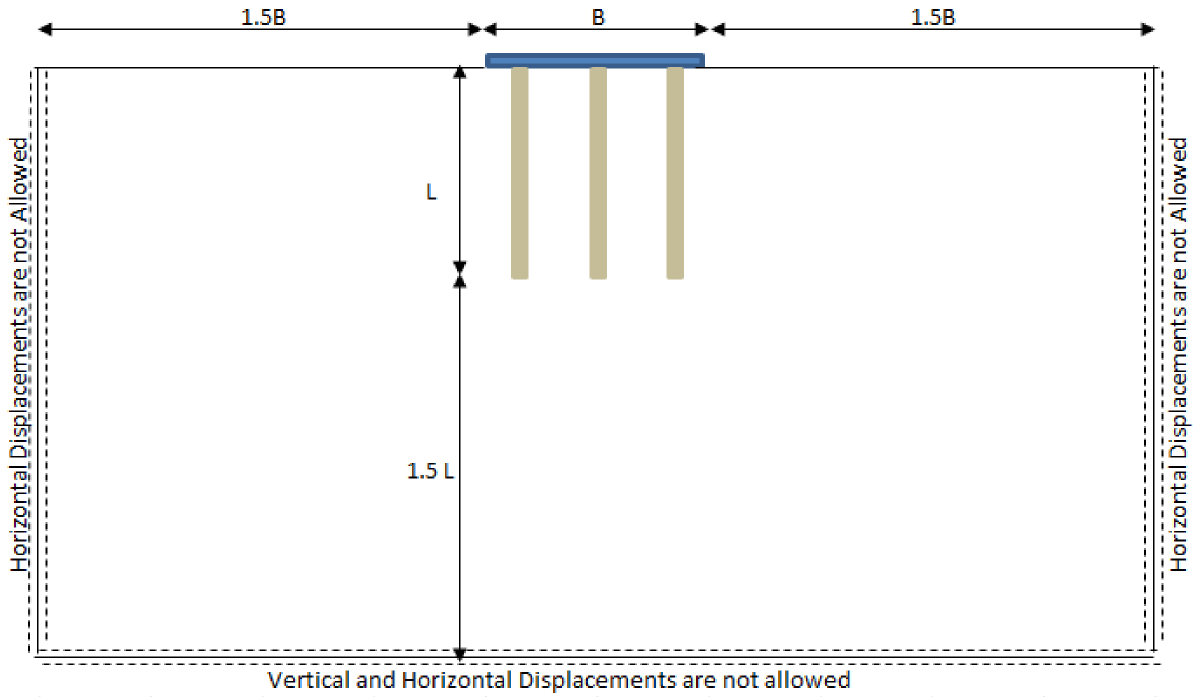


Figure 4-1: Typical Raft Foundation Details

4.1.2 Soil Layer's Parameters and Classification

The soil parameters used in the software are extracted directly from the recommendations of the soil report in case of first case of study and typical soil parameters of Abu Dhabi region are considered in case of second case of study. Common input parameters include unit weight, angle of internal friction, cohesion and young's modulus of soil etc.

4.1.3 Numerical Analysis and Results for Case Study 1

As explained earlier, the results for case study shown erroneous results and hence another case study is modelled to complete the research.

4.1.4 Numerical Analysis and Results for Case Study 2

A rectangular raft foundation of size 20m x 17.5m x 1.5m is selected to be supported by using Pile foundations of 1m diameter and 26.5m deep. The dimensions of the model used are 80m x 80m x 60m. All the pile foundations are designed to carry a column load of 8000 KN. The stresses and the displacements under the Piled raft foundation are analyzed using Plaxis 3D software.

Typical details of the Piled raft are shown in the Fig. 4.2 to 4.17

4.1.5 GROUND MODEL

The ground model for this project is selected based on the typical soil strata found in the Abu Dhabi region.

The idealized ground model at the site, adopted as part of the analyses carried out, comprises the following sequence:

- Superficial deposits, generally including silty to dense sand, extending to a depth of approximately 8.5mbelowgroundlevel.

- Gypsum layer, often inter bedded with layers of Mudstone.
- Mudstone.

The assumed soil strength and stiffness parameters are summarized in Table 4.1

All the above strata have been modelled as drained, using the Plaxis Mohr-Coulomb model.

It is assumed that the strength and stiffness properties of the rock formation improve with depth.

A hydrostatic groundwater pressure distribution has been assumed, with groundwater table at 1.80m

Table 4-1: Soil Properties

Soil Type	Level (m, bgl)		γ_{bulk} (KN/m^3)	c' (KN/m^2)	φ' Degrees	E (KN/m^2)
	From	To				
Silty Sand	0.0	-6.5	18.4	0	33.0	8,250
Dense Sand	-6.5	-7.5	20.6	0	39.0	11,750
Medium Sand	-7.5	-8.5	18.8	0	37.0	11,000
Gypsum	-8.5	-22.7	22.0	50	34.0	150,000
Mudstone	-22.7	-60.0	20.0	90	30.0	120,000

4.1.6 Material Properties

The material properties used in the model are given in Table 4.2:

Table 4-2: Properties of Raft used in the Plaxis 3D analysis

Raft Slab		
Raft Thickness (m)	**Area of Raft Slab (m^2)**	**E (kN/m^2)**
1.5	1.5	26.59E+06

Table 4-3: Properties of Piles used in the Plaxis 3D analysis

Bored Piles						
Diameter (m)	**A (m^2)**	**I (m^4)**	**E (kN/m^2)**	**Skin Friction at top (kN/m)**	**Skin Friction at Bottom (kN/m)**	**End Bearing (kN)**
1.0	0.785	0.049	26.59E+06	0.0	500	4500

4.1.7 Finite Element Modeling

Numerical Finite-Element (FE) modeling shows a significant aid in the determination of the static and dynamic response of complex geotechnical models, due to its inherent capability of detailed simultaneous prediction of stress distribution and displacements/deformations in the system without assuming any failure modes.

It is generally recommended to consider the boundaries located at a distance of at least one to one half times the width or depth of foundation. In our present problem, the size of the foundation is 20m x 17.5m. Hence, we consider the model limits as 80mx 80m to be at least one-half times the size of the foundation.

The construction sequence used in the modelling of piled raft foundation is shown Table 4.4:

Table 4-4: Typical Construction Sequence used in the Plaxis 3D analysis

Stage	**Description**
1	K_0 stage analysis considering the in-situ stresses at the site
2	Analysis by activation of Raft foundation and Piles, along with the loadings

4.1.8 Results from the Analysis

Plaxis 3D analysis is carried out using the soil and material properties mentioned in the earlier sections and as per construction sequence explained in the earlier section.

Fig. 4.2 below shows the deformed mesh from the Plaxis 3D analysis.

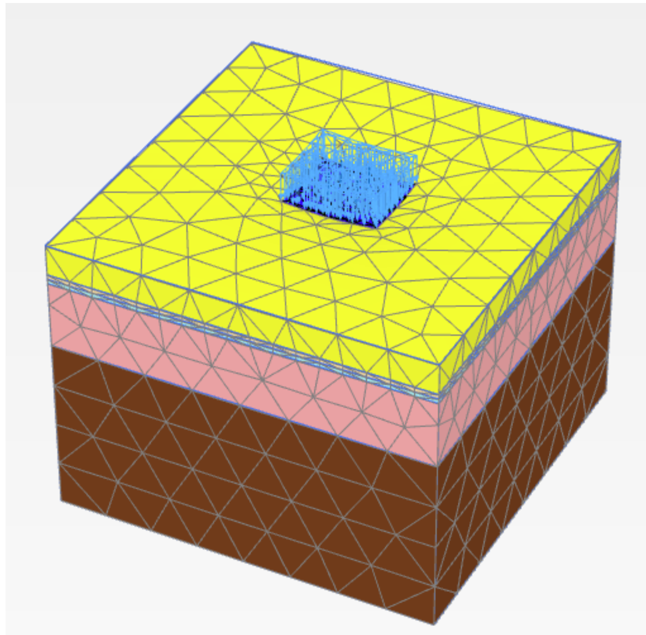


Figure 4-2: Deformed Mesh from the Plaxis 3D analysis

Fig. 4.3 below shows the deformed mesh from the Plaxis 3D analysis by hiding the soil elements. It clearly shows the deformation in the piles founded beneath the raft.

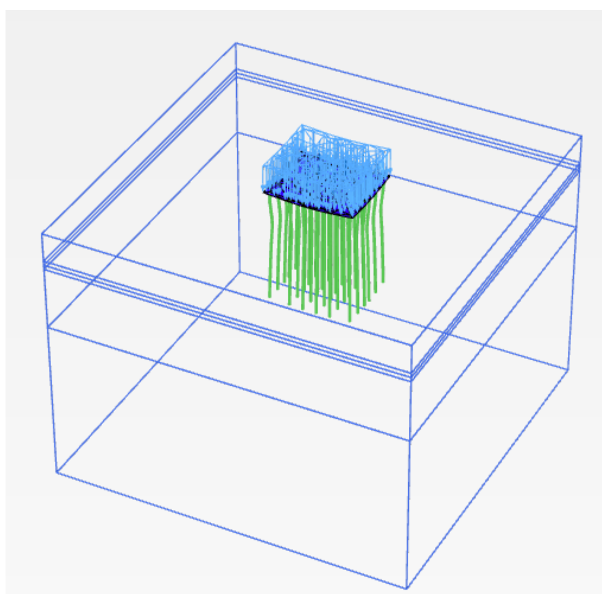


Figure 4-3: Deformed Mesh showing Piles from the Plaxis 3D analysis

Fig. 4.4 below shows the total displacements in the model. A maximum value of 35.6 mm is found below the raft level.

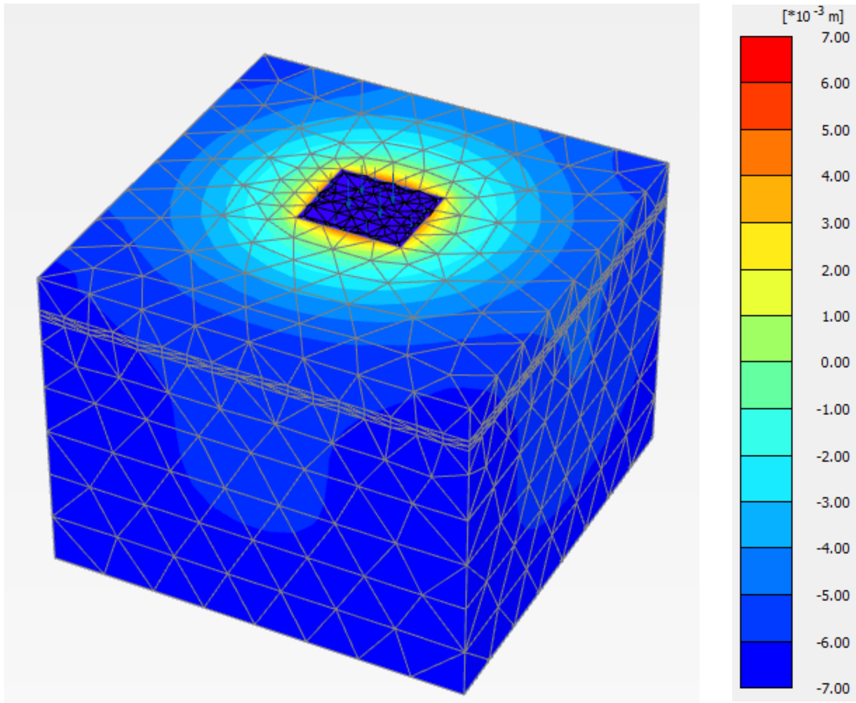


Figure 4-4: Deformed Mesh showing Piles from the Plaxis 3D analysis

Fig. 4.5 below shows the maximum positive horizontal (ux) displacements in the model as 6.32 mm and maximum negative horizontal displacement as 6.49 mm.

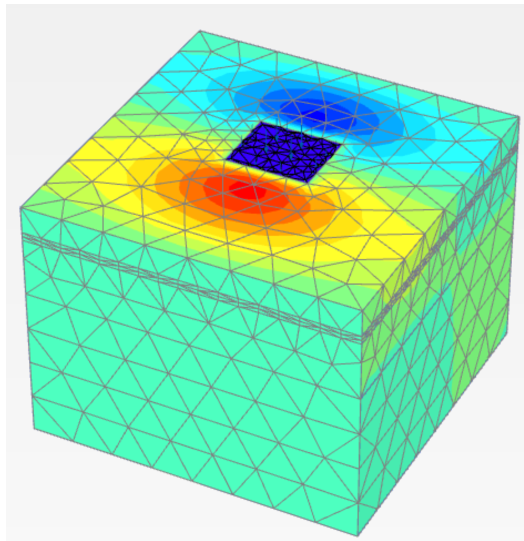


Figure 4-5: ux Displacement Contour from the Plaxis 3D analysis

Fig. 4.6 below shows the maximum positive horizontal (uy) displacements in the model as 7.29 mm and maximum negative horizontal displacement as 6.31 mm.

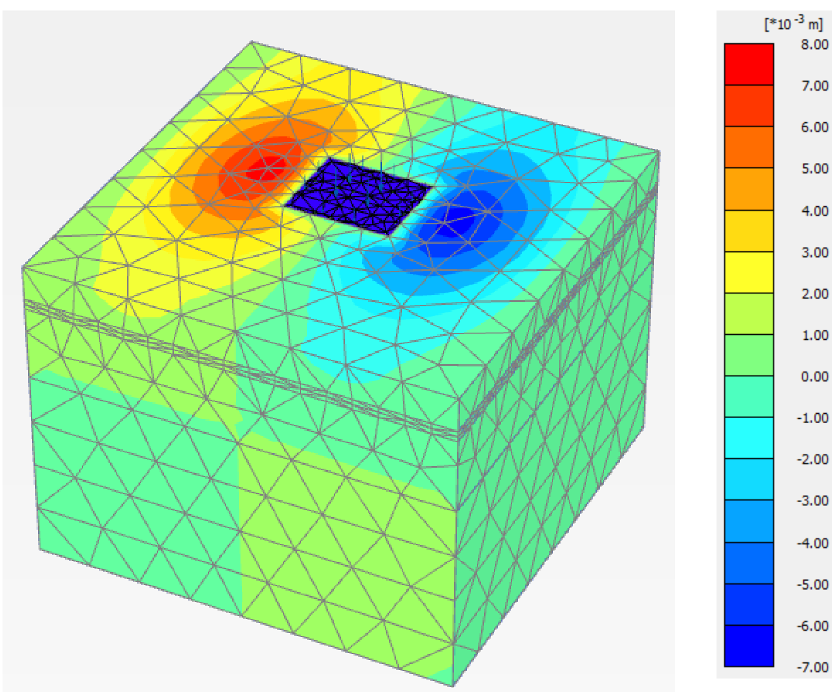


Figure 4-6: uy Displacement Contour from the Plaxis 3D analysis

Fig. 4.7 below shows the maximum positive vertical (uz) displacements in the model as 0.0 mm and maximum negative vertical displacement as 35.6 mm

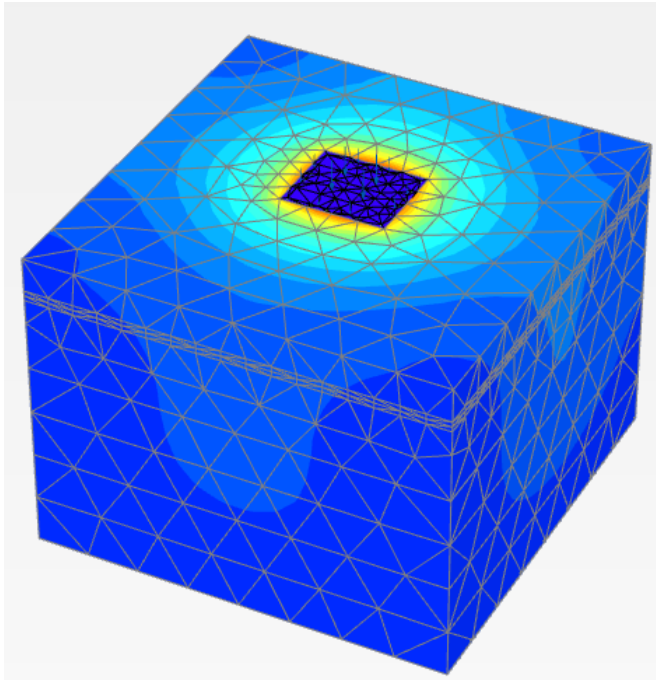


Figure 4-7: uz Displacement Contour from the Plaxis 3D analysis

Fig. 4.8 below shows the maximum displacement in the raft as 35.6 mm.

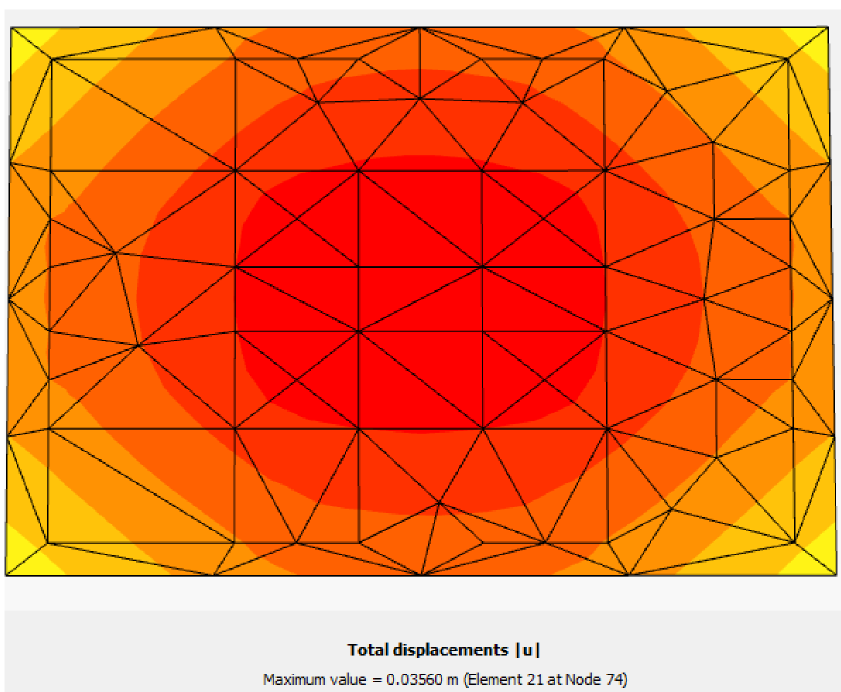


Figure 4-8: Total Displacements under the Raft from the Plaxis 3D analysis

Fig. 4.9 below shows the maximum positive horizontal (ux) displacements in the raft as 0.05 mm and maximum negative horizontal displacement as 13.58 mm.

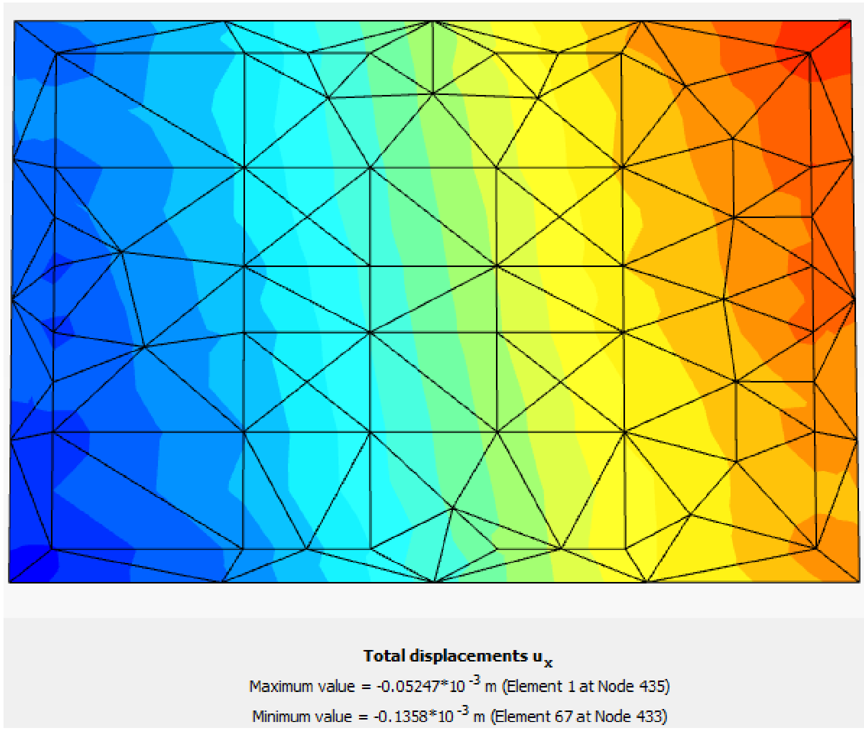


Figure 4-9: ux Displacements under the Raft from the Plaxis 3D analysis

Fig. 4.10 below shows the maximum positive horizontal (uy) displacements in the raft as 0.44 mm and maximum negative horizontal displacement as 0.38 mm.

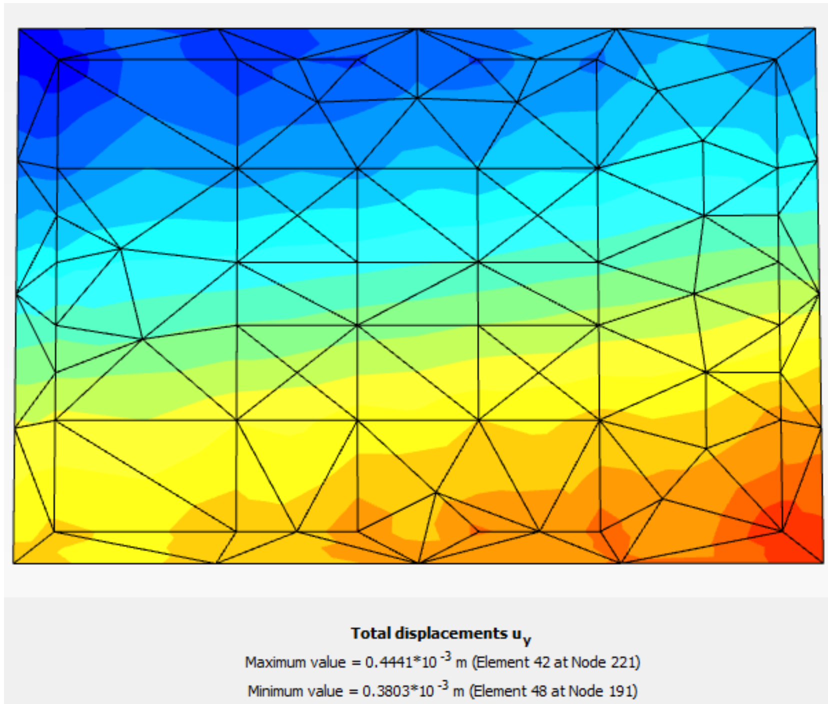


Figure 4-10: uy Displacements under the Raft from the Plaxis 3D analysis

Fig. 4.11 below shows the maximum positive vertical (uz) displacements in the raft as 0.0 mm and maximum negative vertical displacement as 35.6 mm.

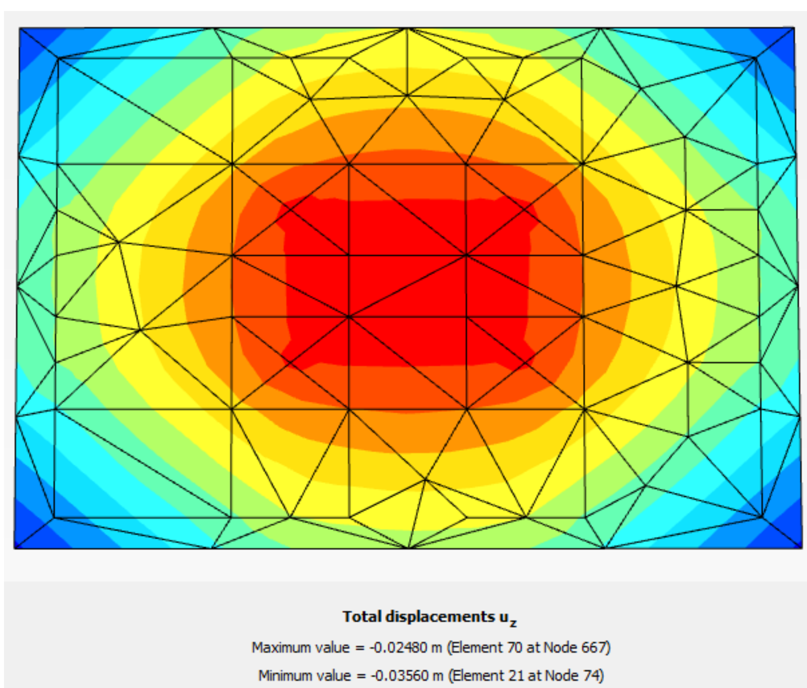


Figure 4-11: uz Displacements under the Raft from the Plaxis 3D analysis

Fig. 4.12 below shows the maximum positive M11 moment in the raft as 532.8 KN.m/m and maximum negative M11 moment in the raft as 4436 KN.m/m.

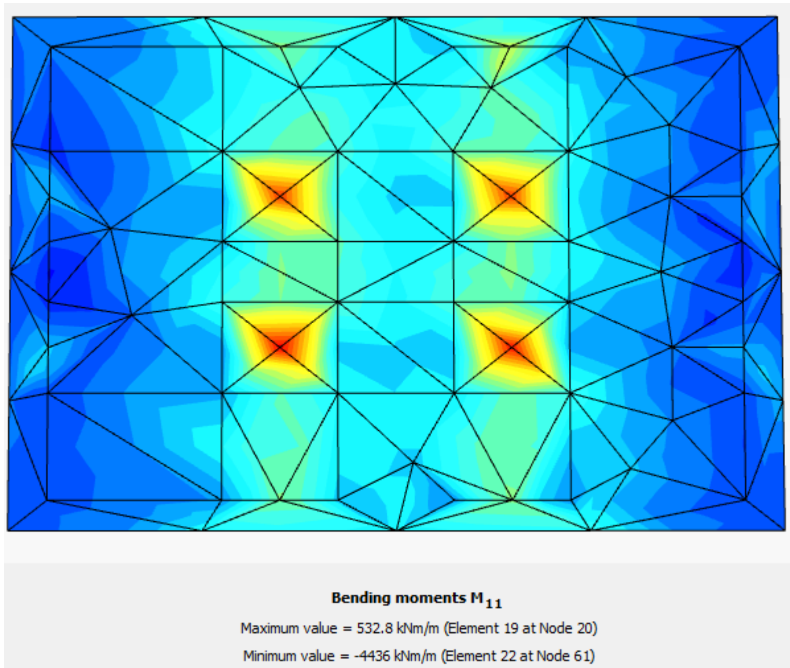


Figure 4-12: Moment M11 under the Raft from the Plaxis 3D analysis

Fig. 4.13 below shows the maximum positive M22 moment in the raft as 767.6 kN.m/m and maximum negative M22 moment in the raft as 3857 KN.m/m

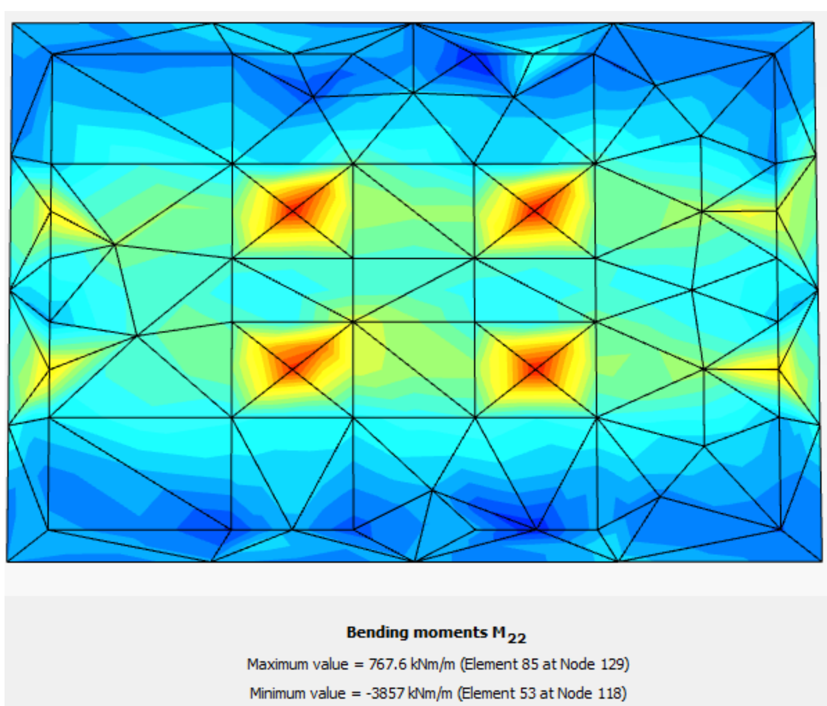


Figure 4-13: Moment M22 under the Raft from the Plaxis 3D analysis

Fig. 4.14 below shows the maximum positive M12 moment in the raft as 654.4 kN.m/m and maximum negative M12 moment in the raft as 792.3 kN.m/m

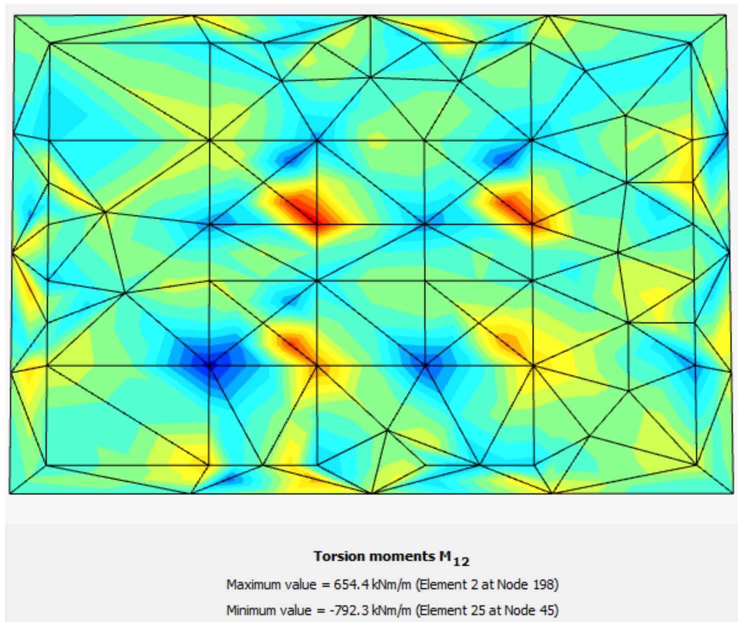


Figure 4-14: Moment M12 under the Raft from the Plaxis 3D analysis

Fg.4.15 below shows the maximum positive Q12 Shear in the raft as 59.96 kN/m and maximum negative Q12 Shear in the raft as 79.13 kN/m.

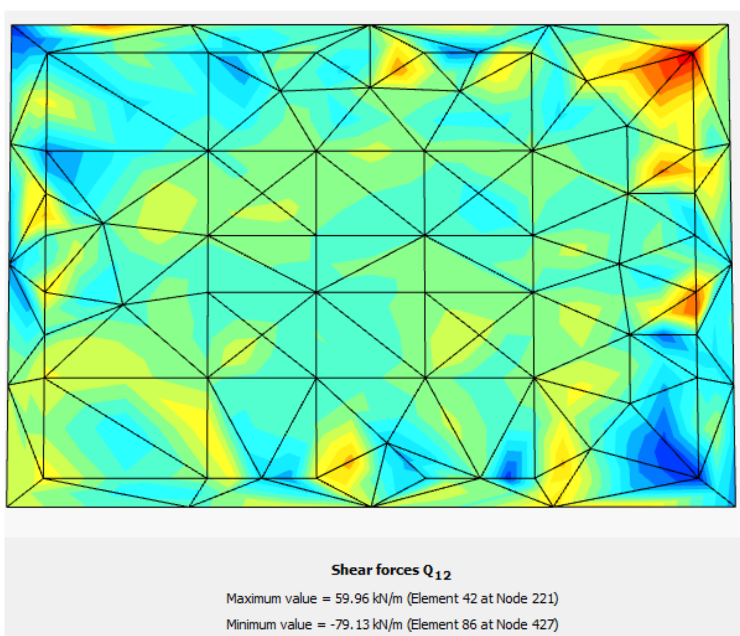


Figure 4-15: Shear Q12 under the Raft from the Plaxis 3D analysis

Fig. 4.16 below shows the maximum positive Q23 Shear in the raft as 3144 kN/m and maximum negative Q23 Shear in the raft as 3065 kN/m

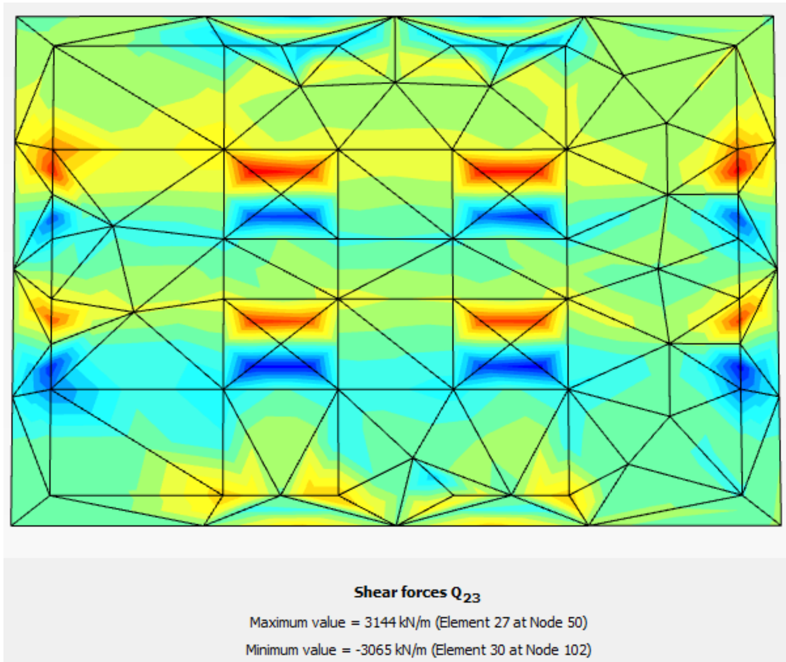


Figure 4-16: Shear Q23 under the Raft from the Plaxis 3D analysis

Fig. 4.17 below shows the maximum positive Q13 Shear in the raft as 3019kN/m and maximum negative Q13 Shear in the raft as 3092 kN/m

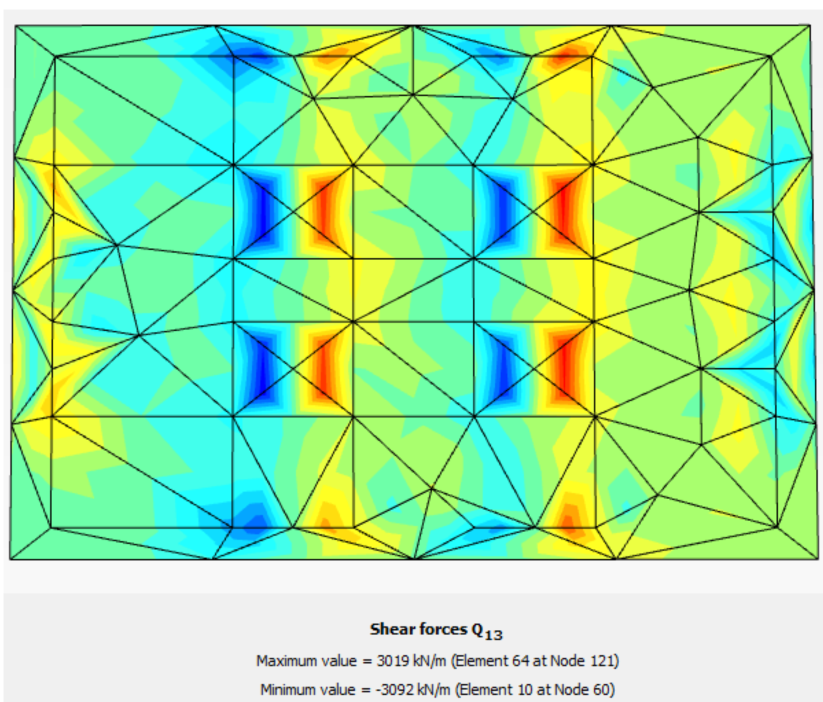


Figure 4-17: Shear Q13 under the Raft from the Plaxis 3D analysis

4.2 CSI SAFE Analysis

CSI SAFE software is used to model the selected pile raft foundation for each case of study. The modelling procedure used is discussed in the section 4.2.1.

4.2.1 Modelling Procedure

The following steps summarized the modeling procedure using CSI SAFE.

A. Define the different structural materials like steel reinforcement & concrete.

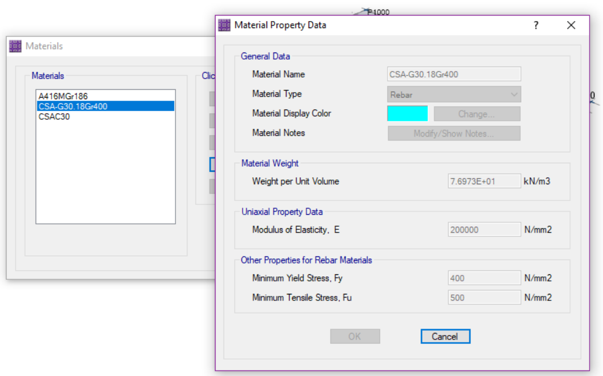


Figure 4-18: Define the Structural Material

B. Define the structural sections (raft section 1500 mm).

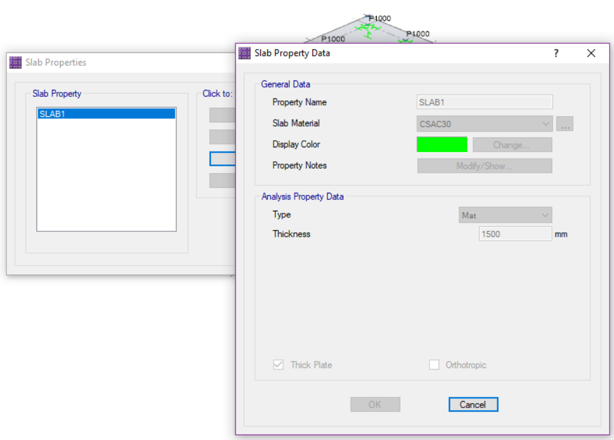


Figure 4-19: Define the Structural Sections

C. Define the point spring properties, which it will be used to represent the piles.

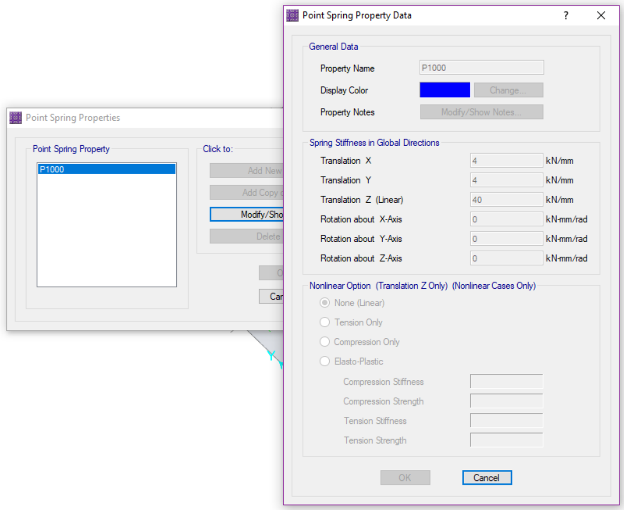


Figure 4-20: Point Spring Properties

D. Model the Pile – raft foundation by representing the raft as shell element and piles as spring points.

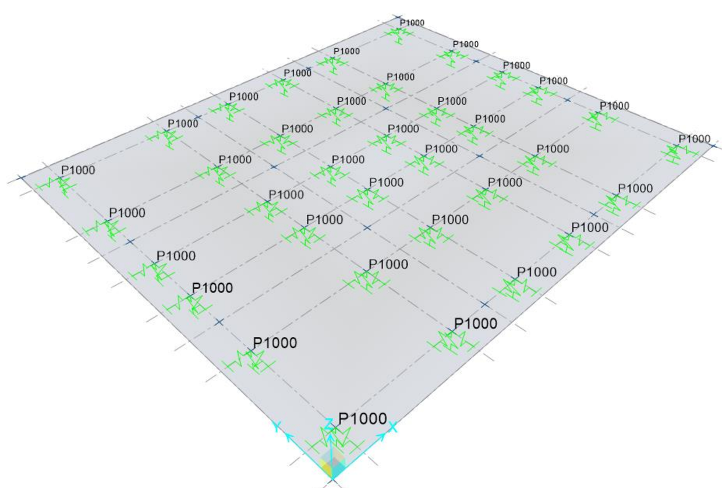


Figure 4-21: Pile Raft Model

E. Assign the external loads (point loads represent the column reactions & area load represent the distributed loads on the raft).

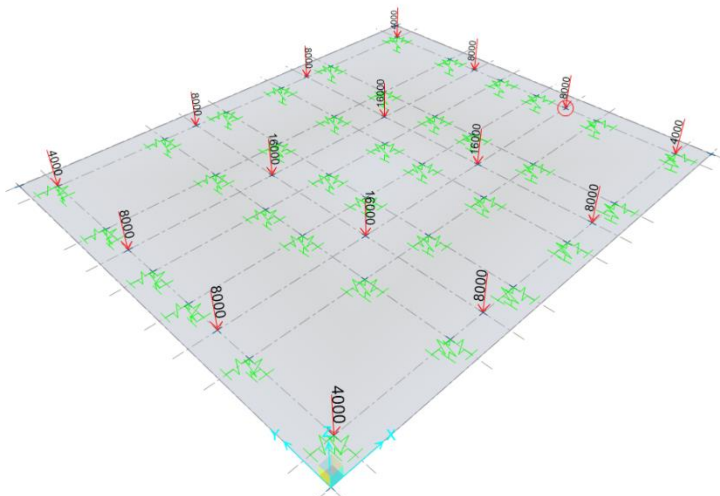


Figure 4-22: Loads on Raft

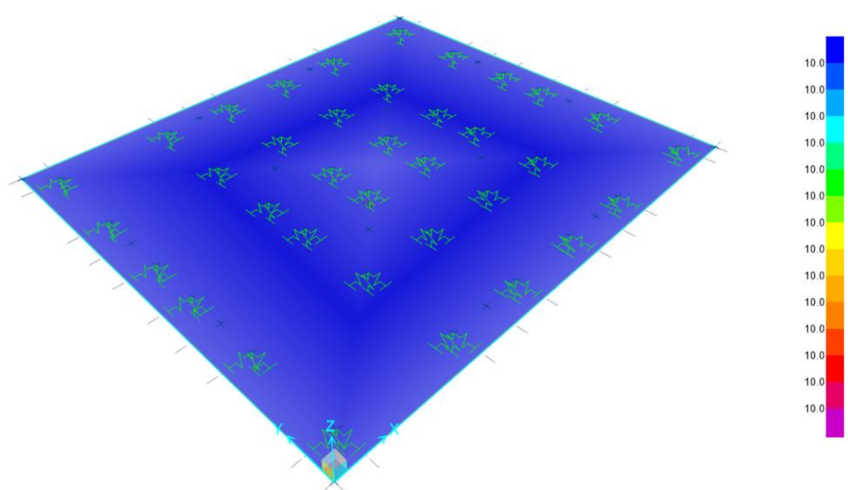


Figure 0-1: Assign the external Loads

Chapter 5 Comparison between Plaxis 3D and SAFE

Chapter five will discuss the comparison of results of the second case study which has been stated in the earlier chapter with the SAFE analysis. The key purpose of this research is to compare between the bending moments, shear forces and displacements of the selected case study between Plaxis 3D and SAFE models.

5.1 Displacement:

The maximum and minimum displacements of the plate as found from the analysis of Plaxis 3D are 35.60mm and 24.80mm which are 112.256mm and 108.524mm in case of analysis in SAFE. The maximum and minimum displacements are 215% and 338% higher in the case of SAFE.

The large difference in the displacements is mainly because of the type of modelling. Plaxis 3D simulates the actual ground conditions and proper soil-structural interaction between the raft, piles and the soil. While the SAFE models the piles as springs and do not consider the effect of soil into account. Hence it can be inferred that Plaxis 3D is more reliable in case of displacements.

Table below shows the comparison of results between Plaxis 3D and SAFE in brief.

Table 5-1: Comparison of Displacements between Plaxis 3D and SAFE analyses

Item	Plaxis 3D	SAFE
Maximum displacement of Plate (mm)	35.60	112.256
Minimum displacement of Plate (mm)	24.80	108.524

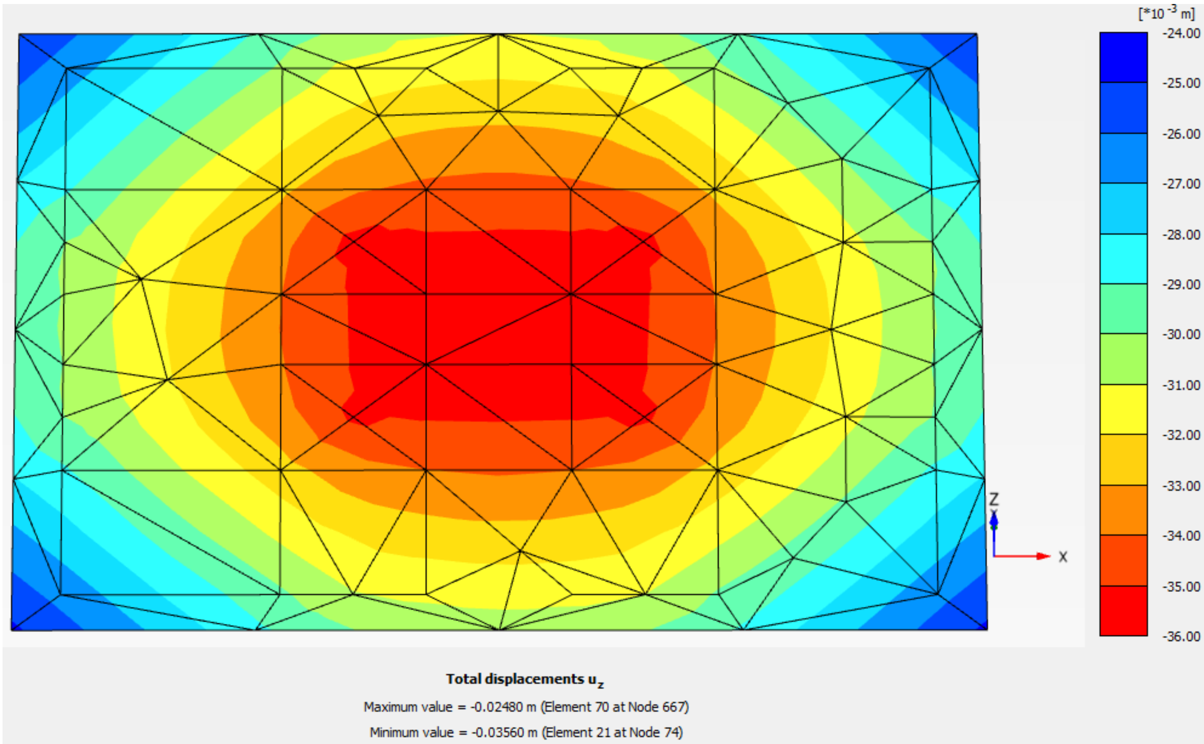


Figure 5-1: Settlement from the Plaxis 3D analysis

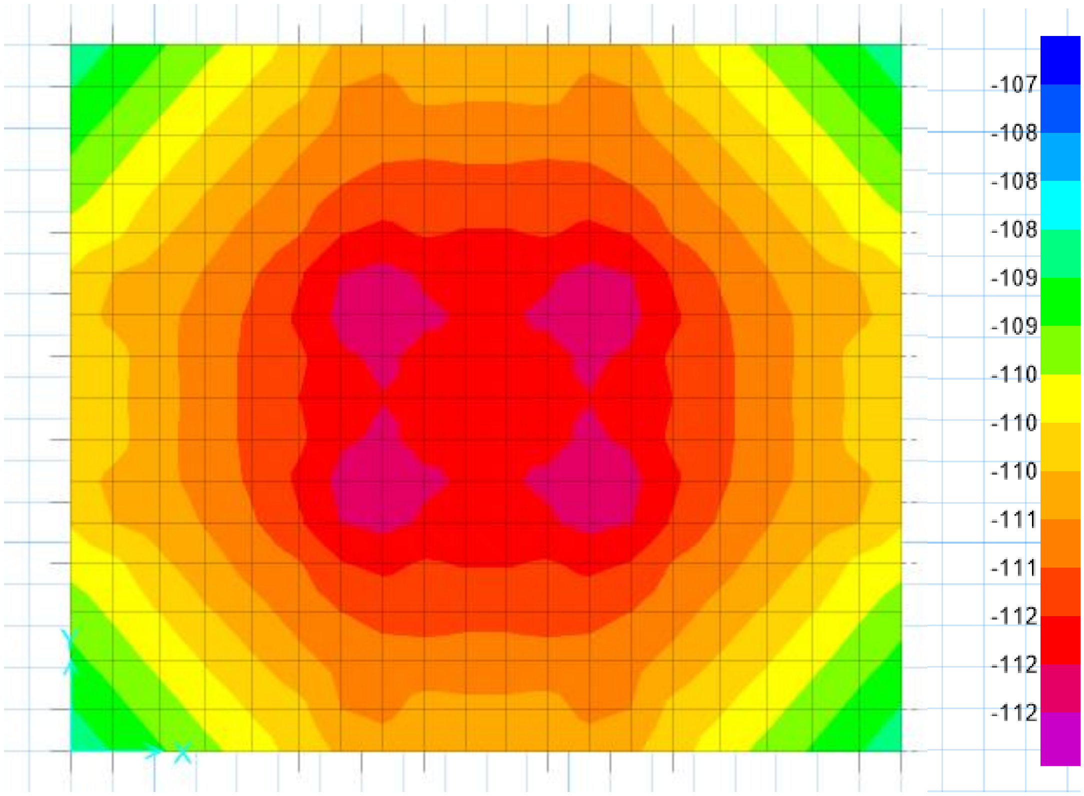


Figure 5-2: Settlement from the SAFE analysis

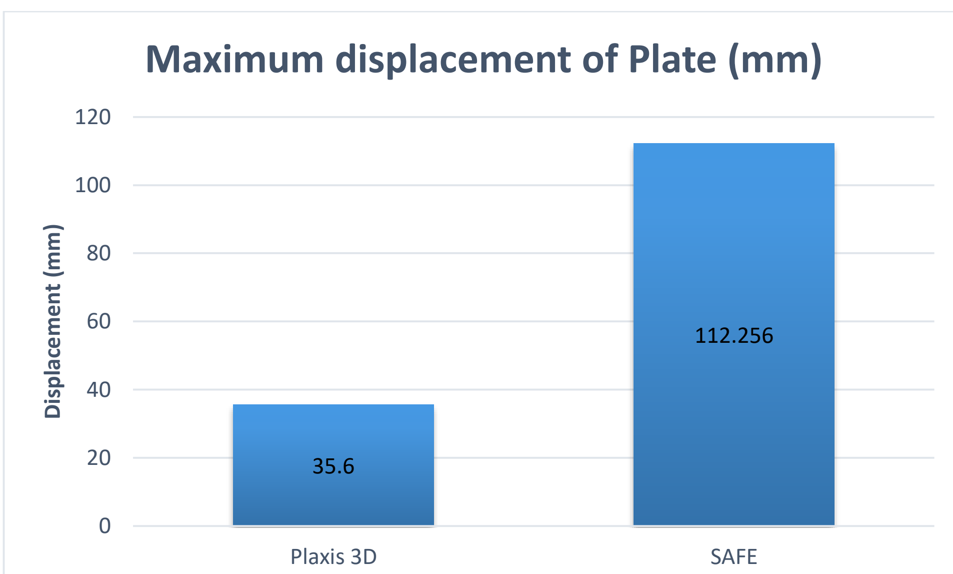


Figure 5-3: Maximum Displacement Comparison

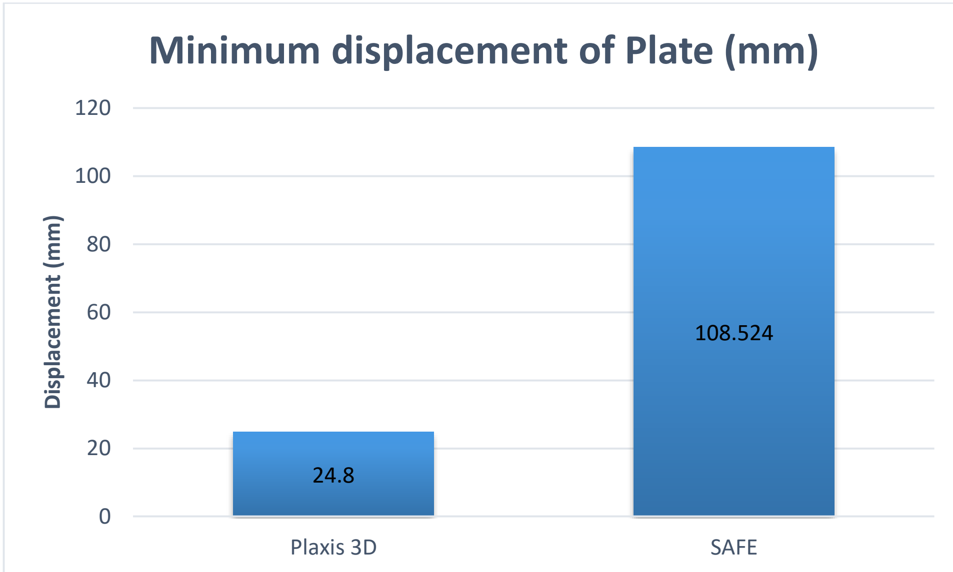


Figure 5-4: Minimum Displacement Comparison

5.2 Shear Force:

Plaxis 3D gives positive and negative shear (V_{13}) values as 3019kN/m and 3092kN/m which is 2073kN/m in both cases of the analysis from SAFE. The maximum negative and positive shear values in case of Plaxis 3D analysis are 46% and 49% higher than SAFE.

This is because the soil structural interaction is properly simulated in case of Plaxis 3D, which is not the case in SAFE. The mobilization of shear stresses is properly simulated in case of Plaxis 3D and hence it can be concluded that Plaxis 3D is more reliable for the calculation of the shear stresses.

Table 5-2: Comparison of Shear V13 between Plaxis 3D and SAFE analyses

Item	Plaxis 3D	SAFE
Maximum positive Shear V_{13} (kN/m)	3019.00	2073
Maximum negative Shear V_{13} (kN/m)	3092.00	2073

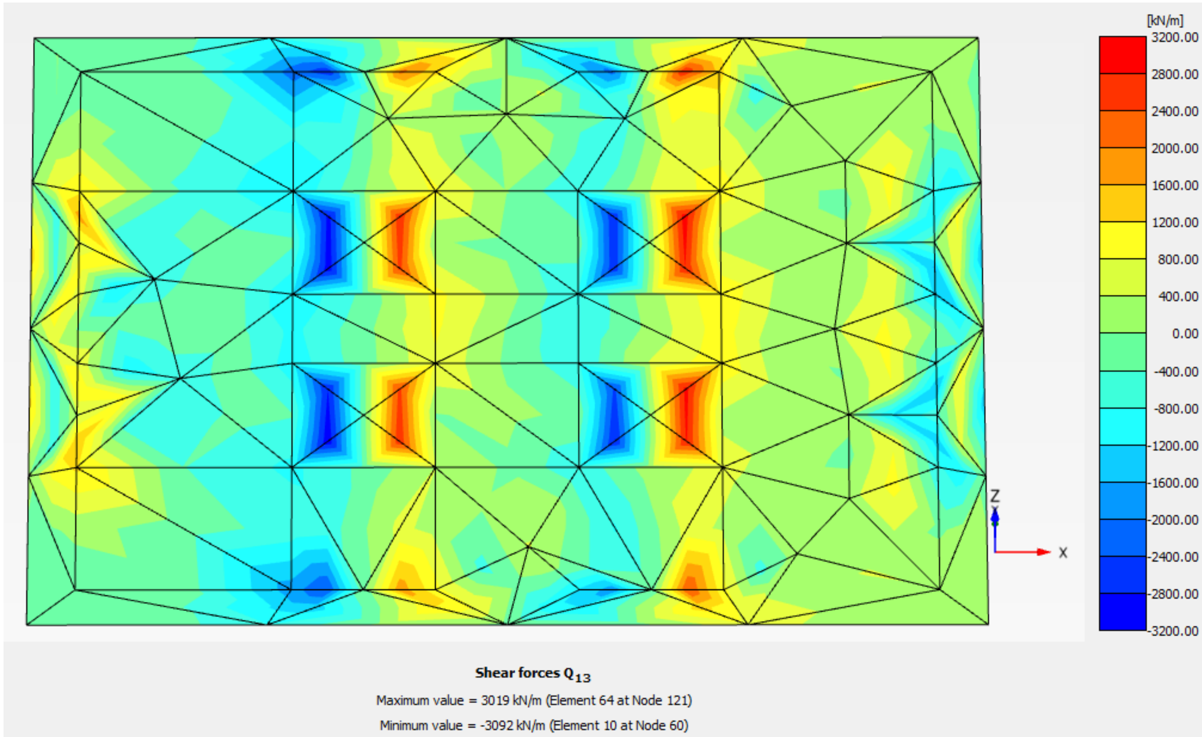


Figure 5-5: Shear V13 from Plaxis 3D Analysis

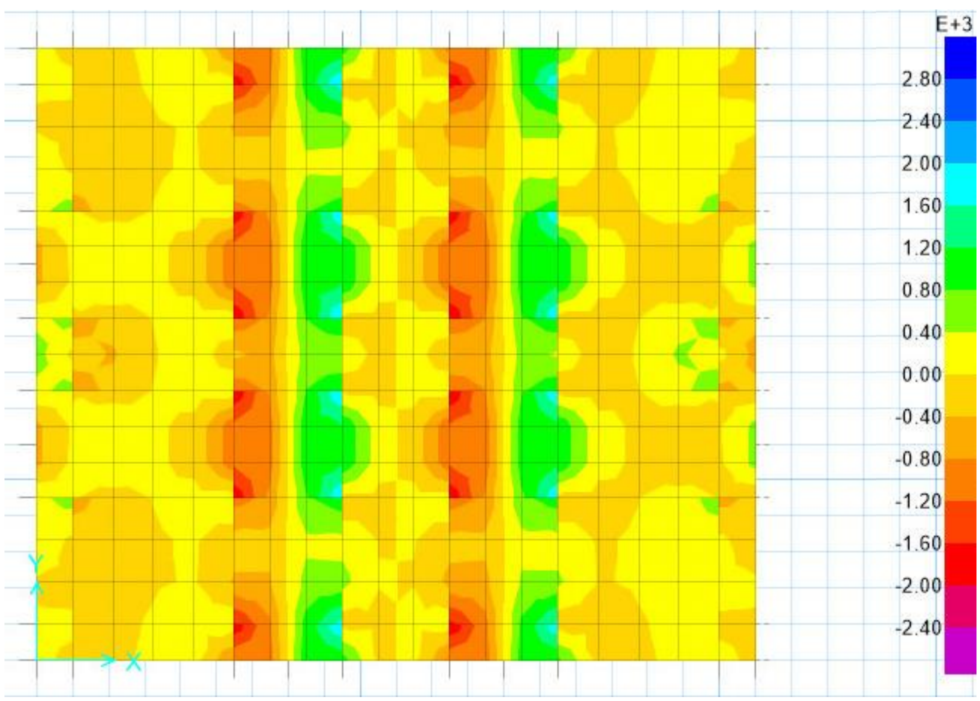


Figure 5-6: Shear V13 from SAFE Analysis

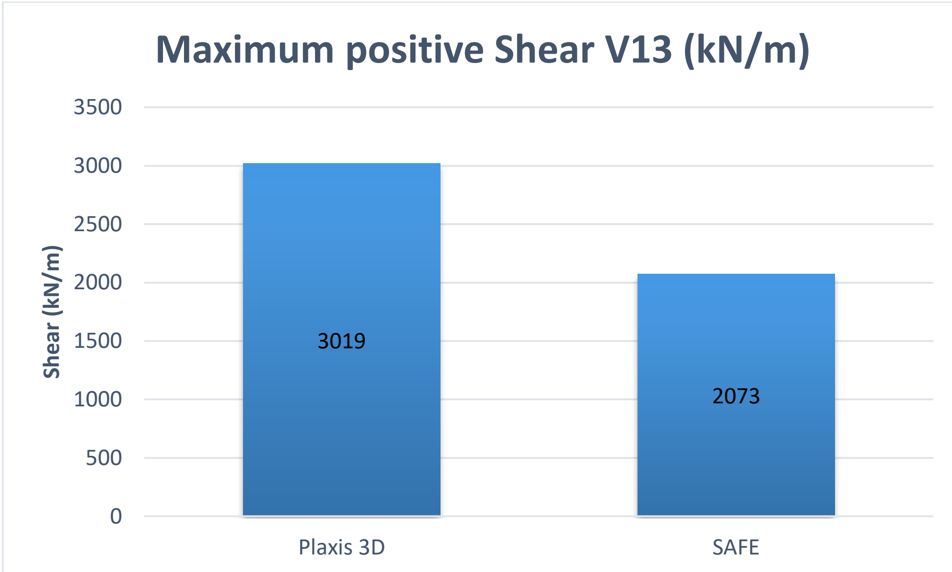


Figure 5-7: Positive Shear V13 Comparison

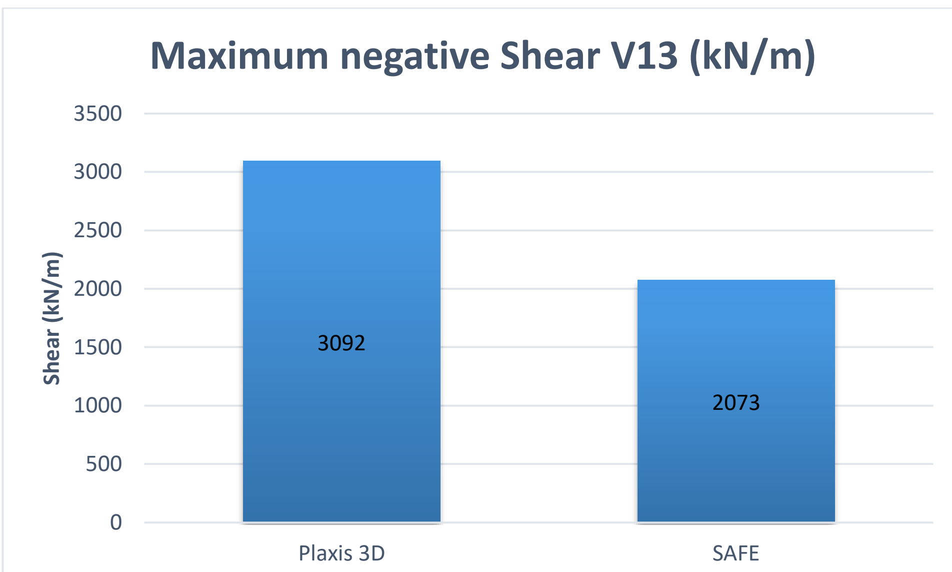


Figure 5-8: Negative Shear V13 Comparison

Results from the analysis show the maximum positive and negative shear (V_{23}) values to be 3144kN/m and 3065kN/m from Plaxis 3D which is only 2050kN/m in case of the analysis from SAFE. The maximum negative and positive shears in case of Plaxis 3D analysis are 53% and 50% higher than SAFE.

As mentioned earlier, SAFE do not consider the influence of soil on the structure. Hence the results from the analysis may not represent the actual conditions in the site. Hence Plaxis 3D is more reliable in calculation of the shear stresses.

Table 5-3: Comparison of Shear V23 between Plaxis 3D and SAFE analyses

Item	Plaxis 3D	SAFE
Maximum positive Shear V_{23} (kN/m)	3144.00	2050
Maximum negative Shear V_{23} (kN/m)	3065.00	2050

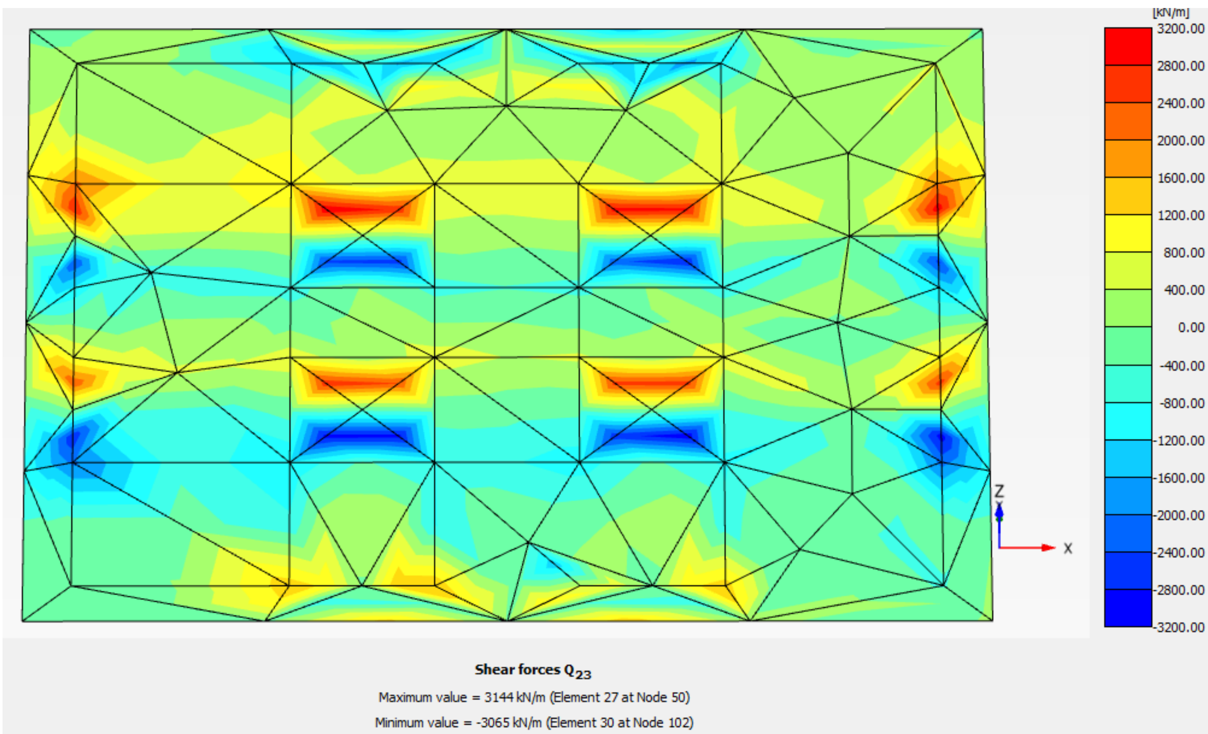


Figure 5-9: Shear V23 from Plaxis 3D Analysis

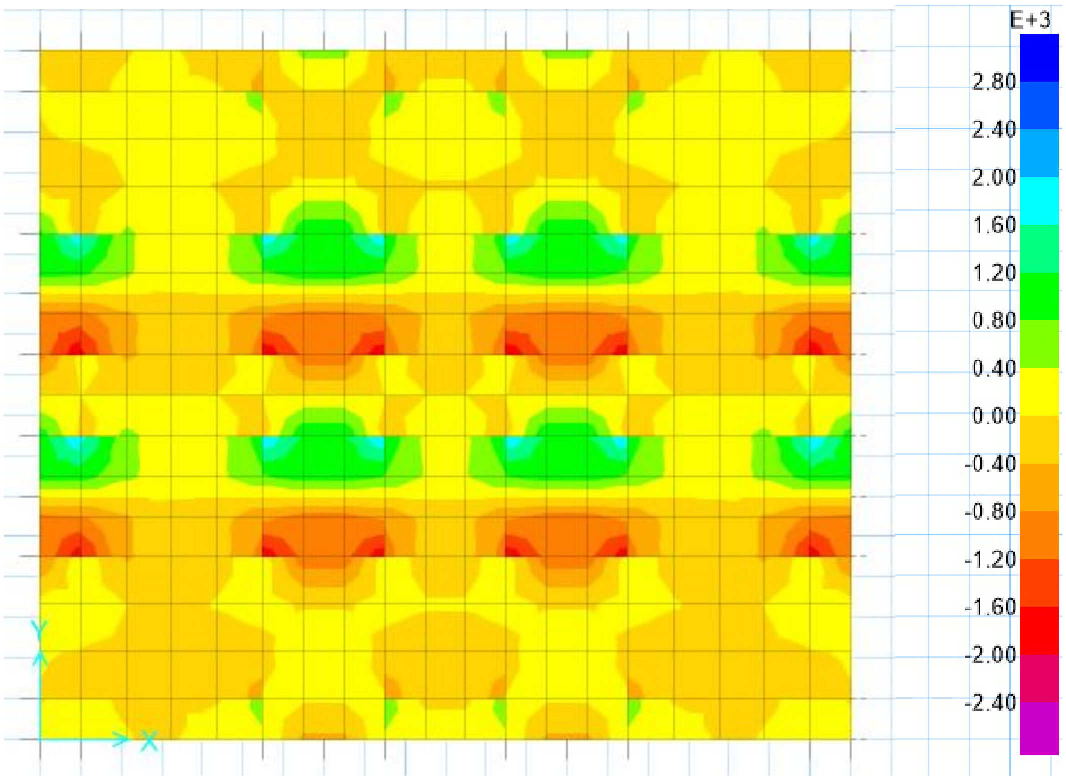


Figure 5-10: Shear V23 from SAFE Analysis

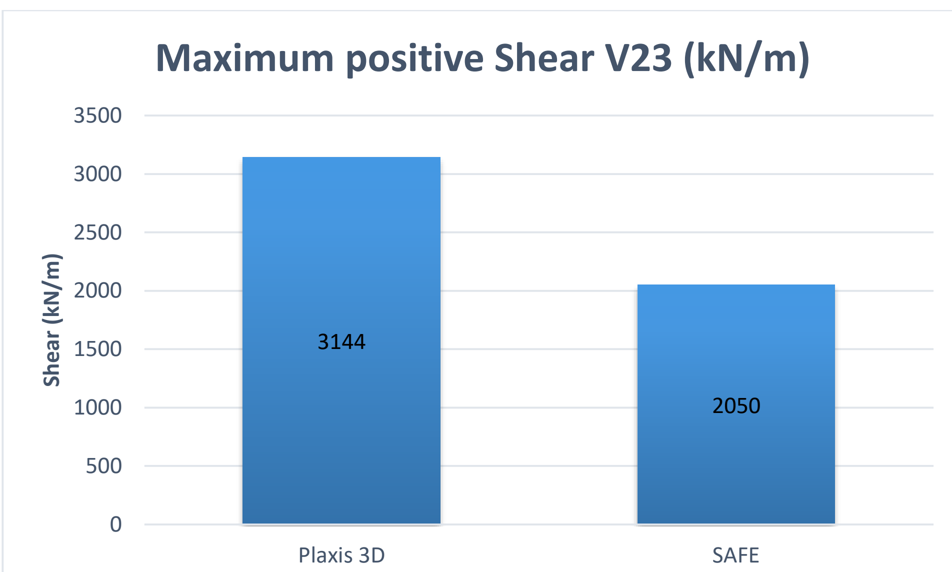


Figure 5-11: Positive Shear V23 Comparison

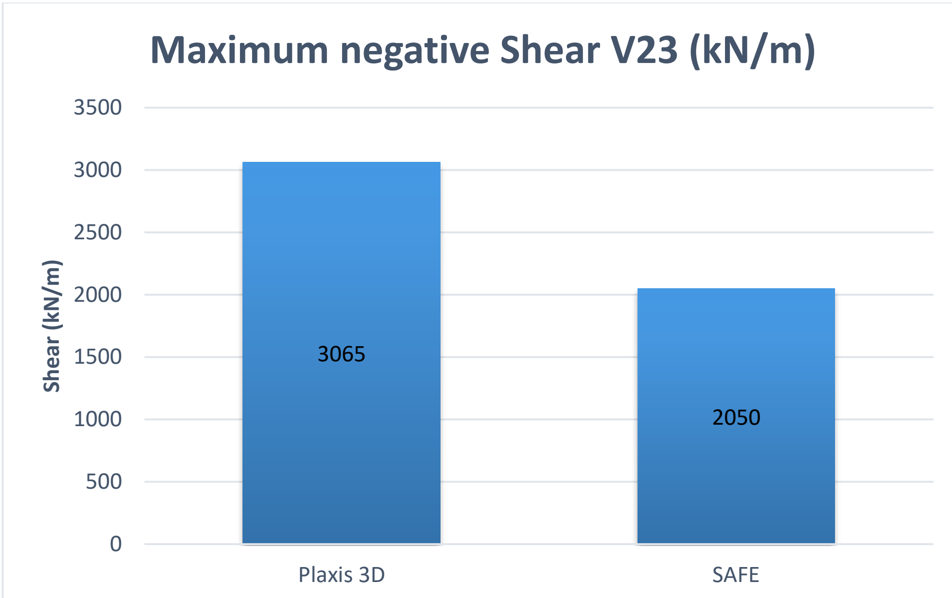


Figure 5-12: Negative Shear V23 Comparison

5.3 Moment

The maximum positive and negative Moments (M_{11}) are found to be 532.8kN-m/m and 4436.0kN-m/m from the analysis of Plaxis 3D, which are 2049kN-m/m and 653kN-m/m in case of the analysis of SAFE. Neglecting the sign, the maximum moment in case of Plaxis 3D analysis was 116% higher than SAFE.

It can be seen from the above results that there is a huge variation in the bending moments of the raft calculated from the Plaxis 3D and SAFE Analysis. Since the proper ground model is considered in case of Plaxis 3D by assigning proper constitutive models to the soil layers and modelling the piles supporting the raft exactly by assigning the skin friction and end bearing values, the actual scenario on site is mostly reflected in case of Plaxis 3D analysis. Hence it can be concluded that Plaxis 3D is more reliable in calculation of Bending moments of rafts and piles.

Table 5-4: Comparison of Moment M11 between Plaxis 3D and SAFE analyses

Item	Plaxis 3D	SAFE
Maximum positive M_{11} (kN-m/m)	532.80	2049
Maximum negative M_{11} (kN-m/m)	4436.00	653

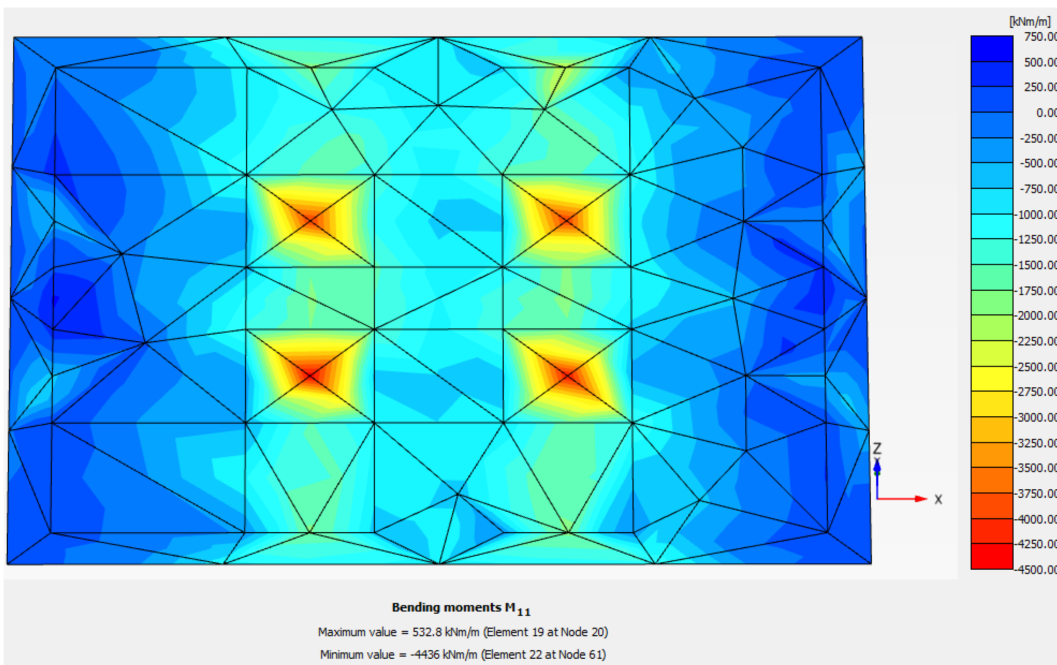


Figure 5-13: Moment M11 from Plaxis 3D Analysis

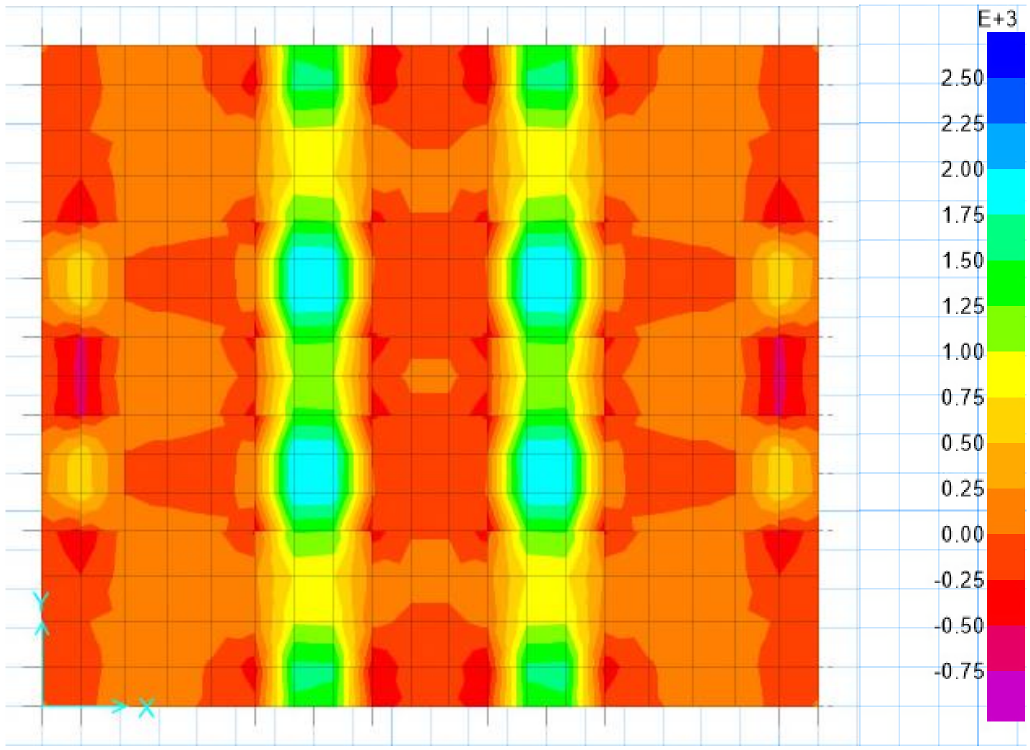


Figure 5-14: Moment M11 from SAFE Analysis

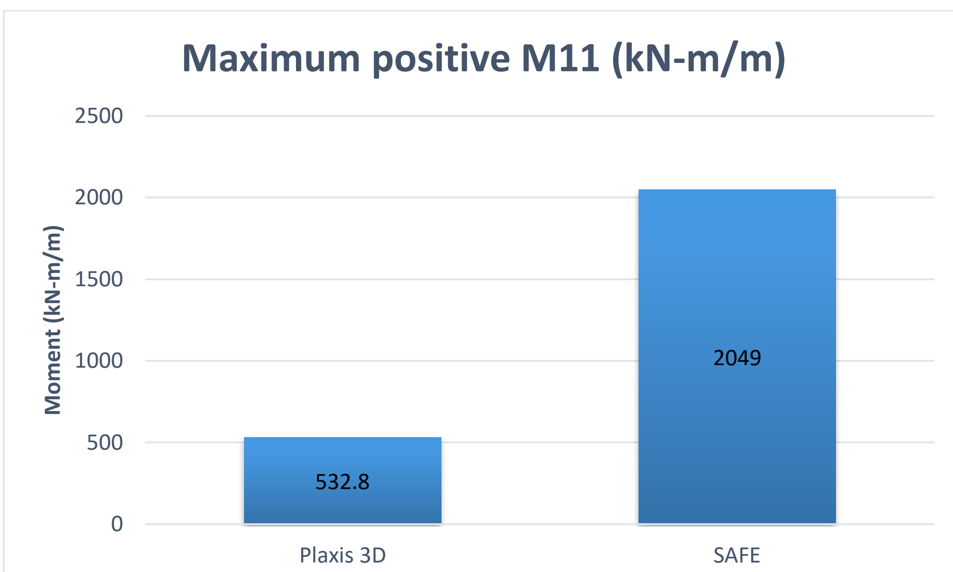


Figure 5-15: Positive Moment M11 Comparison

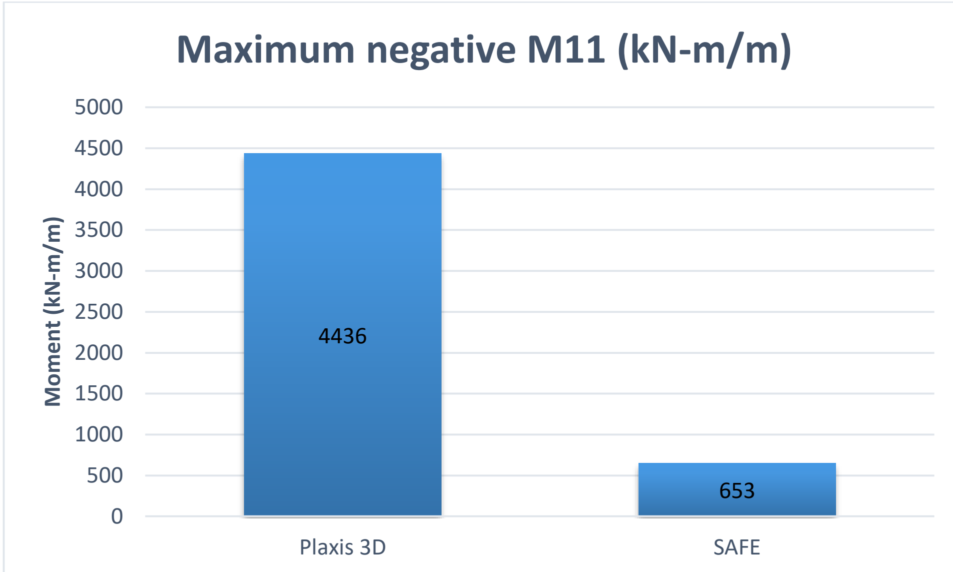


Figure 5-16: Negative Moment M11 Comparison

Plaxis 3D analysis show the maximum positive and negative Moments (M_{22}) as 767.6kN-m/m and 3857kN-m/m, which are 1976kN-m/m and 644kN-m/m in case of the analysis of SAFE. Neglecting the sign, the maximum moment in case of Plaxis 3D analysis was 95% higher than SAFE.

The results from the Plaxis 3D analysis generally confirm to the test results after completion of project. Hence Plaxis 3D is more reliable in case of calculation of Bending moments.

Table 5-5: Comparison of Moment M22 between Plaxis 3D and SAFE analyses

Item	Plaxis 3D	SAFE
Maximum positive M_{22} (kN-m/m)	767.60	1976
Maximum negative M_{22} (kN-m/m)	3857.00	644

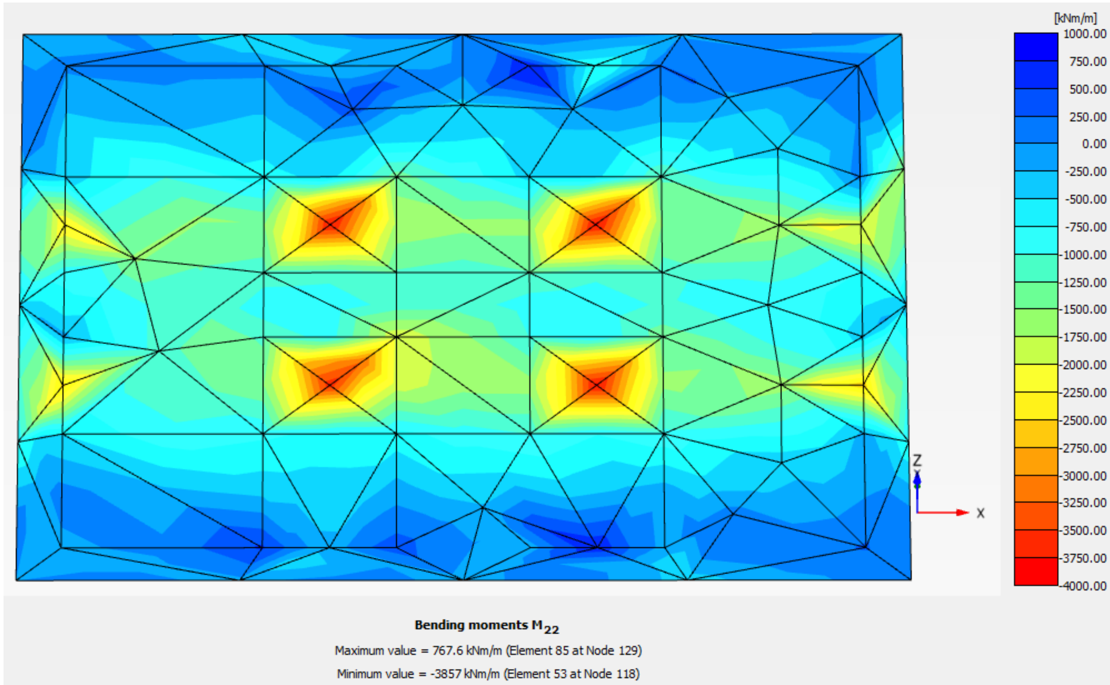


Figure 5-17: Moment M22 from Plaxis 3D Analysis

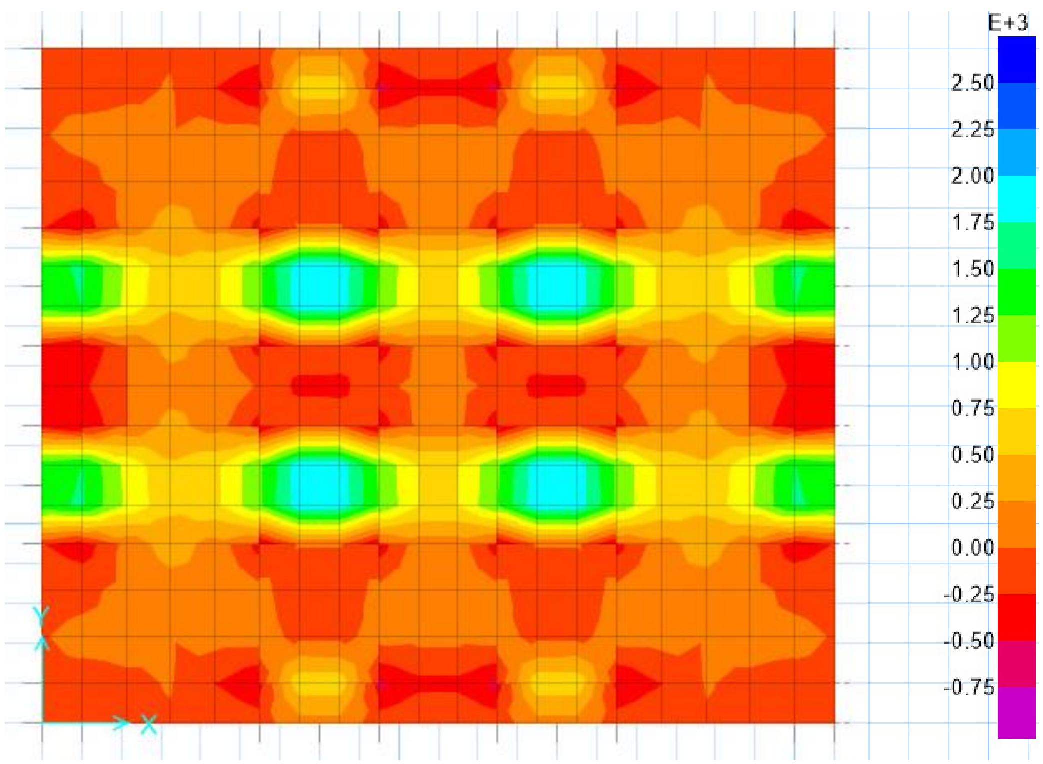


Figure 5-18: Moment M22 from SAFE Analysis

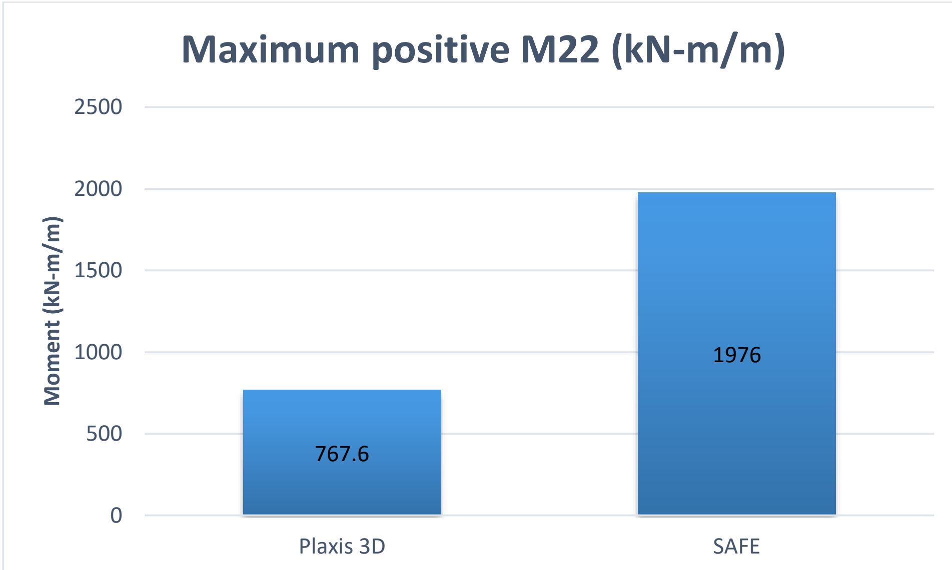


Figure 5-19: Positive Moment M22 Comparison

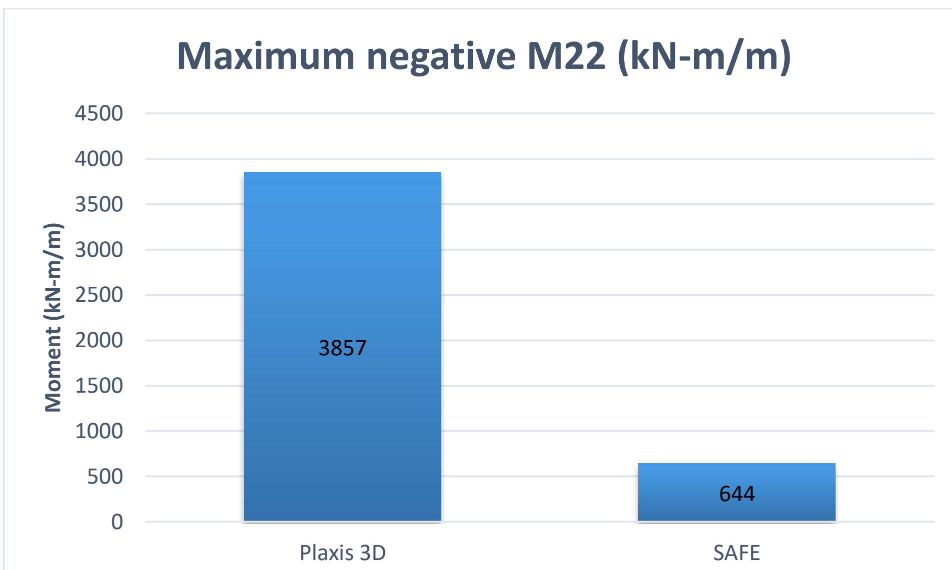


Figure 5-20: Negative Moment M22 Comparison

Results from the Plaxis 3D analysis show the maximum positive and negative Moment (M_{12}) values as 654.4kN-m/m and 792.3kN-m/m, which are 334kN-m/m and

334kN-m/m in case of the analysis of SAFE. Neglecting the sign, the maximum moment in case of Plaxis 3D analysis was 137% higher than SAFE.

It can be seen that there is no difference in the positive and negative moment values from SAFE, since it does not consider the actual soil-structure interaction into account. Hence it is more reliable to use Plaxis 3D in case of calculation of bending moments of structures in contact with the soils.

Table 5-6: Comparison of Moment M12 between Plaxis 3D and SAFE analyses

Item	Plaxis 3D	SAFE
Maximum positive M_{12} (kN-m/m)	654.40	334
Maximum negative M_{12} (kN-m/m)	792.30	334

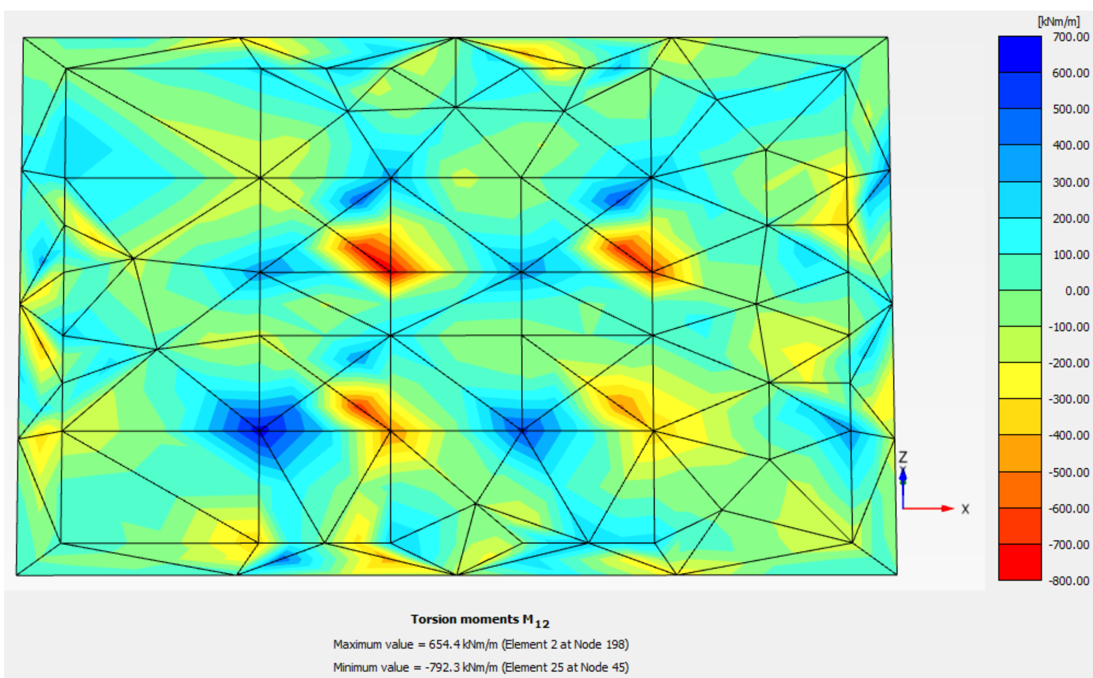


Figure 5-21: Moment M12 from Plaxis 3D Analysis

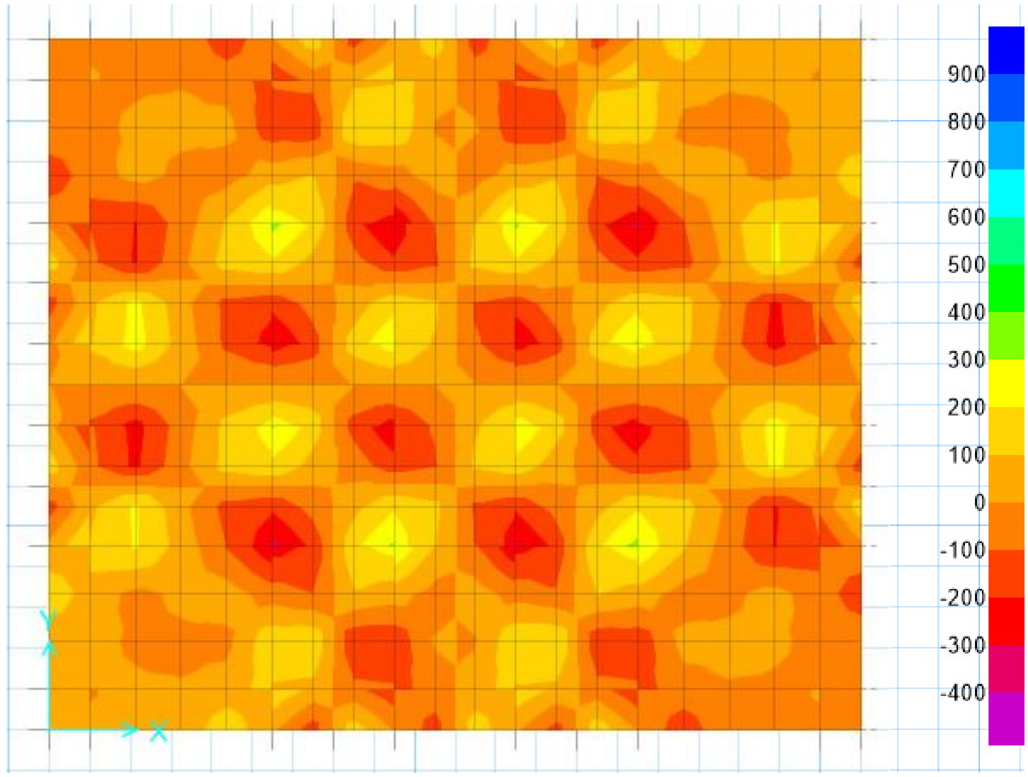


Figure 5-22: Moment M12 from SAFE Analysis

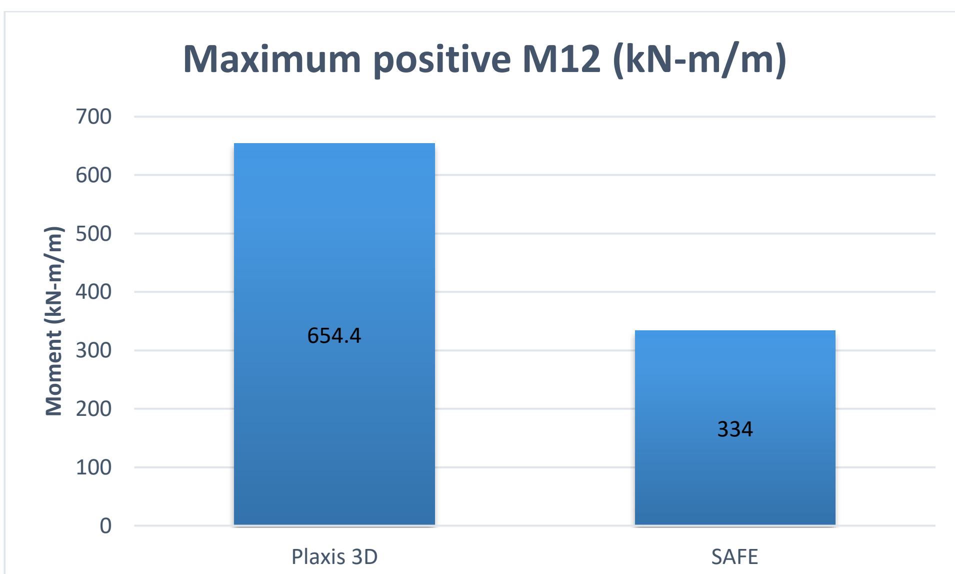


Figure 5-23: Positive Moment M12 Comparison

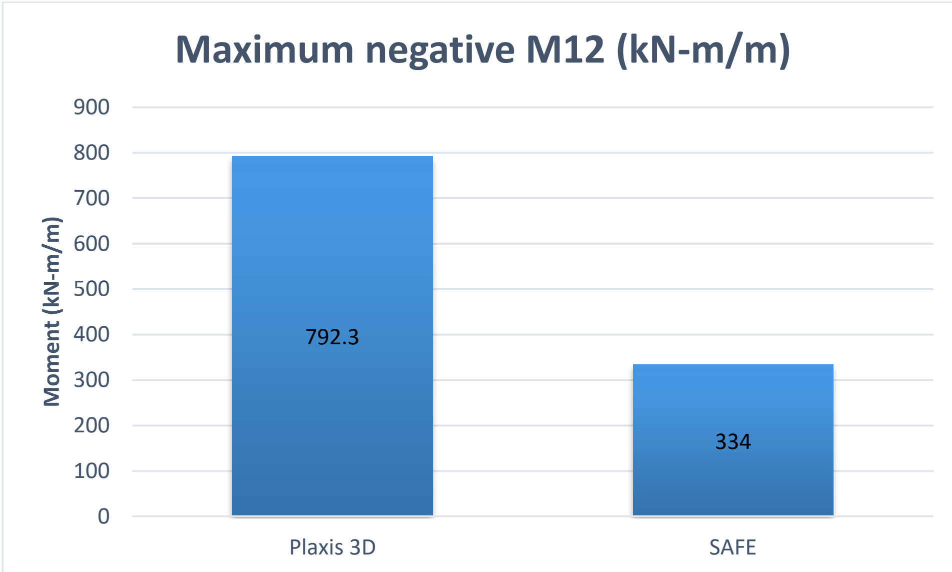


Figure 5-24: Negative Moment M12 Comparison

Chapter 6 Conclusion and Recommendations

This chapter will discuss the conclusions of the case study which are stated in the previous chapters. The case study is checked with two different software Plaxis 3D and SAFE. Each software gives different bending moments, shear forces and displacements for the case of study. The results from the software are discussed in the previous chapter. The main purpose of this research is to highlight the differences between the two software that are used.

The chapter will be divided to two key sections as the following:

1. The first section is "research conclusion" which will summarize all results of this research and choose the better software that can be used for geotechnical applications based on the case study and result.
2. The second section is "research recommendations" which will cover an important aspect which is the final recommendations in respect to the research results.

Research conclusion

In summary of the research, it has been proved by using two different software that the calculated results have a large difference. Table 6.1 below gives a glimpse of all the results from the two-software showing the main differences.

Table 6-1: Comparison of Results between Plaxis 3D and SAFE analyses

Item	Plaxis 3D	SAFE	Remarks
Maximum displacement of Plate (mm)	35.60	112.256	Plaxis is less by 215%
Minimum displacement of Plate (mm)	24.80	108.524	Plaxis is less by 338%
Maximum positive Shear V_{13} (kN/m)	3019.00	2073	Plaxis is more by 45%
Maximum negative Shear V_{13} (kN/m)	3092.00	2073	Plaxis is more by 49%
Maximum positive Shear V_{23} (kN/m)	3144.00	2050	Plaxis is more by 53%
Maximum negative Shear V_{23} (kN/m)	3065.00	2050	Plaxis is more by 49%
Maximum positive M_{11} (kN-m/m)	532.80	2049	Plaxis is less by 284%

Maximum negative M_{11} (kN-m/m)	4436.00	653	Plaxis is more by 579%
Maximum positive M_{22} (kN-m/m)	767.60	1976	Plaxis is less by 157%
Maximum negative M_{22} (kN-m/m)	3857.00	644	Plaxis is more by 499%
Maximum positive M_{12} (kN-m/m)	654.40	334	Plaxis is more by 96%
Maximum negative M_{12} (kN-m/m)	792.30	334	Plaxis is more by 137%

It is clear from the results shown in Table 6.1 that the output from CSI SAFE shows same results for both positive and negative values. This is not actually the case in practical. Since the Raft is supported over ground, and due to application of loads from the top, there will different results (bending moment, shear forces) from positive to negative. Further based on the results, the following inferences can be made.

1. Plaxis 3D gives better displacement values compared to CSI SAFE.
2. SAFE gives better bending moment and shear force values compared to Plaxis 3D.

However, it is to be noted that the straining actions obtained from SAFE are not representative of the actual scenario, while the results from the Plaxis 3D are mostly acceptable and are been confirmed matching with the results from various completed projects.

It can be concluded from all the results and available literature that Plaxis 3D has following advantages over CSI SAFE in geotechnical applications.

1. Models the soil properties and piles in close relation to the actual conditions.
2. SAFE do not model the soil properties and the piles are modelled as springs.
3. Plaxis 3D models the soil-structure interaction more accurately.

Following are the disadvantages of Plaxis 3D over CSI SAFE in geotechnical applications.

1. CSI SAFE gives lower bending moments for the raft plate compared to PLAXIS 3D.

2. CSI SAFE gives lower shear forces for the raft plate compared to PLAXIS 3D.
3. Less bending moments as well as shear forces will result in less steel and will reduce the cost of project.
4. Analysis modelling and running time is less in case of SAFE compared to PLAXIS 3D.

CSI SAFE is better applicable more to analysis of superstructures, while PLAXIS 3D is more applicable to sub-structures, i.e underground. Both the softwares are in built with international design codes and have easy user interfaces.

Research recommendations

The research has been analysed considering an empirical case of study for piled raft foundation in Abu Dhabi using two different software. The major soil classifications are sand soil for the first 2 to 6 m of N.G.L and alternate layers of Mudstone and Gypsum stone for the lower soil layers. The major conclusion is that there is huge difference from the results of the two software.

Finally, we can summarize the research recommendation in the following points:

1. At early stage, Proper soil investigation report for the project should be done as well as before the starting of the design stage. The main purpose of the detailed soil report is to identify the soil layers' classifications and different soil parameters.

2. Proper geotechnical software like Plaxis 3D shall be used to model the sub-structure and for the analysis.

3.Using of the software which has the options to model the different soil layers and the underground structures (Plaxis 3D) show that the results have a significant impact compared to the results from

CSI Safe. This impact mainly happened because the modelling of the soil and piles in CSI Safe represented by using springs elements. This is approximation method shows big variations in the results. Therefore, it is recommended in case of studying the soil - structure interaction is to use that software which has the ability to model all the different elements in the proper way.

References

A.E. Yates Group 2018, History of piling. Available from https://www.aeyates.co.uk/tritech-ground-engineering/about/history. (Accessed 28 Apr. 2018)

A.Tejchman. (2013). analysis of settlements of piled foundations . Geotechnical department , Technical University of Gdansk, Poland.

Alessandro Mandolini. (1996). Settlement of piled foundation .

Chen, X 2011, 'Settlement analysis and case study on rock foundation and combined diaphragm wall-end-bearing pile-box (raft) foundation' In *Settlement Calculation on High-Rise Buildings* (pp. 391-401), Berlin, Heidelberg: Springer.

Dang Dinh. (2013). Settlement of pile rafts with different pile arrangement schemes via centrifuge tests. *American society of civil engineering* .

El-Mossallamy, Y 2008, 'Modeling the behaviour of piled raft applying Plaxis 3D Foundation Version 2', *Plaxis Bulletin*, (23).

Fabio tradigo. (2016). Finite element analysis of soil structure interaction in disconnected pile raft foundation .

George, BE, Banerjee, S and Gandhi, SR 2017, 'Numerical analysis of helical piles in cohesionless soil', *International Journal of Geotechnical Engineering*, pp.1-15.

H.G Poulos. (2016). Pile group settlement estimation- research to practice.

Kim Sung Ryul. (2014). Design for settlement of pile groups by the unified design method. Acase history .

lassaad hazzar. (2017). Influence of vertical load on lateral response of pile fundations in sands and clay. *Journal of rock mechanics and geotechnical engineering*.

Maharaj, DK 2004, ‘Three dimensional nonlinear finite element analysis to study the effect of raft and pile stiffness on the load-settlement behaviour of piled raft foundations’, *Electronic Journal of Geotechnical Engineering*.

Mandolini, A & Viggiani, C 1997, “Settlement of piled foundations’, *Géotechnique, 47,* no. 4, pp.791-816.

Mandolini, A, Russo, G and Viggiani, C 2005, ‘Pile foundations: Experimental investigations, analysis and design’. In *Proceedings of the International Conference on Soil Mechanics and Geotechnical Engineering*, Amsterdam: AA Balkema Publishers.

Manjareakar, J, Neridu, S & Guntupali, SK 2018, ‘Analysis and design of mat foundation using safe’, *Indian Journal of Scientific Research* 17, no. 2, pp. 421 – 424.

Reza Amini Ahidashti. (2013). A non linear methods to estimate elastic settelment of shallow foundations using smaill strain stiffness. *International conference on case histories in geotechnical engineering* .

Rolf Katzenbach. (2015). Realistic modelling of soil structure interaction for high rise building . *Sciencedirect*.

Poulos, HG, Small, JC & Chow, H 2011, ‘Piled raft foundations for tall buildings’, *Geotechnical Engineering Journal of the SEAGS & AGSSEA, 42*, no. 2, pp.78-84.

Singh, B & Ningombam TS 2011, ‘Influence of piles on load-settlement behaviour of raft foundation”, *International Journal of Engineering Science and Technology* 3, no. 12, pp. 8385-8394.

Sitharam, TG 2013, ‘Pile Foundation,’ *Advanced Foundation Engineering.* Available from: http://nptel.ac.in/courses/105108069/mod07/lec07.pdf. (Accessed 28 April 2018).

Small, JC and Poulos HG 2007, ‘A method of analysis of piled rafts’, *Foundations and Pavement,* pp. 660-665.

Tomlinson, M & Woodward, J 2014, *Pile design and construction practice*, Boca Raton: CRC Press.

Viggiani, C, Mandolini, A and Russo, G 2014. *Piles and pile foundations*. Boca Raton: CRC Press.

Wulandari, PS & Tjandra, D 2015, ‘Analysis of piled raft foundation on soft soil using PLAXIS 2D. *Procedia Engineering*’, *125*, pp.363-367.