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Comparison of 2D and 3D Numerical Procedures in Analysing Piled Raft Foundations Under Different Loading Conditions

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Abstract

Piled rafts are considered as effective ways to minimize settlements in raft foundations while improving the bearing capacity at the same time. Due to the complex nature of the interactions between the three elements; soil, piles and raft, analysis of a piled raft has become a daunting task. Among the available methods for analysis of piled-rafts, the use of two-dimensional software is an interest, when it comes to computer hardware capacity, time consumption and associated cost, in comparison to 3D analysis. The 3D problem is simplified to a 2D problem by introducing plane strain properties with corresponding smeared parameters. This paper presents a systematic study that compares 2D analyses to corresponding 3D analyses for a variety of material, geometric and loading conditions.

PLAXIS 2D is one such software that can be used to analyse piled rafts. For piled rafts with equally spaced and identical piles subjected to a uniform vertical load, PLAXIS 2D analysis overestimates settlement by approximately 45%. Despite the inherent limitations of PLAXIS 2D, reasonably closer values for horizontal displacement can be obtained for piled rafts subjected to lateral loads, with values varying between –30% and +18% compared to field measurements and 3D analysis results. However, for piled rafts under non-uniform combined loading, the horizontal deformation results obtained from PLAXIS 2D can be overestimated by up to 140% compared to 3D analysis.

Keywords: Piled-raft, PLAXIS 2D, plane strain properties, smeared parameters

1. Introduction

The piled-raft is a composite construction consisting of the three elements: piles, raft and soil, which is used in Foundation Engineering in order to limit total and differential settlements and to increase bearing capacity of a raft foundation. The researchers have developed theoretical and empirical approaches in order to analyse this foundation system. However, since each case application differs from another, the possibility to simplify problems so that global conclusions can be made, is quite limited.

Raibei (2009) classifies the analysis methods available for the piled-rafts under three broad classes.

(a) Simplified calculation methods
(b) Approximate computer-based methods
(c) More rigorous computer-based methods

Two-dimensional software analysis via PLAXIS 2D comes under the third class. Few researchers have studied and published articles regarding the applicability of this software for piled-rafts under vertical loads. This study aims to explore the applicability of PLAXIS 2D software for analyzing piled raft foundations subjected to lateral and combined vertical-lateral loading conditions, an area that has not been examined in previous research.

Out of number of experimental and numerical piled-raft cases found in previous research studies, four cases have been simulated using PLAXIS 2D software to evaluate its performance. To assess the accuracy and applicability of PLAXIS 2D, the simulated settlement values were compared against measured field data or 3D analysis data.

2. PLAXIS 2D Software

PLAXIS 2D software is a two-dimensional finite element program used to perform deformation, stability and flow analysis for various types of geotechnical applications. Real situations can be modelled either by a plane strain or an axisymmetric model in PLAXIS 2D. In this study, the piled rafts are simulated as plane strain model.

Among the five types of elements available in software, soil element, plate element and interface element are used for simulation of subsurface condition, raft and piles, and soil-pile interface respectively.

PLAXIS 2D software provides room to define different levels for meshing into finite elements, different material models and number of calculation types. The level of meshing, material models and calculation types used in the analysis are mentioned under each example below.

3. Modelling of piled raft foundations in PLAXIS 2D

As demonstrated by Ryltenius (2011), the piled-raft is simulated as a plane strain model in PLAXIS 2D. The raft and piles are modelled as plate elements of unit length. Soil is modelled by triangular soil elements with each element having 15 nodes and 12 stress points. In transforming the 3-dimensional problem into a 2-dimensional model, the rows of piles that extend out of the plane are simplified as plate elements, known as 'plane strain piles' (Figure 1). In simple terms, the four piles in row 'i' (shown in Figure 1) are represented in PLAXIS 2D by a single plate element. This plane strain pile is defined in such a way that it represents the equivalent properties and behavior of all four actual piles.

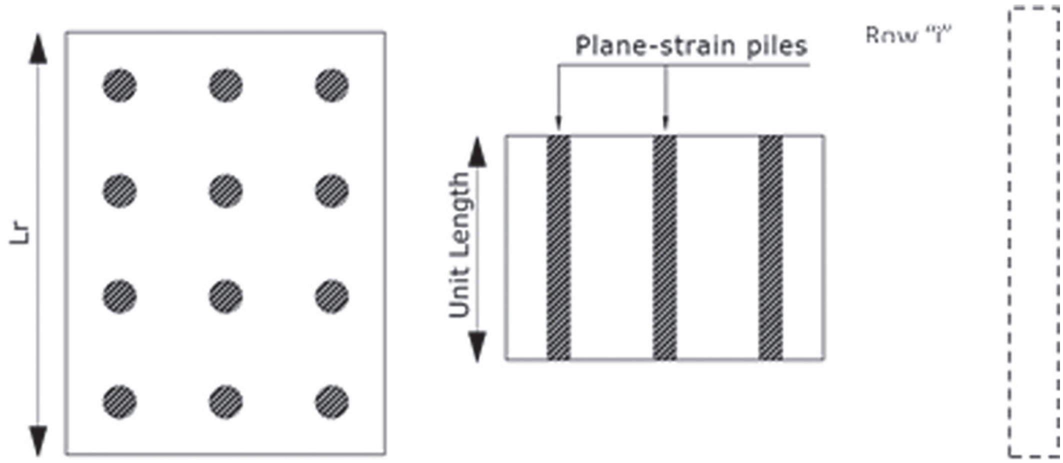

Figure 1: Plane-Strain piles

As to Ryltenius (2011), the plane strain pile is defined by parameters per unit length, identified as "smeared-parameters" and calculated as follows;

Normal stiffness (EA_{psp}) $= EA_P \frac{n_{p-row-i}}{L_r} =$ (1)

Bending stiffness (EI_{psp}) $= EI_P \frac{n_{p-row-i}}{L_r} =$ (2)

Weight (w_{psp}) $= w_p \frac{n_{p-row-i}}{L_r} =$ (3)

Where;

E = Young's modulus of the pile material

I_p = Second moment of Inertia of pile cross section

A_p = Cross section area of pile

I_{psp} = Second moment of Inertia of plane strain pile cross section

A_{psp} = Cross section area of plane strain pile

w_p = Weight of pile

$n_{p\text{-}row\text{-}i}$ = Number of piles in row "i"

w_{psp} = Weight of plane strain pile

Lr = Raft length in plane

With the introduction of plane strain piles in PLAXIS 2D, the actual peripheral area of the pile's changes, affecting the skin friction of the shaft. Thus, it is required to introduce an equivalent shaft resistance.

In 3 dimention, shaft resistance is;

R_{shaft} = perimeter x length x unit friction --- (4)

As explained by Ryltenius (2011), a plane strain pile has a periphery defined by its two sides, the shaft resistance is modified as,

$$f_{shaft,eq} = \frac{n_{p-row-i} A_s f_{shaft}}{2L_r} = \alpha_{ar} f_{shaft} \quad (5)$$

Where;

A_s = Shaft area per unit depth

α_{ar} = Area ratio; total circumference area of the row of piles/ area of plane-strain pile

$f_{shaft,eq}$ = Equivalent shaft resistance of plane stain pile

f_{shaft} = Shaft resistance of the raw of piles

In PLAXIS 2D, the interface elements can be defined to simulate the displacement discontinuity between the pile and the soil mass. As to Ryltenius (2011), the interface element has the strength properties of the surrounding soil reduced by a factor called strength reduction factor ($R_{inter)}$. This factor reflects the imperfect contact between the pile and the soil and is applied in models such as the Mohr-Coulomb model. It has value of one, when in perfect contact, and less than one when in partial contact (weaker interface).

Therefore, to accurately simulate the pile–soil interaction in PLAXIS 2D , the strength reduction factor for interface is redefined as,

$$R_{inter,eq} = \alpha_{ar} R_{inter} = \frac{n_{p-row-i} A_s}{2L_r} R_{inter} \tag{6}$$

where;

$R_{inter,eq}$ = The equivalent strength reduction factor for interface

R_{inter} = The strength reduction factor for interface

The typical values for strength reduction factor (R_{inter}) given by Ryltenius (2011) are;

- Cohesive soils : 0.7-0.8
- Frictional soils : 0.9

According to Ryltenius (2011), the raft parameters for 2-dimensional simulation are calculated as follows;

Normal stiffness = EA_{pc}

Bending stiffness = EI_{pc}

Weight (w_{psp}) = A_{pc} x ρ_c

where,

E = Young's modulus of the raft material

A_{pc} = Cross section area of raft per meter

I_{pc} = Second moment of Inertia of raft cross section per meter

P_c = Density of raft material

The loads were calculated per unit length to apply in the PLAXIS 2D model.

4. Simulation of examples

Four example problems have been selected from literature so that the current approach can be compared to already published results. The Mohr-Coulomb soil model was assigned for all four examples and the mesh assigned was fine global mesh followed by cluster mesh and line mesh around piles. Interface element has been defined around the piles.

4.1 Example from Ryltenius (Ryltenius, 2011):

Master's Dissertation of Ryltenius (2011) presents a hypothetical example of vertical load application on a piled-raft (Figure 2), simulated in PLAXIS 2D software and maximum and minimum settlement results have been published. Table 1 and 2 shows the sub surface parameters and smeared parameters for piles and raft respectively. Table 3 presents the result comparison and it is observed that results are identical. Figure 3 presents the PLAXIS 2D model created and Figure 4 presents the vertical deformation result obtained from PLAXIS 2D simulation.

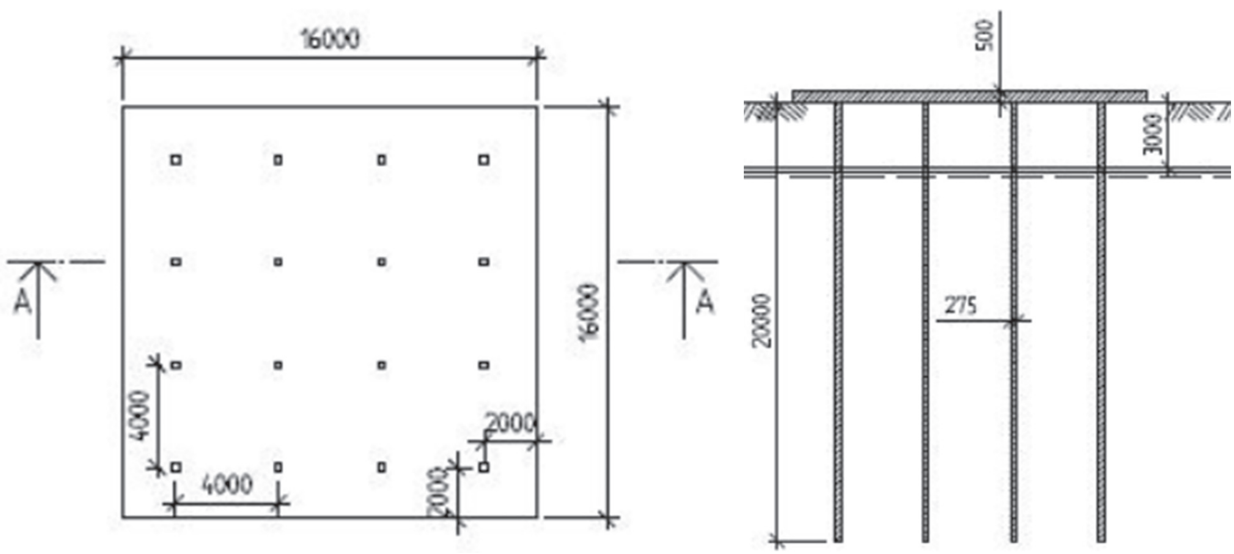

Figure 2: Piled-raft layout and cross section of example, (2011)

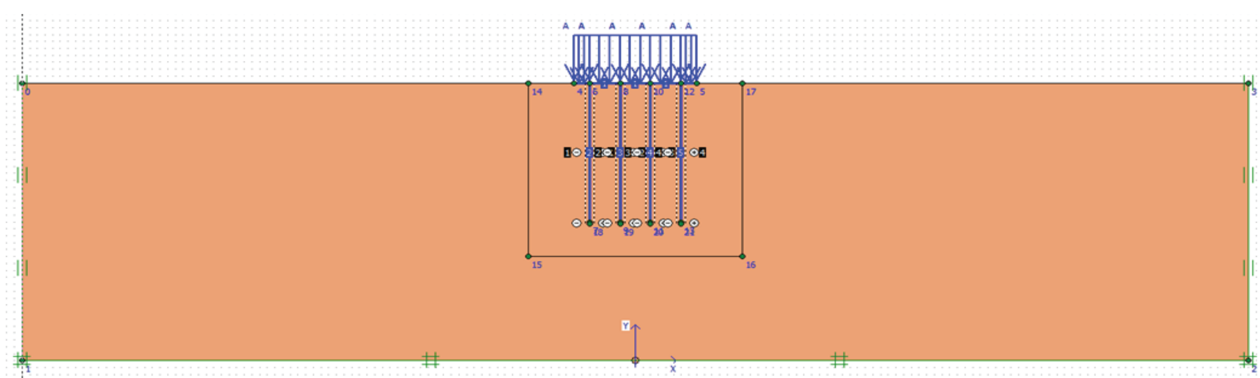

Figure 3: Plaxis 2D model of the problem

Table 1: Sub surface parameters, (2011)

Input Parameter	Clay
Young's modulus, E	5000 kN/m^2
Poisson's ratio, ν	0.35
Saturated unit weight, γ_{sat}	18 kN/m^3
Unsaturated unit weight, γ_{unsat}	kN/m^3
Cohesion, c	4 kN/m^2
Friction angle, Φ	30°
Dilatancy angle, ψ	0°
$R_{inter,eq}$	0.11

Table 2: Smeared Parameters for the plain strain pile and the raft for example 1

Input Parameter	Raft	Pile
Normal stiffness, EA (kN/m)	17.5x10^6	662 x 10^3
Bending stiffness, EI (kNm^2/m)	365x10^3	4170
Poisson's ratio, ν	0.2	0.2
Weight, W (kN/m/m)	12.5	0.47

Table 3: Maximum and Minimum settlement of the raft

	PLAXIS 2D Results of Ryltenius (2011)	PLAXIS 2D Results in this research work
Maximum Settlement of the raft (mm)	121	121
Minimum Settlement of the raft (mm)	105	105

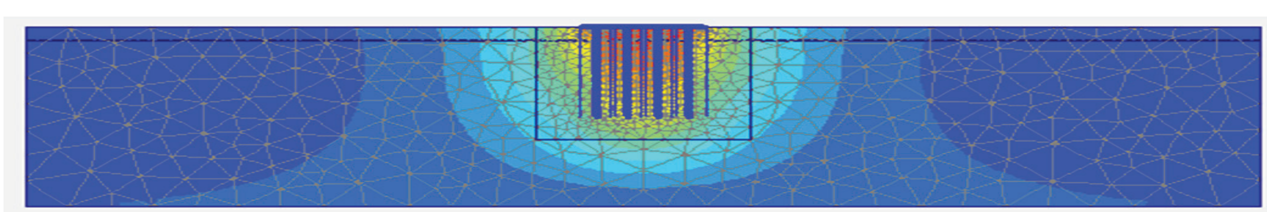

Figure 4: Vertical deformations-PLAXIS 2D result

4.2 Example from Small and Poulos (Small & Poulos, 2007):

A research paper by Small and Poulos (2007) presented an experimental investigation of actual scenario of a piled raft under a vertical load, with measured results and analysis results from GARP computer program.

In current study, the field settlement values of one of twin piled-rafts of Messe-Torhaus building in Germany, as reported by Small and Poulos (2007) were compared with PLAXIS 2D software simulation of the same.

The piled-raft arrangement is shown in Figure 5. The sub surface properties and calculated smeared parameters for raft and plane-strain piles are presented in Tables 4 and 5 respectively. A uniform vertical load of 404 kPa was applied to the model referring to Small and Poulos (2007).

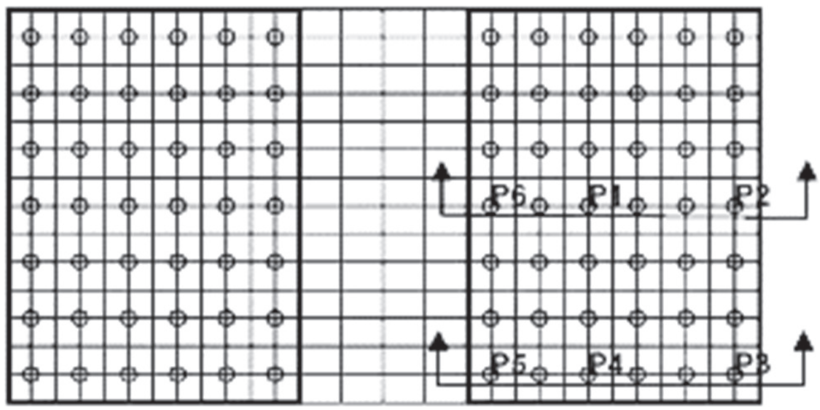

Figure 5: Piled-raft arrangement of Messe-Torhaus building, (Small & Poulos, 2007)

Table 4: Sub surface parameters for example 2

Properties	Soil layer (0-20m) depth	Soil layer (20-50m) depth
Young's modulus, E (kN/m^2)	47000	62800
Poisson's ratio, v	0.15	0.15
Saturated density, γ_{sat} (kN/m^3)	18.5	18.5
Cohesion, c (kN/m^2)	20	20
Friction angle, Φ	20˚	20˚
Strength reducing factor for pile-soil interface	0.202	0.202

Table 5: Smeared Parameters for the plain strain piles and the raft for example 2

Input Parameter	Raft	Pile
Normal stiffness, EA (kN/m)	85x10^6	4,269,279
Bending stiffness, EI (kNm^2/m)	44,270,833	216,132
Poisson's ratio, ν	0.2	0.2
Weight, W (kN/m/m)	62.5	4.54

PLAXIS 2D analysis as well as GARP analysis overestimate the settlement of the raft. The results are tabulated in Table 6. The variation of settlement along the raft axis is graphically presented in Figure 6. Figure 7 shows the settlement of the soil mass. These variations cannot be compared with measured results or results of GARP analysis as they were not presented by the researchers.

Table 6: Measured and calculated settlements of raft at end of the construction

	Field measured mean settlement (Small & Poulos, 2007) (mm)	Average settlement of two rafts (mm)	Mean settlement of GARP analysis (Small & Poulos, 2007) (mm)	Mean settlement of PLAXIS 2D analysis (mm)
Northern raft	65	72.5	85	105
Southern raft	80			

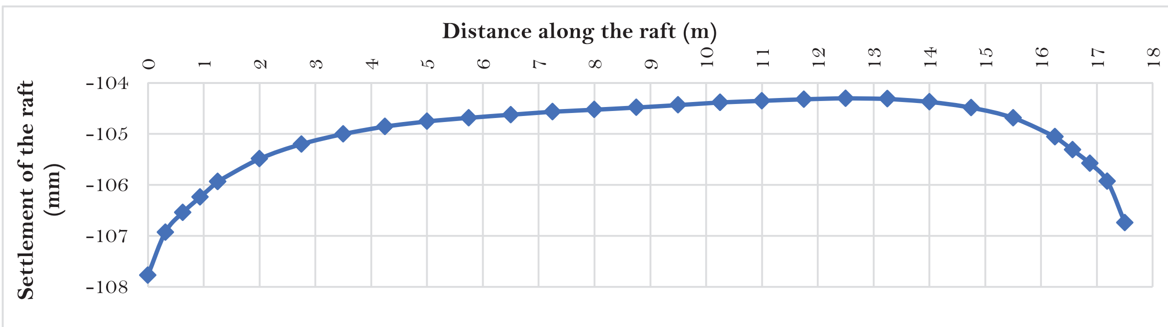

Figure 6: Settlement of the raft obtained from PLAXIS 2D analysis

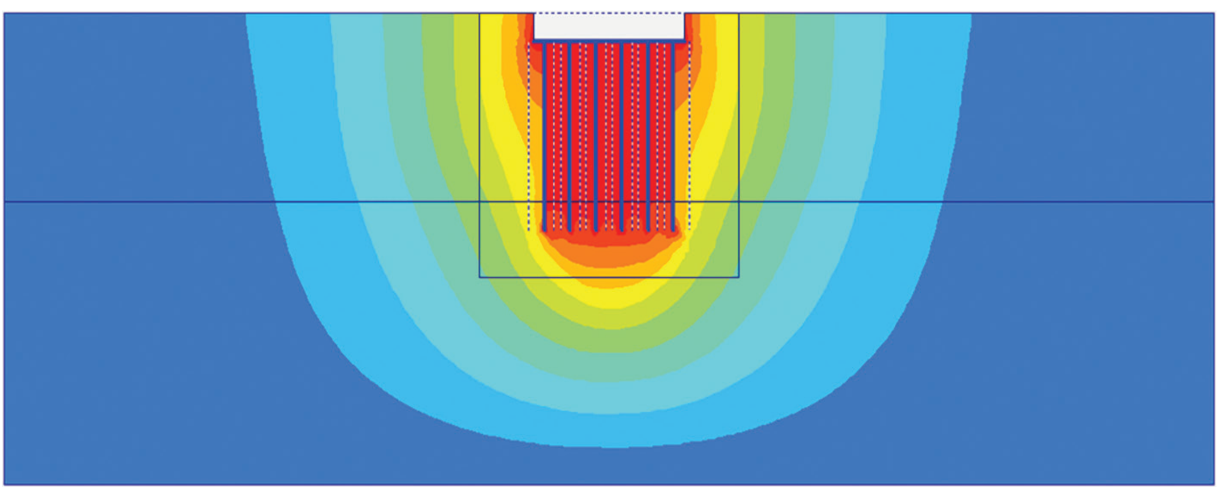

Figure 7: PLAXIS 2D output of settlement for piled raft of Messe-Torhaus building

4.3 Example from Rollins and Sparks (Rollins & Sparks, 2002):

Rollins and Sparks (2002) presented experimental investigation of a piled raft subjected to incremental horizontal loads, with measured displacement results. The horizontal load was applied by two hydraulic jacks. The test set up is shown in Figure 8. The sub surface consists of number of different soil strata and the relevant parameters are tabulated in Table 7. The strength reduction factor for cohesive soils and frictional soils has been calculated using the formula (Rollins & Sparks, 2002) mentioned above, and the values are 0.39 and 0.5 respectively. The water table level was just below the bedding beneath the raft. The water pressures were generated by defining the phreatic level.

The calculated smeared parameters for raft and plane-strain piles are presented in Table 8.

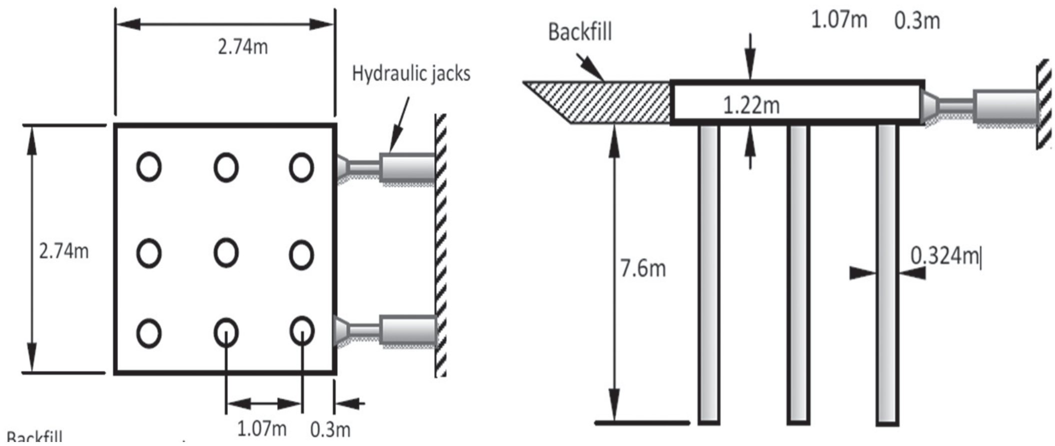

Figure 8: Test set up for example 3

Table 7: Sub surface parameters for example 3 (Rollins & Sparks, 2002)

No	Soil Type	Layer Thickness (m)	γ_{sat} (kN/m³)	k_x,k_y (m/s)	E_s (kN/m²)	ν	c' (kN/m²)	φ' (°)
1	Compacted sandy gravel	1.4	33.41	1x 10^{-1}	45000	0.2	-	42
2	Sandy Silt	0.6	18.86	1x 10^{-6}	7400	0.3	37	-
3	Grey clay	1.5	18.86	1x 10^{-7}	9000	0.35	42	-
4	Light grey sandy Silt	0.9	18.86	1x 10^{-6}	6000	0.3	30	-
5	Light brown sand	2	20.41	1x 10^{-4}	45000	0.3	-	39
6	Grey clay	0.6	18.86	1x 10^{-7}	5000	0.35	25	-
7	Light grey silt	0.6	18.86	1x 10^{-6}	12000	0.3	60	-
7	Light brown sandy silt	0.9	18.86	1x 10^{-6}	12000	0.3	60	-
8	Light grey silty sand	1.4	20.41	1x 10^{-4}	30000	0.35	-	36
9	Grey silt	1.5	18.86	1x 10^{-6}	15000	0.3	75	-

Table 8: Smeared Parameters for the plain strain pile and the raft for example 3

Input Parameter	Raft	Pile
Normal stiffness, EA (kN/m)	39.4x10^6	5.5 x10^6
Bending stiffness, EI (kNm²/m)	4.8 x10^6	36,448
Poisson's ratio, ν	0.2	0.25
Weight, W (kN/m/m)	29.28	2.726

In the PLAXIS 2D analysis, 7 number of phases were defined for calculation stage. Construction of the structure was defined as phase number 1, and the rest were for definition of each load increment imposed on the structure. The field test has been carried out 485 days after the consturction and that time period was defined at phase 1, before the application of loads.

The backfill (marked in Figure 8), that consists sandy gravel, could not be considered as a soil layer in load application phases, because, the raft can only be simulated as a 1D plate element in which the physical thickness is unable to visually represent in the model (the actual thickness of raft is incorporated in calculation of smeared parameters). Thus, the effect of sandy gravel backfill was included into the model by the application of a vertical line load for self-weight and a horizontal point load for passive pressure in definition of phases (Figure 9).

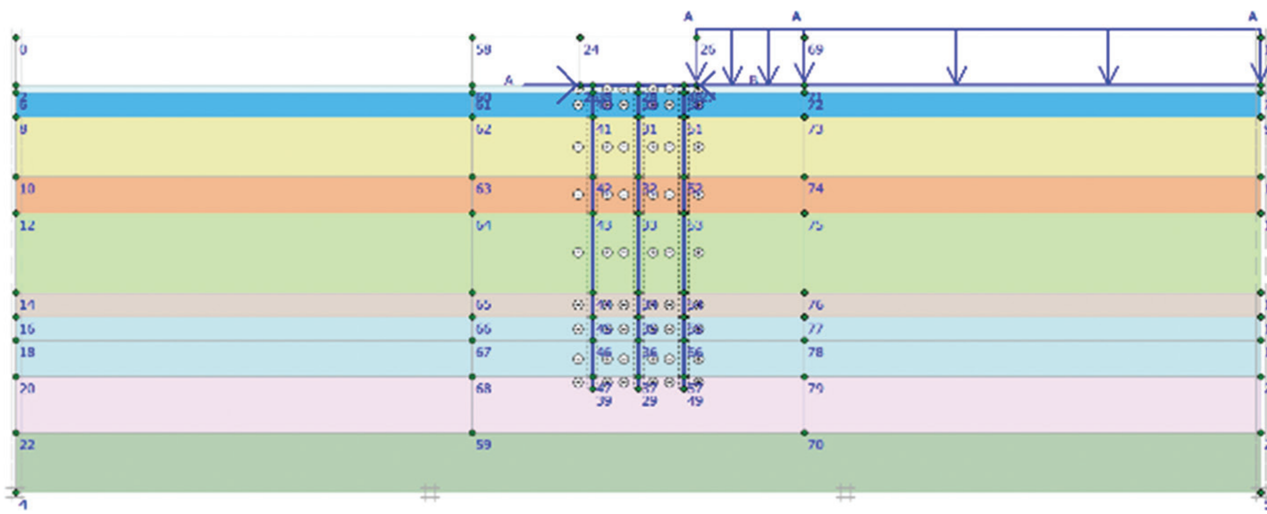

Figure 9: Application of vertical pressure and passive pressure of sandy gravel backfill

Inability to simulate the visible raft thickness is a limitation in software, which is a drawback while designing buried rafts. The passive pressure development in soil mass is unable to be automatically carried out by finite element analysis due to this limitation.

The maximum passive pressure was considered as 755 kN when the raft displacement is 49 mm with reference to Poulos et al. (2011). The passive pressure on the raft at initial stage of loading was calculated from Rankine's earth pressure theory, which is 246.8 kN.

Although the passive pressure is a function of deflection of raft, and it varies non-linearly with the load increment, it was assumed to be a linear variation considering the practical difficulty in calculations. Therefore, passive pressure was imposed in phase 2 to phase 7 assuming linear variation from 247kN to 755kN against loading variation from 0 to 2225kN. The calculated self-weight of the backfill was 29 kN/m/m.

Figure 10 shows the analysis result at second load increment. Figure 11 is the graphical interpretation of the result comparison.

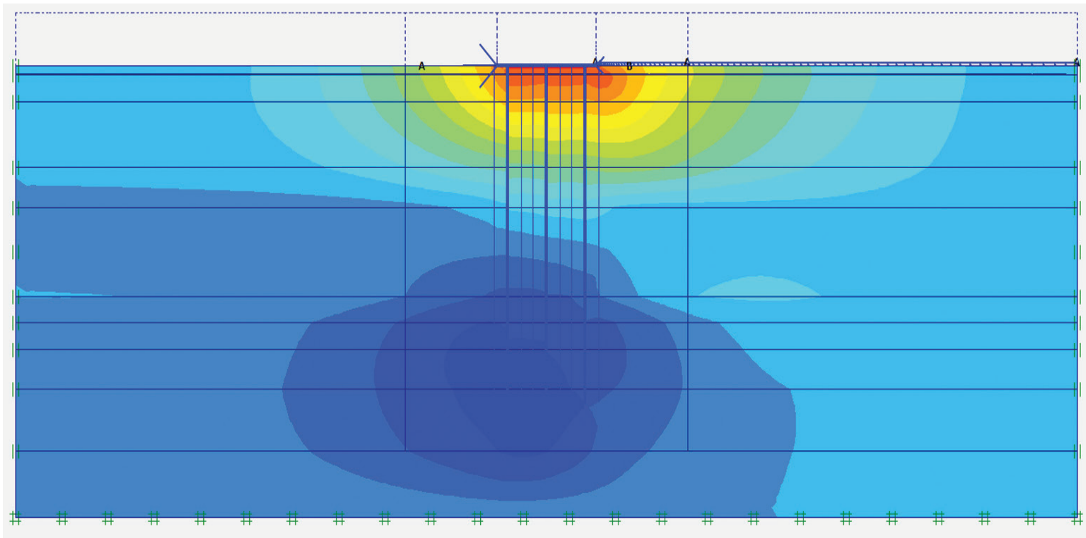

Figure 10: Horizontal displacement at phase 3 (2nd load increment)

Table 9: Loads applied on the model and the analysis result for example 3

Load increment	Load applied in the field (kN)	Load applied on model (kN/m)	Horizontal displacement at the load application point in Plaxis 2D(mm)	Horizontal displacement measured at the load application point in the field (mm)
1	650	237	1.6	9.0
2	1110	405	11.0	16.0
3	1550	566	20.0	26.0
4	2000	730	32.5	37.0
5	2225	812	44.0	46.0
6	2650	967	90.0	60.0

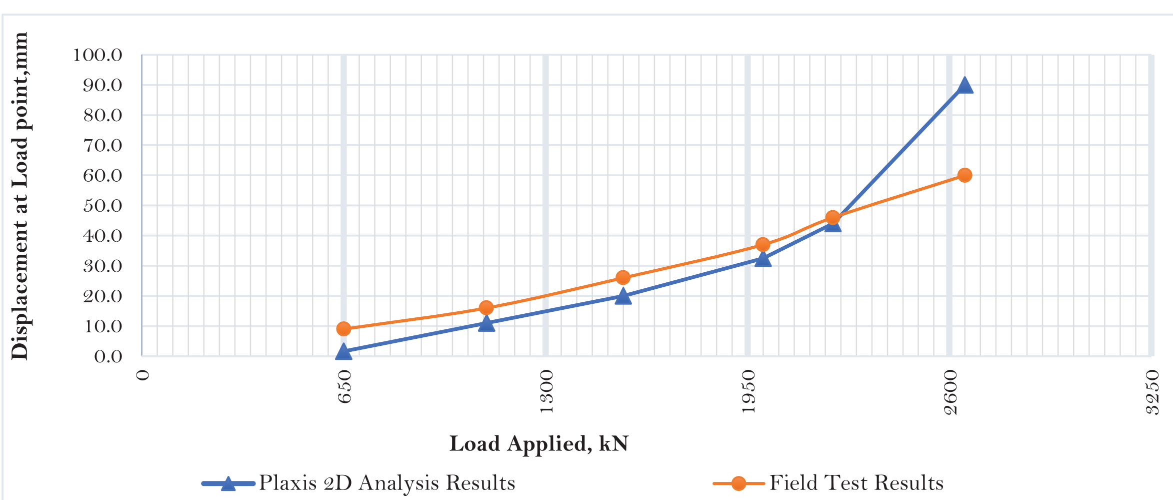

Figure 11: Applied load vs. raft displacement at load point

It is apparent that the PLAXIS 2D results approximate the experimental data quite well except for the last load increment. The reasons for the differences between the two curves could be as follows;

1. The actual passive pressure would deviate to some extent from the calculated value.
2. A sheet pile wall had been constructed in load application set up. Its depth and other relevant details were not presented in the research paper. The effect of sheet pile wall in the subsurface was not simulated in PLAXIS 2D model.
3. In the actual scenario the loads had been applied at a height of 0.4m above the base of the pile cap face. Since the pile cap can only be represented by a 1D plate element, the load was applied at one edge of the element.

If one considers the trend, it is clear that the last field result is not consistent with the others. This could be due to some error in measurement.

4.4 Example from Salahshour and Ardakani (Salahshour & Ardakani, 2017):

Nguyen et al. (2013) performed a centrifuge test for a piled raft subjected to vertical loads, and Salahshour and Ardakani (2017) had simulated the same scenario using PLAXIS 3D software and presented result comparison in this research paper. Further, Salahshour and Ardakani (2017) performed a parametric study for the same piled raft model under lateral loads and also a combination of vertical and lateral loads, using PLAXIS 3D software.

The arrangement of the piled raft is shown in Figure 12. A raft of 19 m x 19 m is supported by 16 number of 0.6 m diameter circular piles. The loads are applied from four columns C1, C2, C3, and C4 as marked on the layout.

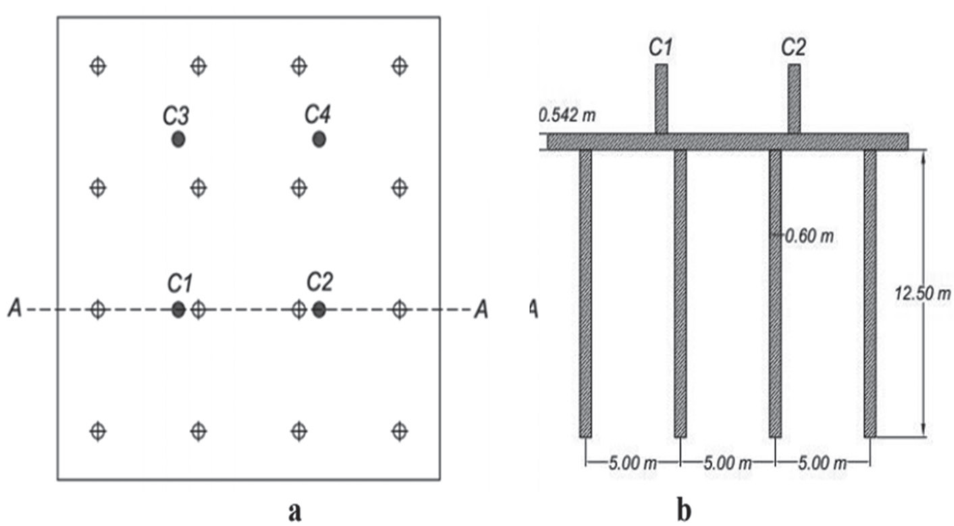

Figure 12: Pile raft arrangement for example 4

The parameters of loose silica sand used for subsurface condition are presented in Table 10. The Strength reducing factor for pile soil interface calculated using formula number 5 for cohesionless soil is 0.178.

Table 10: Soil Parameters for example 4

Parameter	Value
Saturated Density (γ_{sat})	18.5 kN/m^3
Dry Density (γ_d)	13.7 kN/m^3
Dilatancy angle (ψ)	8°
Friction angle (Φ)	40°
Poisson's ratio (ν)	0.25
Young's Modulus (E)	
0 m-10 m:	16.11 MPa
10 m-15.2 m:	24.87 MPa
15.2 m-22.8 m:	47.68 MPa
22.8 m-35 m:	109.68 MPa

4.4.1 PLAXIS 2D Simulation for vertical loads

Loads of four different values have been exerted on four points, in the experiment and 3D analysis. However, in order to simulate it two dimensionally, loads of same row were added together, and were applied in two points as load P1, P2 in the PLAXIS 2D model as indicated in Figure 13.

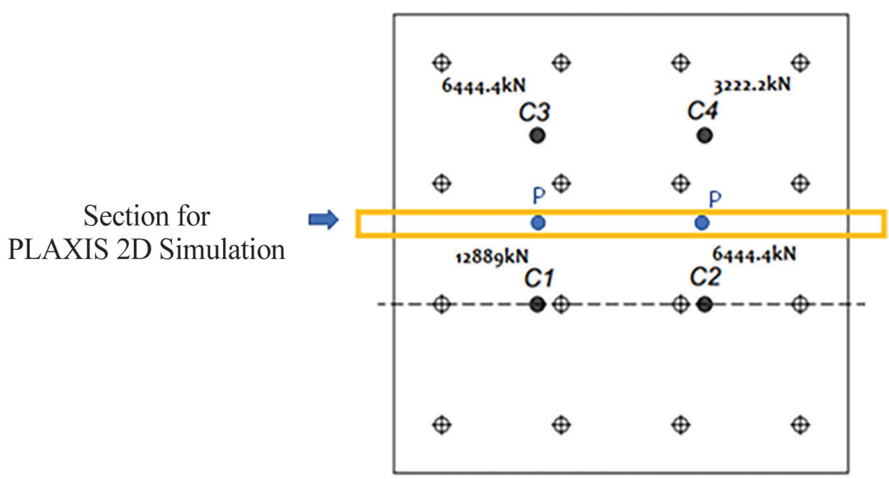

Figure 13: Application of Vertical loads

P1 = (6444.4+12889)/19 = 1017.54 kN/m

P2 = (3222.2+6444.4)/19 = 508.77 kN/m

The results of settlement along raft were compared with that of the experiment (Nguyen et al., 2013) and 3D FEM analysis (Salahshour & Ardakani, 2017) in Figure 15.

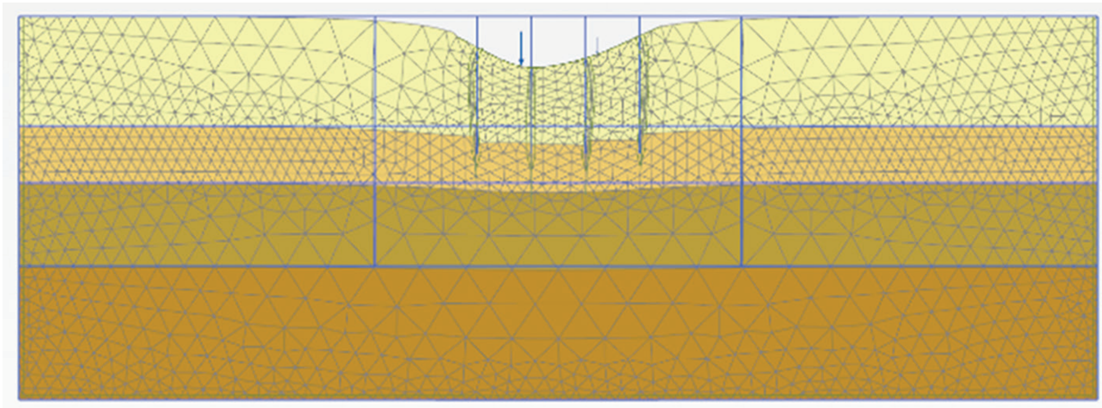

Figure 14: Deformed shape of the model after application of vertical load

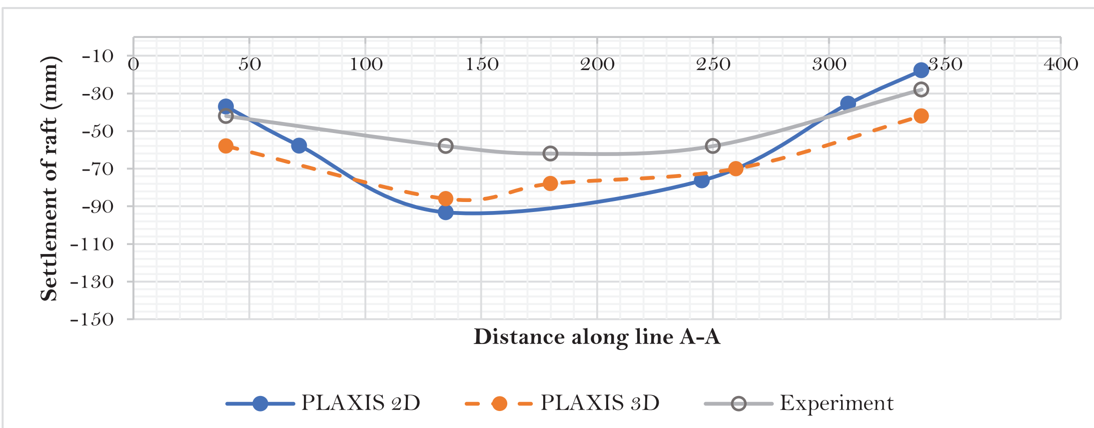

Figure 15: Settlement along raft under vertical load- result comparison

In the Figure 15, it could be observed that, the curve of PLAXIS 2D result agrees quite well with the curve of PLAXIS 3D result at the middle part of the raft. Outside the middle area, it predicts the settlement better than that by the 3D model.

The maximum settlement occurs at the same distance along the raft in both PLAXIS 2D and PLAXIS 3D analysis, as well as the difference is only 7mm (about 8%). The maximum settlement as predicted by FEM analyses occur closer to P1 load point. However, the maximum settlement of raft has occurred closer to the centre in the centrifugal test results.

These differences indicate the following limitations of usage of PLAXIS 2D software;

1. When the point loads of different magnitudes acting on different planes of raft are simplified and applied in PLAXIS 2D, the differential settlement along perpendicular axis of the raft in actual 3-dimensional case is not visible in results.
2. Even though variation of settlement values along different sections of raft will be different to each other, the PLAXIS 2D can show settlement of simplified section only.
3. Differential loading perpendicular to the 2D section considered for the analysis is not represented.

4.4.2 PLAXIS 2D Simulation for Lateral loads

Salahshour and Ardakani (2017) performed 3D numerical analysis for the same piled raft with lateral loads of equal magnitude of 2900 kN in "x" direction on each loading point C1, C2, C3 & C4 of Figure 11. The example is simplified to 2D modelling as follows;

P1 =P2 = (2900+2900)/19 = 305.26 kN/m

Figure 16 presents the total displacement of the piled raft that is subjected to horizontal loading. A graphical comparison of the horizontal deformation obtained from PLAXIS 2D and PLAXIS 3D is presented in Figure 17.

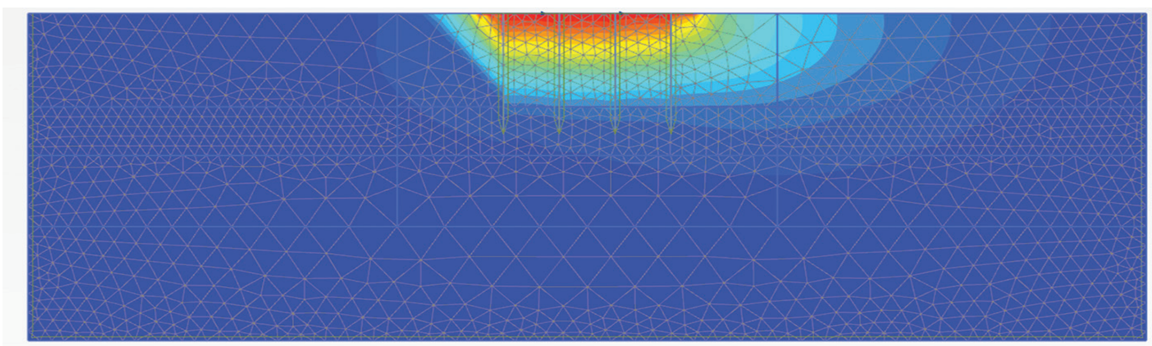

Figure 16: Total displacements of piled raft subjected to lateral loading

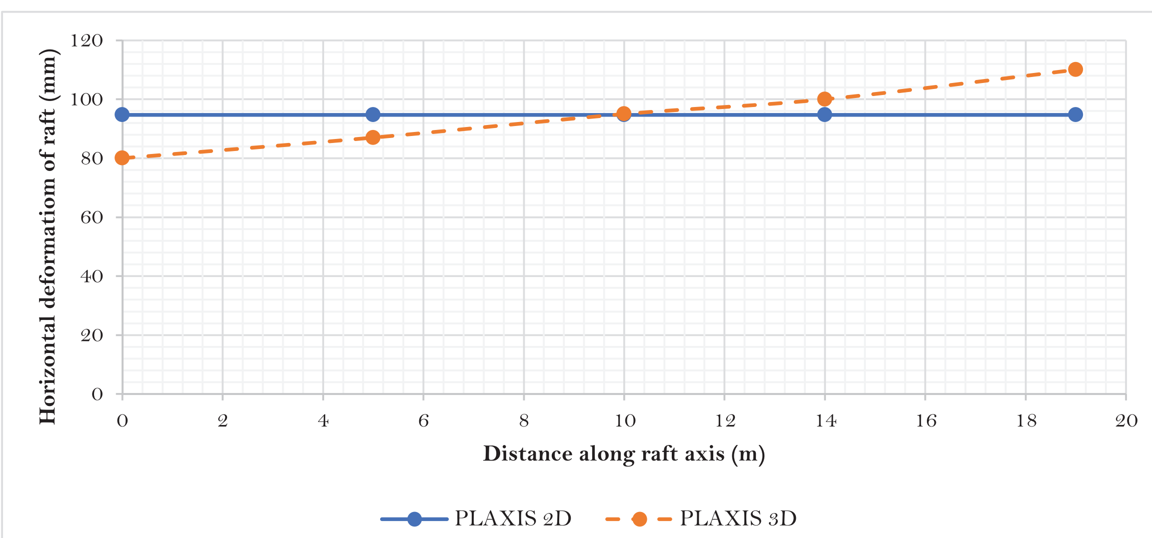

Figure 17: Horizontal deformation of raft along raft axis- result comparison of PLAXIS 2D vs. PLAXIS 3D Foundation result of Salahshour and Ardakani (2017)

In Figure 17, it clearly appears that the PLAXIS 3D result from Salahshour and Ardakani (2017) varies linearly along the raft, while in the PLAXIS 2D simulation, the deformation value remains constant along the raft. Percentage differences are small although they change sign from one end to the other. The difference of results is supposed to be due to the difference in load application, and simplification of problem from 3-dimensional to 2-dimensional scenario.

Moreover, the deformation results presented in paper are along axis A-A (Figure 12). But since the loads are scattered, the results would vary along center line or another line along the piled raft.

It is apparent that rotation has been occurred in 3D case leading to a linear variation rather than a constant value. Therefore, inability to interpret actual rotation of raft is a limitation of PLAXIS 2D. It is also noted that the numerical value of the deformation predicted by the 2D model is within an acceptable value of that of the 3D model and represents a value close to the average deformation of the 3D result over the length of the raft.

4.4.3 PLAXIS 2D Simulation for Combined Loads

Salahshour and Ardakani (2017) performed 3D numerical analysis for combined loading on the same pile raft using PLAXIS 3D software. The loads applied were a combination of vertical and lateral loads, the separate effects of which were discussed sections 4.4.1 and 4.4.2 respectively. The total displacements obtained after analysis in PLAXIS 2D is shown in Figure 17. The horizontal deformation of raft obtained from PLAXIS 2D was compared with that of PLAXIS 3D presented by Salahshour and Ardakani (2017). The graphical representation of result comparison is shown in Figure 19.

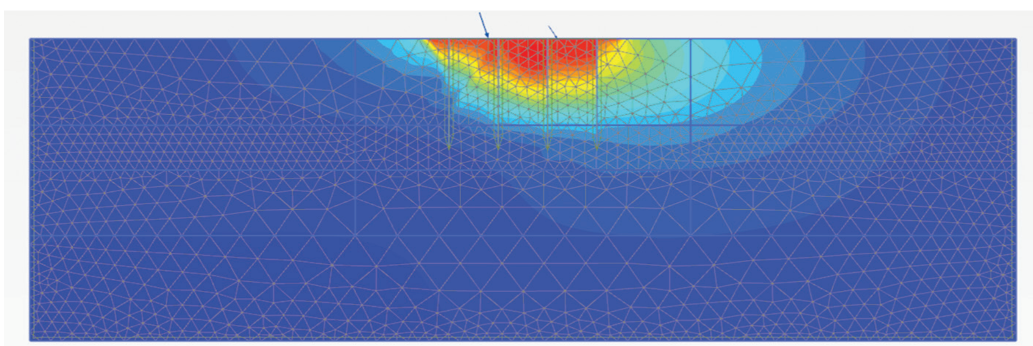

Figure 18: Total displacements of piled raft subjected to combined loading

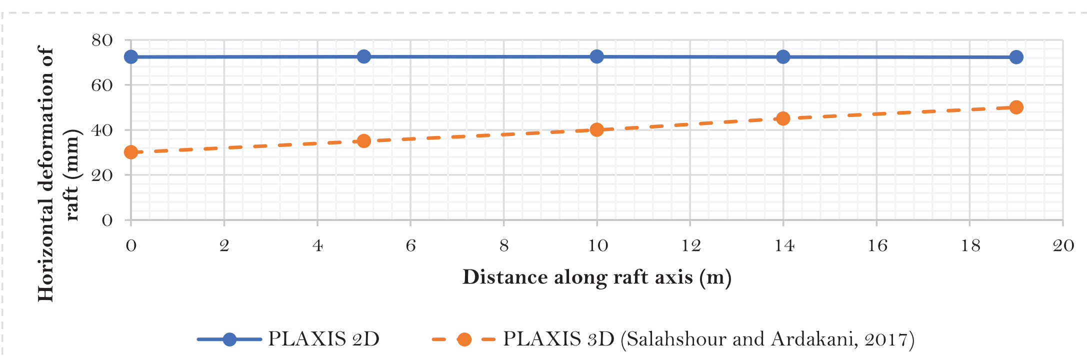

Figure 19: Horizontal deformation of raft along raft axis- result comparison of PLAXIS 2D Vs. PLAXIS 3D result of Salahshour & Ardakani (2017)

As in the case of lateral loading, in the combined loading also, the horizontal deformation varies linearly in PLAXIS 3D Foundation result while the PLAXIS 2D result remain constant throughout the raft axis. However unlike in the case of lateral loading, the 2D analysis considerably overestimates the deformation value of PLAXIS 3D in this case. These differences are believed to be due to the following reasons;

1. Loads were applied in couple of planes in experiment and 3D model (Salahshour & Ardakani, 2017). On contrary in two-dimensional analysis, it can only be applied in a single plane. The real loading scenario cannot be simulated. Only an approximation can be done. Thus, the rotation of the raft which is a 3-dimensional phenomenon is not visible in PLAXIS 2D results.
2. The horizontal deformations presented in Salahshour & Ardakani (2017) are along axis A-A (Figure 12), which is drawn on a line of piles, therefore has greater resistance than the plane considered in PLAXIS 2D analysis which has an average resistance of the piled-raft.

The vertical settlement result obtained from PLAXIS 2D is presented in Figure 20. The respective results (vertical settlements) of 3D modelling have not been presented in Salahshour & Ardakani (2017) and hence a-comparison is not possible. The impact of the lateral loading on vertical settlement can be observed in the graph, when compared with vertical loading only. It is noted that the load combination result shows an increased settlement in general and the effect of lateral force can be seen in the variation of shape.

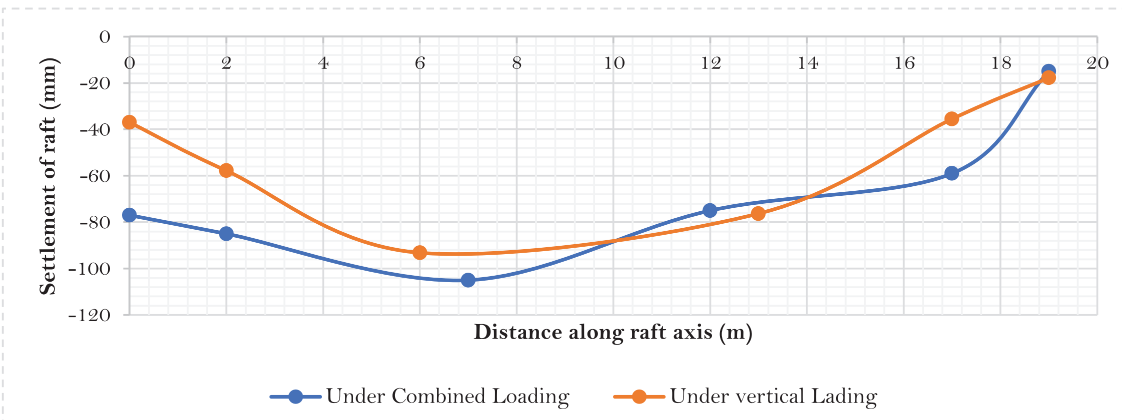

Figure 20: *Vertical Settlement of raft along raft axis from PLAXIS 2D subjected to Vertical Loading and Combined Loading*

5. Results and Discussion

1. In the second analysis (Section 4.2), a notable discrepancy of 23% was observed between the measured settlements of two supposedly identical rafts under vertical loading, with no clear explanation. When comparing the average of these field measurements with numerical predictions, PLAXIS 2D overestimated settlement by 45%, while GARP showed a comparatively lower overestimation of 17%.
2. In the third analysis (Section 4.3), PLAXIS 2D predicts the horizontal displacements under lateral loading reasonably well. The values obtained were 4%-31% lesser than the field measured values at the initial load increments and goes 50% greater at the last load increment.
3. The fourth analysis (Section 4.4.1) PLAXIS 2D results agrees quite well with PLAXIS 3D at the raft center and predicts the edge settlements better than that by PLAXIS 3D. The variation of PLAXIS 2D results with respect to field measured result is -12% to 62% and with respect to PLAXIS 3D result is -57% to 8%.
4. In the fourth analysis (Section 4.4.2), lateral loads were applied at two points in the PLAXIS 2D model, compared to four points in different planes in the 3D model, which cannot be replicated in 2D. The 2D model showed a constant horizontal deformation of 95 mm, while the 3D results varied

from 80 mm to 110 mm, with differences ranging from -14% to 18%. This shows that the results are comparable in magnitude although the variation is not captured by the 2D model.

5. In the latter part of the fourth analysis (Section 4.4.3), combined vertical and horizontal loads were applied by simplifying four load points into two in PLAXIS 2D. The 2D model showed a constant horizontal deformation of 72 mm, while PLAXIS 3D results varied from 30 mm to 50 mm, with differences ranging from 44% to 141%. This indicates a considerable deviation, likely due to both the 2D simplification and load application.

6. Conclusions

Based on the analysis of examples of piled raft foundations using PLAXIS 2D software following conclusions can be made;

1. For the cases of piled rafts with equally spaced and identical piles, subjected to uniform vertical loads, the settlement values obtained from both PLAXIS 2D and PLAXIS 3D simulations are higher than the actual values.
2. Despite the limitations of the PLAXIS 2D software, reasonably closer values for horizontal displacement can be obtained for piled rafts subjected to lateral loads. As per the worked examples, the values vary between -30% to 18% compared to field measurements and 3D analysis results. In formulation of the analysis the PLAXIS 2D software itself is unable to analyse the contribution to resistance from the sides of raft and the passive resistance. Those values have to be calculated and fed to the software as loads.
3. The horizontal deformation results obtained from PLAXIS 2D for a piled raft under non-uniform combined loading, exhibit an overestimation compared to 3D analysis. The overestimation could be upto 140% of the 3D analysis results. Yet PLAXIS 2D software can be recommended for preliminary analysis for a piled raft subjected to combined loading.

To carry out further analysis, it is recommended to simulate a piled raft subjected to combined vertical and lateral loading where the actual field measured results available.

References

Bentley Systems. (2021). *Virtuosity: A Bentley Company.* https://blog.virtuosity.com

Nguyen, D.D.C., Jo, S.B. & Kim, D.S. (2013). Design method of piled-raft foundations under vertical load considering interaction effects. *Computers and Geotechnics, 47*, 16-27. https://doi.org/10.1016/j.compgeo.2012.06.007

Poulos, H.G., Small, J.C. & Chow, H. (2011). Piled raft foundations for tall buildings. *Geotechnical Engineering Journal of the SEAGAS and AGSSEA, 42*(2), July, 78-84

Rabiei, M. (2009). Parametric study for piled raft foundations. *Electronic Journal of Geotechnical Engineering, 14*.

Rollins, K.M. & Sparks, A. (2002). Lateral resistance of full-scale pile cap with gravel backfill. *Journal of Geotechnical and Geoenvironmental Engineering, 128*(9), 711.

Ryltenius, A. (2011) *FEM modelling of piled raft foundations in two and three dimensions* [Master's dissertation, Lund University]. http://lup.lub.lu.se/student-papers/record/5204468

Salahshour, Y. & Ardakani, A. (2017). Evaluation of piled raft behavior based on the Taguchi method subjected to combination of vertical and horizontal loads. *Journal of Engineering Geology, 11*(3), 181-202.

Small, J.C. & Poulos, H.G. (2007). Non-linear analysis of piled raft foundations. *Contemporary Issues in Deep foundations.* https://doi.org/10.1061/40902(221)14