A CASE STUDY ON PILED-RAFT FOUNDATION DESIGN IN BANGLADESH

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ABSTRACT

The selection of foundation systems in very soft soil conditions is one of the major challenges for geotechnical engineers, as there are lots of uncertainties and limitations. The piled-raft foundation system is extensively applicable in such conditions around the globe. However, the practice of designing and implementing piled-raft foundations is limited in Bangladesh. As a result, the main focus of this study is to investigate the design and application of piled-raft foundation systems from Bangladesh's perspective. Moreover, non-linear analysis is known to provide more accurate results, but it can be complex and challenging to utilize. Hence, finding a linear analysis method that is user-friendly and can offer reasonably accurate outcomes, serving as a potential replacement for non-linear analysis, was another objective of this research. To conduct this study, a piled-raft foundation system was chosen in a very soft soil condition situated in Khulna, Bangladesh. In order to accurately analyse the soil's behaviour, a non-linear constitutive model was developed using PLAXIS 3D. By incorporating subsurface investigation data, settlements were calculated manually and compared with the numerical results, encompassing both elastic and consolidation settlement behaviors. The findings revealed that the total consolidation for a period of 90 days amounted to 46.48 mm from non-linear analysis, whereas the total consolidation from linear analysis incorporation with Terzaghi's 1-D consolidation theory and Vesić's method were found to be just 5.14 % and 4.15% less than the non-linear analysis results, respectively. Furthermore, valuable insights obtained from this study helped to build a guideline to design and implement a piled-raft foundation for practitioners. Hence, the linear approaches suggested by this study could be an effective alternative to nonlinear analysis to evaluate the performance of foundation systems.

Keywords: *Very soft soil, piled-raft foundation, nonlinear analysis, PLAXIS 3D, alternate linear approach*

1. INTRODUCTION

The foundation of a building is the most crucial, as it serves as the fundamental base for all other construction. The foundation system of any building structure depends on the type of structure and condition of the soil. The bearing capacity of soil is a key parameter for designing the foundation of any structure. When adequate bearing capacity is not available in the shallower layers of the soil, the practitioners choose a deep foundation system to transfer the load to the desired depth where adequate bearing capacity is available. Though a deep foundation has several advantages, it comes with different challenges and is more costly than a shallow foundation. Hence, it was a great concern for the foundation engineers and researchers to find a more effective foundation system that could be convenient for poor soil conditions. The piled-raft foundation system is one of the best foundation systems that have been developed by the researchers under these given conditions. The bearing elements of the piled-raft foundation system are pile, raft, and supporting soil. The combined effect of these three elements makes this system more efficient than other deep foundation systems (Jamil et al., 2022). The benefits of both shallow and deep foundations can be achieved from piled-raft foundation systems in terms of stability, cost, and load distribution capability.

An effective foundation system can enhance the stability as well as the structural performance of any structure. As this study focuses on the analysis of piled-raft foundation systems, settlement is one of the key factors to be considered. The analysis method to evaluate the settlement of the foundation is a crucial factor, as the precision of settlement calculation has a direct impact on the performance of the piled-raft foundation system. The settlement behaviour of individual pile and raft foundations has been investigated by several researchers over the years. However, the settlement behaviour of the piled-raft foundation and the insightful guidelines for analysis of the settlement are limited. The settlement behaviour of a structure that is supported by a pile foundation, a raft foundation, or a piled-raft foundation was analysed and compared by Poulos H.G. (2001). Another study from Poulos et al. (2011) was done on the behaviour of the piled-raft foundation system of a tall building, and it was found that the contact between the raft and soil provides an additional advantage to the structural performance of the piled-raft foundation. Moreover, the study by Reul & Randolph (2009) also enlightened the effectiveness of the piled-raft foundation system compared to only pile or mat foundations in terms of settlement.

Based on the previous studies, it can be summarised that piled-raft foundations showed less settlement compared to individual pile and raft foundations. However, nonlinear analysis results could predict the settlement with much precision, whereas the analysis method is rigorous and time-consuming compared to linear analysis and manual calculation. This study aims to contribute to existing knowledge on the performance and behaviour of piled-raft foundation systems by investigating the settlement behaviour of foundations using several analytical approaches.

Different studies suggest various methods of numerical analysis and design of piled-raft foundations (Clancy & Randolph, 1993; Jamil et al., 2022; Lin & Feng, 2006; Nguyen et al., 2013; Poulos & Davis, 1980). The elastic and consolidation settlements are calculated by utilising PLAXIS 3D and ETABS 2016 software and manual calculation in this study. Finally, the most appropriate method was found by comparing several combinations for calculating the settlement. These findings contribute to the understanding and advancement of piled-raft foundation analysis and design, specifically regarding settlement, stiffness, and design approaches. The findings will benefit engineers, researchers, and practitioners involved in similar foundation projects.

2. METHODOLOGY

2.1 Structural Geometry of the Selected Project

The chosen structure for this study was a market building with multiple floors (2 basements, 1 ground floor and 9 floors). The rectangular-shaped building has a length of approximately 152.5 m and a width ranging from 15.24 m to 21.34 m.

2.2 Geometry of the Superstructure

This section contains the floor plan of the structures, as shown in Figure 1. The finite element modelling was developed by utilising the ETABS 2016 software. A 3D view of the finite element model is illustrated in Figure 2.

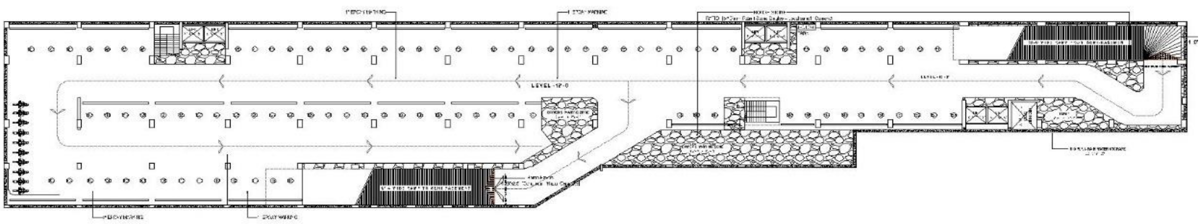

Figure 1: Floor plan of the basement.

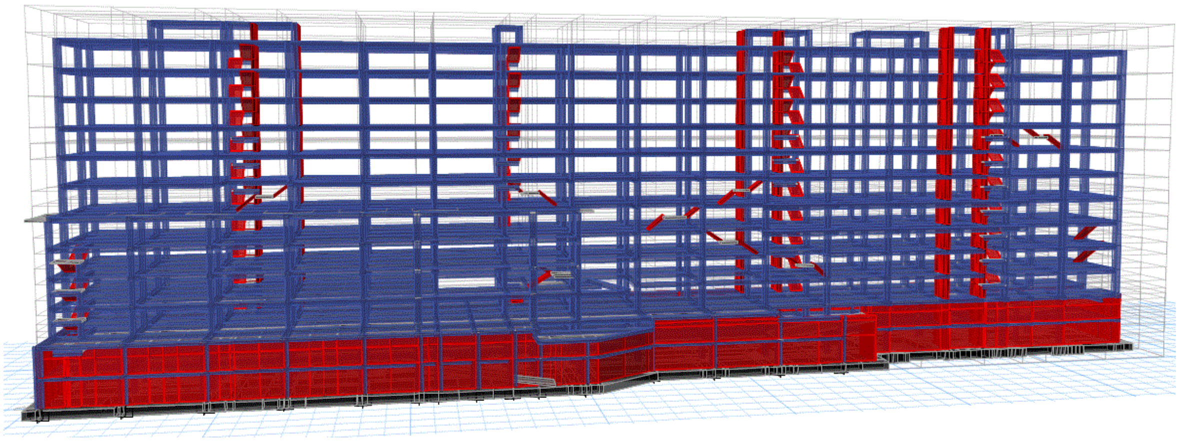

Figure 2: 3D view of the structural model.

2.3 Geometry of the Substructure

The foundation system was the main focus of this study. Among several foundation systems, the piled-raft foundation system was found to be the most effective for this given structure. The layout plan of the pile and mat is presented in Figures 3 and 4.

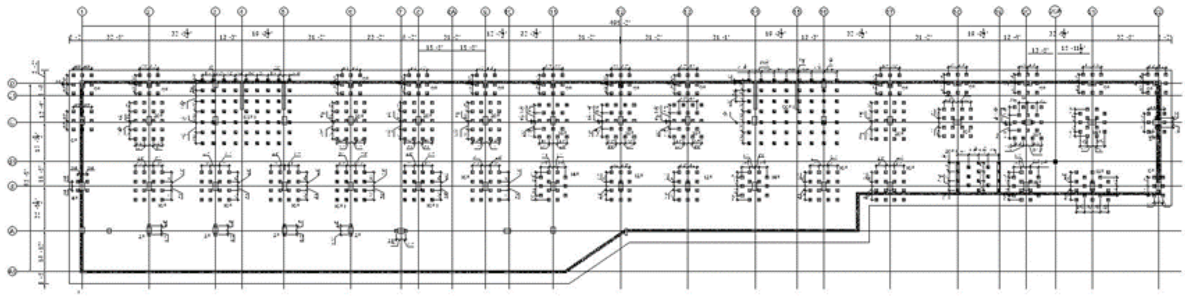

Figure 3: Pile layout plan.

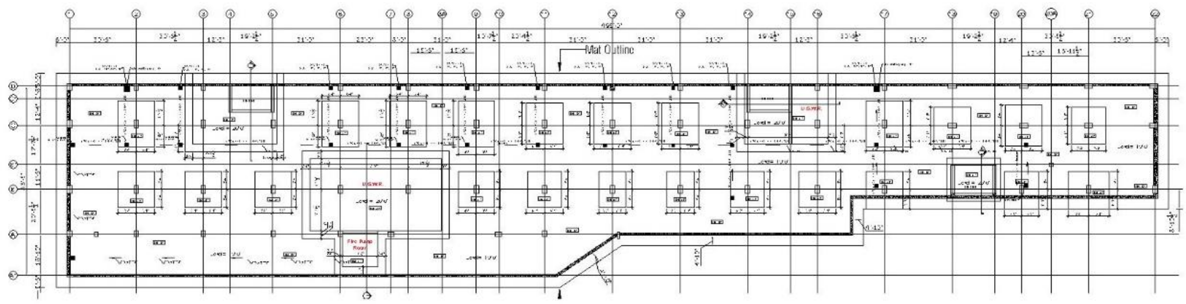

Figure 4: Mat pile detail plan.

2.4 Soil Properties of the Project Site

To find out the soil properties of the site, a total of 18 investigation points were selected. Geotechnical engineering properties derived from the sub-soil investigation are discussed in this section. Here, Figure 5 represents the borehole location plan for the building site. In addition, some studies suggest different correlations between soil densities, SPT N values, and shear wave velocities (Anbazhagan et al., 2016; Cubrinovski & Ishihara, 1999; Marto et al., 2013; Shakeen et al., 2021). Properties of piles and properties of the soil from the subsoil investigations are presented in Table 1.

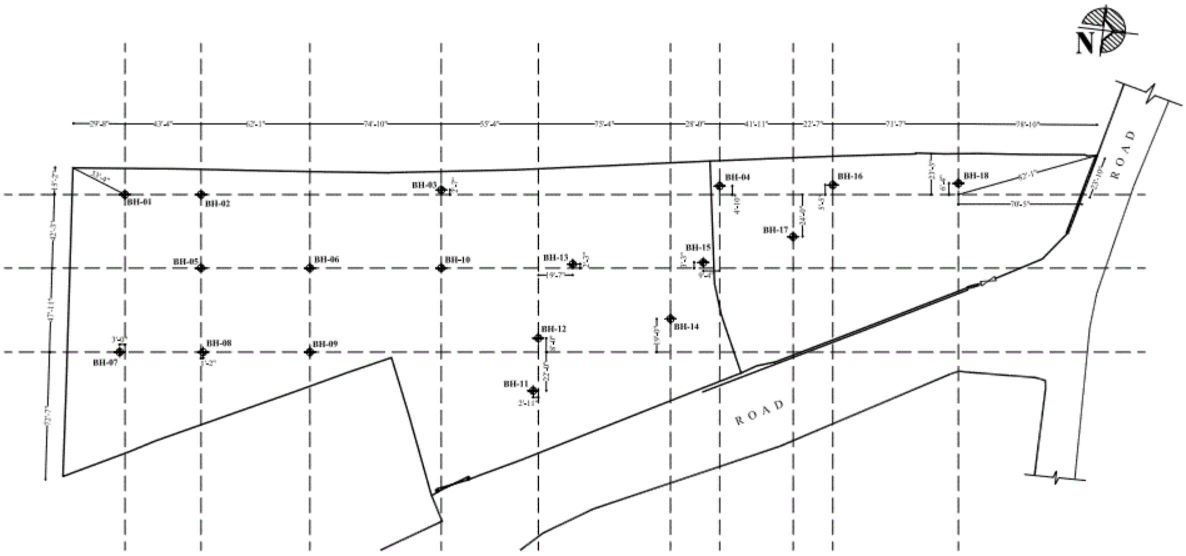

Figure 5: Location plan of the boreholes.

2.5 PLAXIS 3D Model

A soil non-linear model was created with PLAXIS 3D. The steps of soil modelling using PLAXIS 3D are given below. All the data was utilised from the soil test report.

Step 1: Defining the borehole layers: This step was defined with soil stiffness, wave velocity, and shear strength according to the soil test report.

Step 2: Defining the pile cap: Pile caps were defined with properties of pile size, pile area, and the plate types.

Step 3: Defining the piles: In this step, the piles were defined by considering the axial skin resistance, pile section type, and base resistance data.

Step 4: Defining the soil layers: The soil layer was defined by considering the soil properties.

Step 5: Meshing: Mesh structure with medium element distribution and global scale factor was considered.

Table 1: Engineering Properties of the Soil and Piles

Properties of soil and piles	**Layer – 01** Silt, Plastic, Very Soft	**Layer – 02** Sandy Silt, Non-Plastic, Medium Dense	**Layer – 03** Silt, Plastic, Medium Stiff	**Layer – 04** Silt, Plastic, Medium to Very Stiff
F’$_c$ (MPa)	27.58	27.58	27.58	27.58
Modulus of Elasticity of the piles, E_p (MPa)	25076	25076	25076	25076
Pile Area, A_p (mm^2)	165161	165161	165161	165161
Depth (m) (from EGL)	6.1-13.4	13.4-16.5	16.5-32	32-36.6
Avg. N_f	4.42	22.14	7.55	11.47
Shear Wave Velocity, V_s (m/s) Marto et al. (2013)	98.04	187.70	121.64	144.00
Unit Weight of Soil, g (kN/m^3)	18.85	18.85	18.85	18.85
Shear Modulus of Soil, G (MPa)	18.45	67.63	28.40	39.80
Stiffness of Pile, K_v (kN/m)	459329	879385	569907	674662
Avg. C (MPa)	0.0186	-	0.0426	0.0675
Avg. ϕ (degrees)	-	31.31	-	-
q_{all} (MPa)	0.026	0.132	0.045	0.068

FS	3	2	3	3
q_{ult} (MPa)	0.079	0.079	0.004	0.205
K_s (MPa)	0.951	3.180	1.626	2.471

2.6 ETABS Model

ETABS can't directly analyse the constitutive behaviour of soil. Therefore, a spring support was used to represent the subgrade modulus of the soil in the model, just like the hypothetical model illustrated in Figure 6. The spring deformed according to the superstructure load. The deformation values were obtained from the ETABS results and then analysed. This approach allows for the evaluation of the piled-raft foundation system's response to applied loads, providing valuable insights for design considerations and optimisation.

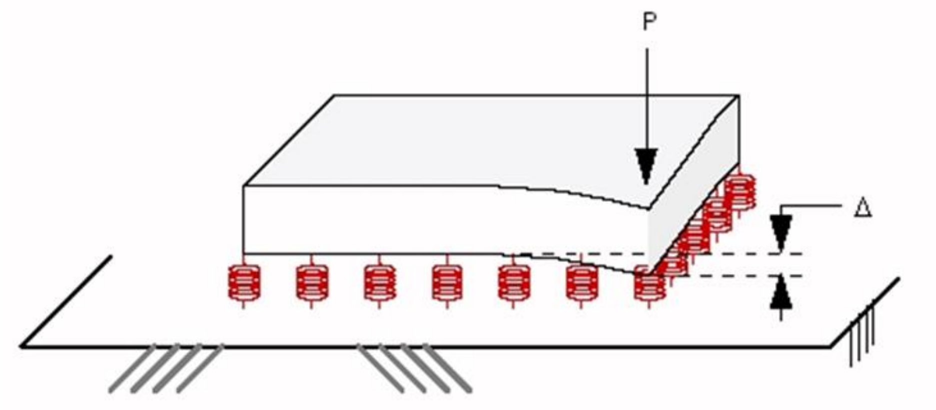

Figure 6: Soil spring hypothetical model

3. RESULTS AND DISCUSSIONS

3.1 Manual Calculation of Settlement

Evaluating the subsurface report, the soil type was found to be pre consolidated. By using Terzaghi's one-dimensional consolidation theory (Terzaghi, 1943),

$$S = \frac{C_c}{1+e_0} \log_{10}\left[\frac{P_o+\Delta P}{P_o}\right] H \tag{1}$$

Where,
S = the consolidation settlement
Cc = 0.3192 from the sub-surface exploration report
P0 = overburden pressure
e0 = 1.26 from the sub-surface exploration report
H is the depth of the layer of soil where the settlement needs to be determined.
P0 = 0.248 MPa
ΔP = 0.054 MPa
By using Equation 1, the settlement was found to be 54.86 mm.
The ultimate bearing capacity is 21.95 mm.
Total settlement = 45.31 mm.
There is another way of calculating pile settlement, which is known as Vesić's method of estimating the settlement (Vesic, 1977).
The settlement caused by the axial deformation of the pile shaft,

$$W_s = \left(Q_p + \alpha_s * Q_s\right)\frac{L}{AE_p} \tag{2}$$

The settlement of pile when load transmitted at the point,

$$W_{pp} = \frac{C_p\, Q_p}{B\, q_o} \tag{3}$$

The settlement of pile due to the load carried by the pile shaft,

$$W_{ps} = \frac{C_s \, Q_s}{D \, q_o} \tag{4}$$

Using Equation 2 to Equation 4,
The total settlement of a single pile, $W_0 = W_s + W_{pp} + W_{ps} = 22.40$ mm

3.2 Settlements from PLAXIS 3D

PLAXIS 3D uses non-linear methods to calculate settlement. The data collected from sub-surface investigations was inputted into soil properties. Then, the settlement was evaluated for 30 days, as shown in Figure 7. The analysis was done for both matt and piled-raft.

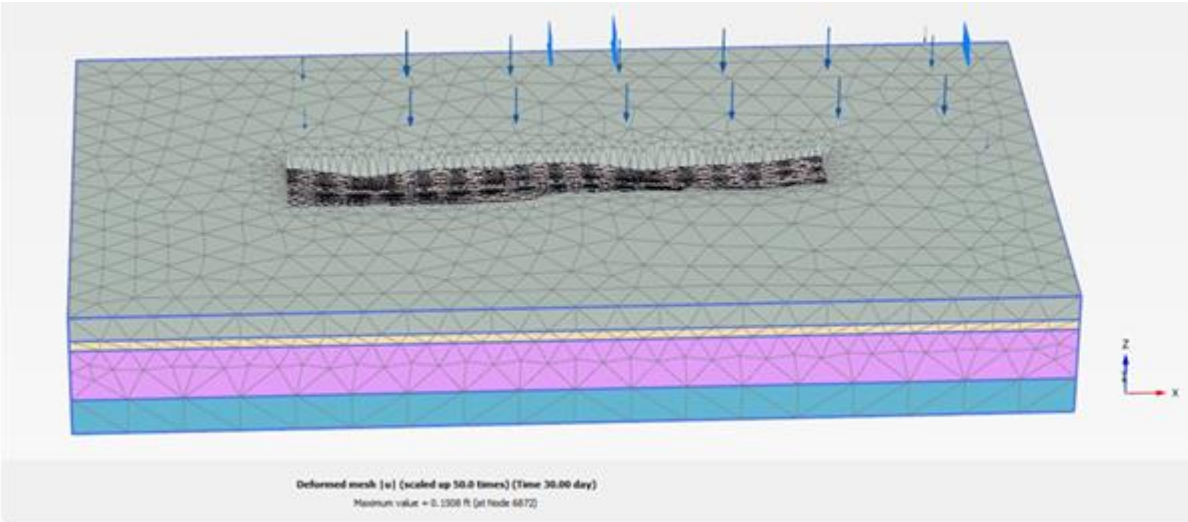

Figure 7: Maximum displacement for 30 days.

According to PLAXIS 3D, the maximum deformation after 30 days was 45.72 mm. After performing the same analysis for 90 days, the maximum deformation was found to be 46.48 mm, as illustrated in Figure 8.

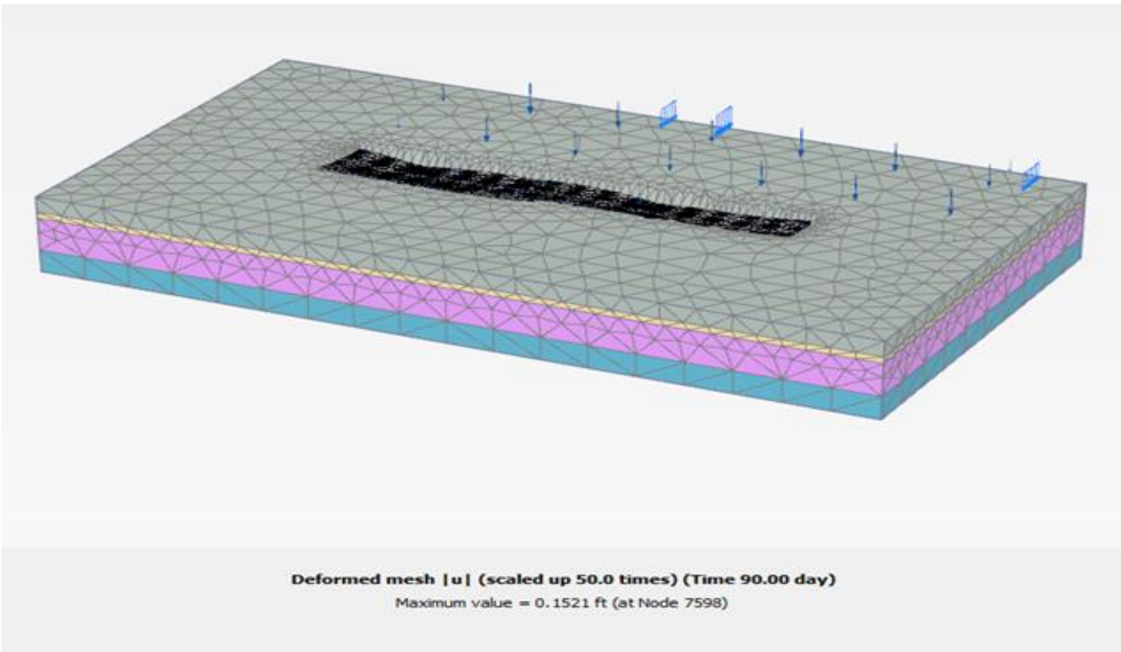

Figure 8: Maximum displacement for 90 days.

3.3 Settlements from ETABS

The maximum elastic deformation was found to be 55.37 mm from the ETABS analysis. For ultimate bearing capacity, elastic deformation was found at 22.15 mm, as illustrated in Figure 9.

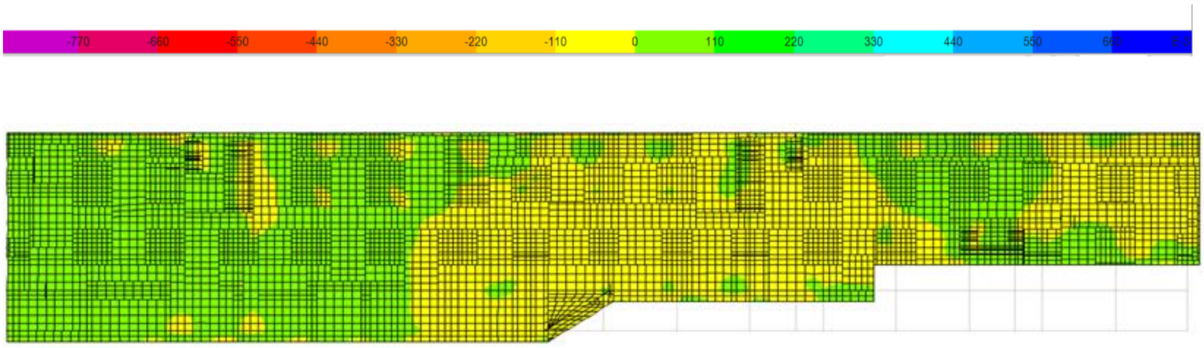

Figure 9: Maximum displacement on ETABS.

3.4 Comparison Among Analysis Methods

The settlements calculated using different methods are presented in Table 2. In combination with manual and numerical analysis, settlements are easily calculated compared to the rigorous non-linear method. Different combinations are shown in Figure 10. The results exhibited that the difference between non-linear and hybrid methods is not significantly different from each other's. However, a combination of linear numerical analysis and theoretical manual calculation could significantly reduce the analysis time and provide reliable data.

Table 2: Settlement value for different methods

Method	Elastic settlement (mm)	Consolidation settlement (mm)	Total settlement (mm)
Terzaghi's 1-D consolidation theory	23.37	21.95	45.31
ETABS 2016	22.15	-	
Vesić's Method	-	22.40	
Plaxis 3d (90 days)			46.48

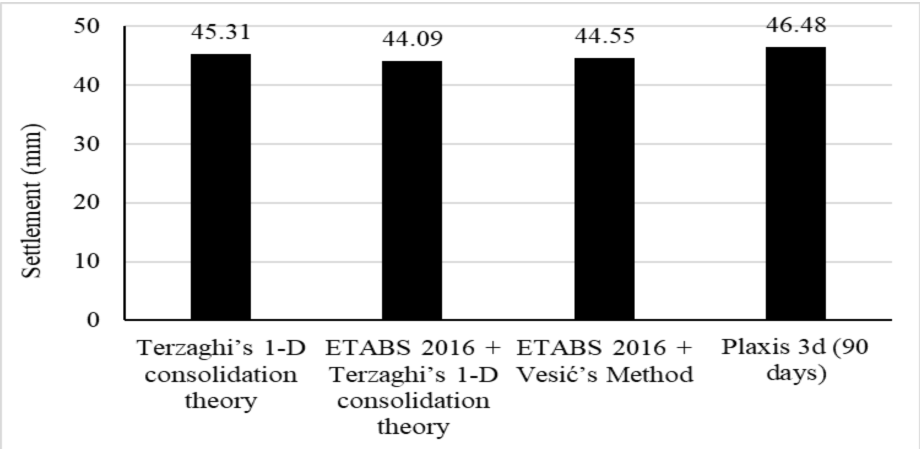

Figure 10: The combination of elastic and consolidation settlement.

4. CONCLUSIONS

After analysing the results, it is concluded that PLAXIS 3D numerical analysis predicts a settlement of 46.48 mm for a consolidation period of 90 days, whereas Terzaghi's 1-D consolidation theory, when combined with ETABS 2016, provides a 5.14% lower settlement prediction of 44.09 mm. Additionally, the combination of ETABS 2016 with Vesić's method yields a settlement prediction of 44.55 mm, which is 4.15% lower than that of the nonlinear analysis. The results describe the importance of the combination of both empirical and numerical approaches. From the proposed nonlinear analysis methods of piled raft foundations by Huang et al. From the proposed nonlinear analysis methods of piled raft foundations by Huang et al. (2011) and Jeong & Cho (2014), it was shown that their methods could forecast almost similar results compared to PLAXIS 3D's results. Here, the present hybrid method also showed very close results compared with nonlinear software analysis result. As the findings of the hybrid linear approaches are very close to those of nonlinear analysis, this method can be used as a potential alternative to nonlinear analysis.

According to the study by Wulandari & Tjandra (2015), a small increase in the number of piles could decrease the settlement. However, after a certain number of piles, the increase in pile numbers has no substantial effect on decreasing the settlement. The same behaviour was observed in this study, as the effective number of piles was found to be 737. No significant reduction in settlement was observed after increasing the pile numbers.

However, time-dependent linear analysis has not been done due to the lack of some soil test results in this investigation. It is recommended to perform tri-axial and shear tests for better predictions in future studies.

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