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A COMPUTER-BASED PROGRAM FOR PILE DESIGN WITH CONSIDERATION OF RESISTANCE, SETTLEMENT, AND NEGATIVE FRICTION SIMULTANEOUSLY

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ABSTRACT: Pile design is an important aspect of construction engineering, and it involves the use of physico-mechanical formulas that are suggested by national standards. Finite element software can be used to validate the results obtained from these formulas. According to design standards, pile group design usually determines the resistance capacity with a large safety factor. This safety factor is meant to maintain the elastic behavior of piles in the soil environment. However, pile group settlement is often calculated based on different theories, such as equivalent rafts, which can make it challenging for engineers to understand piles' resistance and settlement behavior. To overcome this limitation, a study was conducted using a modified Unified Method integrated with MATLAB programming. This resulted in a program that can compute the bearing capacity and validate the elastic behavior of pile-soil interaction while using reasonable safety factors. The program simultaneously calculates piles' bearing capacity and elastic settlement based on unified soil input parameters. The program was verified through the design and construction analysis of the apartment project Connect 1 in Binh Duong, Vietnam. The settlement of piles, the lengths of which were reduced from 29.0 m to 16.5 m, ranges from 2.0 to 4.5 mm, indicating that the pile-soil behavior remains elastic. This demonstrates that the program has the potential to be used in practice, at least allowing engineers to understand the unified behavior of the pile groups.

Keywords: Pile Design, Computer-based Program, Modified Unified Method, Pile Optimization.

1. INTRODUCTION

Piled foundations are commonly used to increase the depth of the footing and transmit loads to soil layers with a high bearing capacity. [1]. When discussing the philosophy behind using piles to reduce settlement and the conditions under which this approach may be successful, many researchers agreed on four scenarios that affect piled foundation behavior [2]. Firstly, if a shallow raft foundation is used, it can result in excessive settlement. Secondly, if a pile group is designed with a large safety factor, the piles bear the entire load, the settlement will be small, and the pile soil behave as elastic. Thirdly, if the pile group is designed with a small margin of safety, the settlement still meets the design requirements, the pile bears most of the load, and the settlement behavior is almost plastic. Lastly, if piles are used as settlement reducers and placed in critical locations, the pile's ultimate resistance capacity is fully utilized. Therefore, understanding the behavior of each pile and the entire pile foundation system can help engineers come up with reasonable foundation solutions.

The development of computer technology has made finite element methods and boundary element methods more popular as they provide faster and more accurate calculation results [3,4]. Various soil constitutive models are used in these programs, but the calculation results are still subject to many uncertainties due to the nature of the soil. In geotechnical engineering, the behavior of geomaterials [5] is often nonlinear and depends on the rate of loads applied to them. In addition, in many cases [6], part of the pile is present in unsaturated soils that are subject to soil suction, which can affect the behavior of the soil. However, according to Lambe [7], the simplest approach to solving geotechnical problems is to treat the subsoil as an elastic material. This allows geotechnical engineers to apply their practical knowledge to predict the actual behavior of the soil. Therefore, the conventional design of pile groups still relies mainly on physico-mechanical formulas, particularly in conventional approaches where engineers with practical experience can easily detect abnormalities from input data and intervene. One of the research directions to keep up with the current trends in science and technology is the computer simulation of pile behavior using traditional calculation formulas.

National codes and standards, as well as conventional concepts, often determine the resistance capacity of piles based on the pile group concept, which comes with a large safety factor. Therefore, this approach [8,9] usually applies the safety factor 2.5 times for toe resistance and thrice for shaft friction resistance. Conventional pile design methods do include a factor to account for negative friction, but

Fellenius' assessment [10] is that negative friction only affects the material capacity of the pile. However, the conventional design concept assumes that the pile-soil behavior is completely elastic at minimum displacement.

In their study, Randolph & Wroth [11] proposed a simple method to determine pile head stiffness for a single pile. They also suggested a proportional relationship between pile head and pile tip resistance. Other studies [12,13] developed the above mentioned method of the estimation of the settlement of a single pile to calculate the settlement of the entire pile groups. However, in reality, the most commonly used methods for calculating the settlement of the whole foundation are the "Equivalent raft" [14] and the "Equivalent column" [15] methods. Nevertheless, these methods do not take into account the interaction between the soil and the pile.

A load transfer method proposed by Coyle & Reese [16] simulates the transfer of load from the head to the tip of the pile through the soil stiffness coefficient. The calculation is iterated with assumed pile displacements and coefficients of subgrade reaction. This method can handle multi-layered soil. However, all these methods [11-13] cannot be used for a pile group because they do not consider the influence of neighboring piles.

There are various simplified computer-based methods available to design pile foundations. Poulos [17,18] proposed methods where a piled raft foundation is simulated as a strip on springs (Geotechnical Analysis of Strip with Piles, GASP), or the entire piled raft is simulated as a plate on pile springs (Geotechnical Analysis of Raft with Piles, GARP). However, these methods have considered the interaction between the piles using empirical factors. Clancy & Randolph [19] and Kitiyodom & Matsumoto [20,21] proposed a hybrid method by combining the Finite Element Method (FEM) and the theory of elasticity. In this method, the behavior of the soil is simulated using springs mounted on rafts or piles of element nodes. This method computes raft-soil-pile, pile-soil-pile, pile-soil-raft, and raft-soil-raft interactions using Mindlin's first solution. Although many advanced pile-soil models have been proposed, the elastic load-displacement model [22] is the easiest model to help engineers visualize the behavior of piles and pile foundation systems.

To summarize, conventional pile design is often evaluated based on the resistance and displacement of the pile at the pile head. However, using the influence coefficient to assess the impact of negative friction does not reflect its true nature. On the other hand, many of the above-mentioned methods analyzed pile behavior, neglecting negative friction or pile-soil interaction, and most of them used different soil input parameters. It is important to note that evaluating a pile's bearing capacity and settlement behavior as separate design items may not bring the optimal solution for each item, resulting in a waste of resources. The unified method and its variants [10,23,24] offer a separate approach to pile design while considering bearing behavior, settlement, and the influence of negative friction. This approach may overcome the mentioned limitations.

In this article, the study presents a simplified computer program developed based on the unified approach. The program uses a combination of standard formulas and Mindlin's elastic pile-soil interaction formula to compute pile resistance and settlement. Its main purpose is to help engineers better understand the unified bearing behavior and settlement behavior of piles and pile groups at the same time. Additionally, the program aims to reduce manual calculation time.

The following sections will discuss the mathematical and pile group models and the MATLAB pseudo codes. Finally, the program's accuracy is verified by analyzing the design and construction of an apartment building in Bình Dương, Vietnam.

2. RESEARCH SIGNIFICANCE

The purpose of this study is to finalize the computer-based program that was described in Cao and Nguyen [24]. The study has made some adjustments to the codes to vary the N-SPT and updated the formula used to calculate the low-strain shear modulus.

The program has been used to verify the pile lengths for the Connect 1 apartment building. Initially, the designer proposed a length of 29 m for the piles but later reduced it to 16.5 m. From a technical standpoint, the designer's decision appears unreliable since it was based solely on the latest Pile Driving Analyzer (PDA) tests, disregarded preliminary calculations, and executed pile load tests.

In contrast, the computed results by this program clearly explain why the piles could be reduced.

3. MATERIALS AND METHODS

3.1 Mathematical Formulas

According to the Modified Unified Method – the Pile Design with Consideration of Down-drag (PDWDD) method, the purpose of this program is to seek pile length so that load, resistance, pile settlement, and soil settlement curves meet at a single neutral plane.

The external load from the structure acts on the pile head, including negative friction, and is distributed along the pile length toward the pile tip [25,26]. It can be written by:

$$P_z = P_{ex,i} + \int U f_s dz \quad (1)$$

Where:

$P_z, P_{ex,i}$: Are the pile load at depth and the load acting at the pile head, respectively;

U : Is the pile's perimeter;

f_s : Is the shaft friction resistance;

z : Is depth along pile length.

The pile's resistance capacity is determined by shaft friction resistance and toe resistance [25,26], as per the following formula:

$$R_z = Q_u - \int U f_s dz \quad (2)$$

$$Q_u = A f_t + U f_s L \quad (3)$$

Where:

R_z, Q_u : Are the pile resistance at depth and ultimate resistance, respectively;

A : Is the pile toe's area;

f_t : Is the unit toe resistance;

L : Pile length;

Pile displacement along its length includes pile toe displacement and elastic deformation of the pile body, which can be determined by [25,26]:

$$s_{pz} = 20 + \int \frac{3P_i}{2E_p A_p} dz \quad (4)$$

Where:

s_{pz} : Pile displacement at depth z ;

P_i : Load acting at pile node i ;

E_p : Is the young modulus of pile material;

A_p : Pile cross-section area.

Settlement of the soil at any location in the half-space is determined according to Mindlin's first solution as follows:

$$s_{ij} = \sum_{i=1}^{n} \left(\frac{P_i}{16\pi \overline{G}(1-v)} \left[\frac{3-4v}{R_{1,ij}} + \frac{8(1-v)^2 - (3-4v)}{R_{2,ij}} + \frac{(z_t - c_{ij})^2}{R_{1,ij}^3} + \frac{(3-4v)(z_t + c_{ij})^2 - 2z_t c_{ij}}{R_{2,ij}^3} + \frac{6z_t c_{ij}(z_t + c_{ij})^2}{R_{2,ij}^5} \right] \right) \quad (5)$$

Where:

$\overline{G}$: Is the average shear modulus of soil;

$z_i, c_j, R_{1,ij}, R_{2,ij}$: Are the parameters as defined in the Mindlin's formula.

v : Poisson coefficient.

3.2 Hybrid Numerical Model

The soil in the hybrid model is simulated as interactive springs connected to pile nodes. The piles are represented as one-dimensional elements. The model is illustrated in Fig. 1.

Loads from the superstructure are distributed to the piles, which are calculated using the SAFE program or another similar program. However, the loads used in this analysis are taken from the design report to compare with the design calculation on the same input data. These loads, including negative friction, are distributed along the pile body using Equation (1). The pile's resistance capacity is computed based on the Vietnamese National Standard, based on Equations (2, 3).

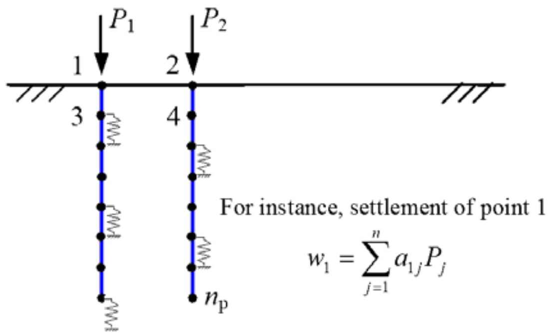

Fig.1 Hybrid numerical model of pile-soil interaction.

Soil settlement is computed based on the first Mindlin solution Equation (5) and follows the model illustrated in Fig. 1. The pile settlement, including pile body deformation, is taken as permissible and computed according to the recommendation of Vietnamese National Standards using Equation (4).

3.3 Matlab codes

The pseudo-code of the algorithm for the pile design program written in the Matlab environment is shown below:

```
InputData: cordinates x,y,z, pile
length,   pile   diameter,   pile
elements, concrete young modulus;
Set up pile data;
Load.m;
Resistance.m;
Piledisplacement.m;
Soilsettlement.m;
function main
Pile Parameter:
    Pile number(t)=;
Soil parameter
```

```
    Nspt=[];% by layer.
    Average N=;
    Pile toe Nspt=;
    Allowable settlement=;
    nuy=;
y1=Load(t,N);
y2=Resistance(t,N,Navr.);
y3=Piledisplacement(t,salw,Econ);
y4=Soilsettlement(t,N,Ntb,nuy);
 Seeking     for     intersection
coordinates
load(['Coc',num2str(t),'.mat']);
    l=Data(:,3);
    [yo12,
xo12]=Lookvalue(l,y1,y2);
    [yo34,
xo34]=Lookvalue(l,y3,y4);
Figures
End
```

In the example of Connect 1, as analyzed below, the program simulates 320 piles, each divided into eight 1-D elements, resulting in 2560 elements and 2880 nodes. The program takes two minutes to run.

4. EXAMPLE

4.1 The Connect 1 Apartment Building

The construction process of the Connect 1 apartment project in Thu Dau Mot City, Binh Duong Province, Vietnam, was used to verify the above-described program. The building is 63 meters long, 53.6 meters wide, and 43.6 meters tall, with 13 floors and a basement. Construction started on June 29, 2018, and was completed on December 30, 2019. The pile arrangement is displayed in Fig. 2.

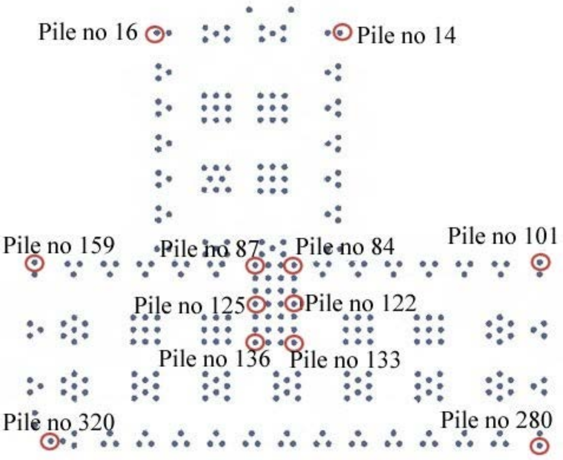

Fig.2 Pile arrangement

SSTCIC Company, which has a registered office in Go Vap District, Ho Chi Minh City, has conducted soil investigations and laboratory tests, including direct shear, triaxial, and consolidation tests. The company carried out three boreholes to a depth of 50.5 m. The underground water level was found at a depth of – 8.5 m. The subsoil below the ground level to the pile toe is composed of three main layers:

The first layer, ranging from -4.5 to -12.1 m, is sandy clay, firm to stiff. The main mechanical criteria for this layer are γ_d =1.73 T/m^3, φ =15^0, C =28 kN/m^2.

The second layer, ranging from - 12.1 to -27.5 m, is fine, medium-dense sand. The main mechanical criteria for this layer are γ_d =1.68 T/m^3, φ =24^0, C =5.5 kN/m^3.

The third layer, ranging from - 27.5 to -33.8 m, is hard clay. The main mechanical criteria for this layer are γ_d =1.7 T/m^3, φ =15.2^0, C =41.3 kN/m^3.

Below these soil layers are layers of sand and clay that are interbedded. Standard penetration tests were also performed in all three boreholes, and N-SPT values versus depth are shown in Tab. 1. SSTCIC engineers propose a pile group foundation with a pile length of about 21.30 m, and the pile tip must be placed in a soil layer with N value > 20.

Table 1 N-SPT value

No.	Soil type	Elev-ation (m)	N-SPT	γ_d (T/m^3)	C (kN/m^2)	φ (^{0})
1	Clay	-4.5	0.0	1.73	28.0	15.0
2	Clay	-5.8	12.3	1.73	28.0	15.0
3	Clay	-7.8	10.3	1.73	28.0	15.0
4	Clay	-9.1	9.7	1.73	28.0	15.0
5	Sandy	-12.1	10.0	1.73	28.0	15.0
6	Sandy	-14.1	10.7	1.68	5.5	24.0
7	Sandy	-16.1	13.3	1.68	5.5	24.0
8	Sandy	-18.1	14.0	1.68	5.5	24.0
9	Sandy	-20.1	16.0	1.68	5.5	24.0
10	Sandy	-22.1	16.3	1.68	5.5	24.0
11	Sandy	-24.1	16.7	1.68	5.5	24.0
12	Sandy	-25.5	18.7	1.68	5.5	24.0
13	Clay	-26.8	22.7	1.68	5.5	24.0
14	Clay	-28.8	14.0	1.7	41.3	15.2
15	Clay	-30.8	18.5	1.7	41.3	15.2
16	Clay	-33.8	18.5	1.7	41.3	15.2

The designer has chosen the pile-group founding method, where the friction piles bear the entire load of the upper structure. The raft's bottom is placed at a depth of - 4.5 m. The layout of the piles is shown in Fig. 2. To determine the load distribution for each pile, they used SAFE software, estimating the maximum load applied to the pile head to be about 1800 kN. Based on Vietnamese standard VNS 10304 – 2014, the pile is designed to withstand this load with a safety factor of 2. From that, the designer recommends using 320 PC piles with a diameter of 500 mm and a length of 29 m for the entire foundation of the building.

The chosen piling method is press-in, but it is challenging to use for 29 m long, and passing through a 15.4 m thick layer of sand is very difficult. The designer recommends pre-drilling before pressing in the piles to ensure smooth piling work. However, when piling the static loading test piles, they can only be pressed into a depth of 21 to 22 m. The results of static loading tests at this length show that the piles have enough bearing capacity so the press-in work can proceed with the project.

As the first piles were pressed in without pre-drilling, it was discovered that their length only reached about 16 to 17 m. Therefore, engineers requested additional PDA tests to confirm the actual bearing capacity. Based on the PDA test results, the engineers decided to reduce the pile length to 16.5 m. It appears that decisions to reduce pile length were influenced more by construction situations rather than technical background.

To simplify the analysis of the project's pile foundation system, the N-SPT value is used in this article. The soil properties obtained from direct shear, triaxial, and consolidation tests are utilized to calibrate the N-SPT value before it is applied to the computer-based program.

4.2 The Computed Results

After reviewing the computed results, it was found that piles at the perimeter of the foundation tend to settle less than piles in the foundation's center. This is consistent with many research [20,21]. Therefore, two groups of piles are selected for further analysis: (1) Six piles that are located on the foundation boundary and (2) Six piles that are located in the center foundation.

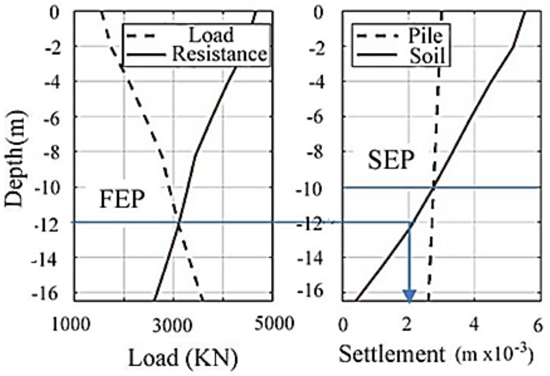

Fig.3 Pile No. 14, an outer pile: SEP and FEP planes

Fig.3 shows the soil settlement and pile displacement equilibrium planes (SEP) and the load and bearing capacity equilibrium planes (FEP) of pile No. 14 from Matlab analysis. The depth of FEP at an elevation of -12m is lower than that of SEP at an elevation of about -10 m, showing that this pile is strong enough to bear the load; the expected settlement is very small, about 2.0 mm. If the above settlement is accepted, the neutral plane is at an elevation of approximately 12 m.

Fig. 4 indicates that the piles on the outer edge of the raft have a displacement ranging from 1.5 to 2.2 mm. The piles appear to be longer than necessary due to the significant difference in elevation between SEP and FEP.

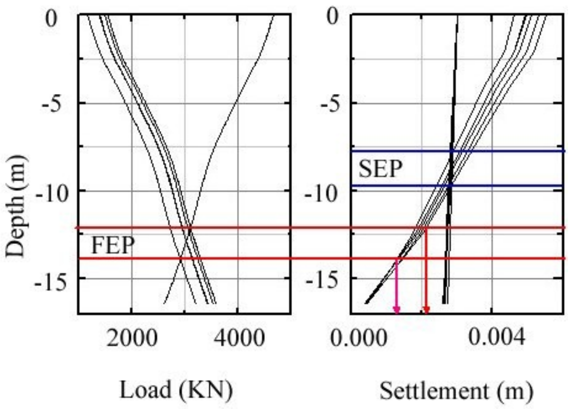

Fig. 4. FEPs and SEPs of the six boundary piles.

In Fig. 5, the results of the Matlab analysis for pile No. 122 are presented. If the allowable settlement of 8 mm is set in the program, the load equilibrium plane (FEP) is shown at approximately -12 m, and the settlement equilibrium plane (FEP) is at a level of -6.5 m. This means that the pile length is reduced or the pile settlement is reduced so that the two equilibrium planes coincide, and then the settlement of the pile will be 4.5 mm or 7.0 mm, respectively. This settlement is larger than the settlement of the edge piles. The trend shows that the piles in the raft's center settle more than the piles at the edges of the raft.

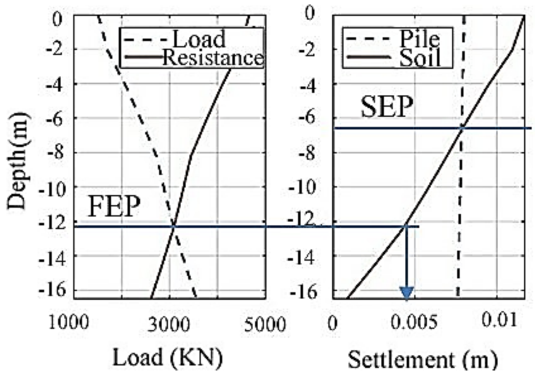

Fig.5 Pile No. 122, a center pile: FEP and SEP

Fig. 6 shows the SEP and FEP in the raft's center area. The zone of load-resistance equilibrium planes ranges from -11.0 to -14.0 m, while the zone of settlement equilibrium planes ranges from -1.5 to -7.0 m. If the allowable displacement of the piles is set so that the two planes coincide, the displacement ranges from 2.5 to 5 mm.

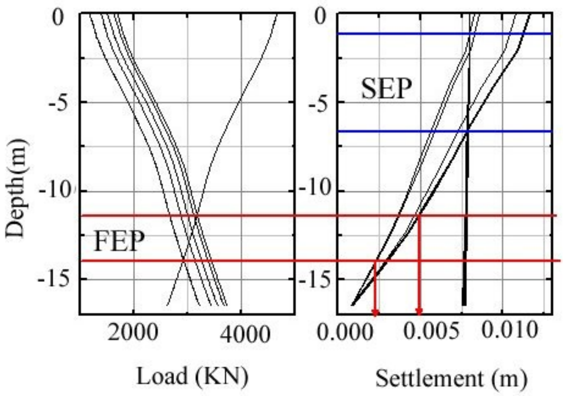

Fig.6 Load-resistance and Settlement planes of six piles at stairs case.

4.3 Evaluation of Computed Results

There are two ways to match the two equilibrium planes SEP and FEP:

(1) Keep pile length unchanged and adjust allowable settlement. In this case, the pile length may be over-designed, resulting in a small estimated settlement. To do so, the SEP must be brought to the same level as the FEP elevation; the settlement is determined at the intersection of the soil settlement curve and the SEP.

(2) Keep the allowable settlement unchanged and adjust pile length. In this case, the pile length may become rational while the pile displacement satisfies design codes. However, repeated calculations are necessary to achieve the optimal pile length, which consumes time.

Based on the curves presented in Fig. 4 and Fig. 6, it has been observed that different piles have different elevations of SEP and FEP. Therefore, piles should be designed in varying lengths to ensure no differential settlement. Piles at the raft's center are commonly longer than the perimeter's.

For the pile head load ranging from 1,165 to 1,688 kN, the computed displacements of 320 piles, each with a diameter of 500 mm and a length of 16.5 m, are varied from 2.0 to 4.5 mm. The static loading tests on three piles of 500 mm in diameter and lengths varying from 21 to 24.5 m, with a 100% designed load (about 1800 kN), determined the settlement to be 3.1mm and 6 mm, respectively. These results were consistent with the program's computed displacement. It can be noted that the plastic settlement from static loading test diagrams was determined to be only about 1.0 mm. This means that the soil-pile interaction still behaves elastically, as the design codes assumed.

The ultimate resistance of a pile with a diameter of 500 mm and a length of 16.5 m was determined using VNS 10304-2014 and found to be 4,661 kN, equivalent to a safety factor of 2.59. However, per two PDA tests, the ultimate resistance capacity was 3,650 and 3,950 kN, respectively, equivalent to a safety factor of about 2.0 and 16% less than the resistance calculated using VNS. The toe resistance calculated using VNS was determined to be 942 kN, but the PDA test results showed that it was about 550 kN, which is 41% less than the calculated resistance.

5. DISCUSSION

Initially, the pile length of the Connect 1 project was designed to be 29 m. However, the test piles could only be pressed into a length ranging from 21 to 24.8 m, so static loading tests were performed on piles of this actual length. Based on the test results, the designer proposed reducing the pile length to 21 m. The first piles of mass-piling could only be pressed into a length of 16.5 m. The designer then proposed performing two additional PDA tests to confirm the resistance of these piles, which showed that the resistance of a 16.5 m pile can reach 3,650 to 3,950 kN, satisfying the required design load of 1,800 kN. Finally, the pile length was chosen to be 16.5 m. Although the decision to reduce the length from 29 m to 16.5 m was correct, there could be more convincing technical reasons to support the change.

The program was used to compute the resistance and settlement, and the results were displayed in graphs. The graphs (see Fig. 3, 5) showed that at the proposed pile length of 16.5 m, the resistance is larger than the load, and the pile's displacement was 2 and 4 mm, respectively. Therefore, the piles with a length of 16.5 m are sufficient to bear the design load of 1,800 kN and ensure soil pile behavior is elastic as per the assumption of the conventional pile group design concept.

The elastic settlement value at the pile head in the program was set to be between 6 and 8 mm based on the results of the static loading test. Therefore, the elastic displacement at the pile tip should be around 2 to 5 mm. This elastic behavior of the pile and subsoil in the pile group remained throughout the project's life to ensure the balance of load with resistance and pile displacement with the soil settlement.

However, the most unstable input data for this program and many other pile design methods are subsoil parameters that are obtained through site and/or laboratory tests, including:

N-SPT value: The program determined the pile's resistance capacity using VNS based on the N-SPT index. However, this index often has a wide range when compared to N60. The lower limit of the N-SPT index is the measured value, while the upper limit is N60.

Elastic shear modulus: The shear modulus value varies when determined using N-SPT. The pile-soil interaction coefficient, determined through Mindlin's first solution, significantly affects the subsoil settlement. The coefficient mentioned is in inverse proportion to the shear elastic modulus. To ensure that the subsoil settlement is elastic, it is essential to consider the low-strain elastic shear modulus.

Negative friction: Negative friction can be activated on a pile when the soil surrounding it settles. Many studies [8] have shown that even a slight settlement of a few millimeters is enough to mobilize maximum negative friction. This means piles are constantly subjected to bear down-drag force due to negative friction, even if the subsoil has only a small elastic settlement.

These parameters can vary greatly, including the N-SPT values and low-strain elastic shear modulus. They could be processed using a machine-learning model. Therefore, multi-objective optimization design research can be a solution that can determine pile length with a variation of the subsoil parameters while still ensuring resistance capacity and settlement criteria.

It is essential to note that, as per Fellenius [20] and many studies, the long-term settlement of the pile group is caused by the consolidation settlement of subsoil below the neutral plane. From the analysis, it can be seen that there are two stages of the behavior of the pile group foundation: the short-term stage and the long-term stage. In the short-term stage, the calculation ensures the balance of bearing capacity with load and the elastic behavior of pile-soil interaction, while in the long-term stage, it calculates the consolidation settlement of the soil layer under a neutral plane. Despite this, this study on the elastic behavior of pile groups remains invaluable.

In summary, this program and the Modified Unified Method promise to design piles considering bearing capacity and settlement immediately after construction. Engineers should use their experience and the elastic settlement calculated from this program to predict long-term settlement using other available methods.

6. CONCLUSION

The program’s results were compared with static loading tests, PDA tests, and the “optimizing process” performed during Connect 1’s piling work. Figs. 4 and 6 display the results computed, indicating that the pile's resistance capacity is greater than the load, and the elastic settlement of analyzed piles ranges from 2.0 to 4.5 mm. The results are consistent with static loading tests ranging from 3.1 to 6.0 mm. The comparisons showed that the program offered a clear explanation for reducing the pile length from 29 m to only 16.5 m. Further study should be conducted to optimize the pile’s length, which may result in an additional reduction.

According to the study, the approaches to the traditional design method are reliable. The separated approaches for calculating pile resistance and settlement for the pile group are reasonable. These approaches correspond to the two stages of design: the initial elastic behavior of the pile and the later calculation of the long-term plastic settlement of the pile group. However, this program can provide engineers with more information on the relationship between pile bearing capacity and load and the elastic soil settlement and pile displacement along the pile length (refer to Fig. 3 to 6).

The parameters such as lengths, diameters, pile head loads, N-SPT value, and shear modulus can vary during computation to justify the results. The formulas included in the program can be customized based on national standards or the engineer's personal experience. This should make the program practical and applicable in real-world situations.

While the study findings appear optimistic, conducting more research and verification to confirm their validity is essential. This includes performing a sensitivity analysis of the primary parameters that affect the program's outputs, such as soil properties and pile dimensions. Such an analysis will provide more profound insights into the study's findings.

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