Estimation for Minimum Reinforcement Requirements Length in Large Diameter Bored Piles with Statistical Analyses of Finite Element Method Resulting

Nopparit Taweechai[1,*] and Li Jingye[2]

[1] *Department of Civil Engineering, Faculty of Engineering, Thammasat University, Pathum Thani, Thailand*
[2] *China Construction Civil Engineering Co., Ltd, Ayutthaya, Thailand*
**Corresponding author; E-mail address: nopparit.taw@dome.tu.ac.th*

Abstract

The purpose of this article is to present the estimation of reinforcement requirement length in large diameter bored piles with statistical results of design with finite element analysis. This study case has been recorded of 4,822 bored piles with dimeter of 1.0, 1.2, 1.5, and 2.0 m. in Thai-Chinese high-speed rail project, contract 4-3: Nava Nakorn to Ban Po, Ayutthaya, Thailand. A practical procedure for defining of reinforcement length in piles has been simulated by pile-soil models under the independent variables of geological drilling and interpretation in engineering properties of soil including pile's properties to compute model with finite element method. The results of finite element analysis have been observed with principle of behavior of long elastic pile to define an effective length due to lateral load condition. The statistical analysis of effective length results in all of bored piles is minimum reinforcement length with 39 percentage of bored pile length. All purposes and recommendations are presented which intend to be used a reliability of finite element analysis together with accumulated its resulting data to obtain final estimation of bore piles with minimum reinforcement case.

Keywords: Estimation, Bored Piles, Reinforcement Requirement, Finite Element Method

1. Introduction

Pile foundations are the type of deep foundation that commonly known as a large diameter bored piles which are the most traditional usage and common form of piling worldwide which are capable of supporting very high loads and coping with complex ground conditions. It is mainly used in the foundations of heavy structures also used in retaining structures and secant bored pile walls. Generally, bored piles are constructed with specified materials of concrete and reinforced steel bar so, it is very important to know the behavior of these mainly requirement. To select and design, it has many approaches or code of standard practices developed to analyze the capacity of the pile foundations with different types of soil. Bored piles are usually cast in place with concrete and reinforcement steel so, the main importance for consideration, it will be a part of concrete material and reinforced steel; however, we can select the type of concrete except reinforced steel complex analysis and design to use how's area of analysis to compute and length of reinforcement requirement for bore pile section. In recent years, Taweechai N., L. Jingyue, and Z.J. Ming (2024) [1] have studied how to apply for defining the minimum reinforcement length in pile for fixed head type by comparison of two methods between non-dimensional solution and finite element, both results are almost nearly approximately answerable with the 0.83 percentage of minimum reinforcement length difference, in the study still has proposed a minimum of reinforcement length equation from modified the relative stiffness factor value in type of variable depth increasing subgrade modulus with all total results of pile analysis in Thai-Chinese high-speed rail project.

So, in this study has the purpose to use the finite element method to find out a solution of how to reinforce the steel bar in bored pile, finite element method has been adopted to analyze the solution of how length of reinforcement steel can be installed on pile shaft, finite element analysis known as a type of numerical method which solution finds out with relationship of mathematical equations. Especially, FEM known as complex solution for engineering useful in design engineering since 1940 finite difference were used to solve a laterally loaded pile's problem with defining of important parametric of soil such as modulus of horizontal subgrade reaction with nonlinear of soil behavior in form of p-y curve to improve coefficient of modulus of subgrade reaction for using in linear type [2] until nowadays finite difference is replaced by finite element due to finite element can be defined in original shape of problems to increase the accuracy of the solution. Finally, in this paper need to compile all statistical results of a large diameter bored pile design in Thai-Chinese high-speed rail construction contract no.4-3 to study the estimate of minimum reinforcement length in bored piles based on finite element analysis, and in this study still will expect that a large bored pile can be considerate with condition of geological drilling test results with parameters interpretation and force on pile condition to apply and adapt how the length of reinforced steel can require to use along the pile shaft.

2. Purpose and scope

In this paper, it will have the main purpose and scope as shown:

1. To compute the bending moment as an independent variable with finite element method.
2. To analyze the result of minimum reinforcement length, LR_{min} as a dependent variable in bored piles.
3. To estimate and summarize the trend of results for minimum reinforcement length in each diameter type of bored piles.
4. To study with example from high-speed rail bridge structure project.

3. Review of finite element in pile foundation

The finite element method is one of the most accurately approximate solution methods that can be applied to solve a wide range of problems represented by ordinary or partial differential equations. The power of such a method derives from the fact that it can easily accommodate changes in the material stiffness which are evaluate at element level will be explained shortly. Also, it allows for different boundary conditions to be applied in such a way that an acceptable global approximate solution to physical problem can be achieved. For basically part of laterally loaded pile can be analyzed as shown in fig. 1. It was shown in a non-linear curve of relationship between soil pressure and lateral displacement or be called in p-y curve with different specify in each soil properties, it will be an advantage to analyze for a subgrade modulus value(k) from non-linear behavior of soil.

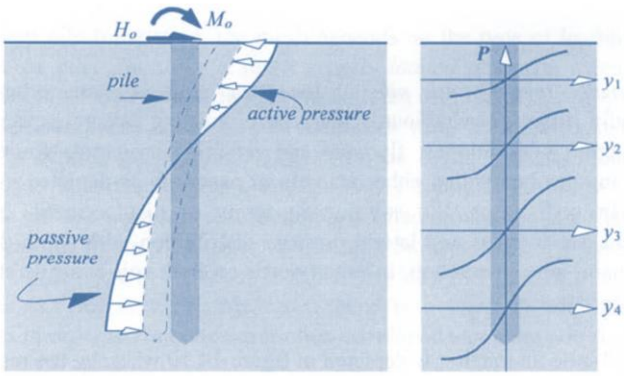

Fig. 1 Soil-structure interaction along the pile shaft of an actively laterally loaded single pile. [3]

Considering that closed form solutions can't be elaborated for a large number of complex physical problems, due to the impossibility of satisfying the boundary conditions related to corresponding equilibrium equations, the finite element method therefore provides an ideal alternative or approximate solution method. For example, the typical 3-D model type of pile-soil interaction for finite element analysis as shown in fig. 2

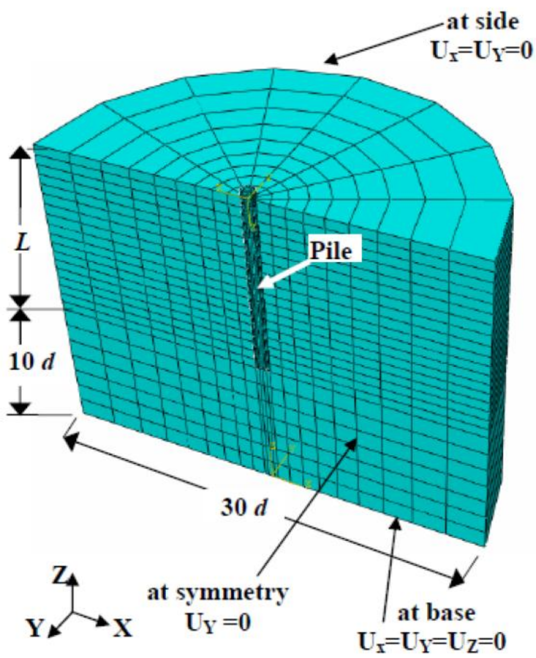

Fig. 3 3-D Mesh and boundary condition for a pile-soil interaction in finite element analysis. [4]

From fig. 3 all combination of model between soil model and pile foundation can be described by the boundary are used for constraint with U_x, U_y, and U_z for analysis condition. To adopt the finite element analysis in pile, the finite element solution is a suitable method to solve complicated deep foundations such as a laterally loaded pile. One can use the same procedure for the beam-on-elastic foundation model described by Bowles, (1996) [5]. The fundamental equations in the finite element method of analysis are following:

$$P = AF \tag{1}$$

$$e = A^T X \tag{2}$$

$$F = Se \tag{3}$$

Where:

P, The external nodal forces

A, Constant of Proportionality

e, The internal member deformation

F, The internal forces

X, The external nodal displacement

S, The stiffness of member

4. Methodology of finite element for bored piles

In this methodology, the pile is considered with the main causes of tensile stresses in a pile section from lateral loads and/or bending moments, to provide the reinforcement length of pile shaft that is subjected to tensile stresses. For this reason, an engineering software with Midas GTS NX was used in analysis to check the result of lateral force effect that will only be required to cover the tension zone of the pile.

4.1 Modelling

To provide the finite element analysis, the most importance is the modelling of structural model problem as shown in fig. 4 for some part of bridge pier between number 1168 to 1173

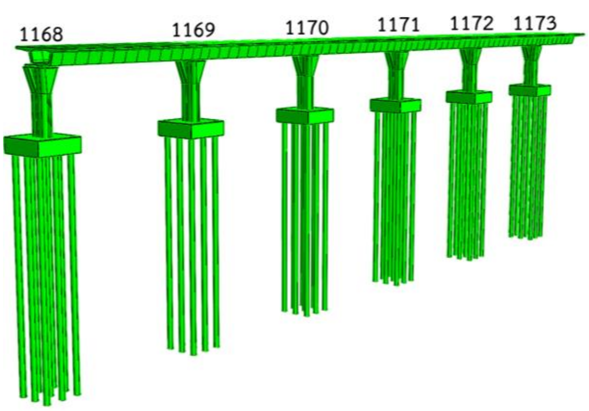

Fig. 4 Example for bridge pier in high-speed rail bridge structure modelling in this project for finite element analysis.

4.2 Geological Condition

Generally, the important parameter from soil investigation is practical process that should be done under area of structure to get an accuracy soil interpretation for using in analysis, for bridge pier 1170 example as shown in fig 5.

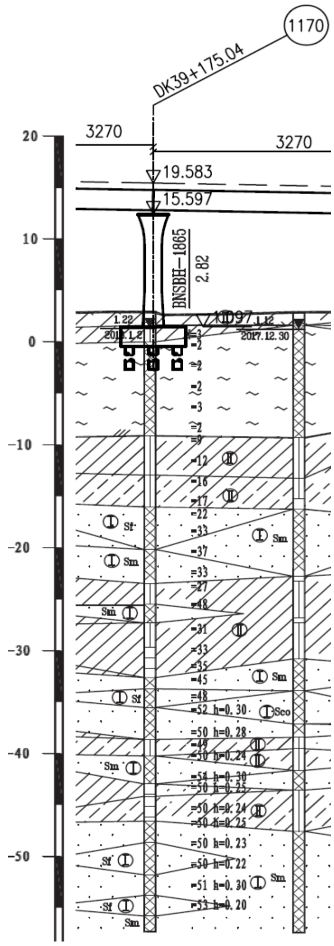

Fig. 5 Bridge pier 1170 combination with geological results.

From geological drilling results in area of Phra Nakorn Si Ayutthaya province as shown in fig 5. The geological results were the layered soil of clay and sand in type of alluvial soils nearly along the Chao Phraya River with upper cover of very soft clay until strength layer of very dense sand and hard clay, for field test in type of soil penetration test value (SPT-N value) increasing along with depth as shown in table 1.

Table 1 Geological result of 1170 location.

Layer No.	Depth		Type of Soil	SPT
	From	To		
1	0.00	-1.30	Very Soft Clay	2
2	-1.30	-9.50	Soft Clay	3
3	-9.50	-15.80	Stiff Clay	12
4	-15.80	-18.90	Very Stiff Clay	17
5	-18.90	-23.00	Medium Sand	17
6	-23.00	-26.30	Dense Sand	37
7	-26.30	-28.30	Hard Clay	43
8	-28.30	-30.10	Dense Sand	48
9	-30.10	-35.40	Hard Clay	35
10	-35.40	-36.50	Dense Sand	45
11	-36.50	-38.30	Dense Sand	48
12	-38.30	-41.40	Very Dense Sand	52
13	-41.40	-43.00	Hard Clay	50
14	-43.00	-45.70	Very Dense Sand	54
15	-45.70	-57.50	Very Dense Sand	50

The basic parameters for clay and sand from interpretation of geological drilling results by reference of geotechnical and index properties [6] as shown in table 2.

Table 2 Specification parameter of clay and sand.

Layer No.	Unit Weight, γ (kN/m3)	Undrained Shear Strength, S_u (kN/m^2)	Friction Angle, $\emptyset$ (°)
1	14.0	14.7	
2	14.5	19.6	
3	17.0	77.5	
4	17.5	112.8	
5	18.0		32.1
6	19.5		37.8
7	20.0	284.5	
8	20.0		40.5
9	19.5	235.4	
10	20.0		39.8
11	20.0		40.5
12	20.0		41.5
13	20.0	326.7	
14	20.0		42.0
15	20.0		42.0

Finally, to analyze with finite element, it is important to interpret the engineering properties of soil in type of stress-strain behavior such as Elastic modulus and Poisson's ratio as shown in table 3. need to be used in Midas GTS NX with interpretation by reference of SPT-N value of geological drilling results [7].

Table 3 Parameters for using in soil model of finite element method

Layer No.	Elastic Modulus, E_S (MPa)	Poisson Ratio, υ
1	1.5	0.42
2	2.0	0.42
3	19.4	0.40
4	28.2	0.40
5	16.0	0.33
6	26.0	0.33
7	71.1	0.40
8	31.5	0.33
9	58.9	0.40
10	30.0	0.33
11	31.5	0.33
12	33.5	0.33
13	81.7	0.40
14	34.5	0.33
15	33.7	0.33

Finally, to compute the soil materials in finite element analysis with Midas GTS NX will use type of isotropic material with Mohr-Coulomb model function for soil in Midas GTS NX.

For basic of Linear Mohr-Coulomb [8] can be described in the equation as shown:

$$\tau = \sigma \tan(\emptyset)+c \quad (4)$$

where:

τ, The shear strength of soil

σ , The normal stress

$\emptyset$, The internal friction angle of soil

c, The cohesion of soil

4.3 Pile properties

In this part of bored pile section and material properties are used in isotropic material in Midas GTS NX as shown in table 4 and table 5 respectively.

Table 4 Specification parameter of bored pile sections

Pile Diameter (m)	Section Area (m^2)	Perimeter (m)	Moment of inertia (m^4)
1.00	0.785	3.141	0.0491
1.20	1.131	3.770	0.102
1.50	1.767	4.712	0.248
2.00	3.142	6.283	0.785

Table 5 Specification parameter of bored pile materials

Concrete (MPa)	Elastic Modulus, E_S (MPa)	Poisson Ratio, υ
30	25,742.96	0.15
35	27,805.57	0.15
40	29,725.41	0.15

4.4 Pile-Soil Interaction and boundary conditions

A bridge structure and bored pile of pier 1170 needs to be merged with soil model and generate mesh all together as shown in fig. 6 to solve with Midas GTS NX for solution.

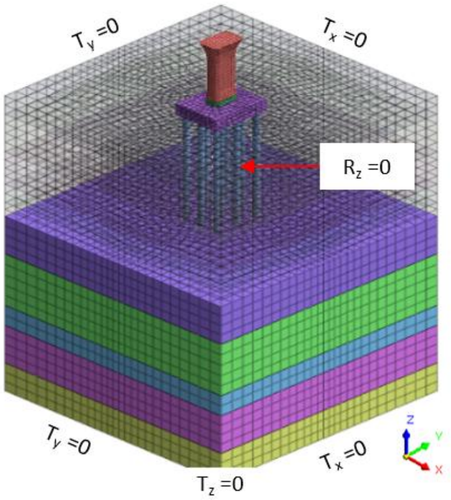

Fig. 6 Meshing and boundary conditions in finite element analysis of bridge pier 1170.

From fig. 3, the boundary conditions for finite element analysis reference in Midas GTS NX, the translation and rotation are replaced with T and R symbol respectively, following:

1. At bottom of model are T_x, T_y, and T_z = 0
2. At side of model are T_x and T_y = 0
3. For pile will use only R_z = 0

4.5 Load condition

From structural analysis, it has a load combination of vertical load and horizontal load with Chinese code [9], in the study will interest in horizontal force which transfer from pile cap to pile head with type of fixed head also maximum horizontal force H as shown in fig. 7.

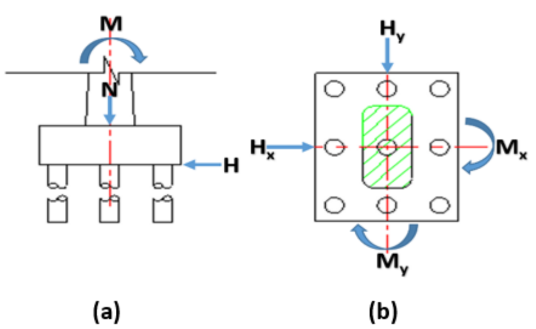

Fig. 7 Vertical load and bending moment direction on pile cap for bridge pier 1170, a) side view and b) top view.

The main horizontal force at 716.214 kN [10] was approximate from earthquake prediction in Phra Nakorn Si Ayuttaaya province, Thailand from defining due to earthquake effect zone of soft Bangkok clay in 2nd group criterion of Thai ministerial regulations for earthquake (2564) together with announcement of ministerial regulation (2564) for earthquake resistance or announcement of DPT 1301/1302 handbook for design and calculation.

5. Results

The finite element of 42.00m length of bored pile of bridge pier 1170 analyze in Midas GTS NX, it has the result of bending moment effect length which can be considered and checked with a length from pile top downward to 12.1 m with less or nearly zero bending moment as shown in fig. 8.

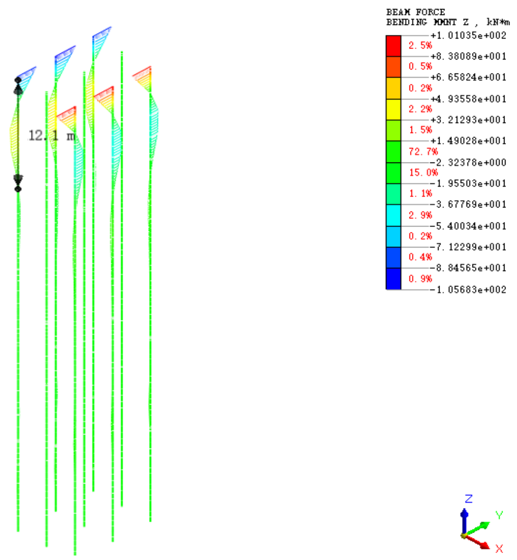

Fig. 8 Part of example for results of pile foundation analysis with lateral load condition in GTS NX.

Therefore, the minimum reinforcement length of bored pile will be combined of bending moment effect length including embedment length of rebar.

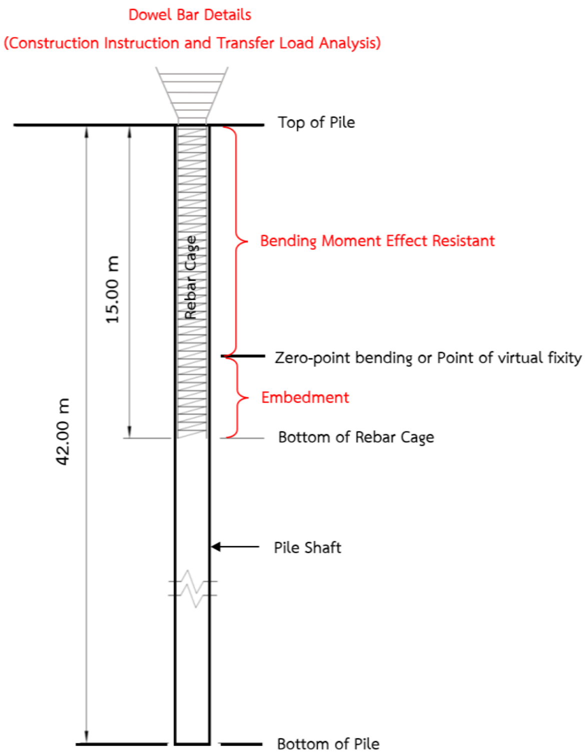

Fig. 9 Total of rebar cage in bored pile shaft for bridge pier 1170

Due to pile cap will be considered as a shell element to analyze for vertical load and bending moment resisting, so the bored pile will be directly supporting a vertical load and shear force will transfer from bottom of pile cap to pile head.

Finally, all bored piles have been analyzed with results as shown in table 6, 7, 8, and 9.

Table 6 Total of bored piles diameter 1.00 m in construction

No.	Shaft Length, m	Reinforcement Length, m	Quantity, piles
1	30.00-35.00	15.00	507
2	35.01-40.00	15.00	971
3	35.01-40.00	16.00	91
4	40.01-45.00	15.00	553
5	40.01-45.00	16.00	79
6	40.01-45.00	17.00	9
7	45.01-50.00	15.00	65
8	45.01-50.00	16.00	70

Table 7 Total of bored piles diameter 1.20 m in construction

No.	Shaft Length, m	Reinforcement Length, m	Quantity, piles
1	25.00-30.00	17.00	20
2	30.01-35.00	15.00	8
3	30.01-35.00	16.00	10
4	30.01-35.00	17.00	30
5	35.01-40.00	15.00	150
6	35.01-40.00	16.00	178
7	35.01-40.00	17.00	188
8	35.01-40.00	18.00	10
9	40.01-45.00	15.00	524
10	40.01-45.00	16.00	509
11	40.01-45.00	17.00	216
12	40.01-45.00	18.00	20
13	45.01-50.00	15.00	56
14	45.01-50.00	16.00	104
15	45.01-50.00	17.00	82
16	45.01-50.00	18.00	10
17	45.01-50.00	21.00	10
18	50.01-55.00	16.00	32
19	50.01-55.00	17.00	12
20	50.01-55.00	18.00	16
21	50.01-55.00	20.00	16
22	50.01-55.00	23.00	20
23	55.01-60.00	17.00	8
24	55.01-60.00	19.00	8
25	55.01-60.00	20.00	16

Table 8 Total of bored piles diameter 1.50 m in construction

No.	Shaft Length, m	Reinforcement Length, m	Quantity, piles
1	50.00-55.00	19.00	42
2	50.00-55.00	21.00	30
3	55.01-60.00	16.00	16
4	55.01-60.00	17.00	16

Table 9 Total of bored piles diameter 2.00 m in construction

No.	Shaft Length, m	Reinforcement Length, m	Quantity, piles
1	45.00-50.00	18.00	24
2	45.00-50.00	19.00	9
3	45.00-50.00	20.00	6
4	45.00-50.00	21.00	15
5	50.01-55.00	19.00	15
6	50.01-55.00	20.00	6
7	50.01-55.00	21.00	9

6. Discussion and Conclusion

As the result was shown in fig. 8 and fig. 9, can be described that bored pile has the bending moment effect in part of upper zone, so the criterion for consideration in minimum reinforcement length, LR_{min} will be considered the bending moment resisting with embedment like a cantilever beam behavior as shown in fig. 10

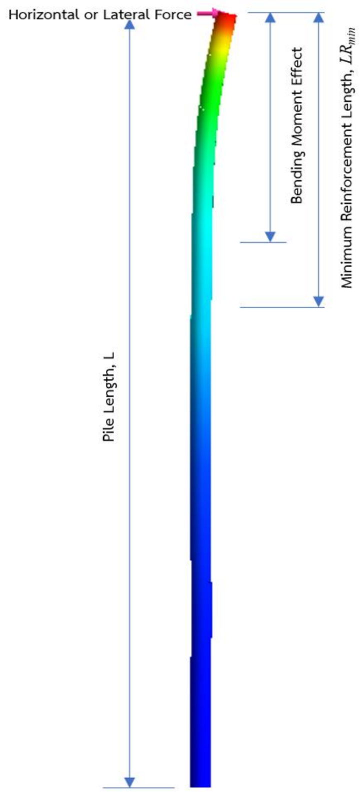

Fig. 10 Simplify of individual bored pile with effect of bending moment to define reinforcement length by FEM result.

Based on the result of finite element analysis for all bored piles can describe that the minimum reinforcement lengths (LR_{min}) as a result of between 15- 21 m or 30- 50 percentage of bored pile length with total statistical result of table 6, 7, 8, and 9 in previous heading as shown in fig. 11, 12, 13, and 14 for the relationship between minimum reinforcement length and type of diameter bored piles 1.00 m, 1.20 m, 1.50 m, and 2.00 m, respectively.

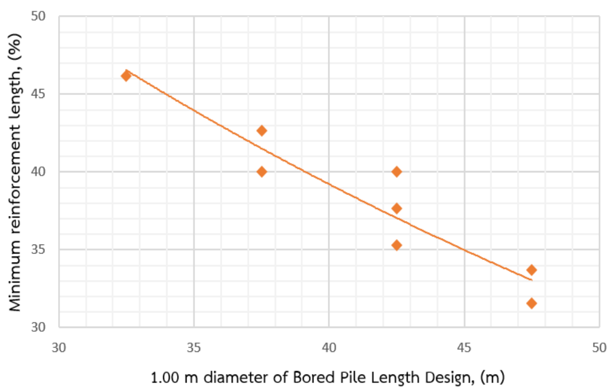

Fig. 11 Relationship for minimum reinforcement length of bored pile with diameter of 1.00 m

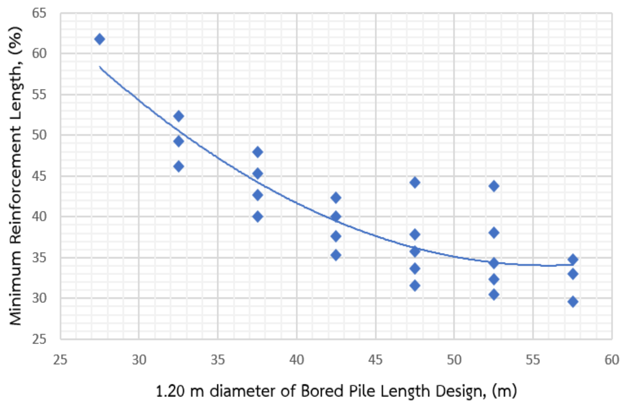

Fig. 12 Relationship for minimum reinforcement length of bored pile with diameter of 1.20 m

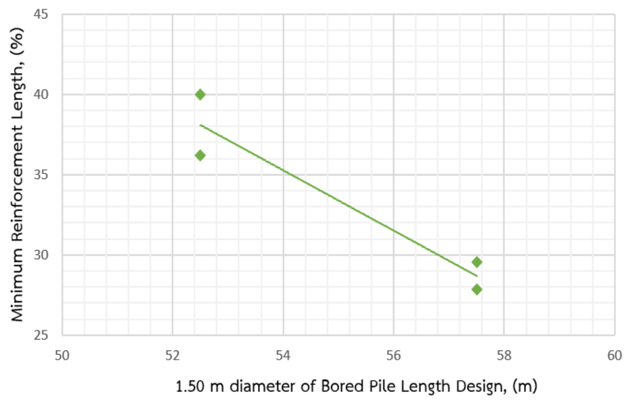

Fig. 13 Relationship for minimum reinforcement length of bored pile with diameter of 1.50 m

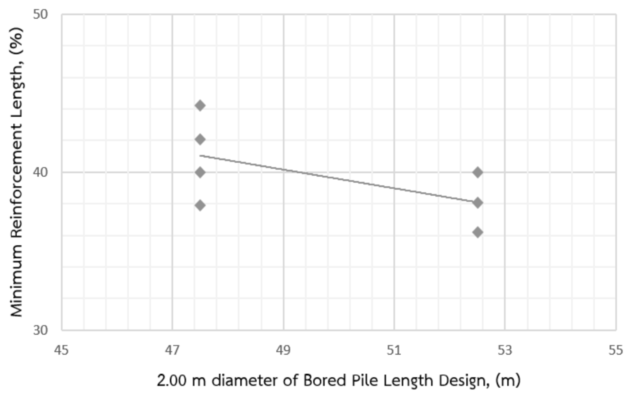

Fig. 14 Relationship for minimum reinforcement length of bored pile with diameter of 2.00 m

Finally, for cast in situ bored piles type, the design for a minimum reinforcement of steel bars should be provided to resist the tensile stresses. Not only the main problem is complex with condition of various soils but also how to model and assembly between the main structure and bored piles is initial importance to use for solving in finite element method. The average minimum reinforcement of all cases can be presented by an interval between 35–45 percentage of bored pile's length and the most value usually use 39 percentage.

In addition to the above conclusion, the following points are found:

1. In this study, presented for minimum reinforcement length, especially for cast in situ bored piles that assumed to have the behavior in long friction pile with pile section area need a minimum requirement of reinforcement area, excepting bored piles type of tension pile and rock socket.
2. An importance for soil model in finite element analysis is considered to use the stress-strain parameter of soil such as Elastic Modulus and Poisson's Ratio, so it is main suffix to interpret these values in appropriate using.
3. The uncertainty of finite element method in this presented paper the reliability in analysis with combination of between bridge structure and layered soil model to generate the pile-soil interaction with boundary condition, also including specified value of Elastic modulus and Poisson's ratio of each soil will be considered as linear Mohr-Coulomb model in Midas GTS NX software for finite element analysis process.
4. A comparison with other analytical method has studied between finite element method and non-dimensional solution [1], the results have shown that both lengths are nearly approximate with 12.0 m for non-dimensional solution and 12.1 m for finite element method, however, the difference of non-dimensional method is a soil parameter using in type of subgrade modulus (k) to define the relative stiffness factor (commonly replaced with R or T) used with depth coefficient to calculate the displacement and bending moment.
5. It will not have any significant influence for tension stress happening in pile to cause a bending moment in upper zone of pile other than important suffix that is a lateral or horizontal force which can be mostly predicted from wind load and earthquake condition.

References

[1] Nopparit Taweechai, Li Jingyue, and Zhang Jiu Ming (2024). *Reinforcement length design in case of minimum for bored piles by analysis of bending moment in long flexible pile under the action of lateral force. 29th National Convention on Civil Engineering, Chiang Mai, Thailand, 29-31 May 2024, pp.1679-1685*.

[2] Davisson, M. T. (1970). *Lateral load capacity of piles*. Highway Research Record No. 333, Highway Research Board, Washington, D.C., pp.107–109.

[3] Fethi Azizi (2000). *Applied Analyses in Geotechnics*. Published E&FN Spon, Inc., pp.727-737.

[4] Mohamed I.Ramadan, Stephen D.Butt, and Radu Popescu (2015). *Effect of padeye depth on the behavior of offshore achor piles under mooring force*. 34th International Conference on Ocean, Offshore and Arctic Engineering, St. John's, Newfoundland, Canada, May 31-June 5, 2015.

[5] Bowles, J.E. (1974). *Analytical and Computer Methods in Foundation Engineering,* The McGraw-Hill Companies, Inc., pp.292.

[6] Bowles, J.E. (1996). *Foundation and Analysis Design*. The McGraw-Hill Companies, Inc., pp.163-165

[7] Bowles, J.E. (1996). *Foundation and Analysis Design*. The McGraw-Hill Companies, Inc., pp.316-317

[8] Fethi Azizi (2000). *Applied Analyses in Geotechnics*. Published E&FN Spon, Inc., pp.224.

[9] National Railway Administration of People's Republic of China (2017). *TB 10002-2017 Code for Design on Railway Bridge and Culvert. Part 4 Load Design*.

[10] Nopparit Taweechai and Zhang Jiu Ming (2023). *Pile foundation design by Chinese standard of Thai-China high-speed rail project construction phase 1 (Bangkok-Nakhon Ratchasima) contract 4-3: civil works (Navanakorn-Ban Po). 28th National Convention on Civil Engineering, Phuket, Thailand, 24-26 May 2024*.