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Modelling and Validation of 3D FEM for Laterally Loaded Single Pile

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Abstract: At present, researchers are increasingly in favour of Three-Dimensional Finite Element Method (3D FEM) during design process to better understand ground mechanisms and soil-structure interactions. Subsequently, it is essentially a back-analysis modelling procedure for applications in design and post-construction or failure investigation. This research aims to use 3D FEM to validate laterally loaded single pile response. Two different case studies are selected, Firstly, a published case study comparing the p-y method and finite element method for the behaviour of single pile subjected to the horizontal forces is investigated. The second case is one of published centrifuge data and finite element method for the behaviour of pile behind retaining wall subjected to excavation-induced soil movement. Through comparison with the results from case studies, 3D FEM is in good agreement with the general trend observed in field or centrifuge measurements and gives better validation or prediction of lateral deflection characteristics compared to other conventional methods.

Keywords: p-y method, 3D FEM, laterally loaded single pile, back-analysis modelling

1. Introduction

This research project explores the behaviour of laterally loaded piles in two different case studies with 3D FEM. A general understanding of the laterally loaded piles was reviewed with the insights of the behaviour of single pile or pile groups subjected to horizontal loading. This research project explores different method of analysis for laterally loaded piles and how 3D FEM could best be used as a reliable tool to predict the behaviour of the laterally loaded piles. The contribution to knowledge could be better understanding on the mechanism of laterally pile by using 3D FEM.

A proper understanding of load transfer mechanism for pile is necessary for analysis and design. The natural of lateral loading can be divided into ‘active’ loading and ‘passive loading’ as suggested by Fleming [7]. Reese & Van Impe [15] considered the active loading as ‘time-dependent or live loading’ and passive loading as ‘time-independent or dead loading’. The active loading could be in the form of wind, wave, current, scour, ice, ship impact; and loads from other sources. Whereas, the passive loading, in the form of earth pressure, moving soil and thrusts from dead loading of structures is also noted.

A study of several types of analysis method and the soil-structure interaction of laterally loaded pile would show the options and suitability for a practical method. Although many methods had been proposed by researchers to solve such problems, the reliability and uncertainties of such methods are open for discussion. Conventional analytical methods such as Broms’ theory, Winkler approach, p-y method and Elasticity theory do require assumptions and empirical data to solve or provide some insights, which can be ambiguous in term of analysis. As such, the 3D FEM is a more reliable and easier tool to study behaviour of laterally loaded piles. The comparison of p-y method and finite element analyses was validated with a case study. The comparison of centrifuge model and finite element analyses was also validated with another case study.

Literature review shows that many researchers [1, 4, 8, 9, 18] favour p-y method and they have proposed a lot of improvement or development [2, 3] to it. However, this method uses a p-y curve as an input to a finite difference program for solutions. In the past, the development of p-y curve is based on centrifuged or full-scale experimental data [13, 16], and the formulation of p-y curve can be characterized under sand and clay. Recent papers from [6, 10] use finite element analysis to generate p-y curve for single pile and pile groups. Their process is rather tedious, but the advantage of p-y method can provide profile of deflection and bending moment of the laterally loaded pile as compared to other methods. But in other means, 3D FEM analysis can better provide better prediction with substantial number of parametric analyses.

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2. 3D FEM Modelling Procedure

2.1 3D Prototype Configuration

In this study, the prototype of the model includes different type of elements in two different studies. The first prototype, case study is to model the behaviour of laterally loaded piles comprise two major type of elements which are soil and pile. The second prototype contain three major type of elements which are soil, pile and retaining wall. The view of different models in the software is presented in Fig. 1.

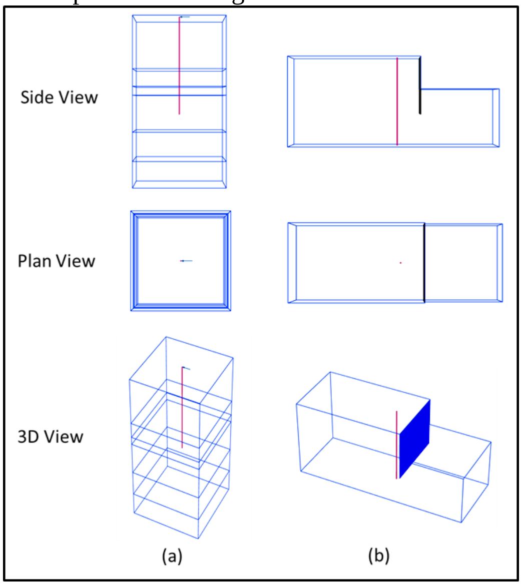

Fig. 1 Prototype configuration of (a) Case Study; (b) Centrifuge Study.

2.2 Parameters for Different Models

2.2.1 Soil Model

There are many different soil models are available in the PLAXIS 3D. Each model has specific usage for different scenarios. The ‘Mohr-Coulomb’(MC) model is still widely acceptable by most researchers for laterally loaded pile problem, as it does not require complex parameters. The advance models like ‘Hardening Soil’(HS), ‘Soft Soil’(SS) and ‘Modified Cam Clay’(MCC) require some technical knowledge on how each model works in certain soil conditions. Hence, MC and HS models are proposed in this project. MC model is chosen for the case study instead of HS because it does not require unloading/reloading stiffness parameters from HS model. However, both MC and HS models are chosen for centrifuge study to understand the difference between the soil models. The material properties of the models for both cases are presented in Table 1 and Table 2.

2.2.2 Pile Model

The pile is modelled using embedded pile model in PLAXIS 3D that is composed of beam elements with special interface elements to describe soil-structure interaction located at the pile skin and foot. The embedded pile model has 3-node line elements with six degrees of freedom per node: Three translational degrees of freedom (Ux, Uy, Uz) and three rotational degrees of freedom (φx, φy, φz). A volume around the pile (elastic zone) is assumed in embedded pile model. This elastic zone is based on the pile diameter according to the corresponding material data set. This makes the embedded pile behaves like a conventional volume pile and does provide a faster computational time during analysis. However, the installation effects of piles are not taken into consideration [14]. Hence, it is suitable to model bored piles, but certainly not driven piles or soil displacement piles. The material properties of this model are presented in Table 3.

2.2.3 Retaining Wall Model

The wall is modelled using plate elements that are composed of 6-node triangular plate elements with six degrees of freedom per node: three translational degrees of freedom and three rotational degrees of freedom. The concept for this element is based on Mindlin’s plate theory. The material properties of this model are presented in Table 4.

Table 1 Soil parameters for the case study [11].

Model	Soil Type	γ_{sat} (kN/m^3)	Cu (kPa)	E (MPa)	ε_{50}	R_{inter}
MC	Upper clay[1]	17.5	15-30	3-15	0.02	0.5
	Lower clay[2]	17.5	30-50	15-25	0.01	0.5
	Silty clay	17.8	70	27	0.005	0.65
	Residual soil[3]	18.0	-	35	-	0.70
Elastic	Weather-ed rock	20.2	-	110	-	-
	Soft rock	20.5	-	200	-	-

1: O’Neil, Matlock p-y curve, 2: Reese p-y curve, 3: ϕ = 34

Table 2 Soil parameters for the centrifuge study [12].

Model	γ (kN/m^3)	E (kN/m^2)	m power	ϕ, phi Ψ, psi	e_{init} e_{min} e_{max}
HS	15.78	6z (z=12.5)	0.77	43° 13°	0.642 0.605 0.977

Table 3 Pile parameters for two different studies.

Pile parameters	Case study	Centrifuge study
E (kN/m^2)	200e6	28.5e6
γ (kN/m^3)	78	24
Pile type	Circular tube	Massive circular pile
Diameter, m	1.0	0.63
Thickness, m	0.016	-
Skin resistance	Layer dependent	Layer dependent
$T_{top,max}$ (kN/m)	-	-
$T_{bot,max}$ (kN/m)	-	-
T_{max} (kN/m)	6900	100

Table 4 Wall parameters for centrifuge study.

Wall parameters	Centrifuge study
E (kN/m^2)	226.4e6
γ (kN/m^3)	78.9
Thickness, m	0.304

3. Case Studies Details

Two different type of studies (Active and Passive loading) are discussed in this paper. Firstly, a published case study is based on field lateral load tests performed at Incheon in South by Kim & Jeong [11]. The ground geology consists mostly of marine deposit. A full-scale of field load tests were performed on six instrumented piles under a free pile head condition. A comparison between finite element and p-y method, covering single steel pile was studied in terms of the lateral deflection and bending moment distribution. A strength and modulus designation on four groupings were generated to summarise the given range of values for undrained shear strengths (Cu) and Young Moduli (E) in PLAXIS 3D simulation. These values were grouped to 'LOWEST', 'HIGHEST', 'AVERAGE' and 'INCREMENTAL' with two different soil layers and are presented in Table 5. 'LOWEST', 'HIGHEST', and 'AVERAGE' designation model constant E in soil layers whereas 'INCREMENTAL' model E in incremental depth. The purpose of this study is to understand how E affects the results. In brief, 'INCREMENTAL' parameters in PLAXIS 3D FEM gives more accurate prediction compared to the p-y method.

Secondly, a published centrifuge study is based on centrifuge model tests conducted at 50g on the National University of Singapore by Leung et al. [12]. The model container has internal dimensions of 540 mm in length, 200mm in width, and 470 mm in height. Toyoura Sand is used in their experiment with supporting literature [5,17]. The model pile is made of a hollow square aluminium tube, instrumented with 10 pairs of strain gauges protected by a thin layer of epoxy. Whereas the model retaining wall is made of an aluminium alloy plate with a thickness of 3.175mm. To simulate the excavation process, the researcher replaces the sand that was placed in the excavated area with a latex bag containing zinc chloride sodium having the same density as the sand. The excavation process starts after a 10-min lapse upon getting 50g in the test, the zinc chloride solution is drained from the latex bag by turning on the valve. In the centrifuge study, two different soil models and mesh investigation have been carried out. The study of different soil models gives us clear understanding on the suitability of each model. Mesh investigation is also important in PLAXIS 3D FEM as the results varies from coarse to very fine mesh. In short, the analysis result of PLAXIS 3D FEM can predict closely with the centrifuge tests.

Table 5 Strength, modulus designation for different parameters of Cu & E.

Strength, Modulus Designation	Layers *	Undrained shear strength, Cu (kPa)	Young modulus, E (MPa)
LOWEST	1st	15.0	3.0
	2nd	30.0	15.0
HIGHEST	1st	30.0	15.0
	2nd	50.0	25.0
AVERAGE	1st	22.5	9.0
	2nd	40.0	20.0
INCREME-NTAL (Figure 2 ,3)	1st	Increment of 0.625 for every 0.548m	Increment of 0.5 for every 0.548m
	2nd	Increment of 2.5 for every 0.5m	Increment of 1.25 for every 0.5m

*1st layer = Upper clay, 2nd layer = Lower clay

4. Results from Case Studies

4.1 Comparison of 3D FEM Results with Measured Data from Case Study

The software modelling of the real behaviour of soil-pile interaction for the different 'Strength & Modulus Designation' on the 3D FEM was demonstrated and only the results of INCREMENTAL' are presented in Fig. 2 and 3. Besides that, the finite element results are also compared with existing p-y curves (O'Neil p-y curve and Matlock p-y curve). The 'LOWEST' and 'INCREMENTAL' designations for both 200kN and 600kN loading cases indicated the closest prediction with the measured field data. 'LOWEST' designation for the 200kN loading case deviates 4.09mm for deflection and 2.8 % for bending moment, whereas the 600kN loading case deviates 9.1mm and 6.5% respectively. In the 'INCREMENTAL' for the 200kN loading case deviates 0.04mm for deflection and 5.1% for bending moment, whereas the 600kN loading case deviates 27.73mm and 7.1 % respectively. As for the p-y method, O'Neil p-y curve is the only close prediction for 200kN loading. The summary of the results is presented in Table 6 and 7.

Table 6 Deflection and bending moment against analysis methods – 200kN loading

Analysis methods – 200kN loading		Maximum Deflection (mm)	Deviation (mm)	Maximum Bending Moment (kNm)	Deviation (%)
Field data	Case Study	20.44	<<Reference	481.08	<<Reference
p-y method	Existing (M*)	32.03	11.59	781.68	62.5
	Existing (O*)	23.60	3.17	540.28	12.3
Finite element method	LOWEST	24.52	4.09	494.49	2.8
	HIGHEST	8.30	-12.13	354.23	-26.4
	AVERAGE	11.75	-8.69	394.10	-18.1
	INCREMENTAL	20.48	0.04	505.63	5.1

M* = Matlock, O* = O'Neil

Table 7 Deflection and bending moment against analysis methods – 600kN loading

Analysis methods – 600kN loading		Maximum Deflection (mm)	Deviation (mm)	Maximum Bending Moment (kNm)	Deviation (%)
Field data	Case Study	106.56	<<Reference	1950.76	<<Reference
p-y method	Existing (M*)	164.68	58.12	3172.64	62.6
	Existing (O*)	140.33	33.77	2794.07	43.2
Finite element method	LOWEST	97.46	-9.1	1823.01	-6.5
	HIGHEST	32.35	-74.21	1227.26	-37.1
	AVERAGE	47.50	-59.06	1421.03	-27.2
	INCREMENTAL	78.83	-27.73	1812.48	-7.1

M* = Matlock, O* = O'Neil

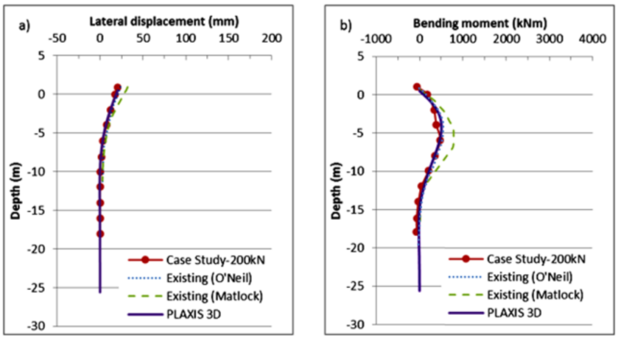

Fig. 2 Response of steel pile for 200kN loading case (a) Lateral displacement vs Depth; (b) Bending Moment vs Depth (INCREMENTAL)

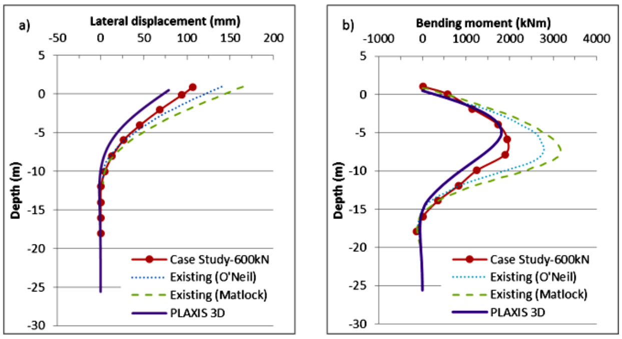

Fig. 3 Response of steel pile for 600kN loading case (a) Lateral displacement vs Depth; (b) Bending Moment vs Depth (INCREMENTAL)

4.2 Comparison of 3D FEM Results with Measured Data from Centrifuge Study

In this study, the analysis is only performed on the final excavation depth (4.5m) from the published paper. All the data from the centrifuge study is adopted for the construct of the 3D finite element model in PLAXIS 3D. Besides that, the results are also compared with two different soil models (Mohr-Coulomb, Hardening soil) and with interface elements. From the presented graph shown in Fig. 4a and 4b, the 'HS-F43 with interface' which has 'Hardening soil' model with interface element indicated the closest prediction with the deflection profile of centrifuge data, however, the bending moment profile for the remaining models as shown in Table 4.3 have poor prediction. 'HS-F43 without interface' and 'MC-F43 without interface' deviate 32% from the measured data respectively. From Table 8, 'Hardening Soil' model for 'HS-F43 with interface' deviates 0.07mm for deflection and 5.8% for bending moment whereas 'HS-F43 without interface' model deviates 2.82mm and 32% respectively. 'Mohr-Coulomb' model for 'MC-F43 with interface' and 'MC-F43 without interface' deviates 4.7mm, 6.23mm(deflection) and 47.1%, 71.1% (bending moment) respectively. In brief, 'Hardening soil' model can predict better than 'Mohr-Coulomb' model, especially in excavation case.

Table 8 Deflection and bending moment against two different soil models (HS & MC)

Comparison of two soil models (HS & MC) on final excavation depth of 4.5m		Maximum Deflection (mm)	Deviation (mm)	Maximum Bending Moment (kNm)	Deviation (%)	Location of Maximum Bending Moment (m)
Centrifuge data		12.46	<<Reference	87.40	<<Reference	7.23
3D FEM	HS-F43 with interface	12.53	0.07	82.35	-5.8	7.40
	HS-F43 without interface	9.64	-2.82	59.46	-32.0	8.58
	MC-F43 with interface	7.76	-4.70	46.21	-47.1	6.36
	MC-F43 without interface	6.23	-6.23	25.25	-71.1	8.28

HS = Hardening Soil MC = Mohr-Coulomb F43 = Friction Angle of 43°

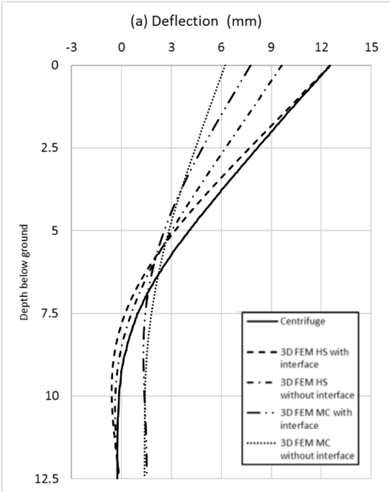

Fig. 4a Response of pile subjected to excavation with different soil models - Deflection vs Depth.

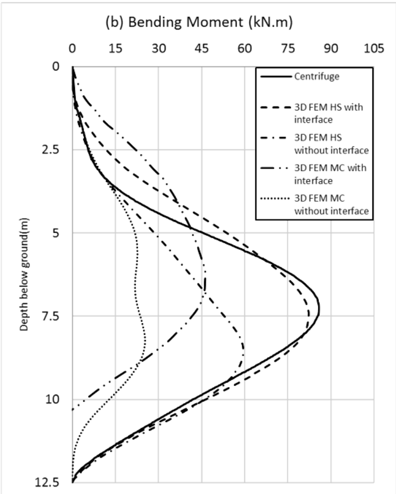

Fig. 4b Response of pile subjected to excavation with different soil models – Bending Moment vs Depth.

4.3 Mesh Investigation

It is important to carry out the analysis of different meshes available in PLAXIS 3D because the type of element and boundary is not the only factors that can affect the accuracy of the results but also depends on the size and arrangement of the element. In PLAXIS 3D, the arrangement of elements is auto-generated by PLAXIS 3D. The purpose of this study is to select the most suitable mesh for 3D FEM. Therefore, 'HS-F43 with interface' model is used as a reference to carry out the mesh study. Five default meshes (very coarse, coarse, medium, fine and very fine) are used in this study. The advantage of using PLAXIS 3D (type specific) finite element software can arrange the elements automatically. The number of soil elements and nodes for the different mesh is presented in Table 9.

In brief, very fine mesh option in PLAXIS 3D discretized the whole model into smaller elements which result in many elements and nodes as compare to other meshes shown in Table 9. Greater number of elements resolved around embedded pile and retaining wall. Besides that, the result of this study was determined based on deflection and bending moment of the embedded pile. Based on the observation from Fig. 5a and 5b, very fine and fine mesh have similar result. As such, both mesh is found to be the most suitable meshes for 3D FEM analysis.

Table 9 Number of elements, nodes and average element size for different mesh.

Mesh	No. of soil elements	No. of nodes	Average element size (m)
Very course	2456	4307	1.172
Course	4197	7113	0.8967
Medium	12233	19445	0.5253
Fine	31460	47785	0.3275
Very Fine	89628	130820	0.1941

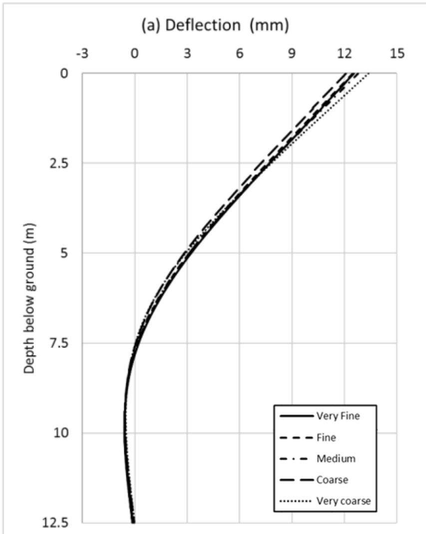

Fig. 5a Mesh results at the excavation depth of 4.5m - Deflection

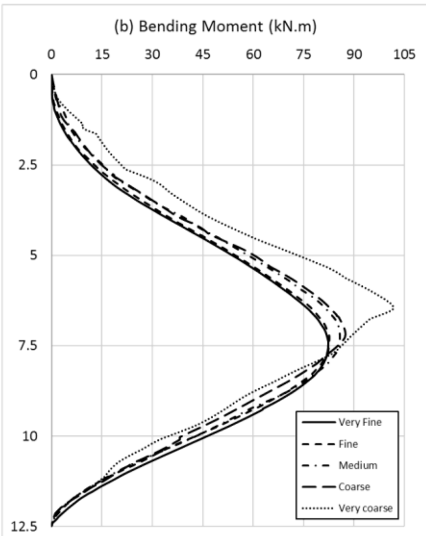

Fig. 5b Mesh results at the excavation depth of 4.5m – Bending Moment

5. Results and Discussion

The purpose of these two case studies is to check the accuracy of the software. Author used PLAXIS 3D version 2013 for both analyses. In the case study, the PLAXIS 3D simulation and the analysis results were validated with the full-scaled field load test in marine clay in terms of pile deflection, bending moment along the length of the pile. In conclusion, it is recommended to use the lowest value for the input parameters if the soil is modelled as one homogenous layer, as such consideration will result more conservative in design. However, if the soil is modelled as non-homogenous layer (Incremental young modulus with depth) one must input the correct parameters in the advanced section of soil model parameters in PLAXIS 3D program. Besides that, the results of 3D FEM shows closer prediction as compared to p-y method. As for centrifuge study, the PLAXIS 3D is carried out to validate with the published data together with two different soil models, with or without interface elements. The results of centrifuge study show that Hardening Soil (HS) model can predict the soil-pile interaction better as compared to Mohr-Coulomb (MC) model because MC models use only a single Young's modulus (E) value, but HS models use unloading/reloading stiffness (Eur) and secant stiffness (E50) which can accommodate different soil stiffness in assessing excavation problems where the stress paths of soil elements behaves in unloading-reloading condition. Therefore, HS model can predict more realistic wall deformations, bottom heave behind wall than MC model especially in excavation condition. The results also show that modelling with interface elements on the wall will get closer prediction to the measured data. Hence, proper input parameters on each model is essential and understanding on the soil behaviour is important to ensure a good interpretation on the 3D FEM results.

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