

Analysis of Single Pile subjected to Lateral Load

Sheng Luo¹

¹ Ranken Railway Construction Group Co., Ltd., Chengdu, Sichuan, 610045, China

*Corresponding author's e-mail: 14691436@qq.com, *phone: 18615720077*

Abstract. Lateral load on a pile can give a catastrophic impact on the foundation itself and the structure above. To assess the pile behaviour, several analytical, empirical and semi-empirical solutions have been adopted in previous engineering practice. In this study, finite element analyses have been conducted for both a slender pile and a monopile. Then the results are compared with a semi-empirical solution. The limitation of the semi-empirical solution is addressed based on the analyses conducted. It is necessary to modify the semi-empirical solution when predicting the behaviour of a monopile under lateral load.

1. Introduction

Civil structures are sensitive to the lateral deformation of their foundations. If the lateral deformation of the pile exceeds what the structure can sustain, tragedy may happen. Potential sources of lateral loads include vehicle acceleration and braking, wind loads, wave loading, debris loading, ice forces, vessel impact, lateral earth pressures, slope movements, and seismic events. [1-5]

It is necessary to find a reliable method to calculate the lateral displacement of pile foundation under the lateral load. Several analytical, empirical and semi-empirical solutions have been used for the past decades in the engineering practice. However, there can be limitations of them once these solutions are usually based on specific assumptions.

2. Semi-empirical Solution

A semi-empirical solution for this problem has been adopted to benchmark the FEA results. This semi-empirical solution is given by Poulos and Davis[6] and a whole example by use of this solution is provided by Prakash and Sharma[7]. The main formulation of the semi-empirical solution for free-head pile can be seen in eq. (1).

$$y_g = \frac{Q_g}{N_h L^2} \left(I'_{\rho H} + \frac{e}{L} I'_{\rho M} \right) \div F'_\rho \quad (1)$$

where $I'_{\rho H}$, $I'_{\rho M}$ and F'_ρ are the empirical coefficients which can be got from the figures provided by Poulos and Davis[6]. y_g means the lateral displacement of the pile head, Q_g means the lateral force on the pile head, N_h is the rate of increase of E_s with depth, L is the length of pile and e is the vertical distance from lateral load to the ground surface.

3. Finite Element Analysis

For the pile design process, usually, it is only necessary to conduct static analyses (sometimes even simplify earthquake load as static one), which consider the largest capacity and deflection of the pile foundation. For this research, the focus is on the deflection of the single pile under lateral design load.



3.1. Geometry

Pile-soil interactions are investigated by modeling the buried section of the single pile and surrounding soil. Considering geometry of the problem and loading conditions, the advantage of symmetry is considered and only half of the model under lateral load is analyzed. Relevant boundary conditions have been used for this symmetric model. The detailed information of the boundary conditions can be seen in a later chapter.

Only the area of the surrounded soil can influence the behavior of the pile, which means, it is only needed to model a certain area of soil instead of the whole earth. Following the popular rule for pile-soil finite element modeling, soil domain of diameter should be larger than $15D$ and depth need to exceed $1.67L$ (as seen Figure 1) so that the boundary effects are not obvious on the simulation results. And the pile is at the centre of domain.

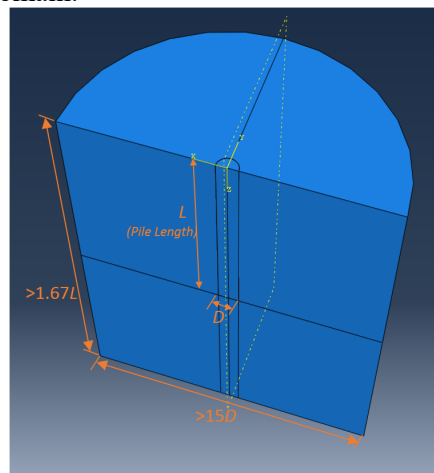


Figure 1. Main geometric parameters for the numerical model

Two models have been simulated in this study. Their detailed geometric parameters which follow the rule displayed in Figure 1 can be seen in Table 1. Both of the two models analyze a free-head steel pile (solid inside) and the lateral load just on the pile head which is at the same height with ground surface. The pile in the first model is slender and relatively long, which is common in onshore projects. On the other hand, the pile in the second model is short and thick as it represents the monopile in offshore projects, especially for wind turbine foundations.

Table 1. Geometric parameters for each model

Model Number	Pile Diameter (mm)	Diameter of soil domain (m)	Pile Length (m)	Depth (m)
1	273	4	9.144	19.144
2	3000	45	30.000	60.000

3.2. Load

For the both models, surface traction has been loaded on the top surface of the pile (see Table 2). Though the position of lateral load may be higher than the ground surface (or the surface of seafloor) in engineering practice, it is still reasonable to simulate this basic situation of which the lateral load is at the same height with ground surface, as it can be a good beginning to establish a reliable method to calculate more complex cases.

Table 2. Value of lateral load

Model Number	Surface Traction Pressure (Pa)	Transfer into Force (N)
1	379824	22241
2	50000	353429

Gravity has been added before the lateral load. Due to the difference of density between pile and soil, two steps are needed to get the initial stress distribution. In the geostatic step, the pile density is

set to the same value with soil when adding gravity. In the following step, body force is added on the whole pile to compensate the density difference between soil and pile. Only after this step, the initial stress can be obtained and then the lateral load can be added in the following step.

3.3 Boundary Conditions

By using symmetry method, the half model has been used for modeling. As the result, the symmetric vertical xz plane is restrained from any movement in the y -direction. The bottom of the soil domain is restrained from any vertical displacement and the curved vertical surface is restrained from any lateral displacement using roller constraints. At the same time, no constraints are applied on the ground surface.

3.4 Contact

The contact between the pile and surrounding soil is modeled using the Coulomb friction model, which defines the friction coefficient μ as $\mu = \tan(\phi_\mu)$, where ϕ_μ is the pile-soil interface friction angle. The value of ϕ_μ depends on surface roughness of the pile and effective angle of internal friction, ϕ' . For smooth steel pipe piles, ϕ_μ/ϕ' is in the range of 0.5–0.7. The value of $\mu = 0.354$ has been used here in these two models.

3.5 Material Model

It is unacceptable to reach plastic stage under the design load for the pile foundation. Once getting the plastic range, the pile fails and excessive deformation may happen. Therefore, elastic model can be adopted for the pile when dealing with design load. On the other hand, as mentioned above, soil is easy to reach plastic stage under a certain strain. Considering past engineering practices all over the world, Mohr-Coulomb Model (MC model) has been chosen for this study. Material parameters of pile and soil can be seen in Table 3 and Table 4, respectively.

Table 3. Material parameters of pile

Material type	Modulus of elasticity of steel E (Pa)	Poisson's ratio ν	Density (kg/m ³)
steel	2.07×10^{11}	0.3	7850

Table 4. Material parameters of soil

Type	Model 1	Model 2
	sand	sand
Young's Modulus (change with depth z) E (Pa)	$4721067 \times z$	$1333333 \times z$
Poisson's ratio	0.3	0.3
Density(kg/m ³)	2000	2000
Friction angel	30	30
Dilation angle	10	10

3.6 Element

The solid homogeneous elements which are 8-noded linear brick elements with reduced integration and hourglass control, have been used for both pile and soil modeling. To avoid shear locking and volumetric locking, reduced integration elements have been used. As the reduced integration elements are prone to create hourglassing, hourglassing control option has to be used here.

3.7 Mesh and Mesh Convergence Analyses

As the main purpose is to analyze the behavior of the pile, finer mesh has been adopted for the pile and the surrounded soil. In other words, coarser mesh (with poor aspect ratio) at the outskirts of the model will not greatly influence the results of the pile.

The size of the mesh usually has a significant effect on finite element modeling. That is why it is necessary to do a mesh convergence analysis to find out a proper mesh size. Mesh convergence analyses have been conducted for both models and the different meshes used for Model 2 in MCA are displayed from Figure 2 to Figure 5. The lateral displacement of the pile head has been considered as the indicator of MCA. The results of MCA can be found in Figure 6 and Table 5. For the purpose of accuracy, the finest mesh in this MCA will be adopted for later discussion.

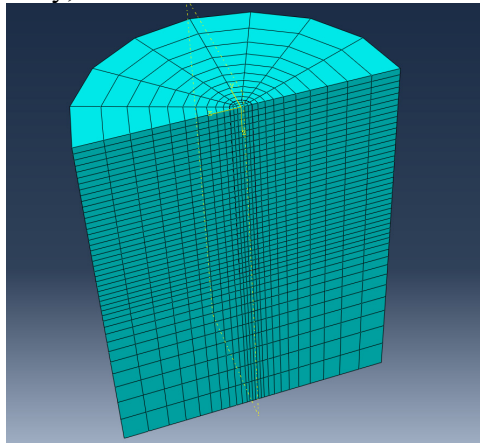


Figure 2. Coarse mesh for No.2 model

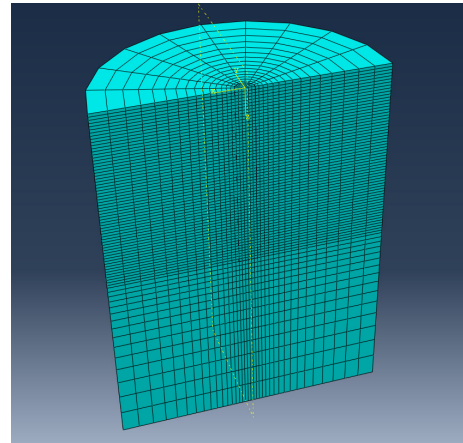


Figure 3. Medium size mesh - 1 for No.2 model

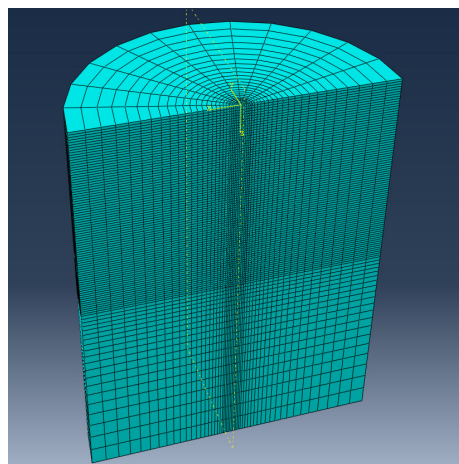


Figure 4. Medium size mesh - 2 for No.2 model

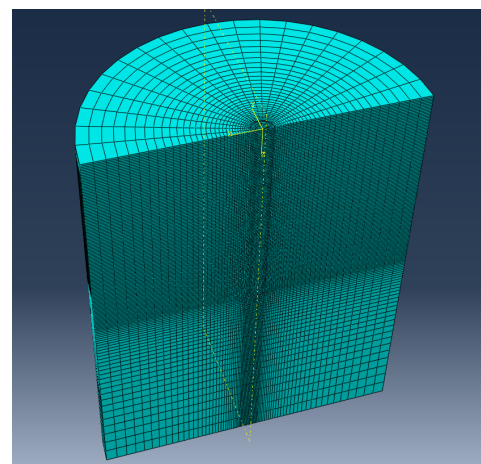


Figure 5. Fine mesh for No.2 model

Table 5. Mesh convergence analyses for the two models

Model number	Number of pile elements	Number of soil elements	x-displacement of pile head (mm)
1	1600	11120	4.154
	3000	23760	4.168
	10400	56640	4.125
	480	3552	3.221
2	1320	11565	3.186
	4080	24980	3.161
	17280	94230	3.132

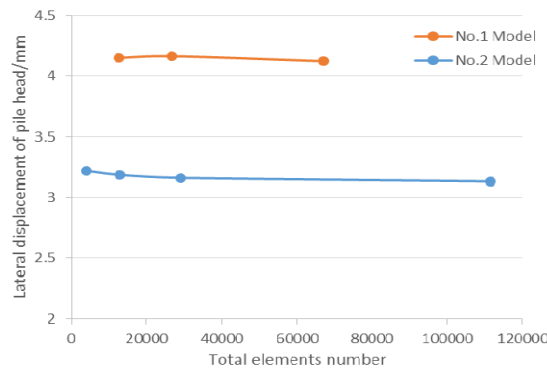


Figure 6. Mesh convergence analyses for the two models

4. Comparison between FE and Semi-empirical Solution

The value of main parameters of the semi-empirical solution are presented in Table 6. Compare with the semi-empirical results, the lateral displacement of the thinner pile (Model 1) in the FE solution is quite close, while the FE solution for pile in Model 2 is smaller than we expected (seen in Table 7).

From Table 7, the FE solution for Model 1 is close to its semi-empirical solution and the FE solution of lateral displacement for Model 2 is less than the semi-empirical solution. There can be several reasons for this phenomenon. The main one might be that semi-empirical solutions or empirical solutions are usually based on specific assumption. As the thick monopiles are not common in onshore projects, it may be not the original purpose of the semi-empirical solution. So when we use this semi-empirical solution to predict the 3m diameter pile behavior under lateral load, it appears a gap between them and the displacement of finite element analysis. The FE results can be seen in Figure 7 and Figure 8.

Table 6. Main parameters for the semi-empirical solution

	Model 1	Model 2
N_h (N/m ³)	4721067.1	1333333.3
L (m)	9.144	30
I_p (m ⁴)	0.000272859	3.976078202
D (m)	0.27305	3
$I'_{\rho H}$	80	22
$I'_{\rho M}$	300	40
Q_g (N)	22241.1	353429.2
F'_p	1	1
e (m)	0	0
y_g (mm)	4.507	6.480

Table 7. Comparison between FE and Semi-empirical solution of the lateral displacement of pile head

	FE solution (mm)	Semi-empirical solution (mm)
Model 1	4.125	4.507
Model 2	3.132	6.480

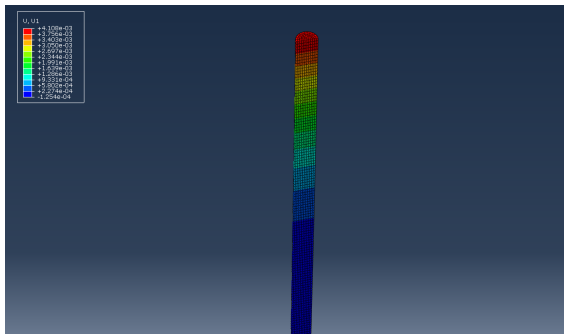


Figure 7. Lateral displacement of Model 1

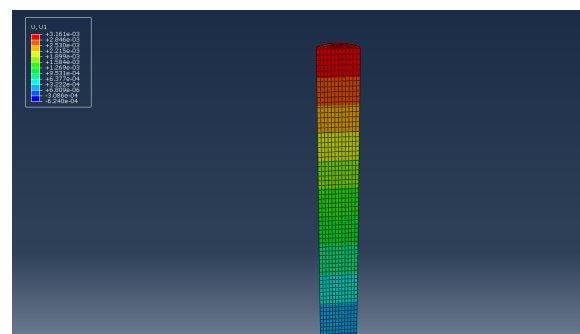


Figure 8. Lateral displacement of Model 2

5. Conclusion

The semi-empirical solution gives close results to the FE analysis when dealing with the slender pile which is more common in onshore projects.

However, there is a gap for the monopile when using the two different analyzing technique. Considering it, the modification will be necessary for the semi-empirical solution to predict the behavior of a monopile.

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