Preliminary 3D numerical pushover analysis of laterally loaded pile groups

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Abstract. This paper reports the results of 3D numerical pushover analyses of laterally loaded pile groups. The effects of pile structural models, soil strengths, and foundations systems are evaluated. Single piles, single pile groups, and multi pile groups are considered in the analyses. The main objective of this paper is to examine important parameters to be considered further. The findings include the overestimation of pile-soil interactions (lower efficiency factors), as well as the highly complex pile internal forces warranting a further examination in the context of high seismic demands in Indonesia.

1. Introduction

Pile foundations – typically used in pile groups – are widely used for construction in Indonesia and worldwide. One of the design criteria is lateral performance of the pile groups. This topic is still examined further in many recent international publications [e.g., 1-7]. The approach to address this topic includes the pushover analysis and the use of non-linear pile-soil interactions [e.g., 8-12].

The Indonesia geotechnical code SNI 8460:2017 [13] stipulates that the maximum lateral displacement of laterally load single piles is 12 mm for nominal seismic loads and 25 mm for strong seismic loads. There have been discussions whether these limits would be compatible with the seismic demands for infrastructures in Indonesia as stipulated in the Indonesia seismic code SNI 1726:2019 [14].

This paper reports the results of a series of preliminary 3-dimensional numerical pushover analyses of laterally loaded pile groups. Different effects are to be evaluated, namely the effect of pile structural models, the effect of soil strengths, and the effect of foundations systems. Single piles, single pile groups, and multi pile groups are considered in the analyses. The objectives of this paper are to assess the suitability of the numerical models used and to examine important parameters to be considered further.

2. Numerical models

The assumed geotechnical conditions consist of two soil layers. The thickness of the upper soil layer is 7.5 m, overlying a 9 m thick, lower soil layer; the basic sketch is shown as figure 1. The undrained shear strength $s_u$ of the upper soil layer is varied to evaluate the effect of the strength on the behavior
of laterally loaded pile groups, while the undrained soil modulus $E_u$ is $150 \times s_u$. The $s_u$ values considered are 20 kPa, 40 kPa, 60 kPa, 80 kPa, and 100 kPa. The $s_u$ and $E_u$ of the lower soil layer are 200 kPa and 50 MPa, respectively. The undrained friction angle of both soil layers is zero, and the groundwater is not modeled explicitly. The soil constitutive model used is the Mohr-Coulomb model. The assumed piles are 500 mm square piles, driven to the top of lower soil layer; the length is then 7.5 m, and the pile tip may numerically rotate freely. The modulus of the piles is 30 GPa. In some analyses, the elastoplastic piles are assumed to have an ultimate bending moment capacity of 400 kN-m. The piles are modeled numerically as embedded piles.

In each pile group, there are nine (9) piles spaced 1.5 m center-to-center, and the pile cap is $4.5 \times 4.5$ m, as shown in figure 2. The stiffness of the concrete pile caps is determined based on a thickness of 1.0 m. For the multi pile group model as shown in figure 3, there are $0.25 \times 0.75$ m concrete tie-beams connecting the nine pile caps, and there are 0.25 m thick concrete floor slabs connected to the pile caps and tie-beams.

The series of analyses was conducted using Plaxis 3D [15], and the so-called “Undrained C” type of analysis (total stress analysis) was implemented. The soil elements were 10-node tetrahedral elements. The embedded pile and the tie-beam elements were 6-node beam elements, while the pile cap and floor slab elements were 15-node thin shell elements. All the elements for $40 \times 40 \times 16.5$ m meshes were automatically generated by Plaxis 3D as shown in figure 1; the number of nodes was between 215,000 and 244,000 nodes, while the number of soil elements was between 157,000 and 178,000 elements. The lateral loads were applied at the pile cap level.
3. Results and discussion

Different effects were evaluated in three series of analyses, namely the effect of pile structural models, the effect of upper soil layer properties, and the effect of foundations systems. For the analysis of pile structural models (elastic piles and elastoplastic piles), the single pile group 1PC9 model was modified by removing the upper soil layer. In addition, the pile tips were restrained for translational movement, but were free for rotational movement. The pile cap was then laterally displaced by an amount of 0.1 m.

The results are shown in figure 4 for both structural models. For the elastic 1PC9, the lateral force increases linearly with an increase in lateral displacement. However, for the elastoplastic 1PC9, the lateral force increases linearly up to a lateral force of 336 kN, and it subsequently starts to behave non-linearly and becomes plastic at a lateral force of about 440 kN. By comparing both results, one could conclude that the elastoplastic pile structural model could provide elastoplastic pile structural behavior.

The effect of upper soil layer properties on the behavior of laterally loaded single piles are analyzed and shown as figure 5. The elastoplastic single piles have no pile caps, and the pile heads were laterally displaced by an amount of 0.1 m. As expected, the initial stiffness of the single pile responses increases linearly with an increase in undrained shear strength $s_u$.

Referring to [13], the lateral loads at 25 mm displacement for $s_u$ values of 20 kPa and 80 kPa are 125 kN and 520 kN, respectively. However, the overall response curves would become more non-linear with an increase in $s_u$. The lateral loads at 50 mm displacement for the above $s_u$ values are about 240 kN and 735 kN, respectively. All these indicate that the soil-pile interaction becomes more complex for greater soil shear strength and modulus.
The behavior of laterally loaded single pile group 1PC9 is analyzed and shown as figure 6. Note that there is a gap between the pile cap and the upper soil layer. The pile heads were laterally displaced by an amount of 0.1 m. Referring to [13], the lateral loads at 25 mm displacement for $s_u$ values of 20 kPa and 80 kPa are about 550 kN and 2340 kN, respectively. The lateral loads at 50 mm displacement for the above $s_u$ values are 1000 kN and 4050 kN, respectively. The efficiency factor for 1PC9 with upper soil layer $s_u$ of 20 kPa at 25 mm lateral displacement is about 0.49 $= 550 \text{ kN} / (9 \cdot$
125 kN)], while that with upper soil layer $s_u$ of 80 kPa is about 0.50 \( [= 2340 \text{kN} / (9 \cdot 520 \text{kN})] \). The efficiency factor for 1PC9 with upper soil layer $s_u$ of 20 kPa at 50 mm lateral displacement is about 0.46 \( [= 1000 \text{kN} / (9 \cdot 240 \text{kN})] \), while that with upper soil layer $s_u$ of 80 kPa is about 0.61 \( [= 4050 \text{kN} / (9 \cdot 735 \text{kN})] \). In addition, the 25 mm and 50 mm efficiency factors for 1PC9 with upper soil layer $s_u$ of 40 kPa are 0.48 and 0.52, respectively, while those for 1PC9 with upper soil layer $s_u$ of 40 kPa are 0.50 and 0.63, respectively. For a lower lateral displacement, the efficiency factor appears to be relatively independent of the soil shear strength and modulus, while for a higher displacement, the efficiency factor appears to increase with an increase in $s_u$. It is highlighted that these efficiency factors tend to be lower than the factors suggested by Reese et al. [16], indicating the models tend to overestimate the interaction among the piles in 1PC9.

The behavior of laterally loaded multi pile group 9PC9 is analyzed and shown as figure 7. Note that there is a gap between the pile cap and the upper soil layer. The pile heads were laterally displaced by an amount of 0.1 m. Referring to SNI 8640:2017, the lateral loads at 25 mm displacement for $s_u$ values of 20 kPa and 80 kPa are about 4 MN and 13 MN, respectively. The lateral loads at 50 mm displacement for the above $s_u$ values are 8 MN and 23.5 MN, respectively. The efficiency factor for 9PC9 with upper soil layer $s_u$ of 20 kPa at 25 mm lateral displacement is about 0.39 \( [= 4 \text{MN} / (81 \cdot 125 \text{kN})] \), while that with upper soil layer $s_u$ of 80 kPa is about 0.30 \( [= 13 \text{MN} / (81 \cdot 520 \text{kN})] \). The efficiency factor for 9PC9 with upper soil layer $s_u$ of 20 kPa at 50 mm lateral displacement is about 0.41 \( [= 13 \text{MN} / (81 \cdot 240 \text{kN})] \), while that with upper soil layer $s_u$ of 80 kPa is about 0.39 \( [= 23.5 \text{MN} / (81 \cdot 735 \text{kN})] \). These efficiency factors were lower than the factors for single pile groups, indicating complex interactions among pile groups. It is highlighted that these efficiency factors again tend to be lower than the factors suggested by Reese et al. [16], indicating the models tend to overestimate the interaction among the pile groups in 9PC9.

Figure 6. Lateral load vs displacement for single pile group (1PC9) for various $s_u$ (elastoplastic pile, gap beneath pile cap)
Figure 7. Lateral load vs displacement for multi pile group model (9PC9) for various $s_u$ (elastoplastic pile, gap beneath pile cap)

The pile lateral displacement, bending moment, and shear force for 1PC9 with upper soil layer $s_u$ of 20 kPa at 100 mm lateral displacement are shown in figures 8, 9, and 10, respectively. It can be seen that the pile lateral displacement in figure 8 is not exactly uniform, caused by the complex interaction among the piles. The pile bending moment diagrams shown as figure 9 in general are different among the piles, and the maximum pile bending moments occurred in the connection between the piles and the pile cap. The trailing piles (piles in the back) have the highest pile bending moments ($375 - 385$ kN-m), while the middle piles have the lowest bending moments ($295 - 363$ kN-m). For lateral displacement smaller than or equal to 10 mm, the leading piles (piles in the front) have the highest bending moments and the trailing piles (piles in the front) have the second highest bending moments, while the middle piles have the lowest bending moments. The piles would not experience pile structural plastification at the same time, an important feature warranting a further examination in the context of high seismic demands in Indonesia [14].

The pile shear force diagrams shown as figure 10 in general are different among the piles, and the maximum pile shear forces occurred expectedly in the connection between the piles and the pile cap. The average maximum pile shear forces for the leading and trailing piles is about $256$ kN and $210$ kN, respectively, while that for the middle piles is about $134$ kN. This difference in pile shear force is also an important feature warranting a further examination in the context of high seismic demands in Indonesia [14].

4. Conclusions
The results of numerical pushover analyses of laterally loaded pile groups using Plaxis 3D were reported in this paper. The effects of pile structural models (elastic and elastoplastic models), soil strengths, and foundations systems (single piles (P1), single pile groups (1PC9), and multi pile groups (9PC9)) were evaluated. The highlighted observations are as follows:
• The pile structural models could provide the expected elastic and elastoplastic pile foundation system behavior.
• The single pile behavior is a function of soil shear strength and modulus, and the behavior would change for more complex soil-pile interactions.
• The pile group efficiency factor for single pile groups appears to be relatively independent of the soil shear strength and modulus for a relatively low lateral displacement, but it would change for more complex soil-pile interactions. The efficiency factors observed in the 3D models appear to be lower than the factors typically suggested in literature.
• The pile group efficiency factor for multi pile groups was lower than the factor for single pile groups, indicating complex interactions among pile groups. The efficiency factors observed in the 3D models again appear to be lower than the factors typically suggested in literature.

The pile internal forces (bending moments and shear forces) are highly complex. The pile structural plastification and the pile shear ultimate behavior would not occur at the same time, important features warranting a further examination in the context of high seismic demands in Indonesia.

**Figure 8.** Lateral displacement diagram for single pile group (1PC9) at lateral displacement of 100 mm ($s_u = 20$ kPa, elastoplastic pile)

**Figure 9.** Bending moment diagram for single pile group (1PC9) at lateral displacement of 100 mm ($s_u = 20$ kPa, elastoplastic pile)
Figure 10. Shear force diagram for single pile group (1PC9) at lateral displacement of 100 mm ($s_u = 20$ kPa, elastoplastic pile)

5. References
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