A hybrid approach to investigate the group effect of a small-scale model pile under uplift loads

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ABSTRACT

For over 50 years, research on piles under uplift loads has primarily focused on single piles with less attention paid to the group capacity and efficiency of pile groups embedded in sand. Methods can be grouped into analytical, semi-empirical (combining theoretical and experimental methods) and experimental methods. However, these methods do not always account for the effect of the influence zone of an individual pile within the group, the interaction mechanism within the group and the combined shape of the group during the application of an uplift load. Despite decades of research in this area, these pile group actions are still not clearly understood. This study investigated the influence zone of a single micro-pile under uplift loads and the effect of pile spacing to diameter ratio (*s/d*) on the behavior within a pile group. A hybrid approach combining analytical method and numerical analysis were used which resulted a block shaped influence zone when an uplift load was applied at close pile spacing.

Keywords: group efficiency; uplift load; influence zone; numerical analysis; analytical method

1 INTRODUCTION

For over 50 years, research on the shaft resistance of piles has primarily been focused the capacity of piles under axial compressive loads. Various equations have been developed for estimating for group efficiency in compressive loads such as the Converse-Labarre formula (Bolin, 1941), Bakeer and Sayed (1992) and 1/8 empirical rule. In addition, various building codes also provide guidelines for the design of piles under compressive loads such as the National Building Code (1976), the Basic National Building Code (1993) and Building Code of Chicago (1994). In contrast, considerably less research has been undertaken on pile groups under uplift loads as noted by Gaaver (2013), Das et al. (1976), Chattopadhyay (1994), and Patra and Pise (2003). Current research methodology carried out on group efficiency under uplift loads can be categorized as analytical, experimental or numerical analysis. In this study, an analytical method and numerical analysis were combined to analyze the group efficiency of a pile subjected to uplift loads. The influence zone of a single pile under uplift loads was investigated first by a hybrid approach combing analytical method and two-dimensional finite element analysis (2D FEA). Then the effect of pile spacing to diameter ratio (*s/d*) within a pile group was studied using three-dimensional (3D FEA).

2 LITERATURE REVIEW

2.1 Influence zone

Randolph and Wroth (1978) used concentric cylinders in shear to idealize the soil deformation around a pile shaft. By ignoring the second-order terms in the differentiation equation, and assuming insignificant change in vertical stress in respect to vertical direction and displacement being predominantly vertical, the vertical force equilibrium, shear stress distribution and inferred influence zone (relating to the shear stress and displacement of the surrounding soil) at distance (z) above pile toe are obtained in Eq. (1-3) respectively.

$$\frac{\partial[\tau_r(z)\, r]}{\partial r} + r\frac{\partial \sigma_r(z)}{\partial z} = 0 \qquad (1)$$

$$\tau_r(z) = \frac{\tau_0(z) r_0}{r} \qquad (2)$$

$$w_r(z) = \frac{\tau_0(z) r_0}{G} \ln\left(\frac{r_m}{r}\right) \qquad (3)$$

Where $w_r(z)$, $\tau_r(z)$ and $\sigma_r(z)$ are the induced vertical displacement, vertical shear stress and effective vertical stress in the soil mass at the radial distance (r) away from the pile center respectively, G is the soil shear modulus, $\tau_0(z)$ is the induced shear stress at pile shaft, r_0 is the pile radius, and r_m is the radial distance away from the pile where the induced shear stress becomes negligible.

2.2 Analytical and semi-empirical methods

Madhav (1987) adopted the boundary integral technique to study the interaction between two identical piles in tension. The reduction in individual capacity was found to be dependent on the pile spacing (s) and length to depth ratio (L/d). It also found that the reduction factor decreases with the increase of spacing and was greater for long piles than short piles.

Patra and Pise (2003) proposed a simplified method to predict the ultimate capacity of a pile group based on the experimental observations that the soil between the piles was displaced simultaneously with the piles as they were displaced. The group capacity is contributed by the components of the shear resistance of the enclosed block and the self-weight.

Shelke and Patra (2008) based their study on the observed rupture surface of single screw anchor from Ghaly and Hanna (1994) to predict the net ultimate uplift capacity of driven pile groups in sand considering the arching effect by limit equilibrium analysis.

Shanker et al. (2013) used the experimental results to suggest a semi-empirical method to predict the uplift capacity of the pile group by considering the overlapping of the failure surfaces of individual piles.

2.3 Experimental Method

Heins (1976) presented the results of the field pulling tests performed in 1972 for the construction of sluices, weirs, and tunnels by the Netherlands government ministry, Rijkswaterstaat. The results demonstrated that the group effect on the pulling capacity is higher in the center piles than the edge piles.

Das et al. (1976) performed small-scale model tests for the uplift capacity of buried single and group rough wooden piles. This research concluded that the isolation spacing was about 4 to 6 pile diameters. Das (1986) performed further laboratory model tests to investigate the uplift capacity of single and group metal piles embedded in saturated, medium and dense sand. The group efficiency was observed to decrease with the increase in the number of piles, soil denseness, and *L/d* ratio.

Das and Azim (1985) conducted laboratory model tests to investigate the ultimate capacity of group steel piles embedded in clay. It was found that the group efficiency increases approximately linear and reaches a magnitude of about 100% at *s/d* ratios of about 6 to 7. The group efficiency decreases with the increase of *L/d* ratio and the number of piles.

Gaaver (2013) conducted tests on vertical steel piles to understand pile behavior of single piles and pile groups. The pile diameter was 26mm and *L/d* ratios were 14, 20 and 26 embedded in cohesionless soils with different relative density. The tests showed that efficiency decreases with an increase in the number of piles and *L/d* ratio, but an increase in the relative density of the cohesionless soil can slightly increase efficiency.

Sadhukhan and Borthakur (2015) conducted tests on micro-pile groups and observed that the group failed as a block at very close spacing with higher group efficiency. Efficiency was at its lowest at mid-spacing and piles failed as individual piles. This was explained by the overlapping of the plastic zone developed inside soil mass. Group efficiency increases as spacing increases.

2.4 Numerical Method

There has been limited research undertaken using numerical methods to investigate the behavior of pile groups.

Kranthikumar et al. (2016) used 3D FEA to examine the effect of the number of piles, *L/d* ratio and construction effects on the group efficiency for granular anchor piles (GPA) in loose sandy soil. The results showed that group efficiency decreases with an increase in the number of piles under constant spacing (due to the overlapping of the stresses transmitting in the piles to the surrounding soil) and increases as pile length increases. A 10% lateral strain was applied to a single pile and group piles to stimulate the effect of construction. The lateral strain increases the uplift capacity, but the group efficiency decreases.

3 ANALYSIS AND MODEL IN THIS STUDY

3.1 Hybrid approach

The initial part of this study adopted a “hybrid” approach by combining analytical and numerical analysis to investigate the influence zone of a single pile subjected to uplift loads. A study of a pile with a *L/d* ratio equal to 30 was conducted. The extent of influence zone was back-calculated by taking the results from the 2D FEA model and using these in the analytical method. Shear stress and vertical displacement were calculated along the pile shaft from the 2D FEA model and then input into the concentric cylinder equations (Eq. 2 and 3). The vertical shear stress and displacement in surrounding soil mass along the radial distance away from the pile center under concentric cylindrical theory were compared to the results of 2D FEA by adjusting an influence zone number in the concentric cylindrical equations. This number is taken as the extent of influence zone of the pile under the uplift load.

An axisymmetric model was developed in the 2D FEA software PLAXIS 2D. Details of the model are summarized in Tables 1 and 2. The total number of soil elements used were in the order of 15,000 with an element size of approximately 0.015m (Fig 1).

Table 1. Soil parameters for FEA axisymmetric model.

Constitutive Model	Cohesion (c)	Internal Friction (ϕ)	Poissons Ratio (υ_s)	Modulus of Elasticity (E_s)
Mohr-Coulomb	1 kPa	30°	0.3	10 MPa

Table 2. Pile parameters for FEA axisymmetric model.

Constitutive Model	Modulus of Elasticity (E_p)	Poissons Ratio (υ_p)	Length (L)	Diameter (d)
Linear elastic	30 GPa	0.15	3.0m	0.1m

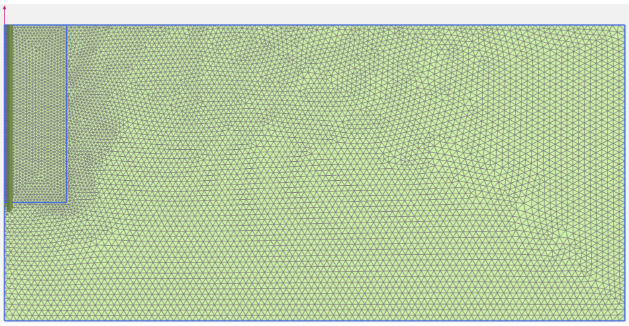

Fig. 1. FEA PLAXIS 2D Axisymmetric model

The comparison of vertical shear stress ratio (τ_r/τ_o) and displacement of soil along the radial distance (r) away from the pile between analytical concentric cylindrical theory (Eq. 2 and 3) and FEA at the mid-depth section of the pile are shown in Fig. 2 and 3.

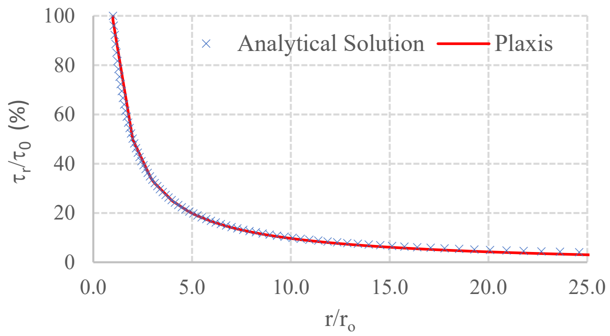

Fig. 2. Shear Stress Distribution in Soil

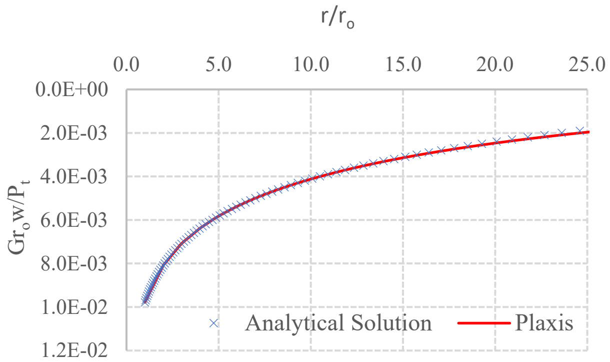

Fig. 3. Dimensionless Vertical Displacement of Soil

A comparison between the FEA and analytical solution show a close correlation in predicting behavior of a single pile. Results between the FEA and analytical solution are consistent. The inferred influence zone obtained in this study is about 2-2.5m (20-25d) away from the pile center. Outside this zone, the induced shear stress becomes negligible.

3.2 Three-dimensional Numerical Model

A 3D FEA model was developed in PLAXIS 3D. This model used volume piles to investigate the effect of the s/d ratio on the behavior of a pile group with pile spacings varying from 0.4m to 3.0m at 0.2m increments (equating to a total of 14 different analyzed scenarios). The number of soil elements and element size around the pile were respectively about 750,000 and 0.015m (Fig. 4). To eliminate any difference in mesh that might affect the results, one model was used to maintain the same geometry and mesh for varying pile spacing. Volume piles were then activated across the different pile spacing scenarios analyzed (Fig. 5).

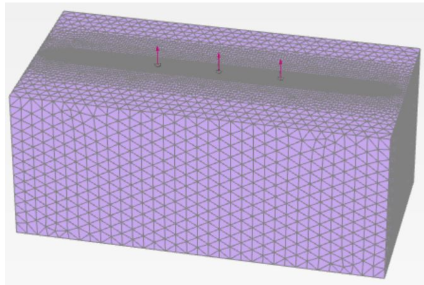

Fig. 4. Volume Pile Model by FEA PLAXIS 3D

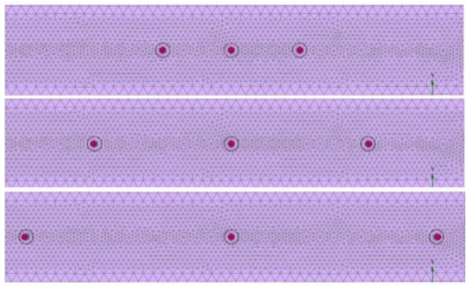

Fig. 5. Top View of 3D Model: (top) 1.0m, (middle) 2.0m and (bottom) 3.0m spacing (other models not shown)

Results from the 3D FEA models are provided in Fig. 6. The group efficiency (the ratio of the mobilized vertical load in the central pile of a group to single pile at a prescribed vertical displacement) against different pile spacing is plotted in the left axis in Fig. 6. The right axis of Fig. 6 shows the vertical shear ratio (τ_r/τ_o, the ratio of the mobilized vertical shear stress to that at the pile shaft) in the soil mass along the radial distance, which demonstrates the effect of shear ratio on the group efficiency. It shows that group efficiency obviously reduces when adjacent piles are located within the influence zone where the vertical shear stress ratio is still significant. This indicates that shear ratio, influence zone and group efficiency are closely related. Piles displace as a block was observed for piles at close spacing (Fig.7), and the group effect is mobilized.

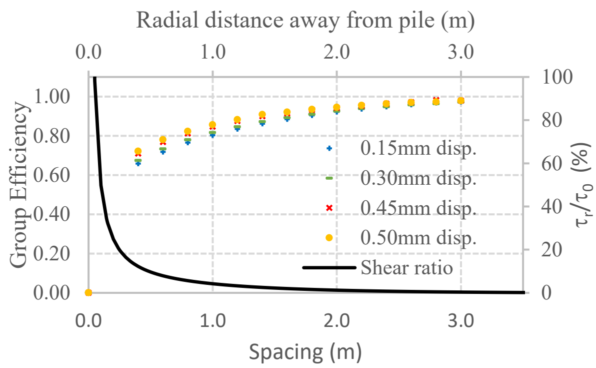

Fig. 6. Results of FEA PLAXIS 3D

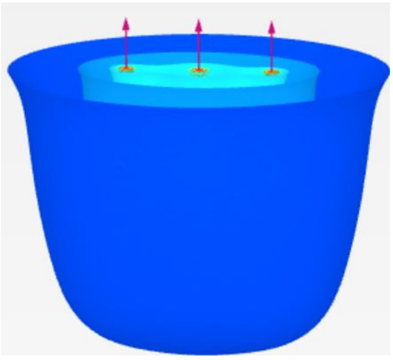

Fig. 7. A combined block at close spacing

4 CONCLUSIONS

A hybrid approach combining concentric cylindrical theory and numerical analysis has been undertaken to investigate the influence zone and the effect of *s/d* ratio for a pile under uplift loads. The pile of *L/d* ratio equal to 30 was analyzed. Results indicate that shear ratio, influence zone and group efficiency are closely related. The inferred influence zone under this approach is approximately 2.0m (20*d*), which is higher than previous empirical guidelines such as 8*d* prescribed for compression loads with no relation to the *L/d* ratio. Many researchers already emphasized group efficiency reduces at higher *L/d* ratios. From this study, it is recommended to include the factor of *L/d* ratio when investigating the effect of pile spacing on group efficiency.

In addition, O'Neill (2001) and De Nicola and Randolph (1993) noted that the induced effective vertical stress of surrounding soil is different under compression and uplift loads. van Baars and van Niekerk (1999) also identified that the principal stress rotations under compression and uplift loading are different. Based on the above and the results of this study, it may be concluded that the influence zone is different for piles under compression and uplift loads. In the next step of this research, laboratory tests will be conducted to optimize and verify this hybrid approach.

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